CICAR

Theme I: Earth System Modeling

Individual & Collaborative PI Research Projects

1. ARCHES modeling scope: Southern Ocean Modeling and Analysis, D. Martinson
2. ARCHES modeling scope: Mechanisms of Abrupt Climate Change, R. Seager
4. Thermocline Circulation and SST Variability in the Eastern Tropical Pacific and Atlantic, R. Bleck
5. Predictions and Predictability of El Niño Events: Epochs and Biases, M. Cane
6. Investigating Some Practical Implications of Uncertainty in Observed SSTs, L. Goddard
7. The Integrated Role of Snow, Orography and Dynamical Waves in Facilitating Western US Land Surface-Climate Linkages, G. Gong
8. Tropical Influences on Recent and Historical Droughts over North America, H. -P. Huang
10. South Atlantic Ocean-Atmosphere Interaction, A. Robertson
11. Global Oceanic 3HE Data Sets: Calibration for Models of the Upward Branch of the Ocean Global Conveyor, P. Schlosser
12. The Role of Orography on the North American Monsoon Onset and Interannual Variability, M. Ting
**Research Goals**

Improve our quantification of the nature (magnitude, temporal-spatial distributions) of ocean-ice variability in the western Antarctic Peninsula region, and the ocean’s role in contributing heat responsible for the warming and unprecedented glacial melt ongoing in the Antarctic Peninsula (87% of the glaciers are in retreat, contributing to sea level rise). We wish to estimate the total ocean heat flux, and determine what fraction went to each of these, and ultimately, the underlying mechanisms driving these fluxes and their sensitivity in order to estimate possible future scenarios.

**Education Goals**

Acquaint school children and general public with the importance of the Antarctic polar system; including implications of the undergoing change, impacts of this change from local (e.g., penguins) to global (sea level rise), and care and feeding of the Antarctic polar system.

**Research Progress**

**Objectives**

The Year 7 Work Plan, continuing 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)” with the goal of quantifying the ocean heat flux to the atmosphere (contributing to the earth’s fastest winter warming) and to glacial melt.

**Progress**

We made substantial progress toward this goal of decomposing the ocean heat flux into the atmospheric venting and glacial melt by recovery of a temperature mooring that monitored the actual change in ocean heat content as a function of time over an entire year. The idea is to compare our scaling law estimates of the ocean-atmosphere heat flux to the total heat flux, given by the observed change in ocean heat content, with the difference being attributed to glacial melt (not accounted for in the scaling law estimates). For the first time we documented (in 2007) the total ocean heat loss from our one recovered mooring (recovered, serviced and redeployed it; then deployed 4 other moorings to improve spatial coverage and provide statistical robustness to future estimates). We computed the total heat flux by examining the net loss of ocean heat (ignoring transient events); we checked this estimate by using current meter estimates giving the
total heat flux onto the continental shelf; both estimates were unusually high but agreed remarkably well (69 Wm$^{-2}$ for the upwelling flux and 64 Wm$^{-2}$ for the change in heat content; Figure 1). While these heat fluxes are remarkably high (over twice the typical amount), they are internally consistent despite different methods and variables used to estimate them, and are consistent with the extremely anomalous upwelling forcing. The 2007 data occur during a year showing the 5th largest +SAM bias and the 2nd largest La Niña event; both associated with frequent/intense cyclonic storms driving strong upwelling. 2007 also showed the latest ice advance on record, forming 2 full months later than typical (consistent with an unusual venting of ocean heat). This result is presently being evaluated further for publication (the results have been presented orally at 3 different conferences). We also deployed an ocean glider, which clearly demonstrated that the entire sample grid is one of upwelling, something not previously documented directly due to lack of meteorological forcing observations (though circumstantial evidence such as dynamic topography, showed an upwelling environment).

Figure 1.

![SSA estimate of signal in daily Q](image)

**Figure 1:** Black narrow line with dots show daily sub-surface ocean heat content (Q) on WAP continental shelf; solid red line is estimate of signal in that daily Q; blue lines with arrows show times of heat loss; red lines with arrows show heat gain by flooding of the shelf by ACC waters transporting warm UCDW. Inset box lower left gives net ocean heat flux from change in Q and from separate estimate based on current profile.
Results from last year's findings (WAP ocean heat content has changed dramatically since the 1960s; see Figure 2 below) were presented to global oceanographers at the Gijon Spain meeting on "Effect of Global Warming on World's Oceans" to solicit input from that community regarding the source of this warming (discussions following my presentation suggested from this community that ocean absorption of global warming in tropics/subtropics is most likely responsible (this led to a new set of collaborators with the goal of tracking the source of this heat).

**Figure 2.**

- Documented total annual ocean heat flux for 2007 (to atmosphere and glacial melt). Two different methods of ocean heat flux estimates yield consistent and high ocean heat fluxes (over 60 Wm$^{-2}$).
- Deployed 4 additional moorings to give better spatial distribution and statistical robustness in our future estimates (including mooring near strong glacial melt locations).
- Showed feasibility of ocean glider in these frigid polar waters, measuring currents, standard CTD water properties and numerous ecosystem variables (e.g., PAR).

**Societal Benefits**

Quantification of ocean's contribution to the WAP warming and possibly to rapid melt of
glaciers on WAP, leading toward eventual ability to estimate impact of global warming on Antarctic glacial melt (including time scale and sensitivity).

Other Research Connections

*Interagency and research partnerships*
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.

*Collaborators*
Ducklow (MBL), Smith, Ross, Quetin (UCSB), Vernet (Scripps), Large (NCAR), Schofield (Rutgers), Steinberg (VIMS), Stammerjohn (LDEO)

*Education & Outreach*

- K-12: Communication with children in K-12 school while we are at sea, followed by talks in classrooms after cruise is completed
- Sharon Stammerjohn (recently accepted tenure faculty position at UC Santa Cruz)
  Natalia Zakharova (starting Ph.D. program at Columbia University)

*Personnel*

Research Scientists: 2, Research Support Staff: 2, Graduate Students: 1

*Publications*

*Journal articles*


*Ph.D. dissertations*
Project Title: ARCHES: Mechanisms of Abrupt Climate Change

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

NOAA Program & Manager: James Todd, Climate Variability & Predictability
301-734-1258  jим.todd@noaa.gov

Research Goals

- To continue the transition to the new ARCHES, we planned to further examine model-projected hydroclimate change, compare and contrast that with both recent hydroclimate variability and late Holocene hydroclimate variations.
- To improve understanding of the atmosphere dynamics associated with hydroclimate change.
- To further develop the capacity to model Medieval and Little Ice Age hydroclimate variations as a means of comparing past and future hydroclimate change.

Education Goals

- To continue to involve the next generation of research scientists in our work through PhD research thesis and through working with undergraduate interns and interns from Columbia University and Barnard College.
- To continue to disseminate research findings to the wider public via online, print and broadcast media and through presentations open to the general public.

Research Progress

We have completed studies of drought in Mexico and the southeast US. Both of these studies examine recent droughts (post 1995 in Mexico and 2006-8 in the Southeast) in the context of instrumental and late Holocene records and of model-projected climate change. Model simulations are used to determine the mechanisms and predictability of drought in these areas.

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

**Figure 1**

North Atlantic SST index (NASSTI) defined as SST averaged over the ocean grids from equator to 60°N, and 7.5°W to 75°W and normalized. Black solid line: observations; color lines: coupled ocean-atmosphere models of the IPCC 20th century simulations averaged over multiple realizations starting from different initial conditions; dashed black line: average of all models. The index is defined as the deviation from long-term climatological mean for the entire 20th century and the time series are subject to a low-pass tangent Butterworth filter with a 10-year cutoff (from Ting et al. submitted to *J. Climate*).

**Forced and Internal 20th Century SST Trends in the North Atlantic:** In this project, models and observations are used to detect and attribute long-term (multi-decadal) 20th century North Atlantic (NAtl) SST changes to their anthropogenic and “internal” (unforced externally) causes. A suite of IPCC 20th century (C20C) coupled model simulations with multiple ensemble members are subjected to multivariate analysis procedures, particularly a *signal to noise maximizing empirical orthogonal function analysis*, to identify a model-based estimate of the forced, anthropogenic component in NAtl SST variability. Comparing the results to observations, it is argued that the long-term, observed, North Atlantic basin-averaged SSTs combine a forced, global warming trend, with a distinct multi-decadal “oscillation”. The latter is distinctly outside of the range of the model-simulated forced component, which has most likely resulted from an internal ocean-atmosphere interaction. This internal variability (previously dubbed the *Atlantic Multidecadal Oscillation* (AMO) produced a cold interval between 1900 and 1930, followed by 30 years of relative warmth and another cold phase from 1960 to 1990, and a warming since then. The amplitude of the AMO is large enough to deserve consideration in assessing the impact of climate change in and around the Atlantic Basin.
Holocene climate variability in the Eastern Mediterranean (Levant) region: In recent years a well-dated record of Dead Sea Level was assembled which provides a remarkable account of droughts and pluvials in the Levant region since the last glacial period with evidence for several abrupt changes that have been linked to cultural changes in the region. In this study we look at the Dead Sea Level record over the last 10,000 years and its antiphase association with hydroclimate variability in sub-Saharan Africa, and the North Atlantic. We compare these linkages to evidence from the instrumental era and find a compelling similarity to 19th ad 20th century variability on multi-decadal times scales. Based on these finding we hypothesize that hydroclimate variability in the Levant and sub-Saharan Africa are linked to and orchestrated by multidecadal to millennial changes in North Atlantic SST.

We have also been working with Mike Evans of U. Arizona to prepare coral-based records of tropical Pacific SSTs for forcing atmosphere models. Currently we plan to create an ensemble of coral SST-forced records that goes from 1800 to 1920. This will overlap our instrumental SST-forced simulations that begin in 1856 but ends before the period used to calibrate the coral records. This will allow testing of this methodology of model forcing.

Currently we are working on the mechanisms that govern why transient eddies – storm systems – take different propagation paths across the North Pacific Ocean during El Nino winters and La Niña winters. Since these storm systems are responsible for a significant amount of the precipitation that falls over the American West this is relevant to explaining patterns of precipitation anomalies. The work is using daily observational data, climate simulations, controlled experiments with GCMs as well as idealized GFD models.
Highlights

- Demonstration that the Dust Bowl drought was not a purely SST-forced phenomena but was made worse and altered in spatial location by poor land use practices that led to de-vegetation and dust storms that caused warming and further reductions of precipitation.

Figure 3.

- ‘Dust Bowl’ drought is poorly resolved in models with SST forcing only.
- Devegetation from crop failure creates the warm anomaly over the Great Plains through changes in the Bowen ratio (shift from latent to sensible heating); dust aerosol forcing intensifies the negative precipitation anomaly and moves it northward by cooling the surface and reducing evapotranspiration (reducing supply of moisture from the surface).
- When both factors are included in the model simulations, the precipitation and temperature anomalies are of similar magnitude and in a similar location compared to the observations.

- Examined the hydroclimate history of the US Southeast and Mexico to show that both areas have experienced past droughts more severe than recent ones and that in both areas winter drought is linked to La Niña conditions in the tropical Pacific and, for Mexico, warm conditions in the tropical Atlantic Ocean. Mexico is threatened by drying due to global warming while projections for the Southeast are not robust.
- Examined the extent to which natural climate variability and forced climate change contribute to Atlantic SST variations.
- Coupled climate models provide useful information for separating between externally forced and internal variability and help identify clearly an important internal variability mode in the North Atlantic.
- In making future climate change projections in and around the North Atlantic it is important to consider the impact of The Atlantic Multidecadal “Oscillation”.
- Atlantic multidecadal to centennial SST variability affects hydroclimate variability in the Eastern Mediterranean region throughout the Holocene and explains the antiphase
Coupled climate models provide useful information for separating between externally forced and internal variability and help identify clearly an important internal variability mode in the North Atlantic.

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Atlantic multidecadal to centennial SST variability affects hydroclimate variability in the Eastern Mediterranean region throughout the Holocene and explains the antiphase relationship between the latter and sub-Saharan Africa hydroclimate fluctuations, relationship between the latter and sub-Saharan Africa hydroclimate fluctuations.

