Annual Report to NOAA July 1, 2008 - June 30, 2009

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NOAA Award Numbers

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- NA08OAR4320754 July 1, 2008 to June 30, 2013
- NA08OAR4320912 (shadow) July 1, 2008 to June 30, 2013
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Preface

Document Purpose

The annual report for the Cooperative Institute for Climate Applications and Research (CICAR), a Cooperative Institute (CI) funded by the National Oceanic and Atmospheric Administration Office of Oceanic and Atmospheric Research (OAR), is a requirement of the OAR CI Program. The CICAR annual report describes all actively funded research projects, education initiatives, and public information and outreach programs conducted under CICAR NOAA grants NA03OAR4320179, NA08OAR4320754, and shadow award NA08OAR4320912 for the fiscal year ended June 30, 2009.

Looking forward to FY10 the CICAR annual report presents a window to future research activity as well as the Institute’s administrative and public outreach program development. As a contributor to the OAR Cooperative Institute Program, CICAR research will, on a yearly basis, actively address NOAA’s mission goal to “Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond.”

Document Distribution

The CICAR annual report is distributed in hard and soft copy to the NOAA/OAR Cooperative Institute Program Office and is available in PDF version on both the NRC CI web site and the CICAR web site. Copies of the report will be made available to the members of the Columbia University, Earth Institute, and Lamont-Doherty administrative and scientific communities as well as other interested agencies and individuals.

Document Contents

The 2009 CICAR annual report is a comprehensive written review of all administrative and research activity for the Institute’s sixth year of operation that began July 1, 2008 and ended June 30, 2009.
About CICAR

Mission Statement
The Cooperative Institute for Climate Applications and Research evaluates, understands, and predicts climate variability and change through the collection and analysis of modern and paleoclimate data and the use of Earth system models. We provide climate information to society through education and the development of applications and tools for assessing climate-related risks.

Overview
The Cooperative Institute for Climate Applications and Research (CICAR) was established in November 2003 as a research partnership between the National Oceanic and Atmospheric Administration and Columbia University In The City of New York. CICAR research themes are: (1) Earth system modeling; (2) Modern and paleoclimate observations; and (3) Climate variability and change applications research.

The NOAA funded research portfolio at Lamont grew out of a clear strategic vision of scientists at LDEO and NOAA. This vision stipulated that ocean observations and coupled ocean-atmosphere modeling is key to understanding long-term climate variability and change and to developing climate prediction capabilities. It also emphasized paleoclimate research as providing climate scenarios quite unlike those revealed in the short instrumental record, thus helping to expand our view of the Earth climate system and challenging our conceptual understanding and modeling capability. Actively pursuing these ideas, LDEO scientists have conducted research based on observations (instrumental and proxy), analysis, and models and worked with NOAA to form programs and set research directions.

At the core of the CICAR research agenda is the collaboration between LDEO and two NOAA climate-oriented organizations: the Climate Program Office (CPO) and the Geophysical Fluid Dynamics Laboratory (GFDL). The CPO leads the NOAA involvement in the U.S. Climate and Global Change (C&GC) Program and sponsors scientific research aimed at understanding climate variability and its predictability. GFDL is “charged with producing timely and reliable knowledge and assessments on natural climate variability and anthropogenic change” through the development of Earth system models and theoretical understanding. Both these missions are consistent with the CICAR climate research agenda.

Structure
CICAR is administered by Columbia University through its Lamont-Doherty Earth Observatory and is located at the Observatory’s Palisades, New York campus. The Institute consists of the Director, who is an official of Columbia University, an administrative staff, an Advisory Committee, an Executive Board, and the scientific and support staff of the CICAR, who are members of LDEO and other units of the Earth Institute, Columbia University. The Geophysical Fluid Dynamics Laboratory, a NOAA Research facility, is the Institute’s principal connection to NOAA.
Research Overview

The Cooperative Institute for Climate Applications and Research develops and promotes research to address a wide range of physical and social science topics consistent with the CICAR mandate. The project summaries appearing in the research section include: observations and model development required for the prediction of seasonal-to-interannual and long-term climate variability; collecting instrumental observations and developing and archiving proxy records for deepening the understanding of climate variability and change; and for the development of tools for providing climate information to society to assess risk and make decisions.

The CICAR program of research and education strives to:

• Create a center of excellence dedicated to understanding the evolution of the Earth’s past and present climate and predict its future trajectory.
• Create a long-term research partnership between NOAA and the Columbia University climate research community to enhance NOAA’s research capabilities in the area of climate observations, modeling, and prediction.
• Contribute to NOAA’s goal to enhance society’s ability to plan and respond to climate variability and change by developing methods and tools for providing climate information to users and decision makers.
• Provide a basis for streamlining the administrative process for several established cooperative projects within Columbia University and NOAA – e.g. Abrupt Climate Change Studies (ARCHES), Climate Variability and Prediction program (CLIVAR), the IRI Applied Research Centers program, and the NOAA Economics and Social Science program.
• Develop specific research projects that address critical research needs in:
  o Climate modeling and prediction
  o Modern and paleoclimate research
  o Climate forecast applications research
• Create undergraduate-to-graduate level research and education opportunities that reflect NOAA priorities and interest through student participation in related science projects and by bringing NOAA science perspectives into the classroom.
• Identify opportunities and establish means to communicate climate research development to the public to facilitate broader understanding of climate related issues and their impact on society.

Synergies

The CICAR partnership benefits NOAA through synergies with various research centers at Columbia University (CU) particularly within the Earth Institute (EI). Collaborations and joint activities exist between CICAR and the International Research Institute for Climate and Society (IRI) and the Center for International Earth Science Information Network (CIESIN). CICAR also maintains ties with Columbia University’s Center for Research on Environmental Decisions (CRED); the Earth Institute Center for Hazard and Risk Assessment (CHRR); and the Columbia Climate Center (CCC).
Research projects and related education activities under CICAR address three overarching themes:

**Theme I: Earth System Modeling**
- Developing and improving climate models and modeling tools (e.g., data assimilation procedures) to simulate and predict climate variability and change.
- Designing climate experiments with numerical models of varying complexity to test hypotheses regarding, and to promote the understanding of, climate variability and change.
- Applying statistical tools to data and model output to study observed modes of climate variability, their simulation by climate models, and their predictability.
- Analyzing historical data to create spatially and temporally uniform information for research and applications.

**Theme II: Modern and Paleoclimate Observations**
- Developing, collecting, analyzing, archiving, and interpreting climate proxy data records to improve understanding of past climate variability and change on all time scales.
- Monitoring and observing the key ocean regions to understand the ocean role in climate and to improve climate models.

**Theme III: Climate Variability and Change Applications Research**
- Developing applications and tools that enable the translation of climate research and information to decision makers in the areas of agriculture, water resources, health, economics, and policy.
- Studying the interaction between providers of climate information and users and decision makers to improve communication for the benefit of society.

**Operational Strategy by Task**
The Institute’s primary operational and research strategy is divided into four (4) tasks:
- Task I: Administrative activities
- Task II: Specialized science support activities
- Task III: Proposed and currently funded individual projects
- Task IV: Collaborative education program
Executive Summary

1. Overview

The CICAR 2009 Annual Report summarizes the research, administrative, and educational activities during the 2008-09 fiscal year (hereafter FY09). This was the first of a 5-year continuation of our renewed cooperative agreement with NOAA and to some extent, our activities reflect a transition from the research agenda set in our 2003 proposal to NOAA to the revised agenda that was shaped during our 2006 review as well as the renewal proposal of 2007. The Institute’s changing foci, wherever they exist, reflect the dynamical nature of learning from our own research results and continuously examining the ways CICAR could best contribute to the evolving NOAA and National climate agenda.

The CICAR report gives a detailed, project-by-project account of our achievements including projects’ goals, their societal benefits, linkages to other projects, and related educational and outreach activities. Also listed are the related scientific publications, and participating personnel. Several summary tables and graphs reflect the activities of CICAR as a whole. All this is consistent with the reporting guidelines provided by the NOAA/OAR/Cooperative Institute Program Office.

The majority of NOAA funding for CICAR has been directed to the Lamont-Doherty Earth Observatory (LDEO) – the University’s primary Earth science research unit. Lamont’s strength in modern climate research – particularly oceanography and air-sea interaction – and in the study of the Earth’s paleoclimate history, make it a natural partner to NOAA under the agency’s mission to “understand climate variability and change to enhance society’s ability to plan and respond.”

CICAR research strategy addresses NOAA’s climate goal through collaboration with NOAA partners as well as independent research entities. CICAR’s primary NOAA partners are the Climate Program Office (CPO) in Silver Spring, MD and the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, NJ. The CPO leads NOAA’s participation in the interagency U.S. Climate Change Science Program (CCSP) and sponsors scientific research aimed at understanding climate variability and its predictability. GFDL is charged with producing timely and reliable knowledge and assessments on natural climate variability and anthropogenic change through the development of Earth system models and theoretical understanding. Both these missions are consistent with the CICAR climate research agenda. Additional collaborations with NOAA extend to other offices and laboratories such as the Office of Climate Observations (OCO), the National Climatic Data Center (NCDC), the Earth System Research Laboratory (ESRL), and the Atlantic Oceanographic and Meteorological Laboratory (AOML). CICAR continues to strive for building a research and education relationship with the NOAA-CREST Center at the City University of New York. This year a working relationship has been established between the Columbia Water Center and CREST on collaborative work in hydrology. In this spirit we have collaborated with CREST on a RISA proposal submitted in summer to NOAA CPO.

During FY09, CICAR administered 46 research and education projects in addition to the Institute’s core administrative budget. This number includes 23 projects that were funded under the original CICAR award number and, with the exception of three projects that will expire in 2010, were closed as of June 30, 2009. We are looking forward to continue competitive CPO
funding under the Shadow Award mechanism, which proved to perform well during this report year.

This year, as was the case in FY07 and FY08, GFDL continued to experience budgetary constraints and was unable to renew its support to CICAR PIs, which in the past funded collaborative research between the Laboratory and LDEO. We also suffered a de-facto cut to our administrative funding (also provided by GFDL) that limited our ability to continue and build on past education and outreach activities.

CICAR research and education projects are organized along three themes: (I) earth system modeling, (II) modern and paleoclimate observations, and (III) climate variability and change applications research. In FY09 we identified 18 projects under theme I, 26 projects under theme II, and 2 under theme III (this includes projects that were continued from the previous CICAR award under a no cost extension).

Collaboration with GFDL continued to be one of CICAR’s key objectives. The CICAR director maintains contact with the GFDL director and CICAR PIs, particularly those involved in Theme I who interact with GFDL scientists, to identify a collaborative research agenda for the two groups. Out of these efforts grew a new project funded by CPO entitled: “Predicting North American hydroclimate change and variability on the interannual to multidecadal timescale”, which will look into the skill of the realistically initialized decadal prediction runs with the new generation of GFDL coupled climate models. Work on this project will begin this fall. This direct support of CPO to a collaborative project with GFDL will be enhanced by other work related to building predictive understanding of decadal climate variability. Previous plans to collaborate with GFDL on a climate model simulation of the last millennium, involving intensive comparisons with proxy data are still in development and are reflected in a proposal submitted to CPO this summer.

2. Research highlights

CICAR research spans a broad range of subjects that are classified by the three Themes indicated above. This classification is the basis for the organization of the bulk of this report. To evaluate the impact of CICAR research it is helpful to sub-group the works under each Theme according to the scientific context of the research as is attempted below. Note that this quick review of research highlight is not meant to be comprehensive. The interested reader should follow the individual reports to gain better appreciation of the CICAR scientific achievements.

**Theme I: Earth System Modeling:** Work under this Theme focused in four different areas: (i) Advancing seasonal-to-interannual climate prediction methodologies; (ii) Building predictive understanding of Global to Continental scale climate variability, particularly in the world semi-arid regions; (iii) Modeling and understanding the late-Holocene climate and the implication to future climate change; and (iv) Modeling and understanding regional climate processes.

Under subcategory (i) we count the advances in ENSO forecasting (Cane) and in translating these results into climate prediction worldwide in the IRI two tiered prediction system (Goddard). Under subcategory (ii) we count the modeling, with limited success, the role of local “preconditioning” and the remote influence of ENSO in the subsequent evolution Atlantic tropical Atlantic SST anomalies using a coupled GCM and the implication for predicting precipitation variability over South America (Robertson). Also under subcategory (ii) is the emergence of a perplexing consensus between IPCC AR4 models, which do not agree on the trend in precipitation at the peak of the West African Monsoon season agree on a yet unexplained delay in the onset of the rainy season that leads to an overall significant reduction in annual mean precipitation.
precipitation (Biasutti). Bridging the two subcategories (ii) and (iii) is the continued work of our Climate Modeling and Diagnostic group on the origin, predictability of North America and Mediterranean region hydroclimate variability and change. Here we made progress in linking the changes to SST variability on time scales from decades to millennia using models, and modern and paleoclimate records (Seager reports). Of particular interest is work that highlights the role of the Atlantic in linking climate variability in North America and the Mediterranean. Also important is work that exposes the role of Aeolian dust in enhancing the impact of droughts, showing that the Dust Bowl of the 1930s was shaped by the dust created due to bad farming practices. Under subcategory (iv) are advances in documenting and understanding the climate influence on tropical storms (Camargo) and the dynamics of local ice-ocean-atmosphere interactions in the Southern Ocean (Martinson).

**Theme II: Modern and Paleoclimate Observations:** Work under this Theme can be broadly divided into two subcategories: (i) Modern observations of oceanic variability and (ii) Analysis of paleoclimate observation to advance understanding of long-term, free and forced climate variability.

Under subcategory (i) CICAR scientists continued to extend previous established time series of ocean variability in some of the key choke points of the world ocean – the Indonesian Straights (Gordon reports) and the Western Antarctic Peninsula (Gordon, Huber, and Martinson). These data make it possible to understand crucial processes of inter-ocean exchange and the production of important water masses, both playing a role in the global thermohaline circulation. The monitoring of the Indonesian Throughflow this year revealed information on the impact of interannual variability on the circulation. The long time series from deep moorings in the Weddell Sea reveals considerable seasonal variations as well as a response to the interannual variability of the overlying atmospheric circulation. This sensitivity to surface forcing provides useful information for understanding the dynamics and for modeling of the production of deep water-masses around Antarctica. Another direction of ocean circulation monitoring work done by CICAR is the analysis of tracer data from the deep North Atlantic and Southern Ocean (Schlosser, Smethie). The analysis and synthesis of CO₂ exchange between atmosphere and ocean worldwide is an ongoing NOAA supported project. Here scientists are able to come up with better understanding of the underlying process and to more accurate information on the ocean surface fluxes of CO₂, regionally and globally (Takahashi).

Under subcategory (ii) is work that spans a wide range of time scales, from the Last Glacial Maximum to the Late Holocene using a variety of paleoclimate proxies derived from trees to mountain glacier moraines to paleo-lakes to ocean sediment cores. The continued work to improve the tree-ring bases, 2000-year North American Drought Atlas concluded by establishing a methodology for a live update of incoming new information that seamlessly blends instrumental observations and proxy information (Cook). Work is expanding to create a similar (if not that far reaching in time) atlas for Europe and the Mediterranean Region (Cook). Other work to establish methodologies for generating worldwide gridded reconstructions of the climate of the last one to two millennia has been launched as well (D’Arrigo, and see also Seager’s ACCWW report under Theme I). Breakthrough work on the dating Holocene advances and retreats of mountain glaciers in the Southern Hemisphere, using cosmogenic nuclei, is continuing. Lamont has become a world-leading laboratory in this type of analysis and the amount of information is increasing. The data now span key Southern Hemisphere glaciers in New Zealand and South America. This accurate dating information is helping to establish a global database of the timing of important and still poorly understood multi-decadal to millennial climate fluctuations such as the Medieval Climate Anomaly and the Little Ice Age (Denton, Schaeffer). Recent interest in the response of
the global hydrological cycle to external forcing – particularly in semi-arid regions – has lead to renewed interest in hydroclimate reconstructions from paleo lake levels. A comparison between tropical and subtropical lakes is underway in CICAR to contrast model projections of the drying of subtropical regions under greenhouse gas warming to what the records indicate regarding the Last Glacial Maximum (LGM). Early results suggest that the reverse has happened then – subtropical lake levels were high while tropical levels were low (Broecker). Further confirmation of this phenomenon would help solidify understanding of (and trust in) the IPCC projections. Finally, CICAR scientists were able to provide evidence for the influence of changes in the wind-driven upwelling of the Southern Ocean on atmospheric CO₂ concentrations during the LGM (Anderson). This mechanism could have played a critical role in past abrupt shifts in the global circulation.

Theme III: Climate Variability and Change Applications Research: Research under Theme III is not well reflected in this report as little work on this Theme is directly funded by NOAA. Here we continue to point out that CICAR PIs are involved in synergetic activities with groups and individuals from engineering, biological, health, social, and political sciences within the Columbia University Earth Institute. This interaction is facilitated within the Columbia Climate Center (CCC) and the Columbia Water Center (CWC), which are two new structures combining various research units within the University. The CCC aims to enhance collaborative research projects between all of Columbia’s Earth Institute units that study the Earth climate and its impact on humans and the environment. The CCC continues to work on increased funding for research on climate and society with the active participation of CICAR PIs. This is reflected in the number of cross-disciplinary proposals submitted this summer to NOAA in response to the FY2010 CPO FFO. CICAR is also represented in Earth Institute committees such as the Cross Cutting Initiative and the Earth Institute Postdoctoral Fellowship, which supports interdisciplinary projects between climate science and the other sciences represented in the Earth Institute. These cross-disciplinary activities are generally funded by other government agencies, internal university funds, and private organizations. The CWC is seeking to tackle the issue of global water scarcity through innovations in technology, public policy and private action. Combining the rigor of scientific research, including climate science, with the impact of effective policy, and aim to design reliable, sustainable models of water management and development that can be implemented on local, regional and global levels. As such the CWC works with CICAR scientists. CICAR collaborations with CCC and CWC scientists constitute an added value to and leveraging of the NOAA funded climate science research. NOAA funded research under CICAR provides a core for a broad array of Earth Institute efforts that address social issues.

3. Education and outreach

CICAR education and outreach activities are intertwined with our research work as many of our PIs mentor graduate and undergraduate students, summer interns, and interact regularly with postdoctoral research scientists. All these activities are addressed in the following individual research reports. CICAR research outcomes feed into and benefit from links to the Columbia University Department of Earth and Environmental Sciences, the Department of Earth and Environmental Engineering, and the School of International and Public Affairs. These links are manifested by the design and scope of many programs and courses that bring climate education to a wide spectrum of disciplinary and inter-disciplinary students, by direct participation of CICAR PIs in the education process, and by the reciprocal process of the participation of advanced degree students in CICAR research.

We also conduct education and outreach activities under our administrative budget, updating our web site by presenting material from CICAR research achievements, workshops, and symposia
and by developing special educational aids directed at the young K-12 audience. In addition we continued our tradition of maintaining a CICAR tent in the Lamont Open House activity – an annual fall-time event open to the local and regional community and visited by youngsters and adults, families and school groups. Here we provide a showcase to all of NOAA supported research on campus as well as a showcase to other NOAA activities, such as weather prediction and ocean explorations.

Last year we participated in the competitive award program administered by NOAA Education proposing to develop new methodologies of teaching Earth science (with climate emphasis) in the public middle and high school environment. This proposal was unfortunately not funded and the PIs directed their attention to obtaining NSF funding for their project.
CICAR

Task I Administrative

Addresses the administrative functions of the Institute and supports the CICAR director and one (1) administrative staff member.

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The CICAR Executive Board members are charged with invigorating the Institute’s commitment to new and existing scientific program areas and counseling the CICAR Director on matters of policy, budget, and ways to improve coordination of research programs with other institutions or agencies.
Administrative Activities July 1, 2008 – June 30, 2009

**Education**

**Sponsored Interns**

This year the Institute provided partial support for two interns under the Lamont-Doherty Earth Observatory Summer Internship Program for Undergraduates. The CICAR 2008-09 intern papers and posters appearing in this report are the result of research projects carried out in conjunction with the Earth Institute Centers for International Earth Science Information Network (CIESIN) and the International Research Institute for Climate and Society (IRI) in support of the CICAR Theme III: climate variability and change application research.

### Building Socioeconomic Scenarios For The Analysis Of Climate Impact

**Vulnerability**

Orly Stampfer  
LDEO Interns 2009  
Marc Levy, Valentina Mara, Maria-Ioanna Kairi  
Center for International Earth Science Information Network  
Lamont Doherty Earth Observatory  
Columbia University

**Introduction**

Many scientists have created models of climate change scenarios, which depict the probability, location, and time of the occurrence of climate outcomes. However, scenarios of socioeconomic conditions to assess vulnerability to the impact of climate change are not as detailed or robust as the climate scenarios. Some social scientists simply use current conditions as a proxy for the future, while others create only a small number of scenarios. Neither approach is adequate to identify a wide array of plausible future socioeconomic conditions. In general, socioeconomic scenarios reflect a world that exhibits normal and predictable behavior, have low temporal and spatial variation (for example, low variation across countries), cover a small range of outcomes, and are deterministic, without including an element of chance. Such scenarios typically would predict steadily increasing incomes without the occurrence of a recession, and a consistent trend towards peace. Specific examples include models that depict Africa as always becoming wealthier, and China continuing to grow at its current rate. Furthermore, most socioeconomic scenarios lack a probability distribution, suggesting that all outcomes are equally likely (Parson et al, 2007; O’Neill et al, 2008; Cork et al, 2005).

The IPCC (Intergovernmental Panel on Climate Change) models illustrate the wide discrepancy in quality between climate scenarios and socioeconomic scenarios. The IPCC has created four income scenarios under the SRES (Special Report on Emissions Scenarios), as well as temperature projections. There are many more temperature projections than income scenarios, and they cover a wider range of outcomes. The income scenarios cover a small range of outcomes, are deterministic, and have low variation. (Arnell et al, 2004).

Inadequate socioeconomic scenarios reduce the effectiveness of models that evaluate the impact of climate change, as vulnerability to climate impacts depends on both climate exposure...
and underlying social and economic conditions. A rich country at peace will be able to cope better with a climate disaster than a poor country at war. Thus, socioeconomic scenarios require new and more rigorous models. We developed an initial version of a socioeconomic scenario model that is based in history but allows for variation, is non-deterministic, evaluates multiple socioeconomic dimensions, and may be simulated repeatedly. Despite these improvements, our model retains many limitations which we address at the end of the paper, and suggest possible strategies for future work. Because of these many limitations, this paper mainly illustrates concepts for a more rigorous model, rather than a presentation of a fully developed socioeconomic model.

**Methods**

We explored a method of simulating plausible socioeconomic scenarios that are likely to affect a country’s ability to cope with climate change impacts, and the well-being of its citizens. Using Microsoft Office Excel 2007, we simulated regional income scenarios, and country level income, government type (democratic or non-democratic), and instance of internal armed conflict scenarios. The income data are from the World Bank Group, World Development Indicators, and are measured in GDP (Gross Domestic Product) per capita, PPP (Purchasing Power Parity) constant 2005 international dollars, with GDP per capita value for each country for each year from 1980 to 2007. Governance data are from the Political Instability Task Force. The original data assigns a polity value between -10 and 10 for each country for each year from 1950 to 2007. Scores of 8 to 10 and -10 to -8 are considered strong democracies and autocracies, respectively. Scores of 1 to 7 and -7 to -1 are considered partial democracies and partial autocracies, respectively. A score of 0 refers to an anocracy. In our model, we only distinguished between democracy and non-democracy, that is, a score between 8 and 10 and a score between -10 and 7. The conflict data are from the Uppsala Conflict Data Program at Uppsala University and the Centre for the Study of Civil War at the International Peace Research Institute in Oslo Armed Conflict Dataset Version 4, 2009 (Gleditsch et al, 2002). We used the data for major internal armed conflict, which refers to an intrastate, armed conflict, which resulted in 1,000 or more deaths per year. We indicated whether or not such a conflict had occurred within each country for every year from 1946 to 2007. For our simulations, we divided countries into regions geographically, according to the World Bank Group regions. These regions are Sub-Saharan Africa, Europe and Central Asia, South Asia, East Asia and the Pacific, the Middle East and North Africa, Latin America and the Caribbean, and we used the United States instead of a North America region, for ease in downloading the data.

To create our simulations, we first calculated the mean and standard deviation across the annual GDP per capita growth rates of each region from the year 1980 to 2007, which were used as the parameters in the Excel random number generator to generate a random number in a normal distribution. This normally distributed random number acted as the regional growth rate. We multiplied the simulated growth rate of 1981 by the actual income in 1980 to create a simulated income for 1981. We then multiplied the simulated growth rate of 1982 by the simulated income in 1981, and so forth until the year 2100. We started with regions instead of countries in order to create a consistency check between country income and regional income. We simulated global incomes as well using the same method, though global incomes do not affect regional or country income simulations. Each country’s growth rate was simulated in a similar method, except the parameters used for the normal distribution were the simulated regional growth rate of that year (mean) and the historical regional standard deviation calculated originally (standard deviation). Using this simulated country growth rate and each country’s actual income in 1980, we simulated country incomes up to the year 2100. To simulate country level governance, we created equations relating probability of a governmental transition to income. These equations were based on a linear extrapolation of a graph of the relationship between
probability of democratic transitions and income by Epstein et al, 2006. Epstein created two graphs based on historical data: the probability of transitioning from a democratic government to a non-democratic government vs. the natural log of income, and the probability of transitioning from a non-democratic government to a democratic government vs. the natural log of income. We took the values at each end point of the graphs to extrapolate two linear equations. For a country with a democratic government in the previous year, the probability of transitioning to a non-democratic government in the current year is equal to: \(-0.0431 \times \ln(\text{GDP per capita of current year}) + 0.436\). For a country with a non-democratic government in the previous year, the probability of transitioning to a democratic government in the current year is equal to: \(0.0267 \times \ln(\text{GDP per capita of current year}) - 0.150\). If this probability was greater than an Excel generated random number between 0 and 1, a government transition was deemed to have occurred in the simulation, using the actual dichotomous governance in 1980 as a starting point. To simulate country level onset and duration of major internal armed conflict, we created an equation relating the probability of the onset of a conflict to income. This equation was based on a linear extrapolation of a graph showing the relationship between probability of onset of conflict and GDP per capita by Humphreys, 2002. Humphreys created a graph based on historical data that showed the probability of the onset of a conflict vs. the natural log of income. We took the values at each end point of the graph to extrapolate a linear equation. The probability of the onset of a conflict is equal to: \(-0.017 \times \ln(\text{GDP per capita of current year}) + 0.183\). If this probability is greater than an Excel generated random number between 0 and 1, a conflict is deemed to begin. The duration of the conflict is simulated by the absolute value of a normally distributed random integer with mean 0 and standard deviation 10, which is approximately the actual standard deviation of historical global conflict duration from 1946 to 2004. Using both conflict onset and duration simulations, we simulated country level instances of major internal armed conflict up to the year 2100.

Results

With multiple runs of the model, we observed scenarios that were non-deterministic and highly variable, with a wide range of income levels. Virtually all of the runs included some instance of negative growth, and many of the runs included negative growth every few years. A few runs included enough negative growth to actually simulate a lower income in the year 2100 than the current income.

Figure 1 shows a graph of three different simulations of global income, whose trends are not only different shapes, but cover a range of about $35,000 in the year 2100. The global historical income trend is also shown. These runs were chosen based on typical high, low, and average values based on a several runs of the model.
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In many instances, our scenarios allowed countries of the same region with diverse historical income trends to continue along divergent income paths. Figure 2 shows a typical simulation (based on several runs of the model) and historical data of Ecuador, Bolivia, Haiti, and Nicaragua, countries in the same region with very different historical income trends. The simulations have dissimilar shapes and cover a difference in the year 2100 of about $10,000. Even the simulated trends for Nicaragua and Haiti, which have more similar historical trends than the others, have different shapes.
However, we also encountered scenarios where different countries followed almost identically shaped income trends, and in some cases the trends even overlapped, suggesting serious inaccuracies in the model. Figure 3 shows a typical simulation (based on several runs of the model) and historical data of Ghana and the Democratic Republic of Congo, two countries in the same region with very different historical income trends. The simulations are virtually overlapping.
It is difficult to assess the plausibility of the governance scenarios, although it is useful to note that a dip in income does not always coincide with a non-democratic regime. Similarly, it is difficult to assess the plausibility of the onset of major internal armed conflict, although there are many occurrences of negative growth that do not include onset of conflict. The simulations of conflict duration generally simulate more frequent longer conflicts than occurred historically. However, there are also many instances of conflicts that last under five years, which is more consistent with historical data. Table 1 shows simulated conflict durations of one run of the model for Ecuador, Haiti, Ghana, the Democratic Republic of Congo, and Malaysia, for the years 2008 to 2100. These examples show that the model simulates many conflict durations of over five years, and just a few conflict durations of under five years.
Table 1: Simulated conflict durations for Ecuador, Haiti, Ghana, the Democratic Republic of Congo, and Malaysia (2008-2100)

<table>
<thead>
<tr>
<th>Conflict number</th>
<th>Ecuador</th>
<th>Haiti</th>
<th>Ghana</th>
<th>Dem. Rep. Congo</th>
<th>Malaysia</th>
</tr>
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<td>1</td>
<td>4</td>
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<tr>
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<td>3</td>
<td>No conflict</td>
</tr>
<tr>
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<td>3</td>
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<tr>
<td>5</td>
<td>5</td>
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</tr>
<tr>
<td>7</td>
<td>No conflict</td>
<td>No conflict</td>
<td>No conflict</td>
<td>9</td>
<td>No conflict</td>
</tr>
</tbody>
</table>

In general, the global and regional parameters for income growth rates produced mostly plausible simulations. However, certain regions with recent rapid growth produced unrealistically high means. For example, the region East Asia and the Pacific has a high annual growth rate mean from 1980 to 2007, so the model often simulates 2100 income values near $100,000. Some regions also produced low standard deviations, which impaired the model’s ability to simulate highly variable scenarios. Table 2 shows the mean and standard deviation of the annual percent growth rate of each region and the world that were used in the normal distribution of the random number for the growth rates. The means and standard deviations were derived from the historical income data from 1980 to 2007. The United States is used instead of a North America region. Mexico is included in the Latin America and Caribbean region.

Table 2: Mean and standard deviation of the annual percent growth rate of each region and the world used to simulate the growth rate.

<table>
<thead>
<tr>
<th>Region</th>
<th>Mean (%)</th>
<th>Standard deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>1.74</td>
<td>1.28</td>
</tr>
<tr>
<td>Sub-Saharan Africa</td>
<td>0.18</td>
<td>2.22</td>
</tr>
<tr>
<td>Europe and Central Asia</td>
<td>1.04</td>
<td>6.00</td>
</tr>
<tr>
<td>South Asia</td>
<td>3.82</td>
<td>1.93</td>
</tr>
<tr>
<td>East Asia and the Pacific</td>
<td>6.81</td>
<td>2.19</td>
</tr>
<tr>
<td>The Middle East and North Africa</td>
<td>1.40</td>
<td>2.93</td>
</tr>
<tr>
<td>The United States</td>
<td>1.97</td>
<td>1.73</td>
</tr>
<tr>
<td>Latin America and the Caribbean</td>
<td>0.89</td>
<td>2.35</td>
</tr>
</tbody>
</table>

We also compared our scenarios to the IPCC SRES scenarios. As a specific example, we looked at a particular typical run (based on several runs of the model) of our scenarios for Ecuador and Haiti, and compared it to the SRES B1 scenarios for Ecuador and Haiti. Our trends (CIESIN) are simulated from 1981 to 2100, and the IPCC SRES trends are simulated from their starting point of 1996 to 2100. Figure 4 shows the historical and simulated income trends, both our trends and the SRES trends, for Ecuador and Haiti.
Ecuador and Haiti have divergent historical income trends, with Ecuador’s income erratically increasing from 1980 to 2007, and Haiti’s income decreasing relatively smoothly. The IPCC SRES scenarios show future GDP per capita trends for both Ecuador and Haiti that are smoothly increasing. The trend for Ecuador increases more rapidly than the trend for Haiti, but the overall shape and smoothness are quite similar. Both trends are completely devoid of recession, and have almost no discontinuities over time. Our scenarios depict more temporal variation, including significant negative discontinuities. Furthermore, our scenarios project Ecuador and Haiti as following dissimilar trends, both in shape and amount of erratic variation, consistent with their divergent historical GDP per capita trends. Our simulated trend for income in Ecuador increases more rapidly than the trend for Haiti, and also includes more striking discontinuities. Haiti’s simulated income trend is flatter, while still increasing, and less erratic.

**Discussion**

While the increased range, variability, and instances of negative growth in our income scenarios are improvements to general income modeling, there are major problems to address. Firstly, it is problematic that we do not have an efficient way of organizing many runs of the model in order to look at, for example, the median value of 1,000 runs. Looking at one run of the model in isolation is not useful. Secondly, using regional data as parameters for country simulations produces flawed results, as shown by the occurrence of scenarios which show two countries with very different historical income trends following overlapping paths into the future. This may be because the mean and standard deviation of each
countries with very different historical income trends following overlapping paths into the future. This may be because the mean and standard deviation of each country within one region is the same, and the only differences are in the 1980 value and the random numbers. Thus, if one country’s income has been steadily decreasing, and another’s has been steadily increasing, and they meet at a similar value in 1980, they may end up following similar paths. Therefore, the scenarios may work well in this case if the countries are from different regions, but if they are from the same region the scenarios become implausible.

Secondly, in certain regions that have experienced recent rapid growth, the income scenarios depict overly optimistic incomes by 2100, and an extremely steep upwards curve. This may reflect too much dependence on recent history in the model, or perhaps a need for a different type of distribution of the random numbers. For example, a normal distribution may be appropriate for one region, while a gamma distribution may be appropriate for a different region. It would be helpful to run the simulations many times with different types of distributions for random numbers, and assess their plausibility. A similar problem arises with countries whose recent income trends have low standard deviations – in these cases the model produces low range and low variation scenarios. This may also be because of the limitations of a normally distributed random number, and perhaps a different type of distribution would be more accurate.

Another issue is that our model projects more frequent longer conflicts in the scenarios than have occurred historically. This is probably partly because we force the duration to follow a normal distribution, while the historical conflict duration curve follows a slightly steeper than normal curve. The model could be improved by using a more realistic distribution.

In general, it is difficult to assess the plausibility of the governance and conflict scenarios, because it is quite uncertain what to expect in the future. It may be an error to assess plausibility based on similarity to past governance and conflict trends, though the model does assume that the future is somewhat based on the past. Furthermore, the relationships between conflict and governance are complex. We elaborate on the possible solutions to these issues as well as other improvements in the following section.

**Conclusions and future work**

Our multidimensional, nondeterministic, and variable scenarios permit more effective assessment of vulnerability to climate change impact due to socioeconomic conditions, especially in their ability to account for historical differences between countries and to allow for negative growth. However, many limitations remain. Looking forward, a major question to resolve is how to treat different countries and different regions differently. One solution would be to vary the random number distribution by region and/or country. For example, one region’s growth rate could use a random number on a gamma distribution, while another region’s growth rate could use a random number on a normal distribution. This could be determined by graphing the historical annual growth rates and examining the resulting distribution. Apart from different distributions, it may be helpful to categorize regions differently. For example, countries within a certain income group may match each other better than countries within a certain geographic region. One way to determine which kinds of regions are best would be to graph annual income growth rates of different types of regions and compare the distribution and parameters to a country’s annual income growth rate. That way, one could determine which type of regions matches most countries. It is also important in future improvements to apply consistency checks between the world, the regions, and the countries while allowing the country income trends to be somewhat independent of the regional trends. It would be implausible for one country’s income to grow rapidly while its neighboring countries and the world are experiencing negative growth. However, it is also important to allow country income growth rates to differ from that of their neighbors. In the current model, countries within the same region have the same mean and standard deviation for their growth rates as the region. This may be causing the country growth
rates to be too dependent on the regional growth rates, and also interfere with allowing countries in one region to follow different paths. Currently there is also no consistency check between the global income and the regional and country incomes.

As the model becomes more automated and open, a major improvement would be to add additional constraints on all variables. There are an overwhelming number of factors, which affect income, governance, and instance of armed conflict, but it is important to identify the major factors and include them in the model. For example, it may be useful to include literacy rate, life expectancy, and a measure of natural resources in the model as factors affecting income, governance, and conflict.

Some specific developments to this model include imposing random income growth shocks, according to countries’ historical income trends. Another specific improvement would be to include partial democracy in the governance scenarios. Partial democracies are distinct from full democracies and full autocracies, so it may be much more informative to consider them a separate category from autocracies (Epstein et al, 2006). As noted earlier, it would be more effective to use a non-normal distribution for the duration of conflicts. Furthermore, it would be more effective to impose a relationship between past conflict duration and future conflict duration. For example, if a country is currently in its twentieth year of an armed conflict, the probability of it continuing for another twenty years should be different from that probability during the first year of the conflict. Similarly, the model needs to take into account whether the country is currently in a conflict before simulating future conflict. Lastly, in the current model, occurrence of armed conflict is dependent on income but not vice-versa. As the relationship between conflict and income is complex and mutual, it is important to add an effect of conflict on income.

The format of the model also leaves room for improvement. A future model should allow the user to begin simulations at whichever year they wish. If the user wants to simulate starting at the year 2000, it is important that the model uses the historical data from 1999, not 1980 as in the current model. Also, region characterization should be further developed to allow a user to be able to specify which regions they care to simulate, such as landlocked, low-income, or regions with high risk of flooding. In order to make the model more automated, we plan to create a reference table with all of the country and regional parameters. Equations for the model would refer to this reference table. In terms of data, we would like to use a dataset by Maddison, 2009, which fills in missing data from the World Bank. Lastly, the model would be much more effective if we used a more automated and open source program. Clearly, it would be helpful to run the simulations many times and add error bars to the income trends. Unfortunately, this is not feasible in Excel but is easy to implement in many statistical software packages, such as R. This would help us assess the range and distribution of our scenarios.

It would also be informative to look at the economic conditions in which a conflict arises. For example, if we ran the scenarios many times and looked at instance of conflict in different income and government groups, the instance of a conflict in a wealthy democracy should be rare. If it is occurring frequently, we would know to change the conflict simulation model, perhaps by increasing its dependence on income and governance, and decreasing its random number effects.

Finally, we hope to graph our socioeconomic scenarios in juxtaposition to climate exposure scenarios, to simulate different combinations of climatic and socioeconomic conditions. For example, we could graph a drought time series for a certain country superimposed on a socioeconomic time series for the same country, and identify when a drought, recession, conflict, and certain type of government overlap. Different combinations of these four variables, income, instance of armed conflict, governance, and climatic condition, would describe different kinds of situations to consider. Furthermore, we would conduct additional research on which combinations of conditions historically produced the greatest human impacts, and look for these combinations in the joint climate-socioeconomic scenarios.

CICAR 2009 Annual Performance Report
From July 1, 2008 to June 30, 2009
PI Yochanan Kushnir
Once an accurate socioeconomic model is developed, the door will be open to building a method of simulating more robust socioeconomic scenarios to be examined in conjunction with climate exposure scenarios. Eventually, this will create a clearer and more comprehensive idea of plausible vulnerability, and researchers will be able to more completely analyze climate change impacts. Of course there is no way to know the future, but imagining alternative scenarios of the future is helpful in grasping the wide array of possible impacts climate change will have on human beings.
Assessment of the Climate Predictability Tool’s effectiveness in mitigating risk to developing countries from short-term climate variation

Monica Quaintance
LDEO Interns 2009
Intern of: Dr. Malgosia Madajewicz
International Research Institute for Climate and Society

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Section I. Introduction and Purpose
Developing countries are especially susceptible to seasonal variation in climate. Rainfall and temperature influence the spread of diseases such as malaria, dengue, and cholera, as well as agricultural yield. Floods and drought can pose a severe risk to economic output and human life. Climate information can help mitigate those risks by predicting the spread of disease, the next season’s rainfall, or the potential crop yield. The International Institute for Climate and Society (IRI) has developed forecasting software, the Climate Predictability Tool (CPT), to enable creation and dissemination of local climate information. The CPT is intended to allow local meteorological organizations to make their own advance-warning forecasts in the hope that it will reduce the risk to these variations in climate. Before the CPT, making climate forecasts was extremely time-consuming and required extensive statistical training; use of the CPT facilitates a wider distribution of climate information.

The goal of this paper, in general, is to explore the assessment process being used to evaluate the effectiveness of the Climate Predictability Tool (CPT). Specifically, the paper details the investigation into how the CPT functions, who is using the CPT, how these people are using the CPT, and for what purpose these people are using the CPT.

The end goal of this project is to determine if the CPT has made a positive impact on the end users’ lives by allowing them to better adapt to seasonal climate variation, and whether this impact is commensurate with the time, effort, and funding that IRI has invested in the CPT. A positive impact can be measured by increased efficiency in meteorological organizations’ output, reduced loss of end-user life or property from seasonal climate variation, or increased agricultural yield because of better knowledge of seasonal climate variation. These data would be gathered both from national meteorological organizations around the globe as well as the end users who receive their outputs made with the CPT. However, due to time constraints on the direct-from-user data-gathering process, I will use scope of CPT knowledge and usage as a rough proxy for positive CPT influence, making the assumption that local and national meteorological institutions
that choose to use the CPT do so because it is inherently beneficial to the end users of their meteorological outputs made with the CPT.

_What is the CPT?_

The CPT is a statistical package designed by scientists at IRI specifically for short-term (i.e. monthly to seasonal) climate prediction. These scientists designed the software to be used by persons with limited statistical training at national meteorological organizations in areas with limited or non-dedicated climate prediction services. In the words of Simon Mason, the CPT’s principal designer,

“The IRI’s Climate Predictability Tool enables scientists from the national meteorological services of developing countries to quickly produce their own seasonal climate forecasts. Countries can then use the information to make decisions on water allocation, estimate crop yields and disease outbreaks, and forecast energy requirements, for example.”

For purposes of this paper, I have defined the purpose of the CPT, as intended by IRI, to be as a follows:

_To make readily and widely available the tools by which an organization with limited resources can generate and disseminate climate variation models._

If the CPT fulfills this purpose then it will be increasing the efficiency of local meteorological organizations by allowing them to create forecasts more frequently, allowing them to create forecasts they did not make before, or allowing them to devote time that they previously dedicated to making forecasts to other tasks. When these organizations become more efficient more people in the region will have access to climate data, hopefully furthering IRI’s own goal of enabling a wider scope of people to adapt to seasonal climate variability.

_Section II. About the CPT’s Functionality_

The scientists at IRI developed the CPT specifically with statistical climate prediction in mind. This has enabled them to accomplish some very specific goals for a specific set of organizations. The CPT accomplishes a small set of tasks very efficiently, hopefully reducing the individual time-per-forecast of an organization that made these types of analyses previously. The CPT’s design, according to IRI, has been “tailored for producing seasonal climate forecasts using model output statistic (MOS) corrections to climate predictions from general circulation model (GCM), or for producing forecasts using fields of sea-surface temperatures.” The time saved by organizations using the CPT could be spent making forecasts more frequently or diversifying the number of products provided by said organization. In terms of diversification, the CPT “can be used in more general settings to perform canonical correlation analysis (CCA) or principal components regression (PCR) on any data, and for any application.” For an organization that was previously not making forecasts, hopefully the CPT allows them to make statistical analyses where they did not before.

