CICAR

NOAA SPONSORED PROJECT SUMMARIES

July 1, 2008 – June 30, 2009
Theme I: Earth System Modeling

Individual And Collaborative PI Research Projects
CICAR Award # NA03OAR4320179 the following 11 projects ended June 30, 2009:

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

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

CICAR Continuation Award #NA08OAR4320754
None to date

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

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

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\(^1\) Granted a no cost extension through June 30, 2010
Research Goals

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

Research Progress

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

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

Highlights

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

Figure 1. The global delay in the seasonal cycle of precipitation and sea surface temperature; a.) CMIP3 ensemble mean of the first empirical orthogonal function (EOF1) of climatological precipitation in the 20th century integrations (monthly climatology was calculated over the 1975-1999 period). b.) Same as (a.), but for SST. c.) Ensemble mean first principal component (PC1) associated with EOF1 of precipitation climatology in the last 25 years of the 20th (blue) and 21st (red) centuries. Ocher and ice-blue backgrounds highlight the months of positive and negative PC1, respectively. d.) as in (c.) but for SST. e.) 21C-20C difference in precipitation PC1 for each calendar month (each panel) and each model in the CMIP3 dataset (x-axis in each panel). The background colors indicate the sign of PC1. The anomalies are in quadrature with PC1 itself, indicating a shift in the seasonal cycle. f.) as in (e.), but for SST. g.) 21C-20C difference in the time of 0-crossing of PC1 in spring (green) and fall (orange). Each bar is a model in the CMIP3 dataset, the horizontal lines indicate the ensemble mean. h.) as in (g.), but for SST. (Adapted from Biasutti and Sobel, 2009)
Research Goals

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

Research Progress

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

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

Research Progress

Predictability of El Niño: epochal dependence

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

Predictability of El Niño: roles of initial error and atmospheric noise

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

The role of external forcing in ENSO variability

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

Advancement of forecast skill assessment

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

**Role of surface heat and freshwater fluxes**

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

**Operational ENSO forecasting**

We continued to produce seasonal ENSO forecasts on a monthly basis. Our forecast is used by IRI in several different ways. In particular, it is used as one of the few members of the IRI ensemble forecasting, thus being an integral part of the official IRI forecasts. Our predictions are also used by NCEP/CPC, and published in the monthly Climate Diagnostic Bulletin and the quarterly Experimental Long-Lead Forecast Bulletin. Because of the different requirements of various operational centers, we updated our forecast at least three times a month. Our model output was sent to IRI at the beginning of each month, to CPC on the 5th, and to COLA in the middle of the month. We also implemented a new system for the uniform treatment of the input data sets, which extends their monthly versions to the current month by averaging all daily or weekly records available for it. We reran our model each time to take advantage of new data. Our forecast webpage (http://rainbow.ldeo.columbia.edu/~dchen/forecast.html) is updated accordingly. The maintenance of this forecast system required retuning of the system every time when the nature of the input data streams change (e.g. CLS altimetry and FSU wind data analysis methodology and analyzed grids changed). A suite of forecast experiments had to be run to ensure a smooth transition.
Figure 1. Response of the Zebiak-Cane model to volcanic forcing during the past millennium. [From Emile-Geay et al. 2008].
Figure 2. Level surfaces of the approximate 6-month ensemble spread in NINO3 from LDEO4 predictions, as a function of the error in initial conditions. Color levels range from 0.1°C (blue) to 1°C (red) in intervals of 0.05°C. The scales represent the magnitude of each error field relative to the standard estimate. [From Karspeck et al. 2006].
Figure 3. LDEO model ensemble forecast skill measured by relative operating characteristics (ROC). (a) ROC curves for warm, cold and near normal conditions, respectively, at 6-month lead-time; (b) ROC curves for warm conditions at various lead times. These are calculated based on 5-member retrospective ensemble forecasts for all months over the period 1856–2003. [From Chen and Cane, 2008].
Work on this project was completed by June 30, 2008 and was reported on in the CICAR 2008 Annual Report. The research accomplishments achieved under this funding resulted in publication of the following journal article:


*Abstract*

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

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

Research Progress

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

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

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

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

**Figure 1.** Seasonal SWE (black contour lines) and surface temperature (color-filled contours) response to EY snow forcing during (a) fall, (b) winter, (c) spring and (d) summer. Positive SWE contours (solid lines) drawn at 0.5, 5, 15, 25 cm. Negative SWE contours (dashed lines) drawn at -3, -2, -1, -0.5 cm. Only statistically significant (>95%) surface temperatures are plotted.
Figure 2. Spring season spatial gradient response to EY snow forcing at 750 hPa. a) Vertical shear \(-\partial W/\partial p\); contours drawn at ± 0.001 m s\(^{-1}\) intervals. b) Meridional temperature gradient \(\partial T/\partial y\); contours at ± 4, 6, 8, 10, 12, 16, 20, 24 °C 1000km\(^{-1}\). Red (blue) contours denote a positive (negative) response. 90% (95%) statistical significance indicated with light (dark) grey shading.

Figure 3. Three month running mean 500 hPa geopotential height variance \((\bar{Z}^2)^{1/2}\) response to EY snow forcing. Seasons begin with fall (SON, top-left) and progress left to right, top to bottom ending with ASO. Contours drawn at ± 1, 2, 3, 4 m; red (blue) contours denote a positive (negative) response. 90% (95%) statistical significance indicated with light (dark) grey shading.
**Research Goals**

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

**Research Progress**

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

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

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

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

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

Research Progress

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

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

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

In the second stage of the project, hindcast experiments for the tropical Atlantic sea surface temperature (SST) gradient, G1, defined as tropical North Atlantic SST anomaly minus tropical South Atlantic SST anomaly, were performed using an atmospheric general circulation model coupled to a mixed-layer ocean over the Atlantic to quantify the contributions of the El 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 dryness in boreal Spring 1983, wetness in Spring 1996, and wetness in Spring 1994 over northern Brazil that are qualitatively consistent with observations. An inclusion of the Atlantic preconditioning is found to help the prediction of South American rainfall in boreal spring. For the ENSO years, discrepancies remain between the hindcast and observed precipitation anomalies over the northern and equatorial South America, an error that is partially attributed to the biased atmospheric response to ENSO forcing in the model. The hindcast of the 1993-94 neutral year does not suffer this error. It constitutes an intriguing example of useful seasonal forecast of G1 and South American rainfall anomalies without ENSO. This component of the work was published in Huang et al. (2009).
Research Progress

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

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

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

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

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

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

We created software to combine 4He, DHe, DNe and d3He data into mantle helium contributions in the Pacific Ocean.

We have, separately, collected He, 3He, 3H and Ne data from large non-WOCE programs (mainly: TTO, GeoSecs, LDEO/NGL collections) and databased them.
We have met with the Princeton/GFDL group (Sarmiento, Gnanadesikan, Key and Bianchi) to establish a strategy for data integration, archiving, modeling and analysis. We will use the GloDAP routines for data interpolation. (Note that the GloDAP interpolation routines are not available publicly, so we will still need the interpolation and objective analysis routines developed here for quality control and analysis purposes.)

Collection of some of the unpublished transects from other laboratories has been postponed from Year 1 to Year 2 as we developed a strategy for collaboration, synthesis and archiving. We believe that our recent one day workshop with the Princeton group, including both the GLODAP PI (Robert Key) and the lead PIs on in our modeling effort (Gnanadesikan and Sarmiento), has clarified those questions and we are currently reaching out to the other laboratories.
Research Goals
To determine the physical mechanisms through which the North American circulation interacts with the topography to produce summer precipitation over North America and to help a better seasonal prediction of the North American summer precipitation.