Societal Benefits

Hydroclimate change is a matter of serious concern worldwide and research on how climate change will impact water availability and quality and how hydroclimate has changed in the last receives considerable attention from the public and from decision makers. Although our work addresses the planetary and continental scale dynamics of climate change – and cannot be directly used by, for example, water resource managers - it is being taken into consideration by such people and their organizations as they plan for current and future climate change.

Other Research Connections

Interagency
This work meshes well with projects we have funded by NSF that examine the basic dynamics of hydroclimate variability and change.

Research Partnerships:
In this year we have begun a partnership with NASA GISS examining climate impacts of dust aerosols during droughts over North America. We continue to collaborate with GFDL on climate change, most recently on tropical Pacific climate change.

Collaborators
Dave Stahle (U. Arkansas), Mike Evans (U. Arizona), Nili Harnik (Tel Aviv U.), several scientists as GFDL, Ron Miller (GISS)

Awards & Honors
R. Seager awarded in 2007 the Lamont Director’s Award for Outstanding Research Performance.

Education & Outreach

Research advisor / mentor
Undergraduate: Alexandrina Tzanova (senior, Columbia College)

Graduate: Colin Kelly, Columbia University, School of International and Public Affairs; Wenchang Yang, Columbia University (first year Ph.D student)

Presentations
Abrupt Climate Change: The case of imminent Southwestern and subtropical drying. Climate Research Committee of the National Research Committee of the National Academy of Sciences, November 2007 (Seager).

Seminars
The atmosphere-ocean dynamics of persistent North American drought: From the Medieval megadroughts to the greenhouse future. GISS Seminar, November 2007 (Seager).

North American Drought: From Medieval megadroughts to the imminent transition to a more arid future. Brown University, October 2007 (Seager).


North American Drought: From Medieval megadroughts to the imminent transition to a more arid future. Lamont Director's Award seminar, September 2007 (Seager).


Was the Medieval period an analog to future subtropical drying? Drylands Hydrology ARCHES miniconference, June 2007 (Seager).


Porter School of Environmental Studies, Tel Aviv University, Israel: “Climate Change and Subtropical Drying”, 24 October 2007, (Kushnir).


The Weizmann Institute, Rehovot, Israel: “Climate Change and Subtropical Drying”, 1 November 2007, (Kushnir).


The interdisciplinary Climate and Society MA Program, Asheville, NC, July 30, 2007, (Cane).


Climate in the Currents of History, Rutgers University, October 2007, (Cane).

Climate Change; Is Al Gore Right?, February 2008, Harvard University, (Cane).

The Solar-ENSO- Drought Connection, Tel Aviv University, March 2008, (Cane).


Fellowship programs / internships
Alexandrina Tzanova (Columbia)

Public relations
- Public Outreach: (community relations) Seager has given numerous interviews to print, broadcast and Internet media. His research was prominently featured in the New York Times Sunday magazine and in National Geographic and The Nation.
- Intranet / Internet sites or pages: Web pages are maintained describing the ongoing research of the group in a style of use to both other researchers and the interested layperson: http://www.ldeo.columbia.edu/res/div/ocp/drought/
- Databases: All model simulations are served for unrestricted access via our data library.

Personnel
Research Scientists: 6, Research Support Staff: 4, Administrative: 1, Graduate Students: 2

Publications

Journal Articles


**Reports**

Research Goals

Understanding sources of disagreement in projected rainfall changes in the Sahel in the CMIP-3 dataset.

Research Progress

I have completed the analysis of the relationship between Sahel rainfall and circulation at interannual and longer time scales, showing that the mid-latitude circulation affects the strength of the Sahara low and the monsoon circulation at the beginning and end of the rainy season. In contrast, the simulated tropical teleconnections are stronger during the core of the rainy season. Currently we are investigating how this result depends on the biases in the models’ simulation of ENSO’s locking to the seasonal cycle and its implications for the scatter in rainfall projections.

A paper reporting on these results is in preparation for Journal of Climate.

Societal Benefits

In the long term, reducing uncertainty in tropical rainfall projections will greatly aid in the design and implementation of adaptation strategies in some of the most vulnerable regions of the world.

Personnel

Research Scientists: 1
**Research Goals**

The Columbia-based activity is a small piece of a project headquartered at NOAA/PMEL. The goal of the project is to gain knowledge of the temporal variability of thermohaline-forced circulations (specifically the Subtropical Cell) in the eastern tropical Pacific and Atlantic, and to better understand the messenger role these circulations play in modulating decadal low-latitude climate variability. The Columbia PI functions primarily as a supplier of diagnostic tools that allow tracking of water mass anomalies in numerical ocean circulation models responding to regime changes in surface forcing.

**Research Progress**

The PI has developed an efficient tracer advection code that depicts the ocean as a stack of layers of differing water density. Thermohaline-forced circulations differ from purely wind-driven ones in that they involve water exchange between layers. Diagnosing where and at which rate this happens is the central piece of information provided by this tool. Lately, the PI has added the capability to depict transport processes backward in time, allowing the transport tool to function as an "inverse" model. Tracing water mass anomalies in oceanic density space, both forward and backward in time, is expected to bring to light changes in climate-relevant current systems.

**Other Research Connections**

*Interagency*

NOAA/ESRL, NASA/GISS
Research Goals

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

Education Goals

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

Research Progress

Volcanic Eruptions And ENSO Predictability
We investigated the effects of volcanic forcing on ENSO predictability using the LDEO5 version of the intermediate coupled model, different from the original Zebiak-Cane intermediate model by the system of interactive statistical corrections, and similar to the version used currently in our operational forecasts. Surprisingly, the sign of the response of the tropical Pacific ocean-atmosphere system to a volcanic eruption turned out to depend on the interactive statistical correction. We implemented the system that scales down individual correction components with a factor between 0 and 1 and performed a series of experiments with scaled versions of statistical corrections, tracing the role of individual components and mechanisms in controlling the sign of response to volcanic eruptions. These results were compared with experiments where the model's wind drag coefficient was varied.

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

**Figure 1.**

**Role Of Surface Heat And Freshwater Fluxes**

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

Figure 2.

Impacts of observed anomalous fluxes of latent heat (LH), shortwave radiation (SW) and evaporation minus precipitation (E–P) on tropical temperature and salinity distributions in the Lamont OCGM. Shown in each panel are the differences of temperature (color) and salinity (contours) between model experiments with and without these fluxes. The two columns in (a) display surface maps of winter 1997–1998 and 1999–2000, representing El Niño and La Nina conditions, respectively, while the two columns in (b) are corresponding vertical sections along the equator (5S–5N). The top three rows show the individual effect of each flux whereas the bottom row displays the combined effects of these fluxes. The contour interval for salinity difference is 0.15 for surface plots and is halved for subsurface plots, with solid (dashed) curves for salinity increase (decrease). [From Chen and Cane, 2008]
**Operational ENSO Forecasting**

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

**Highlights**

- Use of LDEO5 in operational predictions of ENSO events; evaluation of model skill using ROC approach;
- Use of intermediate model versions for ENSO predictions to study the impact of external forcing (volcanic emissions) on ENSO variability;
- Investigation of the role of heat and freshwater surface fluxes in ENSO variability and predictability using Lamont ocean GCM.

**Societal Benefits**

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

**Education & Outreach**

**Research advisor / mentor**
Undergraduate: M.A.Cane, A.Kaplan / A.Vasilyeva (Columbia Engineering School, went on to an M.S. program in Munich Technical University)
Graduate: M.A.Cane, D.Chen / D.Wang (Ph.D. student, Columbia University, Department of Earth and Environmental Science)

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

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


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

Personnel

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

Publications

Journal articles


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 activity under this additional task explores the implications of uncertain SSTs prescribed as boundary forcing in AGCM experiments.

The impact of SST uncertainty, as estimated by added information from satellites, on climate simulations from AGCMs is evaluated 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 (OIV2) 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?” Two sets of experiments have been conducted to address these questions. The first applies the observational error estimate to the global oceans. The second applies the observational error estimate only over the western Pacific where the observational network has known deficiencies.

Research Progress

Publication is in process for results reported here.

Model integrations using global error fields and using error estimates only over the Western Pacific have been completed. The experimental design is the same for each case. For each of the three ENSO states, two scenarios have been run: one in which the estimated sampling error field is added to the observed SSTs and one in which the error field is subtracted. The years chosen are: JFM 1983 (El Niño), 1986 (ENSO-neutral), and 1988 (La Niña).

In all cases examined, the SST errors lead to a discernible modification of tropical precipitation anomalies, and often on extra-tropical anomalies also. The more noticeable impact is on global temperatures. In the first set of experiments, the error field is applied over the global ocean. Thus, it is difficult to discern how much of the temperature response is driven by errors in the tropics and how much due to fact that the global oceans are slightly cooler/warmer than “observed”. In the second set of experiments, the error field is applied only over the Western Pacific, and in that case the modification of temperature anomalies remains similar in magnitude, and to a lesser degree spatial structure, as was seen with the application of global error. This implies that errors in SSTs in the Western Pacific dominate the perturbation response, and that the atmospheric circulation is quite sensitive to SST errors there, at least as evidenced in this AGCM.
Climate anomalies over the US indicate substantial modification of the simulated anomalies by the SST errors. In some cases, the temperature or precipitation modifications due to the ‘error modified SST field’ are of comparable magnitude to those forced by the ‘true SST anomalies’. Furthermore, the modifications due only to the SST errors in the Western Pacific bear a strong resemblance to those imposed by the global SST error. These differences in the ensemble mean predictions due to uncertainties in the SSTs used to force the model have several implications for seasonal climate forecasting. First, the added climate uncertainty confounds estimation of potential predictability of the climate. Second, if these SST uncertainties are not treated rigorously, the probabilistic calibration of models is likely to be sub-optimal. Third, if the uncertainties are treated rigorously and the models calibrated accordingly the resulting seasonal probability distributions will be more diffuse than they would be with more precise estimates of the SST forcing. Finally, conclusions from diagnostic attribution exercises that estimate the causes regional climate variability will be somewhat degraded.

The results point to the need for accurate estimation, and prediction, of SST anomalies, particularly in the Western Pacific.

**Highlights**

- SST errors lead to a discernible modification of both tropical and extra-tropical precipitation and temperature anomalies.

- Over the United States, the temperature or precipitation modifications due to the ‘error modified SST field’ can be of comparable magnitude to the climate anomalies forced by the ‘true SSTs’.

- The seasonal climate, globally and specifically over the US, appear particularly sensitive to SST errors in the Western Pacific.

**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**

*Interagency*

Results are providing input to our use of uncertainty in SST for developing SST scenarios that force the AGCMs used in IRI's real-time predictions, which are largely funded by NOAA.

*Collaborators*

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

**Personnel**

Research Scientists: 1
Research Goals

The specific objective for this year was to design and run a new set of 40-year ensemble GCM experiments, which 1) focus explicitly on snow forcings over North America, 2) apply snow forcings over the entire snow season instead of just the autumn-winter season as was done in the preliminary experiments last year. These experiments were then to be analyzed to determine the local and remote atmospheric response to a North American snow perturbation, throughout the course of the year. Based on the results of these experiments, associated objectives were to 3) conduct separate experiments to delineate specific snow forcings (i.e., snow extent vs. snow depth), and 4) conduct a more detailed dynamical analysis using a diagnostic stationary wave model.

Education Goals

Continue the education of the doctoral candidate funded by this project, Stefan Sobolowski.

Research Progress

Figure 1 shows the seasonal running mean of the storm track response to snow based on geopotential height variances computed from the 2-8 day high bandpass filtered 500mb height field. The response initiates in the fall along the western Atlantic storm track entrance region before pulsing across the Atlantic and extending through Eurasia and the western Pacific entrance region through the winter-spring months. The signal decays quickly in the spring, disappearing almost entirely by May. The eddy kinetic energy at 500mb, another high-pass filtered transient eddy statistic used as a storm track diagnostic, yields similar results (not shown). The enhanced eddy activity response to a positive NA snow forcing presented here appears consistent within the framework of storm track dynamics. The eddy variance statistics presented are coherent and consistent with known storm track dynamics, e.g. the manner in which the response pulses across the mid-latitudes is consistent with Chang et al.’s (2002) description of nonlinear wave packets and downstream development.
Mean climatic state responses are consistent with the storm track response. Figure 2 shows latitude-pressure profiles of seasonal zonal-mean zonal wind over North America, which indicate a strengthening and southward shift of time-averaged flow during winter and spring that likely results from increased storm track activity. Figure 3 shows a positive spring surface temperature response occurs across northern Eurasia, co-located with the downgradient storm track propagation. Figure 4 shows a sustained negative temperature response over the North America snow forcing region, which initiates at the surface during autumn and propagates upward over subsequent seasons. This suggests snow-forced local diabatic heating anomalies, which can

Figure 1. Seasonal running mean storm track response \( (\frac{Z}{f}) \) to positive snow forcing. Contours at +/- 100,250,500,600 mb, 90%-95% statistical significance in grey
influence both transient and stationary circulation activity. However, the stationary wave streamfunction response itself is somewhat ambiguous (not shown).