Previous informal feedback regarding the CPT functionality indicates the most often identified limitation of the CPT lies in its inability to allow specific tailoring to climate prediction beyond certain basic components such as rainfall. The most common comment of scientists at IRI that do not use the CPT was that they prefer to program their own software and tailor it more specifically to their project, most often using FORTRAN, MATLAB, or another programming language. The statistical packages in the CPT are non-customizable, which suggests that this makes the CPT effective for people without statistical or programming experience but frustrating for people who do. Clarification regarding the CPT’s current and future functionality are important components of the assessment process.

The CPT is available via download from the IRI website at [http://iri.columbia.edu/outreach/software/cpt/download/cpt_install_910.msi](http://iri.columbia.edu/outreach/software/cpt/download/cpt_install_910.msi). The installation file,
Section III. Training for and Awareness of the CPT

The primary concern identified by programmers of the CPT is not that users of the CPT would be unable to make a forecast, but that they would make nonsensical forecasts with bad data or that they would misinterpret correctly completed forecasts. To combat this problem, as well as to spread awareness of the CPT, the IRI has launched an aggressive training campaign that compliments their already existing programs.

The map in Appendix 2 shows the locations at which IRI personnel conducted CPT trainings over the past six years. The number of workshops conducted each year has grown (see Appendix 3 for statistics), which speaks to IRI’s increasing focus on including the CPT in its outreach programs. The map includes locations where the CPT was introduced as well as CPT-specific workshops.

The breakdown of training by region strongly favors Africa, most likely because the largest portion of IRI’s activities center on Africa and so it is easiest to train users for the CPT there by adding CPT training to previously scheduled programs. Europe is not favored in the distribution of workshops because it is not considered to be a developing region and therefore does not factor very highly in the priorities of IRI training. The users we have identified in Europe are mainly from research or educational institutions. Also, as CPT use has become widespread, we can certainly infer that there has been a lot of “secondary” training conducted by non-IRI personnel.

The widespread distribution of CPT training has been progressing even further over the past six years, with both the number of CPT workshops held and the number of participants at each workshop increasing, especially in the developing region of Africa. Given these facts, it is reasonable to hypothesize that the number of people, and perhaps organizations, using the CPT has been increasing over the past six years.

Section IV. Evaluation Survey

In order to progress to the next level in our evaluation we have created a survey, in print and online, in English, Spanish, and French. A copy of the survey is available in Appendix 4. We distributed this survey via email to representatives at meteorological services in seventy-five countries. The information that we hope to obtain is how the CPT has changed the effectiveness of meteorological organizations, if at all, and for what end-user sectors these organizations produce forecasts using the CPT. We anticipate there being a substantial positive bias to the returned surveys, i.e. mostly users with positive experiences will be willing to contribute to research with regard to the CPT, and we do not expect a particularly high response rate. However, given the volume of potential survey respondents we are hopeful of enough data to further our investigation.

Section V. Process of Analyzing the Results

In order to truly make the determination whether the increased distribution of the CPT has or has not bettered the lives of end users in developing countries we would like to be able to compare the lives of individuals before and after they received forecast information. While the survey data that we will ideally receive is from end users themselves, including local farmers, health organizations, and aid organizations in developing countries, it will not directly address the question of whether CPT has impacted the lives of end users. Acquisition of this data directly is not feasible because of the volume of footwork involved due to a lack of an easy communication network.
In place of this ideal project, our next step in this investigation will be to analyze the end-user information that we receive from the people who take the multi-lingual surveys that we distributed. If the data we receive indicate that the CPT has increased the efficiency of meteorological organizations forecast making, we will infer that this has increased their effectiveness in disseminating climate information to end-users. This increased effectiveness will signal that there has been an improvement in the livelihood of end-users in developing countries.

In summary, increases in the number of people trained in use of the CPT are a good preliminary indicator of the likelihood of increasing climate forecast generation particularly in Africa and thus mitigating risk from short-term climate variations. The assessment process currently under way will provide sufficient data to validate this assumption as well as evaluate the current effectiveness of the CPT and provide guidance for future software functionality enhancements, distribution and training.

Section VI. Appendix 1

The following is a forecast of rainfall accumulation in the Southeastern United states, made with the assistance of Dr. Tony Barnston, using the Climate Predictability Tool. The predictions were generated using the NOAA NCDC ERSST set, an extended reconstructed global sea surface temperature data based on COADS data. The data can be accessed here: http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.ERSST/

The statistical mode used in this case was Canonical Correlation Analysis.

![Figure 1: US rainfall prediction and correlation to ENSO, made using SST.](image)

Section VII. Appendix 2

The following distribution map shows the distribution of CPT training workshops conducted by IRI personnel since 2003. An interactive version of this map, complete with number of workshop participants, name of the workshop organizer, and the date of the workshop, can be found here:

http://www.umapper.com/maps/view/id/35860/

The map was made using UMapper, a free, universal web-based map authoring application: www.umapper.com
Section VIII. Appendix III

CPT Workshop data and statistics

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<th>Contact</th>
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<td>2003</td>
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<td>Harare</td>
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<td>Region</td>
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CICAR 2009 Annual Performance Report
From July 1, 2008 to June 30, 2009
PI Yochanan Kushnir
People trained to use the CPT, by region

Number of people trained per year, by region

CICAR 2009 Annual Performance Report
From July 1, 2008 to June 30, 2009
PI Yochanan Kushnir
Section IX. Appendix IV

Included below is the CPT Evaluation Survey print version in English that was distributed to national meteorological organizations in 75 countries. We also made this survey available online, at:

http://www.surveymonkey.com/s.aspx?sm=5dTH0ZvPE1XjZEQ2Bjqslg_3d_3d

The survey was also available in French (included below) and Spanish in print and online at:


http://www.surveymonkey.com/s.aspx?sm= 2fBARaLPt6SwRo95wLx4ltQ_3d_3d
CPT Evaluation Questionnaire
International Research Institute for Climate and Society

The purpose of this survey is to assess the usefulness of the Climate Predictability Tool (CPT). Information about your experience with using the CPT is essential to us in order to improve the CPT so that it better serves your needs. We would also like to know about the forecasting needs that you have that are not well served by the CPT. If you and your organization do not use the CPT, then please just answer questions 1 – 5.

The information you provide is anonymous. We will not know who filled out each questionnaire. If you send the survey back by email, we will not save your name or email information. You may have someone else email it back for you if you prefer.

Thank you very much in advance for taking the time to complete the survey.

SECTION 1: Background information

1. In which region is the organization for which you work located? Please select one:
   - [ ] Africa
   - [ ] Asia
   - [ ] South America
   - [ ] North or Central America
   - [ ] Australia/Pacific
   - [ ] Europe

2. Is it your responsibility to make operational forecasts?
   Please circle one: Yes   No

SECTION 2: Your experience with the CPT and evaluation of the CPT

3. Do any staff in your organization use the CPT?
   Please circle one: Yes   No

4. If the staff in your organization do not use the CPT, please tell us why they do not. Check all of the choices that apply. Leave this question blank if your staff use the CPT.
   - [ ] Do not know about the CPT
   - [ ] Do not know how to use the CPT
   - [ ] Do not think the CPT would be useful – Please explain in more detail below why you do not think CPT would be useful to your organization
   - [ ] I don’t know
   - [ ] Other – Please explain in more detail below:

5. How did your organization first learn about the CPT? Please check all that apply:
   - [ ] IRI’s web page
   - [ ] CPT training carried out by IRI personnel
If you answered “Yes” to question #3, then please complete the rest of the questionnaire.

If you answered “No” to question #3, then you are done with the questionnaire. Thank you for your time.

6. Please explain how the CPT has helped your organization? Please check all that apply:

☐ It has improved forecasting skill
☐ It has enabled my organization to make and/or update forecasts more often
☐ It has enabled my organization to make types of forecasts that it did not make before. Please list the types of forecasts that the CPT has enabled you to make:

☐ It has enabled my organization to provide information products that are useful to users of forecasts in sectors such as agriculture, health, or water.
☐ It has enabled my organization to make products that are easier to understand for users of forecasts in sectors such as agriculture, health, or water.
☐ I don’t know
☐ Other – please explain

7. Overall, are you satisfied with the CPT? Please circle one:  Yes  No

8. Please leave this question blank if you answered “Yes” to question #7. If you are not satisfied with the CPT, please tell us more about why you are not satisfied. Please check all that apply.

☐ The CPT is too difficult to use
☐ The data necessary to use the CPT are not easily available
☐ The CPT is not useful for my objectives – please tell us which of your objectives the CPT does not satisfy:

☐ I don’t know
☐ Other – Please explain in more detail below:

9. How many people in your organization routinely use the CPT?

10. Which version of the CPT do you use?
11. What features of the CPT do you use? Please answer this question based on your own use of the CPT. If you know what features of the CPT others in your organization use, then please mention what features others use under the option “Other.” You can also use the “Other” category to tell us about features which are not on the list. Please check all that apply.

- Data output
- Graphics
- Contingency tables
- Verification of retroactive forecasts
- Cross-validation
- Skill measures
- CCA
- PCR
- MLR
- Forecast for individual stations
- Probability of exceedance plots
- Forecast probability maps
- Forecast values maps
- Adjust thresholds to make own forecasts
- Adjust prediction intervals to make own forecast
- Bootstrapping
- Other – Please explain in more detail below:

12. What features of CPT do you like best? Please answer this question based on your own use of the CPT. If you know what features of the CPT others in your organization like, then please mention what features others like under the option “Other.” You can also use the “Other” category to tell us about features which are not on the list. Please check all that apply.

- I like all the features
- I do not like any of the features
- Data output
- Graphics
- Contingency tables
- Verification of retroactive forecasts
- Cross-validation
- Skill measures
- CCA
- PCR
- MLR
- Forecast for individual stations
- Probability of exceedance plots
- Forecast probability maps
- Forecast values maps
- Adjust thresholds to make own forecasts
- Adjust prediction intervals to make own forecast
- Bootstrapping
- Other – Please explain in more detail below:
13. What features of the CPT do you not like? Please answer this question based on your own use of the CPT. If you know what features of the CPT others in your organization do not like, then please mention what features others do not like under the option “Other.” You can also use the “Other” category to tell us about features which are not on the list. Please check all that apply.

- [ ] I like all the features
- [ ] I do not like any of the features
- [ ] Data output
- [ ] Graphics
- [ ] Contingency tables
- [ ] Verification of retroactive forecast
- [ ] Cross-validation
- [ ] Skill measures
- [ ] CCA
- [ ] PCR
- [ ] MLR
- [ ] Forecast for individual stations
- [ ] Probability of exceedance plots
- [ ] Forecast probability maps
- [ ] Forecast values maps
- [ ] Adjust thresholds to make own forecasts
- [ ] Adjust prediction intervals to make own forecast
- [ ] Bootstrapping
- [ ] Other – Please explain in more detail below:

14. Please tell us briefly why you do not like each of the features that you checked in question #13.

15. What do people in your organization want to be implemented/added to the CPT?

16. What parts of making a forecast with the CPT do people in your organization wish they understood better?

17. What forecasts did your organization make before staff started using the CPT and what forecasts does your organization make now? For each forecast type, please answer the question in each of the columns. Leave blank the space in the last column for those types of forecasts for which you answered “No” in the second and third columns.

<table>
<thead>
<tr>
<th>Forecast type</th>
<th>Did your organization make this type of forecast before your organization started using the CPT?</th>
<th>Does your organization make this type of forecast now?</th>
<th>If you answered “Yes” in the second and third columns, then does your organization make or update this forecast more often now than it did before staff started using the CPT? Leave this column blank if you answered “No” here.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPT?</td>
<td>答：No in one of the previous columns.</td>
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<td>------</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Seasonal total rainfall</td>
<td>Yes</td>
<td>No</td>
<td>I don’t know</td>
</tr>
<tr>
<td>Seasonal rainfall frequency</td>
<td>Yes</td>
<td>No</td>
<td>I don’t know</td>
</tr>
<tr>
<td>Seasonal average temperature</td>
<td>Yes</td>
<td>No</td>
<td>I don’t know</td>
</tr>
<tr>
<td>Other – please specify below</td>
<td>Yes</td>
<td>No</td>
<td>I don’t know</td>
</tr>
</tbody>
</table>

18. For each type of forecast that your organization makes, please tell us whether your organization uses the CPT to make that forecast or not. Leave the space blank for those forecasts that you do not make.

<table>
<thead>
<tr>
<th>Forecast type</th>
<th>Does your organization use CPT to make this forecast?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasonal total rainfall</td>
<td>Yes</td>
</tr>
<tr>
<td>Seasonal rainfall frequency</td>
<td>Yes</td>
</tr>
<tr>
<td>Seasonal average temperature</td>
<td>Yes</td>
</tr>
<tr>
<td>Other – please specify below</td>
<td>Yes</td>
</tr>
</tbody>
</table>
19. What forecasts does your organization regularly make or would like to be able to make for which CPT is not helpful?

20. Does your organization provide forecast products which are designed to be used in particular sectors? Please check the box next to each sector to tell us whether your organization provides forecast products to users in this sector.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Does your organization provide forecast products to users in this sector?</th>
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</thead>
<tbody>
<tr>
<td>Agriculture</td>
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<tr>
<td>Health</td>
<td>☐ Yes  ☐ No  ☐ I don’t know</td>
</tr>
<tr>
<td>Water</td>
<td>☐ Yes  ☐ No  ☐ I don’t know</td>
</tr>
<tr>
<td>Other – please specify the sector</td>
<td>☐ Yes  ☐ No  ☐ I don’t know</td>
</tr>
</tbody>
</table>

21. If your organization provides forecast products to users in some sectors, then please tell us what kind of products your organization provided before its staff started using the CPT, and what kinds of products it provides now. Please check yes or no in each box.

<table>
<thead>
<tr>
<th>Products</th>
<th>Did your organization provide this product to users before its staff started to use the CPT?</th>
<th>Does your organization provide this product to users now?</th>
</tr>
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<td>Raw climate data</td>
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<td>☐ Yes  ☐ No  ☐ I don’t know</td>
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<tr>
<td>Summary statistics of climate data</td>
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<td>☐ Yes  ☐ No  ☐ I don’t know</td>
</tr>
<tr>
<td>Probability of exceedance maps</td>
<td>☐ Yes  ☐ No  ☐ I don’t know</td>
<td>☐ Yes  ☐ No  ☐ I don’t know</td>
</tr>
<tr>
<td>Forecast value maps</td>
<td>☐ Yes  ☐ No  ☐ I don’t know</td>
<td>☐ Yes  ☐ No  ☐ I don’t know</td>
</tr>
<tr>
<td>Forecast probability maps</td>
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<td>No</td>
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<tr>
<td>Other – please describe</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

22. Does your organization use the CPT for research (in addition to its operations)?

Please circle one: Yes No

23. Please explain any ways not covered above in which the CPT has enabled your organization to change the climate information that it produces or how it produces climate information.

SECTION 3: Your experience with CPT training

24. How many people in your organization have received training to use the CPT from IRI personnel?

25. How many people in your organization have received training to use the CPT from an organization other than IRI?

26. Have you trained anyone outside of your organization to use the CPT?

Please circle one: Yes No

27. Is there anything else you would like to tell us about the CPT which might help us improve your experience?

THANK YOU FOR YOUR TIME

Section X. Bibliography


Hansen, James W., Mannava V. K. Sivakumar. Advances in applying climate prediction to

CICAR 2009 Annual Performance Report
From July 1, 2008 to June 30, 2009
Pl Yochanan Kushnir

Outreach

Background

LDEO’s annual open house is an exciting opportunity for adults and children of every age to learn about Earth in fun and engaging ways! Although Lamont Doherty is called a research institution, it can also play a vital role in education. One of our most important events, to foster a greater public understanding of the earth is our annual open house.

Photo credit: Bruce Gilbert 2008

Shortly after Lamont-Doherty Earth Observatory was founded in 1949, its founder, Maurice “Doc” Ewing, realized that Lamont’s neighbors were not aware of the nature of the research conducted here. Therefore he started Open House, and opened up the campus one day each year for neighbors, students and the wider Columbia University community.

In 1999, in recognition of Lamont’s 50th Anniversary, Open House was expanded to include nearly 40 exhibits, lectures and demonstration, and attracted over 4,000 people. Attendees learn about the current developments in the Earth Sciences, and about how our increasing understanding of the Earth helps preserve its future. Different exhibits are aimed at different ages and educational levels, from elementary school-age children to college students to those well versed in the earth sciences.

The highlight of the CICAR exhibit featured the important drought research sponsored by NOAA being carried out by CICAR investigators The CICAR director assisted by Columbia graduate students discussed ways in which current weather patterns are related to the climate research
conducted by CICAR investigators. Visitors were interested to learn about the importance of the historical drought record and how the data is developed.

What follows is a sampling of the materials that were available to visitors at the CICAR exhibit:
All living things depend on water to survive. To help you appreciate just how important water is to all of us, here are a few interesting WATER FACTS:

- Without water there could be no life. We live on a "water planet". When viewed from space, earth is blue and white. The blue is the oceans and the white is water vapor.
- The human body is about 75% water.
- Tomatoes are 90% water, potatoes 80%, and chickens 75%.
- Less than 2% of the Earth's water supply is fresh water.
- Nearly 50% of the world's population lacks access to clean water for sanitation, drinking and other needs.
- You can save 5 gallons of water a day just by turning off the faucet when you brush your teeth.
- A leaky faucet can waste 100 gallons of water a day.
- One newspaper a day means the use of 66,000 gallons of water a day.
- It takes 6 gallons of water to produce one gallon of gasoline.
- About 75% of your brain is water--use it wisely to learn to make water conservation an everyday habit.

TRY TO DO ONE THING EACH DAY TO CONSERVE WATER.

EVERY DROP COUNTS!

SOURCES: Learning To Be Waterwise Resource Action Programs and the Mojave Water Agency
EXPERIMENT

Make your own mini water cycle...
Then use it to conduct some of your own investigations!

WHAT YOU WILL NEED:
✓ A large, clear bowl
✓ Plastic wrap
✓ A weight
✓ A smaller container (a cut-down yogurt cup works well)
✓ A rubber band or piece of string

WHAT TO DO:
✓ Place the small container in the middle of the large, clear bowl. Fill the bowl with a little water, being careful not to fill the small container inside.
✓ Cover the bowl with plastic wrap, and fasten the plastic wrap around the rim of the bowl with your rubber band or string.
✓ Put a weight on top of the plastic wrap in the center. (See figure below.) Now put your contraption on a windowsill or somewhere that the sun will hit it.

continued...
How long does it take for water to evaporate and condense on the plastic wrap? Where does the water go after it condenses on the plastic wrap?

WHAT'S HAPPENING?

The heat of the sun evaporates the water, which rises, condenses on the cool plastic, and falls into the small container. You've created a small-scale replica of the water cycle that occurs on Earth!

Now that you've made a mini water cycle, you can use it to conduct your own investigations. Here are some ideas:

Some people are worried about the effects of pollution on the Earth's polar ice caps. If particles in the air make the white ice caps darken, the ice caps might melt. How do you think discoloration would affect your water cycle? Would dark-colored water evaporate more quickly or more slowly than plain water? Find out! Try making two water cycles: one with regular water and one with water tinted with food coloring. Which do you think will evaporate faster? Why? What happens?

Is air temperature or water temperature more important to evaporation? First, make some predictions about what you think and why. Then to investigate, use warm water in one water cycle system and cold water in the other to see which evaporates more quickly. Then compare evaporation in one system that sits in a cold room and another system that sits in a warmer room. What happens?

Next, investigate how direct sunlight affects evaporation. Try placing one water cycle system in the sun and one in the shade. What do you discover?

Does ice evaporate in cold weather? If you live in a cold climate, try making a water cycle with ice chips--instead of water--and put the water cycle system in the sunshine on a cold, clear day. Would you see any signs of evaporation? Why?
What are Some Examples of Regional Applications of Global Climate Models?

With the increased availability of climate model simulation output, impacts and applications users are rapidly applying the model results for their needs. Just as quickly, the breadth and diversity of applications will continue to grow in the future as climate is no longer considered stationary.

WATER RESOURCES IN THE WESTERN UNITED STATES

The possibility that climate change may adversely affect limited water resources in the mostly arid and semiarid western United States poses a threat to the prosperity of that region. A group of university and government scientists, under the auspices of the U.S. Department of Energy-sponsored Accelerated Climate Prediction Initiative Pilot Project, conducted a coordinated set of studies that represented an end-to-end assessment of this issue. This project is noteworthy because of close coordination between production of GCM simulations and the needs of impacts modeling.

Through downscaling the global climate simulations so that higher resolution regional information could be achieved, daily time series of temperature and precipitation were used in a set of studies to assess water resource impacts. The studies, which assumed continued growth of greenhouse gas emissions, indicate that warmer temperatures will melt the snowpack about a month earlier throughout western North America by the end of the 21st Century. The shift in snowmelt will decrease flows and increase competition for water during the summer in the Columbia River Basin. In the Sacramento River and San Joaquin River basins, the average April 1 snowpack is projected to decrease by half. In the Colorado River basin, a decrease in total precipitation would mean that total system demand would exceed river inflows.

URBAN HEAT WAVES

This estimation of changes in heat-wave frequency and intensity can be accomplished using only near-surface temperature. Because heat waves are large-scale phenomena, regional downscaling is not usually required for their analysis. Global climate model output from for 2080 to 2099 was used to calculate measures of extreme heat; from this study it was found that heat waves will increase in intensity, frequency, and duration.

The use of computers to simulate complex systems has grown in the past few decades to play a central role in many areas of science. Climate modeling is one of the best examples of this trend and one of the great success stories of scientific simulation.

Building a laboratory analog of the Earth’s climate system with all its complexity is impossible. Instead, the successes of climate modeling allow us to address many questions about climate by experimenting with simulations—that is, with mathematical models of the climate system. Despite the success of the climate modeling enterprise, the complexity of our Earth imposes important limitations on existing climate models.
Climate modeling is one of the best examples of the use of computers to simulate complex systems and one of the great success stories of scientific simulation.

What are Global Climate Models?

Modern computer climate models are composed of a system of interacting model components, each of which simulates a different part of the climate system. The individual parts often can be run independently for certain applications. The models typically include four primary components: atmosphere, land surface, ocean, and sea ice. The atmospheric and ocean components are known as “general circulation models” or GCMs because they explicitly simulate the large-scale global circulation of the atmosphere and ocean. Distinct from weather prediction, the focus in climate modeling is not on individual weather events, which are unpredictable on long time scales, but on the statistics of these events and on the slow evolution of oceans and ice sheets.

There are several different ‘classes’ of climate models each of which can be used for different purposes. Coupled atmosphere-ocean models are the most complex and on long time scales, but on the statistics of these events and on the slow evolution of oceans and ice sheets. Climate models have shown steady improvement over time as computer power has increased, our understanding of physical processes of climatic relevance has grown, and our computational algorithms have improved. However, the complexity of our Earth imposes important limitations on existing climate models. What are Global Climate Models?

Developing Regional Models

Climate models allow us to experiment with global climate in a way that we cannot with ‘real’ data. For example, we can simulate future climate with or without human-induced greenhouse gases and see what the difference is - this helps to identify the magnitude of climate response to a given change in driving forces. However, in order for us to have confidence in the ability of models to project future climate conditions, the models must be able to simulate present and past climate. Accurate simulation of present-day climate for near-surface temperature and precipitation is necessary for most practical applications of climate modeling. The seasonal cycle and large scale geographical variations of near-surface temperature are indeed well-simulated in recent models, however, there are still elements of the climate that are not well-simulated including regional details of precipitation and clouds - in part due to cloud processes occurring at scales that are smaller than a typical grid square in most global climate models.

In an assessment of how well many different models simulated the climate of the late 20th century, results showed that all models have improved over previous versions. By taking the average of all the models, an even more accurate representation of the climate emerges. This is known as an ensemble approach and is now well-accepted as a valuable method of simulating global climate. How Accurate Are Global Climate Models?
10 Things Kids Should Know About Drought

Drought is caused by less rainfall or snowfall than is expected over an extended period of time, usually several months or longer. Drought can occur in any climate — arid or humid almost anywhere on earth and its effects vary from place to place because of different geographical features and how people in different cultures use water.

- **Weather patterns** develop over the years and determine our climate. Winds cause these routine weather patterns to move around the globe and when these patterns change and cause unusual weather, we get less (or more) precipitation than expected.

- **Economic problems** occur when there is not enough water in the soil for crops to grow properly. Pastures will not produce enough grass for livestock. Drought can cause food shortages and rising prices. Restrictions on water affect all of us, inside the home and outside too.

- **Environmental losses** from drought include: forest fires; soil erosion; damage to plants, animals and their habitat; and air and water quality decline. Sometimes the damage is temporary but it can last a long time or even become permanent. Drought can increase stress on endangered species and cause a loss of wildlife.

- **The National Integrated Drought Information System** was developed by NOAA to improve drought monitoring and forecasting capabilities. Drought can last longer and extend across larger areas than hurricanes, tornadoes, floods and earthquakes causing hundreds of millions of dollars in losses.

- **Drought monitoring** is an important part of drought planning, preparedness and mitigation efforts. Drought can develop in all regions of the continent, with devastating effects. Since 1980, major droughts and heat waves within the U.S. have resulted in costs exceeding $100 billion dollars, easily one of the most costly weather-related disasters on the continent during that time.

- **Mitigation** means actions taken before, or at the beginning of a drought to help reduce the impacts of drought. Actions such as constructing dams and reservoirs for water storage; canals, pipelines and aqueducts for water distribution; desalination plants to remove salt from seawater; and water conservation help mitigate the effects of drought.

- **The Drought Index** is a numerical scale that scientists use to describe the severity of a drought. Scientists use many kinds of data such as rainfall, temperature, streamflow and snowpack and blend it into a single number called a drought index value, to make it easier to understand. There is no one "correct" way to measure drought.

- **Streamflow** is the amount of water passing a specified point along a river or stream. Accurate measurements of streamflow are critical for determining how much water is available to each water owner. Hydrologists and engineers also track streamflows carefully in order to know how large to build bridges, culverts, canals, dams, spillways, etc. to safely convey water from snowmelt and from heavy rains.

- **Snowpack** is the total snow and ice on the ground. It includes both new and previous snow and ice that hasn't melted. The water content of that snowpack is what water officials monitor so closely since that relates closely to the amount of water that will end up in our rivers and streams, reservoirs and irrigation canals during the late spring and summer.

- **People** can also play a big role in drought. All living things, including humans, require a certain amount of water to live. Humans have developed lifestyles that require additional water. When drought occurs this additional water can make the difference between having enough water and running out. Through water conservation we can all help!
On September 8, Dr. Wallace S. Broecker, Columbia University Newberry Professor of Earth and Environmental Sciences and principal investigator with NOAA’s Cooperative Institute for Climate Applications and Research (CICAR) was named winner of the 2008 Balzan Prize for his seminal work on global climate change. A statement released by the Milan-based Balzan Prize Foundation cited Broecker’s “extraordinary contributions to the understanding of climate change through his discoveries concerning the role of the oceans and their interactions with the atmosphere, as well as the role of glacial changes and the records contained in ice cores and ocean sediments. His contributions have been significant in understanding both gradual and abrupt climate changes.”

The $885,000 prize, one of the world’s largest, is given to honor outstanding science, culture and humanitarian initiatives that advance world peace. The prize, started in 1956, is given in memory of the independent Italian journalist and publisher Eugenio Balzan and will be presented in Rome on November 21. Previous recipients have included zoologist Ernst Mayr, composer Paul Hindemith, oceanographer Roger Revelle, and Mother Teresa of Calcutta.

Background. Broecker is often credited with inventing the term “global warming.” In 1987 he published a paper in the journal Nature in which he proposed that heat is transported around the world by massive ocean currents that interact with the atmosphere—the so-called great ocean conveyor, and an idea still regarded as a breakthrough in climatology. Broecker is the author of over 400 scientific articles and several textbooks. He recently co-authored the book Fixing Climate, in which he proposed to remove large amounts of globe-warming carbon dioxide from the air and store it underground, in order to avert what he sees as a potential climate catastrophe. He has already received numerous honors, including a 1996 National Medal of Science, presented by U.S. president Bill Clinton, and the 2006 Crafoord Prize in Geosciences, from the Royal Swedish Academy of Sciences.

Significance: Broecker is the lead principal investigator on CICAR’s Abrupt Climate Change Studies research project funded by the NOAA Climate Program Office through CICAR. This research supports NOAA Mission Goal 2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond.
CICAR Scientists Theorize that Wind Shifts May Stir CO2 from Antarctic Depths
Cooperative Institutes - C1
This story entered on 27th May, 2009 01:09:58 PM PST

In a recent article in the journal Science, scientists at the Cooperative Institute for Climate Applications and Research (CICAR) hypothesize that releases of carbon dioxide from the depths of the Southern Ocean due to shifting wind patterns amplified global warming at the end of the last ice age, and that this phenomenon could be repeating itself in the current climate change period. With regard to the mysterious rise in CO2 about 15,000 years ago, CICAR researcher Robert Anderson posits that this warming triggered a southward displacement in westerlies in the Southern Ocean around Antarctica, pumping dissolved carbon dioxide from the deep ocean to the surface. Changes in the southern westerlies coincided with two sharp cooling events in the Northern Hemisphere at that time.

Background: Two years ago, J.R. Toggweiler, a scientist at NOAA’s Geophysical Fluid Dynamics Laboratory, proposed that westerly winds in the Southern Ocean around Antarctica may have undergone a major shift at the end of the last ice age, which would have raised more CO2-rich deep water to the surface, and thus amplified warming already taking place due to the earth’s new orbital position. Anderson and his colleagues are the first to test that theory by studying sediments from the bottom of the Southern Ocean to measure the rate of deep water pumping. In a recent interview Toggweiler commented, “I think this really starts to lock up how the CO2 changed globally. Here’s a mechanism that can explain the warming of Antarctica and the rise in CO2. It’s being forced by the north, via this change in the winds.”

Significance: Anderson says that if his theory is correct, the impact of upwelling “will be dwarfed by the accelerating rate at which humans are burning fossil fuels.” And, he said, “It could well be large enough to offset some of the mitigation strategies that are being proposed to counteract rising CO2, so it should not be neglected.” This research supports NOAA Mission Goal 2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond. Related information:
The Alliance Program, the Earth Institute and the European Institute are pleased to invite you to attend a keynote address by:

**Ambassador Fernando Valenzuela**  
Head of the Delegation of the European Commission to the United Nations

*“Climate Change Challenge, the European Perspective”*

Introduced by Professor John Coatsworth, Dean of the School of International and Public Affairs

**Moderated by Professor Yochanan Kushnir, Director of the Cooperative Institute for Climate Applications and Research**

**Thursday, October 30, 2008**  
6:00p.m – 8:00p.m.  
International Affairs Building, Room 1501  
420 West 118th Street, 15th floor

H.E. Ambassador **Fernando M. Valenzuela** has been the Head of the Delegation of the European Commission to the United Nations since 2005. Prior to that, he served as the Political Director of the European Commission and Deputy Director General responsible for CFSP (Common Foreign and Security Policy) and Multilateral Affairs. Prior to that, this Spanish Diplomat was the Special Representative of the Secretary General of the United Nations, Head of the United Nations Preventive Deployment Force in the Former Yugoslav Republic of Macedonia (UNPREDEP), Ambassador of Spain to Canada (1996-1999) and Ambassador of Spain to the United Nations in Geneva (1991-1996).

The **Alliance Program** is a joint-venture between Columbia University and three French institutions: Ecole Polytechnique, Sciences Po and Universite Paris I Pantheon-Sorbonne. For more information on the Alliance Program, please visit our website: [www.columbia.edu/cu/alliance](http://www.columbia.edu/cu/alliance)
Students in the MA Program in Climate and Society Give Presentations at Local High Schools and Libraries

As part of their core course, Dynamics of Climate Variability and Climate Change, students in the MA Program in Climate and Society (CS) are giving presentations at local high schools and libraries across New York City and its suburbs.

This 12-month, intensive graduate degree began in 2004 to train professionals and academics to understand and cope with the impacts of climate variability and climate change on society and the environment. Taking the scientific knowledge they have gained throughout the semester, students learn to distill a particular climate issue, make it relevant and interesting, and present it to a public audience.

Dr. Lisa Goddard, a research scientist at the International Research Institute for Climate and Society and the professor of the course, states the importance of communicating climate change: “I believe it is important to communicate clearly on climate change, because it is such an important topic that has been, and continues to be, misrepresented often by both skeptics and zealots. One of the most important messages about climate change, at least as we experience it, is that it will not happen in isolation. Natural year-to-year variability will dominate our local experience with the climate, in most cases. In this way, trends due to man-made climate change act to increase or decrease our odds of certain climate events, and open the possibility for experiencing unprecedented climate events.”

Brian Kahn, CS ’09, and his three group members gave a presentation entitled “Aerosols: A problem to Aero-solve?” to students at the Young Women’s Leadership School in East Harlem last week. Brian states: “It was a great opportunity to step outside of the climate science we’ve been intensively studying this semester and apply it to real world questions. Having spent the semester really exploring climate change in depth, it was tough to decide which thread of climate change we wanted to focus on and then how to boil it down to a 40-minute presentation. For me, the best part of going into a high school was how heartening it was to see how much the kids already knew about climate change, and that they were critically thinking of how to adapt in the future.”

There are twelve presentations in all, encompassing climate issues from the impact of aerosols on climate and health to the ocean’s role in global warming. A complete list of presentations titles and descriptions is below.
Abrupt Climate Change in a Warming World Annual Meeting
LDEO Campus, Lamont Hall
July 8 - 10, 2009

Wednesday July 8

9:00: Welcome and Introduction: Peter Schlosser (LDEO)

9:15: Wally Broecker (LDEO): Abrupt climate change in a warming world: the challenge we face

THE CHANGING CRYOSPHERE

10:00: Rob DeConto (U. Mass): Neogene perspectives on the stability of the West Antarctic ice sheet

10:30: Coffee

11:00: Mark Fahnestock (UNH): Understanding the causes of rapid change in ice discharge from the Greenland ice sheet

11:30: Bruno Tremblay (McGill): Observing and modeling Arctic sea ice loss

12:00: Lunch

HOLOCENE CLIMATE CHANGE I

1:00: George Denton (U. Maine): Holocene Climate Change- Overview

1:30: Joerg Schaefer (LDEO): Timing of Holocene mountain glaciers events and relation to inter-hemispheric patterns of climate change

2:00: Peter DeMenocal (LDEO): Reconstructing Holocene Atlantic Ocean climate change

2:30: Coffee

3:00: Jason Smerdon (LDEO): Reconstructing global climate fields during the Common Era: Motivations and challenges

3:30: Brendan Buckley (LDEO): Tree ring reconstructions of Asian monsoon variations over the last several centuries

CLIMATE CHANGE AND THE CARBON CYCLE

4:00: Bob Anderson (LDEO): Reorganization of global winds associated with abrupt climate change and its impact on atmospheric CO₂

4:30: Jorge Sarmiento (Princeton): Changing carbon uptake by ocean and terrestrial biosphere

CLIMATE CHANGE AND TROPICAL STORMS 1

5:00: Suzana Camargo (LDEO): How can we predict future changes in tropical storm frequency and intensity?

5:30: Adjourn/Group Dinner (Lamont Hall)
Thursday July 9

CLIMATE CHANGE AND TROPICAL STORMS 2

9:00: Jim Kossin (NOAA/NCDC): Hurricane Track Variability and Secular Potential Intensity Trends

9:30: Tom Knutson (GFDL): High resolution modeling of Atlantic hurricanes and climate change

10:00: Amy Frappier (Skidmore): Geological records of past tropical cyclone activity

10:30: Coffee

PAST, PRESENT AND FUTURE HYDROCLIMATE CHANGE

11:00: Gisela Winckler (LDEO): Global patterns of paleo dust transport and deposition

11:30: Wally Broecker (LDEO): Late Pleistocene and Holocene hydroclimate change

12:00: Ben Cook (NOAA): Climate-dust interactions in a warming climate.

12:30: Lunch

1:30: Richard Seager (LDEO): Is anthropogenic subtropical drying already occurring?

2:00: Michela Biasutti (LDEO): Projections of African climate change

THE OCEAN CIRCULATION AND CLIMATE CHANGE

2:30: Peter Schlosser (LDEO): The changing high latitude ocean circulation and interactions with the cryosphere

3:00: David Lund (U. Michigan): Holocene changes in North Atlantic Ocean circulation

3:30: Coffee

HOLOCENE CLIMATE CHANGE II

4:00: Sidney Hemming (LDEO): Deglacial lake level history in the Mono Basin, CA

4:30: David Rind (GISS): Solar variability and climate change over the Holocene

5:00: Yochanan Kushnir (LDEO): Atlantic Ocean-North Africa-Middle East climate linkages through the Holocene

Adjourn
Friday July 10

SOCIAL IMPACTS OF CLIMATE CHANGE

9:00: Judy Omumbo (IRI): Climate and disease: an on the ground perspective

9:30: Tobias Siegfried (Columbia U.): Managing transborder water resources under environmental and economic uncertainty

10:00: Balaji Rajagopalan (U. Colorado): Climate and Societal Tipping Points - Socio-economy of India and Colorado River Water Management

10:30: Coffee

11:00: David Battisti (U. Washington): Climate change and agricultural productivity

11:30: Klaus Lackner (Columbia U.): Title TBA

12:00: Lunch

Adjourn
Task II Specialized Science Support Activities

Task II provides for specialized support scientists employed by Columbia University, Lamont-Doherty Earth Observatory but located at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey. These CICAR employees are meant to enhance the technical and scientific expertise at GFDL required to execute collaborative projects and to address specific needs that require expertise not available at GFDL.

The Institute’s initial 5-year budget cycle allowed for five scientific support hires as does the CICAR continuation award, which began in July 2008. To date these positions have not been filled.
Task III Individual and Collaborative PI Research Projects

Task III encompasses the bulk of individual and collaborative PI research at the Lamont-Doherty Earth Observatory, The Earth Institute at Columbia University that is supported by grants from NOAA and compliant with the themes of CICAR. It is comprised of currently funded research projects that strengthen the CICAR research agenda in line with the themes. Task III represents the main thrust of the CICAR research agenda for the coming year.
Theme I: Earth System Modeling

Individual And Collaborative PI Research Projects
CICAR Award # NA03OAR4320179 the following 11 projects ended June 30, 2009:
2. Bleck, R., *Thermohaline Circulation and SST Variability in the Easter Tropical Pacific and Atlantic*
3. Cane, M., *Predictions and Predictability of El Niño*
4. Goddard, L., *Investigating Some Practical Implications of Uncertainty in Observed SSTs*
5. Gong, G., *The Integrated Role of Snow, Orography and Dynamical Waves in Facilitating Western U.S. Land Surface-Climate Linkages*
6. Huang, H.-P., *Tropical Influences on Recent and Historical Droughts over North America*
7. Robertson, A., *South Atlantic Ocean-Atmosphere Interaction*

Abrupt Climate Change Studies (ARCHES)
10. Martinson, D., *Southern Ocean Modeling and Analysis*
11. Schlosser, P., *Infrastructure*  
12. Seager, R., *Mechanisms of Abrupt Climate Change*

CICAR Continuation Award #NA08OAR4320754
None to date

CICAR Shadow Award #NA08OAR4320912
13. Camargo, S., *Towards a Better Understanding of the Relationship Between Climate Change and Tropical Cyclone*
14. Cane, M., *Generation and Evaluation of Long-Term Retrospective Forecasts with NCEP Climate Forecast System: Predictability of ENSO and Drought*

Abrupt Climate Change in a Warming World (ACCWW)
17. Martinson, D., *Abrupt Change in the West Antarctic Peninsula in a Warmer World*
18. Schlosser, P., *Infrastructure (sub-theme II)*
19. Seager, P., *Modeling and Understanding Late Holocene and Near Term Future Hydroclimate Change*

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1 Granted a no cost extension through June 30, 2010

CICAR 2009 Annual Performance Report
From July 1, 2008 to June 30, 2009
PI Yochanan Kushnir
Research Goals

The goal of this project was to make sense of the disparate projections for Sahel rainfall in the 21st century by the CMIP3 models. The literature had provided two mechanisms that could explain changes in Sahel rainfall: (i) in analogy to interannual variability, a warmer Indo-Pacific was to induce drying and (ii) in analogy with the annual cycle, a stronger land-sea thermal contrast was to induce a wetting. The focus of our project was to check whether this last mechanism applied to the CMIP3 models.

Research Progress

We have made progress on two fronts, one expected and the other unexpected. Our analysis of the role of thermal contrast in driving the monsoon has led to a broader investigation of the relationship between monsoon rainfall and the Sahara Low. We show (Biasutti et al. 2009) that, in both observations and models, the two are related at timescales from annual to interannual to that of the trend, with the Low inducing variability in rainfall with one-month lead. Unpublished work also shows that the sources of variability in the Low are more complex than just the thermal gradient and, in particular, are related to variability in the mid-latitude jet. Currently, we are extending this work to identify whether this information can help predict the time of monsoon onset.

The unexpected result was that we were able to report a remarkable agreement across the CMIP3 models in the seasonal evolution of Sahel rainfall anomalies under global warming: the rainy season is projected to start later and be shorter. Moreover, this phenomenon appears to be linked to a global delay of the seasonal cycle in both SST and rainfall. This result is summarized in Figure 1: the global seasonal cycle of precipitation and sea surface temperature is captured by the first pair of Empirical Orthogonal Functions (EOFs) and Principal Components (PCs). The change in the timing of the seasonal cycle is seen as the difference in PC1 between the 21st century and the 20th century. In all CMIP3 models, the anomalies are in quadrature with PC1 and indicate a shift in the seasonal cycle. We estimate the shift to be of about 4 days.
**Highlights**

We believe that the projection of a delayed annual cycle is our most important result. First of all, this provides a mean to interpret changes in rainfall in large regions of the Tropics in terms of basic principle and simple models. Second, it can guide (or change) the interpretation of many studies on the effect of global warming, studies that have been performed with fixed seasonal means.

**Societal Benefits**

Our study provides a robust estimate for future changes in the duration of the rainy season in the African Sahel. The length of the rainy season is an especially important variable for agriculture in the region: when they come, the rains are always sufficiently abundant, but they may stop before the crops are mature. Therefore, it is the length of the rainy season, and not the amount of rainfall at the peak of the rains, that decides whether there will be a good harvest.

**Education & Outreach**

These results have been presented at the 33rd Climate Diagnostics and Prediction Workshop (Lincoln, Nebraska), the KORDI Climate workshop (Seoul, South Korea), the Abrupt Climate Change Workshop (Palisades, NY), and at MOCA09 (the IAMAS IAPSO IACS 2009 Joint Assembly in Montreal, Canada). The lead investigator has been invited to present this work in the course of the fall seminar series at Harvard and UMD.

**Personnel**

Research Scientists: 2.

