CICAR
The Cooperative Institute for Climate Applications and Research
2006 Annual Report to NOAA

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Preface

Document Purpose
The Annual Report for the Cooperative Institute for Climate Applications and Research (CICAR), a Cooperative Institute funded by the National Oceanic and Atmospheric Administration Office of Oceanic and Atmospheric Research (OAR), is a requirement of the OAR Cooperative Institute Program. The CICAR annual report describes all actively funded research projects, education initiatives, and public information and outreach programs conducted under CICAR NOAA grant NA03OAR4320179 for the fiscal year ended June 30, 2006.

Looking forward to FY 07 the CICAR annual report presents a window to future research activity as well as CICAR’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 Strategic 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 OAR JI 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 2006 CICAR Annual Report is a comprehensive written review of all administrative and research activity for the Institute’s third year of operation that began July 1, 2005 and ended June 30, 2006.
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.

CICAR’s research is directly aligned with NOAA’s mission goal to Understand climate variability and change to enhance society’s ability to plan and respond.

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 are 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 at 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:
  - Climate modeling and prediction
  - Modern and Paleoclimate research
  - 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 Climate for Research on Environmental Decisions (CRED) and the Earth Institute Center for Hazard and Risk Assessment (CHRR).

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 Institutes 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 2006 Annual Report summarizes the administrative, educational, and research activities performed during year three of the NOAA cooperative agreement and gives a detailed, project-by-project account including research goals and progress, key achievements, societal benefits, linkages, educational and outreach activities, scientific publications, and participating personnel.

In addition to the Institute’s core administrative budget, CICAR administered twenty-six funded research and education projects between July 1, 2005 and June 30, 2006. Compared to the previous budget year CICAR showed modest growth in Theme I Earth system modeling and Theme III climate variability and change applications research. The majority of NOAA funding for CICAR is directed to the Lamont-Doherty Earth Observatory (LDEO) – the primary Earth science research unit of Columbia University (CU). Lamont’s strengths in modern climate research, particularly oceanography and air-sea interaction, and the Earth’s paleoclimate history, make it a natural partner to NOAA under the agencies mission to “understand climate variability and change…”

CICAR research strategy emphasizes addressing NOAA’s climate goal through collaboration with NOAA partners as well as independent research. 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 the 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 extend to other NOAA offices and laboratories such as the Office of Climate Observations (OCO), the National Climatic Data Center (NCDC), the Earth System Research Laboratory (ESRL), the Atlantic Oceanographic and Meteorological Laboratory (AOML), and the Pacific Marine Environmental Laboratory (PMEL).

2. Research highlights

CICAR research is organized along three themes and in budget year three we identified ten projects under Theme I: Earth system modeling; fourteen projects under Theme II: modern and paleoclimate observations; and two projects under Theme III: climate variability and change applications research. We strive to achieve more balance within these themes as we move into our remaining budget years.

During 2005/06 the Institute hosted two significant events consistent with CICAR research priorities. An open symposium “Climate of the Last Millennium” featured speakers from CICAR, GFDL, the Woods Hole Oceanographic Institute, and the Goddard Institute for Space Studies. An internal Columbia workshop “North American Drought” brought together physical and social science investigators to discuss possible contributions to the national drought information initiative.

Central in CICAR research are the 9 projects conducted under the umbrella of ARCHES (Abrupt Climate Change Studies). Together these projects represent a comprehensive collaborative effort to “describe, understand and assess the likelihood of (future) abrupt changes in the climate system, and to identify the mechanisms involved” (see CORC-ARCHES Homepage). This effort is unique in that it combines paleoclimate research with modern ocean observations and numerical modeling addressing the search for the pattern, cause, and dynamics of abrupt
climate change. Looking mainly to the past and increasingly focusing on the post-glacial world and the late Holocene, ARCHES is now in its synthesis stage and is slated to produce a comprehensive review of past research. During 2005/06 ARCHES paleoclimatologists added new information on the global pattern of past events abrupt change. They identified changes in Southern Ocean ventilation during abrupt Northern Hemisphere cooling (Heinrich) events and evidence for interhemispheric synchronicity in mountain glacier advances during the Holocene. ARCHES oceanographers continued to collect Southern Ocean and data on deep and intermediate water formation around Antarctica and ARCHES climate modelers studied the response of tropical Pacific atmosphere-ocean interactions to small changes in solar irradiance during the Holocene. They found that the tropical Pacific displays enhanced east-west SST gradient (a condition akin to La Niña) with increased insolation and decreased gradient (El Niño-like condition) with weak insolation. They also argued based on observations and models that such SST variability could have affected the circulation over the North Atlantic in a way consistent with previous ARCHES research, which identified variations in southward North Atlantic sea-ice penetration into the North Atlantic synchronous with solar variability. Tropical Pacific response to solar variability was also found consistent with our current understanding of the origin of droughts in the American West and paleoclimatic evidence on the prevalence of such events during the medieval period (a time of relatively high insolation) and the abundance of rainfall during the subsequent Little Ice Age (a time of low insolation).

The collaboration with GFDL under the title “Understanding Climate Change from the Medieval Warm Period to the Greenhouse Future” bridges between the goal of understanding past climate variability and predicting the future. It was established to support research by students, postdocs, and early career scientists working under the joint mentorship of senior investigators from Lamont and GFDL. Research efforts included an array of projects seeking to compare climate variability from the past with that of the present and future using observations and models. This work included inter-model comparisons of the simulation of persistent droughts over North America and over Africa. These studies worked to test the robustness of previous hypotheses regarding the origin of these phenomena and their future in a greenhouse world. Also studied was the simulation of Arctic sea ice reduction in the 21st century in the GFDL and NCAR coupled model with the goal of understanding the similarity and difference between these models.

Most remaining CICAR research is supported under competitive grants from the CPO. These individual PI projects address a broad range of observational and modeling studies. Observational studies here examined the feasibility of using surface ocean salinity to obtain information on the temporal variability of precipitation over the ocean. New instruments to measure surface CO₂ and heat exchange are being developed via collaboration amongst CICAR and investigators from NOAA and NASA and the collection and mapping of global ocean CO₂ exchange over the ocean – crucial information for understanding and monitoring the global carbon cycle – continued. In the 2005/06 budget year CICAR scientists continued their modeling and analysis research to improve the prediction of seasonal-to-interannual climate variability by assessing the influence of data errors on forecast performance and improving intermediate model performance. Several independent investigations addressed regional climate variability and predictability over the Americas and the Atlantic, which together contribute to the overall goal of improving the capability of global climate prediction for the 21st century.

4. Education and outreach

CICAR education and outreach activities are intertwined with our research work as many of the PIs mentor graduate and undergraduate students and 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 CU Department of Earth and Environmental Sciences (DEES), the Department of Earth and Environmental Engineering, the School of International and Public Affairs, and the Department of Environmental Science at Barnard College. 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.

The Institute also conducts education and outreach activities under the administrative budget, continually 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 forefront to all of NOAA supported research on campus as well as a showcase to other NOAA activities, such as weather prediction and ocean exploration.

This year three CICAR projects were specifically funded for the purpose of promoting education and outreach. NOAA directly funded scholarships to select students in the Columbia Masters program in “Climate and Society”, a 12-month program that trains professionals and academics to understand and cope with the impact of climate variability and change on society worldwide. NOAA support for the 2005 International SOLAS Summer School and the LDEO-GFDL collaborative project “Understanding Climate Change from the Medieval Warm Period to the Greenhouse Future” emphasized funding to train junior investigators in either their graduate or postdoctoral research.

5. Synergies

CICAR synergies with other Columbia University units continued to benefit the overall research activity within the Institute. Central activity within year three was the CICAR "North American Drought Workshop" where Columbia University investigators from CICAR, IRI, CIESIN, and CRED met to present their work on the physical and societal aspects of droughts in North America and elsewhere. In the 2006/07-budget year we plan to facilitate periodic meeting of this group of investigators as a background for our participation in the national drought related activities.

As we approach year-four of operation, the CICAR is preparing for the NOAA Cooperative Institute site review scheduled for October 4-5, 2006.
CICAR

Tasks

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 Advisory Committee includes representation from the Institute’s director and deputy director, the administrative staff, and senior scientists representing various Columbia University research divisions and affiliates. Committee meetings are convened at the discretion of the Director and address areas of scientific leadership, research coordination, strategic planning, and priority setting. The group’s collective knowledge is a valuable resource for the Director in his decision-making responsibilities.
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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.
CICAR

Administrative Activities July 1, 2005 – June 30, 2006

Education

Sponsored Interns
Under the Lamont-Doherty Earth Observatory Summer Internship Program for Undergraduates, CICAR sponsored one (1) student intern for summer 2005 and is sponsoring one (1) student intern for the 2006 program. The 2005 internships began on May 31 and ended August 4, 2005. The 2005 intern project abstract appears below and was carried out in conjunction with this report’s Task IV GFDL collaborative project Understanding Climate Change from the Medieval Warm Period to the Greenhouse Future.

Analysis and Modeling of Precipitation Variability in the Middle East / Central Asia
Eric Jacobson, LDEO / CICAR Summer Intern, 2005

Using observational datasets we show that precipitation variability in the Middle East / Central Asia is correlated with both the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), but more heavily with the latter. EOF analysis of precipitation data shows several spatial patterns of rainfall, many of which exhibit an inverse relation between the northern and southern halves of the region under study. Consistent with previous studies on the influence of NAO on this region, portions of surprisingly robust positive correlation was found further south, however, extending farther eastward than commonly acknowledged, showing both high and low frequency coupling between rainfall and sea level pressure over the Atlantic.

This project also focused on assessing the suitability of climate models for studying the atmospheric dynamics behind precipitation variability in the Middle East (specifically, the near CCM3 with prescribed SST). We determined that though neither timing nor positioning was always comparable between droughts simulated in the model and those observed in reality, negative precipitation anomalies in the model could be comparable in structure and intensity to real events. Moreover, NAO is simulated in the models to a high degree of correlation with the real phenomena. Although the relationship between modeled NAO and modeled precipitation data is not yet well explored, hopefully with more analysis the models will provide greatly needed embellishment to the data available for understanding how climate works in the Middle East and Central Asia.

The LDEO Summer Intern Program funded primarily by the National Science Foundation offers the chance to experience scientific research as an undergraduate. The program is open to US citizens or permanent residents who have completed their sophomore or junior year in college with majors in earth science, environmental science, chemistry, biology, physics, mathematics, or engineering. Applicants are asked to demonstrate an interest in conducting research in the Earth or Ocean sciences.
Sponsored Seminars
As part of the LDEO Ocean and Climate Physics Seminar Series scholarly talks are presented to give Lamont scientists an opportunity to learn more about their colleagues’ research and to interact with these visiting scientists in an informal setting. During the academic year 2005/2006 CICAR hosted the following speakers:

- October 28, 2005 – Peter Foukal, Heliophysics, Inc, MA: Solar Irradiance as a Possible Driver of Climate Change
- September 16, 2005 – Sukyoung Lee, Department of Meteorology, Penn State: On the Relationship Between Internal Variability and Climate Predictability

CICAR CREST Initiative
CICAR Director Yochanan Kushnir and Reza Khanbilvardi, Director of the NOAA Cooperative Remote Sensing Science and Technology Center (CREST) at The City University of New York met in January 2006 to discuss possible areas of collaboration:

- Exchange seminars – CICAR scientists visit CREST and CREST scientists visit LDEO to introduce research topics of mutual interest
  - March 23, 2006 - CICAR PI Richard Seager: Hydrological History of the West over the Last Millennium
- Summer intern program – CREST undergraduates participate in a research-oriented enrichment program in climate and ocean related issues
- Joint mentorship of graduate students – define mutually interesting topics from which collaborations can be developed
- Joint research proposals – planned rather than opportunistic
  - CICAR proposal Electronic Climate Textbook (ECT) submitted OESD February 2006 (awaiting acceptance for funding) – CREST Letter of Support and participation as a student test bed for evaluation and enhancement in undergraduate courses at CCNY
Outreach

Web Site
- Web redesign introduced May 2006 CICAR
- Created and maintained by LDEO Web Services and CICAR Administration
- New features and enhancements include:
  - Outreach Section: teacher resources, and kids only
  - Research publications and project summaries
  - Links section enlarged to include science, education, and public interest sites

Promotional Material
- CICAR Poster
  - Content development by CICAR Administration
  - Creative development and editing supervised by Mark Inglis, Creative Director for the Earth Institute at Columbia University, at no cost to CICAR

Lamont-Doherty Earth Observatory Open House
Saturday, October 1, 2005

The theme for LDEO Open House 2005 was Secret Earth and last year’s event attracted thousands of visitors. CICAR hosted an exhibit showcasing NOAA-sponsored science at Lamont and in particular the research on North American droughts done in collaboration with GFDL. Members of the CICAR research community interacted with students, educators, and the general public, discussing important scientific concepts and research achievements in paleoclimate research, ocean observations, and climate modeling. The relevance of CICAR research to climate issues such as Global Warming and Abrupt Climate Change was of particular interest to participants. CICAR administration distributed a variety of educational materials including kid-friendly Checklists designed to stimulate environmental awareness through active participation.

The NOAA Office of Atmospheric Research (OAR) is a strong supporter of CICAR’s outreach efforts. The OAR Cooperative Institute Office through Alice Gottschling contributes a variety of climate-related posters and brochures for Open House that engage the public and foster a greater understanding of NOAA’s message “to better observe and understand the climate system, improve forecasts and allow society to better respond and adapt to climate variability and change”.

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Visitors learn about the NOAA CI program and interact with CICAR PIs and staff.
External Activities

NOAA OAR JI Directors and Administrators Meeting - Silver Spring – April 3-5, 2006
The CICAR director along with both the CICAR grants and program administrators attended this year’s meeting. Program elements of particular interest included the NOAA OAR Assistant Administrator Richard W. Spinrad address to the CI Directors and the Administrators Best Practices session led by John Cortinas.

Hosted Activities

Advisory Committee Meetings
November 9, 2005 agenda items:
- NOAA 2006 site review requirements
  - NOAA Policy on Cooperative Institutes NOAA AO 216-107DOC NOAA OAR Joint Institute Review Format
  - Used SAB published CI Review Team Executive Summary as template for CICAR observations – strengths and areas of interest
- Discuss September 29, 2005 Executive Board meeting
  - Outcomes
  - Plan response to action items

March 17, 2006 agenda items:
- CICAR update including:
  - CI Memorandum of Agreement
  - 2006 NOAA site review – administrative
  - 2006 NOAA site review – science
  - Develop candidate pool for Science Review team
  - Discuss science review presentations

Executive Board Meetings
The CICAR Executive Board held its inaugural meeting on September 29, 2005 and a second meeting on May 18, 2006.
Agenda items for the first meeting:
- Strengthening the Institute’s partnership with NOAA
- Broadening involvement of Columbia University units outside LDEO in research that addresses NOAA goals
- Strengthening outreach and education activities stemming from and reflecting the achievements of NOAA funded research at Columbia
- Developing ties to other regional research and education institutions to create regional research partnerships on climate related issues
- Preparing for the 2006 NOAA site review

May 18, 2006 agenda items:
- Continue development of CICAR drought initiative to bridge between science and applications by articulating research areas consistent with Columbia University expertise and capabilities and the needs articulated in the NIDIS plan
- Identify areas of collaboration with GFDL in developing methodologies to fill gaps in modeling and understanding abrupt climate change. Particular emphasis on tropical
convection and ocean atmosphere interaction, on sea ice response to global warming
and on ice sheet dynamics

- Continue to identify opportunities to expand climate education beyond the current
  Columbia academic programs and with emphasis on engaging minority constituents
- Articulate areas of CICAR strength in preparation for the October 2006 NOAA site review

CICAR Symposium – LDEO - September 28, 2005

Climate of the Last Millennium: Towards Modeling the Climate from the Middle Ages into the Greenhouse Future

Presented as part of the ongoing collaboration between Columbia University’s Lamont-Doherty
Earth Observatory under CICAR and NOAA’s Geophysical fluid Dynamics Laboratory, the
program included a review of what we know about changes in global and regional climate during
the last 1,000 years, the relevance of these changes to society, and the underlying physical
mechanisms driving the climate. The symposium attracted university educators and students
from Columbia, Rutgers, Princeton, Hofstra, Barnard, and Rockefeller. Also in attendance were
researchers from NASA, CIESIN, and the IRI. NOAA attendees included Ants Leetmaa, James
Todd and Randall Dole.

Presenters:
- LDEO: Wally Broecker, Erica Hendy, Ed Cook, Julien Emile-Geay, Michela Biasutti, and
  Richard Seager
- GFDL: Suki Manabe, Gabriel Lau, Rong Zhang,
- WHOI: Lloyd Keigwin, Ruth Curry
- GISS: David Rind
- UARK: David Stahle

View symposium presentations in PDF at: CICAR Symposium: Climate of the Last Millennium
Panel tracks climate changes
By LAURA INCALCATERRA
THE JOURNAL NEWS
(Original Publication: September 29, 2005)

PALISADES — From prolonged droughts to hard-hitting hurricanes, the weather sure seems to be acting up.

But determining if and when such weather events will occur isn’t an easy task.

Nonetheless, it is the job that scientists at the Cooperative Institute for Climate Applications and Research have eagerly taken on. Some of those scientists spoke yesterday during a one-day symposium that focused on climate change. The program, held at Columbia University’s Lamont-Doherty Earth Observatory, where CICAR is based, drew more than a dozen presenters.

CICAR was established in November 2003 to form a collaboration between Columbia University and the National Oceanic and Atmospheric Administration, which wants to better understand climate change and increase the ability to plan and respond to it.

The theme of yesterday's session was "Climate Change of the Last Millennium: Towards Modeling the Climate from the Middle Ages into the Greenhouse Future."

Yochanan Kushnir, the director of CICAR, said the approach behind the program was simple.

"The whole idea was to try to put the future in the context of the past," Kushnir said.

Scientists wanted to take "just the last 1,000 years," Kushnir said, and see if they could use proxies to determine what happened before and create models that would allow them to gauge what might occur in the future.

Scientists who spoke yesterday explained how they used different methods to obtain climate data, including acquiring "proxies" in the form of coral samples, land and sea-floor borings and tree-ring cores, among others. By applying various techniques, the scientists endeavored to reconstruct a record of climate.

The researchers also explained that as good as their studies were, nothing was exact and, in fact, much of the information they secured only raised more questions.

"That’s always the way," Kushnir said.

Most of the scientists showed graphs and other illustrations that indicated the year and the type of climate.

For example, David Stahle of the University of Arkansas used tree-ring records to show a significant North American drought in the 1950s and the severe Dust Bowl drought in the 1930s. He showed that 1833 was the wettest year on the continent of the previous 500 years, while 1864 was the driest.

He took the information a step further by explaining the significance of these weather events to humans. For example, the Dust Bowl helped cause massive migration and crop failure, while flooding from the 1833 rains drowned Seminole Indian farmers who had previously been forced off their native lands.

CICAR also works with NOAA’s Geophysical Fluid Dynamics Laboratory in Princeton, N.J., whose scientists specialize in developing scientific models to advance the theoretical understanding of the planet’s climactic system.
CICAR PI Meeting – LDEO – April 10, 2006
CICAR Director Yochanan Kushnir and CICAR Executive Board Chair Mike Purdy conducted a state-of-the-Institute dialogue with members of the CICAR research community. Topics discussed included:

- Projects and funding
- Partnership with GFDL
- Proposal reporting and submit guidelines
- CICAR science and education plan for 2006-2008
  - NOAA budget
  - ARCHES successor
  - North American Droughts initiative
  - Collaboration with NOAA CREST at City College
  - PhD students and postdoctoral scientists (funding challenge)
- Role of PIs in the NOAA 2006 site review

CICAR Drought Workshop – LDEO – May 8, 2006
Participants were charged with developing a multidisciplinary research program to advance the scientific understanding of North American droughts and their predictability, and to develop effective methods of communicating drought information to decision makers in areas such as agriculture, water resources, and public policy.