Figure 2. North American seasonal zonal-mean zonal wind profile (latitude-pressure) response to positive snow forcing. Contours at +/- 0.5, 1, 1.5, 2 m/s.

Figure 3. Spring (March-May) surface temperature response to positive snow forcing. Contours at -7, -5, -3, -1, 1, 1.5, 2, 3 °C.
Because snow is an internal surface state variable in GCMs, prescribing snow conditions as an external forcing is a non-trivial exercise. Two iterations of snow-forced experiments were needed to properly and consistently prescribe the desired snow anomalies throughout North America each year. Due to the computation time required to run large-ensemble GCM simulations, this impeded our research progress somewhat, i.e. delineation of snow depth vs. snow extent forcings has not yet been applied. The ultimate snow forcings prescribed observed extreme snow conditions at individual grid cells, and initiated each ensemble member using independent September 1 initial conditions derived from a 40-year control simulation. The results indicated a clear transient eddy response as described above, while the anticipated stationary wave response based on last year’s preliminary experiments was somewhat ambiguous. Exploration of this transient response and conceptual reconciliation with the ambiguous stationary response has led to a postponement of the stationary wave model diagnosis.

A manuscript describing the storm track and associated responses is in preparation, and this work will be presented at the Fall 2008 AGU Meeting. The interaction between transient and

Figure 4. North American seasonal zonal-mean temperature profile (latitude-pressure) to positive snow forcing. Contours at +/- .25, .5, 1, 1.5 °C
stationary responses, and the specific role of diabatic heating anomalies diagnosed via the stationary wave model, is currently being investigated.

**Highlights**

- Positive snow forcings over North America lead to a clear transient eddy atmospheric response in the form of increased storm track activity from North America through Eurasia during autumn-winter seasons.
- Local and remote mean climatic state responses (i.e. temperature and zonal wind) are consistent with the storm track response, but the anticipated stationary wave response is ambiguous.

**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**

**Research Partnerships**

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

**Education & Outreach**

**Research advisor / mentor**

Graduate: PI Gavin Gong is the thesis advisor for Stefan Sobolowski, doctoral candidate, Columbia University Department of Earth and Environmental Engineering

**Fellowship programs / internships**


**Personnel**

Research Scientists: 2, Graduate Students: 1

**Publications**

**Journal articles**

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

301-734-1226 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 primary goal of the budget year is to advance our understanding of subtropical drying in the context of droughts and climate change.

Research Progress

Extending the work performed in previous years, we have focused on the analysis of the mechanisms for droughts in the past year of this project. Using a moist "aquaplanet" model, we have performed a series of simulations with specified tropical and global sea surface temperature anomalies to determine the response in the hydrological cycle in the midlatitudes. Our latest efforts include the simulations under both equinoctial and non-equinoctial conditions. The latter allows us to look into the seasonal dependence of the hydrological response. This analysis is combined with an analysis of the GFDL coupled climate model simulations with an increasing concentration of greenhouse gas. The results indicate that, even with a globally uniform surface warming, the increase in atmospheric water vapor in midlatitude can cause changes in the stability property of the climatological mean flow (e.g., Fig. 1) in the subtropics and midlatitude, which consequently leads to a poleward shift of the storm tracks and the subtropical drying.

Fig 1: (a) The static stability parameter, N2, for the climatological mean state from the control run of an aquaplanet simulation. (b) The trend in N2, defined as the difference between a "warming run" with a uniform +2.5C increase in the surface temperature and the control run. The scale indicated at left is approximately the sigma level of the model. Color scales are shown at right in s-1. Regions where N2 is negative or ill-defined are masked in brown. This figure shows that in the subtropics and midlatitude the troposphere becomes statically more stable as a response to the surface warming.
Continuing our work from previous years, we have also extended many of the "repeated seasonal cycle (SCYC) runs" from 20 to 50 years to ensure the statistical significance of the results. Most of the conclusions that we obtained with the 20-year runs are shown to be robust. We have also extended our analysis to the combined influences of the tropical Pacific+Atlantic SST forcing on North American droughts. The combination of a cold tropical Pacific and a warm tropical North Atlantic is found to be conducive to the formation of droughts in the U.S.

**Highlights**

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

**Societal Benefits**

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

**Education & Outreach**

*Research advisor / mentor*
- Undergraduate: Liz Logan
- Graduate: Yutian Wu

**Personnel**

Research Scientist: 3

**Publications**

*Journal articles*
Research Goals

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

Education Goals

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

Research Progress

During the first year of this project we performed systematic intercomparisons of spatial and temporal variability of sea surface heights in satellite altimetry, tide gauges, and ocean model simulations (baroclinic and barotropic components), targeted at constraining short-term and small-scale area of wavenumber-frequency spectra, which controls a component of the observational error due to imperfect sampling and inconsistent averaging. Dynamic response to wind and pressure simulated Mog2D FE barotropic model is now routinely removed by AVISO from the altimetry data in order to reduce aliasing of variability with periods shorter than 20 days; in this work we had to apply these corrections to tide gauge data in order to make them comparable to altimetry products and also to the GMAO simulations with the reduced-gravity Poseidon ocean model. Multi-taper spectra were calculated from these adjusted time series, and then integrated over desired frequency ranges. At sub monthly time scales baroclinic variability simulated by the reduced-gravity GMAO Poseidon was comparable to the total sea level height variability from tide gauges in the large area of tropics, while for 2-10 days variability it compared well only near Equator. Model variability on monthly-to-annual timescales was much larger and generally comparable to observations, i.e. AVISO gridded weekly altimetry maps and along-track Topex/Poseidon data (10-day repeat). The model tends to overestimate variability at certain latitudinal peaks (25°S, 10°S, 15°N, 35°N), and underestimates it at high latitudes.
Figure 1: Baroclinic variability, simulated by the reduced-gravity version of the GMAO Poseidon model, compared at the tide gauge locations to the map of monthly-to-annual variability from Topex/Poseidon altimetry, dominates total sea level variability in the tropics and at low frequencies.

Figure 2: Variability at midlatitudes and high frequencies is predominantly barotropic, and, as frequency spectra demonstrate, is reproduced well by the Mog2D model output (obtained from AVISO); frequency is in cycle/day, spectral power is in cm$^2$ day/cycle.
Highlights

- Systematic intercomparison of spatial and temporal variability of sea surface heights in satellite altimetry, tide gauges, and ocean model simulations (baroclinic and barotropic components), targeted at constraining short-term and small-scale area of wavenumber-frequency spectra, which controls a component of the observational error due to imperfect sampling and inconsistent averaging.
- Development of the estimation approach, based on the analysis of satellite – in situ data differences needed for constraining short-term and small-scale area of wavenumber-frequency spectra.

Societal Benefits

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

Other Research Connections

Interagency: GMAO/NASA
Research Partnerships: JCSDA
Collaborators: M. Rienecker, C. Keppenne, J. Jacob (GMAO, GSFC, NASA)

Education & Outreach

Research advisor / mentor
Undergraduate: N.P. Arnold was employed as a full-time research assistant from May 2007 to July 2008, after his graduation from Columbia Engineering School with a B.S. in Applied Physics. He is starting his Ph.D. studies in Harvard (Earth Sciences) in September 2008.

Presentations
A. Kaplan, “Reduced space data assimilation and historical SST,” a lecture at the JCSDA Workshop on Applications of Remotely Sensed Observations in Data Assimilation, University of Maryland, July 23-August 10, 2007.


Personnel

Research Scientists: 2, Research Support Staff: 2
**Research Goals**

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

**Research Progress**

During the reporting period, the research results from years 2 & 3 of the 3-year project were written up and submitted for publication. The paper was revised according to reviewer comments, and is currently under review at Journal of Climate. The abstract of the paper follows and serves as an updated report of progress.

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

Personnel

Research Scientists: 3

Publications

Journal articles
Huang, H.-P., A. W. Robertson, Y. Kushnir, and S. Peng, 2008: Hindcasts of tropical Atlantic SST
gradient and South American precipitation: the influences of the ENSO forcing and the Atlantic
**Research Goals**

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

**Research Progress**

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

First, we have examined the influence of orography on the downstream storm track intensity. It is found that depending on the jet structure, whether a single or double jet, the impact of topography on the storm track intensity shows completely opposite tendency. When a single jet is interacting with a topography, the storm track tends to decrease its strength in the presence of the mountain compared to no mountain case, whereas, when a double jet is present, the storm track intensifies. Since precipitation is closely related to the storm activity, the results are of significance to orographic impact on precipitation, which is a topic needs to be explored further in a more realistic setting. A paper is accepted for publication on the Journal of Atmospheric Sciences (Son, S.-W, M. Ting, and L. Polvani, 2008: The Effect of Topography on Storm Track Intensity in Relatively Simple General Circulation Model. *J. Atmos. Sci.*, in press.)

Second, in collaboration with colleagues at Tufts University, we have examined the seasonality of the trend and variability of the US precipitation in the past 50 years, with emphasis on the fall precipitation variabilities. In the past, the focus of most research on US precipitation is on either the winter or summer. The transitional season received little attention in the literature. Recent studies have shown that the fall precipitation shows a large positive trend and significant decadal variability. The mechanism of the trend and variability in fall precipitation, however, is not clear. We contrasted the fall season to the more familiar winter and summer, in particular, the role of the Great Plains low-level jet in determining the trend and variability of fall precipitation in this project. A GRL paper (Small, D., S. Islam, and M. Ting, 2008: Linkage of Trends and Decadal Variations in Fall Precipitation in the United States to the Atmospheric Circulation. *Geophy. Res. Letter*, under revision) is currently being revised, and further analysis on the role of topography on the fall precipitation and low-level jet is currently under way.

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

**Highlights**

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

**Societal Benefits**

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

**Other Research Connections**

*Research partnerships*

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

**Personnel**

Research Scientist: 1, Research Support Staff: 1, Post Doctoral Fellow: 1
Publications

Journal articles


Theme II: Modern and Paleoclimate Observations

Individual & Collaborative PI Research Projects

1. ARCHES Paleoclimate research: Paleo Sea-Ice Distributions, R. Anderson
2. ARCHES Paleoclimate research: Understanding Abrupt Change and the Glacial to Interglacial CO$_2$ Record, W. Broecker
3. ARCHES Paleoclimate research: Mountain Snowlines in the Southern Hemisphere, G. Denton
4. ARCHES Paleoclimate research: High Resolution Quantitative Studies of High Latitude Deep-and Shallow-living Radiolarian Accumulation Rates Used to Track Glacial/Interglacial Carbon Respiration Depth Changes, J. Hayes
5. ARCHES Paleoclimate research: Constraining Changes in Winds, the Conveyor and Local Currents During Periods of Abrupt Climate Change, S. Hemming
6. ARCHES Paleoclimate research: Southern Ocean Modern Observations, A. Gordon
7. ARCHES Paleoclimate research: Tracer Observations of Deep Formation and Circulation in the Southern Ocean, P. Schlosser
8. ARCHES Paleoclimate research: Tracer Observations of Deep Formation and Circulation in the Southern Ocean, W. Smethie
10. Monitoring the Indonesian Throughflow in Makassar Strait, A. Gordon
11. Multivariate Approach to Ensemble Reconstructions of Historical Marine Surface Winds from Ships and Satellites, A. Kaplan
13. SOLAS OASIS Platform, W. McGillis
15. Underway CO$_2$ Measurements Aboard the RV IB Palmer and Data Management of the Global VOS Program, T. Takahashi
**Project Title**
ARCHES: Paleo Sea-Ice Distributions

**Principal Investigator**
Robert F. Anderson

**Affiliation**
Lamont-Doherty Earth Observatory

**NOAA Program & Manager**
James Todd, Climate Variability & Predictability  
301-734-1258  jim.todd@noaa.gov

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**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 and sea surface temperature 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 circulation of the Southern Ocean, with a focus on its variability during 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.
- Support the training and professional development of a post doc, Dr. Simon Nielsen

**Research Progress**

At the time we submitted our report last year we just hired Dr. Simon Nielsen, a diatom micropaleontologist, as a post doc to develop a high-resolution record of sea ice abundance and summer sea surface temperature in the Atlantic sector of the Southern Ocean. The intent was to construct a record covering the period from the last glacial maximum back through Marine Isotope Stage 4; i.e., over the period during which abrupt climate changes are recognized in many northern hemisphere climate records. This is also the interval spanning four prominent warm events evident in Antarctic ice core records. Our goal is to establish the behavior of sea ice in the Southern ocean during this interval, with a view toward understanding the role of Antarctic sea ice in abrupt climate change. In addition, we sought to establish the pattern of sea surface temperature variability over the time interval of interest. The sediment core used for this study was TN057-14PC, recovered from a site in the Atlantic sector of the Southern Ocean located on, or just south of, the Antarctic Polar Front (51° 59.059’S 4° 30.976’E 3648 m water depth).
A total of 326 samples were processed from the 14-m long piston core, spanning an age interval between approximately 10,000 and 90,000 years before present.