**Publications**

**Journal articles**


Figure 1. The global delay in the seasonal cycle of precipitation and sea surface temperature:

a.) CMIP3 ensemble mean of the first empirical orthogonal function (EOF1) of climatological precipitation in the 20th century integrations (monthly climatology was calculated over the 1975-1999 period). b.) Same as (a.), but for SST. c.) Ensemble mean first principal component (PC1) associated with EOF1 of precipitation climatology in the last 25 years of the 20th (blue) and 21st (red) centuries. Ocher and ice-blue backgrounds highlight the months of positive and negative PC1, respectively. d.) as in (c.) but for SST. e.) 21C-20C difference in precipitation PC1 for each calendar month (each panel) and each model in the CMIP3 dataset (x-axis in each panel). The background colors indicate the sign of PC1. The anomalies are in quadrature with PC1 itself, indicating a shift in the seasonal cycle. f.) as in (e.), but for SST. g.) 21C-20C difference in the time of 0-crossing of PC1 in spring (green) and fall (orange). Each bar is a model in the CMIP3 dataset, the horizontal lines indicate the ensemble mean. h.) as in (g.), but for SST. (Adapted from Biasutti and Sobel, 2009)
Research Goals

The Subtropical Overturning Cells (STCs) are a prominent and climate-relevant feature of the wind-driven ocean circulation. While the STCs ventilate the upper pycnocline, the subSTCs ventilate the lower pycnocline, thereby providing a link between Subantarctic Mode Water (SAMW) formation, Tsuchia Jets (TJs), lower Equatorial Undercurrent (EUC), and equatorial upwelling. Preliminary results suggest the importance of the eastern tropical Pacific and Atlantic where the STCs and subSTCs can potentially perturb the tropical SST. In these regions, decadal variance of SST is largest, and all climate models fail to simulate the correct mean SST. We diagnose pathways and strength of different branches of the STCs and subSTCs associated with tropical upwelling in observational datasets, various data assimilation products, and coupled and forced model simulations. We also investigate the role of the pycnocline circulation on the mean and decadal variability of tropical SST in different models and different climatic states. In addition, we examine the links between Southern Ocean wind anomalies and tropical pycnocline ventilation. This model–data comparison project will not only improve our understanding of the roles of STCs and subSTCs on tropical SST, but also the impact of tropical pycnocline ventilation on uptake of carbon dioxide.

Research Progress

This is a cooperative research effort directed by scientists at NOAA/PMEL. Bleck’s role is to numerically simulate the world ocean circulation using atmospheric forcing spanning the past half century. The forcing strategy has changed in the course of the project as we attempt to highlight the effect of atmospheric regime changes on the ocean circulation. We have finally settled on a combination of forcing fields that involve monthly-averaged fields containing information about long-term atmospheric regime changes, superimposed by “normal-year” fields expressing short-term (synoptic-scale) variability.

Interagency

NOAA/ESRL, NASA/GISS
Personnel

Research Scientists: 1
Research Goals
Main goals of this project were the investigation of ENSO predictability, systematic biases in models of the coupled ocean-atmosphere system, their correction schemes, and ways to improve the overall forecast skill. In the course of this research we also continued producing operational ENSO forecasts on a monthly basis.

Education Goals
Training students in ENSO research and predictions; educating public by making real-time ENSO forecasts available via our own and others' websites.

Research Progress

Predictability of El Niño: epochal dependence
Response of the ENSO dynamics to natural radiative forcing changes over the past 1000 yr, as captured by Zebiak-Cane model, were used to explain mean shifts in the state of the global climate system (Mann et al. 2005, Emile-Geay et al. 2007, Linsley et al. 2006). Emile-Geay et al (2007) simulated the response of the ENSO system to solar and orbital forcing over the Holocene. As estimates of the difference since the Maunder Minimum range from 0.05% to 0.5% of the solar "constant", we considered these two extreme scenarios, along with the intermediate case of 0.2%, corresponding to differences of, respectively, 0.17, 0.68 and 1.7 W/m², in terms of top-of-the-atmosphere insolation. We show that for large or moderate forcings, the low-passed filtered east-west sea-surface temperature gradient along the equator responds linearly to irradiance forcing, with a phase lag of less than a year. In contrast, the 0.05% case shows no significant variability above that inherent to the model's chaotic behavior. Wavelet analysis suggested a statistically significant enhancement of the century-to-millennial scale ENSO variability for moderate-to-strong irradiance forcing. Orbitally driven insolation forcing is found to produce a long-term trend of increased ENSO variability from the early Holocene onwards. It added approximately linearly to the solar response. Given the importance of ENSO in the climate system, the results suggested a potentially significant mechanism for long-term solar irradiance variability as a driver of natural climate change.
A comparison to key Holocene climate records, from the Northern Hemisphere sub-tropics and midlatitudes, showed support for this hypothesis.

**Predictability of El Nino: roles of initial error and atmospheric noise**

We also evaluated the relative roles, which the growth of the initial error and the impact of internal atmospheric variability play in restricting the model forecast skill when the bias is compensated for via the optimal choice of initial conditions (Karspeck et al. 2006). The seasonal and interannual predictability of ENSO variability in a version of the Zebiak-Cane coupled model was examined in a perturbation experiment. Instead of assuming that the model is "perfect", it was assumed that a set of optimal initial conditions exists for the model. These states, obtained through a non-linear minimization of the misfit between model trajectories and the observations, initiate model forecasts that correlate well with the observations. Realistic estimates of the observational error magnitudes and covariance structures of sea surface temperatures, zonal wind stress and thermocline depth were used to generate ensembles of perturbations around these optimal initial states, and the error growth was examined. The error growth in response to subseasonal stochastic wind forcing was presented for comparison. In general, from 1975 to 2002, the large-scale uncertainty in initial conditions led to larger error growth than continuous stochastic forcing of the zonal wind stress fields. Forecast ensemble spread was shown to depend most on the calendar month at the end of the forecast rather than the initialization month, with the seasons of greatest spread corresponding to the seasons of greatest anomaly variance. It was also demonstrated that during years with negative (and rapidly decaying) NINO3 SST anomalies (such as the time period following an El Nino event), there was a suppression of error growth. In years with large warm ENSO events, the ensemble spread was no larger than in moderately warm years. As a result, periods with high ENSO variance had greater potential prediction utility. In the realistic range of observational error, the ensemble spread had more sensitivity to the initial error in the thermocline depth than to the sea surface temperature or wind stress errors. The thermocline depth uncertainty is the principal reason why initial condition uncertainties are more important for ensemble spread than wind noise.

**The role of external forcing in ENSO variability**

Following our investigation of the influence of solar forcing on the frequency of El Nino events (Emile-Geay et al, 2007), we used estimates of volcanic forcing over the past millennium and the Zebiak and Cane intermediate coupled model to draw a diagram of El Nino likelihood as a function of the intensity of volcanic forcing. We showed that in the context of this model, only eruptions larger than that of Mt. Pinatubo (1991, peak dimming of about 4 W/m²) can shift the likelihood and amplitude of an El Nino event above the level of the model's internal variability. This reconciles, on one hand, a recently demonstrated relationship between explosive volcanism and El Nino (Mann et al 2005) and, on the other hand, the ability of our model (LDEO5) to predict El Nino events of the last 148 years without knowledge of volcanic forcing (Cane et al 2005, Chen and Cane 2008). We focused (Emile-Geay et al. 2008) on the strongest eruption of the millennium (1258 A.D.), and showed that it is likely have triggered a moderate-to-strong El Nino event.
event in the midst of prevailing La Nina-like conditions induced by increased solar activity during the well-documented Medieval Climate Anomaly. Compiling paleoclimate data from a wide array of sources, we documented a number of important hydroclimatic consequences for neighboring areas. We proposed, in particular, that the event briefly interrupted a solar-induced megadrought in the Southwestern US.

**Advancement of forecast skill assessment**

Due to the errors in both initial conditions and model itself, a useful forecast strategy is to perform ensemble predictions and evaluate ENSO’s predictability using probabilistic methods, e.g. via relative operating characteristics (ROC). This method was applied to the LDEO5 skill analysis (Chen and Cane, 2008). Model forecasts are considered skillful when ROC curves are above the diagonal to a sufficient extent, and the farther to the upper right corner the better is the skill (the higher is the hit/false alarm ratio). It is clear that warm and cold events are equally predictable while near normal conditions are harder to predict. For instance, if four out of five ensemble members predict an event (80% probability) at 6-month lead, we expect a hit rate of 0.52 and a false alarm rate of 0.13 for both warm and cold conditions, but the corresponding rates are 0.40 and 0.17 for near normal conditions. While at short lead times the skill decreases as the lead increases, it reaches a plateau at about 9-month lead. Forecasts made two years in advance are not much worse than those made at 9-month lead. This further indicates that skillful ENSO prediction at long lead times is indeed possible.

**Role of surface heat and freshwater fluxes**

The effects of anomalous fluxes of latent heat (LH), shortwave radiation (SW) and evaporation minus precipitation (E-P) have been examined in the Lamont ocean GCM (Chen and Cane 2008). At the surface both LH and SW have strong impact on SST during El Niño as well as La Niña periods, with the effect of the former generally against that of the latter. However, they do not cancel out and the combined effects are still very large. Anomalous E-P has relatively small impact on SST, but it is the main contributor to the interannual surface salinity variability. These anomalous heat and freshwater fluxes also have significant effects on subsurface temperature and salinity distributions, especially in the equatorial regions. E-P has a much larger impact on subsurface temperature than on SST. In the western equatorial Pacific, the subsurface response to these anomalous fluxes is stronger and penetrates deeper during La Niña as compared to El Niño. This is because of the stronger upper ocean mixing during La Niña, when the cool water coming from the east with the enhanced South Equatorial Current overrides the warm water in the west. Surface heat and freshwater fluxes play significant roles in the ocean–atmosphere interaction on interannual time scales; they are fundamentally important in controlling the SST variability in the western tropical Pacific; and they are quantitatively not negligible even in the central and eastern tropical Pacific.
Operational ENSO forecasting

We continued to produce seasonal ENSO forecasts on a monthly basis. Our forecast is used by IRI in several different ways. In particular, it is used as one of the few members of the IRI ensemble forecasting, thus being an integral part of the official IRI forecasts. Our predictions are also used by NCEP/CPC, and published in the monthly Climate Diagnostic Bulletin and the quarterly Experimental Long-Lead Forecast Bulletin. Because of the different requirements of various operational centers, we updated our forecast at least three times a month. Our model output was sent to IRI at the beginning of each month, to CPC on the 5th, and to COLA in the middle of the month. We also implemented a new system for the uniform treatment of the input data sets, which extends their monthly versions to the current month by averaging all daily or weekly records available for it. We reran our model each time to take advantage of new data. Our forecast webpage (http://rainbow.ldeo.columbia.edu/~dchen/forecast.html) is updated accordingly. The maintenance of this forecast system required retuning of the system every time when the nature of the input data streams change (e.g. CLS altimetry and FSU wind data analysis methodology and analyzed grids changed). A suite of forecast experiments had to be run to ensure a smooth transition.

Highlights

- Use of LDEO5 in operational predictions of ENSO events; evaluation of model skill using ROC approach;
- Evaluation of relative roles of the initial error in the various components of the system state and of the internal atmospheric variability on restricting the model forecast skill;
- Use of intermediate model versions for ENSO predictions to study the impact of external forcing (solar variability and volcanic emissions) on ENSO variability;
- Investigation of the role of heat and freshwater surface fluxes in ENSO variability and predictability using Lamont ocean GCM.

Societal Benefits

ENSO variability has a profound influence on year-to-year climatic changes experienced by American public and people around the world. This project strives to improve predictions of ENSO events and investigates the nature of this predictability and its limiting factors. This project also contributes towards the emerging understanding of the interactions between ENSO variability and global change: another issue of significant public interest.

Other Research Connections

Collaborators: S.Zebiak, D.DeWitt, M.Tippett (all IRI); A.Karspeck (LDEO, NCAR); J.Emile-Geay (LDEO, Georgia Tech, University of Southern California), B.Linsley (SUNY-Albany); M.Mann (Penn State University)
Awards & Honors


Alexey Kaplan: AGU Editors' Citation for Excellence in Refereeing (2005).

Education & Outreach


Graduate students: M.A.Cane/ J.Emile-Geay (Columbia Ph.D. Program); M.A.Cane, D.Chen/ D.Wang (Columbia Ph.D. Program)

Symposiums


CLIMAR-3, Gdynia, Poland, May 6-9, 2008: Dake Chen, Alicia Karspeck, Alexey Kaplan, Mark Cane, and Richard Seager, ENSO forecasts with an intermediate coupled model initialized and verified by historical climate datasets.

Intranet / Internet sites or pages

http://rainbow.ldeo.columbia.edu/~dchen/forecast.html


http://iri.columbia.edu/climate/ENSO/currentinfo/SST_table.html

Personnel

Research Scientists: 4, Research Support Staff: 2, Administrative: 1, Graduate Students: 2, Undergraduate Students: 2
Publications

Journal articles


Reports


Ph.D. Dissertations

Figure 1. Response of the Zebiak-Cane model to volcanic forcing during the past millennium. [From Emile-Geay et al. 2008].
Figure 2. Level surfaces of the approximate 6-month ensemble spread in NINO3 from LDEO4 predictions, as a function of the error in initial conditions. Color levels range from 0.1°C (blue) to 1°C (red) in intervals of 0.05°C. The scales represent the magnitude of each error field relative to the standard estimate. [From Karspeck et al. 2006].
Figure 3. LDEO model ensemble forecast skill measured by relative operating characteristics (ROC). (a) ROC curves for warm, cold and near normal conditions, respectively, at 6-month lead-time; (b) ROC curves for warm conditions at various lead times. These are calculated based on 5-member retrospective ensemble forecasts for all months over the period 1856–2003. [From Chen and Cane, 2008].
CICAR 2009 Annual Performance Report
From July 1, 2008 to June 30, 2009
PI Yochanan Kushnir

AWARD NO. NA03OAR4320179
PROJECT TITLE Investigating Some Practical Implications of Uncertainty in Observed SSTs
PROJECT ACCOUNT NO. 5-62037 FINAL REPORT
CICAR TASK AND THEME Task III Theme I
PRINCIPAL INVESTIGATOR Lisa Goddard
AFFILIATION International Research Institute for Climate & Society, The Earth Institute of Columbia University
NOAA PROGRAM & MANAGER Climate Observation Department
Joel Levy 301-427-2462 joel.levy@noaa.gov

Work on this project was completed by June 30, 2008 and was reported on in the CICAR 2008 Annual Report. The research accomplishments achieved under this funding resulted in publication of the following journal article:


Abstract
Uncertainties in the accuracy of observed sea surface temperature (SST) estimates limit a number of efforts relevant to seasonal-to-interannual climate variability and its prediction. Some of the efforts that may be hampered by uncertain SSTs include estimates of skill in predicted SSTs, attribution studies of seasonal climate anomalies, and calibration of probabilistic seasonal climate forecast systems. This study examines the explicit impact of SST uncertainties on the climate response from an atmospheric general circulation model. Uncertainties in Western Pacific SSTs play a substantial role in the sensitivity of the seasonal climate.
Research Goals

The goal for this year (2008-2009) was to fully understand the apparent transient eddy–based climatic response to North American snow anomalies, as produced by snow-forced GCM simulations conducted last year (2007-2008). One specific objective was to identify the physical storm-track dynamical processes involved in this modeled teleconnection pathway. A second objective was to reconcile this transient eddy–based climatic response with the stationary wave–based climatic response found in a prior set of GCM simulations (2006-2007), and reported in Sobolowski et al. (2007). These objectives were to be achieved via careful diagnostic analyses of GCM simulation results, additional GCM simulations, and the use of a diagnostic stationary wave model to delineate the various drivers of any stationary wave response. Thus an associated goal was to gain a better understand the overall interactions between stationary and transient waves, through their response to snow anomalies over North America.

Education Goals

The educational goal for this year was to continue to education of Stefan Sobolowski, the doctoral candidate funded by this project. Stefan’s required coursework and doctoral qualifying exam were successfully completed in prior years, so the specific objectives for this year were to develop and defend his doctoral thesis proposal, and to gain teaching experience by serving as a teaching assistant for one of the lead PI’s undergraduate courses.

Research Progress

Careful diagnostic analysis of GCM simulations with snow forcings applied throughout the year (EY; Figure 1) depict a snow forced atmospheric teleconnection pathway that stretches from NA to eastern Siberia and the North Pacific via transient eddy activity. The immediate effect of the prescribed snow forcing is a pronounced diabatic cooling over NA (Figure 1). As a consequence, the meridional temperature gradient steepens in the southern portion of the forcing region while flattening to the
north. There is also significant steepening of the temperature gradients along the coasts of NA (east, west and south). These snow-forced temperature gradient responses are sufficient to generate enhanced baroclinic growth, as measured by vertical shear and meridional temperature gradients (Figure 2). This response occurs in the vicinity of the North Atlantic storm track entrance region, and so translates into an intensified storm track. The storm track does not depict the movement of individual eddies, but rather is comprised of numerous eddies that grow, dissipate and recycle their energy toward their downstream neighbors. This downstream development, when combined with the baroclinic enhancement at the storm track entrance region, enables the transient response to a NA snow forcing to circumnavigate the globe (Figure 3).

An intensified and extended North Atlantic storm track lead to a remote surface temperature response over northern Eurasia (Figure 1c). The increased low-level meridional temperature flux and negative sea level pressure responses over this region suggests flow of warmer air into Eurasia. Thus, the snow forced changes in meridional temperature gradients lead to enhanced baroclinicity and transient activity over the North Atlantic storm track region which extends into Eurasia and results in a flow pattern that leads to warmer late winter – early spring temperatures.

An additional set of GCM simulations was performed with the snow forcings constrained to the fall season only (FS). The robust hemispheric transient response and associated baroclinic mechanisms are considerably suppressed compared to EY, which suggests that a snow forcing that persists through winter is necessary to yield the atmospheric teleconnection pathway and remote transient/state response in Eurasia.

Neither the EY or FS simulations yielded a stationary wave response comparable to that produced by previous fall season snow-forced simulations (MTN) reported in Sobolowski et al. (2007). Furthermore, the modest transient response for MTN is similar to FS. All three simulations prescribe different snow forcings in terms of magnitude, spatial location and/or temporal duration, which may affect the relative response of stationary vs. transient waves and their interaction with one another. A set of hypotheses reconciling these simulation results, based on established stationary – transient wave interaction theory, was developed as part of Stefan Sobolowski’s successful doctoral thesis proposal defense in April 2009. His proposal also outlines a set of diagnostic analyses to be performed using a stationary wave model, to confirm or refute these hypotheses.

**Highlights**

- Positive year-round snow forcings over North America lead to a clear transient eddy atmospheric response in the form of increased storm track activity from North America through Eurasia during autumn-winter-spring seasons.
- Snow forcings constrained to the autumn season considerably suppress the transient eddy response, which indicates that sustained snow anomalies through the winter season are required to produce this atmospheric teleconnection.
- The stationary wave response to snow forcings is ambiguous, and likely sensitive to the specification of the snow forcing, and the degree of stationary – transient wave interaction that results.
Societal Benefits
The improved understanding of western US snow – climate relationships resulting from this project will provide a sound, physically-based foundation for utilizing any intraseasonal-interannual climate prediction capability contained in land surface snow states. The focus on predicting continental-scale climate phenomena will have far-reaching societal benefits with respect to regional water resource management, hazard mitigation, agricultural planning and anthropogenic climate change throughout the western US.

Other Research Connections
This research strengthens partnerships between Lamont-Doherty Earth Observatory and the Columbia University School of Engineering and Applied Science.

Education & Outreach
• Lead-PI Gavin Gong is the thesis advisor for Stefan Sobolowski, doctoral candidate, Columbia University Department of Earth and Environmental Engineering
• Stefan Sobolowski is a participant in the NASA Earth System Science (ESS) Fellowship Program, Sep 2006 – Aug 2009.
• Presentations

Personnel
Research Scientists: 2, Graduate Students: 1.

Journal Articles
Figure 1. Seasonal SWE (black contour lines) and surface temperature (color-filled contours) response to EY snow forcing during (a) fall, (b) winter, (c) spring and (d) summer. Positive SWE contours (solid lines) drawn at 0.5, 5, 15, 25 cm. Negative SWE contours (dashed lines) drawn at -3, -2, -1, -0.5 cm. Only statistically significant (>95%) surface temperatures are plotted.

Figure 2. Spring season spatial gradient response to EY snow forcing at 750 hPa. a) Vertical shear $-\partial u / \partial p$; contours drawn at ± 0.001 m s$^{-1}$ intervals. b) Meridional temperature gradient $\partial T / \partial y$; contours at ± 4, 6, 8, 10, 12, 16, 20, 24 °C 1000km$^{-1}$. Red (blue) contours denote a positive (negative) response. 90% (95%) statistical significance indicated with light (dark) grey shading.
Figure 3. Three month running mean 500 hPa geopotential height variance $\left(\overline{Z^2}\right)^{1/2}$ response to EY snow forcing. Seasons begin with fall (SON, top-left) and progress left to right, top to bottom ending with ASO. Contours drawn at ± 1, 2, 3, 4 m; red (blue) contours denote a positive (negative) response. 90% (95%) statistical significance indicated with light (dark) grey shading.
Research Goals

This project aims to determine quantitatively the impacts of the tropical sea surface temperature (SST) anomalies on North American droughts and the dynamical mechanisms that facilitate the SST-drought connection on multi-year to multi-decadal time scales. The primary goal of the budget year is to advance our understanding of subtropical drying in the context of droughts and climate change.

Education Goals

• When possible, to expose undergraduate and graduate student to modern climate research through on-site, one-on-one internship/mentorship program.
• To use knowledge gained through research to enrich teaching activities to undergraduate and graduate students in disciplinary and inter-disciplinary programs through lectures and web posting of research results.

Research Progress

In this project, the analysis of an extensive set of atmospheric general circulation model (GCM) simulations forced with imposed sea surface temperature (SST) anomalies in different sub-domains of the tropical and subtropical Indo-Pacific Ocean confirms the importance of the combined tropical Eastern Pacific and Indian Ocean-Western Pacific (IWP) SST anomalies in forcing North American droughts. A detailed modeling experiment using the SST forcing from the sub-domains of the IWP region further reveals that the tropical and subtropical Western Pacific is the essential contributor to the SST-drought connection while a stand alone Indian Ocean SST anomaly is not sufficient for inducing droughts over North America. The atmospheric circulation responses to the SST forcing in different regions of the Indo-Pacific Ocean during the 1998-2002 North American drought is found to depend sensitively on the location of the SST anomalies. The circulation response to an Eastern Pacific SST anomaly comprises a stationary wave component over North America plus a relatively weak zonally symmetric response. The response to an isolated Indian Ocean SST anomaly is overwhelmingly zonally symmetric in both the tropics and midlatitude, while that to the Western Pacific SST forcing has equally strong stationary wave and zonally symmetric components. The inability for the
Indian Ocean SST anomaly to generate stationary wave responses is attributed to the fact that the upper level absolute vorticity gradient is weak over the Indian Ocean sector, a condition that prohibits the generation of Rossby wave source despite the presence of a strong SST-forced diabatic heating.

Recently we have focused on the analysis of the mechanisms for droughts in the past year of this project. Using a moist "aquaplanet" model, we have performed a series of simulations with specified tropical and global sea surface temperature anomalies to determine the response in the hydrological cycle in the midlatitudes. Our latest efforts include the simulations under both equinoctial and non-equinoctial conditions. The latter allows us to look into the seasonal dependence of the hydrological response. This analysis is combined with an analysis of the GFDL coupled climate model simulations with an increasing concentration of greenhouse gas. The results indicate that, even with a globally uniform surface warming, the increase in atmospheric water vapor in midlatitude can cause changes in the stability property of the climatological mean flow in the subtropics and midlatitude, which consequently leads to a poleward shift of the storm tracks and the subtropical drying.

We have also extended many of the "repeated seasonal cycle (SCYC) runs" from 20 to 50 years to ensure the statistical significance of the results. Most of the conclusions that we obtained with the 20-year runs are shown to be robust. We have also extended our analysis to the combined influences of the tropical Pacific+Atlantic SST forcing on North American droughts. The combination of a cold tropical Pacific and a warm tropical North Atlantic is found to be conducive to the formation of droughts in the U.S.

**Highlights**

- Obtained New Understanding of the mechanism of subtropical drying
- Consolidated the statistical significance of the influence of tropical Indo-Pacific SST forcing on North American droughts.
- Explored the combined influences of the Pacific and Atlantic SST forcing; demonstrated the relevance of the "cold tropical Pacific+warm tropical North Atlantic" pattern to the formation of North American droughts.

**Societal Benefits**

The results of this study are useful for understanding and predicting the hydrological variations over North America that is of benefit to all water users in communities, agriculture, and energy production.

**Education & Outreach**

Research advisor / mentor
- Undergraduate: Liz Logan, Tyler Ruff
- Graduate: Yutian Wu

**Personnel**

Research Scientists: 3, Graduate Students: 1, Undergraduate Students: 2.
Journal articles


Figure 1. Multiple regression of the observed precipitation anomaly (from GHCN station data weaved into 4°x4° grids) onto the SST anomalies over the tropical Eastern Pacific ((a) winter, (c) summer) and tropical North Atlantic ((b) winter, (d) summer). The color scale, shown at bottom, is in unit of mm/month per standard deviation of SST anomaly.
Figure 2. Observations (OBS) and simulation of the precipitation anomaly over the Americas associated with the shift in equatorial Pacific SST from relatively cold to relatively warm in 1976 (rainfall averaged between July 1976–June 1998 minus the average of July 1961–June 1976). POGA refers to a simulation where equatorial Pacific SST were allowed to vary realistically from month to month but the rest of the oceans were held at their climatological seasonal cycle. GOGA is a similar simulation with SST varying realistically worldwide. SCYC is an experiment where the difference in tropical SST between the intervals July 1976–June 1998 and July 1961–June 1976, which represents the change due to the 1976 climate shift, was prescribed and held fixed in the tropical oceans while the model was marching to a repeating annual cycle for 30 years. The results indicate the prominent role played by tropical SST in orchestrating rainfall over the Americas and that the details of monthly SST variability are not important for capturing the decadal climate shift.
Research Goals

Seasonal climate forecasts over tropical Africa and South America are hampered by the lack of skillful predictions of sea surface temperatures (SST) in the tropical Atlantic. The mean seasonal cycle and variability of the tropical Atlantic are closely linked to the South Atlantic through the subtropical anticyclone and shared modes of SST variability. In particular, it is hypothesized that the interactions of the El Niño-Southern Oscillation during boreal spring with pre-existing upper-ocean anomalies over the South Atlantic Ocean yield increased predictability of tropical Atlantic variability (TAV). The goal of this project is to make advances in two areas in order to improve seasonal prediction over the tropical Atlantic: (1) physical understanding of ocean-atmosphere interactions over the South Atlantic and their interactions with ENSO and TAV, and (2) simulation of the mean climate and seasonal cycle by coupled ocean-atmosphere general circulation models (GCMs) over the South Atlantic, as a prerequisite to successful dynamical seasonal prediction over the Atlantic sector.

Research Progress

During the initial stage of the project, we explored the hypothesis that preconditioning of the Atlantic’s response to ENSO can yield an important source of seasonal predictability, as proposed by Giannini et al. (2004). This work is in preparation for hindcast experiments to quantify the usefulness of this source of predictability, using an atmospheric GCM coupled to a simplified ocean model.

The influence of El Niño on South Atlantic is investigated in the context of the meridional SST gradient across the tropical Atlantic. This gradient, denoted as G1 and defined as the difference between the North Atlantic SST (tNA) averaged over 5N-25N and South Atlantic SST (tSA) over 5S-25S, is known to regulate rainfall over the northern Brazil. Previously, Giannini et al. (2004) found that for 1950-1994 El Niño events are dominated by those with a negative G1 (South Atlantic warmer than North Atlantic) in March-May, called "discordant" cases (with opposite signs for NINO3 index and G1), while La Niñas are dominated by "concordant" cases. Using a long and detrended SST data set for 1876-1999, we clarified that concordant cases are actually
more common than discordant ones for both El Niño and La Niña. This is consistent with our further analyses of the lag correlation between the NINO3 index and tNA, tSA, and G1, performed using the same SST data for 1876-1999. The NINO3 index in January is found to be positively correlated with both tNA and tSA in March-May. However, the correlation between NINO3 and tNA is 0.6 compared to 0.3 for that between NINO3 and tSA. Consequently, the sign of (tNA-tSA) more often than not agrees with that of the tropical Pacific SST anomaly associated with ENSO.

The weak correlation between El Niño SST and tSA indicates a substantial non-ENSO influence due to local dynamics in the South Atlantic. Searching for hints of the local processes, we found that in the composite of the concordant cases described above a distinctive structure of SST anomaly exists off the coast of Angola and extends northwestward (covering part of the tSA region) to near the equatorial Atlantic. This pattern broadly resembles the so-called Benguela Niño (Florenchie et al. 2004); the strongly concordant cases are those with a warm (cold) ENSO event coinciding with a cold (warm) Benguela Niño. This picture did not emerge clearly in a similar composite in Giannini et al. (2004), likely because the shorter SST record they used does not contain a large enough number of Benguela Niño events (which occur less frequently than El Niños). As the oceanic upwelling pertinent to Benguela Niño is located beneath the northward branch of the South Atlantic anticyclone, the relationship between the two and their further connection with ENSO will be investigated. This component of the work was published in Huang et al. (2005).

In the second stage of the project, hindcast experiments for the tropical Atlantic sea surface temperature (SST) gradient, G1, defined as tropical North Atlantic SST anomaly minus tropical South Atlantic SST anomaly, were performed using an atmospheric general circulation model coupled to a mixed-layer ocean over the Atlantic to quantify the contributions of the El Nino-Southern Oscillation (ENSO) forcing and the preconditioning in the Atlantic to G1 in boreal spring. The results confirm previous observational analyses that in the years with a persistent ENSO SST anomaly from boreal winter to spring, the ENSO forcing plays a primary role in determining the tendency of G1 from winter to spring and the sign of G1 in late spring. In the hindcasts, the initial perturbations in Atlantic SST in boreal winter are found to generally persist beyond a season, leaving a secondary but non-negligible contribution to the predicted Atlantic SST gradient in spring. For 1993-94, a neutral year with a large pre-existing G1 in winter, the hindcast using the information of Atlantic preconditioning alone is found to reproduce the observed G1 in spring. The seasonal predictability in precipitation over South America is examined in the hindcast experiments. For the recent events that can be validated with high-quality observations, the hindcasts produced dryness in boreal Spring 1983, wetness in Spring 1996, and wetness in Spring 1994 over northern Brazil that are qualitatively consistent with observations. An inclusion of the Atlantic preconditioning is found to help the prediction of South American rainfall in boreal spring. For the ENSO years, discrepancies remain between the hindcast and observed precipitation anomalies over the northern and equatorial South America, an error that is partially attributed to the biased atmospheric response to ENSO forcing in the model. The hindcast of the 1993-94 neutral year does not suffer this error. It constitutes an intriguing example of useful seasonal
forecast of G1 and South American rainfall anomalies without ENSO. This component of the work was published in Huang et al. (2009).

**Personnel**

Research Scientists: 3.

**Journal articles**


Research Progress

We have downloaded all of the WOCE and CLIVAR Repeat datasets and created a relational database of all the initial (“one time”) cruises. From this database, we have extracted the stations that have helium data in the Pacific Ocean into a separate dataset for testing and development purposes.

We created software to display and semi-automatically quality control the data grouped by individual station profiles. Using that software, we have passed through all of the Pacific data, and updated the WOCE quality flags in our “development” database.

We created software to calculate “neutral” density coordinates, DNe, and DHe for the WOCE data, and have added those values to our development database. We developed software to interpolate the helium, d3He, tritium, and neon, DNe and DHe data to standard depths and neutral density surfaces, using a local least-squares polynomial fitting routine. We have plotted the various data against pressure, potential density, and neutral density, and quality controlled these data for our Pacific “development” database.

We developed an optimal interpolation routine for fitting data on pressure and isopycnal coordinate surfaces. The routine has been tested on Pacific data, but not yet applied for creation of property maps.

Based on profile plots, we divided the South Pacific into 10 regions within which the d3He data can be said to follow a particular pattern. We created 10 averaged profiles for each variable, one for each region.

We plotted all of the Neon data for the Pacific basin, in aggregate and by profile; compared it to Atlantic Neon profiles and Southern Ocean profiles, and analyzed it in the context of recent literature on Neon saturation levels. Neon concentrations are necessary to calculate the mantle helium contribution from Neon data.
We created software to combine 4He, DHe, DNe and d3He data into mantle helium contributions in the Pacific Ocean.

We have, separately, collected He, 3He, 3H and Ne data from large non-WOCE programs (mainly: TTO, GeoSecs, LDEO/NGL collections) and databased them.

We have met with the Princeton/GFDL group (Sarmiento, Gnanadesikan, Key and Bianchi) to establish a strategy for data integration, archiving, modeling and analysis. We will use the GloDAP routines for data interpolation. (Note that the GloDAP interpolation routines are not available publicly, so we will still need the interpolation and objective analysis routines developed here for quality control and analysis purposes.)

Collection of some of the unpublished transects from other laboratories has been postponed from Year 1 to Year 2 as we developed a strategy for collaboration, synthesis and archiving. We believe that our recent one day workshop with the Princeton group, including both the GLODAP PI (Robert Key) and the lead PIs on in our modeling effort (Gnanadesikan and Sarmiento), has clarified those questions and we are currently reaching out to the other laboratories.

**Highlights**

- Analysis of the Pacific “development” dataset led to the identification of a mantle helium plume emanating from the SW section of the Pacific Antarctic Ridge, spreading onto a very dense (neutral surface gamma = 28.2) isopycnal. This plume confirms a (previously presumed) Southern source of mantle helium, and identifies a tracer for ventilation processes south of the ACC.

- The South Pacific d3He profiles have been translated into mantle helium profiles and used to constrain a family of 1-D advection-diffusion (Munk) models, which have yielded some constraints on diapycnal mixing as well as the mantle plume injection rates.

**Societal Benefits**

Communication between the surface and abyss is important to estimate both the absorption and the residence time of anthropogenic carbon, a prime driver in global warming.

The stratification, and degree of isolation, between the benthos and the thermocline is important in estimating the feasibility and efficiency of deep-ocean sequestration of CO2.

Large-scale dispersion of chemical signals in the abyss is important to the nutrient budgets of the global ocean, which are the ultimate limit on the global mining of the oceans for protein.

For each of these problems, mantle helium provides unique information. It is the only easily measured, biologically conserved, highly soluble signal that has its origin in the abyss. As such, it should be helpful in getting quantitative results in each of these areas.
**Other Research**

**Partnerships**
We are partnering in this with GLODAP (Robert Key, Princeton), which will provide mapping routines and archival services. We are working with Princeton’s Atmosphere and Ocean group (Sarmiento, Gnanadesikan and their graduate student Daniele Bianchi) on integration of the data with models.

**Collaborators**
Robert Key, Jorge Sarmiento, Anand Gnanadesikan, Daniele Bianchi

Inquiries have been sparked from several other university research groups as a result of presentation of preliminary results, most recently from Jake Gebbie, in Peter Huybers’ group at Harvard.

**Education & Outreach**

**Fellowship Programs / Internships**
- Brenden Cline, Frontiers of Science Fellow (Columbia Univ. Sophomore).
- Gold Truong, NSF-sponsored work-study intern (Columbia Univ. Junior/Senior).

**Public Relations**
- Databases: Global Helium Database, including: 4He, d3He, 3H, Neon, integrated with GLODAP datasets for salinity, temperature and pressure.

**Personnel**
Research Scientists: 3, Administrative: 1, Undergraduate Students: 2.
Research Goals

To determine the physical mechanisms through which the North American circulation interacts with the topography to produce summer precipitation over North America and to help a better seasonal prediction of the North American summer precipitation.

Research Progress

In the past year, we have made progress in the following areas pertaining to this project.

First, we have examined the influence of orography on the downstream storm track intensity. It is found that depending on the jet structure, whether a single or double jet, the impact of topography on the storm track intensity shows completely opposite tendency. When a single jet is interacting with a topography, the storm track tends to decrease its strength in the presence of the mountain compared to no mountain case, whereas, when a double jet is present, the storm track intensifies. Since precipitation is closely related to the storm activity, the results are of significance to orographic impact on precipitation, which is a topic needs to be explored further in a more realistic setting. A paper is published in the Journal of Atmospheric Sciences (Son, S.-W, M. Ting, and L. Polvani, 2009: The Effect of Topography on Storm Track Intensity in Relatively Simple General Circulation Model. J. Atmos. Sci., 66, 393–411.)

Second, in collaboration with colleagues at Tufts University, we have examined the seasonality of the trend and variability of the US precipitation in the past 50 years, with emphasis on the fall precipitation variabilities. In the past, the focus of most research on US precipitation is on either the winter or summer. The transitional season received little attention in the literature. Recent studies have shown that the fall precipitation shows a large positive trend and significant decadal variability. The mechanism of the trend and variability in fall precipitation, however, is not clear. We contrasted the fall season to the more familiar winter and summer, in particular, the role of the Great Plains low-level jet in determining the trend and variability of fall precipitation in this project. A GRL paper
(Small, D., S. Islam, and M. Ting, 2009: Trends and Decadal Variations in Fall Precipitation in the United States. *Geophy. Res. Letter*, submitted) is currently being revised, and further analysis on the role of topography on the fall precipitation and low-level jet is under way.

Third, we worked with colleagues at the Illinois Water Survey on the simulation of the North American monsoon in the state-of-the-art coupled ocean-atmosphere models, as well as atmospheric GCMs with prescribed SSTs. We examined observational circulation features that are associated with North American monsoon onset and retreat as well as the total monsoon precipitation. These observational linkages are then examined in the GCMs to see whether models are able to reproduce similar circulation features. We also examined the models with the same atmospheric component but differing oceanic component to see if oceanic processes dominate the NAM simulation. The results are summarized in a paper to Journal of Climate (Liang, X.-Z., J. Zhu, K. E. Kunkel, M. Ting, J. X.-L. Wang, 2008: Do CGCMs Simulate the North American Monsoon Precipitation Seasonal-Interannual Variability? J. Climate, DOI: 10.1175/2008JCLI2174.1).

**Highlights**

- Orography plays a different role in the environment with double or single jets in influencing the downstream storm track intensity and precipitation. This may have important implications to the mid-winter suppression of the Pacific storm tracks.
- The fall precipitation in the US is showing a significant increasing trend in the past 50 years, but coupled ocean-atmosphere models are unable to simulate this trend.
- The NAM seasonal cycle is not well simulated in most coupled ocean-atmosphere GCMs, but the one with prescribed SST of the same atmospheric model is able to more correctly simulate the NAM seasonal cycle, suggesting the SST simulation is essential in the process.

**Societal Benefits**

The public needs to act on the future climate change when change is robustly projected, as is the case of the Southwest US drying trend. This is particularly useful information to water resource management. At the same time, it is important to understand the seasonality and locality of the precipitation trend and variability as in the case of the US fall precipitation, since the water resource management needs to know as much information as possible to make their decisions.

**Other Research Connections**

- Research Partnerships: It helped me to establish research connections with Tufts University on extending our original studies focusing on the summer, now extended to the fall. This research continues to enhance the partnership between Lamont-Doherty Earth Observatory of Columbia University with the State Water Survey at the University of Illinois at Urbana-Champaign. It also helped to establish a collaboration between LDEO and Department of Applied Physics and Applied Mathematics within Columbia University
Collaborators: Shafik Islam, Dave Small, Xin-Zhong Liang, Lorenzo Polvani

Personnel
Research Scientists: 1, Research Support Staff: 1, Post Doctoral Fellows: 1.

Journal articles


Research Goals

Improve our quantification of the nature (magnitude, temporal-spatial distributions) of ocean-ice variability in the western Antarctic Peninsula region, and the ocean’s role in contributing heat responsible for the warming and unprecedented glacial melt being experienced in the Antarctic Peninsula (87% of the glaciers are in retreat, contributing to sea level rise). We wish to estimate the total ocean heat flux to the atmosphere and glacial melt, and determine what fraction went to each of these, and ultimately, the underlying mechanisms driving these fluxes and their sensitivity in order to estimate possible future scenarios. Also, to determine the mechanisms by which the ocean heat is delivered to the continental shelf where it can melt glacial ice. Desire is to ultimately estimate that fraction of ocean heat that goes into glacial melt, and an understanding of the distribution of changes in \( Q \) to the atmosphere, glacial melt and advection.

Specific goals for 2008: continuing the year 07 Work Plan, promised (as its primary goal): "to continue our investigation of better quantifying the nature of the change in ocean heat content flooding the continental shelves of the western Antarctic Peninsula (WAP)" with the goal of quantifying the ocean heat flux to the atmosphere (contributing to the earth’s fastest winter warming). That is, we wish to relate observed changes in ocean heat content \( (Q) \) as a function of depth to specific mechanisms: \( DQ = DQ_{\text{air}} + DQ_{\text{melt}} + DQ_{\text{adv}} \), where \( Q \) is the integral of \( r_c(T-T_f) \) from the lowest thermistor sensor (close to the anchor) to the base of the winter mixed layer (= Winter Water, which is near freezing at about 75 m depth); subscripts are: air = vented to atmosphere; melt = loss to glacial melt, and adv = residual lost to advection. 2008 research goal is to estimate the first term, eliminating it from the system via tested scaling laws (most uncertainty in the estimate is attributed to poor knowledge of the surface energy budget due to limited, almost nonexistent meteorological measurements in the region forcing us to use reanalysis products). For the first year of mooring data (and more recently two years of data), we wish to isolate that portion of the water column providing \( DQ_{\text{air}} \) — presumably a layer of water losing heat closest to the surface. Then, in 2009 we will remove \( DQ_{\text{air}} \) from the total change in \( Q \), and attempt to estimate the glacial melt via an inversion involving excess freshwater in the water column.
Education Goals

Acquaint school children and general public with the importance of the Antarctic polar system; including implications of the undergoing change, impacts of this change from local to global, critical role of the ocean in the change and sensitivity of the polar system.

Research Progress

Much of this work is still in progress given our recent recovery of the mooring data. We have performed initial analyses designed to find that coherent layer of water showing consistent change in Q near the top of the mooring profile that represents DQair (where a “coherent” layer, is a layer of water that does not show both gain and loss of Q). Presumably heat vented to the atmosphere will be in the layer closest to the surface, and that layer, while expanding or contracting in depth, will be somewhat consistent in time. We have attempted several means for isolating this layer. We have fit “waterfall” plots of the temperature profiles as a function of time, and then contoured these showing depths where Q(z) changes sign. These contours isolate coherent layers (CL), and they revealed (particular the shallow ones) short-lived CLs, but over the length of the time series proved inadequate for consistency. Lack of consistency over time may not be a fatal flaw given the nature by which heat is vented (storms will vent heat from thicker layers). We are currently regressing the heat fluxes estimated by tracking the temporal change in Q in the uppermost coherent layer and comparing that time series to ones showing: (1) our scaling law estimates of the heat flux to the atmosphere, (2) storm intensity (for corrections), and (3) Tair, the latter two related to the forcing of the flux.

We also estimated the uppermost CL via averaging all Q(z) profiles, and via an EOF analysis. The EOF produced the best results, though the variability in depth confounds that method somewhat. But, we were able to define, from mode 1 a canonical shape of the uppermost coherent layer, and fit this layer to each profile (in time) to track the depth and direction of the change. This was promising but clumsy, so we are now attempting to quantify this better through use of a complex EOF analysis (still in progress). However, the (clumsy) success does suggest that we will be able to define a reasonable estimate of DQair(t) against which we can compare our scaling law estimate — regression of the two estimates should help refine (ideally, optimize) our methodology for estimating DQair, especially now that we have full–year results for 5 moorings.

Highlights

• Successfully recovered, serviced and redeployed 5 moorings on the WAP, with nearly complete data recovery (only two, of over 100 sensors, failed)
• Ability to define signal from noise in records looks convincing through a set of physical consistency tests (Figure 1)
• Data allow different means for estimating Qair
• Encouraging results for initial estimates of defining water layer from which Qair originates
**Societal Benefits**

Quantification of ocean's contribution to the WAP warming and possibly to rapid melt of glaciers on WAP, eventual ability to estimate impact (including time scale) of global warming on Antarctic glacial melt. Rapid melt by increased warm water, can destabilize ice streams, accelerating their delivery (flow speed) to the ocean by a factor of 7 or more, thus knowing how to model fraction of ocean heat to glacial melt is critical for future assessments.