Presentations:

- History and Dynamics of North American Drought Ed Cook, Richard Seager, Mingfang Ting, Gavin Gong, Huei-Ping Huang
- Social Responses to Drought Roberta Balstad, Marc Levy, Christian Webersik, Upmanu Lall, Bob Chen
- Communicating Information about Drought Brad Lyon, Dan Osgood, Jim Hansen, Casy Brown, Lisa Goddard
- CRED research – David Krantz

Discussions:

- Survey of national activities to address North American Droughts – Randall Dole
- Group discussion

The meeting was followed by a steering group session to articulate:

- Ways to address Workshop goal
- Identify opportunities for internal (Columbia) and national collaborations
- Identify areas for new proposals for funding and from what agency

To read more about this workshop go to: CICAR North American Droughts Background
CICAR

Task II: Specialized Science Support Activities

This task provides for specialized support scientists that are employed by Columbia University, Lamont-Doherty Earth Observatory but are located at the Geophysical Fluid Dynamics Laboratory (GFDL). These CICAR employees are hired to enhance the technical and scientific expertise at GFDL required to execute collaborative CICAR projects or to address specific needs that require specific expertise not available at GFDL. In the present 5-year budget cycle we propose to allow for five such support scientist positions. It should be noted that, to date, these slots have not been filled.
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Task III: Specialized Science Support Activities

This task 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 complies with the themes of CICAR. It is comprised of currently funded research projects as well as new ones that strengthen the CICAR research agenda in line with the themes. Task III represents the main thrust of the CICAR research agenda for the next two years.
A abrupt Climate Change Studies (ARCHES) Modeling Scope

Project Title: ARCHES: Mechanisms of Abrupt Climate Change

Principal Investigator: Richard Seager
Affiliation: Lamont-Doherty Earth Observatory

NOAA Program Manager: James Todd, CLIVAR-Atlantic
                       301-427-2383  james.todd@noaa.gov

Research Goals
For this last year our goals were:
1. To further develop understanding of the dynamics of persistent multiyear North American droughts and to better understand the Medieval megadroughts.
2. To critically examine theories of glacial era abrupt change and examine the role of regimes of atmospheric circulation.
3. Examine the response of the North Atlantic Ocean circulation to changes in wind regime and tropically induced changes in P-E.
4. Examine the stationary wave response to future anthropogenic climate change.
5. Further understand feedbacks between clouds and atmosphere and ocean circulation and their role in climate change.

Education Goals
1. To educate the general public on matters of climate change on timescales of seasons to millennia.
2. Through our graduate student and postdoctoral programs to train the next generation of top rate climate scientists.

Research Progress
In this period we have extended our work on North American droughts back in time to examine in more detail than has heretofore been possible the Medieval megadroughts. Using gridded, annually resolved, tree ring records we have demonstrated that the Megadroughts had spatial patterns and severity, in any single year, the same as modern droughts. What distinguished them from modern day droughts was the persistence – they lasted decades instead of years. We have also examined proxy records of Medieval hydroclimate from around the world and demonstrated that the global pattern of Medieval hydroclimate appears similar to that accompanying the droughts of the modern period. These results suggest the causes of the Medieval megadroughts were the same as those causing recent droughts: persistent variations of tropical sea surface temperatures (SSTs). What caused these changes in SST is the next task.

Using an intermediate model of the tropical Pacific atmosphere-ocean system, we have demonstrated that the small changes in solar irradiance during the Holocene (reconstructed from isotopes) could have been amplified by the coupled system into changes in SST of large enough size to have impacted climate worldwide. We claim that periods of high irradiance could be translated by this mechanism into periods of drought in North America and periods of low irradiance into periods of high ice-rafted debris in the North Atlantic Ocean (as recorded by Gerard Bond).
Turning to glacial era abrupt change we have reviewed the global footprint and temporal evolution of Dansgaard-Oeschger events and have argued that it is hard to explain this in terms of the reigning paradigm of abrupt change: shutdowns and resumptions of the North Atlantic branch of the THC. Instead we have argued that recent work on atmospheric circulation has demonstrated regimes may exist with tropical forcing being able to act as a trigger to move from one to the other. It is suggested that these regimes involve changes in the jet streams and storm tracks and ocean circulation. Simulations of the Last Glacial Maximum support this contention in that, although the jet stream and baroclinity was strengthened, transient eddy activity decreased and the circulation across the North Atlantic was more zonal. This arrangement would correspond to the stadial states of D/O events. It is proposed that some trigger – perhaps in the tropical atmosphere-ocean system – can cause a rearrangement to a state of jet stream-storm track-ocean circulation akin to that of today and, hence, a transition to the interstadial states of the D/O events.

We have also further considered relationships between the tropical warm pools, the Hadley Circulation and atmosphere and ocean heat transports. Our prior work has shown the importance of coupled processes in defining some of the large-scale features of the tropical climate. In year 5, we have extended that work to show that not only are oceanic phenomena (such as the warm pool) established by coupled processes, but the large-scale meridional circulation in the tropical atmosphere, the Hadley circulation, is as well. This work has shown that when the ocean heat transport is reduced relative to today, the Hadley circulation is dramatically different both in its mean strength and seasonal cycle. This is a new contribution to the literature on the Hadley cell, which has been dominated by the study of atmosphere-only processes. Together with prior studies, our work has shown that the partitioning of heat transport between the ocean and atmosphere is fundamental to determining the main features of the tropical climate. It follows that if there are other possible configurations for this partitioning, the tropical climate could be dramatically different even under the same external forcing. Work in the final year of the proposal will test how this partitioning can change. In particular, we will test the role of the tropical thermocline in determining this partitioning using coupled GCMs.

**Highlights**

- First detailed look at the spatial patterns and temporal properties of the North American medieval megadroughts. Tree ring records show these to have very similar spatial patterns to modern droughts but a persistence of decades instead of years. This points to equally persistent tropical ocean temperature anomalies as the cause.
- Two review and idea papers on glacial era abrupt climate change advance the idea of regime changes in global atmosphere-ocean circulation being responsible.
- Identified a mechanism whereby the tropical Pacific atmosphere-ocean system amplifies small changes in solar irradiance during the Holocene to create climate anomalies worldwide such as megadroughts in western North America.
- Examined impact of changes in ocean heat transport on the Hadley Cell.

**Societal Benefits**

Drought is the most costly natural disaster in the U.S. and poses a recurring risk to cities and agriculture in the arid West. Understanding of the causes of persistent drought will lead to potential predictability and the ability to plan for reductions in water supply and a reduction in relief payments and financial losses.

Our work on the response of the climate system to external forcing – e.g. Holocene irradiance changes – allows for a better understanding of the response to anthropogenic change, a matter of giant importance. Whether we can expect the West to get drier or wetter in coming years to decades is one example.

**Education and Outreach**
Research advisor / mentor
- Graduate: Celine Herweijer, Julien Emile-Geay, Natasha Walker

Academic participation
Presentations


North American drought of the last millennium: reconstruction, causes and consequences. Harvard University, February 2005.


The future of drought risk. BIOTECH 2006 Annual Conference organized by Dupont, Pioneer Hybrid etc. Chicago, April 2006.


Public relations
Public outreach
- Frequently interviewed by print and broadcast media on climate matters of concern to the general public.
- New York Academy of Sciences talk on the Hydrological History of the American West (Seager)
- ‘The Source of Europe’s Mild Winters’, an article in the popular magazine, American Scientist (Seager)

Databases
- All model simulation data is served online immediately after computation to act as a resource for the global research community

Personnel
Research Scientists: 7, Research Support Staff: 2, Administrative: 1

Publications
Journal articles


Books / articles-in-books


Conference proceedings / workshops

The tree-ring reconstructed Palmer Drought Severity Index (PDSI) for four Medieval megadroughts. The spatial pattern of the megadroughts (shown on the left) was very similar to that of modern day droughts. The plots at right show the PDSI averaged over the West for each year in the drought and emphasize the multidecadal persistence of the megadroughts.
**Project Title:** Describing, Understanding, and Predicting Oceanic Variations Associated with Tropical Variability and the North Atlantic Oscillation

**Principal Investigator:** Dake Chen  
**Affiliation:** Lamont-Doherty Earth Observatory

**NOAA Program Manager:** James Todd, CLIVAR-Atlantic  
301-427-2383  james.todd@noaa.gov

**Research Goals**  
As a part of this multi-institute research project, our goal this year at LDEO is to start the development a hybrid prediction model, in particular, to carry out sensitivity experiments to examine how uncertainties in input precipitation may affect the simulation and prediction of the coupled ocean-atmosphere system.

**Research Progress**  
This research is a collaborative project of NOAA/CPC, U. Maryland and CU/LDEO. Here we only briefly describe the progress made at LDEO. A comprehensive annual report of the whole project, including LDEO component, has already been submitted through CPC. At LDEO, we have made considerable progress in evaluating the sensitivity of ocean simulations to the uncertainties in precipitation, as summarized below.

Uncertainties in rainfall estimation are notoriously large. Presently available precipitation products differ from one another not only in magnitude but also in detailed spatial structures, despite their general similarity in large-scale patterns. It is important to understand how strongly and in what way such uncertainties would affect ocean models that include freshwater forcing. In order to quantify the sensitivity of ocean simulation to rainfall, we carried out a suite of experiments using the Lamont OGCM, forced with a large collection of precipitation products, including CMAP, NCEP, GPCP, OPI, GPI and TRMM. The standard model run is for the period from 1979 to 2003 with the CMAP precipitation analysis. Then for each additional run the CMAP forcing is replaced by another set of precipitation forcing for the period that data set is available. The results of each model run are then compared to those of the standard run for their common period. As an example, Figure 1 shows the differences between each of these model runs and the standard run, in terms of precipitation forcing as well as simulated sea surface salinity (SSS) and temperature (SST) fields, for the global tropical oceans.

It is clear that there are significant uncertainties in precipitation forcing, with the difference between the model-based product (NCEP) and CMAP being particularly large. The differences in SSS are basically a direct response to the different freshwater inputs, whereas those in SST show different spatial patterns. This is because the latter largely depends on the dynamical ocean responses. To demonstrate this, Figure 2 shows the equatorial ocean responses for the upper 300m. There are several points worth noting here. First, the effects of precipitation are not limited to the surface; both salinity and temperature have significant subsurface variations. Second, in contrast to salinity, which shows maximum differences at the surface due to different precipitations, the temperature differences have subsurface maxima obviously related to different thermocline responses. Third, both ocean dynamics and thermodynamics are sensitive to the prescription of precipitation. For instance, over most of the tropical Atlantic, NCEP reanalysis gives heavier rainfall as compared to CMAP, which freshens up the upper ocean and increases SST by trapping surface heat input to a shallower mixed layer. In the meantime, because the precipitation is more excessive in the western than the eastern Atlantic, the zonal pressure gradient is reduced, resulting in a flattening of the thermocline, as indicated by the negative subsurface temperature anomaly in the west and the positive one in the east. The situations for the model runs with the other precipitation products are just the opposite, because
they all give less rainfall in the tropical Atlantic as compared to CMAP. The same reasoning can also be used to explain the thermohaline responses in the tropical Pacific and Indian Oceans. More detailed discussion can be found in Chen et al. (2006).

**Highlights**

- The effects of precipitation are not limited to the surface; both salinity and temperature have significant subsurface variations in response to precipitation forcing.
- In contrast to salinity, which shows maximum differences at the surface due to different precipitations, the temperature differences have subsurface maxima obviously related to different thermocline responses.
- Both ocean dynamics and thermodynamics are sensitive to the prescription of precipitation.

**Societal Benefits**

Our study aims at a better understanding, description, and prediction of Atlantic oceanic precipitation, which will directly benefit the surrounding countries of the Atlantic Ocean.

**Other Research Connections**

**Interagency**

This research is an integral part of our long-standing effort on climate prediction funded by NOAA, NASA and NSF.

**Research partnerships**

The success of the research depends on the partnerships among LDEO, CPC/NCEP and UMD.

**Collaborators**

P. Xie (CPC), Y. Xue (CPC), P. Arkin (UMD), Z. Wang (LDEO).

**Personnel**

Research Scientist: 1, Research Support Staff: 1
Difference maps of salinity and temperature on the equatorial vertical section (5S-5N) between model runs forced by various precipitation products and that by CMAP, respectively.
Differences of salinity and temperature on the equatorial vertical section (5S-5N) between model runs forced by various precipitation products and that by CMAP, respectively.
**Project Title:** Investigating Some Practical Implications Of Uncertainty In Observed SSTs

**Principal Investigator:** Lisa Goddard

**Affiliation:** International Research Institute for Climate & Society, The Earth Institute of Columbia University

**NOAA Program Manager:** Joel Levy, Office of Climate Observation

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**Research Goals**

Evaluate the impact of uncertainty in observed SSTs on seasonal-to-interannual prediction. One of the important goals of the Sustained Ocean Observing System for Climate is to improve the SST accuracy over the global ocean. The activities described here are intended to provide feedback to the climate observing community on the apparent impact of that improvement for seasonal climate simulations and predictions.

The activities under this additional task are two-fold.

1. Estimate the impact of SST uncertainty, as estimated by added information from satellites, on climate simulations from AGCMs. This is done by running an atmospheric general circulation model (AGCM) over a set of years with two different analyses of the observed SSTs: one that includes satellite data (Olv2) and one that does not (ERSSTv2). The questions being addressed are, “Is the simulation with satellite SST data more representative of the observed climate?” and “Are there any detectable systematic, SST-related differences between the simulations?”.

2. Evaluate what maximum skill should be expected from SST predictions given uncertainty in the “truth”. This will be estimated verifying the observed time series of SSTs against the same time series including a normally distributed error that is either fixed at 0.4 degC (FY06 target), or that is spatially and temporally varying according to the estimated sampling error of the ERSSTv2 data.

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**Research Progress**

(1) **AGCM Sensitivity Experiments:**

Two sets of historical simulations have been run with the ECHAM4.5 AGCM (T42,L18) over the 1982-2003 period: (a) 20 members forced with ERSSTv2 observed SSTs, which is based on in-situ data only; (b) 20 members forced with Olv2, which is based on in-situ data plus infra-red (IR) satellite data. Analysis comparing the correlation skill and the magnitude of interannual variability between the 2 sets of experiments has begun. It appears that the differences between the 2 experiments are relatively small. We are currently developing estimates of the statistical significance of the differences. A map of correlation skill differences for JFM 2m air temperature is shown in figure 1. A journal article is in preparation for GRL.

(2) **SST Potential Predictability Estimates:**

The analysis has been completed. A paper is in preparation for GRL. The results illustrate the spatial reality that even a perfect forecast model cannot be expected to attain an anomaly correlation coefficient against observations if those observations contain uncertainties, in this case primarily sampling errors.

The proximity of the low skill areas (Figure 2) to warm pool and other convergence regions (shown by heavy black contours on Figure 2) in part explains their existence. Where the SST is relatively warm, convective clouds hamper the IR satellites from accurately measuring SST. These also are unfortunately regions with typically little in situ data. The implications of the low skill regions for simulating the climate with AGCMs is that incorrect representation of changes in these fringe areas of the warmest SST regions adversely affect the spatial representation of SST.
anomalies, altering the strength and location of convection and associated upper and lower tropospheric flow.

A related point is that CGCM SST correlation maps (not shown) exhibit low-skill areas roughly consistent with the regions of lower potential predictability or verifiability. Since the uncertainties in the SSTs suggest that an upper limit of skill should be something similar to what is shown in Figure 2, SST predictions should present skill results relative to such an upper limit and explicitly account for the uncertainties in the verification data.

Implications for the AGCM sensitivity experiment emerge from comparison of expected skill limit for the ERSSTv2 data (Figure 2b) and the ERSSTv2 versus OIv2 correlation (Figure 3). Since the correlation between the two datasets is higher than the ‘expected maximum skill’ from a single dataset, the AGCM experiment will not tap the full magnitude of SST uncertainty. Either common errors exist between the two datasets that have not been quantified for OIv2, or the error variances are overestimated for parts of the tropics in ERSSTv2. The former explanation is the more likely one. Therefore, activity 1 will not fully address the issue of implications for simulations/forecasts of observational uncertainty in the SST forcing data. That question will be more specifically examined in the FY06/07 work.

Highlights

- Current state-of-the-art coupled models exhibit correlation skills more consistent with expected “perfect” correlations than currently perceived due to uncertainties in observed SSTs, which make it difficult to discern imperfections in model variability from uncertainties in verification data.
- Largest uncertainties in SST observations exist near warm pool regions, the variability of which influences global climate variability. Thus the global ocean observing system should invest more in situ observations for these areas.

Societal Benefits

Main societal benefit potentially derives from demonstration of gaps in ocean observing network. Action to remedy those gaps should benefit NOAA’s ability to monitor and predict the climate system.

Other Research Connections

Collaborators

Richard W. Reynolds, NOAA’s National Climate Data Center

Education and Outreach

Academic participation

Presentations


Personnel

Research Scientist: 1, Research Support Staff: 1
Maps of anomaly correlation coefficients for Jan-Feb-Mar 2m air temperature over land for the period 1982-2003. Observed terrestrial temperature analysis from CRU-UEA is compared to ensemble means of 20 member experiments with ECHAM4.5 AGCM forced with (a) OIv2 SSTs, and (b) ERSSTv2 SSTs. The difference in skill (c) is positive if experiment using OIv2 SST forcing demonstrated higher skill.
Correlation between observed time series, taken as “truth”, and that time series with random Gaussian error described by assumed error variance. (a) Error variance assumed fixed at 0.4 deg.C, which is the FY06 target for SST accuracy. (b) Error variance taken from estimated sampling error variance of the ERSSTv2 data. Superposed black contour indicates climatological SST at 27, 28, 29 deg.C, demarking the warmest and most convective regions of the tropics.
Anomaly correlation between two observed datasets: ERSSTv2 (in situ data only) and OIv2 (in situ + satellite data).
**Project Title:** The Integrated Role of Snow, Orography and Dynamical Waves in Facilitating Western US Land Surface – Climate Linkages

**Principal Investigator:** Gavin Gong  
**Affiliation:** Department of Earth and Environmental Engineering  
Columbia University

**NOAA Program Manager:** Jin Huang, Climate Prediction Program for the Americas  
301-427-2371  
jin.huang@noaa.gov

**Research Goals**

The overall goal of this project is to identify physically based mechanisms by which land surface snow anomalies over the western US can influence atmospheric circulation and regional climate phenomena such as the winter Pacific-North American (PNA) pattern and the summer North American Monsoon System (NAMS). The specific goals for the first year were to ascertain the effect of early season snow anomalies on winter climate, by analyzing archived GCM experiments from a previous project, supplemented by one additional simulation, and conducting a more detailed dynamical analysis using a diagnostic stationary wave model.

**Research Progress**

The initiation phase of this project has been completed, which consisted of 1) purchasing a new LINUX workstation and transferring archived GCM experimental output for analysis, 2) installing the diagnostic Stationary Wave Model with attendant pre- and post-processors, and 3) performing an additional GCM experiment that complements the existing experiments and results in a complete and consistent set of experiments for analyzing the combined influence of North American orography and early-season snow anomalies on autumn-winter climate.

Initial analysis of the GCM experiments indicates a number of mean flow and stationary wave parameters that appear to respond significantly to the prescribed snow forcing, when North American mountains are present. Latitude-pressure profiles of snow-forced zonal-mean zonal wind anomalies during autumn (SON) and winter (DJF) are shown in Figure 1. Coherent and significant dipole anomalies occur throughout the troposphere in both seasons, indicative of a northward shift of the subtropical jet in response to a positive snow forcing. In contrast, the polar front jet appears to weaken somewhat in autumn but strengthen slightly in winter, though these results are not statistically significant. Zonal-mean temperature exhibits a similar dipole response (not shown). Figure 2 shows snow-forced meridional wave activity flux (WAF) anomalies during winter, at 250 hPa and 850 hPa elevation. Equatorward anomalies occur over the two primary “centers of action” for stationary wave activity, centered roughly over east Asia / western North Pacific and western Europe / eastern North Atlantic. Statistical significance is modest, however the anomaly regions are large and coherent, especially at 250 hPa. This is indicative of a strengthening of the prevailing winter meridional stationary wave activity in response to a positive autumn snow forcing over North America.

The current task is to understand the physical and dynamical processes responsible for this snow-forced climatic response. A working hypothesis consistent with the aforementioned results is that positive autumn snow anomalies enhance the zonal land-ocean temperature contrast, which intensify stationary wave patterns and subsequently affect mean circulation via wave – mean flow interactions. Analogous experiments with North American mountains removed do not produce significant zonal-mean zonal wind and meridional WAF responses to the same snow forcing (not shown). This indicates that the orography of North America is instrumental to the snow-forced climate response, and points to stationary waves as a responsible dynamical mechanism.
Other parameters, such as stationary wave stream function, do not indicate significant responses that corroborate our working hypothesis (not shown). A possible explanation lies in the nature of the snow-forced experimental design for these archived GCM experiments, which were not originally intended for studying North America. Modified forcings and/or larger ensembles may yield more significant results. Observational analyses are being performed, and more meaningful GCM experiments are being designed, to better understand the precise atmospheric response to autumn snow forcings over North America. Diagnosis with the stationary wave model is being postponed until the potential role of stationary waves in the observed response becomes clearer.