The results of this study were disappointing in that they showed no systematic or significant variability in either sea ice presence or in summer sea surface temperature at the core site. This finding baffles us because (a) application of the same technique (Modern Analog Technique applied to diatom species assemblages) has shown strong signals of climate-related variability in other cores from this region, and (b) application of a Principal Component Analysis to the diatom assemblage record shows a very clear pattern of variability that is well correlated with temperature records over the same time interval estimated from Antarctic ice core records. Details of our results are described below and are illustrated in the appended figures.

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**Figure 1:** Paleoclimate records from marine sediment core TN057-14PC from the Atlantic sector of the Southern Ocean (51° 59.059'S  4° 30.976'E   3648 m water depth). (A) Oxygen isotope composition of planktonic foraminifera published previously by Nielsen et al., 2007 (Origin and significance of ice-rafted detritus in the Atlantic sector of the Southern Ocean. Geochemistry Geophysics Geosystems, 8: Q12005, doi:10.1029/2007GC001618).
Figure 2: Paleoclimate records from marine sediment core TN057-14PC from the Atlantic sector of the Southern Ocean (51° 59.059'S 4° 30.976'E 3648 m water depth). (A) Oxygen isotope composition of planktonic foraminifera reproduced from Figure 1 for reference. (B) Relative abundance of *Eucampia Antartica* reproduced from Figure 1 for reference. (C) Relative abundance of *Rhizosolenia antennata var. semispina*. (D) Relative abundance of *Azpeitia tabularis*. (E) Relative abundance of an ensemble of species characteristic of the Permanently Open Ocean Zone located between the Antarctic Polar Front and the northern limit of sea ice. Blue and red shaded regions represent cold and warm intervals, respectively.

*Figure 2 continued:* (B) Relative abundance of *Eucampia Antartica*. (C) Relative abundance of *Rhizosolenia antennata var. semispina*. (D) Relative abundance of *Azpeitia tabularis*. (E) Relative abundance of an ensemble of species characteristic of the Permanently Open Ocean Zone located between the Antarctic Polar Front and the northern limit of sea ice. Blue and red shaded regions represent cold and warm intervals, respectively.
The general pattern of climate variability is illustrated in Figure 1, where the coldest intervals (Marine Isotope Stage 4, approx 65 to 75 ka BP) and the Last Glacial Maximum (18 to 28 ka BP) are highlighted in blue. These intervals are evident in the oxygen isotope record of planktonic foraminifera (Figure 1a, more positive values during colder intervals) and in the relative abundance of two diatom species whose abundance increases in the presence of ice, or of melting ice (Figure 1 b, c); i.e., during the coldest periods. The relative abundance of a rare subantarctic (warm) species (Figure 1d) as well as the combined abundance of total open water species (Figure 1e) shows a pattern inverse of that seen in the ice-related species (Figure 1 b, c), indicating that we have a robust and internally consistent data set.

Despite the internally-consistent data set, application of the Modern Analog Technique produced little or no systematic differences between warm and cold intervals for either sea ice presence (Figure 2c, expressed in terms of months per year) or summer sea surface temperature (Figure 1d). The oxygen isotope and E. Antarctica records from Figure 1 are reproduced for reference.

Figure 3: Paleoclimate records from marine sediment core TN057-14PC from the Atlantic sector of the Southern Ocean (51° 59.059'S 4° 30.976'E 3648 m water depth). Here, results are plotted against depth in core rather than against age. (A) Oxygen isotope composition of planktonic foraminifera reproduced from Figure 1 for reference. (B) First eigenvector from principal component analysis of the entire diatom data set. PCA results show that the diatom assemblage holds robust paleoclimate information, with negative values of component 1 representative of the coldest intervals (Last Glacial Maximum, 200-400 cm and Marine Isotope Stage 4 around 1200 cm) and positive values characteristic of the warmest intervals (Marine Isotope Stage 5a, below 1250 cm and the early Holocene above 150 cm). Four intermediate warm periods are evident, as indicated by the red shaded band. We believe that these correspond to the well-known Antarctic Warm Intervals A1 through A4.

Although the diatom assemblage does not provide a record of sea ice variability as we had hoped, it nevertheless contains valuable climate information. In addition to the individual assemblages shown in Figures 1 and 2, the first eigenvector from a principal component analysis of the total diatom assemblage exhibits a pattern (Figure 3b) that is remarkably similar to the pattern of temperature variability that is seen in ice core records from many sites in Antarctica. Thus, it is clear that the diatom assemblage in Southern Ocean waters is changing in ways that are tightly coupled to high latitude climate change in the Southern Hemisphere.
It would be interesting to pursue in detail the linkages between diatom assemblages and climate variability. Undoubtedly this would reveal clues about the role of the Southern Ocean in past climate change. Unfortunately, this NOAA-funded project has come to an end, so any future research along these lines will require support from another source.

**Highlights**

- Diatom assemblages in Southern Ocean sediments provide a robust record of past climate variability. Principal component analysis reveals a pattern of variability closely coupled to changes in Antarctic temperature estimated from ice core records.
- Application of the Modern Analog Technique to the diatom assemblage record produced no systematic variability coupled to climate change for either sea ice presence or for summer sea surface temperature variability.
- Given the strong climate signal evident in the principal component analysis of the same data set, we suspect that there may be an unrecognized problem in the modern analog technique.

**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*

We have an NSF-funded project to measure opal fluxes in the same core as a proxy for past climate related changes in upwelling in the Southern Ocean. The diatom results generated with NOAA support will help interpret the opal fluxes, and vice versa.

**Education & Outreach**

*Research advisor / mentor*

Graduate: PhD student Shahla Ali was partially supported by this award.

**Personnel**

Research Scientists: 1, Research Support Staff: 3, Post Doctoral Fellows: 1, Graduate Students: 1

**Publications**

*Journal articles*


NOTE: The above papers were supported primarily by a NSF grant, but post doc Simon Nielsen was supported by this NOAA award during the final preparation of the manuscripts, and the results of these papers aid in our interpretation of the diatom results described here.
Project Title: ARCHES: Understanding Abrupt Change and the Glacial to Interglacial CO$_2$ Record

Principal Investigator: Wallace Broecker
Affiliation: Lamont-Doherty Earth Observatory

NOAA Program & Manager: James Todd, Climate Variability & Predictability
301-734-1258  jim.todd@noaa.gov

Research Goals
To find a means to reconstruct carbonate ion changes in the deep sea over the last 150,000 years.

Education Goals
To alert the public regarding the likely necessity to capture and store CO$_2$.

Research Progress
We found that as foraminifera calcite dissolves an order of magnitude faster than coccolith calcite that the ratio of foraminifera calcite to coccolith calcite provides a measure of the degree of undersaturation. We are exploring the use of this approach.

We are using reconstructions of the sizes of glacial age closed basin lake as a list of the Held and Soden prediction that the extent of focusing of precipitation on the tropics is related to planetary temperature.

Highlights

Societal Benefits
Our research on the changes in the size of closed basin lakes in the world’s drylands adds weight to the prediction that global warming will lead to an increased aridity in these areas.
Other Research Connections

Research Partnerships and Collaborators: Closed basin lake research is conducted in cooperation with Larry Edwards at the University of Minnesota, Ken Adams at the Desert Research Institute and Jay Quade at the University of Arizona.

Awards & Honors


Education & Outreach

Research advisor / mentor
Undergraduate: Liz Krueger
Graduate: David McGee

Seminars

Symposia
Miniconference co-sponsored by CORC ARCHES, 23 and 24 June 2008, The Comer Seminar Room, LDEO Campus, Relative Humidity, Earth Temperature and Climate Change

Personnel

Research Support Staff: 1, Administrative: 1, Graduate Students: 1, Undergraduate Students: 1

Publications

Journal articles
Broecker, W.S., and E. Clark, 2007: Is the magnitude of the carbonate ion decrease in the abyssal ocean over the last 8 kyr consistent with the 20 ppm rise in atmospheric CO₂ content? Paleoceanography, 22, PA1202, doi:10.1029/2006PA001311.


*Books / articles-in-books*
**Research Goals**

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

**Figure 1.** Map of South Island, New Zealand. Yellow box indicates location of the Lake Pukaki field area in the central Southern Alps.

**Education Goals**

The educational goal was to afford three students the background field and laboratory experience to allow them to work toward M.S. and Ph.D. degrees. All three students are registered for their degrees at the University of Maine, but carried out their field research in New Zealand’s Southern Alps (under the supervision of G. Denton) and their laboratory research at Lamont-Doherty (under the supervision of J. Schaefer). They are: Aaron Putnam, Ph.D. student; Alice Doughty, M.S. student; Samuel Kelley, M.S. student.

**Research Progress**

A breakthrough was achieved in establishing a detailed chronology for the moraines adjacent to Lake Pukaki in New Zealand’s Southern Alps (see figures). This chronology complements that...
from nearby Lake Ohau presented as a major result last year. The Pukaki moraines occur in two major sets. Both sets were deposited by an extensive ice lobe that flowed southward from the Main Divide of the Southern Alps to fill the lake and deposit moraines on the adjacent terrain. The resulting map and chronology of these moraine sets is the most detailed ever developed in the Southern Hemisphere, or elsewhere in the world, for that matter. It shows a prolonged LGM, represented by the youngest moraine set, which began about 33,000 years ago and ended about 18,000 years ago. During this long interval of full-glacial conditions, the snowline lowering was 750 m relative to its present-day value. The termination of the last ice age was marked by pronounced recession of the Pukaki ice lobe, beginning close to 18,000 years ago. By 15,000-16,000 years ago, half of the recession and snowline rise had been accomplished. Overall retreat was then interrupted by a readvance, whose maximum was achieved at close to 13,100 years ago (see dates in upper box in the figure). This readvance was followed by subsequent retreat. We were also successful in obtaining a chronology for the second set of moraines, locally known as the Balmoral, that lie outboard of the LGM moraines (see dates in the lower and right boxes in the figure). The many dates that we obtained show that the penultimate moraine set was deposited close to 65,000 years ago. This is the first time that such a moraine set has been extensively dated anywhere.

Figure 2
An important point is that there is a close match between our glacial chronology and the sea-surface record from marine cores near New Zealand published by Barrows et al. (2007, Paleoceanography 22, PA2215, doi10.1029/2006PA001328). The last two intervals of minimum SST's correspond with the LGM and penultimate moraine sets; likewise, the rise of SST's and the glacier retreat during the first half of the termination are identical. The simplest explanation for these similarities is that the sea-surface and glacier records both reflect temperature. Any other explanation is convoluted. This simple correspondence gets around the age-old debate, at least for New Zealand's Southern Alps, as to whether the glacial record predominately reflects temperature or precipitation. What falls out of this is that the combined SST/glacial record from the New Zealand sector of the Southern Hemisphere can be compared with isotopic proxy-temperature records from the Southern Ocean and from Antarctic Ice cores. The resemblance is remarkable, with temperature changes of as much as 4 degrees in the New Zealand sector matching the somewhat larger temperature changes over the Antarctic Ice Sheet. These results indicate that the entire Antarctic/Southern Ocean/New Zealand sector of the planet acted as a unit during at least the last glacial cycle. This discovery sets the scene for determining what orbital parameters paced Southern ice-age climates. As a start, Huybers and Denton (2008) tackled this problem by suggesting that summer duration was the key factor. A solution for the problem of Southern ice ages will afford a background for determining if the trigger for abrupt climate changes can originate at Southern latitudes.