**Other Research Connections**

Collaborators: Ducklow (MBL), Schofield (Rutgers), Steinberg (VIMS), Stammerjohn (UCSC)

**Interagency**

National Science Foundation: Palmer Long Term Ecological Program (PAL LTER) project, and SASSI, mooring array off of the Western Antarctic Peninsula.

**Education & Outreach**

Martinson (and entire science group) communicated with school children from the ship during the January/February 2009 Antarctic cruise recovering moorings; Martinson has given several general presentations on this at a number of university colloquiums: University of South Carolina, LDEO, ODU, and most recently, Dept. of Applied Physics and Math at Columbia University.

**Personnel**

Research Scientists: 1, Research Support Staff: 1.

**Journal Articles**


Prospect Point, Antarctica, ~100 km east of one of the Martinson moorings. Background shows small marine glaciers being melted by warm water monitored by the moorings. Photograph: Z. Cardman at UNC.
Figure 1: Black dotted line is raw time series of ocean heat content ($Q$; definition shown in inset box) for a mooring located in the central continental shelf of the WAP. Solid red line is estimate of signal using first mode of Karhunen-Loève transform (EOF of a time series). A number of tests for physical consistency, such as: warming events all warm at similar rate, and coincide with maximum T, suggest that this is a reasonable estimate of signal in the noisy record.
Research Goals

• To improve understanding of the dynamical mechanisms associated with hydroclimate change, especially in the world semi-arid, subtropical regions.
• To examine model-projected hydroclimate change in comparison with 19 and 20th century observed variations and to determine the role of natural and anthropogenic forcing in most recent changes in North America and world-wide.
• To further develop the capacity to model Medieval and Little Ice Age hydroclimate variations as a means of comparing past and future hydroclimate change and as a measure of hydroclimate sensitivity to external perturbations and internal interactions.

Education Goals

• To train the next generation of scientists specializing in climate variability and predictability and familiarize them with the theoretical background and tools of research in this field.
• When possible, to expose undergraduates student to modern climate research through on-site, one-on-one internship program.
• To use knowledge gained through research to enrich teaching activities to undergraduate and graduate students in disciplinary and inter-disciplinary programs through lectures and web posting of research results.

Research Progress

**Attribution of hydroclimate change in North America to tropical Pacific and Atlantic SST anomalies:** Our work has used large ensembles of long model simulations with various configurations of forcing, as well as observations, to determine that the driver for persistent, multiyear drought in southwestern North America is equally persistent La Niña-like conditions in the tropical Pacific Ocean. In the case of the 1930s Dust Bowl and the 1950s Southwest drought, a warm subtropical North Atlantic Ocean also played a role. This result has been placed on quite firm foundations in that an atmosphere model forced by tropical Pacific SSTs alone from 1856 to 2007 produces all six multiyear droughts in the instrumental record but that, for the 1930s and 1950s, Atlantic SST forcing is also required for the most realistic simulation.
Detecting and understanding of anthropogenic induced drying in SW US: In collaboration with our colleagues at NOAA/GFDL we show that there is a broad consensus among climate models that this region will dry in the 21st century and that the transition to a more arid climate should already be under way. If these models are correct, the levels of aridity of the recent multiyear drought or the Dust Bowl and the 1950s droughts will become the new climatology of the American Southwest within a time frame of years to decades. Our study uses IPCC AR4 models as well as the GFDL CM2.1 model output for specific diagnostic analyses.

Role of dust in shaping the patterns and intensity of the 1930’s Dustbowl: We have completed two studies of the role of human land use practices in the Dustbowl drought of the 1930s. We found that crop failure and the exposure of bare soil to the atmosphere had two effects: 1) the resulting dust storms further suppressed precipitation and moved the drought northward and 2) the reduced evapotranspiration caused by de-vegetation, lead to higher surface temperatures and aided the abnormal warmth of the 1930s. These changes help bring the modeled Dust Bowl drought more into line with that observed and make clear that, although it was initiated by tropical SSTs, the climate of the 1930s was significantly modified by human activity.

Forced and Internal 20th Century SST Trends in the North Atlantic: In this project, models and observations are used to detect and attribute long-term (multi-decadal) 20th century North Atlantic (NAtl) SST changes to their anthropogenic and “internal” (unforced externally) causes. A suite of IPCC 20th century (C20C) coupled model simulations with multiple ensemble members are subjected to multivariate analysis procedures, particularly a signal to noise maximizing empirical orthogonal function analysis, to identify a model-based estimate of the forced, anthropogenic component in NAtl SST variability. Comparing the results to observations, it is argued that the long-term, observed, North Atlantic basin-averaged SSTs combine a forced, global warming trend, with a distinct multi-decadal “oscillation”. The latter is distinctly outside of the range of the model-simulated forced component, which has most likely resulted from an internal ocean-atmosphere interaction. This internal variability (previously dubbed the Atlantic Multidecadal Oscillation (AMO) produced a cold interval between 1900 and 1930, followed by 30 years of relative warmth and another cold phase from 1960 to 1990, and a warming since then. The amplitude of the AMO is large enough to deserve consideration in assessing the impact of climate change in and around the Atlantic Basin.

Holocene climate variability in the Eastern Mediterranean (Levant) region: In recent years a well-dated record of Dead Sea Level was assembled which provides a remarkable account of droughts and pluvials in the Levant region since the last glacial period with evidence for several abrupt changes that have been linked to cultural changes in the region. In this study we look at the Dead Sea Level record over the last 10,000 years and its antiphase association with hydroclimate variability in sub-Saharan Africa, and the North Atlantic. We compare these linkages to evidence from the instrumental era and find a compelling similarity to 19th ad 20th century variability on multi-decadal times scales. Based on these finding we hypothesize that hydroclimate variability in the Levant
and sub-Saharan Africa are linked to and orchestrated by multidecadal to millennial changes in North Atlantic SST.

**Investigating the impact of ENSO on the Asian Summer Monsoon:** We conducted a diagnostic study of the interaction between tropical Pacific SST variability during summer and the strength of the summer monsoon over India. We found that the anomaly of Indian Ocean (IO) SSTs in the summer affects the strength of monsoon rainfall suppression by El Niño. Usually, during an El Niño, IO SSTs are colder in the early and mid-summer than during the late summer and fall – reflecting the remote influence of ENSO on the IO. However, in the case of an early onset of El Niño, IO SSTs warm up early and tend to weaken the Pacific impact on the monsoon, eliminating the suppression of rainfall or weakening it. We suspect that this is due to the changes in atmospheric stability over the IO region and the Indian sub-continent.

**Societal Benefits**

Hydroclimate variability and change are a matter of serious concern worldwide. Research on how these aspects of climate impact water availability and quality is important for building robust prediction capabilities and provide information to decision makers and the general public as they seek specific solution to adapt.

**Other Research Connections**

This work meshes well with and is complemented by research on tropical influences on the atmosphere, which is funded by NSF. In the course of this work we partnered with NOAA/GFDL and NASA/GISS.

**Awards & Honors**

R. Seager was the recipient of the 2007 the LDEO Director’s Award on Outstanding Research Performance. R. Seager (together with M. Cane and E. Cook) received the “California Department of Water Resources Climate Science Paper Award” for two manuscripts that describe the impact of climate variability and climate change on US West water resources.

**Education & Outreach**

We have involved several graduate students in conducting research on various aspects related to the project objectives. In addition we have regularly worked with undergraduate student, either as summer interns or work-study students with the goals of giving them a climate research experience. In most cases these students were funded by other sources and created opportunities to augment our own work.

We presented our work results to various media outlets (radio, TV, and print) on many occasions. Most of media requests for interviews and information came in the wake of the publication of our paper on the future of US hydroclimate in the journal Science.

The results of our work provided material for courses on climate at the Columbia Department of Earth and Environmental Sciences and School of International and Public Affairs.
We routinely updated our “Abrupt Change” and “Drought” web pages with brief research reports that are written for the general public. These reports can be accessed at:
http://www.ldeo.columbia.edu/res/div/ocp/drought and

**Personnel**

Research Scientists: 5, Visiting Scientists: 1, Research Support Staff: 2, Graduate Students: 4, Undergraduate Students: 6.

**Publications**

**Journal articles: (period covered here is 2002-2008)**


Ph.D. dissertations


Julien Emile-Geay: ENSO dynamics and the Earth’s climate: from decades to Ice Ages, Spring 2006.

Chie Ihara: The state of climate over the tropical Indian Ocean and India from the late 19th century throughout the 20th century, May 2007.
Research Goals

The goals of this project are to improve our understanding of what controls the variability of tropical cyclone (TC) activity, to improve the attribution of changes in TC activity to climate change, and to reduce the uncertainty in predictions of changes in TC activity associated with long-term global climate change. The approaches we use involve an empirical genesis potential (GP) index and idealized simulations of tropical cyclones.

Research Progress

- **Genesis Potential Index and the Madden-Julian Oscillation (MJO):**
  The modulation of the tropical cyclone (TC) activity by the MJO is explored using the original empirical GP index. Composite anomalies of the genesis index associated with different MJO phases are consistent with the composite anomalies in TC frequency, which occur in the same phases, indicating that the index captures the changes in the environment, which are at least in part responsible for the genesis frequency changes. Of the four environmental variables, which enter the GP index, the mid-level relative humidity makes the largest contribution to the MJO composite of GP anomalies. The second largest contribution comes from the low-level absolute vorticity, and only very minor contributions come from the vertical wind shear and potential intensity.
  When basin integrated MJO composite anomalies of the GP index are regressed against basin-integrated composite anomalies of TC genesis frequency, the results differ quantitatively from those obtained from the analogous calculation performed on the annual climatologies of the two quantities. The GP index captures the MJO modulation of TC genesis to a lesser degree than the climatological annual cycle of genesis (to which it was originally tuned). This may be due weakness of the reanalysis or indicative of the importance of precursor disturbances, not well captured in the GP index computed from weekly data, to the intraseasonal TC genesis frequency fluctuations.
  This work was done in collaboration with Matthew Wheeler, from the Centre for Australian Weather and Climate Research, in Melbourne, Australia. It was accepted for publication at the Journal of Atmospheric Sciences and is currently available as an “online first” publication.
• Modified Genesis Potential Index
The original GP index used in our research in various papers is dependent on the mid-troposphere relative humidity from reanalysis data. We compared different reanalysis (NCEP/NCAR and ECMWF ERA-40) and their mid-troposphere relative humidity have large differences. Therefore, Kerry Emanuel developed a modified genesis index, which instead of the mid-troposphere relative humidity, per se, the difference between the moist entropy of the boundary layer and that of the middle troposphere is used. The idea behind this modified index is that the middle troposphere entropy is a function of temperature as well as humidity. While the middle tropospheric temperature varies little in the tropics under the current climate, its variations under climate change may be large enough to be significant to trends in TC statistics.

We did extensive calculations with the modified GP index using both the NCEP/NCAR and the ERA40 reanalysis datasets. Although the global climatology of the index look reasonable, when detailed analysis is conducted for the different regions, and ENSO anomalies, the modified index does not perform as well as the original one. It is especially sensitive to the differences of the humidity in both reanalysis. While this modified index may prove useful for some purposes, we have decided to augment it with additional research into developing an additional index.

• Revised Genesis Potential Index
Given all the issues that we noticed when using the reanalysis relative humidity, when using the original GP index, as well as the modified GP index, it was clear that in order to develop a revised GP index we should use a different dataset for humidity. The choice we made is to calculate the total column relative humidity, using the satellite column water vapor data and only the temperature data from the reanalysis.

We just finished producing new column relative humidity datasets, using the SSMI water vapor data from various satellites and temperatures from 3 different reanalysis: NCEP/NCAR, ECMWF ERA40, and Interim ECMWF. The next step is to use these recently obtained humidity datasets to obtain the revised GP index.

We want also to test how many predictors are needed in the revised GP index and how independent they are. Therefore we are testing which are the best predictors to use, for instance comparing the dependence on potential intensity and the relative sea surface temperature (local sea surface temperature minus tropics sea surface temperature). Another important objectives in the development of the revised index are its simplicity, transparency and reproducibility. We did a preliminary development of a modified GP index still using the reanalysis humidity, and using Poisson regression to fit the data, and the results are very encouraging. The next step will be to repeat this analysis using the column relative humidity mentioned above.

Once the modified GP index is sufficiently tested in the current climate and performs as well or better than the original one, we can apply the index to climate change scenarios.
Tropical cyclone activity and Quasi-biennial oscillation

In order to understand better the natural variability of TC activity, it is fundamental to understand how TC activity is modulated by various climate modes. One issue that we think is important to clarify is the role of Quasi-biennial oscillation (QBO) in modulating TC activity. In the 1980s, several studies found significant correlation between the QBO and tropical cyclone activity in the North Atlantic and the western North Pacific. The relationship was strong enough that it was used in the early seasonal TC forecasts for the North Atlantic by Gray and colleagues. In the last 2 decades, this relationship appears to have been much weaker. Considering the entire period from the 1950s to the present, we are examining how the QBO relates to various TC indices in all TC-prone regions, and give special attention to how this relationship has changed in time. We attempt to discern whether the available evidence supports the hypothesis that the QBO has a real physical influence on TCs. Answering this question is important for understanding the potential stratospheric influence on TCs more broadly.

We are currently performing this analysis in detail. Preliminary results suggest that the relationship of the QBO and basin wide TC activity indices is not robust and the early results are due to flawed statistical analysis and there is no real physical modulation of the QBO in indices of TC activity.

Ideal simulations of hurricanes

Recently, George Bryan and Richard Rotunno from NCAR made extensive modifications in the original 2D Rotunno-Emanuel model that we initially proposed to use in this proposal. Besides, they performed with the new model some of the points that we had originally proposed to do with the Rotunno-Emanuel model. Given that, our efforts in the simulations were done using the WRF model.

Using the idealized hurricane WRF model version developed at NCAR, we performed various idealized simulations with the WRF model using NCAR computers. We tried using the set up in a non-nested mode, but in that case, the vortex did not intensify, due to the resolution used. In order to avoid very expensive simulations, we needed to use a 2 nested version of the model, and then the vortex did intensify to hurricane intensity. We did a few simulations with different values of sea surface temperature (SST) as well, in order to test the sensitivity of the model to SSTs.

To realize our research goals we need to develop a greater degree of control and understanding of the model. An important step is to study radiative-convective equilibrium states; idealized hurricane simulations are from some perspectives best performed starting from such states perturbed by initial vortices. Simulating radiative-convective equilibria in WRF requires a number of modifications from the configuration with which we started. We are in the process of making these modifications and studying their effects.

Highlights

The genesis potential index captures the MJO signal in tropical cyclone activity, enabling us to use it to gain a more mechanistic understanding of that signal. Decomposition of the index indicates that relative humidity is the most important
environmental factor by which the MJO modulates tropical cyclones, with low-level vorticity being the second most important factor.

**Societal Benefits**

Our research is leading to a better understanding of the how climate affects tropical cyclones in various time-scales.

**Other Research Connections**

- **Collaborators in specific parts of this project:**
  1. Matthew C. Wheeler, Centre for Australian Weather and Climate Research, in Melbourne, Australia (MJO modulation of TC activity)
  3. Larissa Back, Massachusetts Institute of Technology, Boston, MA (calculation of the satellite column relative humidity).
  5. Shuguang Wang, Columbia University (modifications of the WRF code to obtain radiative equilibrium).

**Education & Outreach**

- **Conferences and workshop contributions:**
  • **Seminars:**
  • North Carolina State University, Department of Marine, Earth, and Atmospheric Sciences, Raleigh, NC, August 22, 2008.
  • University of Wisconsin-Madison, Colloquium of the Department of Atmospheric and Oceanic Sciences, Madison, WI, November 17, 2008.
  • Meteorological Research Institute, Tsukuba, Japan, February 17, 2009.
  • Central Weather Bureau, Taipei, Taiwan, March 9, 2009.
  • National Taiwan University, Department of Atmospheric Sciences, Taipei, Taiwan, March 10, 2009.
  • Rutgers University, Department of Environmental Sciences, March 25, 2009.
  • **Invited Lectures:**
  • **Interviews:**
  • Austrian Broadcasting Corporation – Radio and Television: June 1, 2009.

**Personnel**

Research Scientists: 4, Research Support Staff: 1.

**Journal Articles**


**Books / Articles-in-books**

Research Goals

This year's research objectives are: 1) analyze existing datasets of the CFS using various empirical methods; 2) develop the coupled data assimilation procedure for the CFS; 3) test and refine the procedure with short runs of the CFS in the modern era.

Education Goals

Train graduate students and make presentations at relevant workshops.

Research Progress

In collaboration with our colleagues at NCEP, we have made considerable progress in the following areas:

1) **Analysis of the existing CFS model output.** A prerequisite for our proposed work to succeed is that the CFS has a realistic enough internal variability in the tropics, so that we can keep it on track with reality by assimilating only SST and SLP data. We analyzed the existing CFS free runs and retrospective forecasts for the modern era (1981-2004), and compared them with the outputs of other climate models, especially those from IPCC4. It is found that the CFS has a quite realistic climatology and a relatively small climate drift, and that its interannual variability resembles the observed ENSO in magnitude, spatial pattern, as well as temporal evolution. Its predictive skill for the modern era is one of the best among present climate models.

2) **Development of coupled data assimilation procedure.** The first step of our proposed procedure is a reduced space regression between observed SST/SLP fields and a set of model variables that represent the state of the coupled system, based on patterns identified by the Canonical Correlation Analysis (CCA). In practice, using the predetermined CCA prediction matrix, observed SST/SLP data are converted to a "realistic" coupled model state. The latter is then assimilated into the CFS through a weighted nudging method, which can be considered the simplest form of Kalman filters. Since the CFS is already so realistic, we decided after a few group discussions to try direct nudging first. It is now being tested with the CFS and the preliminary results look promising.
3) **Research on ENSO prediction and predictability.** In a recent article, we reviewed the current status of ENSO prediction, discussed different opinions on ENSO’s predictability, and, more importantly, suggested some potential areas for improvement of predictive skill (Chen and Cane, 2008). In particular, based on observational evidence and modeling results, we pointed out that better model initialization and data assimilation, better simulation of surface heat and freshwater fluxes, and better representation of the relevant processes outside of the tropical Pacific, could all lead to improved ENSO forecasts. All of these can be further verified in our present project. We have also studied the inter-decadal variability (Tang et al., 2008) and biological modulation (Zhang et al., 2009) of ENSO.

**Highlights**

- First attempt at coupled data assimilation with an operational climate prediction system;
- Identification of potentially important areas for improvement of ENSO prediction.

**Societal Benefits**

The project aims at improving predictions of ENSO and drought, which undoubtedly will bring significant societal benefits when completed.

**Other Research Connections**

This project is a collaborative effort of LDEO and NCEP scientists. During the course of our research, we also have close collaboration with the scientists from the University of Maryland and the University of Northern British Columbia.

**Education**

Selected presentations

- Chen, D., Collaborative research on climate change: the oceanographic component. Invited Talk, NSFC-NSF Workshop on Climate Change, Shanghai, China, September, 2008.

**Personnel**

Research Scientists: 3.
Journal articles


Research Goals

To use power spectral descriptions of physical fields to characterize error in satellite data sets for sea surface heights and temperatures in a form convenient for use in ocean data assimilation procedures. The characterization should include location-dependent variances and spatial and temporal covariances. Model representation error will be estimated on the basis of GSFC/GMAO and NCEP/EMC ocean runs with realistic and perturbed forcing and their comparison with satellite data fields. Because the misspecification of observational and representation error are deemed partly responsible for the suboptimality and inaccurate posterior uncertainty estimates in data assimilation systems, improved error estimates are important for the overall success of ocean data assimilation and climate prediction.

Education Goals

To involve students into use of satellite data and statistical analyses of ocean variability.

Research Progress

During the second year of this project we built on the performed earlier systematic intercomparisons of spatial and temporal variability of sea surface heights in satellite altimetry, tide gauges, and ocean model simulations (baroclinic and barotropic components), targeted at constraining short-term and small-scale area of wavenumber-frequency spectra, which controls a component of the observational error due to imperfect sampling and inconsistent averaging. Multi-taper spectra were calculated from these adjusted time series, and then integrated over desired frequency and wavenumber ranges. Using wavenumber and frequency power spectrum estimates, we have computed fields of variance and spectral slopes for sea surface heights. Based on these estimates we produced maps of effective observational error for altimetric observations corresponding to given model grids and assimilation schemes. These maps have a considerable geographical structure. Its interpretation and tuning of error models for the use in data assimilation procedures are underway.
Highlights

Detailed intercomparison of spatial and temporal variability of sea surface heights in satellite altimetry, tide gauges, and ocean model simulations (baroclinic and barotropic components), targeted at constraining short-term and small-scale area of wavenumber-frequency spectra, which controls a component of the observational error due to imperfect sampling and inconsistent averaging.

Frequency spectra of sea surface heights show considerable geographic variation but could be partially summarized due to smooth spectral slope at 30-150 day periods. The resulting maps closely resemble those of eddy activity, and suggest that high-energy eddy-populated regions correspond to a spectral slope of -2 at periods below 150 days.

Maps of wavenumber spectral slope for sea surface heights also produced distinct regions of common spectral shape in the 100-300 km range, and may be useful in guiding theories of ocean dynamics.

Trial maps of effective observational error for satellite altimetry fields for the use in ocean data assimilation were produced.

Societal Benefits

Because the misspecification of observational and representation error may be partly responsible for the suboptimality and inaccurate posterior uncertainty estimates in data assimilation systems, improved error estimates are important for the overall success of ocean data assimilation and climate prediction. This project addresses the NESDIS/JCSDA program priority “Ocean Data Assimilation for Prediction on Daily to Seasonal Time Scales”, mostly its focus area “Estimation of observational error characteristics” with an additional contribution to the focus area “Validation of ocean assimilation products and forecasts with satellite products”.

Other Research Connections

- Interagency: GMAO/NASA, EMC/NCEP/NOAA
- Research Partnerships: JCSDA
- Collaborators: M. Rienecker, C. Keppenne, J. Jacob (GMAO, GSFC, NASA); D. Behringer (EMC, NCEP, NOAA)

Awards & Honors

A.Kaplan received the 6th LDEO Excellence in Mentorship Award (2009).

Education & Outreach

Research advisor / mentor

Undergraduate

D.E. Amrhein was employed as a part-time research assistant to A.Kaplan in this project year. He received a B.S. in Physics from Columbia College in May 2009. He took
a full-time research assistant position in LDEO with J.E. Smerdon and A. Kaplan starting June 1, 2009.

Graduate

N.P. Arnold was employed as a full-time research assistant to A.Kaplan from May 2007 to July 2008, after his graduation from Columbia Engineering School with a B.S. in Applied Physics. He has started his Ph.D. studies in Harvard (Earth Sciences) in September 2008. He is still collaborating p/t with A.Kaplan on research topics relevant to this project.

**Academic Participation**

**Presentations**


**Seminars**


**Personnel**

Research Scientists: 2, Research Support Staff: 2, Undergraduate Students: 1.
**Figure 1.** Frequency spectra from daily tide gauge data from 102 island tide gauges in the University of Hawaii Sea Level Center database (thin lines) compared to similar spectra for satellite altimetry (thick lines). Tidal signal was removed prior to computation, and AVISO’s combined atmospheric correction (static and dynamic response to pressure) was applied. Resulting spectra were compared with the average of all Topex frequency spectra within a 2x2 degree box around each tide gauge. Averages separated by Tropical and Extratropical latitudes are shown, suggesting general agreement between the two instruments, and the possibility of simply extrapolating altimetric spectral slopes into high frequencies.
Figure 2. The map of frequency slopes estimated from satellite altimetry. Note a considerable geographic structure. The coherent regions of spectral slope close to -2 red appear to match regions of high eddy activity.
Research Goals

This project expands the PIs' previous work, supported in part by NOAA/CPPA and focused on the impact of tropical Indo-Pacific SST on North American droughts, to a comprehensive assessment of Indo-Pacific-Atlantic-IAS (Intra-Americas Sea) SST influences on North American hydroclimate. The principal methodology adopted in this study is ensemble numerical modeling using atmospheric and partially coupled general circulation models (GCMs) forced with observed SST. In addition, the outputs from IPCC simulations using fully coupled GCMs driven by greenhouse gas (GHG) forcing are analyzed. The overriding goal is to determine the relationships among global and regional SSTs, GHG forcing, and North American droughts in present and future climate.

Research Progress

1. Atlantic SST influences on North American precipitation

In the first year, a set of ensemble GCM simulations forced with tropical+subtropical Atlantic SST anomaly has been completed. This experiment, called "TAGA" (Tropical Atlantic Global Atmosphere), aims to assess the impact of stand-alone Atlantic SST forcing on North American precipitation, disregarding the origin of the TNA SST anomalies which will be investigated in additional sets of experiments. The simulations from 1865-2005 are forced with observed SST over tropical and subtropical Atlantic (30S - 30N) and climatological SST elsewhere. Figure 1 shows the regression of the simulated precipitation anomaly (color shading) and sea-level pressure anomaly (contour) on the imposed TNA (0-30N) SST anomaly for winter (October-March, top) and summer (April-September, bottom). A positive TNA SST anomaly is found to induce a local increase in precipitation over TNA and the Caribbean regions but a decrease in precipitation over the United States. Given the known results that (i) A cold tropical Pacific SST produces North American droughts, and (ii) TNA SST decreases as a canonical response to La Nina, our latest finding points to the relevance of non-canonical La Nina events as potentially most efficient in producing North American droughts. The mechanisms for an Atlantic influence on N. American hydroclimate were further analyzed. In summer warm TNA SST anomalies force an anticyclone centered to their west, which brings northerly cold advection and descending flow over the southern Plains and Southwest and causes drying. In winter, warm TNA SST anomalies warm the
tropical troposphere and suppress precipitation over the Pacific, which drives a La Nina-like pattern of circulation anomalies over the Pacific-North America sector. This Atlantic-Pacific inter-basin linkage and its influence on N. America were found in five GCMs participating in the CLIVAR drought-working group and appear robust. The results are summed up in a paper that was recently submitted to the Journal of Climate (Kushnir et al. 2009).

Regression of Precipitation (colors) and SLP (contours) on TNA

**Figure 1:** The regression of simulated precipitation (color shading) and sea-level pressure (contour) anomalies on the imposed tropical Atlantic (TNA, 0-30N) SST anomaly for winter (October-March, top) and summer (April-September, bottom) from the TAGA experiment. The simulations for 1865-2005 are forced with observed SST over the tropical Atlantic (30S-30N) and climatological SST elsewhere.
2. Assessing the independent contribution of Pacific and Atlantic SST forcing from hindcast experiments

To further assess the independent contribution from Atlantic and Pacific basins to the precipitation anomalies over North America, we have performed a series of atmospheric GCM simulations with the model partially coupled to a mixed-layer ocean in one basin but forced by observed or climatological SST in other ocean basins. They are short (1-year) hindcast runs using an AGCM modified from the T42L28 version of NCEP MRF model. We have completed six sets of ensemble hindcasts with imposed Pacific SST plus mixed layer ocean in the Atlantic. Each set consists of 75 one-year runs, starting from September of "year 0" with coupling to ocean turned on at first day of November in "year 0". The targets of the hindcasts are Atlantic SST anomaly and the precipitation anomalies over the Americas in boreal spring. The 75 ensemble members are split into 3 subsets, 25 with both imposed (observed) Pacific SST anomaly and Atlantic preconditioning (observed SST anomaly imposed on November 1 when coupling is turned on), 25 with ENSO forcing but no Atlantic Preconditioning, and 25 with climatological SST in the Pacific Ocean but with Atlantic preconditioning. Comparing these runs, we attempt to determine the contribution of Atlantic SST anomalies to precipitation anomalies over the Americas with and without remote ENSO forcing from Pacific. Among the six sets of runs (three ENSO warm events, two ENSO cold events, and a neutral event, see Huang et al. 2009), the results for the neutral event of 1993-94 are the most interesting. Figure 2a shows the ensemble mean of the predicted precipitation anomalies for the Americas in April 1994 from the runs without Pacific ENSO forcing but with Atlantic preconditioning, and Fig. 2b shows the same quantity deduced from a set of 9-member AMIP runs also using (a slightly different version of) NCEP T42 AGCM. Both are qualitatively consistent with observation over North and South America, but Fig. 2a clearly demonstrated a case in which the seasonal predictability of the precipitation anomalies can be attributed entirely to Atlantic SST anomaly without ENSO influence.
Figure 2 (a): The simulated precipitation anomaly for April 1994 from the hindcast runs with the AGCM coupled to a mixed layer ocean over the Atlantic and forced by climatological SST elsewhere. Coupling is turned on at the beginning of November 1993 using the observed SST as the initial state for the Atlantic. Shown is the average of 25 ensemble members. (b): The precipitation anomaly for April 1994 derived from a set of 9-member AMIP runs.

3. Predictability of Dust Bowl drought

We have asked the question: could the Dust Bowl have been predicted had 1930s SSTs been known in advance? We compared atmosphere GCM simulations running from 1929 to 1940 with 1) climatological SSTs, 2) 1929-1940 tropical Pacific SSTs, 3) 1929-1940 tropical N. Atlantic SSTs and 4) 1929-1940 global SSTs. It was shown that advance knowledge of the tropical SSTs would have led to prediction of a multiyear drought but one that was too weak and centered in the S. Plains as opposed to the central and northern Plains as observed. Atlantic and Pacific SSTs were about equally responsible for the 1930s drought. Tree ring reconstructions were used to show that the northward centered Dust Bowl drought was unprecedented except for during the medieval period. It was speculated that northern centered droughts arise from vegetation loss, wind erosion and dust aerosol loading, which was supported by modeling work (Seager et al. J. Climate 2008, Cook et al. PNAS 2009).
4. Subtropical drying in future climate

Investigating droughts in future climate, we have analyzed the mechanisms for subtropical drying and the accompanying poleward shift of storm tracks in IPCC climate model simulations, using primarily the outputs of GFDL coupled model simulations with GHG forcing. Mr. Y. Wu, a graduate student, assisted in this investigation. To understand the poleward shift of storm tracks, we analyzed the stability properties of the zonal mean flow and the zonally integrated energy budget in present-day and future climate. Calculating the moist Eady growth rate for the zonal mean flow, it is found that the change in the growth rate of baroclinic instability (related to the production of storms) is qualitatively consistent with the poleward shift of storm tracks and, moreover, the moisture effect on baroclinic instability is relevant (Wu et al. 2009). In the energy budget, the poleward shift of storm tracks corresponds to an enhanced eddy heat flux into the high latitude, consistent with an enhanced arctic warming. This hints at a possible midlatitude origin of arctic warming. In this picture, subtropical drying is not an isolated local process but is connected to GHG-induced climate changes at other latitudes.

Highlights

· Quantitatively affirmed the robust negative correlation between TNA SST anomaly and Western-Southwestern U.S. precipitation anomaly by ensemble GCM simulations; Clarified the dominant circulation anomaly associated with the TNA forcing of U.S. precipitation anomalies.

· Demonstrated by ensemble hindcast experiments the potential for Atlantic SST anomalies to independently influence seasonal North American precipitation anomalies in the absence of Pacific ENSO forcing.

· Quantified time-lagged influences of Pacific ENSO forcing on North and South Atlantic SST anomalies and the tropical Atlantic meridional SST gradient. This information will be used for further analysis of the Atlantic influence on North American hydroclimate.

· Quantified the predictability of 1930's Dust Bowl drought with given SST; Quantified the relative contribution of Atlantic and Pacific SST to that drought event.

· Advanced our understanding on the projected subtropical drying in IPCC simulations of future climate through the analysis of baroclinic instability of zonal mean flow and the zonally integrated energy budget.

Societal Benefits

Understanding what controls the hydrological variability over North America is key to developing predictive capabilities for the onset and duration of drought period. This is important to decision makers particularly in the area of water resource
management. The importance of this research was recognized last year by an award from the State of California Department of Water Resources.

**Other Research Connections**
Collaborators: Andrew Robertson (IRI, Columbia Univ.); Shiling Peng (CIRES, Univ. Colorado); Ron L. Miller (NASA/GISS); Mingfang Ting (LDEO/Columbia University).

**Awards & Honors**
Richard Seager’s 2007 science paper “The Turn of The Century Drought Across North America: global context, dynamics and past analogues” published in the Journal of Climate, Vol.20, 5527-5552 was honored by the California Department of Water Resources. Lester A. Snow the department’s director announced the award citing the importance of recently published climate science research that provides useful information for water supply planning and management. Snow said “we want to assure researchers that there is interest and support for work that improves the understanding of issues facing water managers. Focused research can help us to reduce and adapt to the uncertainty that accompanies climate change.”

**Interagency**
Part of this work was done in collaboration with Ron L. Miller of NASA/GISS and involves experiments with the GISS atmospheric GCM.

**Personnel**
Research Scientists: Richard Seager, Huei-Ping Huang, Yochanan Kushnir; Research Support Staff: Naomi Naik and Jennifer Nakamura; Post Doctoral Fellows: Benjamin I. Cook (NOAA GCC Postdoctoral Fellow)

**Journal articles**


Research Goals

Goal of the 2008 research was to perform investigation of first year's mooring data to identify mechanisms by which warm Upper Circumpolar Deep Water (UCDW) enters the continental shelf of the western Antarctic Peninsula (WAP), for improved representation in the climate models (some mechanisms will allow rapid infusion of warm water leading to enhanced glacial melt, with the potential of increased ice stream drainage as observed in recent world examples of rapid glacial ice breakup).

Education Goals

Inform the public of the sensitivity of the west Antarctic glacial system to inflow of warm ocean water (responsible for most of the glacial melt, as opposed to the Antarctic atmosphere, which does not contain enough heat per unit temperature above freezing). Most of sea level rise threats have been focused on Greenland, while melting in the western Antarctic can be an equal, or even greater contributor, much of which depends on the availability of "warm" (above freezing) ocean water; this needs to be made clear.

Research Progress

We have recently (January, February 2009) recovered 5 thermistor moorings from the WAP (Figure 1); preliminary analyses of the mooring observations is lending key insights to the nature of the mechanisms of UCDW shelf flooding.

Highlights

Four possible UCDW flooding mechanisms have been considered in the community: (1) shelf-wide flooding of the continental shelf by large meanders in the Antarctic Circumpolar Current (ACC) that transports UCDW, (2) UCDW flows into the canyons cutting across the shelf (observed), then overfills the canyons and floods onto the nominal shelf floor, (3) transients, such as eddies or small meanders from the ACC send in fresh UCDW (Figure 2), and (4) upwelling of UCDW replacing surface water lost offshore via Ekman drift driven by regional winds or polar lows. Preliminary findings show no evidence of the first two mechanisms, and strong evidence for the last 2.


**Societal Benefits**

Improved understanding of ocean heat delivery will lead to better simulations and forecasts of future sea level rise, and disposition of west Antarctic glacial ice. A fundamental issue facing glacial modelers today involves how the warm UCDW is moved onto the shelf where it can make direct contact with glacial ice at the continental margins.

**Other Research Connections**

This research is jointly sponsored by NSF through funding of the Palmer LTER (Long Term Ecological Research) program and to the Antarctic IPY SASSI (Synoptic Antarctic Slope-Shelf Interaction) project.

**Education & Outreach**

Martinson gave a presentation on the preliminary findings at recent meeting of Antarctic SASSI researchers in Montreal, July 25, 2009.

**Personnel**

Research Scientists: 1, Research Support Staff: 1.

**Publications**

Other than the cruise report, which includes mooring recovery, servicing and redeployment. The findings are new and not yet published.

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**Figure 1**: Study location, with moorings located in inset map.
Figure 2: First mode of Karhunen-Loève estimate of signal in shelf-ocean heat content ($Q$; red line) for mooring 1 (in Figure 1) as a function of time, with temperature of $T_{\text{max}}$ (black dotted line) and crosses showing center of transients in $Q$ locations. Coincidence of transients events with spikes in maximum temperature are consistent only with import of nearly pure UCDW, thus suggesting transients are eddies (contributing about 152 Wm$^{-2}$ over the 2008 year).
Highlights

The Abrupt Climate Change in a Warming World (ACWW) is the latest incarnation of a long running NOAA funded program of integrated research at Lamont into the problem of abrupt climate change. The focus is on (1) climate change in the late Pleistocene and Holocene periods and (2) near term future abrupt change, including social impacts of anticipated change.

ACWW was conceived at Lamont as a five-year program but was funded by NOAA for just two years. Here we report on the first annual meeting which brought together Lamont, Columbia and outside experts to discuss a wide range of topics on past and future rapid climate change:

http://climate.columbia.edu/?id=abruptcc_july_meeting

Abrupt Climate Change in a Warming World Annual Meeting
LDEO Campus, Lamont Hall July 8 - 10, 2009

Wednesday July 8

9:00: Welcome and Introduction: Peter Schlosser (LDEO)

9:15: Wally Broecker (LDEO): Abrupt climate change in a warming world: the challenge we face

THE CHANGING CRYOSPHERE

10:00: Rob DeConto (U. Mass): Neogene perspectives on the stability of the West Antarctic ice sheet

10:30: Coffee

11:00: Mark Fahnestock (UNH): Understanding the causes of rapid change in ice discharge from
the Greenland ice sheet

11:30: Bruno Tremblay (McGill): Observing and modeling Arctic sea ice loss

12:00: Lunch

**HOLOCENE CLIMATE CHANGE I**

1:00: George Denton (U. Maine): Holocene Climate Change- Overview

1:30: Joerg Schaefer (LDEO): Timing of Holocene mountain glaciers events and relation to inter-hemispheric patterns of climate change

2:00: Peter DeMenocal (LDEO): Reconstructing Holocene Atlantic Ocean climate change

2:30: Coffee

3:00: Jason Smerdon (LDEO): Reconstructing global climate fields during the Common Era: Motivations and challenges

3:30: Brendan Buckley (LDEO): Tree ring reconstructions of Asian monsoon variations over the last several centuries

**CLIMATE CHANGE AND THE CARBON CYCLE**

4:00: Bob Anderson (LDEO): Reorganization of global winds associated with abrupt climate change and its impact on atmospheric CO$_2$

4:30: Jorge Sarmiento (Princeton): Changing carbon uptake by ocean and terrestrial biosphere

**CLIMATE CHANGE AND TROPICAL STORMS 1**

5:00: Suzana Camargo (LDEO): How can we predict future changes in tropical storm frequency and intensity?

5:30: Adjourn/Group Dinner (Lamont Hall)
Abrupt Climate Change in a Warming World Annual Meeting  
LDEO Campus, Lamont Hall July 8 - 10, 2009

Thursday July 9

CLIMATE CHANGE AND TROPICAL STORMS 2

9:00: Jim Kossin (NOAA/NCDC): Hurricane Track Variability and Secular Potential Intensity Trends

9:30: Tom Knutson (GFDL): High resolution modeling of Atlantic hurricanes and climate change

10:00: Amy Frappier (Skidmore): Geological records of past tropical cyclone activity

10:30: Coffee

PAST, PRESENT AND FUTURE HYDROCLIMATE CHANGE

11:00: Gisela Winckler (LDEO): Global patterns of paleo dust transport and deposition

11:30: Wally Broecker (LDEO): Late Pleistocene and Holocene hydroclimate change

12:00: Ben Cook (NOAA): Climate-dust interactions in a warming climate.

12:30: Lunch

1:30: Richard Seager (LDEO): Is anthropogenic subtropical drying already occurring?

2:00: Michela Biasutti (LDEO): Projections of African climate change

THE OCEAN CIRCULATION AND CLIMATE CHANGE

2:30: Peter Schlosser (LDEO): The changing high latitude ocean circulation and interactions with the cryosphere

3:00: David Lund (U. Michigan): Holocene changes in North Atlantic Ocean circulation

3:30: Coffee

HOLOCENE CLIMATE CHANGE II

4:00: Sidney Hemming (LDEO): Deglacial lake level history in the Mono Basin, CA

4:30: David Rind (GISS): Solar variability and climate change over the Holocene

5:00: Yochanan Kushnir (LDEO): Atlantic Ocean-North Africa-Middle East climate linkages through the Holocene

Adjourn
Friday July 10

SOCIAL IMPACTS OF CLIMATE CHANGE

9:00: Judy Omumbo (IRI): Climate and disease: an on the ground perspective

9:30: Tobias Siegfried (Columbia U.): Managing transborder water resources under environmental and economic uncertainty

10:00: Balaji Rajagopalan (U. Colorado): Climate and Societal Tipping Points - Socio-economy of India and Colorado River Water Management

10:30: Coffee

11:00: David Battisti (U. Washington): Climate change and agricultural productivity

11:30: Klaus Lackner (Columbia U.): title TBA

12:00: Lunch

Adjourn

Personnel

Research Scientists: 2, Administrative: 1.
Research Goals

The overall goal of this project is to study change and variability in the global hydrological cycle during the last millennium and into the future and to contrast the changes due to processes internal to the climate system (ocean-atmosphere-land interactions) or to natural external forcing (solar, volcanic) with anthropogenic forcing (greenhouse gas emissions). For year 1 of this project we set the following specific goals:

- Continue work on understanding mechanism that cause droughts in the subtropical regions, particularly North America but also the Mediterranean and Central and South America.
- Conclude a multi-member ensemble of AGCM integrations forced with global SST and anthropogenic greenhouse gas concentrations from the middle of the 19th century to present (GOGA-VTG). Begin comparing the results to our ensembles forced with global SST only (GOGA).
- Attribute recent climate change to natural variations and to anthropogenic forcing. This involves using observations and model simulations and emphasizes the differing dynamical causes involved.
- Analyzing the response of the tropical Pacific atmosphere/ocean to 20th changes in external forcing in the IPCC CMIP3 simulations. In particular, examining the changes in the east-west gradient of SST and sea level pressure. The models are known to respond in a manner inconsistent with observations and our goal is to determine the source of this discrepancy.
- Begin further attribution work that applies methods we have recently developed to the question of the causes of Sahel hydroclimate change.
- Implement the RSOI method – a climate reconstruction procedure used for application to proxy data – in pseudoproxy experiments and perform real-world historical reconstructions from the ensemble of our developed methodologies for intercomparison.
Education Goals

- To train the next generation of scientists specializing in climate variability and predictability and familiarize them with the theoretical background and tools of research in this field.
- When possible, to expose undergraduates to modern climate research through on-site, one-on-one internship program.
- To use knowledge gained through research to enrich teaching activities to undergraduate and graduate students in disciplinary and inter-disciplinary programs through lectures and web posting of research results.

Research Progress

**Detection of ongoing climate variability and change**: We continued our attribution and detection work intended to separate between anthropogenic forcing and natural variability in the 20th century by focusing on changes in the global hydrological cycle. Unlike our past work (Ting et al. 2009, in *J. Climate*) here we focused on the impact of Atlantic Multidecadal Variability on global winter and summer precipitation with a focus on the West African Monsoon (Ting et al. in progress). We have also been working on attributing climate change in the satellite period (1979 onwards) and have found that much can be explained by a decadal timescale shift in the Pacific system that occurred following the 1997/8 El Nino. For Southwest North America, drying since 1979 can be attributed to, in order of importance, Pacific decadal variability, recent warming of the tropical North Atlantic and, finally, anthropogenic subtropical drying. This indicates that the Southwest can expect a long extended dry period from natural causes that will be augmented by anthropogenic drying (Kushnir and Seager, in progress.) Another paper addresses the causes of Mediterranean region drying since the mid 20th Century and finds this is mostly explained by the NAO trend which itself is dominated by natural decadal variability (Kelley et al. 2009, *Geophys. Res. Lett.*, submitted). The Mediterranean climate study received special attention by a visitor to our group: Dr. B. Ziv (on sabbatical from the Open University in Israel). Ziv and Kushnir collaborated in a study of the rain bearing, wintertime Mediterranean cyclones in a subset of IPCC CMIP3 model simulations and compared those to observations. Results of this comparative study are documented in a paper submitted for publication (Ziv et al., 2009, in *Clim. Dyn.*). Armed with this information they began a study of the impact of climate change on the frequency and intensity of these disturbances with a goal to assess the impact of climate change on the eastern Mediterranean. The mechanisms of tropical Atlantic influence on North American hydroclimate has also been examined (Kushnir et al., 2009 *J. Climate*, submitted). We have also examined the impact that Southern Annular Mode variability and change has had on Indian Ocean SSTs and the East Asian monsoon (Nan et al., 2009, *JGR*).