Results from this phase of the project will be presented at the AGU 2006 Fall Meeting, and a manuscript will be submitted by the end of the year.

**Highlights**
- Hemispheric-scale mean flow and stationary wave parameters indicate a significant GCM modeled response to a prescribed autumn snow forcing over North America.
- The orography of North America is instrumental to the snow-forced climate response, and points to stationary waves as a responsible dynamical mechanism.

**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**
**Interagency**
The archived GCM experiments were supported by a previous NSF project, and this research is a natural extension of that work.

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

**Education and Outreach**
**Research advisor / mentor**
Graduate: Gavin Gong / Stefan Sobolowski, doctoral candidate, Columbia University
Department of Earth and Environmental Engineering

**Academic participation**
**Presentations**
LDEO Drought Workshop, May 8, 2006

**Fellowship programs / internships**
Stefan Sobolowski, NASA Earth System Science (ESS) 2006 Fellowship Program

**Personnel**
Research Scientists: 2, Graduate Student: 1
Figures / Photographs / Illustrations
The Integrated Role of Snow, Orography and Dynamical Waves in Facilitating Western US Land Surface – Climate Linkages

Latitude-pressure profiles of zonal-mean zonal wind anomalies in response to a positive snow forcing over North America, during autumn (SON) and winter (DJF). Contour units are m/s. Dark (light) shading indicates 95% (90%) significance level.

Meridional wave activity flux (WAF) anomalies during Northern Hemisphere winter (DJF) in response to a positive snow forcing over North America, at 250 hPa and 850 hPa elevation. Contour units are m$^2$/s$^2$. Dark (light) shading indicates 95% (90%) significance level.
Project Title: Tropical Influences On Recent And Historical Droughts Over North America

Principal Investigator: Huei-Ping Huang
Affiliation: Lamont-Doherty Earth Observatory

NOAA Program Manager: Jin Huang, Climate Prediction Program for the Americas 301-427-2371 jin.huang@noaa.gov

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 goals of the budget year are to use ensemble numerical model simulations with contrasting global and tropical SST forcing to isolate the tropical influences on droughts, and to determine the origins of two types of extratropical dynamical responses associated with droughts that are characterized by Rossby wave trains and zonally symmetric ridges and troughs.

Research Progress
In the past year, significant efforts have been devoted to finishing a large set of ensemble general circulation model (GCM) simulations designed for the analysis of the SST-drought connection. Using the NCAR CCM3 atmospheric GCM, 64 "GOGA" (model forced with observed global SST) runs for 1959-2005, 16 "POGA-ML" (forced with tropical Pacific SST, coupled with a mixed-layer ocean elsewhere) runs for 1856-2005, and several pairs of "SCYC" (forced with repeated Seasonal CYCle of SST) runs have been completed. The POGA-ML runs include an active Indian Ocean, while the SCYC runs exclude the direct effect of the interannual variability in the SST forcing. These simulations reproduce many important features of the multi-year droughts and pluvials in both North and South America. In addition, surpluses and deficits of precipitation over the American continents on decadal to multi-decadal time scales are reproduced.

Analyzing the three sets of GCM runs, it is revealed that the mean condition in the tropical Pacific SST strongly influences the precipitation anomalies in both Americas. Moreover, due to their common tropical origin, a dry condition in Mexico and the southwest U.S. usually accompanies a wet condition in the northern South America and a dry condition in the central South America. Droughts and pluvials in North America are found to be part of a bigger picture of the variability of a "Pan-American" precipitation pattern. This pattern prevails at not only interannual but also decadal to interdecadal timescales. Using the signal-to-noise ratio deduced from the ensemble GCM simulations, it is found that the causal relationship between SST forcing and the precipitation anomalies at the major centers of the Pan-American pattern is statistically significant (Fig. 1).

The connection of the tropically forced precipitation anomalies over the Americas to different sub-domains of the tropical ocean is investigated. Two types of extratropical dynamical responses to tropical SST anomalies are associated with the North American drought events. The Rossby wave train type of response, having its largest amplitude in boreal winter, is more closely related to the tropical Eastern Pacific SST anomaly because the tight upper-level absolute vorticity gradient there allows an efficient production of Rossby wave source by convective heating (Fig. 2). The zonally symmetric troughs and ridges, on the other hand, are governed by more complicated dynamics involving transient eddies. The SST anomalies in the Western Pacific and Indian Ocean (IWP) region, including those in the subtropics, are found to strongly influence the zonally symmetric midlatitude response. A quest in this direction will
continue to further pinpoint the most critical spot of SST/convective heating within the IWP region that generates the zonally symmetric response.

**Highlights**

- The causal influences of the tropical Indo-Pacific SST anomalies on North American droughts are confirmed by ensemble GCM simulations.
- The simultaneous occurrences of wet-dry-wet (or dry-wet-dry) conditions in the Southwest U.S., northern South America, and central South America are explained by their common tropical origin. The wet-dry-wet Pan-American precipitation pattern is associated with a tropics-wide warmth, and the opposite phase tropics-wide coldness, of SST.

**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 and Outreach**

**Research advisor / mentor**

Celine Herweijer (Ph.D. degree granted 2006, mentor: Project Co-PI Richard Seager)

**Academic participation**

**Presentations:**


**Symposiums:**

**Public relations**

Public Outreach (community relations)
- Lamont-Doherty Earth Observatory Open House event 2005 CICAR exhibit scientist participant

**Intranet / Internet sites or pages**
- Drought research web page for the public (created by project Co-PI Richard Seager)

**Databases**
- Climate model data web portal (creators: Naomi Naik and project Co-PI Richard Seager):

**Personnel**
- Research Scientists: 3

**Publications**

**Journal Articles**

**Conference Proceedings / Workshops**
Determination of the statistical significance of the interdecadal precipitation signals over the Americas using ensemble model simulations. Top left: Observed difference in precipitation between the 1976-1998 and 1961-1976 epoch means. Lower left: Same quantify from a 48-member ensemble GCM simulation forced with observed SST. Brown and green are negative and positive. Contour levels are 0.1, 0.2, 0.5, 1, 2 mm/day. The right panel shows the histogram of the model-simulated shift in precipitation for different boxes indicated in the lower left panel. The SST-induced signals in box 1, 2, and 3, the main centers of the Pan-American precipitation pattern, are highly significant compared to the level of natural variability. In contrast, box 4 has a very small signal-to-noise ratio, indicating that the observed wetness over the Northwest U.S. is likely due to natural variability unrelated to remote SST forcing.
The distribution of January-May Rossby wave sources at 200 hPa deduced from a warm-minus-cold interdecadal shift in the tropics-wide SST. (a) The upper level divergence (red positive) produced by the anomalous tropical convective heating has three centers of equal strength in the Eastern and Western Pacific and Indian Ocean as indicated by green arrows. (b) Yet, the net Rossby wave source has the largest amplitude in the Eastern Pacific. (c) A look at the climatological absolute vorticity (contours) reveals that its tightest gradient is located in the Eastern Pacific. This explains why the Rossby wave train type of responses are more efficiently generated by the Eastern Pacific SST anomalies. Imposed in (c) are the divergent component of the upper-level anomalous velocity vectors.
Project Title: Multivariate Approach to Ensemble Reconstruction of Historical Marine Surface Winds from Ships and Satellites

Principal Investigator: Alexey Kaplan
Affiliation: Lamont-Doherty Earth Observatory

NOAA Program Manager: Christopher D. Miller, Climate Change and Data Detection
301-427-2376  Christopher.d.miller@noaa.gov

Research Goals
To analyze historical winds on the basis of ship data, with the statistical parameters constrained by the scatterometry data. The analysis methodology is based on the reduced space optimal estimation with multivariate constraints and with the representation of uncertainty by an ensemble of possible realizations. The reconstruction is based on surface winds and sea level pressure from International Comprehensive Ocean-Atmosphere Data Set (ICOADS). Performance of the analyses as the forcing for the ocean models, and their uncertainty, is viewed to be one of the most important quality criteria.

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

Research Progress
During the 2nd year of the project, we performed further testing of our trial versions of ocean surface wind and sea level pressure data sets for the latest ICOADS version and further development of the analysis technique. We evaluated trial analyses in the context of other climate variables using instrumental analyses and paleodata, furthering the foundation for the multivariate analyses, tested the performance of various wind products as forcing for ocean models, and advanced the ways of representing the uncertainty in the analyzed values.

1. Trial data set development:
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., 2006). 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.

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.
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 paleoceanographic 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 and currently is being worked on.

2. Performance of the wind analyses as forcing fields for ocean models:
Comparison of the performance of various tropical wind products as forcings for an ocean model identified the equatorial persistence as a crucial controlling factor. Satellite scatterometry 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. This persistence will be used as a statistical constraint in the future versions of wind analyses.

The trial 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.

Highlights
- Use of historical wind analysis to describe Indian Ocean Dipole mode and to model statistically Indian summer monsoon rainfall.
- 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. The trial wind analyses and their error estimates were used in the study of ENSO predictability.

Societal Benefits
- We develop 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 work on the data set which will lengthen significantly wind data sets available for climate simulations, and which will provide the user with a straightforward way to take its uncertainty into account. We also expect wide utilization of our products in statistical studies of climate variability, for calibration and verification of paleoclimatic reconstructions, etc.

Awards / Honors
A.Kaplan received 2005 AGU Editors' Citation for Excellence in Refereeing

Education and Outreach
Academic outreach
Postsecondary: Shane Riordan, a science teacher from New York Harbor High School did a summer 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.

Research advisor / mentor
Undergraduate: A.Kaplan/T.Merlis (Columbia Engineering School senior, Applied Math, entered the Caltech Ph.D. Program in Atmospheric Sciences)

Graduate: M.A.Cane and Y.Kushnir / C.Ihara (Ph.D. student in Columbia University) M.A. Cane (Ph.D. student in Columbia University)

Academic participation
Presentations


Internships
LDEO Summer internships

Public relations
Intranet / Internet
http://www.cgd.ucar.edu/~asphilli/DataCatalog/Data/kaplan.html

Databases

http://www.cdc.noaa.gov/Pressure/Gridded/data.kaplan_slp.html

Personnel
Research Scientists: 3, Graduate Students: 2, Undergraduate Student: 1

Publications
Journal articles


*Figures / Photographs / Illustrations*

Multivariate Approach to Ensemble Reconstruction of Historical Marine Surface Winds from Ships and Satellites

Lagged correlation coefficients in the zonal wind anomalies from the NCEP-NCAR reanalysis (160E-120W averages) show their highly significant persistence for the period of six months and beyond within 10 degrees latitude of Equator. This persistence can be used as a statistical constraint to support the analyses of historical wind fields, when the observational data coverage is poor.
Project Title: CLIVAR – South Atlantic Ocean-Atmosphere Interaction

Principal Investigator: Andrew W. Robertson
Affiliation: IRI – International Research Institute for Climate and Society

NOAA Program Manager: James Todd, CLIVAR-Atlantic
301-427-2383 james.todd@noaa.gov

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 between 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
The project is organized as two parallel efforts at IRI and UCLA. The IRI component is focused on interannual variability and predictability, while a better dynamical understanding of errors in the mean seasonal cycle is the focus of the UCLA component.

IRI Component Progress: Hindcast experiments to explore the role of the Atlantic meridional SST gradient: The roles of ENSO forcing and preconditioning

Following our first-year progress report, the influences of El Niño on the SST anomalies in the North (tNA) and South (tSA) Atlantic and their difference (G1 = tNA-tSA) were further analyzed as published in Huang et al. (2005). It was found that, while El Niño (La Nina) generally contributes to an increase (decrease) in G1 through its influence on tNA, this contribution is often not strong enough to overturn a pre-existing SST gradient when its sign is opposite to the ENSO-induced tendency. This class of “discordant” cases comprises about one-third of all strong ENSO events with NINO3 index greater than 1°C that the role of preconditioning needs to be considered for the seasonal forecast of G1.

Based on this insight, hindcast experiments have been conceived and set-up to separate the contributions of ENSO forcing and preconditioning to the Atlantic SST gradient in spring when the latter has the maximum impact on Brazilian rainfall. The hindcast experiments are being performed with an atmospheric GCM coupled to a mixed layer ocean model for the Atlantic. The models are modified from those used by Peng et al. (2006). Since the ENSO forcing is most prominent in winter and early spring, the hindcast is done from November of year 0 to August of year 1. Following an uncoupled spin-up period, atmosphere-ocean coupling is activated on November 1st with the observed SST anomaly as the initial perturbation. Two sets of 25-member ensemble runs are in the process of being carried out, one with the climatological SST specified outside the Atlantic, the other with an additional ENSO SST anomaly imposed to the tropical Pacific. In the former, the predictability of the Atlantic SST gradient is due entirely to the persistency of the initial condition. The difference between the two runs reflects the true ENSO influence.
Preliminary hindcast results for 1968-69 with ENSO forcing produce a warming in tNA and a positive G1 in late spring following El Nino in winter, consistent with observations. In the corresponding hindcast without ENSO forcing, the initially positive tSA in November 1968 persists into spring while not much happens with tNA. In this case, the GCM experiments clarify that the precondition in tSA contributes to an initially negative G1 in winter and early spring but the ENSO forcing on tNA turns the SST gradient to positive in late spring. The attached figure describes the main results. More hindcast experiments for major ENSO and large-G1 events are currently underway to further quantify the dependence of G1 in spring on the tSA in preceding winter and the integral of ENSO forcing from winter to spring.

**Highlights**

- From an 1876–1999 data record, our results confirm that the meridional gradient of sea surface temperature in the tropical Atlantic during March–May is more often consistent with the remote response to ENSO.
- ENSO forcing does not overturn a pre-existing meridional gradient in one-third of events.
- Preliminary experiments with an atmospheric GCM coupled to a slab-ocean mixed layer confined to the Atlantic basin suggest that pre-existing Atlantic SST anomalies can play an important role in modulating the Atlantic’s response to ENSO.

**Societal Benefits**
Results are an important first step in identifying predictable components of climate in the South Atlantic, in order to improve the skill of seasonal predictions of the West African Monsoon; the latter is of great societal importance to the countries of West Africa.

**Other Research Connections**

**Research partnerships / collaborators**
This project is in partnership/collaboration with Profs. C. R. Mechoso and A. Hall at UCLA’s Department of Atmospheric and Oceanic Sciences.

**Education and Outreach**

**Academic participation**

Symposia

**Personnel**

Research Scientists: 3

**Publications**

**Journal articles**
Overview of observational results and GCM simulations
Project Title: The Role of Orography on the North American Monsoon Onset and Interannual Variability

Principal Investigator: Mingfang Ting
Affiliation: Lamont-Doherty Earth Observatory

NOAA Program Manager: Jin Huang, CLIVAR / PACS
301-427-2371 jin.huang@noaa.gov

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 completed the study on the role of North American topography on the maintenance of low-level jet and the United States summer precipitation using the GFDL AM2. We used the linear and nonlinear stationary wave models to determine the physical mechanisms through which the North American topography maintains the Great Plains time mean low-level jet. Possible mechanisms include the physical blocking of the topography and the induced flow over and around the mountains, the thermal effect due to the elevation of the mountains, and the transient thermal and vorticity forcing due to the modification of transient eddy activities in the presence of the mountains. The linear and nonlinear model results indicate that the dominant mechanism for maintaining the time mean Great Plains low-level jet is through the nonlinear effect of the trade wind along the southern flank of the North Atlantic subtropical high encountering the east slope of the Sierra Oriental and causing the flow to turn northward. As the flow turns north along the east slope of the North American topography, it obtains anticyclonic shear vorticity and thus the low-level jet. The effect of the thermal forcing is negligible, while the effect of transient forcing is only important in extending the jet further northward and eastward. The results suggest that variations in the strength of the North Atlantic subtropical anticyclone and the associated trade wind over the Caribbeans and the Gulf of Mexico may be important for understanding the interannual variation of the Great Plains low-level jet and the United States summer precipitation. A paper summarizing the results based on the GFDL model experiments and the linear and nonlinear model diagnostics is accepted by the Journal of the Atmospheric Sciences (Ting and Wang, 2005). Results from this study have been presented at the drought workshop in Maryland in May 2005 and IAMAS conference in Beijing, China.

We have performed GCM experiments using the NCAR CCM3 to test the role of North American topography on the Great Plains low-level jet and the United States precipitation. Results reproduced the GFDL AM2 conclusions as shown in Ting and Wang (2005) which illustrate that the Great Plains low-level jet disappears completely in the experiment when the North American topography is removed, while the summer seasonal mean low-level jet is well simulated in the experiment with the realistic topography. In the absence of the North American topography, the summer precipitation is significantly reduced over the central United States and increased along the Gulf States and northeast Mexico.

The output from the CCM3 experiments with and without North American topography has been coupled to the regional climate model to downscale the United States precipitation, particularly the North American monsoon precipitation. The purpose here is to illustrate the above GCM results on regional precipitation patterns. We analyzed the regional model results for climatological means as well as the diurnal cycle. The regional model improves greatly the GCM summer precipitation pattern in terms of the Great Plains summer precipitation maximum location, correcting a common bias of the global model’s precipitation being located too far to
The presence of the North American topography is crucial for the Great Plains summer low-level jet, which transports most of the moisture from the Gulf of Mexico to the Great Plains region. The main mechanism through which the topography plays a role is through the physical blocking of the topography to the trade wind from the tropical Atlantic and the Caribbeans, or through potential vorticity conservation. Central US summer precipitation is greatly suppressed by the absence of the North American topography.

Societal Benefits
Prediction of Central US summer precipitation is crucial for agriculture and local economy. Our results point out the potential importance of the variability of Atlantic flow on US summer precipitation. This adds the prediction capabilities of US summer precipitation using the ENSO SST to using the Atlantic SST as well.

Other Research Connections
Research partnerships
This research enhances partnership between Lamont-Doherty Earth Observatory of Columbia University and the State Water Survey at the University of Illinois at Urbana-Champaign.

Collaborators
Dr. Xin-Zhong Liang and Prof. Praveen Kumar at University of Illinois, Dr. Hailan Wang at NASA Goddard.

Personnel
Research Scientist: 1, Research Support Staff: 1

Publications
Journal articles

Figures / Photographs / Illustrations
The Role of Orography on the North American Monsoon Onset and Interannual Variability

850 mb wind vectors for the GFDL GCM experiment with full earth topography (a), without the North American topography (b), and the difference between (a) and (b). Wind vector scale is as shown (in m/s) and shadings indicate the mountain heights (in meters) used in the GCM experiments.
Conterminous United States precipitation for the GCM experiment with full earth topography (a), without the North American topography (b), and the difference between (a) and (b). Shading scales are as shown and in mm/day.
Project Title: The Role of Ocean Dynamics in Tropical Atlantic SST Variability: A model data comparison

Principal Investigator: Martin Visbeck
Affiliation: Lamont-Doherty Earth Observatory

NOAA Program Manager: James Todd, CLIVAR-Atlantic
301-427-2383 james.todd@noaa.gov

Research Goals
- Investigate the mechanisms of tropical Atlantic Climate variability with an emphasis on the role of tropical ocean dynamics in seasonal to interannual climate variability
- Correct model biases in the tropical Atlantic Ocean

Research Progress
In the July 2005 – June 2006 budget year the project was continued at a no-cost extension of the previous budget year. Most of the effort this year was dedicated to studying the role of ENSO variability on the salt budget of the tropical Atlantic and the transport of salt from there to the North Atlantic. An El Niño leads to reduced precipitation over the tropical Atlantic with impact over the western equatorial region and the Amazon Basin. La Niña affect the region in the opposite way (see Figure 1 below). Because of decadal variations in the intensity of El Niño, the changes in ocean salinity can affect long-term variability of the salt budget of the tropical Atlantic and affect the thermohaline circulation. Previous studies with simple models and with coupled GCMs suggest that this effect is significant. In an effort to test the ability of the Lamont Ocean Model (LOAM) to simulate such freshwater forcing and conducted several extended simulations to examine model sensitivity and response. The model was forced by coupling it to the Lamont Atmospheric Mixed Layer model, using climatological winds with additional anomalous, fixed freshwater flux forcing equivalent to the change in rainfall during a moderately strong El Niño. The model responds to reduce tropical Atlantic rainfall by initially displaying a local reduction in surface salinity. The anomalous salt anomaly is transported northward in the western boundary current and reaches the subpolar region in 20 years (see Figure 2). We are planning to continue this investigation under different funding in the upcoming years.