**Highlights**

- The last glacial maximum at middle southern latitudes lasted from 33,000 to 18,000 years ago. The last termination began 18,000 years ago and was interrupted halfway through by a cold reversal that peaked at 13,000 years ago.
- The penultimate glacial maximum was centered at 65,000 years ago.
- The temperature depression responsible for glacial maximum climate in New Zealand’s Southern Alps was 4-5 degrees below today’s values.
- The SST’s in the Tasman Sea and the snowline changes in the Southern Alps of New Zealand appear to have been linked during at least the last glacial cycle. Moreover they match proxy-temperature changes recorded in Antarctic ice cores and elsewhere in the Southern Ocean.
- The implication of the above is that the combined Antarctic/Southern Ocean climate system acted as a coherent unit during at last ice age, and that fluctuations of this unit are somehow linked to orbital variations. As one approach to this problem, Huybers and Denton (2008) suggest that the orbital parameter of most importance in driving Southern climates is the duration of the seasons, which strongly affects radiation balance over the ice sheet, along with sea-ice formation on the Southern Ocean.

**Figure 2.** Lake Pukaki geomorphic maps and surface exposure-age data. Center panel gives overall geomorphic map of Lake Pukaki. Left panel shows the Birch Hill moraine system, bottom panel shows the pre-LGM terminal moraines, right-bottom panel shows the Maryburn side lobe moraine system of the Lake Pukaki sequence, and the right-top panel shows the Lake Pukaki left lateral moraine system. In all panels, red pattern represents moraines deposited during the Last Glacial Maximum, and green pattern indicates moraines deposited during an earlier glacial phase. Yellow/tan shades represent glaciofluvial outwash deposits. All ages are given by black text in white boxes, and black dots and lines show sample locations.
Other Research Connections

There are three primary research connections associated with this project. The first is between the University of Maine and Lamont-Doherty. Personnel from Maine accomplished much of the fieldwork in New Zealand, whereas the exposure-age dating was carried out at Lamont-Doherty and Lawrence Livermore. The second connection was with the Crown Institute of Geological and Nuclear Sciences (GNS-Science) of the New Zealand government. Officers of GNS-Science participated in the moraine mapping and the collection of cores for pollen analysis. Also the geomorphic maps were digitized at GNS-Science. Third, Professor Christian Schluecter of the University of Bern and Professor Bjorn Andersen of the University of Oslo participated in the field work in January and February of 2008.

Education & Outreach

Presentations

Aaron Putnam gave a paper at the Comer Science and Education Foundation conference at Soldier’s Grove, Wisconsin in September of 2007.

Personnel

Research Scientists: 5, Graduate Students: 3

Publications

Journal articles


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


Project Title: ARCHES: High Resolution Quantitative Studies of High Latitude Deep-and Shallow-living Radiolarian Accumulation Rates Used to Track Glacial/interglacial Carbon Respiration Depth Changes

Principal Investigator: James Hayes
Affiliation: Lamont-Doherty Earth Observatory

NOAA Program & Manager: James Todd, Climate Variability & Predictability
Phone: 301-734-1258
Email: jim.todd@noaa.gov

Research Goals

Understanding the mechanism through which the concentration of atmospheric carbon dioxide was reduced during glacial intervals is critical to our understanding of glacial interglacial climate change. The primary reservoir for this lost atmospheric carbon dioxide is the deep-ocean and the oceans biology probably played an important role in its transfer from atmosphere to ocean. Critical to understanding this transfer is knowledge of the depth at which carbon, fixed in surface waters, was respired within the ocean. The goal of this research is to track changes in the depth at which primary production is respired in the high latitude oceans during glacial/interglacial times. This has been done through the quantitative analysis of deep (>200m) and shallow-living (<200m) radiolarians in high latitude (>45° north and south) cores. During the coming year this work will be written up in several publications. One covering northwest Pacific analyses has been submitted and others containing the results of quantitative data gathered from Bering Sea, North Atlantic and Antarctic cores will be submitted during the coming year.

Education Goals

To make the outcomes of this research available to fellow scientists through publications and presentations at meetings, undergraduates through inclusion in undergraduate courses and to the general public through public lectures and popular articles.

Research Progress

The objectives for the past year were to complete analyses on two additional northwest Pacific cores and analyze several North Atlantic cores and select and analyze several Antarctic cores from south of the Antarctic Polar Front. Over the past year quantitative studies of deep- and shallow-living radiolarian accumulation rates and the accumulation rates of opal and calcium carbonate were completed on 160 samples from two well-dated Northwest Pacific cores. Similar analyses were made on four North Atlantic cores and work was completed on 336 samples from three Antarctic Ocean cores from south of the Antarctic Polar Front in the Atlantic, Indian and Pacific sectors. These analyses have revealed that, in both northern and southern high latitudes, dramatic changes occur in radiolarian assemblage accumulation rates across the Pleistocene-Holocene boundary with the accumulation rate of the Shallow Assemblages increasing by 2 to 9 fold, while that of the Deep Assemblages decreases by 2 to 6 fold. Opal accumulation rates do not show such dramatic changes. This, combined with the fact that the deep- and shallow-living species accumulation rate changes move in opposite directions across the Pleistocene-Holocene
boundary, indicates that these assemblages are not responding to changing primary productivity, rather these dramatic accumulation rate changes reflect a shift of radiolarian production from primarily below 200m, in glacial time to above 200 meters in the Holocene. This evidence of a glacial deepening of high latitude carbon respiration is important, for evidence of carbon respiration concentrated at such deep levels is rare in today’s ocean. Today only in the cold highly stratified waters of the Sea of Okhotsk do radiolarians have a similar vertical concentration profile. These similarities make the Sea of Okhotsk a promising modern analogue for the high latitude glacial ocean.

The dominance of deep-living radiolarian accumulation rates in the modern Sea of Okhotsk is a consequence of a cold (-1° to 0° C) near surface (<200m) layer, with low radiolarian concentrations, overlying warmer (1° to 2° C) subsurface (200 to 1000m) water, with higher concentrations. Primary productivity in Okhotsk's thin (10 to 20m) summer mixed layer fully utilizes surface water nutrients. Okhotsk's unusual water column properties are a consequence of very cold Siberian winter air and the nonlinear behavior, at near freezing temperatures, of both seawater's coefficient of thermal expansion and heterotrophic metabolism. Similar conditions probably produced similar physical and biological characteristics in the glacial water column of the northern (>45°N) and southern (>45°S) oceans where deep-living radiolarians dominate LGM sediments. These water column properties would have amplified climate change by promoting the spread of sea ice, reducing winter heat flux from ocean to atmosphere and providing for the efficient transfer of carbon from atmosphere to ocean through a strong biological pump.

Correlations can be made in Antarctic cores between changing deep and shallow-living radiolarian assemblages, responding to changing water column temperature profiles, and temperature changes on Antarctica, recorded in the Vostok ice core (Fig 1). This suggests that temperature changes on Antarctica influence the water column structure in the surrounding ocean to which the biology responds, deepening carbon respiration, exhausting surface water nutrients and draining carbon dioxide from the atmosphere into the deep ocean.

Highlights

- Demonstrating that the vertical temperature and salinity profile of the upper kilometer of the glacial Antarctic Ocean had similarities with the modern Sea of Okhotsk.
- Linking changes of Antarctic deep- and shallow-living radiolarian production to changing Antarctic Ocean water column temperature and salinity structure.
- Linking changes in Antarctic Ocean vertical temperature and salinity structure to temperature changes on Antarctica.
- Providing evidence to support a specific mechanism for the transfer of carbon dioxide from the atmosphere to the ocean in glacial times. Namely that the deeper respiration of organic matter in the glacial Antarctic Ocean stripped the thin mixed layer of nutrients so that nutrient depleted water was returned to the deep-sea by Antarctic intermediate water.
The concentration of shallow living radiolarians in an Antarctic deep-sea core, raised from south of the Antarctic Polar Front in the central Indian Ocean, compared with the temperature record from the Vostok ice core through the last glacial cycle (135,000 to 2,000 years ago). The radiolarians are responding to changes in the thickness and temperature of the oceans surface mixed layer. When this layer is very cold and thin, production is reduced, while when the surface layer warms and thickens, as today near the top of the core, the shallow-living species are more abundant. The numbers represent corresponding temperature peaks of Antarctic air temperature and concentrations of shallow living radiolarians. It should be noted that the radiolarians in this assemblage are all adapted to cold water so there changes in abundance is not a consequence of their being replaced by cold or warm adapted species rather their changes are a response to increasing and decreasing shallow water productivity.
Societal Benefits

Understanding past climate change is important to our understanding of how man’s activities may impact Earth’s climate. Understanding the mechanisms that force natural climate changes provide information on the sensitivity of the climate system to specific forcing mechanisms. My work aims to illuminate how the interaction between physical and biological oceanographic changes can force climate through the transfer of carbon dioxide from the atmosphere to the ocean. This transfer mechanism occurs when the high latitude ocean, primarily the Antarctic ocean, is cooled.

Other Research Connections

Interagency
Yes it benefits a number of projects funded by the National Science Foundation.

Collaborators
Yes it benefits other collaborators at Lamont such as Robert Anderson and Joseph Morley

Education & Outreach

Academic outreach
- K-12: I have spoken to schoolchildren about this work.
- Postsecondary: I have lectured to Columbia undergraduates about this work.
Research advisor / mentor

- Undergraduate: Marland Billings
- Graduate: Edmund Speaker, Bruce Heezen

Presentations

Annual meeting of the American Geophysical Union, San Francisco December 2007 “The high latitude glacial ocean as viewed through the Sea of Okhotsk window, was it like the Arctic”.

Annual meeting of the European Geoscience Union, Vienna, Austria, April 2008, “Antarctic Ocean stratification changes during the last glacial cycle”

Symposiums

Symposium on using past climatic changes to predict future climatic change held in Villeneuve, Belgium, June 2008, “Comparison of changes in the vertical temperature and salinity structure of the glacial Antarctic Ocean with temperature changes recorded in the Vostok ice core.

Personnel

- Research Scientist: 1, Research Support Staff: 1

Publications

Journal articles

**Research Goals**

- Develop and apply proxies in ocean sediments that allow constraining important components of the paleoclimate system
- Integrate the records with existing information in order to constrain winds, and ocean circulation during periods of abrupt climate change

**Education Goals**

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

**Research Progress**

In addition to continued efforts to characterize the behavior and role of northern hemisphere ice sheets in the climate system, a key goal of our research is application of high resolution records of changes in deep water and intermediate water mixing in the South Atlantic in the context of rapid climate changes. Kissel et al. (2008) used detailed correlation, allowed by magnetic paleointensity, between cores in the North Atlantic with magnetic evidence for changes in the vigor of NADW overflow across the Nordic sills and cores in the South Atlantic with detailed Nd isotope records. We have found a remarkable correlation between the two records, but careful evaluation leads to a several hundred-year lag between evidence for reduced vigor in the North Atlantic and evidence for reduced NADW contributions in the deep South Atlantic. Alex Piotrowski et al. (in press) have used the combined high resolution benthic and planktonic stable isotopes and Nd isotope records from South Atlantic cores to examine in detail the relationships among these proxies to better understand the responses of both northern and southern source deep water formation during rapid climate changes. One of the implicit conclusions from our results and interpretations is that, while the North Atlantic and Pacific end members do not appear to have changed appreciably, the Southern Ocean end member most likely changed as a result of the reduced input from the NADW. We are developing a promising record of Southern Ocean composition from an Indian Ocean core (Goldstein et al., 2007, 2008).