**Improved understanding of the Dust Bowl drought**: We have used modeling studies, constrained by historical data on land surface change, to explain that crop failure, erosion and dust storms intensified the 1930s Dust Bowl drought and moved its center into the central and northern Plains (B. Cook et al., 2008, *PNAS*). We are now using the just...
released Compo et al., SLP-based reanalysis to further understand the atmosphere dynamics of the Dust Bowl drought.

**Eddy-mean flow interaction in natural variability and climate change and impacts on the storm tracks:** We have conducted detailed studies of cause and effect in transient eddy-mean flow interaction and the controls on the location and strength of the northern hemisphere storm tracks. The first two papers address tropical Pacific SST related variations (Seager et al. QJRMS, submitted; Harnik et al. QJRMS, to be submitted). We have also been examining what controls the poleward shift and intensification of storm tracks under global warming relating this to mean flow changes and changes in energy transports (Wu et al., to be submitted).

**Future drying of southwestern North America in paleoclimate context:** The character and causes of IPCC model projected climate change in the southwest has been contrasted with what is known from tree ring records of medieval “megadroughts”. This paper makes the point that these appear to arise from different causes which leaves many questions about the exact nature of long-term climate change. (E. Cook et al. JQS, in press.)

**20th Century and future trends in tropical Pacific SSTs:** With the release of the newest NOAA SST analysis, all available analyses show an increasing east-west SST gradient over the 20th Century. More notably the SST gradient has been strengthening most during the northern summer through fall season when the cold tongue is best developed and the ocean dynamical thermostat should be most effective. SLP trends show a weakening east west gradient but little or no weakening in the summer to fall season, broadly consistent with the SST gradients. None of the seasonal changes in gradients are well modeled by the IPCC AR4 models, which, hence, cannot be trusted in this regard for future climate change. (Karnauskas et al., 2009, J. Climate, in press.)

**Links of Atlantic SSTs to Levant hydroclimate over the Holocene:** A well-dated record of Dead Sea Level provides a remarkable account of droughts and pluvials in the Levant region since the last glacial period with evidence for several abrupt changes that have been linked to cultural changes in the region. We have looked at the Dead Sea Level record over the last 10,000 years and its antiphase association with hydroclimate variability in sub-Saharan Africa, and the North Atlantic. We compare these linkages to evidence from the instrumental era and find a compelling similarity to 19th and 20th century variability on multi-decadal times scales. Based on these finding we hypothesize that hydroclimate variability in the Levant and sub-Saharan Africa are linked to and orchestrated by multidecadal to millennial changes in North Atlantic SST. (Kushnir and Stein, in prep.)

**Climate field reconstruction for the last millennium:** We have tested and developed an ensemble of climate field reconstruction (CFR) techniques for the last millennium using pseudoproxy experiments derived from millennial GCM simulations, we demonstrated that all currently employed CFR methods produce reconstructions that: 1) have skill distributions that depend heavily on the distribution of the proxy network; 2) lose
significant variability and suffer from mean biases outside of the calibration interval; and 3) potentially underestimate the magnitude of extreme events. These findings motivate the development and evaluation of the reduced space optimal interpolation (RSOI) technique that uses local calibration as a means of potentially deriving better reconstructions and describing the error in derived CFRs more comprehensively.

**Other ongoing work:** We are revisiting the issue of predictability of the 1976/77 Pacific climate shift, and associated multidecadal change in precipitation across the Americas, using atmosphere model simulations forced by hindcast SSTs. We have also completed an ensemble of atmosphere simulations from 1856 to now with both observed SST changes and changing carbon dioxide and are comparing these to attribute soil moisture changes to SST changes and changes in trace gases. We have also begun to examine and attribute decadal changes in South American hydroclimate.

**Highlights**

- Recent trends in the pattern of global surface temperature and precipitation are strongly influenced by decadal ocean-atmosphere variability in the Pacific and North Atlantic Basins. The patterns affecting the trend are quite distinct from the pattern of anthropogenic forced temperature and precipitation variability portrayed by the IPCC AR4 models.
- Atlantic Multidecadal Variability can compete with or enhance the anthropogenic impact on the summertime, West African monsoon system.
- The Mediterranean region has experienced a significant drying trend over the 20th century. This trend can be attributed mainly to the trend in the amplitude and phase of the NAO. Part of this trend may be due to anthropogenic forcing. However, the observed trend in much stronger than the one depicted by the IPCC AR4 model simulations.
- Atlantic Multidecadal Variability (AMV) has a far-reaching impact on precipitation variability in the Northern Hemisphere. Effect are particularly noticeable in North (and Central) America, in sub-Saharan Africa, and in the Eastern Mediterranean. This impact is transmitted mainly through changes in deep-convection in the tropical Atlantic region, in response to AMV-related SST change.
- Air-born dust, which originated from wind erosion of the soil, was a prominent player in shaping the spatial character and intensity of the Dust Bowl drought. This particularly devastating phenomenon is an example of human impact on climate as the soil erosion was due to bad agricultural practices in the U.S. Great Plains.
- A clear consensus was found between three observed SST datasets regarding the trend in tropical Pacific SST gradient. Our study found the discrepancies and ambiguities revealed in earlier studies of the subject are removed by examining the seasonal evolution of the trend. Within the expected error all datasets agree that during the Pacific “cold-tongue” season (boreal fall) the gradient between west and east equatorial Pacific SST increased over the last 100+ years. This is significant as it stands in contrast to the CMIP3 model simulations, which shows a weakening of the gradient. The impact on the global hydrological cycle due to this difference is significant.
Current employed methods used to produce global, gridded analyses (of temperature) from high-resolution climate proxies all show the following characteristics: 1) they have skill distributions that depend heavily on the distribution of the proxy network; 2) they lose significant variability and suffer from mean biases outside of the calibration interval; and 3) they potentially underestimate the magnitude of extreme climate events.

Societal Benefits

Hydroclimate variability and change are a matter of serious concern worldwide. Research on how these aspects of climate impact water availability and quality is important for building robust prediction capabilities and provide information to decision makers and the general public as they seek specific solution to adapt.

Other Research Connections

This work meshes well with and is complemented by research on tropical influences on the atmosphere, which is funded by NSF. In the course of this work we partnered with NOAA/GFDL and NASA/GISS.

Education & Outreach

We have involved several graduate students in conducting research on various aspects related to the project objectives. In addition we have regularly worked with undergraduate student, either as summer interns or work-study students with the goals of giving them a climate research experience. In most cases these students were funded by other sources and created opportunities to augment our own work.

Personnel

Research Scientists: 9, Visiting Scientists: 1, Research Support Staff: 3, Administrative: 1, Graduate Students: 1.

Journal articles


Figure 1: Model response to Atlantic SST warming. The figure shows the average of 40-year integrations with five different GCMs forced with uniform sign SST anomaly in the Atlantic Basin and climatological SST elsewhere (a pattern associated with Atlantic Multidecadal Variability). In both seasons (winter - top and summer - bottom) the warming leads to enhance precipitation in the north tropical Atlantic (with a maximum in the west), which extends into equatorial Africa. This anomaly is accompanied by reduced precipitation over the US and Mexico, along the entire equatorial Pacific and in the Indian Ocean. This precipitation change in the Atlantic also force lower sea level pressure over the entire North Atlantic Basin and a hemispherically symmetric Pacific pattern of low sea level pressure in the tropics flaked by high pressure anomalies in the extratropics (figure from Kushnir et al, 2009, in review).
Figure 2. Upper three panels: Trends of observed equatorial Pacific SST gradient (went-east) from 1880 to 2005 as a function of calendar month calculated from three different compilations of observations: (a) HadISST1, (b) Kaplan SST, and (c) NOAA ERSST v3. Gray shading denotes 95% confidence intervals based on the nonparametric Sen median slope method. White circles (squares) represent trends significant at the 5% (10%) level based on the nonparametric Mann–Kendall test. The trends in the boreal fall months is significant in all data sets and corresponds to an increasing gradient over time (from Karnasukas et al., 2009). Lower panels: Same as above, but for the east-west sea level pressure gradient based on (a) HadSLP2, (b) Kaplan SLP, and (c) NOAA ERSLP. Note the vertical scale is inverted so that up corresponds to a strengthening of the SLP gradient (DSST), and vice versa. Sea level pressure gradient tends to decrease with time during the boreal spring – indicating a weakening of the trades. However, the trend is weaker or there is no significant change during the boreal fall, when the SST gradient increases.
Theme II: Modern and Paleoclimate Observations

Individual And Collaborative PI Research Projects
CICAR Award # NA03OAR4320179
1. Cook, E., Collaborative Research: Development of a Blended, Gridded Network of Drought Reconstructions of North America
2. Gordon, A., Monitoring the Indonesian Throughflow in Makassar Strait
3. Kaplan, A., Multivariate Approach to Ensemble Reconstructions of Historical Marine Surface Winds from Ships and Satellites
5. McGillis, W., Development of an Autonomous System for Direct Measurement of the Flux of CO2 over the Ocean
6. Takahashi, T., Underway CO2 Measurements Aboard the RVIB Palmer and Data Management of the Global VOS Program

Abrupt Climate Change Studies (ARCHES)
7. Anderson, R., Paleo-Sea-Ice Distributions
8. Broecker, W., Understanding Abrupt Change and the Glacial to Interglacial CO2 Record
9. Denton, G., ARCHES Sub-award: Mountain Snowlines in the Southern Hemisphere
11. Hemming, S., Constraining Changes in Winds, the Conveyor and Local Currents During Periods of Abrupt Climate Change
13. Smethie, W., Tracer Observations of Deep Formation and Circulation in the Southern Ocean

CICAR Continuation Award #NA08OAR4320754
14. Gordon, A., Monitoring the Indonesian Throughflow in Makassar Strait
15. Huber, B., Weddell Sea Moorings
16. Takahashi, T., Underway CO2 Measurements Aboard the RVIB Palmer and Data Management of the Global VOS Program

CICAR Shadow Award #NA08OAR4320912
17. D’Arrigo, R., The Paleoclimate Reconstructions (PR) Challenge: A Community Program to Benchmark Methods Used to Reconstruct the Climate of the Last 1-2,000 Years

Abrupt Climate Change in a Warming World (ACCWW)

1 Denotes continuation under renewal award number
2 No cost extension granted through June 30, 2010
20. Cook, E., Lessons from Holocene Paleo and Modern Instrumental Records and Model Simulations
21. deMenocal, P., Holocene Variability of Atlantic Surface Properties and West African Aridity
22. Denton, G., ACCWW Sub-award: Lessons From Holocene Paleo and Modern Instrumental Records, and Model Simulations
23. Gordon, A., Fluctuations in Ocean Heat and Freshwater Inventory and of Interocean Exchange
24. Hemming, S., Radiogenic Isotope Tracer Paleo-Proxy Scope
25. Jacobs, S., Southern Ocean – Ice Sheet Interactions
26. Schaefer, J., Schaefer Mountain Glaciers
27. Schlosser, P., Synthesis of Tracer Data
28. Smethie, W., CFCs
Research Goals

With Richard Heim and Russ Vose of NOAA in Asheville, we are developing a blended living North American drought reconstruction grid, one that can be continuously updated as new instrumental data becomes available. This grid will be based on single-station monthly precipitation and temperature records from the United States, Canada, and Mexico. These records will be interpolated onto a regular grid covering most of North America using methods that will allow us to seamlessly update the gridded data as new observations become available. The gridded precipitation and temperature data will be used to generate Palmer Drought Severity Indices (PDSI) and Standardized Precipitation Indices (SPI), two widely used measures of relative drought and wetness. These gridded drought/wetness metrics will be used with centuries-long annual tree-ring chronologies to generate well-calibrated and verified drought reconstructions covering the past 500-1000 years or more over most areas of North America. They will be put on NOAA websites, which will be developed by both NOAA in Asheville and in Boulder, for easy access by the public.

Education Goals

None specifically. However, the blended living North American drought reconstruction grid will be made publicly available online at NOAA for scientific and educational purposes.

Research Progress

The final instrumental data fields (monthly temperature, precipitation, and derived drought metrics like PDSI and SPI) to be used for reconstruction from tree rings are still awaiting completion. This is due to the inclusion of new long climate records in certain poorly covered regions of North America and some systematic biases discovered earlier this year that need to be corrected (R. Vose, pers. comm., May 2009). Tests to date indicate that the cross-validation errors in these fields will be comparable to those
produced by PRISM Climate Group (http://www.prism.oregonstate.edu/), a result that is truly excellent.

The tree-ring network needed for reconstructing North American drought continues to be expanded and be filled in. The total number over the life of this project has now increased from 1846 to 1867 since the previous progress report. This includes some new multi-centennial and millennium-length records in critical locations near the Great Plains.

The Point-by-Point Regression (PPR) program used for reconstructing North American PDSI has been rewritten completely now by E. R. Cook and has been extensively tested. In addition, the PPR program has been expanded to include the generation of bootstrap uncertainties on the pointwise reconstructions and the production of PPR ensembles. Preliminary results indicate that considerable improvements in reconstruction quality can be obtained in weakly estimated regions of the grid by averaging the ensemble members together into a mean field.

Even with the delay in producing the final ‘blended living’ drought reconstruction product, preliminary reconstructions based on an earlier version of the instrumental PDSI field have produced stunning results concerning past megadroughts over North America. In particular, two medieval megadroughts first discovered by Scott Stine in California have been reproduced in the drought reconstructions with amazing fidelity. These droughts, based on long PDSI reconstructions averaged over California and Nevada are shown below. The timing and duration of the two megadroughts indicated in the reconstructions fit almost perfectly with the radiocarbon dates (given their uncertainties) and tree ages of the stumps (based on ring counts) provided by Scott Stine. The power of the drought atlas as a scientific research tool is also indicated by the maps showing the spatial patterns of the two megadroughts and the relatively short intervening pluvial. These and other results are now in press in the Journal of Quaternary Science (see the publication list below).
Highlights

- Further expansion of the North American tree-ring network from 1846 to 1867 chronologies.
- Continued development of the living gridded instrumental data grid used to generate PDSI for reconstruction.
- Addition of bootstrap uncertainty estimates and the generation of ensembles of reconstructed field in the PPR program.
- Tests of the ‘blended living’ drought atlas and publication of preliminary results.

Societal Benefits

Drought is perhaps the most serious chronic climate impact on society today. It affects agriculture, water resources and supply, recreation, and the environment (e.g., through promoting forest fires). By providing an operational drought assessment tool for NOAA through the living blended PDSI grid being developed here, it will be possible to track the development of droughts in the future and compare them to reconstructed

Figure 1. Copy of a PowerPoint Slide presented in Session 182 T25: Terrestrial Response to Climate Variability during the Medieval Warm Period: Lakes, Tree-Rings, and Human Adaptation at the GSA Joint Annual Meeting held in Houston, TX on October 5-9, 2008. Richard R. Heim, Jr., Russell S. Vose, and Jay H. Lawrimore from NOAA NCDC in Asheville were co-authors of this presentation.
droughts over the past several centuries to millennium. This may help in predicting how
droughts will develop and spread. The living blended drought reconstruction grid will
also be useful to climate modelers in determining the causes of drought and the likelihood
that global warming is playing an active role in the development of droughts.

**Education & Outreach**

**Presentations**

Times in North America: Results from an Expanded High-Resolution Grid of PDSI
Reconstructions from Tree Rings*. Invited talk presented in Session 182 T25: Terrestrial
Response to Climate Variability during the Medieval Warm Period: Lakes, Tree-Rings,
and Human Adaptation, GSA Joint Annual Meeting, October 5-9, 2008, Houston, Texas.

Cook, E.R. (with K.J. Anchukaitis). *Spatial Reconstruction of Climate Using Multiple
Records*. Invited talk presented at the PAGES Climate Variability in the Greater Mekong
River Basin: Paleo Proxies, Instrumental Data and Model Projections meeting, February

**Personnel**

Research Scientists: 1, Research Support Staff: 1.

**Publications**

**Journal articles**


**Cook**, E.R., Seager, R., Heim, R.R., Vose, R.S., Herweijer, C. and Woodhouse, C.W.
2009. Megadroughts in North America: Placing IPCC projections of
hydroclimatic change in a long-term paleoclimate context. *Journal of Quaternary
Science* (in press).

**Seager**, R., Burgman, R., Kushnir, Y., Clement, A.C., Cook, E.R., Naik, N. and Miller, J.
Testing the concept with an atmosphere model forced by coral-reconstructed

**Seager**, R., Ting, M., Davis, M., Cane, M.A., Naik, N., Nakamura, J., Li, C., Cook, E.
and Stahle, D.W. 2009. Mexican drought: an observational, modeling and tree

Stahle, D.W., Cook, E.R., Villanueva Díaz, J., Fye, F.K., Burnette, D.J., Griffín, R.D.,
in Mexico, EOS 90(11):89-100.

drought from instrumental and paleoclimatic data. *Journal of Climate* (in press).
Reports
Research Goals

Record the flow through Makassar Strait, Indonesia, the primary inflow route (>80%) of Pacific Ocean water composing the Indonesian Throughflow.

Education Goals

Train Indonesian researchers and technical staff in the methods of maintaining a current measuring mooring.

Research Progress

Directly after the recovery of the NSF funded INSTANT western Makassar mooring in November 2006, a NOAA funded mooring was deployed at the same site (2°51' S; 118°28' E; 2147 m) on 22 November 2006. The NOAA-MAK was recovered on 31 May 2009, and re-deployed for another 2 years to continue to build the time series. We now have a 5.5-year continuous time series of Makassar Throughflow; with the 1997/98 Arlindo data we have a full 7 years of Makassar Throughflow recorded.

Highlights

During the INSTANT periods ENSO was in a weak El Niño state, with a brief La Niña phase occurring in early 2006. The NOAA mooring period spans a time of an overall weak La Niña phase. Except for the Arlindo period, there is no clear correlation of the Makassar Throughflow to ENSO, but it is noted that neither the INSTANT nor NOAA time series recorded during strong ENSO episodes. The December 2006 through May 2009 record displays many of the same attributes as revealed by the INSTANT data: a clear seasonal behavior with maximum flow in August, with minimum flow in November. The particularly weak flow of November 2007 may be a consequence of a strong Kelvin Wave derived from the Indian Ocean. The mean flow within the thermocline and deeper as measured by the NOAA-MAK mooring is strikingly similar (less than 10% difference) to that measured during the INSTANT period. However the flow at 40 meters is notably weaker in the NOAA record, with an average southward speed of 0.3 m/sec versus 0.4 m/sec in the INSTANT 2004-2006 record.
**Societal Benefits**

Resolving the link between the regional and larger scale climate variability with the mass/heat transfer of Pacific water into the Indian Ocean, the Indonesian Throughflow, via the pathways of the Indonesian seas, will provide an observational based quantitative appreciation of the ocean role in such climate elements as El Niño and the Asian monsoon.

**Personnel**

Research Scientists: 3, Administrative: 1.

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**Figure 1**: Configuration of the NOAA-ITF Makassar mooring deployed in November 2006 at the Red X in the bathymetry map of Makassar Strait. Recovered 31 May 2009. Redeployed for another ~ two year period.
Figure 2 Meridional speed at Makassar west mooring site 2°51' S; 118°28' E from January 2004 through May 2009. The blue and green lines denote the time series from the first and second deployment of the NSF funded INSTANT program; the red line is from the NOAA funded mooring record.
Research Goals

To develop adequate techniques and to analyze historical winds on the basis of ship data, with the use of the modern scatterometry data. To base the analysis methodology on the reduced space optimal estimation with multivariate constraints and on the representation of uncertainty by an ensemble of possible realizations. To utilize surface winds and sea level pressure from International Comprehensive Ocean-Atmosphere Data Set (ICOADS). To evaluate utility of historical reconstructions in multivariate statistical analyses of climate data and for forcing ocean models. To apply developed products to the investigation of relevant climate questions, especially those pertinent to variability and controls of Indian monsoon.

Education Goals

Historical analyses of ocean climate data developed in this project to be used in research projects of students in the LDEO and outside. Making the analyses available via web-interfaced data server ensures wide accessibility of the results for educational purposes.

Research Progress

In the course of this project we (1) produced RSOI versions of ocean surface wind and sea level pressure data sets on the basis of ICOADS data; (2) compared the results of these analyses with other wind products that are based on different techniques, use satellite data and/or numerical models; (3) evaluated wind analyses in the context of other climate variables and as forcing fields for an ocean model; (4) used historical analyses of climate data in investigations of regional climate problems.

1. Analyzed data set development. Recent releases of the International Comprehensive Ocean Atmosphere Data Set (ICOADS) pushed the compilations of marine observations contained in ship reports back to the beginning of the 19th century. The 19th century exhibits dramatic changes in the marine data availability, from the order of 1000 reports
per year in the first two decades to a quarter of million reports per year at the close of the century. We applied the reduced space objective analysis (RSOI) technique to reconstruct near-global 19th century fields of sea level pressure and surface winds with spatial resolution of 4 degrees and monthly temporal resolution. The quality of these trial reconstructions changes significantly with the amount of available data.

2. Comparison with other analyses. Comparison of the tropical Pacific surface zonal wind stress from four different data sets for a 30 year period 1964-1993 (da Silva successive correction analysis, our RSOI computed for global surface winds, NCEP-NCAR reanalysis, and the FSU subjective analysis of tropical Pacific winds) showed completely different trends, poor overall coherency (an area averaged correlation coefficient between any two products does not exceed 0.56), and substantial difference in the degree of the spatial and temporal smoothness. Nevertheless, certain large-scale aspects of interannual variability, in particular El Nino – Southern Oscillation (ENSO) variability, seem to be faithfully reproduced and can be reconstructed on the basis of historical data (Evans and Kaplan 2004).

3. RSOI analyses in the context of other climate data and model simulations. Averages of tropical sea level pressure showed variability consistent with other observation-based analyses and atmospheric reanalyses. This comparison helped to identify a failure of atmospheric GCMs to reproduce a steep increase in the tropical atmospheric mass after the 1974-75 PDO transition (Seager et al 2004). Central equatorial Pacific zonal wind values proved to be quite consistent with other indices of the interannual ENSO variability and helped to identify the variability in the Hadley circulation of the Pacific sector in the last 150 years (Evans and Kaplan, 2004).

4. Comparison of the performance of various tropical wind products as forcings for an ocean model has identified the equatorial persistence as a crucial controlling factor. This was explained in the context of the general dependence of the tropical sea level and thermocline response to the small-scale variability ("noise") in winds (Kaplan et al. 2004). Satellite data allowed us to estimate the pattern of the small-scale variability in the surface winds and helped to identify a remarkable level of the month-to-month persistence of the equatorial winds anomaly, which could not be identified from the ship data alone. The RSOI wind analyses and their error estimates were successfully used in the study of ENSO predictability (Karspeck et al 2006). More sophisticated approaches to describing the uncertainty in analyzed values will follow the hierarchical Bayesian regression approach applied recently by us to the bias analysis of the SST data (Kent and Kaplan, 2006). With regards to small-scale wind variability and error, Curchitser et al. (2005) established that the improvement in the resolution of the small-scale variability in winds afforded by scatterometry data does not automatically result in better simulations of spatial small-scale sea surface height variability (although it does cause the increase in the short-term sea surface height variability), if the spatial resolution of the ocean model is not refined.

5. Spectral Slopes and Interannual-to-Subannual Variability Ratios. The power law is a popular spectral description in climate dynamics because it can provide a succinct
summary of the spectral shape for a climate variable. Spectral slopes are also important for historical climate reconstructions because of their connections to temporal persistence. However, in regions where clear spectral peaks are present, such as the tropics, the physical meaning of this measure breaks down. We demonstrated that the ratio of interannual to subannual variability is an analogous metric and defined the exact correspondence between these two measures. This ratio is fundamentally a calculation of the spectral power law with the energy binned and averaged in two uneven frequency intervals divided at annual frequency. This partition is logical in a climatological context and yields intuitively comprehensible results. Moreover, the natural connection of this ratio to interannual climate variability patterns such as El Nino, the North Atlantic Oscillation, and global trends helps to clarify spectral slopes and their uncertainties. Earlier estimates of spectral slopes were interpreted in this context. We generalize these associations by evaluating spectral slopes and variability ratios for variables such as sea surface temperature, sea level pressure, surface winds, and precipitation. We use the method of empirical orthogonal functions (EOFs) with specially designed weighting coefficients to identify the dominant modes responsible for spatial patterns of spectral slope. Notably, residual patterns after subtracting only a few leading EOFs appear to be dominated by latitudinal variability and land-sea contrast, particularly for precipitation fields. Finally, we interpret leading principal components as well-known modes of interannual variability, predominantly ENSO and PDO.

6. Application of historical analyses to regional climate problems
6.1. Indian Ocean and Indian Monsoon

A. Equatorial Indian Ocean and ENSO influence on Indian Summer Monsoon Rainfall. The relationship between the state of the equatorial Indian Ocean, ENSO and Indian summer monsoon rainfall using data from 1881 to 1998 were examined (Ihara et al., 2007). We focused on the Indian Ocean Dipole Mode, and used the zonal wind anomalies from the trial wind analysis of ICOADS data and SST anomaly gradient over the equatorial Indian Ocean as indices that represent the condition of Indian Ocean. Although the index defined by the zonal wind anomalies over the equatorial Indian Ocean correlated poorly with Indian summer monsoon rainfall, the linear reconstruction of Indian summer monsoon rainfall based on a multiple regression from the NINO3 and this wind index better specified the Indian summer monsoon rainfall than the NINO3-only regression. Using contingency tables we found that the negative association between the categories of Indian summer monsoon rainfall and the wind index were significant during warm years (El Nino) but not during cold years (La Nina). Composite maps of land precipitation also indicated that this relationship is significant during El Nino events. We concluded that there was a significant negative association between Indian summer monsoon rainfall and the zonal wind anomalies over the equatorial Indian Ocean during El Nino events.

B. Timing of El Nino-Related Warming and Indian Summer Monsoon Rainfall. Using historical analyses of sea surface temperature SST and winds from 1881 to 1998, the relationship between all-India summer monsoon rainfall (ISMR) and the timing of El Nino - Southern Oscillation (ENSO) related warming/cooling was investigated (Ihara et al. 2008a). In the analysis of the evolution of Indo-Pacific SST anomalies, the ISMR was
found to be no less than normal despite the co-occurrence of an El Nino event for the cases when warming over the eastern equatorial Pacific starts on boreal winter and evolves early, so that the western central Pacific and Indian Ocean are warmer than normal during the summer monsoon season. In contrast, when the canonical El Nino - low ISMR relationship holds, the eastern equatorial Pacific starts warming rapidly only about a season before the reference summer so that the western central Pacific and Indian Ocean remain cold during the monsoon season.

C. Indian Ocean warming trend and dipole. The state of the Indian Ocean dipole representing the SST anomaly difference between the western and southeastern regions of the ocean was investigated using historical SST reconstructions from 1880 to 2004 (Ihara et al. 2008b). First, the western and eastern poles of the SST-based dipole mode index were analyzed separately. Both the western and eastern poles display warming trends over this period, particularly after the 1950s. The western pole tends to be anomalously colder than the eastern pole from 1880 to 1919, whereas in the interval 1950-2004 the SST anomalies over the western pole are comparable to those over the eastern pole though there are occasional outliers where the eastern pole is anomalously colder than the western pole. The tendencies of the occurrences of positive and negative dipole events in September-November show three distinct regimes during the period analyzed. In 1880-1919, negative dipole events associated with La Nina events occur more frequently than positive events. In 1920-49, some weak positive events occur relatively independently of El Nino events over the Pacific. The period of 1960-2004 is characterized by strong and frequent occurrences of positive events associated with El Nino events.

6.2. Tropical Pacific

The central equatorial Pacific trade winds were analyzed in the context of the general shifts in the mean state of the ENSO system. Linsley et al. (2006) provided the paleoclimatographic evidence in the form of the O18 and Sr/Ca coral records from the southwest Pacific on the shifts in the position of the South Pacific Convergence zone. The documented eastward extension of its southern component is consistent with the westward shrinking of its equatorial part, and thus is consistent with the hypothesized secular increase in the Pacific trades in the last century or so. However, such an increase is at odds with the directly observed decrease in the Pacific trade winds since 1970s. The analysis involving longer periods requires careful detrending of the historical data.

6.3. ENSO impact on North Atlantic

The evidence was found of a link between ENSO and surface winds over the northern North Atlantic (Emile-Geay et al., 2007). We used wind field data from three sources: historical RSOI analysis of surface observations, a coupled general circulation model (GCM), and a forced atmospheric GCM. POGA-ML ensemble mean showed a clear dynamical linkage between the two ocean basins: the tropical warming due to El Nino displaces subtropical jets equatorward, modifying transient which induce equatorward low-level flow at high latitudes, with a noticeable zonally symmetric component. In nature, however, this signal is potentially swamped by atmospheric dynamics independent of ENSO. Indeed, we found in the surface wind analyses that the
ENSO/North Atlantic connection was very weak north of 48 degree North. Repeating this analysis for five 50-year periods between 1860 and 2000 (sliding the window by 18 years each time), we found that this was due to a strong nonstationarity of the correlation in the northern parts of the basin: well above the 95% level in some decades, well below in some others. This result was also obtained for geostrophic wind fields derived from the sea level pressure (SLP) data. This could occur due either to the observational error (in SST, winds, as well as SLP) or to the noise. However, we found that a similar nonstationarity occurred in the GFDL simulations H1, H2, and H3, which have no measurement error. Therefore local variability is to blame in lowering the observed correlation to NINO3. The conclusion of this study is that the link between the tropical Pacific and the North Atlantic is at work in nature as in the two GCMs, but it is of modest amplitude compared to the natural climate variability of the North Atlantic, which is quite energetic in the multidecadal spectral range. The consequence is that the statistical link only emerges on long timescales. The simulated and instrumental SLP data are consistent with this idea, albeit too short to be conclusive, and perhaps veiled by the confounding influence of anthropogenic greenhouse gas increase.

6.4. Interpretation of a tropical Atlantic paleorecord

We have contributed to the calibration of downcore foraminiferal O18 (Black et al. 2004) and Mg/Ca (Black et al. 2007) records on the basis of historical instrumental sea surface temperature (SST). Mg/Ca measured on the planktic foraminifer Globigerina bulloides from a Cariaco Basin sediment core strongly correlated with spring (March-May) instrumental SSTs between A. D. 1870 and 1990. A specific Mg/Ca SST equation was derived and a paleo-SST record was presented spanning the last 8 centuries, an interval that includes the end of the Medieval Warm Period and the Little Ice Age. The long-term record displayed a surprising amount of variability. The temperature swings were not necessarily related to local upwelling variability but instead represent wider conditions in the Caribbean and western tropical Atlantic. The Mg/Ca SST record also captured the decadal and multidecadal variability observed in records of global land and sea surface temperature anomalies and Atlantic tropical storm and hurricane frequency over the late nineteenth and twentieth centuries. A divergence between the SST proxy record and Atlantic storm frequency around 1970 appears to reflect a fundamental change in Atlantic hurricane behavior noted in historical data. On average, twentieth-century temperatures were not the warmest in the entire record, but they do show the largest increase in magnitude and fastest rate of SST change over the last 800 years. (Black et al. 2007).

6.5. Southeastern U.S. precipitation and Bermudan High

In the studies involving the paleodata, Anchukaitis et al. (2006) identified the strength of the Bermuda high-pressure area as a controlling factor on the type of local climate influence on the tree growth in the southeastern United States. Specifically, the reduction in the summer rainfall in this area, apparently associated with the weakening of the Bermuda High in the last century, starting from 1970s has caused the major stress factor in the tree growth to shift from the spring coldness to the summer drought.
**Highlights**

- Reduced space optimal interpolations (RSOI) of marine surface wind and mean sea level pressure based on historical ship data sets were produced;
- Verifiable skill of RSOI reconstructions for interannual variability of central equatorial Pacific winds was established;
- Remarkable persistence of interannual surface wind anomalies and its importance for wind-forced ocean simulations was established;
- RSOI wind analyses were used in a statistical model for Indian summer monsoon rainfall, in studies of ENSO predictability, and in the evaluation of ENSO impacts on North Atlantic winds.

**Societal Benefits**

In this project we developed and test wind data sets that help to understand and perhaps predict climate changes. The critical importance of surface wind data for climate variability and climate change studies is well recognized. This project responds to this scientific need. National and international climate change assessments (like IPCC) serve to the benefit of the society and scientific community. We worked on the data sets and methodology, which lengthen significantly wind data sets available for climate simulations and which can provide the user with a straightforward way to take its uncertainty into account.

**Awards & Honors**

- A.Kaplan: AGU Editors' Citation for Excellence in Refereeing (2005).

**Academic Outreach**

- K-12: Elizabeth Heller was mentored by A.Kaplan within Nanuet High School Authentic Science Research Program. Her paper “An Evaluation of the 1868 El Nino” was selected for Finals in the 2004 Intel Science Talent Search competition. She is currently a Vassar College student.

- Postsecondary: Shane Riordan, science high school teacher from New York Harbor HS has done summer 2005 research project with A. Kaplan in the framework of Columbia Science Teachers Science Research Program. He worked on the access and quality control of historical climate data from ICOADS and CLIWOC, performing the tasks necessary for detrending and analyzing historical climate data.
Undergraduate Students:

Graduate Students:
- M.A.Cane (primary advisor) and A.Kaplan advised A.Karspeck (Ph.D. Student, Columbia University, graduated in 2004, won NOAA Global Change postdoctoral Fellowship, 2005-2007).
- M.A.Cane (primary advisor) and Y.Kushnir advised C.Ihara (Ph.D. student, Columbia University, graduated in 2007, stayed as a postdoc in LDEO 2007-2008).
- M.A. Cane advised J.Emile-Geay (Ph.D. student, Columbia University; graduated in 2007, did a postdoc in Georgia Tech, landed a faculty position in University of Southern California)

Academic:
- Kaplan, A., Y. Kushnir, and M.A. Cane, Scale separation, uncertainty, and ensembles in objective analyses of climate fields, 26th IUGG Conference on Mathematical Geophysics, Sea of Galilee, June 4-8, 2006.


• A.Kaplan (INVITED) Reduced Space Approach to Objective Analyses of Historical Climate Data Sets: Progress and Problems, a plenary talk at the 10th International Meeting on Statistical Climatology, Beijing, China, August 20-24, 2007.

• J.E.Smerdon, A.Kaplan, Pseudo-proxy tests of the regularized expectation maximization (RegEM) method and their implications for real-world climate field reconstructions of the last millennium, a talk at the 10th International Meeting on Statistical Climatology, Beijing, China, August 20-24, 2007.


• A.Kaplan, Historical chronologies of El Niño Events and Instrumental ENSO indices, talk at CLIMAR-3, Gdynia, Poland, May 6-9, 2008.


Public Outreach
• Kaplan, A., How to use satellite data to reconstruct climates of the past, talk at the LDEO Open House, October 2006.

• Kaplan, Climate Variations in the Last Two Centuries: How Do We Reconstruct the Past? Brownbag Discussion Series of the Earth Institute's Office of Academic and Research Programs, October 1, 2008.

Intranet / Internet sites or pages:
http://www.cgd.ucar.edu/~asphilli/DataCatalog/Data/kaplan.html

Databases:

CICAR 2009 Annual Performance Report
From July 1, 2008 to June 30, 2009
PI Yochanan Kushnir
http://www.cdc.noaa.gov/Pressure/Gridded/data.kaplan_slp.html

**Personnel**
Research Scientists: 3, Research Support Staff: 1, Administrative: 1, Post Doctoral Fellows: 1, Graduate Students: 3, Undergraduate Students: 3.

**Publications**

**Journal articles**


**Books / articles-in-books**


**Ph.D. Dissertations**


Julien Emile-Geay, ENSO dynamics and the Earth’s climate: from decades to Ice Ages, Ph.D. Dissertation, Columbia University

Chie Ihara, The state of climate over the tropical Indian Ocean and India from the late 19th century throughout the 20th century, Ph.D. dissertation, defended in April 2007, Columbia University.
Figure 1. Anomalies of 1877-1878 El Nino illustrated by univariate reduced space analyses.
Figure 2. Intercomparison of ENSO indices: NINO3, degree C, by Kaplan et al. [1998]; Darwin station SLP, mb, [Allan et al., 1991]; Darwin area SLP estimate from ship-based RSOI, mb, [Kaplan et al., 2000]; and Central Equatorial Pacific zonal wind anomaly (5S-5S,160E-120W), 5m/s from the ongoing CICAR project. Pressure and wind data are 5 month running means. [Adapted from Evans and Kaplan, 2004].
Figure 3. Lagged correlation coefficients in the zonal wind anomalies from the NCEP-NCAR reanalysis (160E-120W averages) show highly significant temporal persistence for the period of six months and beyond within 10 degrees latitude of Equator. This persistence has a potential as a statistical constraint to support the analyses of historical wind fields, when the observational data coverage is poor.
Figure 4. ENSO influence over the North Atlantic. (left) Regression patterns of wind vectors from the specified product, smoothed by a 3-month running average, on the NINO3 index, normalized to unit variance. Units of regression coefficients are given per standard deviation of the index. (right) Corresponding correlation patterns, shown for the meridional component only. (a) GFDL H1 surface wind stress regression. (b) GFDL H1 meridional wind stress correlation. (c) POGA-ML surface wind stress regression. (d) POGA-ML meridional wind stress correlation. (e) Analysis of ICOADS data, surface wind regression. (f) Analysis of ICOADS data, meridional wind correlation. [From Emile-Geay et al. 2007]
Research Goals

• Design and fabricate an air-sea CO₂ flux system for shipboard autonomous operation.
• Test and quality control the flux system from ships of opportunity.
• Explore different ocean gas-transfer environmental provinces.

Education Goals

The autonomous CO₂ system will be used by the community through active outreach programs though University of Colorado, Lamont-Doherty at Columbia University and NOAA.

Research Progress

The greatest asset of this project has been the ongoing development of an autonomous infrared-based CO₂ flux system for the measurement of air-sea carbon dioxide fluxes. A meteorological system with IR-based detection of pCO₂ concentrations has been designed, fabricated, and developed at LDEO and ESRL/NOAA and deployed on the Ronald H. Brown (Figure 1). Figure 2 shows data with open-path CO₂ systems, which are susceptible to spray and contamination. This assessment was performed on the Norway Ship G. O. Sars and the NOAA ship Ronald H. Brown (Figure 3). A Null system samples air that is not correlated with atmospheric eddies (Figure 3). The sample unit measures air in an enclosure. This system has been used as autonomous pCO₂ systems operated during shipboard CO₂ flux studies. This opportunity to measure and analyze autonomous system performance from an ocean vessel was invaluable. Preliminary testing in the laboratory also provides a motion free environment. Optimized for the ocean, it was tested in sea trials.

1. High volume in situ air sampling included in the autonomous system was used with CO₂ detectors in environmental enclosures. Remote air-pumps ensure continuous sample delivery over month-long periods, despite heavy aerosol loads in samples.
2. The in-line null pCO2 sensor is used to quantify motion contamination. The atmospheric sample is mixed and sent through a second sensor measured simultaneous with the vertical wind velocity. The carbon dioxide fluctuations are removed and the flux signal from this system will be assessed as the motion bias.

3. Complete autonomous system. The vertical motion corrections, in situ temperature, and motion artifact corrections are implemented to provide real time air-sea carbon dioxide fluxes.


The accuracy of the computed flux is dependent on the sensitivity of the gas analyzer to high frequency fluctuations. A fast-response, enclosed open-path, non-dispersive infrared (NDIR) CO2/H2O gas analyzer is used to measure atmospheric gas samples continuously. The air detectors are mounted 0.5 m from the sonic anemometer sampling volume. The samples air is drawn through the intake tube at a constant high rate, which results in a very small and correctable lag between the gas sample and the sonic anemometer measurement. Figure 1 shows the ultrasonic anemometer, compass, pitch, roll, yaw, accelerometers, and two NDIR systems onboard the BROWN.

The Licor units 7500 mounted up in the mast are sensitive to weather conditions (relative humidity and precipitation) under these conditions the time series clearly shows high noise levels and reporting erroneous readings.

**Highlights**

- Successful testing of autonomous air-sea CO2 flux measurements was made from a research vessel.

- Three Licor 7500 were mounted at the top of the mast as an open path system (direct atmospheric sampling) these three open path systems are from the University of Connecticut; two more Licors from NOAA PSD complete the set of five. The set was operated with one Licor acting as a Null (completely enclosed without air flow) and one Licor operating under a sleeve (enclosed but with an air flow-through). The Null is intended to be used as a white noise filter due to high frequency oscillations related to the ship motion and mast vibration. The air sampled by the sleeved Licor previously went through a mixing chamber that acted as a high frequency filtering function. The sleeved Licor was intended to provide weatherproof measurements.

- Three Licor 6262 units were mounted in the gas flux van on the 02 Fore Deck. These units provided by LDEO were set to sample at 5 [Hz]. The air was drawn from up the mast to the van by three pumps. Pump fluctuations are taken out by setting a mixing chamber between the pump and the Licor units at the end of the sampling line. These chambers stabilize the unit pressure improving the CO2 and H2O measurements. These systems provide solid CO2 concentrations and are
used as a core measurement in the direct flux estimates in conjunction with the faster sampled Licor 7500 units (Figure 4).

- Discovery that open-path sensors have biases and enclosed open-path detection of CO2 measurements are necessary.

- Systems are being fabricated and continued testing in collaboration with Columbia University and NOAA ESRL.

- An Arctic Cruise out of Bergen Norway May 28th- August 3rd on board the G.O. Sars


**Societal Benefits**

With a clear understanding of the sources and magnitude of variability that exists in the world’s ocean will become an integral part of the existing air-sea CO2 flux program. As with other flux measurement studies, the marine boundary layer offers a very stable environment for making CO2 flux measurements.

**Other Research Connections**

**Interagency**

NOAA OGP with interagency collaborations between NSF and NASA.

**Research partnerships**

Duck Field Research Facility

**Collaborators**

Chris Fairall of NOAA/ESRL in Boulder Colorado.

**Education & Outreach**

**Presentations**


Data synthesis meeting at Hawaii in April 2008

Data synthesis meeting in Boulder, July 2008

SF All PI Cruise Data Meeting December 2008

AGU session presentations Dec 2008

AMS session presentations Jan 2009

**Personnel**

Research Scientists: 2, Administrative: 2, Graduate Students: 1, Undergraduate Students: 1.
Publications

Journal articles


Conference proceedings / workshops


Ph.D. dissertations
Alejandro Cifuentes-Lorenzen (University of Connecticut)
Siv Lauvseth (University of Bergen, Norway)
Philip Orton (Columbia University)
Figure 1: Bow mast of the Ronald H. Brown showing the meteorological package for testing of the CO₂ autoflux system. Three sonic anemometers, five open-path 7500-CO₂/H₂O detectors, two RH/T, and intake lines for three closed-path CO₂/H₂O detectors are shown. The 7500-CO₂ sleeved detectors are on the right. The one connected to the blue-hose air sampler pulls bow air at 5 lps. The other 7500-CO₂ sleeved detector draws air in at .05 lpm. The low flow provides air samples of the ambient environment with damped high frequency fluctuations to determine the effect of motion on the carbon dioxide flux measurements.