Highlights
Ocean model integrations support the hypothesis that persistent tropical Atlantic rainfall anomalies due to ENSO significantly affect the surface salinity in the entire North Atlantic Basin. It takes about 20 years for a persistent tropical rainfall anomaly to be advected in the Western Boundary Current and affect the subpolar region.

Societal Benefits
This research examines various factors that can affect the Atlantic thermohaline circulation and as such is important in assessing the direction as size of the Atlantic Ocean response to climate change.

Personnel
Research Scientist: 1

Publications
Conference proceedings / workshops
Results from this study were incorporated in a presentation at the 2005 Fall AGU meeting
Atlantic Freshwater Flux Forcing

Annual mean El Niño-related $P - E$ anomaly (cm/yr)

Data in cm/year - 1979 to 2004 average, ppt from GPCP and E from Reanalysis

Largest forcing is in the tropical Atlantic and is anti-correlated with El Niño

Annual-mean (June-May) Atlantic freshwater forcing (P-E) in response to El Niño. Area integrated forcing over the marked regions is given in Sv.
Atlantic surface salinity anomaly (PSU) in response to a steady ENSO freshwater forcing (as seen in Figure 1), 20 years after the forcing was "switched on".
A Project Title: ARCHES: Paleo Sea-Ice Distributions

Principal Investigator: Robert F. Anderson

Affiliation: Lamont-Doherty Earth Observatory

NOAA Program Manager: James Todd, CLIVAR-Atlantic
301-427-2383 james.todd@noaa.gov

Research Goals
This project has two broadly defined objectives:
1. To calibrate (improve) and later apply transfer functions (algorithms) designed to reconstruct sea ice distributions in the Southern Ocean based on the assemblage of diatom species preserved and buried in sediments. This objective has been modified during the latter half of this project to explore and develop a new proxy, based on the abundance of Interplanetary Dust Particles in sediments, for freshwater supply by melting icebergs.
2. To develop high-resolution records of changes in the ventilation (the degree to which the gases in water are equilibrated with the atmosphere) of Southern-Source Deep Water through periods of Abrupt Climate Change.

Ultimately these two objectives will be integrated in that sea ice cover and meltwater supplied by melting icebergs influences the ventilation of newly-formed deep water, as well as having a major impact on air-sea fluxes of heat, moisture, and momentum.

Education Goals
Support the education and training of a graduate student, Ms. Shahla Ali.

Research Progress
1. Sea Ice Reconstruction / Iceberg Melting
a. As described in previous progress reports, we were unable to hire a diatom micropaleontologist at Lamont to perform the planned study of sediment trap samples to improve the algorithms used to reconstruct sea ice in the Southern Ocean. Consequently, we provided resources to help Ivo Grigorov, a PhD student at Southampton Oceanography Centre, study the samples for his thesis research. The thesis was completed (see below) and a manuscript based on the results is in preparation for submission to Deep-Sea Research. Although Anderson is not a co-author of the manuscript, he worked extensively on it during the past year.


b. As described last year, our pilot study of Helium-3 as a tracer of iceberg melting in the Southern Ocean produced results that are inconsistent with those expected from the previous use of an oxygen isotope proxy for iceberg melting. Those results were presented as a poster at the Ocean Sciences meeting in
Honolulu, February, 2006 (see Section 8 and a Figure showing results in Section 12) and a manuscript is in preparation, with an anticipated submission date by the end of Summer 2006.

2. **Paleo Ventilation**
   We are developing opal burial rates as a proxy to reconstruct the upwelling of deep water in the Southern Ocean. Briefly, the proxy works as follows. South of the Antarctic Polar Front (APF), where most upwelling of deep water occurs, diatoms consume nearly all of the available dissolved silicic acid each summer growing season. The only way to grow more diatoms is to provide them with more silicon, which they use to build their microscopic shells. We measure the accumulation rate of diatom shells in Southern Ocean sediments at sites south of the APF to provide a constraint on past changes in upwelling of deep water (i.e., ventilation of deep water masses).

In all three sectors of the Southern Ocean (Atlantic, Pacific and Indian) we find evidence for greatly increased burial rates of diatom shells during intervals corresponding to abrupt cold events in the North Atlantic region, specifically, Heinrich Event 1 and the Younger Dryas. The fact that upwelling of deepwater is dramatically accelerated during these events informs us that more is involved than a simple interhemispheric transfer of heat, as was postulated previously in the “Bi-Polar See Saw” hypothesis. Rather, the entire process of global meridional overturning circulation is involved during these abrupt climate change events. North Atlantic Deep Water formation was at a minimum during these cold events, which requires that the accelerated overturning of deep water was driven by processes in the Southern Ocean. These results were presented in an invited talk at the Ocean Sciences meeting (Honolulu, Hawaii, February, 2006; see Section 8).

3. While working on the projects above, Anderson wrote a paper clarifying problems in the use of proxies to study past changes in ocean productivity (Anderson and Winckler, 2006).

*Highlights*

- Abrupt cold periods in the North Atlantic region (e.g., Heinrich Event 1 and the Younger Dryas) were accompanied by enhanced upwelling and ventilation of deep waters around Antarctica.
- These periods of enhanced ventilation corresponded to times of minimum North Atlantic Deep Water formation, indicating that the enhanced ventilation was forced by processes in the Southern Ocean.

*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*

**Interagency**
Results generated with NOAA support aid in our interpretation of ice-rafted debris in Southern Ocean sediments, under a project funded by the National Science Foundation.
Collaborators
Our collaborators in the NSF-funded study mentioned above, at the University of Florida, likewise benefit from these synergies.

Awards / Honors
During the past year Anderson received the following awards:
- 2005 A.G. Huntsman Award for Excellence in the Marine Sciences by the A.G. Huntsman Foundation, Dalhousie University, and the Bedford Institute of Oceanography.
- 2005 Elected Fellow of the American Geophysical Union

Education and Outreach
Research advisor / mentor
Graduate: PhD student Shahla Ali is supported by this award.

Academic participation
Presentations


Personnel
Research Scientists: 2, Research Support Staff: 3, Administrative: 1, Graduate Student: 1

Publications
Journal Articles
Results from a pilot study testing the use of extraterrestrial He, contained within Interplanetary Dust Particles (IDPs), as a proxy for iceberg melting. (A) Flux of He determined using the Th-normalization method in core TN057-13PC (63°S, 5°E) plotted against age. (B) Oxygen isotope composition of biogenic opal (diatom shells) plotted against age (published results of Aldo Shemesh). (C) Abundance of ice-rafted grains, measured by collaborators at the University of Florida, plotted against age. (D) Radiocarbon ages of calcium carbonate plotted against depth in the core to provide an age model for the parameters plotted in A - C (published results of Aldo Shemesh and Dave Hodell). IDPs are deposited on the Antarctic ice sheet as snow accumulates, and are released from icebergs as they melt. IDPs contain high concentrations of He, making this a valuable geochemical tracer for IDP concentration. Other studies have constrained the global average flux of He associated with IDPs to be about 0.8 X 10\(^{-12}\) cc cm\(^{-2}\) kyr\(^{-1}\). A mass balance calculation based on the oxygen isotope results, making reasonable assumptions about the oxygen isotope composition and He concentration in the Antarctic ice sheet, led to a prediction that the measured He flux should be as much as an order of magnitude greater than the global average during the negative excursions in the oxygen isotope record (intervals highlighted in white). Contrary to these expectations, we found no detectable increase in He flux during these events. We are presently pursuing several hypotheses to account for this discrepancy. A possible explanation is that the icebergs melted south of the core site, leaving freshwater to migrate northward across a stratified surface ocean to the location of the core.
Flux of biogenic opal determined using the $^{230}$Th-normalization method (core TN057-13; 63°S, 5°E; located south of the Antarctic Polar Front) and a reconstructed temperature anomaly from the Vostok ice core in central Antarctica plotted against age. Periods of high opal flux (16-14 ka, 13-10 ka) are interpreted to reflect enhanced upwelling of deep water. These periods generally correspond to intervals during which central Antarctica was warming. The local of minimum in opal flux is correlated with the Antarctic Cold Reversal (ACR), the time when warming of Antarctica ceased for about 1000 years. Misalignment of the two features corresponding to the ACR (minimum opal flux and interrupted rise in Antarctic temperature) may reflect uncertainties in the age models of one or both records. Regardless of the offset corresponding to the ACR, the generally good alignment of the two records indicates that upwelling of deep water south of the Antarctic Polar Front was much more vigorous than today at times when Antarctica was warming. These times corresponded, roughly, to periods of extreme cold in the North Atlantic region, including Heinrich Event #1 and the Younger Dryas. Production of North Atlantic Deep Water was depressed at those times, from which we infer that the enhanced upwelling south of the Antarctic Polar Front was driven by processes in the Southern Ocean.
**Project Title:** ARCHES: Understanding Abrupt Change and the Glacial to Interglacial CO₂ Record

**Principal Investigator:** Wallace Broecker

**Affiliation:** Lamont-Doherty Earth Observatory

**NOAA Program Manager:** James Todd, CLIVAR-Atlantic  
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**Research Goals**
To understand how ocean circulation has changed over the last 20,000 years and how these changes have impacted climate.

**Research Progress and Highlights**
Changes in the extent of shell fragmentation, the wall thicknesses of foraminifera shells, and the bulk CaCO₃ content of deep Pacific sediments demonstrate that the bottom waters have steadily decreased in carbonate ion concentration during the past 8 kyrs. Based on measurements on sediment core-top material from a range of water depths on the Ontong-Java Plateau, these indices have been calibrated allowing the extent of the decrease in carbonate ion concentration to be quantified. The results suggest that the decrease may have been larger than that of 6 µmol per kg expected to accompany the 20 µatm rise in atmospheric CO₂ content which occurred during this time interval. However, the inconsistency between the magnitude of the change based on shell weight on one hand and that based on the increase in fragmentation on the other is problematic.

If indeed the drop in carbonate ion concentration has been larger than expected, then 8 kyrs ago either a change in the pattern of thermohaline circulation or in the strength of the biological pump must have kicked in and become ever stronger as the millennia passed. If thermohaline circulation is the villain, then a possible explanation is that the strength of deep-water formation in the northern Atlantic has weakened relative to that in the Southern Ocean over the last 8 kyrs. As the major uncertainty in the conclusions reached in this paper has to do with the lag in response introduced by the residence in the calcite-corrosive core-top bioturbated zone, we are conducting radiocarbon measurements on various calcite entities in core top samples. Key to this investigation will be the ¹⁴C age difference between whole foraminifera shells and shell fragments (of the same species). The importance has to do with the difference in the carbonate ion decline obtained using the shell fragmentation proxy and the shell weight proxy.

**Personnel**
Research Support Staff: 2, Administrative: 1

**Publications**

**Journal articles**
Broecker, 2006: Is the Magnitude of the Carbonate Ion Decrease in the Abyssal Ocean Over the Last 8 kyrs Consistent with the 20 ppm Rise in Atmospheric CO₂ Content? Submitted to Paleoceanography.
Project Title: ARCHES Sub Awardee: Mountain Snowlines in the Southern Hemisphere

Principal Investigator: George H. Denton
Affiliation: Climate Change Institute, University of Maine

NOAA Program Manager: James Todd, CLIVAR-Atlantic
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Research Goals
The research goals were (1) to produce a complete set of 10Be exposure ages for moraines of the last glaciation in the Pukaki basin of New Zealand’s Southern Alps, and (2) to collect and date exposure samples from Holocene moraines in the Southern Alps.

Education Goals
The educational goal was to train one graduate student and one undergraduate in glacial geologic fieldwork, as well as to allow the graduate student to collect material for a Ph.D. thesis.

Research Progress
The following was accomplished. Holocene moraines were mapped in the upper Whale Stream and Irishman’s Creek sectors of the Ben Ohau Range of New Zealand’s Southern Alps. In the same vein, the Holocene moraine complex was mapped in the Cameron Valley of the Arrowsmith Range of the Southern Alps. A comprehensive set of samples for exposure-age dating was collected from Holocene moraines associated with the Muller, Hooker, and Tasman Glaciers in Mt. Cook National Park in the Southern Alps.

Samples for exposure-age dating were collected from the left lateral LGM moraine complex in the Pukaki basin on the southeastern flank of the Southern Alps, as well as the frontal LGM moraine complex in the nearby Ohau basin. In addition, samples were collected from the recessional moraine complex in the Pukaki basin.

Mapping at a scale of 1:50,000 was completed for the Rakaia and Rangitata drainage systems on the southeastern flank of the Southern Alps.

All exposure samples were shipped back to Lamont-Doherty. Processing of these samples has been underway since February of 2006. Results are now available for about 30 samples. Another 50 have been processed at Lamont-Doherty and sent to Lawrence-Livermore for measurement at the end of August. A further batch will be sent from Lamont-Doherty to Lawrence-Livermore for measurement at the end of September.

Highlights
- A preliminary exposure chronology for moraines in the Pukaki drainage basin was published in Science (Figure 1). The results demonstrated that the last termination was near-synchronous in middle latitude of both hemispheres, and certainly antedates the abrupt warming in the North Atlantic region at the beginning of the Bölling (Figure 2).
- A suggested scenario for the near-synchronous last global termination demonstrated by exposure dates in both hemispheres was published in Pages (Figure 3). The idea is based on the role of seasonality in abrupt climate change, coupled with the concept of a bipolar seesaw of thermohaline circulation. The basic hypothesis is that the last termination was initiated by the melting of the H-1 iceberg armada released into the North Atlantic from the huge northern ice sheets when they were close to maximum volume. This event shut down MOC in the North Atlantic, leading to...
hypercold winter conditions in northern high latitudes. The winter sea ice also severely curtailed the summer Asian monsoon and pushed southward the Atlantic sector of the ITZC. Second, the shutdown of northern Atlantic MOC caused a reorganization of deep ocean circulation in which Southern Ocean surface waters warmed, with a consequence shrinkage of Antarctica’s apron of sea ice. The rise in atmospheric CO$_2$ from increased outgassing related to retreat of the sea-ice margin is the critical factor that drove the last termination on the global scale revealed by the exposure-age data published in *Science*.

- The available exposure-age dates, maps, and snowline data for New Zealand’s Holocene moraines reveal a fundamental difference between the hemispheres. In the north, advances of mountain glaciers were, in general, successively larger during the course of the Holocene, culminating in the Little Ice Age. The reverse is true in the last 6000 years of the Holocene in New Zealand. Here, the maximum advances occurred in the middle Holocene, with subsequent advances being smaller and smaller. Why this striking difference occurred is a puzzle that will occupy our efforts over the next year.

*Societal Benefits*

Our research efforts are designed to clarify the issue of abrupt climate change — an important issue for humanity in a warming world in which the climate system has numerous tipping points.

*Other Research Connections*

**Research Partnerships**

Our research in New Zealand is carried out in partnership with GNS-Science, the New Zealand equivalent of our Geological Survey. Officers of GNS-Science take part in the fieldwork and supervise map production.

**Collaborators**

Björn G. Andersen, University of Oslo, Norway; Joerg Schaefer, Lamont-Doherty; Trevor Chinn, Glaciological Associates, Hawea, New Zealand

**Awards / Honors**

George H. Denton, Honorary Doctor of Science, University of Edinburgh, Scotland

*Education & Outreach*

**Research advisor / mentor**

Undergraduate: Alice Doughty, B.S. in Earth Sciences, continuing on for a M.S. Degree

Graduate: Aaron Putnam, M.S./Ph.D. student - Sean Birkel, Ph.D. Student

**Academic participation**

**Presentations**

- Graduation Address, late June 2005, University of Edinburgh, Scotland. Humans and Climate Change.

- Invited lecture, late June 2005, Department of Physical Geography, University of Edinburgh, Scotland. The role of seasonality in abrupt climate change.


- Invited lecture, March 2006, University of South Florida, St. Petersburg, Florida. Abrupt climate change.

Publications

Journal articles


Glacial geomorphology map of the Lake Pukaki area, Southern Alps, New Zealand, including all sample sites. Samples Kiwi 333, 336, 404, 405, 406, 407, 408, 602, and 603 were taken from the inner moraines of the LGM complex, whereas Kiwi 524, 800, and 802 were from deglacial moraines representing glacier retreat and are used here as a younger bound for the onset of the LGM termination. Sample NZ 4541 was a radiocarbon-dated organic layer in clay 30 km up-valley from the LGM terminal moraines, also representing a minimum age for the onset of the LGM deglaciation of the Pukaki glacier trough. Figure taken from Schaefer et al. (2006).
Comparison of the onset of the midlatitude glacier LGM termination with polar ice core records. Plotted for each moraine record are (i) the mean age (solid diamonds) and (ii) the oldest $^{10}$Be boulder age of each moraine set (open diamonds). Error bars indicate 1σ standard deviation and 1σ analytical uncertainty, respectively. The solid vertical line is the mean of all individual mean ages (17.2 ky); the dotted vertical line is the mean age of all the oldest $^{10}$Be ages [19 ky, see text and (14)]. No substantial warming was indicated in the isotopic record from Greenland at that time (8), whereas isotopes implied that temperatures started to rise in Antarctica (5) in near-synchrony with the onset of mid-latitude glacier LGM termination. Figure taken from Schaefer et al. (2006).
The Mystery Interval is marked by yellow background. **A** shows the deuterium and CO$_2$ records from the EPICA Dome C ice core on the East Antarctic plateau (Monnin et al., 2001). The chronology is based on Schwander et al. (2001). **B** gives the GISP2 isotope record (Stuiver and Grootes, 2000). **C** illustrates ice-rafted grains and magnetic susceptibility in core SU-8118 off Portugal (Bard et al., 2000). The IRD is expressed as the number of grains per gram for the size fraction greater than 150 µm. The H-1a IRD peak features quartz and feldspars, with minor hematite-coated grains, glauconite, and volcanic shards. The H-1b IRD peak is largely detrital carbonate, with minor amounts of quartz and feldspar (Bard et al., 2000). **D** is SST from two calibrations for alkenone unsaturation ratios from core SU-8118 (Bard et al., 2000). **E** is a $^{231}$Pa/$^{230}$Th profile from core GGC5 from the Bermuda Rise (McManus et al., 2004). YD is Younger Dryas, B/A is Bölling/Alleröd, MI is Mystery Interval, and LGM is Last Glacial Maximum. Figure taken from Denton et al. (2006).
**Project Title:** ARCHES: Constraining Changes in Winds, the Conveyor and Local Currents During Periods of Abrupt Climate Change

**Principal Investigator:** Sidney R. Hemming

**Affiliation:** Lamont-Doherty Earth Observatory

**NOAA Program Manager:** James Todd, CLIVAR-Atlantic

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**Research Goals**
- To develop and apply proxies in ocean sediments that allow constraining important components of the paleoclimate system.
- To integrate the records with existing information in order to constrain winds, and ocean circulation during periods of abrupt climate change.

**Education Goals**
- Training and mentoring graduate students and post docs.
- Involving high school and undergraduate students in hands-on research projects.
- Incorporating discoveries into the classroom.

**Research Progress**
Throughout this funding we have worked on the provenance of clays in the area around Africa to understand changes in the Agulhas Leakage, and have extended our survey to the entire South Atlantic. This has resulted in a paper that was accepted by EPSL recently (Franzese et al., accepted). Additionally, we have made a first step towards characterizing the contributions from Antarctica, leveraged with funding from NSF OPP. It appears there was a northward shift in the fronts, and by implication the wind belts around the ACC during the LGM. During the second, third and fourth years of this project we focused our efforts on producing high resolution records from the authigenic Nd isotopes of the Cape Basin (Piotrowski et al., 2004, 2005) as well as completing the South Atlantic provenance survey and a South Atlantic authigenic Nd survey, which was also partly supported by a grant from NSF OCE. Beginning in year 4, we have been collaborating with Ian Hall, Rainer Zahn and their student Vicky Peck and post doc Elena Colmenaro-Hidalgo to study high-resolution ocean-atmosphere-ice sheet interaction as well as to characterize major ice rafted detritus (IRD) contributors in the North Atlantic region. Vicky Peck is near completion of her Ph.D., with two papers (Peck et al., 2006, in review). We have more than 300 hornblende grains from Elena Colmenaro-Hildalgo, and she plans to do Nd isotopes on the coarse fractions of about 50 samples. This spring Martin Roy (partly funded by this project in year 5) presented $^{40}$Ar/$^{39}$Ar measurements on a series of till samples along the 58th parallel from Hudson Bay to the Labrador Sea as part of our goal of characterizing potential ice rafted detritus contributors around the North Atlantic, and he plans to produce a manuscript on this work. Beginning in year 5 a new and exciting opportunity presented itself, that is the application of U-series and radiocarbon dated deep-sea corals as an archive to get spot recordings of the Nd isotope composition of paleo-sea water. This effort has been led by Postdoctoral Fellow Tina van de Flierdt, and a paper on the first results has been accepted by Paleoceanography (van de Flierdt et al., submitted).