Antarctic Intermediate Water (AAIW) is a major player in ocean-climate interactions, but its behavior under different climate states, and its role in the global ocean-climate system is not well
understood. Paleo-records of past variability are key to pursuing this problem. Katharina Pahnke is using the dispersed ferromanganese fraction of cores from intermediate water sites in the Atlantic to evaluate the role of AAIW in times of rapid climate change. This work is partly supported by CICAR, which has been important for leveraging her funded NSF OCE grant. She has created a high resolution record from the western tropical Atlantic (Pahnke et al., provisionally accepted) and has also done further mapping of the modern and last glacial composition of intermediate waters in the South Atlantic which she presented at the Goldschmidt conference (Pahnke et al., 2008). The new neodymium isotope record from the mid-depth Atlantic shows abrupt increases in the northward incursion of AAIW during times of strongly reduced North Atlantic overturning during the last deglaciation. Simultaneous increases in AAIW formation and warming in the southwest Pacific suggest a tight link with Southern Hemisphere climate. However, the initial incursion of AAIW into the North Atlantic at ~19ky coincided with weak AAIW formation in the Pacific and reduced overturning in the North Atlantic, suggesting Northern Hemisphere forcing of AAIW expansion through reduced competition at intermediate water depth. This early incursion of AAIW would have contributed to freshening of the intermediate depth North Atlantic, perhaps spurring the subsequent collapse of North Atlantic deep convection.

**Highlights**

- Evidence for changes in the composition of the Southern Ocean “end member” composition of Nd isotopes
- Evidence for millennial change in AAIW formation during times of reduced NADW
- Evidence for changes in intermediate water mass mixing associated with rapid climate change

**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 & Outreach**

*Academic outreach*

K-12: we have engaged several high school students in summer research (from Tappan Zee High School)
**Research advisor / mentor**
Undergraduate: we have engaged several undergraduate summer interns in this research (Hadas Kushnir, Stacey Kepler, Caleb Schif, Sean Culkin, Stephanie Pahler, Sarah Gitt). Stephanie Pahler did a senior thesis at Barnard College with Allison Franzese, and Joey Simonson did a senior thesis at Columbia College with Katharina Pahnke.

**Personnel**
Research Scientist: 2, Post Doctoral Fellow: 1, Undergraduate Student: 1

**Publications**

**Journal articles**


**Books / articles-in-books**

**Conference proceedings / workshops**

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


**Project Title**  
ARCHES: Southern Ocean Modern Observations  
Moorings & Observations

**Principal Investigator**  
Arnold Gordon

**Affiliation**  
Lamont-Doherty Earth Observatory

**NOAA Program & Manager**  
James Todd, Climate Variability & Predictability  
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**Research Goals**

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

This project maintains 3 moorings south of the South Orkney Islands to monitor the combined outflow (currents and temperature/salinity) within the lower ~500 m of the water column within the core of dense Antarctic deep and bottom water draining from various sites along the continental margins of the Weddell Sea. These water masses ventilate much of the lower 2 kilometers of the world ocean. Goals for FY08 were to prepare for servicing the moorings in 2009; present preliminary analyses of the data in hand at the 5th International Antarctic Peninsula Climate Change workshop.

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

**Education Goals**

Engage an undergraduate summer intern in the analysis of the mooring time series.

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**Research Progress**

**Moorings**

- A mooring cruise is scheduled for January 2009.
- A poster was prepared and presented at the 5th APCC workshop at the U C Irvine in June 2008.
- A paper was published in J. Climate 2008.

**Observations**

- A paper published in Oceanography 2008

Additional research themes identified and currently being pursued (moorings and observations):

- Relating the time series SSS of the central region of the North Atlantic subtropical regime to:
  1) the shallow subtropical/equatorial overturning circulation of the North Atlantic;  
  2) water vapor flux across Central America; and  
  3) fluctuations of SSS in the tropical Pacific.
- Circum-Antarctic SSS changes associated with SAMS, with focus on the relationship of SSS east and west of Antarctic Peninsula.

- Relating the outflow of Weddell Sea Deep and Bottom water as recorded by the Weddell mooring time series to climate indices, notably SAM and ENSO.

**Highlights**

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

**Societal Benefits**

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

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

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

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

Figure Caption: Top – map of the western Weddell Sea indicating the mooring positions, and schematically illustrating hypothesized flow of deep and bottom waters formed along western boundary of the Weddell. Bottom – time series of speed, temperature gradient and potential temperature from mooring M3. Maximum speeds occur primarily in winter, minimum in summer. The near-bottom temperature gradient increases during the coldest pulses of bottom water (shading).
Other Research Connections

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

Education & Outreach

Symposiums
The 5th International Antarctic Peninsula Climate Change workshop, June 24-26, Irvine, CA. Poster presentation entitled: “Weddell Deep and Bottom Water Characteristics Exiting the Peninsula Region from Eight Years of Moored Measurements”

Personnel

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

Publications

Journal articles

**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, Climate Variability & Predictability  
301-734-1258  jim.todd@noaa.gov  

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

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

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

Societal Benefits

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

Other Research Connections

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

Education & Outreach

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

Personnel

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

Publications

Books / articles in books
Research Goals

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

Education Goals

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

Research Progress

The gridded instrumental temperature and precipitation fields being used for generating the PDSI and SPI drought metrics were first completed several months ago, and the instrumental drought metrics were calculated from them by Richard Heim. However, problems in calculating the PDSIs in certain portions of the grid have necessitated modifying the Palmer program and re-estimating those variables. In addition, the basic climate fields are now being modified and improved through the addition of more precipitation data, especially in Mexico (R. Vose, pers. comm., August 19, 2008). They are also being updated to the end of 2007. These modified and updated fields will be used now to recalculate the drought reconstructions for North America in the coming months. The expected time of delivery of those reconstructions to NOAA is the end of October 2008.
The tree-ring network needed for reconstructing North American drought continues to be expanded and be filled in. The total number over the life of this project has now increased from 835 to 1846.

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. In addition, tests have been run to determine the feasibility of reconstructing monthly PDSI (the other drought metrics will be tested as well). Although certain area like northern Canada will be impossible to directly reconstruct during the winter, most of the temperate and sub-tropical parts of North America can be reconstructed over most of the calendar year months. Missing months at certain grid points will be estimated through the use of optimal interpolation methods.

Copy of a PowerPoint Slide presented at the AMS 88\textsuperscript{th} Annual Meeting in January 2008. The slide shows calibration and verification results for reconstructing three June-August Palmer indices (Z-Index, PDMI, and PHDI) from the tree-ring network over North America. Bright red to yellow regions show the best areas of calibration and verification. This extends even into central Alaska. Improvements are expected in Mexico now through the recent improvement of the instrumental data grid there.
Highlights

- Expansion of the North American tree-ring network from 835 to 1846 chronologies.
- Continued development of the living gridded instrumental data grid used to generate PDSI for reconstruction.
- Re-write of the PPR program.

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 & Outreach

Presentations


Seminars


Personnel

Research Scientists: 1, Research Support Staff: 1

Publications

Journal articles


Reports
Member of the CCSP SAP 3.4 “Abrupt Climate Change” Committee, Lead Author on Chapter 3, “Hydrological Variability and Change” (with P.J. Bartlein, N. Diffenbaugh, R. Seager, B.N. Shuman, R.S. Webb, J.W. Williams, C. Woodhouse). Nearing completion.
Project Title: Monitoring the Indonesian Throughflow in Makassar Strait

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

NOAA Program & Manager: Michael Johnson, Climate Observations
301-734-1225 mike.johnson@noaa.gov

Research Goals

The Indonesian Throughflow (ITF) of Pacific water into the Indian Ocean represents an important part of the ocean system of interocean fluxes. The ITF is believed to govern aspects of ENSO and the Asian monsoon. The ITF amounts to ~12 Sv, 80% of which is channeled through Makassar Strait. Within the Labani constriction of Makassar Strait near 3°S, the throughflow was measured during the NSF funded INSTANT program from January 2004 to November 2006. With NOAA OCO support a single mooring within Makassar Strait was deployed in November 2006 at the site of the INSTANT MAK-WEST. A transfer function based on the Arlindo and INSTANT time series will allow the MAK-WEST data to be converted to a full Makassar ITF.

Education Goals

Capacity building of Indonesian students in the ability to maintain deep-sea current meter moorings and processing and analysis of data obtained from the moorings.

Research Progress

In November 2006 with NOAA-OCO funding an ADCP mooring was deployed at 2°51.11'S; 118°27.33'E within Makassar Strait. This mooring will bridge the gap between the NSF funded INSTANT mooring and development of an ongoing measurement program to measure the flow within Makassar Strait, the major component of the Indonesian throughflow [ITF]. The NOAA Makassar mooring will be recovered and redeployed in November 2008. In June 2008 an Implementation Agreement [IA] was signed between Lamont-Doherty Earth Observatory of Columbia University and BRKP, the responsible Indonesian agency: Agency for Marine and Fisheries Research, Indonesia. The IA defines the program objectives, the responsibilities of each side, associated training for mooring maintenance and associated data processing and quality control activities.

Personnel The NA03OAR4320179 PI, Prof. Arnold L. Gordon, supervised the preparation of the IA. Communications between the US and Indonesia regarding details of the provisions was the responsibility of Dr. R. Dwi Susanto, a Staff Associate at Lamont-Doherty Earth Observatory, who serves as the ‘Director of Indonesian Research Coordination’ at Lamont. The specifics of the November 2008 mooring cruise are in the process of being planned.
Highlights

The NOAA Makassar mooring will be recovered in November 2008, so there are no results yet to report.

Societal Benefits

The ITF links the tropical Pacific to the tropical Indian Ocean, and appears to be a factor in governing the interaction of the ITF to the Asian monsoon. The NOAA time series will provide a long-term time series as required to evaluate this hypothesis.

Personnel

Research Scientist: 1, Research Support Staff: 2
**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**

We performed further testing of our trial versions of ocean surface wind and sea level pressure data. We evaluated our trial analyses in the context of other climate variables using instrumental analyses, paleodata, and numerical model output, furthering the foundation for the multivariate analyses, and advanced the ways of representing the uncertainty in the analyzed values. Historical analyses of were used to investigate the Indian Ocean warming and tropical Atlantic climate variability. We also quantified the connection of the apparent spectral slopes in surface winds and other climate variables with patterns of interannual variability.

A. Indian Ocean warming trend and dipole

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

B. Interpretation of a tropical Atlantic paleorecord

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

C. Interpretation of frequency spectral slopes of climate variables in terms of interannual variability patterns

We showed that slopes of frequency spectra of climate variables computed from months to decades correspond visually and mathematically to a straightforward climatological quantity, namely the log ratio of interannual to subannual variances. We use the method of empirical orthogonal functions (EOFs) with specially designed weighting coefficients to identify the dominant modes responsible for spatial patterns of spectral slope. Notably, residual patterns after subtracting only a few leading EOFs appear to be dominated by latitudinal variability and land-sea contrast, particularly for precipitation fields. Finally, we interpret leading principal components as well-known modes of interannual variability, predominantly ENSO and PDO.

D. Simplified connections between tropical climate variables

For the purpose of improved multivariate historical analyses, we revisited statistical models connecting tropical Pacific climate variables on the basis of our own trial historical analyses, NCEP/NCAR reanalysis, and a coupled GCM from GFDL (CM2.1). Regression coefficients of zonal and meridional winds on NINO3 were quite similar in all data sets. However, a pattern of correlations of zonal wind stress anomaly averaged over the area \([160^\circ E-150^\circ W; 5^\circ S-5^\circ N]\), a wind-based index of ENSO, with the sea level pressure anomalies was quite different in CM2.1 simulations and in NCEP-NCAR reanalysis. In the coupled GCM this pattern was centered on the equator, both to the west and to the east of the wind index area. In observations (reanalysis), however, the strongest correlations were not at the Equator: the western node of the pattern was shifted south of the Equator, while the eastern node was split into two parts, with centers at roughly 20\(^\circ\)N and 20\(^\circ\)S (southern mode is a stronger one, recalling the Southern Oscillation).
Highlights

- Use of historical analyses to study epochal changes in the nature of Indian Ocean Dipole events;
- Interpretation of Atlantic climate variability on the basis of Mg/Ca Cariaco Basin record;
- Connecting the patterns of apparent spectral slopes for frequency spectra of climate variables with patterns of interannual variability;
- Quantifying equatorial zonal wind – sea level pressure connection in observations and coupled models.
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.