Figure 2: Julian Day 90 hour 12, Figure 2 shows a robust plot of the CO₂ time series from the five Licor 7500 units mounted up in the mast. CO₂ and H₂O units are [mmol/m³].
Figure 3: Comparison of the CO$_2$ variance spectra for the 3 Licor 6262 sensors and 4 of the 5 Licor 7500 sensors.

Figure 4: Air-water CO$_2$ flux gas transfer velocity versus windspeed.
Research Goals

The primary objective of this program is to observe and document the space-time distribution of the sea-air \( \text{pCO}_2 \) difference and to estimate sea-air \( \text{CO}_2 \) flux over the regional and global oceans in seasonal, annual and interannual time scales. We operate shipboard underway \( \text{pCO}_2 \) systems installed aboard RVIB Palmer and other research and commercial ships participating the NOAA/VOS program. The data obtained under the NOAA/VOS program by participating members are processed and interpreted at Lamont-Doherty Earth Observatory, and the processed data are archived at and distributed to the public by the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN.

Education Goals

The global database for surface water \( \text{pCO}_2 \) assembled by this program has been made available to the public through the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN, and is being studied in collaboration with researchers and graduate students at a number of national and international institutions.

Research Progress

Approximately 3.6 million observations for the surface water \( \text{pCO}_2 \) have been assembled during this project. This database includes the \( \text{pCO}_2 \) observations made before 2006, and are accompanied with date, time, positions, seawater temperature, salinity and barometric pressure. The processed data (Version 1.0) are archived at and distributed to the public by the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN.

Highlights

Climatological mean air-sea CO2 flux for the contemporary global ocean is estimated using the sea-air pCO2 difference observations and the air-sea gas transfer rate that is parameterized as a function of (wind speed)^2 and the 1979-2005 NCEP-DOE AMIP-II Reanalysis (R-2) wind speed data. The equatorial Pacific (14°N-14°S) is the major source for atmospheric CO2, emitting about +0.44 Pg-C yr^-1, and the temperate oceans between 14° and 50° in both hemispheres are the major sink zones with an uptake flux of -0.64 Pg-C yr^-1 for the northern and -0.98 Pg-C yr^-1 for the southern zone. The high latitude North Atlantic, including the Nordic Seas and portion of the Arctic Sea, is the most intense CO2 sink area on the basis of per unit area, with a mean of -2.3 Tons-C month^-1 km^-2 (1 Ton = 10^6 grams). This is due to the combination of the low pCO2 in seawater and high gas exchange rates. In the ice-free zone of the Southern Ocean (50°S-62°S), the mean annual flux is small (-0.06 Pg-C yr^-1) because of a cancellation of the summer uptake CO2 flux with the winter release of CO2 caused by deepwater upwelling. The annual mean for the contemporary net CO2 uptake flux over the global oceans is estimated to be -1.4 ± 0.7 Pg-C yr^-1. Taking the pre-industrial steady state ocean source of 0.4 ± 0.2 Pg-C yr^-1 into account, the total ocean uptake flux including the anthropogenic CO2 is estimated to be -1.8 ± 0.7 Pg-C yr^-1 in 2000. (See the map at the end of this report; and the reference is in the publication list)

Societal Benefits

Accurate future projection of atmospheric CO2 is needed for the global management of this most important greenhouse gas. Timely information on CO2 emissions and the fate of the emitted CO2 is essential for making sound energy policy. The results of this investigation are used to validate various global carbon cycle models, which are used to provide reliable future projection of the atmospheric CO2 concentrations.

Other Research Connections

Taro Takahashi has collaborated with a large number of national and international carbon cycle researchers. His research collaborators include observational researchers as well as a wide range of ocean and atmospheric modelers in U. S., European and Asian communities.

Awards & Honors

The April 2009 issue of the Deep-Sea Research –II was dedicated to Taro Takahashi for a recognition of his pioneering ocean carbon cycle research.

Interagency

For the past three years, he advised climate research activities in the U. S. agencies as a regular member of the Climate Research Committee, the National Research Council of the U. S. National Academy of Sciences.
**Education & Outreach**
A large global database for surface water pCO$_2$, which has been assembled by this program, was made available to the public through the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN, and is being used by researchers and graduate students at a number of national and international institutions.

**Personnel**
Research Scientists: 1, Visiting Scientists: 1, Research Support Staff: 3.

**Publications (Grant Period: 09/01/05 through 06/30/09)**

**Journal articles:**


Reports

Conference proceedings / workshops

Figure 1. Climatological mean annual air-sea CO₂ flux over the contemporary global oceans based on 3 million measurements of surface water pCO₂. The 1979-2005 NCEP-DOE AMIP-II Reanalysis wind speed data are used for estimating the CO₂ gas transfer rate across the sea-air interface. Yellow-orange areas indicate that the sea is a source of CO₂ to the atmosphere; blue-magenta areas indicate a sink; and green areas indicate neutral. Intense upwelling of deep waters rich in CO₂ and warming of water causes the sea to become a CO₂ source for the atmosphere, whereas cooling of water and the photosynthetic utilization of CO₂ cause the sea to become a CO₂ sink. The total global ocean uptake flux of CO₂ for the year 2000 is estimated to be 1.4 Giga-tons Carbon per year. (Takahashi et al., DSR-II, 2009)
Research Goals

During the past year our primary goal has been to develop high-resolution records of changes in the circulation of the Southern Ocean, with a focus on its variability during periods of Abrupt Climate Change.

Education Goals

This project supports the education and training of a graduate student, Ms. Shahla Ali. Ms. Ali targets December 2009, to defend her thesis. Mark Siddall was partially supported as a postdoctoral fellow by this award.

Research Progress

Progress on publishing results of our work is described in the following sections. Progress on processing samples during the past year was limited because Patricia Malone, who is responsible for most of our initial sample processing, was out on medical leave for 4 months. Ms. Malone works for all of the Paleo PIs under the NOAA ARCHES award. Upon her return from medical leave, she worked on samples for collaborator Sidney Hemming, because Hemming’s work was considered more time sensitive than Anderson’s.

Highlights

The highlight of the past year was publication in SCIENCE of our NOAA supported study linking naturally varying carbon dioxide concentrations in the atmosphere to the rate of wind-driven upwelling in the Southern Ocean. In addition to explaining the tight coupling between climate variability and the concentration of carbon dioxide in the atmosphere, the paper also explained the mechanisms that link initial forcing in the North Atlantic region to the Southern Ocean via a reorganization of global atmospheric circulation.

It is significant that we found evidence for similar linkages between the climate, upwelling in the Southern Ocean, and changing concentrations of carbon dioxide in the atmosphere throughout the last glacial period. Our findings indicate that similar fundamental relationships intrinsic to Earth’s climate system have governed abrupt
climate changes during all phases of the glacial climate cycle, from late interglacial through peak glacial to deglaciation.

Mark Siddall carried out a modeling study to test the reliability of the method we use to exploit Thorium-230 when evaluating fluxes of material to marine sediments. The reliability of this method is vital to all aspects of our work, including the results published earlier this year in SCIENCE. Siddall’s modeling results support the validity of our methods, and this work has been published in PALEOCEANOGRAPHY.

Societal Benefits

This work contributes to our understanding of the ocean’s role in abrupt climate change, and of the specific processes involved in past abrupt climate changes. This knowledge is vital to the development and testing of models that can be used to make meaningful predictions about whether or not increasing concentrations of anthropogenic greenhouse gases might induce abrupt climate changes in the future.

This work has also produced a major advance in our understanding of the tight coupling between climate variability and the concentration of carbon dioxide in the atmosphere that is evident in ice core records covering the past 800,000 years. That knowledge will eventually help improve estimates of the climate sensitivity to future increases in atmospheric carbon dioxide associated with burning fossil fuels.

Other Research Connections (interagency, partnerships, collaborations)

Since publication of our paper in SCIENCE several investigators from institutions in the U.S. and in Europe have contacted us to say that the principles described in our paper have helped them interpret their own paleoceanographic records. We believe that our findings represent the key to unlock one of the great mysteries of climate research by providing an explanation to link the global footprint of past abrupt climate changes to events that occurred in the North Atlantic region. Global reorganization of atmospheric circulation seems to be the long-sought teleconnection.

Interagency

The paper published in SCIENCE (see below) integrated work supported by NOAA covering Earth’s transition out of the last ice age (roughly 25,000 years ago to present) with work supported by NSF covering the last glacial period, roughly between 30,000 and 90,000 years ago.

It is significant that we found evidence for similar linkages between the climate, upwelling in the Southern Ocean, and changing concentrations of carbon dioxide in the atmosphere during these two very different time periods. Our findings indicate that similar fundamental relationships intrinsic to Earth’s climate system have governed abrupt climate changes during all phases of the glacial climate cycle, from late interglacial through peak glacial to deglaciation.
Education & Outreach

As noted above, we hope that Shahla Ali will defend her thesis by the end of this year.

During the past year, the findings described in our SCIENCE paper have been presented in the following venues:

- Fall 2008 AGU meeting
- Marine Sciences Colloquium, Stonybrook University
- Earth and Planetary Sciences Colloquium, University of California Berkeley
- Ocean Carbon and Biogeochemistry scoping workshop on New Frontiers in Southern Ocean Biogeochemistry and Ecosystem Research, Princeton University
- AGU Chapman Conference on Abrupt Climate Change, Byrd Polar Research Center, Ohio State University.
- Abrupt Climate Change in a Warming World, Annual Meeting, Lamont-Doherty Earth Observatory.

Other than the fall 2008 AGU presentation, each of the presentations noted above was invited, indicating the widespread interest in this work. Furthermore, Anderson has been invited to give a presentation on recent developments in this area during the fall 2009 AGU meeting.

Personnel

Research Scientists: 1, Research Support Staff: 2, Post Doctoral Fellows: 1.

Journal Articles


Research Goals

Together with postdoctoral fellow Jimin Yu, we are attempting to reconstruct variations in carbonate ion concentration in the deep sea over the last 150,000 years as a means of constraining the causes of the changes in atmospheric CO₂ content which occurred during this time interval.

Personnel

Research Support Staff: 1, Administrative: 1.
Research Goals

The first research goal for the reporting period was to complete the $^{10}$Be surface-exposure chronology of mapped moraines in the southern middle latitudes of New Zealand’s Southern Alps for the penultimate glacial maximum, the Last Glacial Maximum (LGM), the last termination, and the late-glacial climate reversal. The second research goal was to establish a local calibration site for the production of $^{10}$Be that can be used for the $^{10}$Be chronology of the New Zealand This project was carried out in cooperation with Dr. Joerg Schaefer, director of Lamont-Doherty’s Surface Exposure Dating Laboratory. These goals were achieved, as detailed below.

Education Goals

The educational goal was to afford three students the background field and laboratory experience to allow them to work toward M.S. and Ph.D. degrees. All three students are registered for their degrees at the University of Maine, but carried out their field research in New Zealand’s Southern Alps (under the supervision of G. Denton) and their laboratory research at Lamont-Doherty (under the supervision of J. Schaefer). They are: Aaron Putnam, Ph.D. student; Alice Doughty, M.S. student; Samuel Kelley, M.S. student. Doughty received her M.S. Degree at Maine in December of 2008. She is now enrolled in a PhD program at Victoria University of Wellington, New Zealand. Kelley...
will receive his M.S. Degree at Maine in September of 2009. Putnam is still working on his PhD degree.

*Research Progress*

The detailed 10Be exposure-age chronology for moraines alongside Lake Pukaki (Fig. 1) was completed with field work carried out in January and February of 2009, followed by laboratory work and dating. Figures 2 and 3, given below, show the Pukaki moraine system with all of the dates plotted on the map. This figure is an updated version of a similar one shown in the progress report of a year ago, but with the addition of all of the new dates. Together with a similar chronology previously developed with NOAA funding for the adjacent Ohau moraine system (Figs. 2 and 4), these results give the most complete chronology for Last Glacial Maximum moraines anywhere in the world. They show a prolonged LGM represented by the youngest moraine set. Near-maximum glacier extent was held between about 34,000 and 18,000 years ago. The last termination set in very close to 18,000 years ago, with rapid ice recession. The deglaciation was stalled during a climate reversal in which glaciers halted their recession and underwent a minor advance that culminated at 13,000 years ago. Deglaciation resumed thereafter.

A critical issue in constructing our moraine chronologies is to determine an accurate local production rate 10Be on boulder surfaces. Therefore we dedicated considerable time and effort in establishing a local calibration site in Macauley Valley, located near lakes Pukaki and Ohau. Here a debris flow from a tributary valley buried a scrub forest growing on the valley floor about 9000 years ago. We established the age of the debris flow from radiocarbon dates of the crushed trees. We then measured the 10Be concentration on the surfaces of boulders embedded in the surface of the debris flow. Because the emplacement of the debris flow was essentially an instantaneous event, we could then calculate a local production rate by comparing the two sets of data. The resulting production rate was checked at another site in the Lake Pukaki basin where a moraine surface was associated with radiocarbon and 10Be samples. Both sites gave consistent results, which were then used to determine the moraine ages plotted in Figures 3 and 4.

Field work was also carried out in the Lago Argentino area alongside the Southern Patagonian Icefield in the austral summer of 2009. A radiocarbon chronology was completed for the late-glacial Puerto Bandera moraines deposited by outlets of the Southern Patagonian Icefield. The results show that the Puerto Bandera late-glacial moraines are of the same age as the Birch Hill moraines alongside Lake Pukaki in Figure 3.

*Highlights*

During the last glacial maximum and termination the climate signal from middle latitude glaciers match closely that determined from Antarctic ice cores. This includes the timing and duration of the last glacial maximum, the deglacial signal, and the late-glacial cold reversal. Moreover the timing and magnitude of fluctuations of mountain glaciers was nearly identical to the timing and magnitude of sea-surface temperature changes from marine-sediment cores off shore of New Zealand and South America. These results
mean that the whole Southern Ocean/Antarctic region as far north as the Subtropical Convergence acted as a unit during at least the end of the last glacial cycle. The resulting Southern Hemisphere events of this interconnected Antarctic/Southern Ocean system are plotted in the left column of Figure 5 below. They can be compared with the coeval Northern Hemisphere events shown in the left column. The implications of this comparison are profound. They allow us to establish a comprehensive hypothesis of the termination that brought the last ice age to a close. A prime feature of this hypothesis is that abrupt climate changes in the Northern Hemisphere, introduced by two bursts of icebergs and melt water into the North Atlantic during retreat of the Northern ice sheets. The resulting stadials were characterized by the spread of winter sea ice across the North Atlantic. These Northern stadials correspond to two pulses of Antarctic/Southern Ocean upwelling, warming, and rises of atmospheric CO2. Together, these warming pulses comprise the whole Southern Hemisphere termination. The underlying processes linking northern and southern polar regions involve a southward shift of the southern westerly wind belt when the thermal equator is pushed toward the Southern Hemisphere by the spread of winter sea ice over the northern North Atlantic. Because the collapsing ice sheets were so large, the resulting northern stadials were of sufficient duration to complete the termination by raising CO2 degassed from the Southern Ocean above the threshold to complete the termination. A combined Maine-Lamont group is preparing a paper on this hypothesis to submit to Nature.

Other Research Connections
This project was joint between the University of Maine and Lamont-Doherty. In addition, GNS-Science (Crown Institute of Geology and Geophysics) in New Zealand was an official partner in the project David Barrell, an officer of GNS Science, participated in fieldwork, map preparation, and report preparation. The maps were digitized at GNS-Science.

Education & Outreach
G.H. Denton and J. Schaefer were mentors for the graduate students in the course of the fieldwork and in the laboratory preparation of the samples for 10Be dating.

Personnel
Research Scientists: 1, Graduate Students: 3.

Publications
Journal articles

Hall, B.L., C. Baroni, and G.H. Denton, 2008: The most extensive Holocene advances in East Greenland occurred in the Little Ice Age. Polar Research, 27, 128-134.


**M.S. Dissertations**


Kelley, S., 2009, 10Be chronology of the left-lateral moraine complex deposited by the Pukaki glacier, Mackenzie Region, New Zealand, during the last glacial cycle. University of Maine, M.S. thesis.
Figure 2. Glacial geomorphic map of the Mackenzie Basin, South Island, New Zealand. Red features are moraines deposited during the LGM, and moraines deposited during earlier glacial periods are colored green. Tan colors depict outwash associated with the LGM (dark) and Holocene (light). Black boxes outline the field areas targeted for surface exposure dating, detailed in Figs. 3 & 4. General index map of the South Island is included as inset.
Figure 3. Glacial geomorphic map of the Lake Pukaki region. Symbols and colors are as described for Fig. 2. $^{10}$Be surface-exposure ages determined from the moraine landforms are given in white boxes, and lines with dots designate their locations on the map. We note that this figure has been updated to reflect several new $^{10}$Be ages, including those determined from the Boundary Stream moraines (lower inset box), and the Birch Hill late glacial moraines (upper inset box).
Figure 4. TOP: Glacial geomorphic map of the Lake Ohau LGM terminal moraine system. Features are as defined in Fig. 2. $^{10}$Be surface-exposure dates are given in white boxes and lines with dots denote sample locations. BOTTOM: Probability distribution plots of $^{10}$Be ages from the Ohau moraine belts. Red numbers above boxes are the mean landform ages ($\pm 1\sigma$, in thousands of years) and yellow bands represent the $1\sigma$ uncertainty range. Statistical information occurs as insets.
Figure 5.

*RIGHT:* From top to bottom, top panel shows Chilean SSTs determined from ODP Site 1233 (Ninnemann *et al.*, personal communication, 2009). Following two panels show time-distance diagrams of South American (Denton *et al.*, 1999; J. Strelin, personal communication, 2009) and New Zealand mountain glaciers (this study), respectively. Fourth panel from top shows biogenic opal flux and $^{231}$Pa/$^{230}$Th ratios in the Southern Ocean (Anderson *et al.*, 2009). The bottom two panels are the EDC deuterium (EPICA Community Members, 2005) and Antarctic ice core CO$_2$ data from the EPICA, Taylor Dome, and Byrd ice cores (Indermühle *et al.*, 2000; Flückiger *et al.*, 2002; Monnin *et al.*, 2004; Ahn and Brook, 2008), respectively. EPICA deuterium and CO$_2$ data are plotted on the GISP2 timescale (after Marchitto *et al.*, 2007). The Mystery Interval (‘MI’) and Younger Dryas (‘YD’) are marked with yellow backgrounds, and Bölling/Alleröd (‘B/A’)/Antarctic Cold Reversal (‘ACR’) and LGM are with blue backgrounds.
Research Goals

Moorings: To monitor seasonal and interannual changes in the production of dense waters formed in the Weddell Sea.

This project installed and maintained 3 moorings south of the South Orkney Islands to monitor the combined outflow (currents and temperature/salinity) within the lower ~500 m of the water column within the core of dense Antarctic deep and bottom water draining from various sites along the continental margins of the Weddell Sea (Fig 1). These water masses ventilate much of the lower 2 kilometers of the world ocean.

Observations: Continue investigation of sea surface salinity data as a proxy for the marine hydrological cycle and climate change.

Research Progress

Continued maintenance of the moored array is now funded under a separate project within the Climate Observation Division (Award No. NA08OAR4320754 “Weddell Sea Moorings”). In the final year of this ARCHES project, effort was devoted to procuring equipment and supplies, and preparing for, the next mooring field program.

The mooring array was serviced during a cruise on board the British Antarctic Survey (BAS) vessel RRS ERNEST SHACKLETON, sailing from the Falkland Islands on 21 January 2009 and returning 10 March 2009. During this cruise, moorings M2 and M4 were recovered. M3 unfortunately could not be recovered. Neither of the paired acoustic releases on M3 responded to commands, so we presume the mooring was lost, most likely due to failure of one or more flotation bundles shortly after deployment during the 2007 cruise. This mode of failure has been experienced twice before. The first occurred during the attempted deployment of M2 in 2006, when an imploding float bundle triggered one of the paired releases and the mooring returned to the surface while we were still on site conducting a CTD station. The second implosion occurred on mooring M2 sometime during the 2007-2009 deployment. The mooring was recovered intact, but one float bundle had imploded, causing the failure of its neighboring float package. Both times the failing buoyancy modules were McLane Research Laboratories.
triangular glass float packages, model G6600-2. Both had been previously deployed. We are in the process of replacing all of our McLane flotation with Benthos 17” glass sphere flotation.

Mooring M3 was replaced with a full suite of instruments, and a mix of spare flotation and floats borrowed from other groups on board the vessel. We do not yet have enough instruments and mooring gear to sail with complete backup, so mooring M2 was redeployed in a reduced configuration, with only a single release, and instruments in the lower 250 m instead of the usual 500 m instrument string.

Mooring work was accompanied by more than 200 Conductivity/ Temperature/ Depth/ profiles (CTD) including a high-resolution section across the Orkney Passage. As SHACKLETON is not a research vessel, the CTD system had to remain on deck throughout the cruise, unprotected from the weather. This resulted in large offsets in measure salinity. These will require additional effort to correct, using salinities derived from water samples collected during the cast. Thus, the data are not yet available.

**Highlights**

We now have time series of currents, temperature and salinity of the outflow of dense water from the Weddell Sea spanning 8 years at M3 [Figure 2], which is positioned within the primary pathway of outflow of dense Weddell water, and 6 years at M2. The M2 gap of 2005 and 2006 was due to lack of ship time to re-deploy M2 after recovery in March 2005, but it has now been reinstalled in March 2007.

**Societal Benefits**

The time series reveals significant seasonal and interannual variability in the outflow of dense Weddell Sea water. An annual pulse of the coldest bottom water at the mooring site is evident in the May-July time frame, which suggests [from the mean bottom speed] export of shelf water into the deep ocean at the upstream bottom water formation sites in the Dec-Feb period, i.e. austral summer [a rather unexpected discovery]. However, the exact timing of the outflow events and their temperature and salinity characteristics vary from year to year.

The extended time series will contribute to an understanding the processes that control the transport and characteristics of the bottom waters that emanate from the Weddell Sea, as required to better assess the reaction of the Southern Ocean meridional overturning circulation and associated deep ocean ventilation to a warming climate.

**Other Research Connections**

Collaborators: The Antarctic Program of Brazil provided an opportunity to participate in their Antarctic Operation XIX in 2001, on board their vessel NApOc ARY RONGEL.

We have developed a cooperative agreement with the British Antarctic Survey to maintain the South Orkney Plateau moorings, plus an additional array of moorings across the Orkney Passage to the east to more comprehensively monitor the outflow of deep and bottom water from the western Weddell.
**Interagency**

Installation and maintenance of the moorings was initially made possibly by ship time provided by the Office of Polar Programs, National Science foundation, on the US vessels RVIB Nathanial B Palmer and ARSV Laurence M Gould

**Education & Outreach**

Data are archived and made available as they are recovered from the moorings at the project web site: [http://www.ldeo.columbia.edu/res/div/ocp/projects/corc.shtml](http://www.ldeo.columbia.edu/res/div/ocp/projects/corc.shtml)

**Personnel**

Research Scientists: 1, Research Support Staff: 3, Administrative: 1, Graduate Students: 1.

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**Figure 1.** Location of the Weddell Sea moorings (red dots) and repeat CTD/Tracer line (dashed line). Shown schematically are the pathways of deep and bottom waters formed by interaction of WDW with continental and ice shelf waters.
Figure 2. M3 temperature and bottom speed time series, 1999 to 2007.
Research Goals
• Develop and apply proxies in ocean sediments that allow constraining important components of the paleoclimate system
• Integrate the records with existing information in order to constrain winds, dust, and ocean circulation during periods of abrupt climate change

Education Goals
• Train and mentor graduate students and post docs
• Involve high school and undergraduate students in hands-on research projects
• Incorporate discoveries into the classroom

Research Progress

We have used the resources provided by this grant to characterize the behavior and role of northern hemisphere ice sheets in the climate system, a key goal of our research has been application of high resolution records of changes in deep water and intermediate water mixing in the South Atlantic in the context of rapid climate changes. Kissel et al. (2008) used detailed correlation, allowed by magnetic paleointensity, between cores in the North Atlantic with magnetic evidence for changes in the vigor of NADW overflow across the Nordic sills and cores in the South Atlantic with detailed Nd isotope records. We have found a remarkable correlation between the two records, but careful evaluation leads to a several hundred-year lag between evidence for reduced vigor in the North Atlantic and evidence for reduced NADW contributions in the deep South Atlantic. Alex Piotrowski et al. (2009) have used the combined high resolution benthic and planktonic stable isotopes and Nd isotope records from South Atlantic cores to examine in detail the relationships among these proxies to better understand the responses of both northern and southern source deep water formation during rapid climate changes. One of the implicit conclusions from our results and interpretations is that, while the North Atlantic and Pacific end members do no appear to have changed appreciably, the Southern Ocean end member most likely changed as a result of the reduced input from the NADW.
Antarctic Intermediate Water (AAIW) is a major player in ocean-climate interactions, but its behavior under different climate states, and its role in the global ocean-climate system is not well understood. Paleo-records of past variability are key to pursuing this problem. Katharina Pahnke is using the dispersed ferromanganese fraction of cores from intermediate water sites in the Atlantic to evaluate the role of AAIW in times of rapid climate change. This work is partly supported by CICAR, which has been important for leveraging her funded NSF OCE grant. She has created a high resolution record from the western tropical Atlantic (Pahnke et al., 2008) and has also done further mapping of the modern and last glacial composition of intermediate waters in the South Atlantic which she presented at the Goldschmidt conference. The new neodymium isotope record from the mid-depth Atlantic shows abrupt increases in the northward incursion of AAIW during times of strongly reduced North Atlantic overturning during the last deglaciation. Simultaneous increases in AAIW formation and warming in the southwest Pacific suggest a tight link with Southern Hemisphere climate. However, the initial incursion of AAIW into the North Atlantic at ~19ky coincided with weak AAIW formation in the Pacific and reduced overturning in the North Atlantic, suggesting Northern Hemisphere forcing of AAIW expansion through reduced competition at intermediate water depth. This early incursion of AAIW would have contributed to freshening of the intermediate depth North Atlantic, perhaps spurring the subsequent collapse of North Atlantic deep convection.

We also began collaborating with Peter DeMenocal and post-doctoral fellow Jennifer Colt, working towards using the sources of dust from Africa to develop a more thorough understanding of the relations between climate variability in the oceans and paleo-aridity. We used isotope tracing of dust sources from the west African margin. Cole’s paper on the initial work was recently published in EPSL (from the previous NOAA funding). We are following up on this research and expanding to the Arabian Sea with the current NOAA funding.

**Highlights**

- Evidence for changes in the composition of the Southern Ocean “end member” composition of Nd isotopes
- Evidence for millennial change in AAIW formation during times of reduced NADW
- Evidence for changes in intermediate water mass mixing associated with rapid climate change
- Evidence for ice dynamical changes in the North Atlantic region during times of rapid climate changes
- Evidence for a dominance of newly formed lacustrine minerals in ocean sediments from the Eastern Atlantic during the African Humid Period

**Societal Benefits**

The Greenland Summit ice core records have revealed extreme changes in mean annual air temperature during the last glacial period called Dansgaard-Oeschger (D-O)
events. These changes occurred over the period of a single human lifetime, and encompassed nearly the entire glacial-to-interglacial range of temperatures. Recently, it has been shown that these abrupt warmings in Greenland were accompanied by monsoon failure in China, drought in Venezuela, and extreme wet periods in southeast Brazil. The geographic spread and abrupt nature of these events indicate teleconnections within Earth’s climate system, which act on very short timescales to connect sensitive regions around the globe. Accordingly, this paleoclimate research contributes to our societal need to understand Earth’s climate system by providing new tools and producing significant records of past change.

Other Research Connections

Interagency
NSF-OPP, NSF-OCE

Partnerships
LDEO-Cardiff-Barcelona-GEOTOP

Collaborations
Ian Hall, Rainer Zahn, Vicky Peck, Elena Colmenaro-Hidalgo, Martin Roy

Education & Outreach

Research advisor, mentor
Undergraduate: we have engaged several undergraduate summer interns in this research (Hadas Kushnir, Stacey Kepler, Caleb Schif, Sean Culkin, Stephanie Pahler, Sarah Gitt). Stephanie Pahler did a senior thesis at Barnard College with Allison Franzese, and Joey Simonson did a senior thesis at Columbia College with Katharina Pahnke.

Academic outreach
K-12: we have engaged several high school students in summer research (from Tappan Zee High School)

Personnel
Research Scientists: 2, Post Doctoral Fellows: 1, Undergraduate Students: 1.

Publications
Journal articles (* indicates student author, # indicates post doc author)


Books / articles-in-books


Conference proceedings / workshops

Goldstein, S. L., Zylberberg*, D., Pahnke, K., Hemming, S. R., and van de Flierdrt, T., 2008, Quantifying late Quaternary changes in MOC intensity based on circum-Antarctic Nd isotopes,


Ph.D. dissertations
Allison M. Franzese
Alexander M. Piotrowski
Research Goals
Improve understanding of deep water formation in the Southern Ocean and in the
North Atlantic, including its variability.

Education Goals
Train students and interns in the field of observational studies of oceanic
circulation, specifically in the area of tracer oceanography

Research Progress
The goals for this funding period included evaluation of data sets previously
collected as part of ARCHES, specifically the data in the Ross Sea and the global $^3$He
distributions. The data set from the AS2K cruise in 2000 along the Ross Ice Shelf will
provide insight into the interaction between shelf waters and glacial ice, the global 3He
data set will be used to study the principal return flow of deep waters in the global ocean.
For the latter activity, a collaboration has been started between the LDEO tracer group
and the groups of Jorge Sarmiento (Princeton University) and Anand Gnanadesikan
(GFDL). This collaboration led to a proposal to the National Science Foundation on
studies of the deep ocean circulation using a combination of models and tracers.

Highlights
• We made progress on the Ross Sea data by adding water mass inversions to address
  the problem of melt water fractions and fluxes in water flowing out from underneath
  the floating ice shelf.
• We also moved towards completion of the global $^3$He data set, mainly in terms of
  quality control and plotting capabilities.

Societal Benefits
The project is of public interest because it follows the evolution of the water
masses in the Greenland Sea, which underwent an abrupt change around 1980 (reduction

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in GSDW formation rate by ca. 80%). There are also rapid changes observed in the Arctic Ocean and it will be interesting to see if these phenomena are linked to the transition into the greenhouse world.

Our new line of work based on the global 3He data set will shed new light on the deep circulation of the world ocean, specifically the return path of the global conveyor. This is a key issue for understanding the vulnerability of the ocean circulation.

Other Research Connections

Interagency
The research benefited my projects in the Arctic Ocean funded by NSF because the problems of deep water formation in the Greenland Sea are linked to Arctic Ocean circulation.

Research partnerships
A new research collaboration between GFDL (Anand Gnanadesikan) and Princeton University (Jorge Sarmiento) on the global conveyor has been formed.

Education & Outreach

Research advisor / mentor
Undergraduate: Gold Truong
Graduate: Brice Loose

Seminars
Princeton University, February 2006, August 2006

Personnel
Research Scientists: 1, Research Support Staff: 3, Administrative: 1, Graduate Students: 1, Undergraduate Students: 1.
Example of the results from the global $^3$He distribution work: Distribution of d$^3$He at 2500m depth in the global helium isotope data set presently being compiled by the Lamont group. High values are associated with ridge systems such as the Galapagos Rise. Similar plots can be produced for any desired depth or isopycnal surface.
Research Goals

The research goals for this funding period were to 1) complete the CFC measurements from the 5-year time series of newly formed Denmark Strait Overflow Water and its precursors collected on the seasonal cruises of the Iceland Marine Research Institute, 2) measure the CFC samples collected in the fall of 2006 in the Denmark Strait region on a ship of opportunity cruise (RRS Discovery D311), 3) measure SF6/CFC samples collected on ship of opportunity cruise NBP 07-02 to the Ross Sea and the Amundsen Sea in the austral summer of 2007, 4) measure CFC samples collected from the subtropical western North Atlantic on the R/V Atlantic Explorer in June 2007, 5) continue data synthesis on the Denmark Strait Overflow Water time series and 6) continue our investigation of bottom water formation in the Adelie Depression/Mertz Glacier region.

Education Goals

Provide research opportunities for undergraduate and graduate students in our laboratory and in fieldwork.

Research Progress

The remaining CFC samples from the 5-year time series in the Denmark Strait region (~200 samples) and the samples collected from the Discovery D311 cruise were measured. The samples from the Ross Sea and Amundsen Sea were collected in ground glass-stopper bottles, which were immersed in seawater in larger plastic bottles and stored at about 4°C. All of these samples (330) were measured. At the end of the cruise the samples were shipped from Punta Arenas to Port Hueneme and then to Lamont in special coolers to prevent heating. Unfortunately the samples appeared to have warmed during the transit, which caused degassing and the measurements are of marginal quality. For the Atlantic Explorer cruise to the western North Atlantic, SF6 samples were collected in ground glass-stopper bottles, immersed in seawater as was the case for the Amundsen Sea samples and CFC samples in flame sealed glass ampoules. All of the plastic containers for the SF6 samples leaked and the samples were no good. About 30% of the CFC samples in glass ampoules broke during shipment and we measured the
remaining samples (~60). These results were sent to our collaborator, Andreas Andersson of the Bermuda Institute of Ocean Sciences. We begin examination of the entire 5-year time series of CFC measurements in Denmark Strait Overflow Water and its precursors and continued analysis of data from the Adelie Depression/Mertz Glacier region. An optimum multiparameter analysis of the well-ventilated water masses along the Adelie Land continental slope suggested that 50-80% of this water came from the Ross Sea and most of the remainder from the Adelie shelf region. This work is in its preliminary stages.

**Societal Benefits**

This research focuses on understanding the transformation of surface water into subsurface water masses, particularly at high latitudes, which drives the global thermohaline meridional overturning circulation. This is an important component of the earth’s climate system both in heat transport and in the exchange of carbon dioxide and other gases between the atmosphere and the deep ocean. A better knowledge of this process is crucial for understanding and predicting the earth’s climate and thus for making decisions on how to address problems caused by the increase in greenhouse gases.

**Other Research Connections**

**Collaborations**

Stan Jacobs, Lamont-Doherty Earth Observatory
Jon Olafsson, University of Iceland and the Iceland Marine Research
Andreas Andersson, Bermuda Institute of Ocean Sciences

**Education & Outreach**

**Research advisor, mentor**

Undergraduate: Ilana Somasunderam, undergraduate, worked in my lab measuring CFC samples
Graduate: Abigail Spieler, working on Ph.D, participated on a cruise measuring CFCs

**Personnel**

Research Scientists: 1, Research Support Staff: 4, Administrative: 1, Graduate Students: 1, Undergraduate Students: 1.

**Publications**

**Books / articles-in-books**

Research Goals

Record the flow through Makassar Strait, Indonesia, the primary inflow route (>80%) of Pacific Ocean water composing the Indonesian Throughflow.

Education Goals

Train Indonesian researchers and technical staff in the methods of maintaining a current measuring mooring.

Research Progress

Directly after the recovery of the NSF funded INSTANT western Makassar mooring in November 2006, a NOAA funded mooring was deployed at the same site (2°51' S; 118°28' E; 2147 m) on 22 November 2006 (Figure 1). The NOAA-MAK was recovered on 31 May 2009, and re-deployed for another 2 years to continue to build the time series. We now have a 5.5-year continuous time series of Makassar Throughflow (Figure 2); with the 1997/98 Arlindo data we have a full 7 years of Makassar Throughflow recorded.

Highlights

During the INSTANT periods ENSO was in a weak El Niño state, with a brief La Niña phase occurring in early 2006. The NOAA mooring period spans a time of an overall weak La Niña phase. Except for the Arlindo period, there is no clear correlation of the Makassar Throughflow to ENSO, but it is noted that neither the INSTANT or NOAA time series recorded during strong ENSO episodes. The December 2006 through May 2009 record displays many of the same attributes as revealed by the INSTANT data: a clear seasonal behavior with maximum flow in August, with minimum flow in November. The particularly weak flow of November 2007 may be a consequence of a strong Kelvin Wave derived from the Indian Ocean. The mean flow within the thermocline and deeper as measured by the NOAA-MAK mooring is strikingly similar (less than 10% difference) to that measured during the INSTANT period. However the
flow at 40 meters is notably weaker in the NOAA record, with an average southward speed of 0.3 m/sec versus 0.4 m/sec in the INSTANT 2004-2006 record.

**Societal Benefits**
Resolving the link between the regional and larger scale climate variability with the mass/heat transfer of Pacific water into the Indian Ocean, the Indonesian Throughflow, via the pathways of the Indonesian seas, will provide an observational based quantitative appreciation of the ocean role in such climate elements as El Niño and the Asian monsoon.

**Personnel**
Research Scientists: 3, Administrative: 1

**Publications**
- Conference proceedings / workshops
  Abstract submitted to OceanObs09 in Venice September 2009
Figure 1: Configuration of the NOAA-ITF Makassar mooring deployed in November 2006 at the Red X in the bathymetry map of Makassar Strait. The NOAA-ITF Makassar mooring was recovered 31 May 2009, and redeployed for another ~two year period.
Monitoring the Indonesian Throughflow in Makassar Strait

**Figure 2:** Meridional speed at Makassar west mooring site 2°51’ S; 118°28’ E from January 2004 through May 2009. The blue and green lines denote the time series from the first and second deployment of the NSF funded INSTANT program; the red line is from the NOAA funded mooring record.
**Research Goals**

To monitor the export dense bottom water from the Weddell Sea, the primary component of Antarctic Bottom Water, as required to resolve seasonal and interannual variability of the overturning circulation of the Southern Ocean, a major contributor to global overturning meridional overturning circulation [MOC].

**Research Progress**

This project maintains a suite of instrumented moorings south and east of the South Orkney Islands to monitor the combined outflow (currents and temperature/salinity) within the lower ~500 m of the water column within the core of dense Antarctic deep and bottom water draining from various sites along the continental margins of the Weddell Sea (Fig 1). These water masses ventilate much of the lower 2 kilometers of the world ocean.

The mooring array was serviced during a cruise on board the British Antarctic Survey (BAS) vessel RRS ERNEST SHACKLETON, sailing from the Falkland Islands on 21 January 2009 and returning 10 March 2009. During this cruise, moorings M2 and M4 were recovered. M3 unfortunately could not be recovered. Neither of the paired acoustic releases on M3 responded to commands, so we presume the mooring was lost, most likely due to failure of one or more flotation bundles shortly after deployment during the 2007 cruise. This mode of failure has been experienced twice before. The first occurred during the attempted deployment of M2 in 2006, when an imploding float bundle triggered one of the paired releases and the mooring returned to the surface while we were still on site conducting a CTD station. The second implosion occurred on mooring M2 sometime during the 2007-2009 deployment. The mooring was recovered intact, but one float bundle had imploded, causing the failure of its neighboring float package. Both times, the failing buoyancy modules were McLane Research Laboratories triangular glass float packages, model G6600-2. Both had been previously deployed. We are in the process of replacing all of our McLane flotation with Benthos 17” glass sphere flotation.
Mooring M3 was replaced with a full suite of instruments, and a mix of spare flotation and floats borrowed from other groups on board the vessel. We do not yet have enough instruments and mooring gear to sail with complete backup, so mooring M2 was redeployed in a reduced configuration, with only a single release, and instruments in the lower 250 m instead of the usual 500 m instrument string.

Mooring work was accompanied by more than 200 Conductivity/ Temperature/ Depth/ profiles (CTD) including a high-resolution section across the Orkney Passage. As SHACKLETON is not a research vessel, the CTD system had to remain on deck throughout the cruise, unprotected from the weather. This resulted in large offsets in measured salinity. These will require additional effort to correct, using salinities derived from water samples collected during the cast. Thus, the data are not yet available. Analysis of the first 8 years of the Weddell time series has been prepared for presentation at international meetings and publication. In January 2009 two abstracts were written, and in March 2009 accepted, for presentation at the MOCA09 meeting in Montreal CA.

Gordon and Huber “Seasonal and interannual fluctuations of Weddell Sea Bottom Water outflow” report: An 8 year record (April 1999 to February 2007) of the currents and T/S stratification within the lower ~500 m of the water column, within the outflow of dense Weddell Sea Bottom Water south of the South Orkney Islands, reveals strong T/S seasonal and interannual variability. A cold bottom water pulse is evident in the May-July period, though the precise timing and duration varies with year. Intensification of the near bottom stratification is observed as the bottom water attains its coldest values. The coldest bottom events occurred in 1999 and 2002, while in 2000 it was absent, with slow warming since 2002. (Figures 2).

At bottom temperatures <-0.8°C the salinity variability makes for a ‘fan-like’ appearance in T/S space suggesting a varied source of dense shelf water, with the coldest bottom water associated with the saltiest water, indicating a southwest Weddell Sea origin (Figure 3). In consideration of the isobath following distance from likely source to the mooring array, at typical bottom speed of 10-15 cm/sec, we determine that the export of the dense shelf water occurs during the austral summer (as also observed in the Ross Sea). Relationship of the behavior of the shelf water export to the strength of the Weddell Gyre and to SAM is proposed.

The second MOCA09 abstract by Darren McKee, an undergraduate student at Columbia University working with Yuan, Gordon and Huber at Lamont, explores the relationship of the Weddell time series interannual variability to larger scale climate fluctuations. For presentation at MOCA09 entitled “Climate Forcing of Interannual Variability of Weddell Sea Bottom Water“, they report: A time series of bottom water potential temperature at mooring M3 (4565 m depth) south of the South Orkney Islands extends April 1999 through January 2007. Temperature demonstrates seasonal variability, however, there is an anomalously cold pulse in 2002 with no cold event in 2000. It is our goal to understand this interannual variability. Correlations of the time series with NINO3.4 and SAM index peak with indices leading by 14-20 months. Using NCEP-NCAR reanalysis data, maps of correlations of leading sea level pressure anomalies with temperature
anomalies at M3 are strongly indicative of the spatial patterns of coupled ENSO and SAM impacts, including the summer to fall southeast movement of the pressure center above the Bellingshausen Sea. Due to a strong correlation between ENSO and SAM reinforcing each other's effects in the late 1990's, we conduct multivariate EOF analyses of surface forcing including sea level pressure, surface air temperature, surface winds, and sea ice concentration to capture coherent climate variability. In each case the first mode represents characteristic traits of coupled ENSO and SAM, and is separated nicely from other modes in terms of power, reflecting its unique physical relevance. Its principle component correlates significantly with the time series at a broad 14 month lead, implying a likely relationship between water mass and large scale climate. Physical processes linking climate modes (ENSO and SAM) to water export are investigated.

Further research in May and June 2009 reveal that the interannual variability of the cold pulses of water observed in the Weddell time series may be related to sea ice production rates, which are likely associated with dense shelf water production in the southwest Weddell Sea.

**Highlights**

- The export of dense shelf water from the southwestern Weddell Sea varies seasonally and exhibits interannual fluctuations.
- A cold bottom water pulse is evident in the May-July period. The coldest bottom events occurred in 1999 and 2002, while in 2000 it was absent, with slow warming since 2002.
- Southern Annular Mode [SAM] index leads the bottom water temperature features by 14-20 months. The relationship of the export of Weddell Sea Bottom Water to climate [SAM] variability is likely linked to combination production and escape rates of dense shelf water over the multiyear residence time of the shelf water.

**Societal Benefits**

To detect changes in southern ocean overturning associated with climate change. The extended time series will contribute to an understanding the processes that control the transport and characteristics of the bottom waters that emanate from the Weddell Sea, as required to better assess the reaction of the Southern Ocean meridional overturning circulation and associated deep ocean ventilation to a warming climate.