A further goal is continued method development, both for the authigenic ferromanganese component. This work has been carried out by Lamont student Kevin Jones during year 5, and we have obtained NSF OCE funding for his ground-truthing tests, as well as for the continued support of Allison Franzese’s efforts on the paleo-Agulhas leakage and retroflection. While more tests are needed to understand the cores that do not yield data that reflect the ambient seawater, the cores from the southern Cape Basin have yielded really exciting results and Alex Piotrowski published two papers on the application of the authigenic ferromanganese
component from the Cape Basin to global changes in ocean circulation over the past 100 ka (Piotrowski et al., 2004, 2005).

Highlights
- Evidence for northward shift in the southern westerlies (and the Agulhas retroflection) in the LGM
- Evidence for glacial-interglacial and millennial change in the NADW contribution to southern ocean waters
- Evidence that the NADW composition was constant
- High resolution information on ice sheet-ocean-atmosphere interactions

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

Research partnerships
LDEO-Cardiff-Barcelona-GEOTOP

Collaborators
Ian Hall, Rainer Zahn, Vicky Peck, Elena Comenaro-Hidalgo, Martin Roy

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

Research advisor / mentor
Undergraduate: we have engaged several undergraduate summer interns in this research (Hadas Kushnir, Stacey Kepler, Caleb Schif, Sean Culkin, Stephanie Pahler), and one Stephanie Pahler, did a senior thesis at Barnard College with Allison Franzese

Graduate: Allison Franzese, Kevin Jones

Personnel
Post Doctoral Fellow: 2, Graduate Students: 2, Undergraduate Students: 5

Publications
Journal articles


**Books / articles-in-books**


Figures / Photographs / Illustrations
ARCHES: Constraining Changes in Winds, the Conveyor and Local Currents During Periods of Abrupt Climate Change

(A) Nd isotope ratios and benthic 13C (8, 19, 20, 32) of RC11-83/TNO57-21 and climate records. Nd isotope ratios, representing NADW strength at the RC11-83 site, are plotted as Nd on a reverse axis for comparison purposes. References: GRIP 18O (26, 27), GISP2 18O (25), and Vostok D deuterium (47). All records are on published referenced chronologies and independent of each other. The chronology is based on (20) and (32) for TNO57-21 and (18) for the Holocene to LGM. YD, Younger Dryas; ACR, Antarctic Cold Reversal. (B) Comparison of Nd to GISP2 and Vostok records for deglacial period, showing that the Nd isotopic variations are not affected by the ACR.
Project Title: ARCHES: Southern Ocean Modern Observations
Section 1. Moorings
Section 2. Observations

Principal Investigator: Arnold Gordon
Affiliation: Lamont-Doherty Earth Observatory

NOAA Program Manager: James Todd, CLIVAR-Atlantic
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Section 1. Moorings

Research Goals
Install and maintain three deep and bottom water focused moorings south of the South Orkney Islands in the Northwest Weddell Sea to provide a time series of the combined outflow (currents and temperature/salinity) of Antarctic Bottom Water drawn from various sites within the Weddell Sea. As the time series is compiled, it will be examined for indications of climate variability on sub-decadal time scales. A section of CTD / tracer stations is reoccupied during the service cruises as time and conditions permit.

We rely on opportunistic scheduling of vessel time provided by a variety of sources, so timing of cruises for maintaining the moorings is approximate. Research goals remain flexible so we can take advantage of ship time opportunities as they arise.

Research Progress
The export of Antarctic dense shelf water from the Weddell Gyre is being investigated with the Consortium on Oceans Role in Climate: AbRupt climate CHangE Studies (CORC-ARCHES) Southern Ocean Modern Observations program. Three deep and bottom water focused moorings south of the South Orkney Islands in the Northwest Weddell Sea provide a time series of the combined outflow (currents and temperature/salinity) of Antarctic Bottom Water drawn from various sites within the Weddell Sea.

First installed in April 1999, the moorings are serviced using ship time made available by other programs. The moorings were last visited in late 2001. Severe sea ice conditions prevented servicing the moorings in 2003 and 2004. In March of 2005, we succeeded in reaching the mooring sites, recovering two, and redeploying a mooring at the southernmost site. In addition, in collaboration with E. Domack and co-investigators, five instrumented sediment trap moorings were deployed in the Larsen B embayment during the same cruise, and several CTD stations occupied at the mooring sites and nearby.

The records recovered in March ’05 continuously span more than 3 years in some cases, including the time period corresponding to the breakup of the Larsen B ice shelf of the eastern Antarctic Peninsula in early 2002. It has been hypothesized that the Larsen ice shelves play a significant role in the production of deep and bottom waters in the western Weddell Sea, so the CORC-ARCHES time series may be uniquely positioned to investigate the oceanographic conditions leading up to and following the breakup of the Larsen B.

Preliminary analysis of the now nearly six-year time series clearly reveals the seasonality of the deep temperatures, with longer period signals superimposed.

In collaboration with colleagues from the British Antarctic Survey, an attempt was made to service the moorings in December/January 05/06 from the RRS James Clark Ross (JCR). Excessive sea ice and poor weather conditions prevented the JCR from reaching the sites. The mooring sites were revisited in April-May 2006 on board RVIB Nathaniel B Palmer (NBP0603), with the intention of servicing the moorings still in place, replacing some aging instrumentation,
and potentially add moorings to the array in collaboration with investigators from the British Antarctic Survey. Unfortunately, due to sea ice, weather and time constraints, we were unable to accomplish the planned mooring work on NBP0603. However, several CTD stations were obtained in the Larsen B embayment and near the southernmost mooring site off the South Orkneys.


**Highlights**
- Expanded CTD station coverage of the Larsen B embayment and CTD times series at the S Orkney mooring site
- Continued analysis of the 6-year mooring time series, with publication in progress.

**Societal Benefits**
Changes in deep and bottom water outflow characteristics from the Weddell may be indicators of climate change on global scales. The CORC-ARCHES data set is potentially an important resource for identifying and understanding climate change processes.
Time series of potential temperature from mooring M3, positioned in 4560 m depth to capture the outflowing Weddell Sea Bottom Water (WSBW). The bottom panel displays low-passed speed from the near-bottom current meter. The nearly 6-year time series is rich in variability across a wide range of time scales, including tidal, seasonal and interannual.
Composite potential temperature-salinity plot of low-passed data from moorings M2 and M3, superimposed on data derived from the repeated CTD stations at the mooring sites. Data points for the deepest instrument on M3 are colored red when the corresponding speed exceeded 14 cm/s. WSBW characteristics revealed at M3 appear to follow two or more discrete characteristics in time rather than smoothly varying within an envelope. Embedded in these data are measurements, which may have captured the after effects of the 2002 breakout of the Larsen B ice shelf.
Section 2. Observations:

**Research Goals**

To investigate the utility of historic sea surface salinity data as a proxy for the marine hydrological cycle.

**Research Progress**

Salinity, a sea water equation of state variable, is an explicit regulator of ocean dynamics; additionally, it is a sensitive indicator of the marine hydrological cycle, and associated latent heat implications. How unfortunate that in view of its central role in ocean circulation and climate that our spatial and temporal image of sea surface salinity [SSS] is so poorly depicted by our overly smoothed maps. Contrast these blurry fields with the detailed textured patterns revealed by satellite images of such parameters as sea surface temperature [SST], sea level, fields of sea ice, and even of winds stress acting on the ocean surface. We have a hint of the horizontal scales of SSS variability from the under-utilized underway systems accompanying the WOCE and CLIVAR sections. These show intriguing textures of SSS along the cruise track, which differ from the spatial form of the SSS variability. These imprint a texture to surface density that may affect fronts, mixed layer structures, not obvious from the SST field.

We often see graphics showing the changing SST with time, and recently we are seeing some more studies of SSS temporal. But these are based on averaging SSS data over very large areas, and even then the signal to noise ratio is small. We can achieve a sharper view of SSS temporal changes if we focus on specific ocean regimes, such as the hub of the Ekman transport. Recent studies suggest that the subpolar and polar SSS is decreasing over recent decades, while the subtropical SSS is increasing. There are hints that these fluctuations respond to the various climate oscillations, as ENSO, NAO, PDO, as well as longer-term trends. Regional changes in SSS may indicate a changing nature of the relationship of the shallow overturning circulation cell spanning the subtropics to the ITCZ associated with the sub-surface salinity maximum, and to the more global scale MOC driven in part from the North Atlantic. These subtle changes may alter the ocean meridional heat transports.

Direct measurement of precipitation [P] and evaporation [E] over the ocean is exceedingly difficult and prone to large errors. The marine P-E data uncertainty is arguably the greatest uncertainty in the global hydrological cycle. Inference from satellite data has helped reduce the uncertainty, and re-analysis of the marine data set with sophisticated statistical handling provide us with an improved albeit still blurry view of the marine hydrological cycle. SSS is a surprisingly good indicator of the hydrological cycle over the ocean.

We see this in the excellent time series of SSS [upper 20 meters] offered by the monthly Bermuda [BATS and earlier] data set. Figure 1 upper panel shows the monthly BATS SSS with 12 month running mean; the lower panel shows the ENSO and Pacific Decadal Oscillation [PDO] indices. There are two periods of sustained, decadal SSS swings [purple dashed lines], with a peak in 1965, and generally elevated SSS since late 1980s. Green boxes denote periods of decreasing SSS, which correspond to El Niño while increasing SSS corresponds to La Niña; Re-analysis data does indicate that precipitation increases in the Bermuda region during El Niño periods. The SSS time rate of change at the ENSO periods reveals P-E changes of ~10% of the annual mean P-E value, and so SSS is a powerful method to quantify fluctuations of the marine hydrological cycle. There appears to be a change in BATS SSS/ENSO behavior after 1976 perhaps related to the famous regime shift when PDO switched from mainly negative mode to a more positive attitude.
Highlights
- Using the BATS sea surface salinity (SSS) data time series, it is demonstrated that analysis of SSS patterns is a powerful method to quantify fluctuations of the marine hydrological cycle.

Societal Benefits
Measurement and understanding of precipitation/evaporation patterns (P/E) over the oceans is a critical component of understanding the global hydrologic cycle, yet direct measurement of P/E over the ocean is exceedingly difficult and prone to large errors. Alternative methods, such as SSS analysis, can yield important insights into the marine hydrological cycle.

Other Research Connections
Interagency
This research benefits from ship time provided by the NSF Office of Polar Programs at very nominal cost.

As a member of the NASA Aquarius Scientific Steering committee and CLIVAR Salinity steering committee, this research contributes to efforts to understand satellite measurement of SSS and global patterns of SSS.

Research partnerships
Continued plans with researchers at British Antarctic Survey to collaborate in the servicing and expansion of the CORC-ARCHES mooring array

Collaborators
As a direct result of our ship time arrangement with OPP, we have developed a collaboration with NSF-funded researchers to pursue studies of the Larsen ice shelf region as part of the upcoming International Polar Year.

Awards / Honors
A. Gordon: Sc.D. University of Cape Town, South Africa, 2005 Honoris causa

Education and Outreach
Research advisor / mentor
Graduate: Orton, Philip, PhD candidate; Tillinger, Debra, PhD candidate

Academic participation
Presentations
- AGU Ocean Sciences meeting, February 2006, Honolulu, “Ocean Salinity, a responsive component of the Climate System”. (Invited talk)

Personnel
Research Scientist: 1, Research Support Staff: 3, Administrative: 1, Graduate Student: 1

Publications
Journal articles
The monthly Bermuda [BATS and earlier] time series provides a view of sea surface salinity [SSS] temporal variability. Here are monthly BATS SSS with 12-month running mean, with in the lower panel the ENSO and Pacific Decadal Oscillation [PDO] indices.
**Project Title:** ARCHES: Tracer Observations of Deep Formation and Circulation in the Southern Ocean

**Principal Investigator:** Peter Schlosser

**Affiliation:** Lamont-Doherty Earth Observatory

**NOAA Program Manager:** James Todd, CLIVAR-Atlantic  
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**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 $^{3}$He 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 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 $^{3}$He 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

Academic participation
Seminars
Princeton University, February 2006, August 2006

Symposiums
New material will be presented next year at EGU meeting

Personnel
Research Scientist: 1, Research Support Staff: 3, Administrative: 1, Graduate Student: 1, and Undergraduate Student: 1

Figures / Photographs / Illustrations
ARCHES: Tracer Observations of Deep Formation and Circulation in the Southern Ocean

Example of the results from the global $^3$He distribution work: Distribution of $^3$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.
**Project Title:** ARCHES: Southern Modeling and Analysis

**Principal Investigator:** Douglas Martinson

**Affiliation:** Lamont-Doherty Earth Observatory

**NOAA Program Manager:** James Todd, CLIVAR-Atlantic

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**Research Goals**

Improve our quantification of the nature (magnitude, temporal-spatial distributions) of ocean-ice variability in the western Antarctic Peninsula region.

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**Education Goals**

Acquaint school children with Antarctic field science (accomplished by Rich Iannuzzi's "live" from the field to elementary school classrooms when in the field)

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**Research Progress**

1. The Year 6 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)." The Antarctic Peninsula is undergoing the most rapid regional warming on Earth, with extensive melting of glacial ice on its western side. We have made substantial progress on this issue, and now show (in multiple submitted papers) that: (1) The western Antarctic Peninsula region underwent a regime shift in 1998 following the major El Nino of that year (note that the SE Pacific and Southern Atlantic Antarctic polar oceans show the largest extratropical SAT response to ENSO events on Earth) (2) The regime shift is accompanied by the near complete loss of perennial sea ice in the WAP (inflicting a considerable impact to the ocean-atmosphere-ice interaction (OAI) and ecosystem (3) Ocean properties clearly reflect the climate change through a variety of integrated properties, and surface variables. (4) The change in the ocean heat flux over the last few decades is likely responsible for the remaining 50% of the undescribed source of warming to the peninsula (Thompson and Solomon, 2002) clearly show that ~50% of the warming can be attributed to changes in the Southern Annular Mode (SAM) in response to anthropogenic changes in the Antarctic ozone).

2. Stammerjohn has completed her Ph.D. thesis, showing the role of climate variability and wAP response to changes in global-scale climate patterns. Her success in testing our one-dimensional ocean (kpp-based)-sea ice model is beginning to give insights regarding relative roles of different processes driving ocean heat flux, sensitivities of sea ice coverage to change in atmospheric forcing, etc.

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**Highlights**

- Identified regime shift in wAP marine system following 1998 El Niño
- Documented near-complete loss of extensive perennial sea ice following regime shift
- Further quantified ocean heat flux contribution to wAP, leading to insights helping to decompose ocean’s role in extensive glacial melt in wAP.

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**Societal Benefits**

Quantification of ocean’s contribution to the WAP warming and possibly to rapid melt of glaciers on WAP.
Other Research Connections

Interagency
National Science Foundation, particularly the Palmer Long Term Ecological Program (PAL LTER) project, focused on ecological changes, but NOAA leverage allows me to focus on physical variability in isolation (NOT permitted under my LTER NSF obligations)

Research partnerships
With PAL LTER as stated above

Collaborators
Ducklow (VIMS), Smith, Ross, Quetin (UCSB), Vernet (Scripps), Large (NCAR)

Awards / Honors
Awarded Outstanding Teacher of Year in January, 2005, Department of Earth and Environmental Sciences, Columbia University

Education and Outreach

Academic outreach
K-12: Iannuzzi, communicates via satellite link to elementary schools on Long Island when at sea, and then speaks to the classes upon his return.

Research advisor / mentor
Graduate: Sharon Stammerjohn (now with UCAR post-doc at NASA GISS)

Academic participation
Presentations (NOAA funding acknowledged)
  Martinson (invited speaker; 12 Years of Physical Oceanography in wAP: spatiotemporal variability, Scott Polar research Institute, Cambridge, UK, 6/27/56

  Martinson (invited as UCLA Tod Spieker Colloquium Speaker), Ventilation of ocean heat along the Western Antarctic Peninsula, UCLA, 4/7/06, UCLA, CA

  Martinson (invited as S.O. Ocean Panel representative at International CLIVAR Science Steering Meeting), Ventilation of ocean heat along the Western Antarctic Peninsula, Buenos Aires, Argentina, 4/18/06

  Martinson (invited speaker; 12 Years of Physical Oceanography in wAP: spatiotemporal variability, Boulder, CO, 5/16/06

  Martinson briefing to French Senate delegation charged with investigating climate change in polar regions to evaluate France's needs for involvement (LDEO, 5/22/06)

Personnel
Research Scientist: 1, Visiting Scientist: 1, Research Support Staff: 1, Graduate Student: 1

Publications

Journal articles

Martinson and Pitman (in press), Role of the Arctic in Glacial terminations, Climatic Change.

Martinson, Stammerjohn, Iannuzzi, Smith (submitted), Palmer, Antarctica, long-term ecological research program first twelve years: Physical Oceanography, Spatio-Temporal Variability, Deep Sea Research.

Ross, Quetin, Martinson, Iannuzzi, Stammerjohn, and Smith (submitted), Palmer LTER: Patterns of Distribution of Major Zooplankton Species West of the Antarctic Peninsula over a Twelve Year Span, Deep Sea Research.

Smith, Vernet, Kozlowski, Martinson, Stammerjohn, Iannuzzi, (submitted), Space/Time variability of Pigment Biomass in the WAP region for the period 1993 to 2004, Deep Sea Research.

Vernet, Martinson, Iannuzzi, Stammerjohn, Kozlowski, Smith (submitted). Control of Primary Production

**Ph.D. dissertations**
Sharon Stammerjohn (Ph.D. dissertation deposited 12/23/05): Seasonal sea-ice advance and retreat in the Southern Ocean, sensitivity and response to climate variability
Evidence of dramatic climate change in western Antarctic peninsula (A) shows most rapid winter regional warming on Earth (~5.5x global average; (B) loss of perennial sea ice in wAP from Stammerjohn et al.; (C) recent results from British Antarctic Survey USGS showing that 87% of glaciers in wAP are in retreat.
Results from Martinson et al. (submitted) showing change in ocean heat flux (as proxied by continental shelf water heat content, demonstrated in paper) to atmosphere in wAP over the 1990s, contributing considerable warming to the winter atmosphere.
Project Title: ARCHES: Tracer Observations of Deep Formation and Circulation in the Southern Ocean

Principal Investigator: William Smethie
Affiliation: Lamont-Doherty Earth Observatory

NOAA Program Manager: James Todd, CLIVAR-Atlantic
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Research Goals
The research goals for the 2005/2006 year were to continue collecting and analyzing seawater samples from newly formed Denmark Strait Overflow Water and its precursors and from deep and bottom water outflow from the northwest Weddell Sea, to measure the samples collected in 2005 from the Fimbul Ice Shelf region and the Ice Shelf Water plume flowing from beneath the Filchner Ice Shelf, and to collect CFC data from ship of opportunity cruises to continental shelf/slope regions around the Antarctic continent and from the Denmark Strait region.

Education Goals
To provide research opportunities for undergraduate and graduate students in our laboratory and in fieldwork.

Research Progress
CFC samples were collected on the seasonal Icelandic cruises as planned. We were not able to obtain samples from the deep Weddell Sea outflow at the ARCHES mooring site this year because of the very limited amount of time and manpower to service the moorings. Bruce Huber did collect 30 CFC samples for us from the Larsen embayment, which was created as a result of the breakup of the Larsen B ice shelf, and we will analyze those samples in the coming year. The CFC samples collected along the eastern and western edges of the Fimbul Ice Shelf and in Ice Shelf Water flowing out from beneath the Filchner Ice Shelf were analyzed and we will be collaborating with Povl Abrahamsen on interpretation of these data. There were no samples collected on ships of opportunity this year, but we are preparing to collect samples from a cruise in September upstream and downstream of Denmark Strait, which will provide detailed coverage of this region and will compliment the time series of measurements we have obtained from the Icelandic seasonal cruises. We have begun to examine the CFC and hydrographic data from the Mertz Polynya region taken on the NBP 00-08 cruise in 2000/2001 and will compare these data to data collected in the same region in the austral late winter as part of the NSF supported ANSLOPE project. This work is being done in collaboration with Stan Jacobs. High CFC concentrations are observed in the slope waters and at the base of the slope, suggesting bottom water forms in this region.