Education & Outreach

Research advisor / mentor
Undergraduate: A.Kaplan / D.Amrhein (Columbia College, Physics Major); A.Kaplan / L.Chen (Columbia College, Economics Major)

Seminars

Symposiums

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

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


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


Personnel

Research Scientists: 3, Research Support Staff: 1, Administrative: 1, Post Doctoral Fellow: 1, Undergraduate Students: 2
<table>
<thead>
<tr>
<th>Project Title</th>
<th>Atmosphere and Coastal Ocean CO2 Measurement Platform - SABSOON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principal Investigator</td>
<td>Wade McGillis</td>
</tr>
<tr>
<td>Affiliation</td>
<td>Lamont-Doherty Earth Observatory</td>
</tr>
<tr>
<td>NOAA Program &amp; Manager</td>
<td>Kathy Tedesco, Global Carbon Cycle</td>
</tr>
<tr>
<td></td>
<td>301-734-1255 <a href="mailto:kathy.tedesco@noaa.gov">kathy.tedesco@noaa.gov</a></td>
</tr>
</tbody>
</table>

**Research Goals**

- Measure the pCO$_2$ in the atmosphere and ocean at Offshore Observational Networks. High-resolution Non-Dispersive infrared (NDIR) detection of CO$_2$ comparisons to flask measurements.
- Determine ocean-atmosphere DpCO$_2$ at the offshore observatory using high-resolution IR techniques in order to estimate the coastal air-sea CO$_2$ flux variability.
- Quantify and describe the temporal variability in atmosphere and ocean CO$_2$ concentrations.
- Determine the relative importance of biological and physical controls on coastal CO$_2$ concentrations and air-sea CO$_2$ exchange.
- Determine the influence of coastal ocean carbon on the North American terrestrial carbon cycling.

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

- **Autonomous infrared measurements of atmospheric CO$_2$** was designed:
  - To have a measurements accuracy of 0.1 ppm;
  - To operate for up to 2 months without any direct on-site 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/h;  
  - Air-flow 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 CO$_2$ from tower** include:
  - The development of an equilibrator system, which can handle significant wave action but does not require pumping of seawater greater than 2 meter above mean high water.
Figure 1: Schematic of the autonomous, high-resolution atmospheric monitoring system for tower based observatory measurement.

Ocean Flux Tower
3.5 km offshore
Cabled Data and Power.
18 meter water depth.
20 meter height.
Coupled air-water BL.

Figure 2: Atmospheric and ocean xCO₂ system for ocean tower. This system features a standard/sample gas flow control system controlled by stepper motor and pin valve in a feedback loop with Gas flow meter. Picture shows the MVCO tower and atmospheric xCO₂ and wind direction. This system is installed where inter-calibration with autonomous NOAA/CMDL flasks take place.
Education Goals

The autonomous CO$_2$ system will be used by the community through active outreach programs though University of Colorado, Lamont-Doherty at Columbia University and NOAA.

Research Progress

1) Autonomous infrared measurements of atmospheric CO$_2$ 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 air sampling with an IR detector is very difficult to control in conditions that are expected on offshore towers 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 have achieved measurement accuracy at the 0.1 ppm level was to control the incoming gas and IR detector cell temperature. While this can be achieved using active temperature control we were interested in doing this passively to reduce the power consumption. We performed temperature control by creating a heat sink made from seawater stored in a 150 L barrel. Air is pumped through tubing in the temperature ballast barrel and into an insulated box containing the IR detector. The results of the 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. This suggests that drift corrects with hourly standard analysis are sufficient to account for temperature changes.
   c. Remote operation
      i. In an effort not to lose the advancement of this technological and scientific innovation perform the deployment on the Martha's Vineyard Tower (Figure 2) and the RV LM Gould. With the new airflow control system installed on our RV LM Gould we tested 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 also performed an inter-calibration exercise with NOAA/CMDL flask sample in the end of March 2007 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 has been implemented on the Martha’s Vineyard Tower (Figure 2)

2) Autonomous measurements of seawater CO$_2$ from tower
   a. Developed equilibrator system
      i. The major challenge to measuring seawater from towers was 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 put 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 4 meters above mean water height (Figure 3).

Figure 3 Caption: Aqueous and Atmospheric carbon dioxide schematic system. Detector, equilibrator, acquisition system.
Highlights

- Successful testing of accurate and autonomous CO$_2$ measurements to be made from a coastal tower.
- Systems have been fabricated, tested, and deployed in collaboration with Columbia University and NOAA ESRL.
- Long-term measurements of high-resolution and accurate atmospheric carbon dioxide (Figure 4, 5) and the seasonal, diurnal variability and magnitude have been proven technologically sound and scientifically fruitful.

Societal Benefits

With a clear understanding of the sources and magnitude of variability that exists in 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
Woods Hole Oceanographic Institution and Martha’s Vineyard Observatory organization.

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

Education & Outreach

Presentations

Intranet / Internet sites
http://www.whoi.edu/mvco

Personnel

Research Scientists: 1, Research Support Staff: 2, Administrative: 2, Graduate Students: 11, Undergraduate Students: 1
Project Title: Ocean-Atmosphere Sensor Integration System (OASIS)

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

NOAA Program & Manager: Michael Johnson, Chief, Climate Observations
301-427-2460 mike.johnson@noaa.gov

Research Goals

- Develop an Autonomous Surface Vehicle.
- The goal of this OASIS project was 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.

An Ocean Atmosphere Sensor Integration System (OASIS), a solar-powered (battery stored) surface autonomous vessel that can be controlled by satellite communication. This picture shows the system "set up" last year, but much of the summer internship was actually spent doing engineering work, setting up the instrumentation and cabling to be plug-and-play – when power is cycled on the vessel, instruments automatically start sending data to data loggers without any action by NASA scientists or engineers. This will permit OASIS to collect data during planned year-round transects.
Education Goals

The OASIS project is managed by NOAA Center for Innovative Technology (CIT). This project had 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 designed and implemented the diverse air-sea flux components. Columbia University also participated in the field trials that took place in 2007 near the Wallops Island Flight Facility. The system has been constructed and has been merged with the OASIS platform during the spring/summer of 2007. The in situ testing was performed in 2007.

Central region of the Mid-Atlantic Bight, with location of the OASIS transect on (red line) and the planned transect (black) – this is the "COBY line", run with an additional vessel that makes bio-optical and hydrographic measurements every two weeks. Only the portion of the red ship track when the Lamont payload was turned on is shown.
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 CO$_2$ 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.
Education & Outreach

Fellowship programs / internships

Personnel

Research Scientist: 1, Research Support Staff: 1, Administrative: 1

Publications

Ph.D. Dissertations
Philip Orton: Coastal Ocean Air-Sea CO₂ Flux Measurements from an Autonomous Research Vessel
Research Goals

- Design and Fabricate an air-sea CO₂ flux system.
- Test and quality control the flux system from ships of opportunity.

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

The autonomous CO$_2$ system will be used by the community through active outreach programs through University of Colorado, Lamont-Doherty at Columbia University and NOAA.

Research Progress

The greatest asset of this project has been the ongoing development of an autonomous infrared-based CO$_2$ flux system for the measurement of air-sea carbon dioxide fluxes. A meteorological system with IR-based detection of pCO$_2$ concentrations has been designed, fabricated, and developed at LDEO and ESRL/NOAA and deployed on the Ronald H. Brown (Figure 1). Figure 2 shows some of the problematic issues with open-path CO$_2$ systems, which are susceptible to spray and contamination. Figure 2 shows that two independent sensors may be susceptible to motion. This assessment was performed on the Norway Ship G. O. Sars and the NOAA ship Ronald H. Brown. A Null system samples air that is not correlated with atmospheric eddies. The sample unit measures air in an enclosure. This system has been used as autonomous pCO$_2$ systems operated during shipboard CO$_2$ flux studies. This opportunity to measure and analyze autonomous system performance from an ocean vessel was invaluable. Preliminary testing in the laboratory also provides a motion free environment. Optimized for the ocean, it was tested in sea trials.

1. High volume in situ air sampling included in the autonomous system was used with CO$_2$ detectors in environmental enclosures. Remote air-pumps ensure continuous sample delivery over month-long periods, despite heavy aerosol loads in samples.

2. The in-line null pCO$_2$ sensor is used to quantify motion contamination. The atmospheric sample is mixed and sent through a second sensor measured simultaneous with the vertical wind velocity. The carbon dioxide fluctuations are removed and the flux signal from this system will be assessed as the motion bias.

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

The accuracy of the computed flux is dependent on the sensitivity of the gas analyzer to high frequency fluctuations. A fast-response, enclosed open-path, non-dispersive infrared (NDIR) CO$_2$/H$_2$O gas analyzer is used to measure atmospheric gas samples continuously. The air detectors are mounted 0.5 m from the sonic anemometer sampling volume. The samples air is drawn through the intake tube at a constant high rate, which results in a very small and correctable lag between the gas sample and the sonic anemometer measurement. Figure 1 shows the ultrasonic anemometer, compass, pitch, roll, yaw, accelerometers, and two NDIR systems onboard the BROWN.
Figure 2: (left) Time series of enclosed open-path CO$_2$/H$_2$O sensors. The Null sensor (blue) shows motion. The Sample sensor (red) will have motion and signal from atmospheric CO$_2$.

Figure 3: The motion accelerations measured on the ship near the carbon dioxide measurements. There is some spectral density in the Null sample. The Sample has a much higher spectral density.
Highlights

- Successful testing of autonomous air-sea CO₂ flux measurements was made from a research vessel.
- Discovery that open-path sensors have biases and enclosed open-path detection of CO₂ measurements are necessary.
- Systems are being fabricated and continued testing in collaboration with Columbia University and NOAA ESRL.

Societal Benefits

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

Other Research Connections

Interagency
NOAA OGP with interagency collaborations between NSF and NASA.

Research partnerships
Duck Field Research Facility
Collaborators
Chris Fairall of NOAA/ESRL in Boulder Colorado.

Education & Outreach

Presentations
- AGU, SF 2008.

Personnel

- Research Scientist: 2, Research Support Staff: 3, Administrative: 2, Graduate Student: 1, Undergraduate Student: 1

Publications

- Ph. D. dissertations
  Alejandro Cifuentes-Lorenzen (University of Connecticut)
  Siv Lauvseth (University of Bergen, Norway)
Research Goals

The net sea-air flux of CO₂ may be estimated using the sea-air pCO₂ difference multiplied by the gas transfer rate across the sea-air interface. The primary objective of this program is to observe and document the space-time distribution of the sea-air pCO₂ difference and to estimate sea-air CO₂ flux over the regional and global oceans in seasonal, annual and interannual time scales. We determine the air-sea pCO₂ difference continuously using a shipboard underway pCO₂ system installed aboard a number of research and commercial ships participating the NOAA/VOS program. The data obtained under the NOAA/VOS program are processed and interpreted at Lamont-Doherty Earth Observatory, and the processed data are archived at and distributed to the public by the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN. The gas transfer rate is estimated using wind speed data obtained using satellite observations.

Education Goals

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

Research Progress

The Lamont group is primarily responsible for the acquisition of the surface water pCO₂ data aboard the RVIB Palmer, which serves mostly in the Southern Ocean, one of the least accessible areas due to extreme environments. The research activities of M/V Oleander and R/V Atlantic Explorer (N. Bates) are supported by the NOAA with a subcontract of this LDEO grant to the Bermuda Institute of Ocean Studies (BIOS). Our semi-automated pCO₂ systems have been upgraded with this NOAA grant to make the system more stable and reliable. Atmospheric CO₂ is absorbed by the major water masses that are formed in the Southern Ocean, and is transported to ocean interior (as the Antarctic Bottom Water, Antarctic Intermediate Water and Mode Waters) and stored there for time scale of deep ocean circulation. Hence, our understanding of air-to-sea CO₂ flux over the Southern Ocean is important for estimating the future course of atmospheric CO₂ levels. We analyzed the surface ocean water pCO₂ data in the Southern Ocean collected over the past two decades. Since the photosynthesis is minimum during the austral winter months, the winter-time pCO₂ in seawater reflects primarily physical processes regulating it.
time trend analysis of the winter waters between 45°S and 60°S yields that the winter water pCO$_2$ has increased at a mean rate of 2.1 ± 0.4 uatm/yr. Since the Southern Ocean pCO$_2$ is generally lower than the atmospheric and is a CO$_2$ sink, the observed increase in seawater pCO$_2$ suggests that the sink is weakening. Furthermore, since the rate appears to be faster than the mean rate of atmospheric CO$_2$ increase of about 1.5 uatm/yr, the Southern Ocean CO$_2$ sink is weakening faster than that which is expected from the uptake of atmospheric CO$_2$. This may be accounted for by warming of surface waters and/or an increase in the upward flux of deep waters rich in CO$_2$.