**Other Research Connections**

Collaborators: We have an ongoing cooperative agreement with the British Antarctic Survey to maintain the South Orkney Plateau moorings, plus an additional array of moorings across the Orkney Passage to the east to more comprehensively monitor the outflow of deep and bottom water from the western Weddell.

**Education & Outreach**

Data are archived and made available as they are recovered from the moorings at the project web site: [http://www.ldeo.columbia.edu/res/div/ocp/projects/corc.shtml](http://www.ldeo.columbia.edu/res/div/ocp/projects/corc.shtml)
Personnel
Research Scientists: 2, Research Support Staff: 1, Undergraduate Students: 1.

Publications
Conference proceedings
Gordon et al Fall AGU 2008 presentation; Gordon et al and McKee et al Abstract
accepted for MOCA09 Montreal CA meeting

Figure 1. Weddell mooring locations, and schematic of deep and bottom water flow from source regions to
the mooring array.
Figure 2. Time series of potential temperature, 1999 to 2009, from moorings M2/M4 (top) and M3 (bottom). Data from M4 is used to span the gap in the M2 data between 2005 and 2007. M3 was not recovered in 2009.
Figure 3. Potential Temperature-Salinity data from M2 and M3, color coded for current speed at the bottom. The coldest bottom water is associated with the saltiest water, indicating a southwest Weddell Sea origin. Using an average speed of 10 cm/s implies bottom water escape from the continent shelf of the southwest Weddell in October.
Research Goals

The sea-air net flux of CO₂ is governed by the difference between pCO₂ in surface ocean water and the overlying atmosphere as well as by the gas transfer rate across the sea-air interface. The seawater pCO₂ depends primarily on the processes occurring within the sea (such as seawater temperature, biological productivity and upwelling of deep waters), whereas the gas transfer rate is regulated mainly by atmospheric processes including turbulence of the interface induced by winds. The primary objective of this proposed investigation is to determine the space-time distribution of the ocean surface pCO₂ and the sea-air pCO₂ difference. Combining the sea-air pCO₂ difference with the CO₂ gas transfer coefficient which is being investigated by other scientific groups, a reliable net sea-air flux of CO₂ over regional to global scales can be estimated using improved sea-air pCO₂ difference data.

Education Goals

The global database for surface water pCO₂ assembled by this program has been made available to the public through the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN, and is being studied in collaboration with researchers and graduate students at a number of national and international institutions.

Research Progress

The Lamont group is primarily responsible for the acquisition of the surface water pCO₂ data aboard the RVIB Palmer, which serves mostly in the Southern Ocean, one of the least accessible areas due to extreme environments. The research activities of M/V Oleander and R/V Atlantic Explorer (N. Bates) are supported by the NOAA with a subcontract of this LDEO grant to the Bermuda Institute of Ocean Studies (BIOS). To date, we processed the data obtained by the following field programs and added them to the VOS global database; 1) the R/V Laurence M. Gould, which is supported by NSF as a part of the Long-Term Research in Environmental Biology (LTRE) program in the Drake Passage area, Southern Ocean (C. Sweeney and T. Takahashi); 2) the NOAA’s Ronald Brown program, mostly in the Atlantic Ocean (R. Wanninkhof); 3) the “Explorer of the Seas” program in and around the Caribbean Sea (R. Wanninkhof); 4) the
Kaimimoana program in the equatorial Pacific (R. A. Feely); 5) Columbus Waikato (R. Wanninkhof); and 6) M/V Oleander and R/V Atlantic Explorer (N. Bates, BIOS). Other contributors for the VOS database include researchers from U. K., Japan, Iceland, Norway, France, Australia and Germany. The surface water pCO2 database thus assembled now consists of about 4.5 million pCO2 observations (an increase of about 1 million during this grant period) and supplemental data since 1970’s, and is the most extensive database for world ocean surface water pCO2. The updated VOS database (Version 2007) is available to the public through the CDIAC and at the web site of the LDEO CO2 group <www.ldeo.columbia.edu/res/pi/CO2>.

**Highlights**

An analysis of the (~66,000) surface water pCO2 observations obtained during winter months in the 20 year period, 1986-2007, over the subpolar Southern Ocean (45°S-55°S) indicates that the seawater pCO2 increased at a mean rate of 2.1 ± 0.6 uatm/yr, which is faster than the atmospheric increase of 1.5 uatm/yr. This suggests that the sea-air pCO2 differences decreased, and hence the Southern Ocean CO2 sink flux has weakened due likely to increased upwelling of deep waters that have higher pCO2. Our observations are consistent with the results of the model study by LeQuere et al. (2007).


**Societal Benefits**

Accurate future projection of atmospheric CO2 is needed for the global management of this most important greenhouse gas. Timely information on the rate of CO2 emissions and on changes in the ocean and land CO2 sink intensity is essential for formulating a sound energy policy. The results of this investigation are used to validate various global carbon cycle models, which are used to provide reliable future projection of the atmospheric CO2 concentrations to the policy makers.

**Other Research Connections**

Taro Takahashi has collaborated with a large number of national and international carbon cycle researchers. His research collaborators include observational researchers as well as a wide range of ocean and atmospheric modelers in U. S., European and Asian communities.

**Awards & Honors**

The April 2009 issue of the Deep-Sea Research –II was dedicated to Taro Takahashi for recognition of his pioneering ocean carbon cycle research.

**Interagency**

Since 2007, he advised climate research activities in the U. S. agencies as a regular member of the Climate Research Committee, the National Research Council of the U. S. National Academy of Sciences.
**Education & Outreach**

A large global database for surface water pCO₂, which has been assembled by this program, was made available to the public through the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN, and is being used by researchers and graduate students at a number of national and international institutions.

**Personnel**

Research Scientists: 1, Visiting Scientists: 1, Research Support Staff: 3.

**Publications**

**Journal articles**


**Reports**


Figure 1. The rates of increase in the surface water pCO₂ during the three winter months over the subpolar Southern Ocean, 45°S–55°S. The data for three of the six zonal SST bands around Antarctica are shown. A) 0.8°C < SST < 1.50°C; B) 1.50°C < SST < 2.50°C; C) 4.50°C < SST < 5.50°C. The mean rate of increase for all six zones studied is 2.1 ± 0.6 uatm/yr. (Takahashi et al., 2009, DSR-II). This suggests that the rate of deep water upwelling has been increasing and the CO₂ sink intensity has been decreasing.
PR-Challenge Annual Report 2009

The first partial year of the PR-Challenge was primarily used to explore and develop hardware and software options for data preparation, dissemination to the participants and subsequent retrieval of the reconstruction that make up the full chain of PR-Challenge steps. To support this effort, we hired Laura Landrum (PhD) at 0.5 FTE in January 2009. Her expertise is oceanography and ocean chemistry, but over the past years she has worked extensively in GIS-based data preparation and distribution to various user groups of the US Department of Agriculture's Agricultural Research Service.

Overview: Development of integrated framework for Challenge
1- Workflow development - tight integration with NOAA World Data Center
2- Evaluation of software infrastructure and evaluation of hardware logistics
3- PR-Challenge start at PAGES Open Science Meeting

1- Workflow development

The sequence of steps of the various aspects of the PR-Challenge Workflow is under development. The initial setup was designed in a general fashion to provide overview of the full suite of issues. In this process, we have started to tightly coordinate with the NOAA-World Data Center for Paleoclimatology (Dr. David Anderson and his staff). The motivation for doing so is obvious as the PR-Challenge provides a testbed for reconstruction efforts in real world settings for which the Data Center is the premier data-clearing house. However, the NOAA World Data Center has set ambitious goals for improvements of its data delivery process as well as clear intentions to move towards a reconstruction interface. Because this new development is done initially with high-resolution data for the last 1000 years, this provides an outstanding opportunity to merge certain aspects of our efforts and to closely coordinate. We are exploring the option of using ARC-GIS Server as a frontend interface to visualize the selection, provide direct access to the underlying data together with very simple analysis options. This interface
does not take all the work off scientist’s shoulders, but does simplify data access and to dramatically improve their ability to assess the quality of that data.

We have started extensive discussions between at the science as well as software level. Figure 1 provides an overview of the top level structure. Parallel "streams" are displayed for the “real world paleo proxy” case (left), the PR-Challenge special case with pre-set reconstruction exercises (middle, here called "Model-based experiments"), and finally there is a stream envisioned that is more targeted towards the broader public and education applications (right) that can easily be derived from the other two.

**Figure 1**: Overview of a 1-2000 Year Web-Interface at the NOAA World Data Center for Paleoclimatology. Left column: Real world application, middle column: PR-Challenge type application, right column: educational opportunity to introduce data, reconstruction concepts and reconstruction results to a broad audience.

### 1.1 Data

The first top-level component of the Challenge is to identify proxy networks, extract relevant data from coupled climate models, and then transform the "perfect" model data into pseudo-proxies. Such pseudo-proxy files (one for each exercise), together with a corresponding instrumental quality dataset spanning only 150 years of data, are then made available to the reconstruction community. There are a number of steps that require careful consideration, but primarily we are looking at two challenges:
an advanced way to provide data and openly stimulate careful evaluation of the proxies
provide realistic process models for development of useful pseudo-proxies

We have primarily focused on the first element of these challenges as part of the overall workflow development. Simple noise-adding processes can subsequently be replaced by a call for a process model without changing the overall workflow. Goal of year 2 is to come up with the suite of process models. In our effort to stimulate advancement in how users are receiving data, we are again coordinating very closely with NOAA because the solution should be interchangeable. Details are under development with support of NOAA software engineers. Figure 2 illustrates how a network can be selected by the user. The left column is shown as a hybrid here, top rows are PR-Challenge exercise examples, the lower rows are real world networks as the NOAA World Data Center will provide. The bottom section will provide some meta information about the selected network, and the main window illustrates the spatial distribution of samples and their proxy type.

Figure 2: Illustration of selected network in a visual way. The front end of this interface could be ARC-GIS Server that provides all tools to zoom and select, interface proxy-layer with other spatial information (elevation, climatic zones, instrumental data, etc.)
A key step in using proxy data is that individual time series don't disappear in a matrix or a file but that researchers are explicitly aware of what they are using. The GIS-interface under development here will not only allows anybody to access the meta information of the network (where locations are and what type of proxy is there), but it offers an elegant way of directly accessing the data in a visual sense. Additionally, the maps are freely zoomable, and other data layers can be shown at the same time. E.g., users can put up an elevation map, “instrumental” data, etc. Figure 3 shows the potential of an individual "proxy evaluation" procedure that pulls out the mouse-selected proxy series from the database (real world NOAA application) or the pre-designed proxy network (PR-Challenge).

**Figure 3:** A crucial step in proxy-data evaluation is the comparison against instrumental data. If data is hidden in a matrix or file, a direct comparison with observed climate data is a step that often gets forgotten. The GIS interface would make this immediately possible.

Simple diagnostics will provide a quick-look of the record, and offer a comparison with a selected instrumental data point (e.g. gridded CRU or model instrumental temperature time series in the same grid box respectively). This simple procedure upfront illustrates when proxy records have good or no correlation or relationship with a particular instrumental field. Simple statistics are presented. In the end, this is only an evaluation step and it is up to the scientist to decide what proxy records should be included in the final proxy network. But this simple step should provide a simple yet elegant way to
demonstrate the proxy information and make it accessible to others. We envision that this "evaluation" step at the same time provides in much greater detail information about the chosen network.

1.2 Reconstruction

The reconstruction step in the PR-Challenge is quasi "outsourced", i.e. it is up to the reconstruction community to perform these steps. In passing, we would like to note here that a goal for NOAA is to eventually provide some tools that could be chosen by users that would perform the reconstruction step on the fly. For example the Wahl and Ammann / Ammann and Wahl (2007) code and exercises can be made directly available. As the PR-Challenge progresses, we will encourage all participants to eventually provide their code so that at the NOAA web site there could be a full workflow, currently termed within NOAA as "One-Stop" option.

![Model-based Experiments](image)

**Figure 4:** Uploaded reconstructions need to be verified for correct formats. Additionally, some information about validation/verification will be required as this is one of the key goals of the PR-Challenge to test the accuracy of such estimates.

At the challenge level, there is then the step of users uploading their data. Figure 4 illustrates the rates visualization capability of the GIS front end Server. Immediately, the user can verify if the upload was successful (correct data, format, etc). Important meta
data is captured, and a small suite of validation information is requested. Note, it is one goal of the PR-Challenge to test how well "validation/verification" procedures actually work. There are a host of different approaches, but in the real world we don't quite know how well the work.

Some issues about the upload procedure need to be worked out due to security issues. But a couple of options appear possible. We hope to resolve this soon.

1.3 Diagnostic

Finally, the reconstructions, at least for the Open PR-Challenge, can then be compared with the true underlying climate model fields. A small set of simple diagnostics is being designed and in preparation. This is going to be written in NCL, the powerful NCAR command language that will treat the data in the background and then provide the result to the GIS Server.

![Model-based Experiments](image)

**Figure 5:** Simple diagnostics package offering comparison with target data from full model output.

Two types of short diagnostics are under consideration, one dealing with spatial maps based on time slices, the other option deals with time series (xy-graphs). The small set of diagnostics will be expanded depending on user demand. Figure 5 only shows the map-type. Further development of these will come with user input.
2- Evaluation of software infrastructure and evaluation of hardware logistics

So far we have identified an elegant way using ARC-GIS Server as the front end. Detailed discussions are ongoing with NOAA and NCAR (Laura as the GIS specialists as well as members of the GIS group at NCAR). The current goal is to have a demonstration ready at the PAGES Open Science Meeting in July in Corvallis.

A second option is under consideration for the PR-Challenge to get underway more quickly. This option is under discussion with Don Middleton and the NCAR Earth System Grid (ESG). Although this might not be based on a GIS frontend interface because the new generation of ESG provides an alternative way of interacting with the user, all the background scripts and procedures would remain identical. The ESG solution has both full NCL capabilities in the background, and, most importantly, it is designed to work with large data volumes (for CMIP!). This solution might be the most efficient because it offers a simple upload capability. Going online with the new ESG system is planned for July 1.

Since these decisions are underway right now, it is simply important to stress that whatever the final choice for the PR-Challenge, the parallel "stream" with NOAA remains. The tight coordination is going to be very useful for both sides. Should the NCAR solution be chosen, then we could envision an extended "educational stream" at NOAA where simple Challenge exercises would be made available, rather than the full complexity of PR-Challenge exercises. One benefit of such a solution would be that there is somewhat less time pressure on NOAA to have the infrastructure ready, and second, users would get less confused with real world and model world data, which should never be mixed.

3- PR-Challenge start at PAGES Open Science Meeting

The developments of infrastructure and software make use set for a PR-Challenge start at the PAGES Open Science Meeting in Corvallis. Both from the PR-Challenge as well as from the NOAA side we will make demonstrations to the users. At that time, with web-sites up, we will also release general announcements as indicated in the proposal with targeted audiences in the paleoclimate, climate reconstruction, climate dynamics and modeling as well as statistical communities. We will solicit input from the communities about standard protocol and diagnostic options.

Subsequently to the start with first exercises ready (first examples are resolution of network and various noise colors in the pseudo-proxy data), we will hold a workshop to evaluate what advanced process models could be used and designed for use in the PR-Challenge. This is an ongoing effort of us to stimulate the community to describe and test process-based proxy models. We have organized an AGU session at the Fall meeting of 2008:

Session announcement:
Reconstructions of past climates rely on proxy data that to first order exhibit relatively simple dependencies on specific climate variables. However, as we interpret more subtle details of these datasets on timescales for which their calibration is not directly established, multivariate and frequency dependencies may become important to constrain the significant systematic uncertainties in the representation of climate by a single proxy archive. One approach to identifying possible interpretational biases is to advance our process understanding of how proxies are formed. Modeling the proxies themselves may have the advantages of reliance on physical, biological and/or chemical first principles and more stable statistical behavior. The results may form the basis for more stable formulations of the inverse problem of reconstructing climate fields from proxy observations.

The goal of this session is to provide an overview of the state of the art of such techniques and models, compare the uncertainties between proxy archives, and to discuss the challenges they present for local/regional climate reconstructions as well as large scale climate field reconstructions. Contributions from all high-resolution (seasonal to millennial) proxy archives are encouraged. Additionally, studies illuminating differences between process and regression-based and pseudo-proxy reconstructions, which serve to illustrate potential biases under perfectly known conditions are welcome.
In Prep: Workshop "Process Modeling, Regional Downscaling and Multiproxy Synthesis"

Support: PAGES/CLIVAR Workshop 2009
Location: San Francisco, Fall AGU Meeting

Date: December 2009

Targeted products:
- White paper on "Quantitative assessment of regional and large-scale climate: Missing corner stones and future directions".

Draft Agenda

Day 1: Session 1: Introduction / Overview
- Top-Down: key of telescoping from large scale to small scale impact in understanding
- Bottom-Up: small scale to be embedded in large scale context and its dynamical framework
- Some introduction to hydrologic modeling
- Downscaling techniques
- Proxies as relevant information on Impact

Day 1: Session 2: Process Models
- Tree-ring records
- Stable isotopes
- Pseudo-proxies: Conceptual and Model limitations: how realistic can one get? Toning down expectations... change in how we look at and take proxies: tree-ring and fire
- Downscaling options

Day 2: Session 3: Synthesis based on forward models + downscaling
- Use of regional multiproxy and Earth System concept
- Replication of series
- What happened, when: Where can we answer this? "Regional Syntheses"
- Target of opportunity: multi-proxy cross-validation, quantitative
- Local ground-truthing

Day 2: Session 4: Future directions?
- How realistic can one get with model-based reconstruction tests?
- How to use real world information to test / assess model performance?
- How to use climate models to test proxy fidelity?
Research Goals

The primary goal for this project is to determine the variability in wind-driven upwelling in the Southern Ocean during the Holocene. This project builds on our NOAA-ARCHES work in which changes in upwelling in the Southern Ocean were assessed using an opal flux proxy for upwelling. Results of that work indicate that a reorganization of global wind systems is the primary mechanism linking manifestations of past abrupt climate changes found at many locations worldwide, and we seek to establish whether or not the Southern Ocean has experienced significant variability in wind-driven upwelling during the Holocene period.

Research Progress

Progress on processing samples during the past year was limited because Patricia Malone, who is responsible for most of our initial sample processing, was out on medical leave for 4 months.

Also, during the past year we were informed that NOAA will no longer fund paleoceanographic work after the current two-year period is complete. Therefore, we intend to make use of our remaining resources to produce results with the greatest possible scientific impact. Although we intend to complete a Holocene study of upwelling in the Southern Ocean, we also intend to test the hypothesis that the primary site of deepwater formation during the peak of the last glacial period was located in the Ross Sea. Deepwater formation, and its link to the ocean’s overturning, represents a fundamental component of Earth’s climate system. There has long been speculation about the location and mechanism of deepwater formation under glacial boundary conditions. If the hypothesis is correct, then the near-exclusive formation of deep water in the Ross Sea would represent a mode of ocean overturning circulation heretofore not envisioned, and certainly not depicted in any climate models. If new evidence supports this hypothesis, then it would represent a unique new data set that will be of great value in improving climate models.
Highlights
None to report yet.

Societal Benefits
This work contributes to our understanding of the ocean’s role in abrupt climate change, and of the specific processes involved in past abrupt climate changes. This knowledge is vital to the development and testing of models that can be used to make meaningful predictions about whether or not increasing concentrations of anthropogenic greenhouse gases might induce abrupt climate changes in the future.

Other Research Connections
None to report yet.

Awards & Honors
None to report yet.

Interagency
None to report yet.

Education & Outreach
None to report yet.

Personnel
Research Scientists: 1, Research Support Staff: 2.

Publications
Journal articles
None to report yet.
Research Goals

Our group plans to extend its study of closed basin lakes to those in Mongolia and in northwestern China and also to those in Central America’s zone of maximum E - P. We have added Israel’s Adi Torfstein to our group. He will expand the Middle East record for Israel’s Dead Sea to the north in Turkey and to the south in Negev. For lakes whose records lie buried below their present surface, we plan to exploit the $^{18}$O record contained in their sediments. However, the proper interpretation of these records is complex. It requires at a minimum an independent knowledge of the history of the $^{18}$O to $^{16}$O ratio in precipitation falling in their drainage basins. We will obtain this from $^{18}$O/$^{16}$O measurement on stalagmites in nearby caves. We are currently conducting a test of this approach in the US Great Basin by comparing $^{18}$O records in a Lake Bonneville sediment core with that from stalagmites in Lehmann Caverns (at the base of Mt. Wheeler near the Nevada – Utah state line).

Research Progress

Together with Larry Edwards at the University of Minnesota and Jay Quade at the University of Arizona, I have been compiling information regarding past fluctuations in the size of the world’s closed basin lakes in order to determine how the hydrologic state of their drainage basins has changed over the last 30 kyr (i.e. from the peak of the last glacial period through the deglaciation into the present interglaciation). These changes were driven by a combination of changes in summer insolation, global temperature and interhemispheric temperature difference. Our goal is to evaluate the Held and Soden hypothesis that global warming will intensify the focus of rainfall on the tropics resulting in an increased aridity in the earth’s drylands. So far we have shown that the drylands at 35° to 40° in both hemispheres had considerably higher rainfall during the peak cold of glacial time and that the tropics were less wet. However the situation for the 20° to 25° belts where E – P peaks is not clear. The reason is that in the northern hemisphere these regions experienced maximum wetness during the early Holocene period of maximum summer insolation (i.e. strong monsoons) obscuring the record for earlier times.
Research Goals

The primary goal of the Abrupt Climate Change In A Warming World (ACCWW) project I am engaged in is to develop a drought atlas from long tree-ring chronologies for Europe, North Africa, and the Middle East. The development of this ‘Old World Drought Atlas’ (OWDA) will complement the existing ‘North American Drought Atlas’ (NADA) and the ‘Monsoon Asia Drought Atlas’ (MADA) nearly completed now as part of a National Science Foundation project on “Tree-Ring Reconstructions of Asian Monsoon Climate Dynamics”. By developing the OWDA, we will greatly expand the coverage of gridded drought reconstructions across the Northern Hemisphere to allow for more complete synoptic-scale comparisons of hydroclimatic variability at annual-to-centennial time scales. The OWDA will prove an invaluable tool for assessing the nature and causes of climate variability and change over the last several centuries to millennium. In combination with the NADA and the MADA, it will provide near hemispheric annual reconstructions of drought severity. Currently, it is hard to assess causes of the decade to centennial changes seen in the NADA because much of North America is sensitive to both Pacific and Atlantic SST variations. By examining hemispheric patterns, and bringing in regions where the Pacific and Atlantic influences are stronger or weaker, we stand a much better chance of being able to assess how terrestrial hydroclimate change over decades and centuries links in to ocean variations. Furthermore, the OWDA, in combination with the NADA and MADA will provide invaluable information for model simulations of the climate of the last millennium whether coupled or forced by proxy-reconstructed SSTs.

Education Goals

There are no explicit education goals in this project, but the OWDA will be put online in the public domain for anyone, including students, to use. I also anticipate that Richard Seager will enlist some graduate students to use the OWDA as part of their graduate research activities, similar to the way in which Celine Herweijer analyzed the NADA as the basis for much of her PhD dissertation research conducted under Seager’s supervision and my unofficial guidance.
Research Progress

The OWDA will occupy a crucial region of the Northern Hemisphere for synoptic scale drought studies (see Figure 1). The OWDA will be created on a 0.5° grid of instrumental PDSI data that is being created at no cost to this project by Dr. Gerard van der Schrier at the Royal Netherlands Meteorological Institute (KNMI). The biggest task at hand now is developing the necessary tree-ring network for reconstruction of drought over the OWDA domain. This task has been initiated through a small workshop at the University of East Anglia Climatic Research Unit (CRU) held on June 9-10, 2009. Dr. Keith Briffa at CRU was the local organizer and host. Dr. Briffa has access to a large quantity of tree-ring data from Europe and is also keen to work on the development of the OWDA with us. In addition, we invited a few other important tree-ring scientists to the workshop who have access to or are developing tree-ring chronologies over the OWDA domain.

Figure 1. A map of relevant NH land areas that shows how the OWDA will fit in with the existing NADA and soon to be completed MADA. The spatial domain of the OWDA is highlighted in blue.

To date we have gotten a great deal of support for our OWDA project from colleagues we have contacted, with commitments from them to contribute tree-ring data to it. They include:

• Dr. Keith R. Briffa, Climatic Research Unit, University of East Anglia, UK
• Dr. Rob Wilson, University of Saint Andrews, Scotland
• Dr. Hakan Grudd, University of Stockholm, Sweden
• Drs. Jan Esper and Dave Frank from WSL in Birmensdorf, Switzerland
• Dr. Filipe Campelo, Department of Botany, Coimbra University, Portugal
• Dr. Marco Carrer, Treeline Ecology Research Unit, Università di Padova, Italy
• Dr. Carlo Urbinati, Forest Ecology and Management, Università Politecnica delle Marche, Italy
• Dr. Nesibe Kose, Faculty of Forestry, Istanbul University, Turkey
• Dr. Ramzi Touchan, Laboratory of Tree-Ring Research, University of Arizona, USA
• Dr. Sturt Manning, Malcolm and Carolyn Wiener Laboratory for Aegean and Near Eastern Dendrochronology, Cornell University, USA

This list is very likely to expand considerably. There are many more individuals and
groups we plan to contact for participation in the OWDA project and contributions of tree-ring data to it. Even at this early stage, we still have reasonably good coverage of tree-ring sites (Figure 2). Some are publically available from the International Tree-Ring Data Bank (ITRDB), while others must be obtained through personal contacts.

**Figure 2.** Map of the OWDA domain with locations of currently available tree-ring chronologies. The sources of data are the ITRDB and those committed to our project by other scientists who have agreed to collaborate and contribute their data (OTHER).

The potential for reconstructing drought over the Old World from tree rings is clear. However, the tree-ring chronologies that we will use for the OWDA will all have to be recreated from their raw measurements to guarantee that they are estimated in the best way possible to preserve low-frequency variance due to climate. This is due to important recent advances in the methods used to develop tree-ring chronologies for the reconstructions of past climate. The processing of the chronologies will require revisiting all of the primary ring-width measurement series and applying the newest state-of-the-art “signal free” methods of tree-ring standardization (detrending) developed by Dr. Briffa and his former PhD student Dr. Tom Melvin to preserve as much low-frequency information as possible in the chronologies. This of course is critical if we wish to determine the degree to which megadroughts (droughts of exceptional duration) have occurred in the past over Europe, North Africa, and the Middle East, as they have occurred over North America. E.R. Cook has committed four months time to work off-campus at the Climatic Research Unit with Briffa and Melvin to accelerate the acquisition and processing of the tree-ring data for this OWDA project.
During the time leading up to this progress report, I have also been working on incorporating ways of estimating uncertainty in the drought reconstructions that are not tied to the biased calibration period statistics. The procedure I will use is based on the bootstrap. It will assume a random (versus fixed) model formulation in its resampling scheme to allow for as much uncertainty as possible to be incorporated into the estimates. The bootstrap is also relatively easy to employ and also relatively fast given the thousands of 0.5° grid points of PDSI that will be reconstructed. The bootstrap uncertainties will vary over time depending on the properties of the tree-ring predictors and will cover the full lengths of the reconstructions.

**Highlights**
- The first OWDA Workshop held at the Climatic Research Unit, University of East Anglia on June 9-10, 2009.
- The commitment of many tree-ring scientists doing work in the ‘Old World’ to commit their tree-ring data for use in the OWDA.
- Plans developed for E.R. Cook to work off-campus at the Climatic Research Unit with Keith Briffa and Tom Melvin for 4 months in 2010 to accelerate the acquisition and processing of the tree-ring data for use in the OWDA.

**Societal Benefits**

The OWDA will prove an invaluable tool for assessing the nature and causes of climate variability and change over the last several centuries. For example, the changes in temperature in Europe from the Medieval period to the Little Ice Age and the modern period are reasonably well established, not least from mountain glacier records. However the hydroclimate signature of the Medieval and Little Ice Age periods is not well known. Given the close association between temperature and precipitation within modes of climate variability and change, the addition of tree-ring based hydroclimate reconstructions will be a major advance in our ability to determine the nature and causes of the impressive climate changes of the last millennium within the Old World. Further, in combination with the NADA and MADA, the OWDA will provide near hemispheric annual reconstructions of drought severity for more precisely modeling the causes of drought. Doing so will be a great benefit because it will hopefully lead to improved ways of forecasting future droughts in a changing world.

**Other Research Connections**

Formal collaborations for conducting the OWDA project have been established with Keith Briffa and others at the Climatic Research Unit, University of East Anglia, Gerard van der Schrier at the Royal Netherlands Meteorological Institute, and Hakan Grudde at the Bert Bolin Centre for Climate Research, Stockholm University. Other formal collaborative linkages will be established in the future as this project progresses (see the list of colleagues and contributors above).

**Awards & Honors**

None at this time.
Interagency
None at this time.

Education & Outreach
None at this time, but a great deal of education and outreach is anticipated in the future.

Personnel
Research Scientists: 1, Research Support Staff: 1.

Publications

Journal articles

Reports
Research Goals

The year 1 results were very encouraging and so we plan to continue this work into Year 2 with a detailed AMS radiocarbon stratigraphy for core GC-13 from the NW Atlantic and additional cores off Greenland and new sediment cores from the NW African margin. The goal will be to develop detailed, multidecadal-resolution records of SST variability spanning two periods from 0-1500 years BP and 2500-3000 years BP. The reason for these two windows is that the 14C production peaks, that indicate changes in solar irradiance, have the largest amplitudes in these windows and thus provide the best opportunity to extract SST sensitivity to solar forcing.

We will wash and pick approximately 250 samples to generate high resolution SST and Mg/Ca records, and for the core sites that look most promising we’ll conduct detailed AMS 14C stratigraphies.

Research Progress

During Year 1, I hired Dr. Caroline Cleroux as a post-doc to work part-time on this project, and part-time on another funded project. She is a specialist in Holocene climate variability, deep-sea sediment core, and Mg/Ca and stable isotopic analyses. Under the current NOAA proposal, she is funded 3 months per year for two years.

Over the first year of this project we completed detailed oxygen isotopic and Mg/Ca ratio analyses of planktonic foraminifera at two core sites between 0-3000 years BP, one from the Laurentian Slope (GC-13) and another off the Carolina Margin (Site 1055). Both of these cores have very high Holocene accumulation rates (40 cm/ka) and so the 2cm sampling interval was equivalent to about 50 years. Preliminary AMS radiocarbon chronologies indicated that both cores have bomb 14C coretops and thus were suitable for the more detailed AMS 14C analyses of this project. The oxygen isotopic and Mg/Ca analyses indicated that the Little Ice Age section of the cores exhibited an anti-phase relation, with the northern Laurentian slope site indicating cooler conditions (1-2°C) and the southern Carolina Margin Site 1055 indicating warmer conditions, suggestive of an NAO-like spatial pattern.
At Site 1055 we conducted detailed AMS 14C analyses on every 2-cm sample between 0-60 cm, or the last 150 years BP. These analyses were conducted in collaboration with Scott Lehman at Univ. Colorado, Boulder and John Southon at Univ. California, Irvine. Impressively, the downcore 14C analyses reveal the expected radiocarbon plateaux evident in the atmospheric tree-ring 14C record. The presence of these plateaux allowed the development of a calendric age scale for the Site 1055 core and it’s d18O stratigraphy. These results unequivocally illustrate that conditions at Site 1055 were warmer during the LIA and during the associated minima in solar irradiance at this time.

**Personnel**

Research Scientists: 1, Post Doctoral Fellows: 1, Undergraduate Students: 1.
Research Goals

The research goals were to establish detailed maps of the Holocene moraine sequences of selected glaciers in the Southern Alps of New Zealand. These maps are being used as the basic documents on which to plot accurate and precise exposure dates derived from surface boulders embedded in the moraine crests. The dating is being carried out at Lamont-Doherty’s Exposure Dating Laboratory under the leadership of Dr. Joerg Schaefer. The immediate objective is to develop detailed geomorphic maps and robust chronologies for Holocene climate oscillations centered on 45°S. The longer-term objective is to determine the north-south phasing of Holocene climate events by comparison to the data from Northern Hemisphere records. Therefore mapping and dating was also initiated on the Holocene moraine sequences in the high Wind River Range of Wyoming. A rigorous assessment of the results regarding the inter-hemispheric pattern of climate change should reveal the underlying driving mechanisms. This project is being carried out jointly with Dr. Joerg Schaefer of Lamont-Doherty Earth Observatory of Columbia University. He will submit a separate report under his grant number.

Education Goals

The education goals are to train a new generation of graduate students in the techniques of mapping moraines and producing 10Be exposure ages from surface boulders on these moraines. To accomplish these goals, two University of Maine students carried out the fieldwork in the Southern Alps of New Zealand and, on their return, began processing the samples at Lamont-Doherty under the supervision of Dr. Joerg Schaefer. Three graduate students carried out fieldwork on Holocene moraines in the Wind River Range of Wyoming in July of 2009.

Research Progress

Fieldwork in the Southern Alps of New Zealand was carried out with helicopter support in January and February of 2009. The fieldwork was carried out jointly by personnel from the University of Maine (including two graduate students) and from GNS-Science (the Crown Institute for Geological and Nuclear Studies) in Dunedin, New Zealand.
Zealand. The moraines fronting the Siebald, Mt. Lucia (Leibig Range), and Cameron Glacier (Arrowsmith Range) were mapped in the field. These maps are now being digitized at the GNS laboratory in Dunedin in preparation for publication. An extensive suite of samples for 10Be dating were collected from each complex of Holocene moraines. These samples were shipped back to Lamont-Doherty for processing in the Exposure Dating Laboratory under the supervision of Dr. Joerg Schaefer. A paper published in SCIENCE in May of 2009 showed that the classic millennial-scale oscillations of climate recorded by Northern Hemisphere glaciers is not present in the Southern Alps at middle latitudes of the Southern Hemispheres. This is an important constraint for any model of the drivers of global Holocene changes. Figure 1 given below shows the 10Be chronology of the moraine system of the Mueller Glacier, one of the systems forming the basis of the SCIENCE paper. This chronology is of greater accuracy and precision than any so far published in any other mountain region. Figure 2 given below presents a map and chronology of the Holocene moraine system of the Cameron Glacier in the Arrowsmith Range of the Southern Alps. The important result is that the glacier extent shown by the moraines gets progressively smaller during the course of the Holocene. The implication is that summer climate has warmed during the Holocene, and is now at its warmest in the past 11,500 years. This appears to be the opposite of what happened in the Northern Hemisphere, where the maximum glacier extent was achieved at the height of the Little Ice Age about 150 years ago, implying that Holocene summer climate was then at its coldest.

For comparison with the results from New Zealand at about 43oS, we carried out similar fieldwork on Holocene moraines in the high Wind Rivers of Wyoming at about 43oN. This fieldwork was carried out with three graduate students in July of 2009. The samples have been delivered to Lamont and will be processed there in the coming year. The results will test the emerging idea that summer temperatures in the Southern Hemisphere increased during the course of the Holocene, whereas those in the Northern Hemisphere declined.

**Highlights**

SCIENCE paper published in May of 2009; results showed that the classic Holocene millennial-scale climate oscillations of the Northern Hemisphere were not present in the Southern Alps of New Zealand in middle latitudes of the Southern Hemisphere. Models to explain Holocene climate will have to accommodate this important discovery.

New 10Be chronology of the Cameron Glacier moraine system in the Southern Alps reveals that the glacier extent has decreased steadily throughout the Holocene, implying an increase in summer temperature that has reached its warmest value within the past 20 years

**Other Research Connections**

This project is carried out in cooperation with GNS-Science (Crown Institute of Geological and Nuclear Sciences of the New Zealand Government). Personnel from GNS-Science participate in the fieldwork and digitize the moraine maps. Moreover, this...
project is a collaborative effort between the University of Maine and Lamont-Doherty Earth Observatory of Columbia University.

**Education & Outreach**

- G.H. Denton is the research advisor and mentor for graduate students Aaron Putnam and Kathyrn Ladig
- G.H. Denton presented papers at the Annual Conference of the Comer Science and Education Foundation in Soldiers Grove, Wisconsin in September 2008; at the Past Climates Meeting of INTIMATE at Te Papa in Wellington, N.Z. in May of 2009; and at the AACWW Annual meeting at Lamont-Doherty in July of 2009.
- G.H. Denton presented a public lecture at Victoria University of Wellington, New Zealand on Abrupt Climate Change in February of 2009. He also gave the ST Lee lecture on Antarctic Studies at Te Papa in Wellington, N.Z. in May of 2009.
- Graduate student Aaron Putnam gave papers at the Comer Foundation Annual Meeting in September 2008 and at the Past Climates meeting at Te Papa in Wellington, N.Z. in May of 2009.

**Personnel**

Research Scientists: 2, Graduate Students: 2.

**Publications**

**Journal articles**

Figure 1. Glacial geomorphic map of the Mueller and Hooker Glacier Holocene moraine systems, Mount Cook/Aoraki National Park, Southern Alps, New Zealand. Purple features are moraine ridges and yellow shading depicts Holocene alluvium and glaciofluvial outwash terraces. Dark purple represents moraine and moraine ridges deposited during historical time. Glacial ice is represented by crosshatched blue pattern. $^{10}$Be surface-exposure ages are given in white boxes, and sample locations are marked by yellow dots.
Figure 2. Glacial geomorphic map of the Cameron River valley Holocene moraines, Arrowsmith Range, Southern Alps, New Zealand. Geomorphic features are detailed as in Figure 1, and additional geomorphic features are described in inset figure legend. Bold line outlines the AD1863 position of the Cameron Glacier terminus. $^{10}$Be ages are in white boxes, and yellow dots mark sample locations.
Research Goals

This project falls within the Modern Observation component of ACCWW. It includes the themes: Trends of ocean properties and Choke Points and the Meridional overturning circulation.

Research questions that were developed in ACCWW year 1 include:

• How is the Pacific SSS responding to Atlantic subtropical SSS increase and water vapor flux across Central America? [the Pacific SSS seems to be getting fresher];
• Are we seeing a change in the subducted North Atlantic subtropical water [that induces the ~150 m salinity maximum] that can be related to the SSS trends? [‘Yes’];
• Does the North Atlantic subtropical SSS increase negate to some level the SSS decrease in the northern North Atlantic as driven by excess precipitation, and hence have relevance to the AMOC? [I think ‘Yes’].

Research Progress

Progress in ACCWW year 1 was made in two specific research topics: The Weddell Sea time series [directly related to the ocean meridional overturning circulation issue]; Sea surface salinity [SSS] trends in the subtropical North Atlantic [a topic within Trends of ocean properties].

1. The Weddell Sea time series:

The bulk of Antarctic Bottom Water [AABW] is derived from the continental margins of the Weddell Sea. Since April 1999 the AABW outflow from the Weddell Sea has been recorded with NOAA funding. Since 2008 the observational program funding was shifted over to NOAA/OCO, with the data analysis continuing within ACCWW. The following is the abstract of a presentation to be made at the MOCA-09 [IAMAS-IAPSO-IACS 2009 Joint Assembly] meeting in Montreal in July 2009 based on the ACCWW supported data analysis:
Arnold L. Gordon, Bruce Huber. “Seasonal and interannual fluctuations of Weddell Sea Bottom Water outflow” An 8 year record (April 1999 to February 2007) of the currents and T/S stratification within the lower ~500 m of the water column, within the outflow of dense Weddell Sea Bottom Water south of the South Orkney Islands, reveals strong T/S seasonal and interannual variability. A cold bottom water pulse is evident in the May-July period, though the precise timing and duration varies with year. Intensification of the near bottom stratification is observed as the bottom water attains its coldest values. The coldest bottom events occurred in 1999 and 2002, while in 2000 it was absent, with slow warming since 2002. At bottom temperatures <-0.8°C the salinity variability makes for a ‘fan-like’ appearance in T/S space suggesting a varied source of dense shelf water, with the coldest bottom water associated with the saltiest water, indicating a southwest Weddell Sea origin. In consideration of the isobath following distance from likely source to the mooring array, at typical bottom speed of 10-15 cm/sec, we determine that the export of the dense shelf water occurs during the austral summer (as also observed in the Ross Sea). Relationship of the behavior of the shelf water export to the strength of the Weddell Gyre and to SAM is proposed. The existing Weddell Sea Bottom Water outflow mooring array continues to extend this important time series that detects changes in the Southern Ocean MOC.

We also made advances in the investigation of the relationship of the Weddell Sea AABW outflow to large scale climate indices: ENSO and SAM. This work is being developed with Darren McKee an undergraduate student at Columbia University and Xiaojun Yuan a researcher at Lamont. We find that the bottom water temperature flowing away from the Weddell Sea correlations with NINO3.4 and SAM, with these indices leading the bottom temperature by ~14 months, implying a likely relationship between the AABW formation and surface forcing associated with major climate indices.


The spatial pattern of SSS (Fig. 1) reflects the climate belts associated with the general atmospheric circulation. Comparison of SSS to the net sea-air freshwater fluxes reveals remarkably similar patterns (Fig 1a, 1b). The great subtropical deserts at the poleward edges of the atmosphere’s Hadley Cells are apparent over the ocean as a SSS maximum in the 15° to 30° latitude band. Tropical rain lowers the SSS along the Intertropical Convergence Zone. From mid-latitudes to the Polar Regions, excess precipitation lowers SSS. The marine hydrological cycle varies in longitude too. Net evaporation leads to a relatively salty Atlantic; net input of freshwater generates low salinity characteristic of the Pacific Ocean. Moisture flux from the Atlantic to the Pacific Ocean across the Central American isthmus is an important component of the hydrological cycle, helping set the salinity contrast between the two oceans.

Gordon and Giulivi (2008, funded with ACCWW) discuss the time series of SSS obtained at BATS near Bermuda in the context of the North Atlantic and North Pacific subtropical SSS. Both ENSO and PDO affect the SSS at BATS. The ENSO and PDO influences appear to be linked: the projection of El Niño into the subtropical North Atlantic is much more robust when PDO shifts to a positive phase in 1976. They show
that this is also the situation with precipitations along the US Gulf coast states. The cause for this apparent (atmospheric) telecommunication of the Pacific climate into the subtropical North Atlantic requires further consideration.

During the ACCWW year 1 the trends of SSS of the North Atlantic subtropical have been investigated.

The SSS anomaly (anomaly within 2 by 2 lat/long boxes from the long term mean within that box) within the North Atlantic subtropical regime reveals a long-term trend of increasing values from the 1950s into the 1990s (Fig. 2). This trend is interrupted by brief periods of reduced SSS of the mid-1970s and mid-1980s. Since 2004, another period of lower SSS is observed (also see Gordon and Giulivi, 2008).

The SSS increase in the subtropical North Atlantic may be linked with the water vapor flux that accompanies the westward-directed winds over Central America within the two low altitude conduits (Fig. 3). The southern box displays the largest westward water vapor flux. While there are substantial interannual fluctuations, a long-term trend in the zonal term towards increased Atlantic to Pacific water vapor is suggested (the linear regression for the period 1955-2008 shows an increase rate of 0.88/yr; cc=0.4; p=0.02).

**Highlights**

- Trends of sea surface salinity in the Bermuda region are linked to Pacific climate fluctuations associated with ENSO [wetter during El Niño; drier during La Niña], but this relationship became robust only when the Pacific Decadal Oscillation (PDO) became positive in 1976, the so called climate regime shift.
- The time series recovered to date from the South Orkney moorings display significant seasonal and interannual variability in the outflow of dense Weddell Sea water. An annual pulse of the coldest bottom water at the mooring site is evident in the May-July time frame, which suggests export of shelf water into the deep ocean at the upstream bottom water formation sites in the Dec-Feb period, i.e. austral summer.