Highlights
- The CFC-11 and CFC-12 saturations in the surface waters in the Filchner and Fimbul ice shelf regions of the Weddell Sea are less than equilibrium, on the average 88% for CFC-11 and 84% for CFC-12. This is higher than the 60-70% observed during the period of rapid CFC increase in the atmosphere (1960-1990), but gas exchange is not sufficiently rapid to equilibrate the shelf water that is continually replenished by Circumpolar Deep Water that has a very low CFC concentration, although the CFC-11 concentration has been flat or slowing decreasing in the atmosphere for the past decade. Apparently the ice-free or low ice conditions during summer are not sufficiently long for complete equilibration to occur. This has implications for the exchange of CO2 between the Antarctic shelf waters and the atmosphere since CO2 has a longer gas exchange time constant than CFCs.
Societal Benefits
Understanding gas exchange in the seasonally ice covered waters of the Antarctic shelves, which produce dense water that sinks into the deep and bottom ocean, is important for understanding the exchange of CO2 between the ocean and atmosphere which impacts the earth’s climate.

Other Research Connections
Collaborators
- Stan Jacobs, Lamont-Doherty Earth Observatory
- Jon Olafsson, University of Iceland and the Iceland Marine Research Institute
- Keith Nicholls, British Antarctic Survey
- Povl Abrahamsen, British Antarctic Survey

Research advisor / mentor
Undergraduate: Ashley Cunningham is a summer intern from Washington and Jefferson College who is working in my lab this summer with support from NSF and is measuring CFC samples as part of her internship. She measured the samples collected from the Fimbul and Filchner ice shelf regions.

Graduate: Povl Abrahamsen is a student at the British Antarctic Survey who we are collaborating with on the CFC measurements from the Fimbul and Filchner ice shelf regions, which he collected in 2005.

Personnel
Research Scientist: 1, Research Support Staff: 2, Administrative: 1
**Project Title:** Collaborative Research: Development of a Blended Living Gridded Network of Drought Reconstructions of North America

**Principal Investigator:** Edward R. Cook

**Affiliation:** Lamont-Doherty Earth Observatory

**NOAA Program Manager:** Christopher D. Miller, Climate Change and Data Detection

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**Research Goals**

We are developing a blended living North American drought reconstruction grid, one that can be continuously updated as new instrumental data becomes available and therefore used for operational drought assessment. 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), a widely used measure of relative drought and wetness. This gridded drought/wetness metric will be used with centuries-long annual tree-ring chronologies to generate well-calibrated and verified drought reconstructions covering the past 500-1000 years over most areas of North America.

**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 gridded instrumental temperature and precipitation fields to be used for generating the PDSI and SPI drought metrics are nearing completion now and are expected to be ready for producing drought indices for reconstruction later in 2006. As paraphrased from an email sent by Russ Vose on January 14, 2006, the plan is to use thin-plate splines to grid up the normals (i.e., climatology). Then, for any given year/month, the anomalies will be gridded using a clever inverse distance weighting approach and the gridded anomalies will be added to the gridded climatology to get the map for that year/month. Currently, the planned resolution of this grid is 0.5x0.5 degrees, a far higher (25x) spatial resolution than the 2.5x2.5 degree grid used earlier by Cook to reconstruct North American drought. Doing so will result in a grid of ~10,000 points over North America. While this resolution may for practical purposes be higher than it needs to be, it can be easily degraded to the coarser resolution used by Cook, in this case down to ~400 points, which is still a significant increase over the 286 grid points reconstructed previously. The importance of the finer grid lies in the way that it provides the option to investigate how well the reconstructions do in sharp climate gradient areas such as along the Atlantic and Pacific coasts and in interior mountain regions of North America.

The tree-ring network needed for reconstructing North American drought continues to be expanded and filled in. Many new tree-ring chronologies have been added to the network, bringing the total from 835 up to almost 1500. Many of those in Alaska and Canada come from the archives of Gordon Jacoby and Rosanne D’Arrigo at the LDEO Tree-Ring Laboratory. A large number of new tree-ring chronologies from Mexico have also been added through the generosity of David Stahle and José Villanueva Díaz. At least 25 new chronologies from interior western Canada will be added soon through a generous contribution made by Dave Sauchyn at the University of Regina. Some very long (ca. 600-1000 years) ring-width data sets from the Niagara Escarpment in southern Ontario have also been contributed by Pete Kelly of the Cliff Ecology Lab at Guelph University. Certain parts of the pre-existing network have also been extended back in time through collections of remnant or sub-fossil wood. In particular, our
collaborator Connie Woodhouse has recently produced a number of extended tree-ring chronologies in Colorado that improve the temporal coverage there prior to ca. AD 1400, including four that pre-date AD 1000 when the megadrought described in Cook et al. (2004) occurred.

The Point-by-Point Regression (PPR) program used for reconstructing North American PDSI has been rewritten completely now by E. R. Cook and is being extensively tested now. At the same time, Ken Peters has programmed up innovative new methods of reconstruction that will be tested in the PPR program. These include non-parametric k-nearest neighbor regression and an implementation of a highly robust version of principle components analysis.

Highlights
- Expansion of the North American tree-ring network from 835 to almost 1500 chronologies.
- Development of the living gridded instrumental data grid used to generate PDSI for reconstruction.
- Re-write of the PPR program to include additional methods of reconstruction for testing.

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 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 and Outreach

Academic participation
Seminars


Symposiums
Cook, E.R. May 8, 2006. Drought Workshop held at Lamont-Doherty Earth Observatory. Ed Cook was a keynote speaker on *History and Dynamics of North American Drought* (with Richard Seager)

Personnel
Research Scientist: 1, Research Support Staff: 1

Publications
Journal articles


*Figures / Photographs / Illustrations*
Collaborative Research: Development of a Blended Living Gridded Network of Drought Reconstructions of North America

The North American tree-ring network (D) as of last April, which totaled 1201 annual tree-ring chronologies. The tree-ring network is now up to almost 1500 chronologies
**Project Title:** Ocean-Atmosphere Sensor Integration System (OASIS)

**Principal Investigator:** Wade McGillis

**Affiliation:** Lamont-Doherty Earth Observatory

**NOAA Program Manager:** Jorgeann Hiebert, Climate Observations Program
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**Research Goals**
- Develop an Autonomous Surface Vehicle.
- The goals of the OASIS project is to design, fabricate and test an air-sea flux system on the OASIS platform. The measurements include: sea surface temperature (SST); sea surface salinity (SSS); wind velocity; infrared and solar radiation; ΔpCO₂; air-sea fluxes of carbon dioxide; air-sea fluxes of momentum and heat; air and water temperatures, and surface ocean turbulent kinetic energy.

**Education Goals**
The OASIS project is managed by NOAA Center for Innovative Technology (CIT). This project has a large educational component. Part of the project team consists of educators who (1) bring the real time science to the classroom and (2) provide 1-day to 1-week long educational activities at the NASA Wallops Flight Facility to educate schools, organizations, and special interest groups.

**Research Progress**
Lamont Doherty Earth Observatory, in collaboration with the Chris Fairall of NOAA/ESRL (formerly ETL) work with NASA Wallops Engineers and Scientists to develop the proper synergy and power, data, and mounting protocol. In turn, Columbia University is designing and implementing the diverse air-sea flux components. Columbia University will also participate in the field trials that will take place in 2006 near the Wallops Island Flight Facility and/or the Army Field Research Facility in Duck, NC. The system has been constructed and will be merged with the OASIS platform during the summer/fall of 2006. The testing will be performed in the fall of 2006.

**Highlights**
- First autonomous air-sea flux platform.
- Sophisticated designed and fabricated surface autonomous vehicle to provide the capability to sample with high spatial and temporal resolution the surface ocean.

**Societal Benefits**
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.

**Other Research Connections**
**Interagency**
NOAA and NASA.

**Research partnerships**
NASA WFF; Pacific Gyre, inc; NOAA/ESRL

**Personnel**
Research Scientist: 1, Research Support Staff: 1, Administrative: 1
Photographs of OASIS. The propulsion system, solar panel power arrangement, and mast are shown. Turbulence and carbon dioxide sensors will be mounted on the mast/boom. The sensor enclosure hub will be a cylindrical enclosure ensconced in the OASIS hull.
Schematic of the Air-Sea Interaction sensors being mounted on OASIS.
**Project Title:** Atmosphere And Coastal Ocean CO₂ Measurement Platform - SABSOON

**Principal Investigator:** Wade McGillis

**Affiliation:** Lamont-Doherty Earth Observatory

**NOAA Program Manager:** Kathy Tedesco, Global Carbon Cycle

301-427-2382  kathy.tedesco@noaa.gov

**Research Goals**

- Measure the pCO₂ in the atmosphere and ocean at South Atlantic Bight Synoptic Offshore Observational Network (SABSOON). High-resolution Non-Dispersive InfraRed (NDIR) detection of CO₂ will be compared to flask measurements.

- Determine DpCO₂ at the tower using the high-resolution IR technique in order to estimate the coastal air-sea CO₂ flux variability.

- Quantify and describe the temporal variability in atmosphere and ocean CO₂ concentrations.

- Determine the relative importance of biological and physical controls on CO₂ concentrations and air-sea CO₂ exchange at a coastal site.

- Determine the influence of coastal ocean carbon on the North American terrestrial carbon cycling.

The stated objectives of this project require development of the following:

- Autonomous infrared measurements of atmospheric CO₂ will be designed:
  - To have a measurements accuracy of 0.1 ppm.
  - To operate for up to 2 months without any direct on-sight intervention
  - To control all temperature fluctuations in the NDIR cell passively (to conserve amount of power required for instrument operation) to less than 1 C hr⁻¹.
  - Airflow control system that can handle heavy aerosol load expected in tower environment with minimum amount of dead volume.
  - Long term air drying system

- Autonomous measurements of seawater CO₂ from tower include:
  - The development equilibrator system, which can handle big wave action but does not require pumping of seawater greater than 1 meter above mean high water

**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**

1) Autonomous infrared measurements of atmospheric CO₂ have been designed and include:

   a. Air flow control system
      i. Because of the large temperature variations and large aerosol load flow of gases through IR detector is very hard to control in conditions that we expect on the tower over the long term. Previous attempts to use off the shelf flow controller have been problematic due to dead space problems and aerosol fouling. In an attempt to rectify this problem we have
developed a stepper motor controlled pin valve system, which seems to give us very nice flow control over a variety of pressure regimes (Fig 1).

b. Passive control of IR cell temperature
   i. A key to achieving measurement accuracy at the 0.1 ppm level is control of incoming gas and IR detector cell temperature. While this can be achieved using active temperature control we are interested in doing this passively to reduce the power consumption. We are doing this by creating a heat sink made from seawater stored in a 150 L barrel. Air is pumped through tubing in the barrel and into an insulated box containing the IR detector. The results of the initial design show that temperature change can be controlled to within 1 C/hr which on a normal day that might vary in temperature as much 20 C. While we would like to reduce the temperature change to 0.1 C/hr, the results shown here indicate a very linear change in IR cell temperature despite non-linear changes in outside temperature. This suggests that drift corrects with hourly standard analysis will be sufficient to account for temperature changes.

c. Remote operation
   i. In an effort not to lose time we have decided to perform the deployment on the SABSOON tower after testing in similar conditions on the Martha’s Vineyard Tower and the RV LM Gould. With the new airflow control system installed on our RV LM Gould we are presently in the process of testing how robust the system will be in the long term.

d. 0.1 ppm accuracy test
   i. In addition to testing the flow controlled system on the RV LM Gould we will also be doing an inter-calibration exercise with NOAA/CMDL flask sample in the end of March during a Drake Passage crossing to test the accuracy of our measurements.

e. Long term air drying system
   i. A system for drying air which uses a combination of Naphion and a chemical dryer similar to those used on land-based Tall Towers has been built and is being tested on the Martha’s Vineyard Towers. No conclusive results have been found at the time that this report was prepared.

2) Autonomous measurements of seawater CO₂ from tower
   a. Develop equilibrator system
      i. The major challenge to measuring seawater from towers is choosing a robust system for equilibrating seawater with an air stream that can be measured with infrared analyzers. Because towers are not free floating positioning the equilibration system on a stable platform requires excessive power to pump water to heights that we anticipate putting the IR system at. To reduce power requirements we are testing a system on the Martha’s Vineyard Tower, which is small and compact enough to be mounted separately on the leg of the tower about 2 meters above mean water height.
Highlights

- Successful testing of accurate and autonomous CO$_2$ measurements to be made from a coastal tower.
- System is being fabricated and tested in collaboration with Columbia University and NOAA ESRL.

Societal Benefits

With a clear understanding of the sources and magnitude of variability that exists in the South Atlantic Bight of the United States Continental Margins and coastal ocean will become an integral part of the existing carbon cycle program.

Other Research Connections

Interagency
NOAA OGP with interagency collaborations.

Research partnerships
SABSOON

Collaborators
Colm Sweeney and Pieter Tans of NOAA/ESRL in Boulder Colorado.

Education and Outreach

Academic participation
Presentations

Public relations
Intranet / Internet sites or pages: http://www.frf.usace.army.mil/

Personnel
Research Scientist: 1, Research Support Staff: 2, Administrative: 2, Graduate Students: 1, and Undergraduate Student: 1
Prototype atmospheric and ocean pCO₂ system for SABSOON tower. This system features a standard/sample gas flow control system controlled by stepper motor (red) and pin valve in a feedback loop with Gas flow meter. Picture shows prototype installed on RVIB LM Gould where inter-calibration with NOAA/CMDL Flasks will take place.

Temperature control tests. Magenta line shows cell temperature. Purple and brown lines show outlet and inlet line of air flowing from insulated infrared analyzer box to water barrel. Light blue line shows water barrel temperature and dark blue shows outside temperature. Results show that outside temperature changes are reflected in very linear temperature changes inside the analyzer box indicating that drift correction made from hourly sampling will be sufficient to account for most of the variability outside temperature on tower system.
**Project Title:** Development Of An Autonomous System For Direct Measurement Of The Flux Of CO\textsubscript{2} Over The Ocean

**Principal Investigator:** Wade McGillis  
**Affiliation:** Lamont-Doherty Earth Observatory

**NOAA Program Manager:** Kathy Tedesco, Global Carbon Cycle  
301-427-2382  kathy.tedesco@noaa.gov

**Research Goals**

- Design and Fabricate an air-sea CO\textsubscript{2} flux system.
- Test and quality control the flux system from an ocean tower to assess system performance and capabilities.

**Education Goals**

The autonomous CO\textsubscript{2} 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 assets of this project have been the on going development of an autonomous infrared-based CO\textsubscript{2} flux system for the measurement of air-sea carbon dioxide fluxes. A meteorological system with IR-based detection of pCO\textsubscript{2} concentrations is being designed, fabricated, and developed at LDEO and ESRL/NOAA to be deployed on the Ronald H. Brown. Figure 1 (left) shows the problems with open-path CO\textsubscript{2} systems, which are susceptible spray and contamination. Figure 1 (right) shows that two independent sensors may drift in accuracy. This assessment was performed at LDEO with in stable environmental chambers. This system will be based around the autonomous pCO\textsubscript{2} systems operated during shipboard CO\textsubscript{2} flux studies by the PIs. Figure 2 shows the testing at sea at the Army Field Research Facility in Duck, North Carolina. This provides testing of system designs with out the high cost and time associated with the use of research ships. Preliminary testing from a ship also provides a motion free environment. Once the since is optimized for the ocean, it will be tested in sea trials.

1) Temperature control: Thermal stabilization of the measurement system, vital to highly accurate measurements, is performed in an environmental enclosure used for in situ operation on the Ronald H. Brown. A 1 Kilowatt environmental thermal controller will be used as the thermal fly-wheel to maintain the pCO\textsubscript{2} measurement system to temperature fluctuation less than .01 degrees C/hr. The system uses a simultaneous null flux sensor to remove motion artifacts.

2) Improved sample line delivery system: Included in the autonomous system is the use of filters and remotely adjustable flow control to ensure continuous sample delivery over month-long periods, despite heavy aerosol loads in samples.

3) An in line null pCO\textsubscript{2} sensor will be used to quantify motion contamination. The atmospheric sample with be 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.

4) Complete autonomous system. The vertical motion corrections, temperature fluctuation mitigation, and motion artifact corrections will be implemented to provide real time air-sea carbon dioxide fluxes.

5) The accuracy of the computed flux is dependent on the sensitivity of the gas analyzer to high frequency fluctuations. A fast-response, closed-path, non-dispersive infrared (NDIR) CO\textsubscript{2}/H\textsubscript{2}O
gas analyzer will be used to measure atmospheric gas samples continuously. The air intake line will be mounted 0.5 m from the sonic anemometer sampling volume. The samples will be drawn through the intake tube at a constant rate of 10 l m$^{-1}$, which results in a very small and correctable lag between the gas sample and the sonic anemometer measurement. Figure 5 shows the ultrasonic anemometer, compass, pitch, roll, yaw, accelerometers, and two NDIR systems onboard the R/V G. O. Sars (http://www.uib.no/forskningsfartoy/english/index.html) in collaboration with Truls Johannessen from the University of Bergen. Pressure and temperature fluctuations will be mitigated with pressure and thermal equilibrators. Estimates of biases in the flux system will be made during calibration periods. Calibrations are conducted by flushing the analyzer cell with known CO$_2$ concentrations, so that the system measures the calibration gas rather than the atmospheric concentration. In an ideal system, no fluctuations are measured about the reference level during the calibrations. In the actual system, signals in the CO$_2$ channel of the analyzer caused by any pressure fluctuations due to pump noise and tower vibrations will be quantified.

**Highlights**
- Successful testing of accurate and autonomous CO$_2$ measurements to be made from a research vessel.
- Discovery that open-path sensors have biases and closed-path detection of CO$_2$ signals are necessary.
- System is being fabricated and tested in collaboration with Columbia University and NOAA ESRL.

**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 CO$_2$ flux program. As with other flux measurement studies, the marine boundary layer offers a very stable environment for making CO$_2$ 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 and Outreach**

**Academic participation**
Presentations
- United States Ocean Climate and Carbon (OC$^3$) meeting, Woods Hole Oceanographic Institution, August 1 - 4, 2005. Carbon Transport in the Ocean and Atmosphere

**Public relations**
Intranet / Internet sites or pages: [http://www.frf.usace.army.mil/](http://www.frf.usace.army.mil/)

**Personnel**
Research Scientists: 2, Research Support Staff: 3, Administrative: 2, Graduate Student: 1, Undergraduate Student: 1
Development Of An Autonomous System For Direct Measurement Of The Flux Of CO₂ Over The Ocean

Left: Time series of an open-path and closed-path CO₂/H₂O sensor with pulses of spray. The open path is more susceptible to signal contamination and distortion due to airborne water. Right: Comparison between two closed-path analyzers over time. While the trends track between the two instruments, the calibrations drift.

The ultrasonic anemometer, compass, pitch, roll, yaw, accelerometers, and two NDIR systems onboard the R/V G. O. Sars in collaboration with Truls Johannessen from the University of Bergen. The cruise port started in Iceland and explored the ocean to Greenland. (http://www.uib.no/forskningsfartoy/english/index.html)
Project Title: Underway CO₂ Measurements Aboard The RVIB Palmer And Data Management Of The Global VOS Program

Principal Investigator: Taro Takahashi
Affiliation: Lamont-Doherty Earth Observatory

NOAA Program Manager: Joel M. Levy, Office of Climate Observation 301-427-2375 joel.levy@noaa.gov

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 former depends primarily on the processes occurring within the sea (such as seawater temperature, biological productivity and upwelling of deep waters), and the latter is controlled 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 sea-air pCO₂ difference. In conjunction with CO₂ gas transfer coefficients which are being improved by other scientific groups, a reliable net sea-air flux of CO₂ estimate over regional to global scales can be obtained using improved sea-air pCO₂ difference data.