As a part of the VOS program, we processed 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 (C. Sweeney and T. Takahashi); 2) the NOAA's Ronald Brown program, mostly in the Atlantic Ocean (R. Wanninkhof); 3) the "Explorer of the Seas" program in and around the Caribbean Sea (R. Wanninkhof); 4) the Kaimimoana program in the equatorial Pacific (R. A. Feely); 5) Columbus Waikato (R. Wanninkhof); and 6) M/V Oleander and R/V Atlantic Explorer (N. Bates, BIOS). Other contributors for the VOS database include researchers from U. K., Japan, Iceland, Norway, France, Australia and Germany. The surface water pCO$_2$ database thus assembled now consists of about 3.3 million pCO$_2$ 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 as well as the CDIAC.

Mean Annual Air-Sea CO$_2$ Flux Over The Contemporary Global Oceans Based On 3 Million Measurements Of Surface Water Pco$_2$

The 1979-2005 NCEP-DOE AMIP-II Reanalysis wind speed data are used for estimating the CO$_2$ gas transfer rate across the sea-air interface. Yellow-orange areas indicate that the sea is a source of CO$_2$ to the atmosphere; blue-magenta areas indicate a sink; and green areas indicate neutral. Intense upwelling of deep waters rich in CO$_2$ and warming of water causes the sea to become a CO$_2$ source for the atmosphere, whereas cooling of water and the photosynthetic utilization of CO$_2$ cause the sea to become a CO$_2$ sink. The total global ocean uptake flux of CO$_2$ for the year 2000 is estimated to be 1.4 Giga-tonnes Carbon per year. (Takahashi et al., DSR-II, in press)
Highlights

1) A global ocean database consisting of about 3.3 million surface water pCO₂ measurements obtained since 1970’s has been assembled and made available for public access through the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN.

2) Based upon a newly assembled database for the surface water pCO₂ over the global oceans, a contemporary net CO₂ uptake flux over the global ocean is estimated to be 1.4 ± 0.7 Petagrams (or Giga-tons) of carbon per year. The uncertainty includes errors in the gas transfer rate, wind speeds, and the rate of increase in seawater pCO₂ as well as that due to undersampling.

3) The mean rate of increase in surface water pCO₂ for about 27% of the global ocean area (including the North Atlantic, the North Pacific and some areas of the South Pacific Oceans) has been determined to be 1.5 uatm/yr. This is indistinguishable from the mean rate of increase in atmospheric CO₂, and suggests that the global ocean is responding closely to the atmospheric CO₂ increase. However, the North Pacific (1.2 ± 0.5 uatm/yr) appears to be increasing slower than the mean atmospheric rate of 1.5 uatm/yr, whereas the North Atlantic (1.8 ± 0.4 uatm/yr) is faster than the atmosphere. Causes for this difference are not understood. Since the rate of pCO₂ increase is directly related to the rate of ocean water acidification, this basin-scale difference warrants further study.

4) Half a million measurements of pCO₂ in coastal waters (within 100 km from the shore) surrounding North America yield a small net CO₂ source flux to the air of 19±22 Million tons of carbon per year. The large uncertainty is due to large variability of seasonal upwelling of deep waters, river run-offs, biological blooms and other events that affect pCO₂ in coastal waters.

Societal Benefits

The fate of industrial CO₂ emitted into the atmosphere is an important issue for the future course of atmospheric CO₂ level that affects Earth’s heat balance and hence climate. Of the present annual emissions of about 7 Giga-tons of carbon per year, the global oceans are taking up an amount of CO₂ equivalent to about 25% of the industrial emissions, and the land biosphere another 25%. About 50% of the industrial CO₂ remains in the atmosphere causing rapid increase in this greenhouse gas in the air. From the point of view of managing the atmospheric CO₂ level, the rate of CO₂ uptake by the oceans and how it is changing are important.

Other Research Connections

1) We are closely collaborating with the Antarctic Peninsula group of NSF’s LTER (Long-Term Research in Environmental Biology) program.

2) As a member of NOAA/VOS program, we are closely collaborating with the European CARBOCEAN program.

3) T. Takahashi serves as a member of the Climate Research Committee of the NRC/NAS.

4) N. Bates is a member of the IOC-SCOR International Ocean Carbon Coordination Project (IOCCP) scientific steering group, and SOLAS-IMBER Carbon working group. 5) N. Bates is a member of the US Carbon Cycle Scientific Steering Group (CCSSG), an advisory for the Carbon Cycle Interagency Working Group (CCIWG).

Taro Takahashi, Rik Wanninkhof, Colm Sweeney, Richard A. Feely, Burke Hales, Jon Olafsson and Stewart C. Sutherland (2007). Decadal change and climatological mean surface ocean pCO₂, and net sea-air CO₂ flux over the global oceans. Invited presentation at the Gordon Research Conference, July, 2007, Meriden, NH.

Taro Takahashi et al. (2007). Climatological mean and decadal change in surface ocean pCO₂, and net sea-air CO₂ flux over the global oceans. A keynote address at the 16th meeting of the North Pacific Marine Science Organization (PICES), October, 2007, Victoria, CANADA


Research Scientist: 1, Visiting Scientist: 1, Research Support Staff: 2.5

Publications

*Journal articles*


Reports
CICAR

Theme III: Applications Research

Individual & Collaborative PI Research Projects

1. 2007 SOLAS Summer School, W. McGillis

Two research projects, which are reported under Theme II, have as their secondary definition Theme III:

Research Goals

The International SOLAS Summer Schools are held every two years. (http://www.uea.ac.uk/env/solas/summerschool). Greenhouse gas and aerosol emissions are increasingly recognized as a threat to the quality of life as well as to the economies of the world. This threat requires close observation, forecasting capabilities, and policy decisions. Accountable detection, attribution, and verification of greenhouse gas and aerosol sources and sinks are required. Such verification relies on the quantification of air-sea exchange of greenhouse gases and aerosols, both at the regional and global levels. In the wake of the Kyoto agreement, the political imperative for monitoring greenhouse gases is running well ahead of scientific understanding. The new international research initiative on the Surface Ocean-Lower Atmosphere Study (SOLAS, sponsored by IGBP/SCOR/CACGP/WCRP) aims to achieve quantitative understanding of key biogeochemical-physical interactions and feedbacks between the ocean and the atmosphere, while understanding how this coupled system affects and is affected by climate, weather and environmental change.

Some air-sea exchange processes and feedbacks are understood at the local level, but remain inaccurately quantified globally. This synergy requires long term monitoring, process studies, satellite remote sensing, and modeling activities. For example, in spite of the fact that the partial pressure of CO$_2$ in water and the atmosphere is relatively well measured in the North Atlantic, the mean flux of CO$_2$ is known to less than 50% accuracy and its interannual variability in unknown. For other processes, even the theoretical principles of local interactions remain uncertain. The generation of dimethylsulphide, a precursor of atmospheric sulphate aerosols and a cloud condensation nuclei, is linked to phytoplankton through mechanisms that are not very well understood. Building both on recent oceanographic and atmospheric research, SOLAS advances the understanding of air-sea processes through interdisciplinary collaborations.

The SOLAS Summer School brings young researchers in contact with leading scientists of different components of SOLAS research. The school uses a theoretical framework, practical exercises, and laboratory experiments to promote an enhanced learning environment. Most importantly, the SOLAS Summer School provides the opportunity for young researchers interested in SOLAS science issues to meet one another and to form alliances capable of addressing the significant future challenges that face the field and society. It is our current new scientists who are most likely to meet the challenges of solving significant Earth system problems. For this reason, interaction between the US and other international scientific communities in this field must be strengthened and promoted. The school forges the necessary
bonds between maturing scientists of different nationalities and backgrounds, which will be carried forward as these students become, themselves, leaders in the field.

**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 greenhouse 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 biodiversity of the sea, including the chemical fluxes associated with different species. We will explain how biological processes can be represented in numerical models, and how satellites and data assimilation can be used to quantify the different fluxes of gases at the air-sea interface.

Day 4 to Day 6 is devoted to practical workshops (see description below).

Day 8 will focus on the large-scale cycles of nutrients, which are the basis of marine productivity. The cycles of nitrogen, phosphorus, iron and silicate will be presented and their residence time, continental sources and sinks will be explained.

Day 9 will focus on atmospheric processes such as the formation and transport of dust and marine particles and gas phase reactions, the various chemical reactions that occur at the sea surface, and the turnover time of chemicals in the atmosphere.

Day 10 will focus on integrative research in the complex area of marine particles and the cycle of sulfur and its potential impact on DMS and atmospheric chemistry.

Day 11 will focus on gas exchange processes including large-scale determination of gas exchange coefficients and micrometeorology. Day 12 will also focus on measurements that allow
us to quantify processes relevant to SOLAS. These techniques include satellite remote sensing and ocean time series.

The practical workshops will be held intensively during 3 consecutive days (from Day 4 through Day 6). The students will be split in groups of 12 to be rotated every half day between workshops. The workshops will include a research cruise of half a day in the vicinity of the bay of Cargèse, laboratory experiments, computer modeling exercises, communication skills, and a visit to a meteorological station in Corsica.

The research cruise will focus on giving the students hands-on experience on the complexities and problems associated with measurements at sea. The measurements to be performed will include the standard temperature-salinity-depth profiles and meteorological measurements, as well as more complex techniques such as plankton netting, water sampling from a rosette and gas mass balancing.

Laboratory experiments will show how information can be retrieved from water and air samples. Dissolved oxygen and chlorophyll A will be measured from water samples collected from the rosette casts. If possible, zooplankton samples will be examined to identify major species components.

Computer modeling exercises and numerical models will provide experience in solving complex processes. Exercises will be presented on biological modeling and data assimilation, gas exchange, atmospheric dust transport and analysis of remote sensing data.

The surface ocean physical measurement laboratory will provide a location for in situ demonstrations of turbulent kinetic energy measurements, surface waves, and stratification. These exercises will help elucidate some of the surface ocean and lower atmospheric controls on air-water momentum, heat, and gas exchange.

Much of the advancement of science depends on the ability of today's scientists to present their results. A series of practical workshops on communication will be done. This will include aspects of reading, writing and presenting a scientific paper.

A visit to a meteorological station in Corsica is planned to give students the opportunity to see how radiation, precipitation, wind and cloud cover data are measured and transmitted to the global earth-observing network. In addition, measurements of optical properties of the air will be demonstrated.

Throughout the program, students will be asked to develop their own research projects around SOLAS topics. An example topic would be: seasonal and short-term variability of chlorophyll a concentration in the northwest Mediterranean Sea offshore Corsica. Based on monthly ocean color SeaWiFS images and high resolution satellite images recorded prior to the summer school time period, the student may try to explain the change in surface chlorophyll in the Cargèse area. The students may use observations collected during the field workshop and modeling exercises to support the conclusions and to quantify the potential impact on the air-sea transfer of CO₂, H₂O, and DMS.

Research Progress

Participants and sponsors
The third SOLAS Summer School was held in 2007. The U.S. was represented by 12 students. For the 2007 session, the lecturers (and their affiliations) from the United States included: Margaret Leinen, CLIMOS, 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 CO₂ on time scales of a few thousand years, while contributing to regional patterns of air-sea CO₂ fluxes on shorter time scales. Biological processes also affect the sulfur cycle. Process studies have established a general link between phytoplankton and dimethylsulphide (DMS) levels, although the exact mechanisms responsible for DMS production are not fully understood. DMS is a direct feedback on climate through its radiative forcing, and an indirect feedback because it is a source of cloud condensation nuclei, and thus can change cloud properties.

The physics of gas exchange governs the transfer of greenhouse gases at the air-sea interface. Gas exchange rates have either been extrapolated from laboratory measurements or measured...
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

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.

Awards & Honors

A United States student won best presentation and best poster.

Personnel

Research Scientist: 2, Visiting Scientist: 2, Research Support Staff: 1, Administrative: 2, Graduate Student: 16