**Societal Benefits**

We focus our research in the Southern Hemisphere, the source of the densest of the global water masses, the very cold AABW, and of the relatively low salinity AAIW. Most of the water in the lower two kilometers of the global ocean is derived from AABW, which is formed along the continental margins of Antarctica, notably in the Weddell and Ross Seas. This process represents one of the fundamental processes that overturn or ventilate the deep ocean, affecting the water column mean temperature and the sequestration of carbon within the deep ocean. AAIW is important in closing the freshwater budget of the subtropics by injecting low salinity water into the lower thermocline and forming the base of the thermocline in much of the world ocean.

The Antarctic Circumpolar Current, carrying some 130 Sv eastward (Olbers et al., 2004) serves as the primary deep-water inter-ocean connection. Within the meridional plane, relatively warm, salty circumpolar deep water spreads southward and upward, entering into the ~100 m thick surface layer of near freezing temperature where it can interact.
directly with the polar atmosphere in the Antarctic zone south of the Antarctic Circumpolar Current (Figure 1). Recent estimates of the rate at which surface water is converted to the varied forms of AABW is ~10 Sv. Estimates of the contribution of Antarctic surface water to AAIW is less well defined, but one may assume from continuity that it amounts to the balance of the deep water input to the surface layer, about 10 Sv. The division between that part of the upwelling deep water entering into the bottom water versus that part which enters into the intermediate layer depends on the regional wind and freshwater input.

Complicating the freshwater budget of the Antarctic zone is the contribution of sea ice. With a salinity of about 20-30% that of the sea water from which it forms, sea ice represents a freshwater reservoir. Small amounts of net divergence of sea ice in a season overwhelm the local P-E. This effect has particular importance along the edge of Antarctica. There, as Antarctic continental air descends rapidly over the sloping ice sheet topography and within the confines of coastal valleys, it eventually encounters the ocean. The frigid air creates sea ice, but the associated high wind drives the newly formed ice seaward as fast as it forms, inducing a “coastal polynya”, an expanse of sea water (typically 10-100 km wide) that remains directly exposed to polar air. As sea ice has marked lower salinity than the water from which it forms, this “conveyor-type” process transports freshwater from the polynya region to the (remote) melting region, a process that overwhelms P-E. Zwally et al. (1985) conclude that the continued export of ice from coastal polynyas, “sea ice factories” that produce tens of meters of sea ice thickness per winter, is the primary factor in the production of salty freezing-point shelf water, which eventually leads to AABW.

Another important factor in the salinity budget of the polar ocean is the interaction of the ocean with the glacial ice composing the Antarctic ice shelves. The net effect of ocean-ice interaction is melting of the glacial ice and reduction of salinity, but at generally subsurface levels where the elevated pressure allows subtle thermobaric effects. These effects, combined with the lowering of the seawater freezing point at higher pressure, can lead in places to enhanced continental margin sinking associated with bottom water formation.

Other Research Connections

Collaborators: We have developed a cooperative agreement with the British Antarctic Survey to maintain the South Orkney Plateau moorings, plus an additional array of moorings across the Orkney Passage to the east to more comprehensively monitor the outflow of deep and bottom water from the western Weddell

Personnel

Research Scientists: 1, Research Support Staff: 1, Administrative: 1, Graduate Students: 1.

Journal articles

Figure 1a. Ekman transport vectors in Sverdrups (1 Sv = 10^6 m^3 s^{-1}) and 10 cm contours of mean dynamic topography of the sea surface derived from jointly analyzed data from drifters, satellite altimetry, wind and the GRACE (Gravity Recovery and Climate Experiment Mission) geoid model for the decade 1992-2002. In color, the long-term mean SSS (defined as the upper 20 m salinity average).

Figure 1b. Long-term average (1958-2001) of the vertical integral of the divergence of moisture flux (color; units = kg m^-2 s^{-1} x 1000) computed from monthly ECMWF ERA-40 data. Evaporation -precipitation (contours; units in m yr^{-1}) estimated from ERA-40 monthly surface large scale and convective precipitations and evaporation data.
**Figure 2.** Annual mean SSS (upper 20 m) for the central region of the North Atlantic subtropical gyre and time series of the SSS anomaly. Data extracted from WOAD05 (Boyer et al., 2006). Dark circles represent the yearly average of the data; vertical lines represent one standard deviation. The small gray circles represent the individual yearly values for each box. In green, salinity pentad anomalies for the same region (from Antonov, J. I., R. A. Locarnini, T. P. Boyer, A. V. Mishonov, and H. E. Garcia. 2006. *World Ocean Atlas 2005, Volume 2: Salinity.* S. Levitus, Ed. NOAA Atlas NESDIS 62, U.S. Government Printing Office, Washington, D.C., 182 pp) and its standard deviation, from 1955-59 to 1994-1998, using levels 1 to 3, corresponding to 0 to 20 m.

**Figure 3.** (a) Satellite measurements of surface winds (QuickSCAT 10-m) and sea surface temperature (from a satellite microwave radiometer, TMI) averaged for January 2000. Dark shading over land indicates elevation in excess of 300 m. Strong offshore flow downstream of the gaps in the mountain ranges, with monthly mean wind speeds as high as 10 m s^{-1}, gives rise to local sea surface temperature minima and enhanced chlorophyll concentrations (Fig. from the U.S. Clivar Pan American Research, A Scientific Prospectus and Implementation Pan, January 2001) The 2-boxes indicate the areas where the zonal and meridional water vapor flux components were averaged for the period 1957-2002. (b) Vertical integral of eastward (red) and northward (blue) water vapor flux from ECMWF ERA-40 monthly mean model resolution gridded surface fields. Units = g m^{-1} s^{-1}. Color lines represent the 12-month running mean and the solid black line the annual averages.
Research Goals

During year two, we plan to fully focus our efforts on the goals of reconstructing paleo-hydrological/aridity changes. Hemming has worked on Mono Lake for many years and Goldstein has work on Lisan sediments from the Dead Sea for many years. We are intrigued by the striking similarities in the timing of wet and dry events in these two widely separated regions, and we plan to work together to review the evidence from these two sites in the context of other global records of rainfall/aridity. The chronology at Mono Lake is less well developed so we will be working on that. We will also work toward the goal of characterizing the dust input from Africa into the oceans using sedimentary provenance approaches.

Research Progress

We have continued to pursue our efforts to understand deep ocean circulation changes using Nd isotope compositions. Emerging from this work is further testing of the efficacy of leaching methods (leveraged by NSF OCE and by internal Lamont funds) and further efforts to characterize the Southern Ocean “endmember” in the past. We have also continued to work towards the goal of constraining northern hemisphere ice dynamics in the climate system. We are working towards several goals related to constraining paleo-aridity. We are cooperating with Peter DeMenocal and Jenna Cole to use isotope tracing of dust sources from the Arabian Sea as well as from the west African margin. Cole’s paper on the initial work was recently published in EPSL (from the previous NOAA funding).

Highlights

The dust flux from Africa during the African humid period was very low and had a very different character than in drier times. We have interpreted this as being a newly formed mineral that may have formed during seasonal drying of lakes.

The Agulhas retroflection appears to have been similarly located in the last glacial maximum as today, and thus the changes in Agulhas input into the Atlantic must be related to the vigor of the current rather than the position of the retroflection. This is an
interesting result that needs further study because on the surface of it, it appears to be in
contrast to model predictions.

Societal Benefits
This is important for ground truthing of climate models as well as for helping to
understand the scope of the climate system for rapid and dramatic change.

Education & Outreach
We incorporate the findings of our research in the classroom and we are heavily
involved in undergraduate and graduate student mentoring on topics that are strongly
related to the focus of our research in this program.

Personnel
Research Support Staff: 2, Post Doctoral Fellows: 1, Undergraduate Students: 2.

Publications

Journal articles
2009, Contrasting compositions of Saharan dust in the eastern Atlantic Ocean
during the last deglaciation and African Humid Period, Earth and Planetary
Science Letters, 278, 257-266.

Franzese, A. M., Hemming, S. R., and Goldstein, S. L., in press, Strontium isotopes in
detrital sediments constrain the glacial position of the Agulhas Retroflection,
Paleoceanography.

deposits and the behavior of the Labrador-Québec sector during ice-rafting events
of the last glacial cycle, Quaternary Science Reviews.
Research Goals

The initial objectives of this project were to complete work previously initiated on shelf water properties and their connections to ice shelf melt rates. This has proceeded roughly as planned, although links to satellite work by others have developed more slowly than anticipated. The latter will likely become a focus of the next year’s work, along with analyses of unexpected findings during parallel fieldwork in the Amundsen Sea.

Research Progress

During the foreshortened initial project year we continued work on two manuscripts and a primary ocean data set acquired in the Amundsen and Ross Seas. Key elements of that processed data have now been forwarded to the National Oceanographic Data Center, and made available to collaborators on the specific cruise (NBP07-02). The data have also added to the time series reported in Jacobs & Giulivi 2009, which documented strong salinity declines extending from the IGY to the IPY in and downstream of the Ross Sea. That freshening appears to be linked to change in the large-scale atmospheric circulation and to an accelerating rate of ice shelf melting and glacier advance upstream in the Amundsen Sea. The second paper, by Loose et al., applied multi-parameter analysis to three ocean data sets to infer melting rates of 33-50 km3/yr at the base of the Ross Ice Shelf, consistent with prior estimates. Whether chemical samples still in the processing queue and a higher-resolution sampling pattern can detect melt rate change remains to be determined.

Interagency

The studies noted above and below were jointly supported by NOAA and other agencies.

Personnel

Research Scientists: 1, Research Support Staff: 1
Journal articles


Figure 1. The variability of shelf water temperature and salinity since the IGY in the SW Ross Sea. Temperatures are referenced to the sea surface freezing point, ~1.91°C at a salinity of 34.8. These profiles are located north (solid lines) and west of Ross Island, mostly in a continental shelf depression filled with dense shelf water formed during winter sea ice formation. A long-term drift toward lower salinity (-0.03/decade for >50 years) is responding mainly to larger freshening in lower-salinity surface water transported into the Ross Sea by the Antarctic Coastal Current. From Jacobs, S. & C. Giulivi, 2008: Variability and change in Ross Sea shelf waters. In: Antarctic Climate Change and the Environment, J. Turner et al., (eds), http://www.antarctica.ac.uk/met/SCAR_ssg_ps/ACCE.
Research Goals

The basic goal of this section is to understand in detail the inter-hemispheric pattern (phasing and amplitude) of glacier fluctuations throughout the Holocene period up to present day and, in turn, to add a new perspective towards climate variations during the period of human civilizations. We focus on the synthesis of new results from key moraine sequences in New Zealand and the Swiss Alps with existing data, and the rigorous assessment regarding the inter-hemispheric pattern of climate change and the underlying driving mechanisms. We expect to answer climatic key questions such as (i) was the Little Ice Age global? and (ii) how important is solar forcing for global climate change?

Adjusting to the 2-year time frame of the project, we have selected two moraine sequences for mapping and dating from the Southern Alps in New Zealand (45°S) and the Swiss Alps (46°N), respectively, in order to accomplish the basic goal of north-south phasing of Holocene climate events. It should be noted that the proposed chronological studies in these areas are highly leveraged, as the necessary background geologic investigations in all three areas were funded by the CSEF. What is left to be accomplished is the construction of maps of Holocene moraine systems in each area, the completion of detailed ¹⁰Be surface-exposure chronologies for each mapped moraine system, the synthesis of the results with existing data, and finally the rigorous assessment of the results regarding the inter-hemispheric pattern of climate change and the underlying driving mechanisms. For a detailed list of annual activities, see also the budget justification section. The field areas selected are as follows:

- Southern Alps of New Zealand: Moraine systems of LaPeruse, Cameron, Sibbald, and Leibig Glaciers in New Zealand's Southern Alps. These moraine systems, which are among the best in New Zealand, will test whether we can replicate the pilot results from the ¹⁰Be chronology of moraines in front of Mueller Glacier. The objective is to develop a robust chronology for Holocene climate oscillations centered on 45°S.
- Swiss Alps: The Holocene moraine sequence of the Tsidjiore Nouve Glacier in the Swiss Alps at 46°S. This Holocene moraine system is one of the classics of the Swiss Alps. Our dating work in Switzerland is leveraged by funds from the CSEF, the
Lamont Climate Center, and by cooperation with the research program of Professor Christian Schlüchter of the University of Bern in Switzerland. Our pilot data illustrates the enormous potential of Tsidjiore Nouve Glacier to yield a detailed 10Be chronology for this region of Switzerland, where the northern Little Ice Age and Medieval Warm Period are best defined.

Research Progress

We have mapped selected key moraine sequences in southern (New Zealand) and northern (Swiss Alps) mid-latitudes and have applied new dating techniques (high-precision 10Be surface exposure dating) to produce a record of landice fluctuations unique in depth and breadth. Our inter-hemispheric synthesis resulted in the following key findings: (i) The Little Ice Age/Medieval Warm Period oscillations was not a global signal. Our novel record of high-frequency glacier fluctuations in New Zealand’s Southern Alps points to the importance of regional climate signals driving New Zealand’s glaciers during the Holocene (Schaefer et al., 2009). (ii) Historic Swiss Glacier fluctuations have been closely linked to the Atlantic Multidecadal Oscillation, independently arguing for the importance of SST/airpressure oscillations as regional drivers of Holocene Glacier dynamics (Denton et al., 2008), (iii) Summer duration in the south might be the key driver for southern climate, removing the ‘fly in the ointment of the Milankovitch theory’, how to tie southern climate to northern summer insolation (Huybers et al., 2008).

Personnel

Research Scientists: 1, Research Support Staff: 1.

Publications

Journal articles


Research Goals

The main goals of the original proposal concerning modern circulation was “to utilize the instrumental [modern] observations of the ocean, as well as paleo records for the investigation of climate change across a range of spatial and temporal scales.”

Research Progress

Within this overarching goal we focused our Year 1 activities on goal [A] Trends of ocean properties. Under this objective we investigated the properties of Greenland Sea Deep Water as part of the study of regional fluctuations of temperature and salinity and tracer concentrations and inventories within the ocean water column.

The work built on many years of data collection in the Nordic seas that started in the 1970’s and had its highest density during the 1990’s.

The results of our work show that the Greenland Sea is still in a state of low deep water formation and that the deep circulation scheme has changed considerably. A major follow-on question that emerges from these studies is the link of the changes in the Nordic seas to those in the Arctic and the North Atlantic. These questions will be the focus of our Year 2 work under this project.

The results of the Greenland Sea Work are being summarized as part of a PhD thesis and will be submitted for publication during the coming 6 months.

A second component of our studies was directed towards the processes at the grounding line of the floating Ronne Ice Shelf. We revisited a radiogenic helium signal that we detected a few years ago and we are interpreting it in the context of the cryosphere/ocean interaction (objective [C] of the theme “past and present changes of the ocean circulation and its interaction with the climate system”). The presence of radiogenic helium indicates interaction between the Ronne Ice Shelf and subsurface waters at the grounding line. This could be a very important process for the stability of the Ronne Ice Shelf. We
summarized the results from this study in a manuscript that will be submitted for publication in the coming year.

**Highlights**

- The Greenland Sea is still in a state of low deep water formation and the deep circulation scheme has changed considerably. A major follow-on question emerging from these studies is the link of the changes in the Nordic seas to those in the Arctic and the North Atlantic.

- The presence of radiogenic helium indicates interaction between the Ross Ice Shelf and subsurface waters at the grounding line. This could be a very important process for the stability of the Ronne Ice Shelf.

- The best estimate for the basal melt rate of the Ross Sea Ice Shelf (based on CFC budgets and oxygen and helium isotope measurements) is 33 km$^3$/yr in 1994 and 50 km$^3$/yr in 2000.

**Societal Benefits**

The work conducted as part of this project addresses the issue of how rapidly climate change can affect the natural systems. Such rapid transitions, caused by the non-linear nature of the climate system can pose significant problems to society with respect to its capacity for adaptation on short time scales. Thus, it is of direct societal relevance to document, and ultimately to understand, the nature of rapid climate change, its manifestations, and the time scales on which it occurs.

**Education & Outreach**

The results of the Greenland Sea Work are being summarized as part of a PhD thesis and will be submitted for publication during the coming 6 months (Peter Schlosser, Advisor; Abigail Spieler, Graduate Student).

The work on the interaction between shelf water and glacial ice sheets are part of the PhD thesis of Brice Loose (Advisor: P. Schlosser).

**Personnel**

Research Scientists: 2, Administrative: 1, Graduate Students: 1.

**Publications**

**Journal articles**

A manuscript discussing the Ross Ice Shelf work is in preparation, we plan for submission in the coming year. The work on the interaction between glacial ice and shelf water is in press in JGR Oceans:

Ph.D. dissertations
The results of the Greenland Sea Work are being summarized as part of a PhD thesis (Abigail Spieler) and will be submitted for publication during the coming year.
Research Goals

Acquire WOCE and CLIVAR hydrographic and CFC data along repeat lines to identify the most recently formed deep water components and to determine if the temperature, salinity, and oxygen concentration of these most recently formed components have changed over the past couple of decades. These data will also be used to calculate tracer inventories and deep water mass formation rates.

Education Goals

Provide research opportunities for undergraduate and graduate students in the fields of chemical and physical oceanography.

Research Progress

The funding for this project was delayed until early 2009, so we have just begun work. We have acquired much of the WOCE and CLIVAR hydrographic and CFC data from the Atlantic and Pacific oceans that will be needed for calculation of CFC inventories and comparison of repeat lines for changes in deep water properties. We have continued to examine the temporal variability (seasonal and interannual) of CFCs in conjunction with temperature and salinity in Denmark Strait Overflow Water in Denmark Strait to better establish the boundary condition for CFC input into the deep North Atlantic Ocean by this water mass. We have completed our study of glacial melt from the Ross Ice Shelf based on optimal multi-parameter analysis of helium isotopes, neon, oxygen, oxygen isotopes, temperature and salinity, and water residence times beneath the ice shelf based on CFC measurements, from cruises to the Ross Sea in 1994 and 2000. This work was begun and supported primarily with funding from ARCHES: Tracer Observations of Deep Formations. It is in press (Loose et al., 2009). The basal melt rate was calculated to be 33 km$^3$/yr in 1994 and 50 km$^3$/yr in 2000.

We will continue to acquire high quality CFC data sets collected from various regions of the world ocean. Subsets of these data will be used to determine CFC inventories for North Atlantic Deep Water for the 2003-2005 time period, which in turn will be used to calculate its rate of formation. The CFC inventory method yields an integrated formation...
rate over the time interval between observations. The NADW formation rate based on the 2003-2005 data will be compared to CFC inventory based rates we calculated for 1990 and 1997 to investigate variability in the deep Atlantic limb of the MOC. In addition, these data will be used for comparing WOCE and CLIVAR repeat lines to document water mass property changes in the most recently ventilated deep water, which will be identified using CFC data. We have also begun a project to investigate saturation of CFCs in the surface ocean as a function of time and location and will use the upper ocean data from these stations for this. This is important to establish the concentration boundary condition for uptake of CFCs by the ocean, which is used in OGCMs and in calculating the fossil fuel CO2 uptake by the ocean.

**Highlights**

The best estimate for the basal melt rate of the Ross Sea Ice Shelf (based on CFC budgets and oxygen and helium isotope measurements) is 33 km$^3$/yr in 1994 and 50 km$^3$/yr in 2000.

**Societal Benefits**

This research focuses on understanding the transformation of surface water into subsurface water masses, particularly at high latitudes, which drives the global thermohaline meridional overturning circulation. This is an important component of the earth’s climate system both in heat transport and in the exchange of carbon dioxide and other gases between the atmosphere and the deep ocean. A better knowledge of this process is crucial for understanding and predicting the earth’s climate and thus for making decisions on how to address problems caused by the increase in greenhouse gases.

**Personnel**

Research Scientists: 1, Research Support Staff: 2, Administrative: 1, Undergraduate Students: 1.

**Publications**

**Journal articles**

Theme III: Applications Research

Individual And Collaborative PI Research Projects
CICAR Award # NA03OAR4320179
   No active projects

CICAR Continuation Award #NA08OAR4320754
   1. McGillis, W., *SOLAS Summer School*

CICAR Shadow Award #NA08OAR4320912
   Abrupt Climate Change in a Warming World (ACCWW)
   2. Schlosser, P., *Earth Institute Climate Center*

These research projects, which are reported under Theme II, have as their secondary definition Theme III:
   5. Schlosser, P., ACCWW: *Infrastructure*
Research Goals

The 10 participants from the United States joined more than 40 other students from 19 other nations and met at Institut d'Études Scientifiques de Cargèse in Corsica. One of the purposes of the session was to introduce graduate students and young researchers to different components of SOLAS. The interdisciplinary nature of the SOLAS summer school offered a wide range of educational opportunities. It also provided an opportunity for young researchers, who are interested in SOLAS science to meet one another and the lecturers. The success of the school is also due to the efforts of the organizer, Corinne LeQuéré of the Max-Planck Institut für Biogeochemie, in Jena, Germany, and her committee.

Participants met at the Institut d'Études Scientifiques de Cargèse near the Mediterranean Sea. The course had a theoretical framework and used practical exercises and laboratory experiments to create an intense learning environment. Lectures in early morning and late afternoon alternated with practical lessons and student presentations. Lecture topics focused on broad overviews of the large-scale processes that control the distribution of the compounds relevant to climate in the surface ocean and lower atmosphere. Specifically, there were lectures on the global carbon cycle, biogeochemical modeling, gas exchange, physical and biogeochemical processes in the coastal zone, data assimilation, marine ecology, and atmospheric chemistry.

Workshops gave students exposure to research activities that take place in different settings, such as laboratory experiments, computer modeling, and meteorological observations. Some workshop facilitators also gave instruction on how to give talks and present posters. Small groups went on three-hour research cruises near Cargèse, aboard the French research ship N/O Thetys II. These cruises included CTD casts, net tows, and species enumeration using on-board microscopes.

Students also were shown state-of-the-art flux measurement and air-sea surface process systems, used in studies of heat, momentum, and gas exchange.
In the second week, students gave oral presentations before all of the participants. Many students were able to incorporate techniques that they learned during the previous week’s workshops to give an articulate and concise overview of his or her work and present a poster based on research that they had performed previously.

**Education Goals**

The SOLAS School includes advanced theoretical lectures as well as practical workshops. This combination is meant to give students experience with laboratory work, field measurements and computer models while ensuring that they know and understand the underlying mechanisms. Nine days of theoretical lectures (Days 1-4 and 8-12) are planned along with three days of practical workshops (Days 4-7). To integrate the theoretical and practical concepts, the student will be asked to choose a research project which will be presented at the end of the program. Following are details of theoretical lecture content, practical workshops, and research projects.

Formal lectures will cover specialized topics in marine biogeochemistry, gas exchange, atmospheric trace gas and particle transformations, and climate as well as interdisciplinary topics. Whereas the first week will introduce more general concepts, each day of the second week will focus on a specialized topic.

Day 1 will begin with introductory lectures reviewing (1) the context in which the school is held and the interactions between the different fields, (2) a changing earth system and the role of greenhouse gases, (3) a necessary background in oceanography and atmospheric sciences, and (4) the global carbon cycle. After these two days, we expect that the students will have formed a solid base on which we can build more specialized concepts. We will have a presentation and discussion on the historical and social context of SOLAS research.

Day 2 will focus on gas exchange processes including large-scale determination of gas exchange coefficients and micrometeorology; the green house effect and climate change, and surface ocean biogeochemical cycles.

Day 3 will introduce specialized concepts in marine ecology and provide the students with the theoretical knowledge necessary for the practical workshops. We will focus first on the environmental factors controlling the production of organic matter in the ocean, phytoplankton and its grazing by zooplankton, and remineralization. Then we will lecture on the ecology and bio-diversity of the sea, including the chemical fluxes associated with different species. We will explain how biological processes can be represented in numerical models, and how satellites and data assimilation can be used to quantify the different fluxes of gases at the air-sea interface.

Day 4 to Day 6 is devoted to practical workshops (see description below).

Day 8 will focus on the large-scale cycles of nutrients which are the basis of marine productivity. The cycles of nitrogen, phosphorus, iron and silicate will be presented and their residence time, continental sources and sinks will be explained.
Day 9 will focus on atmospheric processes such as the formation and transport of dust and marine particles and gas phase reactions, the various chemical reactions that occur at the sea surface, and the turnover time of chemicals in the atmosphere.

Day 10 will focus on integrative research in the complex area of marine particles and the cycle of sulfur and its potential impact on DMS and atmospheric chemistry.

Day 11 will focus on gas exchange processes including large-scale determination of gas exchange coefficients and micrometeorology. Day 12 will also focus on measurements that allow us to quantify processes relevant to SOLAS. These techniques include satellite remote sensing and ocean time series.

The practical workshops will be held intensively during 3 consecutive days (from Day 4 through Day 6). The students will be split in groups of 12 to be rotated every half day between workshops. The workshops will include a research cruise of half a day in the vicinity of the bay of Cargèse, laboratory experiments, computer modeling exercises, communication skills, and a visit to a meteorological station in Corsica.

The research cruise will focus on giving the students hands-on experience on the complexities and problems associated with measurements at sea. The measurements to be performed will include the standard temperature-salinity-depth profiles and meteorological measurements, as well as more complex techniques such as plankton netting, water sampling from a rosette and gas mass balancing.

Laboratory experiments will show how information can be retrieved from water and air samples. Dissolved oxygen and chlorophyll A will be measured from water samples collected from the rosette casts. If possible, zooplankton samples will be examined to identify major species components.

Computer modeling exercises and numerical models will provide experience in solving complex processes. Exercises will be presented on biological modeling and data assimilation, gas exchange, atmospheric dust transport and analysis of remote sensing data.

The surface ocean physical measurement laboratory will provide a location for in situ demonstrations of turbulent kinetic energy measurements, surface waves, and stratification. These exercises will help elucidate some of the surface ocean and lower atmospheric controls on air-water momentum, heat, and gas exchange.

Much of the advancement of science depends on the ability of today's scientists to present their results. A series of practical workshops on communication will be done. This will include aspects of reading, writing and presenting a scientific paper.

A visit to a meteorological station in Corsica is planned to give students the opportunity to see how radiation, precipitation, wind and cloud cover data are measured and
transmitted to the global earth-observing network. In addition, measurements of optical properties of the air will be demonstrated.

Throughout the program, students will be asked to develop their own research projects around SOLAS topics. An example topic would be: seasonal and short-term variability of chlorophyll a concentration in the northwest Mediterranean sea offshore Corsica. Based on monthly ocean color SeaWiFS images and high resolution satellite images recorded prior to the summer school time period, the student may try to explain the change in surface chlorophyll in the Cargèse area. The students may use observations collected during the field workshop and modeling exercises to support the conclusions and to quantify the potential impact on the air-sea transfer of CO₂, H₂O, and DMS.

**Research Progress**

**Details of the Curriculum**

The study of surface ocean-lower atmospheric processes requires a thorough knowledge of the state and variability of (1) marine biogeochemistry, (2) air-water gas exchange rates, (3) atmospheric trace gases and particles, and (4) climate. In the past, these fields of research have mostly progressed in parallel and the state of the art in each of these fields is separately reviewed. The challenge of SOLAS and the value of the SOLAS Summer School is to bring scientists from these different backgrounds together to work collaboratively.

Marine biogeochemistry consists of the state of ocean physics, chemistry, and marine biology that determines the oceanic conditions triggering a transfer of gas or particles to and from the atmosphere. Marine biological productivity occurs at the ocean surface, but as organisms die and sink to the deep ocean, trace elements are transported away and become isolated from the atmosphere (this mechanism is known as the "biological pump"). Biological productivity is sustained by the input of nutrients from the atmosphere, rivers and continental margins, and the deep ocean. Whereas nitrate and phosphate are the most common limiting nutrients, recent experiments have demonstrated that iron may also limit biological productivity over large regions of the ocean (Martin et al., 1994; Coale et al., 1996; Boyd et al., 2000). These studies highlight the role of different phytoplankton groups in the efficiency of the biological pump. Efforts are underway to characterize specific properties of the main phytoplankton groups (see for example the iron addition experiments). Biological processes determine the concentration of atmospheric CO₂ on time scales of a few thousand years, while contributing to regional patterns of air-sea CO₂ fluxes on shorter time scales. Biological processes also affect the sulfur cycle. Process studies have established a general link between phytoplankton and dimethylsulphide (DMS) levels, although the exact mechanisms responsible for DMS production are not fully understood. DMS is a direct feedback on climate through its radiative forcing, and an indirect feedback because it is a source of cloud condensation nuclei, and thus can change cloud properties.

The physics of gas exchange governs the transfer of greenhouse gases at the air-sea interface. Gas exchange rates have either been extrapolated from laboratory measurements or measured in the field. Laboratory measurements have proven useful in
elucidating the fundamental physicochemical mechanics of gas exchange. For example, studies in wind tunnels defining the impact of synthetic and natural surfactants on wave slope and gas exchange rates have provided insights into underlying processes. However, some field measurements using the dual tracer technique seem to contradict these findings (for example, Nightingale et al., 2000) and more fieldwork is clearly needed. At higher wind speeds the challenge of making useful measurements of near-surface and interfacial processes increases. Acoustical methods have proven helpful in the study of wave breaking and in delineating bubble distributions. The size distribution depends on the prior life history of the bubbles, from their formation in breaking waves, through turbulent mixing, advection and loss by buoyancy and dissolution. Measurements of bubble sizes in the context of these processes provide a sensitive diagnostic basis for exploring the detailed physics of the upper ocean boundary layer.

In the atmosphere, sea-salt particles are a major reactive medium and precursors for volatile reactive halogens as well as a significant source of atmospheric alkalinity and organic material. The production of several classes of compounds as well as the chemical processing and deposition of important sulphur and nitrogen species are directly tied to sea-salt cycling. Sea salt is also an important source of condensation nuclei and thus can change cloud properties including the radiation effects of clouds. In some regions, reactive halogen compounds (Cl, Br, and I) play major roles in the photochemical processing of air in the marine boundary layer. Currently organo-halogen gases contribute about 25% of the equivalent chlorine to the stratosphere and contribute significantly to the loss of stratospheric O$_3$ (Solomon, 1999). Halogens change greenhouse forcing both directly (through the IR absorption of ozone) and indirectly via the change in the tropospheric oxidation capacity, which controls the lifetimes and atmospheric abundances of greenhouse gases such as CH$_4$ and H-CFCs. The ocean is also a source of biogenic volatile organic compounds and of a myriad of heavier organic compounds, many of biological origin, which may affect air-sea gas exchange rates.

The most recent scientific assessment of climate stated that the increase in greenhouse gases and aerosol concentrations likely caused most of the observed warming of the 20th century (IPCC-2001). Changes in the climate system have also been observed in the global water cycle, cloud cover, and the extent and thickness of sea ice, with potential impact on wind patterns and ocean circulation. Better quantification of the physics of climate can account for most of these changes. In particular, in recent years the radiative forcing of greenhouse gases and cloud-albedo feedback were better quantified. As a consequence of human activities the role of air-sea gas and particle exchange must be put in a global context. Ocean-atmospheric coupling has already made measurable impacts on several aspects of the global climate system. By bringing scientists from different backgrounds together, we plan to teach young scientists the current state-of-the-art research techniques in these different fields. We also hope to find innovative ways to understand and quantify the impact of climate change on air-sea processes and to quantify the magnitude of potential feedbacks on climate and weather.
Highlights
• Training the next generation of climate scientists.
• Successfully collaborating on international environmental and climate science.

Societal Benefits
This project is viewed as having very high relevance to societal benefits – it teaches young scientists on climate studies related to society, exposes them to international communities, and the school discusses human dimensions of research.

Personnel
10 Graduate Students Participated from the USA out of 72.

2007 SOLAS Summer School Participants.
### 2007 SOLAS Summer School Participants

<table>
<thead>
<tr>
<th>Participants</th>
<th>Students from the United States</th>
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<tbody>
<tr>
<td>Laura Acuna</td>
<td><strong>Presentations winner voted for by the students</strong></td>
</tr>
<tr>
<td>Paola Almeida-Guerra</td>
<td><strong>Presentations winner voted for by the lecturers</strong></td>
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<tr>
<td>Andrew Barton*</td>
<td><strong>Poster winner voted for by the lecturers</strong></td>
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<tr>
<td>Mahdia Belounis</td>
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<td>Naiara Berrojalbiz</td>
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<td>Laura Bianucci</td>
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<td>Zhimian Cao</td>
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<td>Amandine Caruana**</td>
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<td>Cecile Cathalot</td>
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<td>Baoshan Chen</td>
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<td>Antonio Cuevas</td>
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<td>Maeva Doron**</td>
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<td>Lauren Elmegreen</td>
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<td>Kathryn Fagan***</td>
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<td>Sheryl Oliveira Fernandes</td>
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<td>Ana Fernandez</td>
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<td>Hector Garcia Nava</td>
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<td>Mirjam Sophia Glessmer</td>
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<td>Maija Heller</td>
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<td>Sofia Hjalmarsson</td>
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<td>Keiji Horikawa</td>
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<td>Kirsten Isensee</td>
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<td>Elizabeth Jones*</td>
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<td>Marie-Pauke Jouandet</td>
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<td>Warren Joubert***</td>
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<td>Sohiko Kameyama</td>
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<td>Kelly Kearney</td>
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<td>Marielle Lacombe</td>
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<td>Aranzazu Lana**</td>
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<td>Rajdeep Roy</td>
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<td>Lauren Zamora</td>
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<td>Kuanbo Zhou</td>
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* Presentation winner voted for by the students
** Presentation winner voted for by the lecturers
*** Poster winner voted for by the lecturers
Research Goals

Per request of the principal investigators of the *Abrupt Climate in a Warming World* (ACCWW) project, the Columbia Climate Center solicited proposals to meet the goal of linking the physical science in ACCWW with decision makers and the general public. It was recognized that social scientists must be engaged to make that connection in a more meaningful way. Two projects were chosen: *Impacts of a Changing Climate on Water Allocation Rules in the SW United States* (Heikkila, Schlager and Siegfried) and *Bridging Social and Physical Sciences, Outreach and Communication* (Carr and Marx). These projects were chosen in January of 2009, thus the period of performance has been shorter than other parts of the ACCWW project.

The goal of *Impacts of a Changing Climate on Water Allocation Rules in the SW United States* is to understand the interaction between climate information and interstate water allocation rules and how water laws and institutions might cope under different climate change scenarios. There are three project components: 1) a survey of water managers in the Southwest to identify how climate information is used and shared, 2) an analysis of policy changes in southwestern states to better assess how policies change and respond to drought conditions, 3) a model of the performance of interstate water allocation rules under different scenarios of climate change and water allocation.

The goal of *Bridging Social and Physical Sciences, Outreach and Communication* is to enhance the outreach and communication of the research team of the ACCWW project by taking advantage of expertise on how information is understood and how decisions are made.

Education Goals

To train students in scientific research, data analysis, programming and communication skills.

Research Progress

Progress has been made in Year 1 on all three components. The Rio Grande Basin has been chosen as the optimal test case as a study site. Questions for the survey of water
managers in the Upper Rio Grande watershed are being developed using information from a prior governance study (component 1). A database of water laws passed each year since the 1930s throughout the three states in the Rio Grande Basin -- Colorado, New Mexico and Texas -- has just been completed and will be the basis of the analysis of how policymakers have responded to periods of severe or extended drought in the past (component 2). The agent-based model (component 3) is being adapted to the Costilla Creek watershed, an interstate tributary to the Rio Grande.

**Highlights**

None to report to date.

**Societal Benefits**

*Impacts of a Changing Climate on Water Allocation Rules in the SW United States* works directly with policymakers. The analysis of existing laws and policies and the agent-based modeling assess how water managers within different institutions have used climate information in the past and how they can better use climate information in the present and future.

**Bridging Social and Physical Sciences, Outreach and Communication** aims precisely to communicate ACCWW results in a manner that enables informed decisions by stakeholders such as water managers, health care agencies, farmers associations, shipping companies, policy makers, and the general public. Given recent research in economics, psychology, anthropology, and political science on how users and groups of users understand and incorporate climate information in their decision process highlights the need for significant collaboration and partnerships between social and physical scientists. The project thus aims to lay the framework to establish these collaborations across disciplines, to be better informed on how best to communicate results to key decision makers, and to have a roadmap on how to place ACCWW results into the appropriate context to raise awareness and enable informed decisions.

**Education & Outreach**

Year 1 has also seen the design of a dedicated webpage; there have been various blog postings on abrupt climate change in the CCC blog at: [http://blogs.ei.columbia.edu/climate/](http://blogs.ei.columbia.edu/climate/) and ACCWW project team members have been active participants at various CCC events, which always include researchers from broad disciplines and are very well attended.

Two presentations have been made to the entire ACCWW team by Heikkila and Siegfried. Siegfried presented also at the First Annual Meeting of the Abrupt Climate Change in a Warming World, July 8-10, 2009.

**Personnel**

Research Scientists: 4, Administrative: 1, Graduate Students: 2, Undergraduate Students: 1.
Task IV Collaborative Education Programs and Projects

In budget year 2008-2009 funds were unavailable to continue the Institute’s commitment to education through funding for graduate students and CICAR postdoctoral fellowships.
Looking Forward

As the FY09 report year was coming to an end CICAR PIs were busy sketching their plans for new research projects. A major focus of this activity was the preparation of new research proposals to be submitted in response to the FY10 NOAA/CPO RFP. In all we submitted 27 letters of intent to various CPO elements and eventually 20 proposals. The CICAR office along with the LDEO division administrators and the contracts and grants personnel did an outstanding job managing the submission. Most of the Institute’s funding portfolio is supported through competitive grants from CPO thus we are looking forward to attain a high rate of success of these proposals.

Unfortunately, CPO decided to discontinue support for a major CICAR research initiative – the funding of a Center for the study of Abrupt Climate Change in a Warming World (ACCWW). Support will terminate June 30, 2010. The ACCWW project and its predecessor program ARCHES provided an umbrella for collaboration between paleo-and modern climate scientists to build a comprehensive understanding of climate change and variability. These activities have been unique among NOAA-sponsored climate research activities. It will be harder to keep such a comprehensive, broad-scoped research activity within CICAR by replacing it with various individual research projects. The depth and long-term perspective of our research experience tells us that it is essential to fill in the large gaps of our understanding of Late Holocene climate variability in order to provide a sound basis for future projections on decade to century time scales. CICAR can provide the science expertise to improve the coverage in time and space of high-resolution climate proxies and assemble them in a form useful for climate modelers and to bring it to bear on the understanding of the present climate state. In our partnership with NOAA lies the potential to strengthen this work.

We discussed with CPO officers various options for continuing to bring CICAR’s unique research skills to support the NOAA Climate Goal, especially through renewing the interest in the “Climate of the Last Millennium” research project. In this work collaboration with GFDL is important for providing the Earth System modeling tools and for collaborating in their analysis and interpretation. We will continue our discussions on this subject with CPO and GFDL with the goal of arriving at a tangible plan of operation for FY2011 and beyond.

Building on advances in climate science and the increasing societal awareness of the need to prepare for climate change impacts our colleagues at the Columbia Earth Institute in such fields as engineering, public health, ecology, policy, and law have increased their interactions with CICAR. This activity is leading to an increase in formal and informal activities and has found expression in several “Climate Applications Research” proposals submitted to NOAA/CPO FY10 competition. One of which was a RISA proposal for establishing at Columbia a “Consortium for Climate Risk in the Urban Northeast” that entails a broad collaboration with other regional research and education centers, among which is City College of CUNY. This particular collaboration focuses on bringing hydrological science and engineering to bear on critical Northeast societal need and would strengthen the collaboration between CICAR and CREST. CICAR thus continues to act as a Center of Excellence, which provides a broad multi-disciplinary approach to the climate challenge of the present and future in support of the NOAA Climate Goal.
## Appendix

Table 1. Principal Investigators & projects by goal/task/theme  
July 1, 2008 - June 30, 2009

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Project</th>
<th>NOAA Goal</th>
<th>Task</th>
<th>Theme</th>
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<tbody>
<tr>
<td>2. Anderson, Robert</td>
<td><em>Doherty Senior Scholar</em></td>
<td>ARCHES: Paleo Sea-Ice Distributions</td>
<td>2</td>
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<td>4. Bleck, Rainer</td>
<td><em>Senior Research Scientist</em></td>
<td>Thermocline Circulation and SST Variability in the Eastern Tropical Pacific and Atlantic</td>
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<td>5. Broecker, Wallace</td>
<td><em>Newberry Professor</em></td>
<td>ACCWW: Meridional Hydrology Variability and Synthesis of Ocean Circulation</td>
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<td>6. Broecker, Wallace</td>
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<td>ARCHES: Understanding Abrupt Change and the Glacial to Interglacial CO2 Record</td>
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<td>7. Camargo, Suzana</td>
<td><em>Doherty Assoc. Research Scientist</em></td>
<td>Towards a Better Understanding of the Relationship Between Climate Change and Tropical Cyclone</td>
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<td>8. Cane, Mark</td>
<td><em>Vetlesen Professor</em></td>
<td>Generation and Evaluation of Long-Term Retrospective Forecasts with NCAEP Climate Forecast System: Predictability of ENSO and Drought Predictions and Predictability of El Nino Events: Epochs and Biases</td>
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<tr>
<td>9. Cane, Mark</td>
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<td>Predictions and Predictability of El Nino Events: Epochs and Biases</td>
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<td>10. Cook, Edward</td>
<td><em>Doherty Senior Scholar</em></td>
<td>ACCWW: Lessons from Holocene Paleo and Modern Instrumental Records and Model Simulations</td>
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<td>12. D’Arrigo, Rosanne</td>
<td><em>Associate Director – Biology &amp; Paleo Environment</em></td>
<td>Paleoclimate Reconstructions (PR) Challenge: A Community Program to Benchmark Methods Used to Reconstruct the Climate of the Last 1-2,000 Years</td>
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<td>13. deMenocal, Peter</td>
<td>Professor</td>
<td>ACCWW: Holocene Variability of Atlantic Surface Properties and West African Aridity</td>
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<td>14. Denton, George</td>
<td>LDEO Sub-Awardee: Institute for Quaternary &amp; Climate Studies, University of Maine</td>
<td>ACCWW: Lessons From Holocene Paleo and Modern Instrumental Records, and Model Simulations</td>
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<td>15. Denton, George</td>
<td>LDEO Sub-Awardee: Institute for Quaternary &amp; Climate Studies, University of Maine</td>
<td>ARCHES: Mountain Snowlines in the Southern Hemisphere</td>
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<td>16. Goddard, Lisa</td>
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<td>Investigating Some Practical Implications of Uncertainty in Observed SSTs</td>
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<td>17. Gong, Gavin</td>
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<td>The Integrated Role of Snow Orography and Dynamical Waves in Facilitating Western US Land Surface-Climate Linkages</td>
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<td>18. Gordon, Arnold</td>
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<td>19. Gordon, Arnold</td>
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<td>Monitoring the Indonesian Throughflow in Makassar Strait</td>
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<td>Associate Professor</td>
<td>ACCWW: Radiogenic Isotope Tracer Paleo-Proxy Scope</td>
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<td>23. Huang, Huei-Ping</td>
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<td>Tropical Influences on Recent and Historical Droughts over North America Weddell Sea Moorings</td>
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<td>24. Huber, Bruce</td>
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<td>25. Jacobs, Stanley</td>
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<td>26. Kaplan, Alexey</td>
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* Indicates sub-theme
Publications 2008-2009


27. Kelly, M.A., T.V. Lowell, B.L. Hall, J.M. Schaefer, B.M. Geohring, R.B. Alley, and G.H. Denton, 2008: A 10Be chronology of late-glacial and Holocene mountain glaciation in the...


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