Education Goals
The global database for surface water pCO₂ is being studied by post-doctoral and graduate students at this and other 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 Antarctic waters. Our semi-automated pCO₂ system has been upgraded continuously with this NOAA grant to make the system more stable and reliable. Since atmospheric CO₂ is absorbed by the major deep water masses that are formed in the Southern Ocean (including the Antarctic Bottom Water, Antarctic Intermediate Water and Mode Waters) and is transported to ocean interior, our understanding of air-to-sea CO₂ flux over this ocean is important for estimating the future course of atmospheric CO₂ levels. Yet, seasonal and interannual variability of the sea-air CO₂ flux in the Southern Ocean, especially areas covered with seasonal ice-field, is poorly documented. Since 1997, we have been conducting measurements of surface water pCO₂ during all seasons. Our measurements include the surface water pCO₂, SST, salinity, wind speeds, barometric pressure and atmospheric CO₂ concentration, and are processed and added to our global database. Approximately 72,500 surface water pCO₂ measurements were added to the database during the calendar year 2005.

As a part of the VOS program, we quality controlled the data obtained by the following field programs and added them to the VOS 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; 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). A total of approximately 259,000 pCO₂ measurements were made during the Gould program from March 2002 through March 2006; and 422,000 measurements during the "Explorer of Sea", R. Brown and Kaimimoana programs from 2001 through the end of 2005. 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 2.8 million pCO₂ observations and supplemental data since 1970’s, and is
the most extensive database for world ocean surface water pCO$_2$. The updated VOS database is available through the web site of the LDEO CO$_2$ group www.ldeo.columbia.edu/CO2.

The pCO$_2$ data obtained and archived by the present grant have been used extensively in the three research papers and government report that have been prepared during this grant period.

**Highlights**

- A large global ocean database for surface water pCO$_2$ has been assembled. It includes about 2.8 million pCO$_2$ observations made since 1970’s, and is the best in the world.
- Based on the pCO$_2$ data obtained in the seasonal ice-fields located around Antarctica, we demonstrated, for the first time, that ocean areas covered partially by ice-field are a CO$_2$ source for the atmosphere.
- We estimate that the global oceans absorbed 1.55 (± 30%) Giga-tons of carbon in 2000. For this estimate, the NCEP climatological mean wind speeds and Wanninkhof’s (1992) formulation for the effect of wind speed on sea-air CO$_2$ gas transfer rate are used.

**Societal Benefits**

Understanding of the fate of industrial CO$_2$ in the oceans is essential for the formulation of the CO$_2$ management strategy.

**Other Research Connections**

**Interagency**

The VOS database has been used extensively for the evaluation of sea-air CO$_2$ exchange over the open and coastal oceans in the SOCCR interagency report, which is presently being reviewed by agency experts.

**Research partnerships**

Our global ocean pCO2 data and resulting sea-air CO2 flux are being used extensively for comparison with the results obtained by the Ocean GCM (N. Gruber, OIP) and Atmospheric GCM groups (K. Gurney, TransCom-3; P. Patra, JAMSTEC).

**Collaborators**

We have been working closely with R. A. Feely of PMEL/NOAA, R. Wanninkhof of AOML/NOAA, and C. Sweeney of ESRL/NOAA.

**Education and Outreach**

**Research advisor / mentor**

Post-doctoral: Juerg Matter, LDEO

**Academic participation**

**Presentations**


Richard A. Feely, Taro Takahashi, Rik Wanninkhof, Catherine E. Cosca, Michael McPhaden, Stewart Sutherland, Mary-Elana Carr and Fei Chai (2006). Interannual and Decadal Variability of the Air-Sea CO₂ Fluxes in the Equatorial Pacific Ocean. AGU-ALSO, Honolulu, HA.


Public relations
Databases
   Established and updated the VOS Global Ocean pCO2 Database

Personnel
Research Scientist: 1, Research support staff: 3

Publications
Journal articles


Reports
Climatological mean sea-air CO$_2$ flux over the global oceans (non-El Nino periods) for a reference year 2000. The map is constructed using 2.75 million measurements for surface water pCO$_2$ made since 1970’s. The NCEP climatological mean monthly wind speed field obtained and the effect of wind speed on the CO$_2$ gas transfer rate by Wanninkhof (1992) are used. The blue-magenta areas indicate that the ocean is a sink for atmospheric CO$_2$; and yellow-orange areas are a source. The strong source areas located in the equatorial Pacific, northwestern Pacific and Arabian Sea are due to upwelling of deep waters rich in CO$_2$. A band of weak source areas around Antarctica is due to vertical mixing of CO$_2$-rich subsurface waters under the seasonal ice-field. The annual uptake rate of atmospheric CO$_2$ by the global oceans is estimated to be 1.55 Giga-tons carbon/yr. The computational method used is described in Takahashi et al. (Deep-Sea Research, 2002).
Two research projects have as their secondary definition Theme III:

1. *Multivariate Approach to Ensemble Reconstruction of Historical Marine Surface Winds from Ships and Satellites* (major Theme I) PI Alexey Kaplan
CICAR

Task IV: Collaborative Education Programs & Projects
**Project Title:** Understanding Climate Change from the Medieval Warm Period to the Greenhouse Future

**Principal Investigator:** Richard Seager

**Affiliation:** Lamont-Doherty Earth Observatory

**NOAA Program Manager:** Ants Leetmaa, GFDL / LDEO Collaborative
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**Research Goals**
To use climate models to understand externally forced and natural variability. To compare and evaluate the simulation of climate variability in the past and future in the GFDL model with other climate models. To study the sensitivity of model simulations of climate variability to changes in external forcing. To lay the grounds for an extended coupled model simulation of the climate of the last millennium under best known estimated of external forcing variations.

**Education Goals**
To train the next generation of climate scientists, to involve undergraduates in cutting edge research, and to educate the general public on matters of climate change and variability.

**Research Progress**
We studied the most recent drought over North America that began in 1998 (and which may not yet be over) and determined its causes through analysis of model simulations done both at Lamont and GFDL. This drought is the latest in a series of droughts forced by persistent cold La Nina-like SSTs in the tropical Pacific Ocean. In an inter-comparison of two major GCMs -- NCAR CCM3 and GFDL AM2 -- both models reproduce the observed circulation anomalies in the upper troposphere when forced with SST from the whole tropics.

The coupled GFDL model was also analyzed to demonstrate that it has a relationship between persistent North American drought and tropical SSTs that is very similar to that observed. The global context of the modeled droughts is also similar to that observed. This raises confidence that the model can be used with some confidence for examining future drought risk in North America which we are now doing.

For all North American droughts an unsolved problem is the relative roles of tropical Pacific and subtropical Atlantic SSTs in forcing drought. Our work to date has emphasized the forcing from a cold tropical Pacific but we have begun work that uses model ensembles to show that a warm subtropical North Atlantic Ocean plays a secondary role. The relative role for the historical droughts will be worked out in the coming months.

We examined the causes of tropical climate change over the last millennium and appealed to a tropical atmosphere-ocean response to changing irradiance and volcanism as the cause of the proposed Medieval La Nina. This work is being extended to examine the tropical ocean response to more recent and future forcing and to a comparison with data studies on tropical climate change conducted at LDEO and GFDL.

We analyzed the model simulations archived at PCMDI for the fourth assessment report of the IPCC. Robust Sahel drying occurs in response to late 20th century forcings. We were able to ascribe at least 30% of the observed long-term drought in the African Sahel to the effect of
anthropogenic emissions of greenhouse gases and aerosols. The focus of our current
investigation is the discrepancy between GFDL and other models regarding the simulation of the
future climate over sub-Saharan Africa. While the IPCC models agree on the response of the
African climate during the 20th Century, there is a perplexing discrepancy between models under
future GHG scenarios. This is a challenging and crucial subject in which involves a close
collaboration with GFDL.

We evaluated Arctic sea ice depictions of 20th Century coupled model simulation and analyzed
the model sea ice mass balance to identify shortcomings and potential solutions. The GFDL
CM2.1 coupled model simulations depict an ice cover that has a large annual cycle amplitude
and is overly thin relative to observations. Comparisons with SHEBA observations indicate
deficiencies in the surface net shortwave radiative energy flux over the Arctic Ocean during the
melt season.

As part of the high latitude climate change work we examined future climate simulated by
CCSM3. The CCSM3 represents well the observed downward trend in ice extent in the last 30
years. It also shows that future decline in ice extent will likely be abrupt (in steps) and occur
between 2030 and 2050. The results are robust. Of additional coupled models participating in
the latest IPCC assessment of those that have a realistic mean climate a large fraction of them
display the same behavior. We looked at the GFDL and CCSM3 models for large downward
trends in ice extent in a long control simulation of today’s climate, i.e. naturally occurring trend.
They can occur but in all cases the sea ice cover recovers to its previous state. Anomalous
winds (linked with ice export) are sometimes responsible, at other times; we believe that the
ocean heat transport (together with the ice albedo feedback) is responsible for initiating the
events.

Other high latitude climate work examined decadal variability in southern hemisphere high
latitude climate modes from in-situ observations, reanalysis data, and twentieth century runs
from a coupled climate model - CCSM3.0. Weather station observations suggest that decadal
variability is more evident in the mid-latitudes than in Antarctica. The reanalysis data reveal a
strong decadal variability in the Southern Annular Mode at 9-12 years period, while the climate
model produces a clear but less strong decadal variability at 9-17 years period. This project
provides an educational opportunity for a summer intern.

For study of long term (e.g. millennial climate change) the spin-up of ocean components of
climate models, which can take centuries of simulation, becomes a limiting problem. As part of
this grant, we are pursuing research on novel numerical techniques for accelerated simulation of
biogeochemical tracers and dynamical spinup of ocean GCMs. In the past year a new
technique, based on "Matrix-free Newton-Krylov" was developed. Initial results from a state-of
the-art OGCM show a factor of 5 speedup in time-to-equilibrium (compared with asynchronous
time integration).

We are also working on the detection of forced and naturally occurring North Atlantic
Multidecadal Variability (AMV) in both coupled models and observations for the 20th century.
Given the recent increase in both intensity and frequency of the Atlantic hurricane activities and
the rapid increase in Greenland ice sheet melting, it is extremely important to determine the
causes of the abrupt changes in climate. The most relevant scientific question is the relative
contribution of those caused by the natural climate variabilities and those due to man-made
greenhouse gas warming effect. Using the IPCC 20th century coupled model simulations,
particularly those with multiple ensemble members (ranging from 4-9 members), we found that
the forced variability can be identified as the first mode of the EOF analysis of the ensemble
average of the model simulations. This forced mode shows a clear global warming signature.
By removing the forced mode, the naturally occurring Atlantic multidecadal variabilities can be
identified. When we separate the forced and the natural AMV in observations, the results show
equal amplitude over the Atlantic for the forced and natural components in terms of both AMO
index and the so-called hurricane main development region index.

Highlights
- Examined the character of North American drought variability in the GFDL coupled GCM
to demonstrate that it is similar to observed in global context, correct amplitude and also
forced by variations in tropical SSTs.
- Began to examine North American drought in future climate projections of the GFDL
model to demonstrate that drought severity intensifies.
- Began determining the relative roles of tropical Pacific and Atlantic SST anomalies in
forcing North American droughts.
- Examined Sahel rainfall in historical and future simulations with the GFDL model to
attribute part of the observed drying to anthropogenic change.
- Determined the causes of the zonally and hemispherically symmetric extratropical
atmospheric circulation response to changing tropical SSTs.
- Examined model simulations of sea ice and its variations to better constrain the future
risk of drastic and rapid sea ice reductions in the Arctic in the near future.

Societal Benefits
Climate change is a current and future problem all over the world. Adaptation to climate change
requires usable forecasts of climate change that, in turn, requires models that correctly predict
the response of climate on a regional scale to external forcing. The point of the current project
is to better constrain climate system response by examining climate change over the last
millennium, including the causes of the Medieval Climate Anomaly and the Little Ice Age and
their distinctive regional expressions. If we can understand how these were brought about by
small changes in irradiance, volcanism and trace gases, and if we can accurately simulate these
changes, we will have more confidence in model simulations of future climate change leading to
potential social benefit.

Other Research Connections
Interagency
A. Gordon is a member of the NASA Aquarius Scientific Steering committee and CLIVAR Salinity
steering committee and his NOAA research contributes to efforts to understand satellite
measurement of SSS and global patterns of SSS.

Collaborators
A. Clement (U. Miami) - G. Lau, T. Delworth, I. Held, A. Leetmaa (all GFDL), D. Stahle (U.
Arkansas), A. Giannini (IRI)

Education and Outreach
Research advisor / mentor

Graduate: Chie Ihara (Ph.D student, Y. Kushnir), Irina Gorodetskaya (Ph.D student, B. Tremblay),
Celine Herweijer (Ph.D student, R. Seager), Debra Tillinger (Ph.D student, A. Gordon), Phil Orton
(Ph.D student, A. Gordon), Julien Emile-Geay (Ph.D student, M. Cane)

Academic participation
Presentations
AMS Atmospheric and Oceanic Fluid Dynamics Conference, Cambridge MA, June 2005.
(L. Polvani)

EGU General Assembly, Vienna, April 2006. (L. Polvani)
AGU Joint Assembly, Baltimore MD, May 2006. (L. Polvani)


North American drought of the last millennium: reconstruction, causes and consequences. Harvard University, February 2005. (R. Seager)


The future of drought risk. BIOTECH 2006 Annual Conference organized by Dupont, Pioneer Hybrid etc. Chicago, April 2006. (R. Seager)


Lamont-Doherty Earth Observatory, Climate and Physical Oceanography Seminar, April 2006. Anthropogenic Carbon Uptake by the Ocean Estimated Using Transit-Time Distributions. (S. Khatiwala)


AGU Ocean Sciences meeting, February 2006, Honolulu, "Ocean Salinity, a responsive component of the Climate System". (A. Gordon, invited talk)


Detection of forced and naturally occurring North Atlantic Multidecadal Variability: GFDL Atlantic Variability workshop, (M. Ting)

Detection of forced and naturally occurring North Atlantic Multidecadal Variability: NCAR CCSM workshop. (M. Ting)

Public relations
Public outreach
- Frequently interviewed by print and broadcast media on climate matters of concern to the general public. (R. Seager)
- New York Academy of Sciences talk on the Hydrological History of the American West (R. Seager)
- ‘The Source of Europe’s Mild Winters’, an article in the popular magazine, American Scientist (R. Seager)

Databases
All model simulation data is served online immediately after computation to act as a resource for the global research community

Intranet / Internet sites
Continuing development of web site on modeling and understanding North American drought
http://www.ldeo.columbia.edu/res/div/ocp/drought/ and gulf stream and climate
http://www.ldeo.columbia.edu/res/div/ocp/gs/

Personnel
Research Scientists: 12, Research Support Staff: 3, Post Doctoral Fellows: 5, Grad Students: 3

Publications
Journal articles


Books / articles-in-books

Ph.D. dissertations
Celine Herweijer - North American Droughts from Medieval Times to the Modern Day: Characterization, Causes and Global Context, April 2006

Figures / Photographs / Illustrations
Understanding Climate Change from the Medieval Warm Period to the Greenhouse Future

Average February sea ice mean thickness and ice motion vectors from 20th Century simulations of the NCAR CCSM3 (left), and the GFDL CM2.1 (right). The ice thickness is shown in meters. The maximum velocity vector corresponds to 0.5 m s\(^{-1}\).
The 200 hPa geopotential height anomalies for the 1998-2002 climate epoch. Left column is from Lau et al. (2006). Top left is observation from NCEP reanalysis, followed by the GFDL AM2 model simulations forced with (top to bottom) global, tropical eastern Pacific, and Indian Ocean + western Pacific SST anomalies. The three panels in the right column are the counterparts of the GFDL simulations performed in LDEO using NCAR CCM3. Contour interval is 10 m for all panels. Blue is negative.
The simulated JJA Sahel rainfall difference between XX (1975-1999 ensemble mean for each model, red and blue circles) and PI (long-term mean). The dark (light) gray shading are one (two) sigma deviations in 25-year mean Sahel rainfall in each PI simulation. Models forced by both natural and anthropogenic forcings are tagged red, those forced only by anthropogenic forcings are tagged blue. Note that the "red" models also tend to have a more complete treatment of aerosol forcings and to include land-use changes. Except for CCMA, PCM1 and HADCM3, drying is significant at the 95\% level.
Project Title: M. A. Program in Climate & Society

Principal Investigator: Mark Cane

Affiliation: Lamont-Doherty Earth Observatory

NOAA Program Manager: Dr. Kenneth Mooney, Deputy Director, OGP, 301- 427- 2381, Kenneth.mooney@noaa.gov

Research Goals
This is an educational program.

Education Goals
The twelve-month M.A. Program in Climate and Society trains professionals and academics to understand and cope with the impacts of climate variability and climate change on society and the environment. This rigorous program emphasizes the problems of developing societies.

Research Progress
The first group of eighteen students to attend the M.A. Program in Climate and Society in Academic Year 2004-05 began the program in September 2004, completed all requirements for the master's degree in August 2005, and were awarded degrees in October 2005. The eighteen students came from a variety of countries and backgrounds, including mid-career professionals from Ethiopia and the United States, recent college graduates from the United States, and a variety of students from fields in policy, activism, and education from the United States, Cameroon, and Philippines.

Students completed a unique 12-month interdisciplinary curriculum especially designed and taught by researchers at the International Research Institute for Climate Prediction (IRI) at Columbia University. Through their intensive contact with these researchers, students gained appreciation for the interplay of climate variability, climate change, policy for development, risk, hazards, and natural and human impacts.

At the end of the program in August 2005, students expressed great satisfaction with twelve months of intensive learning. Their job placements include a Climate Change Policy Coordinator at the British Embassy in Washington, D.C., a Climate Risk Management Professional at the Asian Disaster Preparedness Center in Thailand, and a Program Coordinator at Columbia’s Global Roundtable on Climate Change. One student has completed the first year of a PhD Program at the Rosenstiel School of Atmospheric and Marine Sciences, Univ. of Miami.

Two students will return to their careers in the public sector (health and meteorological services, respectively) in Ethiopia. Another student is a teacher at an independent secondary school in Connecticut, where he designs his own integrated Earth Science Curriculum, using concepts learned in the M.A. Program.

The second cohort of students is equally diverse and impressive, including international students from Sri Lanka, Lesotho, and Zimbabwe. These sixteen students are currently completing internship requirements, including placements at the Environmental Protection Agency, Environmental Defense, and United Nations Development Program. Their degrees will be awarded in October 2006 and job prospects are extremely promising.

Application numbers were extremely high for the 2006-2007 academic year. Twelve countries were represented in our applicant pool and we expect a class size of 18-20 students in the fall of 2006.
Highlights

- Successful design and execution of a unique interdisciplinary curriculum that has not been carried out at the master’s level at any other educational institution.
- Successful completion of the master’s degree by all 18 graduate students in the 12-month timeframe; degrees conferred in October 2005.
- Successful completion of the master’s degree by all 16 graduate students in the second cohort; degrees conferred in October 2006.
- Number of applications to program, diversity and quality of applicants increasing each year.
- Summer internship and job placement at prestigious institutions and prominent names in the field of climate/society interactions (e.g., Pew Center, Environmental Defense, UNDP, CISA)

Societal Benefits

Graduates of the M.A. Program in Climate and Society are a group of uniquely qualified public and private sector professionals and researchers. The interdisciplinary curriculum challenges students to think in an integrated fashion about climate, climate impacts, and challenges to development from the very beginning. These graduates are able to address environmental and social phenomena from an integrated perspective that focuses on understanding multiple facets of a problem, from energy policy, energy demand, malaria epidemic mitigation, famine, drought, and flood early warning and mitigation, water resources management, environmental journalism, communication of climate variability and climate-related risks, and environmental secondary education.

The students’ research has resulted in a number of products that benefit society, including:

- A better prediction scheme for Ethiopian rainfall;
- Integration of climate information into malaria control efforts in Ethiopia;
- Better understanding of climate influences on locusts in the Sahel;
- A curriculum on Climate and Society for secondary schools;
- Improved agricultural data sets for south India;
- Climate-based Reservoir analysis for New York City;
- Information on the impact of climate on water scarcity and malaria risk in the Deduru Oya basin of Sri Lanka; and
- A hurricane vulnerability index useful for hurricane risk management and development in the Caribbean and Latin America.

Other Research Connections

Interagency Research Partnerships

Students in the M.A. Program in Climate and Society learned from and worked on research projects through the International Research Institute for Climate Prediction (IRI); The Earth Institute at Columbia University; the Earth Engineering Center at Columbia’s School of Engineering and Applied Science (SEAS); and Columbia’s Global Roundtable on Climate Change (GROCC), Columbia’s NSF-funded Center for Research on Environmental Decisions (CRED).

Students who completed summer internships for academic credit worked at a variety of environmental and climate research organizations, including Environmental Defense; the Pew Center on Global Climate Change; NOAA-affiliated Carolinas Integrated Sciences & Assessments (CISA); United Nations Development Program (UNDP) Climate Change Management Office.
Awards / Honors

M.A. students were awarded in several ways in academic years 2004-2005 and 2005-2006.

Mr. Diriba Korecha Dadi of Ethiopia won a full scholarship from the Joint Japan / World Bank Scholarship Program to attend the program. Dadi is an early forecast warning team leader at the National Meteorological Services Agency of Ethiopia.

M.A. student Lauren Faber, a recent graduate of Stanford University, was one of two Columbia graduate students to win the "Student Energy Research Fellowship" from the Center for Energy and Marine Transportation and Public Policy at Columbia. This award usually goes to a public affairs or Engineering student, and it is rather unusual for the award to go to a student of the Graduate School of Arts and Sciences.

M.A. student Lauren Faber was chosen to attend the American Meteorological Society’s (AMS) two-week Summer Policy Colloquium in Washington, D.C. This honor usually goes to PhD students.

M.A. student Tara DePorte was awarded a travel grant to attend the SOLAS Summer School in Corsica, France, in August-September 2005. Admission and travel grant are usually awarded to PhD students.

M.A. student Eric Holthaus was a Foreign Language Area Studies Fellowship and an Earth Institute travel grant to pursue research on hurricane preparedness in Cuba and Honduras in summer 2006.

Many students successfully competed for extremely competitive summer internships for academic credit, such as the Pew Center on Global Climate Change and the UNDP.

Education and Outreach

Postsecondary

100% - This is an educational program of the Graduate School of Arts and Sciences at Columbia University.

Graduate

Formal Academic Advisor for 16 students is Professor Mark Cane. All 16 students will receive the M.A. degree in October 2006. All are seeking jobs or have accepted offers. Three have accepted an offer of admission to a PhD program at University of California at Berkeley, Rutgers University, and Michigan State University.

Last Names:

1) Chamberlin
2) Chidzambwa
3) Crane-Droesch
4) Fernando
5) Finnegan
6) Green
7) Hannon
8) Harris
9) Holthaus
10) Lim
11) Morebotsane
12) Ramirez
13) Siebert
14) Soriece
15) Tomijima
16) Underwood

Academic

Coursework in Academic Year 2005-06 is ongoing.
Fellowship programs / internships
Internships: see graduate students #’s 6 & 7 above.

Public relations
Public outreach (community relations)
- Active recruitment campaign to attract new applicants and publicize the M.A. Program
- Brochure, posters, newspaper ads, and website
- Articles in university newspapers and information sessions
- Director interviewed and quoted by several newspapers

Intranet / Internet sites or pages
http://www.columbia.edu/climatesociety

Educational Tools
Entirely unique curriculum taught by Columbia faculty and researchers at the International Research Institute for Climate Prediction (IRI) at Columbia University.

Personnel
Research Scientists: 7, Visiting Scientists: 31, Administrative: 1, Graduate Students: 16

Publications
Journal Articles
Kuena Morebostsane ('06) international student from Lesotho and recipient of full scholarsh award funded through a private donation.

Students in the M.A. Program in Climate and Society participate in a unique interdisciplinary curriculum designed around climate and climate impacts, with particular attention paid to the developing world. These master’s students receive personalized attention from some of the leading researchers in the field.

(Photo credit: Bruce Gilbert)
**Project Title:** 2005 International SOLAS Summer School  
**Principal Investigator:** Wade McGillis  
**Affiliation:** Lamont-Doherty Earth Observatory  
**NOAA Program Manager:** Kathy Tedesco, Global Carbon Cycle  
301-427-2382  kathy.tedesco@noaa.gov

*Research Goals*
The 28 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 CO$_2$, H$_2$O, and DMS.

**Research Progress**

**Participants and Sponsors**

The second SOLAS Summer School was held in 2005. The US was represented by 16 students. For the 2005 session, the lecturers (and their affiliations) from the United States included: Wade McGillis, Columbia University; Rik Wanninkhof, NOAA Atlantic and Meteorological Oceanographic Laboratory; and Eric Saltzman, University of California - Irvine.

**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 are 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 CO$_2$ on time scales of a few thousand years, while contributing to regional patterns of air-sea CO$_2$ 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.

**Other Research Connections**

**Interagency**

NSF Chemical Oceanography, NSF Atmospheric Chemistry, and NASA collaborated in funding this project with NOAA.

**Research partnerships**

The project was educationally based. Research was taught and lectured, however, research was not performed as part of this project.

**Collaborators**

The collaborators were multi-national. From the United States, Rik Wanninkhof of NOAA/AOML and Eric Saltzman from the University of California Irvine collaborated in this project.

**Awards / Honors**

A United States student won best presentation and best poster.

**Education and Outreach**

**Academic participation**

Presentations
- Air-Sea Gas Exchange

**Personnel**

Research Scientist: 2, Visiting Scientist: 2, Research Support Staff: 1, Administrative: 2, Graduate Students: 16
Left: Photograph of SOLAS Summer School Air-Sea interaction workshop on the Pier near the Cargèse School. Right: Photograph of Professor McGillis lecturing on calculating fluxes across the ocean-atmosphere interface.
## Table 2: 2005 United States SOLAS Summer School Students.

<table>
<thead>
<tr>
<th>SOLAS Student</th>
<th>Research Advisor</th>
<th>Academic Institution</th>
<th>Research Area Thesis Topic</th>
<th>Current Activity and Comments 2005 SOLAS Summer School</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toby Woodbury</td>
<td>David Stiegler</td>
<td>University of California Santa Barbara</td>
<td>Remote sensing of Tychopseasium spp. blooms and its relation to atmospheric dust deposition</td>
<td>Just graduated with PHD.</td>
</tr>
<tr>
<td>Cory Tyree</td>
<td>Jonathan Allen</td>
<td>Arizona State University</td>
<td>Size and Composition of Foam Droplets with Applications to the Marine Atmosphere</td>
<td>Fifth year grad student</td>
</tr>
<tr>
<td>Shawn Beza</td>
<td>Michael Hoffmann</td>
<td>California Institute of Technology</td>
<td>Nitrate Oxidation in Ice and Interrelated Chemical Phenomena</td>
<td>Graduate June 2005. Postdoc offer at NASA JPL October 2005</td>
</tr>
<tr>
<td>Douglas Day</td>
<td>Ian Faltos</td>
<td>University of California Davis</td>
<td>Observations of NO2, Total Deposi Nitrates, Total Alkyl Nitrates, and HNO3 in Mid-Sierra and Sacramento Plume Using Thermal Dissociation Laser Induced Fluorescence</td>
<td>Postdoc now.</td>
</tr>
<tr>
<td>Daniel del Valle</td>
<td>Ronald Kiese</td>
<td>University of South Alabama</td>
<td>The removal and flux of dimethylarsinate in seawater.</td>
<td>2nd year PHD.</td>
</tr>
<tr>
<td>Peter J. DiFonzo</td>
<td>Daniel Sigman</td>
<td>Princeton University</td>
<td>N and O isotopes of nitrate: constraints on ocean biogeochemistry</td>
<td>3rd year PHD.</td>
</tr>
<tr>
<td>Jeremy Mathis</td>
<td>Dennis Hansell</td>
<td>University of Miami</td>
<td>Cycling and Transformations of Carbon and Nitrogen in the Western Arctic Ocean</td>
<td>3rd year PHD.</td>
</tr>
<tr>
<td>Nicolas Causer</td>
<td>Michael Rander</td>
<td>Princeton University</td>
<td>Carbon-concentrating mechanisms and baro-carbon fixation: their potential contribution to marine photosynthetic carbon isotope fractionation</td>
<td>1st year postdoc.</td>
</tr>
<tr>
<td>Yohel Shinoda</td>
<td>Anthony Clarke</td>
<td>University of Hawaii</td>
<td>Seawater optical properties over the remote oceans: their vertical profiles and variations with wind speed</td>
<td>5th year of PHD.</td>
</tr>
<tr>
<td>Hasten Graven</td>
<td>Ralph Ebling</td>
<td>University of San Diego</td>
<td>Investigating carbon cycle dynamics with high-precision measurements of radiocarbon in atmospheric CO2</td>
<td>5th year of PHD.</td>
</tr>
<tr>
<td>Oleg Ekinzawa</td>
<td>Iochan Stuht</td>
<td>University of California Los Angeles</td>
<td>The multi-axis DOAS instrument for long term trace gas monitoring and halogen oxides detection in the Maritza boundary layer</td>
<td>3rd year PHD.</td>
</tr>
<tr>
<td>Rachel Stanley</td>
<td>William Jenkins</td>
<td>WHOI/MIT</td>
<td>Noble Gases as Tracers for Air-Sea Gas Exchange and Nutrient Cycling</td>
<td>5th year PHD.</td>
</tr>
<tr>
<td>Patrick Schultz</td>
<td>Jorga Sreteska</td>
<td>Princeton University</td>
<td>Application of Optical Observations of Phytoplankton Carbon Biomass and Growth Rates to Develop an Empirical Ocean Ecosystem Model</td>
<td>3rd year PHD.</td>
</tr>
<tr>
<td>Kyri Alliez</td>
<td>Sybil Stuckinger</td>
<td>Columbia University</td>
<td>Formation of algelons in cloud processing: Reactions of isoprene oxidation products</td>
<td>2nd year PHD.</td>
</tr>
<tr>
<td>Tara Debotta</td>
<td>Kent Enelst</td>
<td>University of California Santa Cruz</td>
<td>Fe and Cu speciation in natural waters: coastal, river plumes, open ocean, HNLC, and depth profiling</td>
<td>5th year PHD.</td>
</tr>
</tbody>
</table>

2005 International Summer School Student Participants from the United States.
As we summarize Institute activities in the funding year 2005/06, we are preparing for our NOAA Review, conducted according to the new regulations regarding Cooperative Institute operation and re-competition put forward by the NOAA Science Council in September 2005. Only three years elapsed since the founding of CICAR as the first CI established in a competitive manner. The emerging transition from a collection of loosely related, NOAA-funded, research activities to a platform motivated by a unique strategic vision set forth in the CICAR proposal while not completed, is clearly visible. Based on our recent research achievements, on our historical and new technical capabilities, on our assessment of national and global needs, and most importantly, on continued engagement with our NOAA partners, we have come to identify two broad priorities that will guide CICAR research in the future:

- “Abrupt Change in a Warming Climate”: engages the partnership between paleoclimatologists, oceanographers, and modelers nurtured under ARCHES. It emphasizes the theoretical study of the continuum of climate variability from the glacial world into the Holocene and the present as a model for understanding climate variability under external and internal forcing and for addressing the future “greenhouse” climate. Particular emphasis in this program is put on assessing the possibility of abrupt climate change in the future – that is the possibility of a change in climate faster than the rate of change in the forcing.

- “Predicting Climate Variability in a Changing Climate”: deals with the practical aspects of predictability the global and regional climate evolution into the middle of the 21-century. Working with existing global models and testing and developing techniques for making model based assessments of future climate variations for the coming decade(s). Emphasis here is on particularly adverse phenomena such as droughts, changes in tropical storm occurrence and intensity, sea level rise, and the occurrence of climate extremes (heat waves and floods) that directly impact societies around the world whether poor or developed.

These research priorities emphasize a strong partnership with NOAA and call for enhancing internal collaboration within Columbia, building on existing synergies, and maintaining the link to social science research at the Earth Institute.
### Table 1. Principal Investigators & projects by goal/task/theme

July 1, 2005 - June 30, 2006

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Project</th>
<th>NOAA Goal</th>
<th>Task</th>
<th>Theme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anderson, Robert</td>
<td>Doherty Senior Scholar</td>
<td>ARCHES: Paleo Sea-Ice Distributions</td>
<td>2</td>
<td>3</td>
<td>2</td>
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<tr>
<td>Broecker, Wallace</td>
<td>Newberry Professor</td>
<td>ARCHES: Understanding Abrupt Change and the Glacial to Interglacial CO₂ Record</td>
<td>2</td>
<td>3</td>
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<tr>
<td>Cane, Mark</td>
<td>Vetlesen Professor</td>
<td>M. A. Program in Climate &amp; Society</td>
<td>2</td>
<td>4</td>
<td>3</td>
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<tr>
<td>Cane, Mark</td>
<td>Vetlesen Professor</td>
<td>Predictions and Predictability of El Nino Events: Epochs and Biases</td>
<td>2</td>
<td>3</td>
<td>1</td>
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<tr>
<td>Chen, Dake</td>
<td>Doherty Senior Research Scientist</td>
<td>Describing, Understanding and Predicting Oceanic Variations Associated with Tropical Atlantic Variability and The North Atlantic Oscillation</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Cook, Edward</td>
<td>Doherty Senior Scholar</td>
<td>Collaborative Research: Development of a Blended Living Gridded Network of Drought Reconstructions of North America</td>
<td>2</td>
<td>3</td>
<td>2     (*3)</td>
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<tr>
<td>Denton, George</td>
<td>LDEO Subcontractor: Institute for Quaternary &amp; Climate Studies, University of Maine</td>
<td>ARCHES: Mountain Snowlines in the Southern Hemisphere</td>
<td>2</td>
<td>3</td>
<td>2</td>
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<tr>
<td>Goddard, Lisa</td>
<td>Research Scientist</td>
<td>Investigating Some Practical Implications of Uncertainty in Observed SSTs</td>
<td>2</td>
<td>3</td>
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<tr>
<td>Gong, Gavin</td>
<td>Assistant Professor</td>
<td>The Integrated Role of Snow, Orography and Dynamical Waves in Facilitating Western US Land Surface - Climate Linkages</td>
<td>2</td>
<td>3</td>
<td>1</td>
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<tr>
<td>Gordon, Arnold</td>
<td>Professor</td>
<td>ARCHES: Modern Observations</td>
<td>2</td>
<td>3</td>
<td>2</td>
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<tr>
<td>Hemming, Sydney</td>
<td>Associate Professor</td>
<td>ARCHES: Constraining Changes in Winds, the Conveyor and Local Currents During Periods of Abrupt Climate Change</td>
<td>2</td>
<td>3</td>
<td>2</td>
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<tr>
<td>Huang, Huei-Ping</td>
<td>Post Doctoral Research Scientist</td>
<td>Tropical Influences on Recent and Historical Droughts over North America</td>
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<td>3</td>
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<tr>
<td>Kaplan, Alexey</td>
<td>Doherty Research Scientist</td>
<td>Multivariate Approach to Ensemble Reconstruction of Historical Marine Surface Winds from Ships and Satellites</td>
<td>2</td>
<td>3</td>
<td>2     (*3)</td>
</tr>
<tr>
<td>Kushnir, Yochanan</td>
<td>Doherty Senior Research Scientist</td>
<td>The Cooperative Institute for Climate Applications and Research</td>
<td>2</td>
<td>1</td>
<td>N/A</td>
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<tr>
<td>Name</td>
<td>Title</td>
<td>Project/Topic</td>
<td>#1</td>
<td>#2</td>
<td>#3</td>
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<tr>
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<tr>
<td>Martinson, Douglas</td>
<td>Doherty Senior Research Scientist</td>
<td>ARCHES: Southern Ocean Modeling and Analysis</td>
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<tr>
<td>McGillis, Wade</td>
<td>Doherty Research Scientist</td>
<td>Atmosphere and Coastal Ocean CO₂ Measurement Platform - SABSOON</td>
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<tr>
<td>McGillis, Wade</td>
<td>Doherty Research Scientist</td>
<td>SOLAS OASIS Platform</td>
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<tr>
<td>McGillis, Wade</td>
<td>Doherty Research Scientist</td>
<td>Development of an Autonomous System for Direct Measurement of the Flux of CO₂ over the Ocean</td>
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<td></td>
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<tr>
<td>McGillis, Wade</td>
<td>Doherty Research Scientist</td>
<td>2005 SOLAS Summer School</td>
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<tr>
<td>Robertson, Andrew</td>
<td>Research Scientist</td>
<td>South Atlantic Ocean-Atmosphere Interaction</td>
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<tr>
<td>Schloesser, Peter</td>
<td>Professor</td>
<td>ARCHES: Tracer Observations of Deep Formation and Circulation in the Southern Ocean</td>
<td></td>
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<tr>
<td>Seager, Richard</td>
<td>Doherty Senior Research Scientist</td>
<td>ARCHES: Mechanisms of Abrupt Climate Change</td>
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<tr>
<td>Seager, Richard</td>
<td>Doherty Senior Research Scientist</td>
<td>Understanding Climate Change from the Medieval Warm Period to the Greenhouse Future</td>
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<tr>
<td>Smethie, William</td>
<td>Doherty Senior Research Scientist</td>
<td>ARCHES: Tracer Observations of Deep Formation and Circulation in the Southern Ocean</td>
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<tr>
<td>Takahashi, Taro</td>
<td>Doherty Senior Scholar</td>
<td>Underway CO₂ Measurements Aboard the RV IB Palmer and Data Management of the Global VOS Program</td>
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<tr>
<td>Ting, Mingfang</td>
<td>Doherty Senior Research Scientist</td>
<td>The Role of Orography on the North American Monsoon Onset and Interannual Variability</td>
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<tr>
<td>Visbeck, Martin</td>
<td>Adjunct Senior Research Scientist</td>
<td>The Role of Ocean Dynamics in Tropical Atlantic SST</td>
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</table>

* Indicates sub-theme
Table 2. CICAR Funding Analysis by Goal/Task/Theme

<table>
<thead>
<tr>
<th>Total: Projects Funded</th>
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</tr>
</thead>
<tbody>
<tr>
<td>BY: NOAA Goal # 2</td>
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<tr>
<td>Task I</td>
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<td>Task II</td>
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<td>Task III</td>
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<td>Task IV</td>
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<tr>
<td>CICAR Administration</td>
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<tr>
<td>Theme I</td>
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<tr>
<td>Theme II</td>
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<td>Theme III</td>
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<td></td>
<td>27</td>
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</table>
Table 3. Personnel Information

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
<th>H.S.</th>
<th>B.A.</th>
<th>B.S.</th>
<th>M.A.</th>
<th>M.S.</th>
<th>Ph.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research Scientist</td>
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<td></td>
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<tr>
<td>Postdoctoral Fellow</td>
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<tr>
<td>Research Support Staff</td>
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<tr>
<td>Administrative</td>
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<td></td>
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<td>1</td>
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<tr>
<td><strong>TOTAL Support &gt; 50%</strong></td>
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<td>1</td>
<td>1</td>
<td>6</td>
<td>3</td>
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<tr>
<td>Undergraduate</td>
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<tr>
<td>Graduate</td>
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<tr>
<td><strong>Total Support &lt; 50%</strong></td>
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<td>@ GFDL</td>
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<tr>
<td>Obtained NOAA Employment</td>
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</table>
Table 4. Lead Author Publication Table

<table>
<thead>
<tr>
<th></th>
<th>JL Lead Author</th>
<th>NOAA Lead Author</th>
<th>Other Lead Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peer Reviewed</td>
<td>4</td>
<td>36</td>
<td>31</td>
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<tr>
<td>Non Peer Reviewed</td>
<td>1</td>
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<tr>
<td>Lamont – Doherty Earth Observatory</td>
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<tr>
<td>Peer Reviewed</td>
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<tr>
<td>Non Peer Reviewed</td>
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<td>11</td>
<td></td>
</tr>
<tr>
<td>University of Maine, Quaternary &amp; Climate Studies</td>
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<td></td>
</tr>
<tr>
<td>Peer Reviewed</td>
<td>2</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

Total publications July 1, 2005 – June 30, 2006: 71
CICAR

Publications
The following lists represent research papers that were prepared and published with full or partial support of NOAA funding. These are papers that either saw print during the 2005/06 reporting period, are still in press, or have been submitted to scientific journals or publishers and are still under review.

Journal Articles


Books / Articles in Books


Reports


Conference Proceedings / Workshops


Ph. D. Dissertations


Total publications July 1, 2005 – June 30, 2006: 71
Awards & Honors


Anderson, Robert F.: 2005 Elected Fellow of the American Geophysical Union

Gordon, Arnold: Sc.D. University of Cape Town, South Africa, 2005 Honoris causa

Kaplan, Alexey: 2005 AGU Editors' Citation for Excellence in Refereeing

Martinson, Douglas: Awarded Outstanding Teacher of Year in January 2005, Department of Earth and Environmental Sciences, Columbia University
Task II provides for specialized support scientists that are employed by Columbia University (LDEO) but are located at the Geophysical Fluid Dynamics Laboratory (GFDL). To date, these slots have not been filled.