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

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

Second, in collaboration with colleagues at Tufts University, we have examined the seasonality of the trend and variability of the US precipitation in the past 50 years, with emphasis on the fall precipitation variabilities. In the past, the focus of most research on US precipitation is on either the winter or summer. The transitional season received little attention in the literature. Recent studies have shown that the fall precipitation shows a large positive trend and significant decadal variability. The mechanism of the trend and variability in fall precipitation, however, is not clear. We contrasted the fall season to the more familiar winter and summer, in particular, the role of the Great Plains low-level jet in determining the trend and variability of fall precipitation in this project. A GRL paper (Small, D., S. Islam, and M. Ting, 2009: Trends and Decadal Variations in Fall Precipitation in the United States. Geophy. Res. Letter, submitted) is currently being revised, and further analysis on the role of topography on the fall precipitation and low-level jet is under way.
Third, we worked with colleagues at the Illinois Water Survey on the simulation of the North American monsoon in the state-of-the-art coupled ocean-atmosphere models, as well as atmospheric GCMs with prescribed SSTs. We examined observational circulation features that are associated with North American monsoon onset and retreat as well as the total monsoon precipitation. These observational linkages are then examined in the GCMs to see whether models are able to reproduce similar circulation features. We also examined the models with the same atmospheric component but differing oceanic component to see if oceanic processes dominate the NAM simulation. The results are summarized in a paper to Journal of Climate (Liang, X.-Z., J. Zhu, K. E. Kunkel, M. Ting, J. X.-L. Wang, 2008: Do CGCMs Simulate the North American Monsoon Precipitation Seasonal-Interannual Variability? J. Climate, DOI: 10.1175/2008JCLI2174.1).
**Research Goals**

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

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

**Research Progress**

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

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

![Figure 1](image.png)

**Figure 1:** Black dotted line is raw time series of ocean heat content ($Q$; definition shown in inset box) for a mooring located in the central continental shelf of the WAP. Solid red line is estimate of signal using first mode of Karhunen-Loeve transform (EOF of a time series). A number of tests for physical consistency, such as: warming events all warm at similar rate, and coincide with maximum $T$, suggest that this is a reasonable estimate of signal in the noisy record.
Research Goals

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

Research Progress

Attribution of hydroclimate change in North America to tropical Pacific and Atlantic SST anomalies: Our work has used large ensembles of long model simulations with various configurations of forcing, as well as observations, to determine that the driver for persistent, multiyear drought in southwestern North America is equally persistent La Niña-like conditions in the tropical Pacific Ocean. In the case of the 1930s Dust Bowl and the 1950s Southwest drought, a warm subtropical North Atlantic Ocean also played a role. This result has been placed on quite firm foundations in that an atmosphere model forced by tropical Pacific SSTs alone from 1856 to 2007 produces all six multiyear droughts in the instrumental record but that, for the 1930s and 1950s, Atlantic SST forcing is also required for the most realistic simulation.

Detecting and understanding of anthropogenic induced drying in SW US: In collaboration with our colleagues at NOAA/GFDL we show that there is a broad consensus among climate models that this region will dry in the 21st century and that the transition to a more arid climate should already be under way. If these models are correct, the levels of aridity of the recent multiyear drought or the Dust Bowl and the 1950s droughts will become the new climatology of the American Southwest within a time frame of years to decades. Our study uses IPCC AR4 models as well as the GFDL CM2.1 model output for specific diagnostic analyses.

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

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

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

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

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

Research Progress

• Genesis Potential Index and the Madden-Julian Oscillation (MJO):
The modulation of the tropical cyclone (TC) activity by the MJO is explored using the original empirical GP index. Composite anomalies of the genesis index associated with different MJO phases are consistent with the composite anomalies in TC frequency, which occur in the same phases, indicating that the index captures the changes in the environment, which are at least in part responsible for the genesis frequency changes. Of the four environmental variables, which enter the GP index, the mid-level relative humidity makes the largest contribution to the MJO composite of GP anomalies. The second largest contribution comes from the low-level absolute vorticity, and only very minor contributions come from the vertical wind shear and potential intensity. When basin integrated MJO composite anomalies of the GP index are regressed against basin-integrated composite anomalies of TC genesis frequency, the results differ quantitatively from those obtained from the analogous calculation performed on the annual climatologies of the two quantities. The GP index captures the MJO modulation of TC genesis to a lesser degree than the climatological annual cycle of genesis (to which it was originally tuned). This may be due weakness of the reanalysis or indicative of the importance of precursor disturbances, not well captured in the GP index computed from weekly data, to the intraseasonal TC genesis frequency fluctuations.

This work was done in collaboration with Matthew Wheeler, from the Centre for Australian Weather and Climate Research, in Melbourne, Australia. It was accepted for publication at the Journal of Atmospheric Sciences and is currently available as an “online first” publication.

• Modified Genesis Potential Index
The original GP index used in our research in various papers is dependent on the middle-troposphere relative humidity from reanalysis data. We compared different reanalysis (NCEP/NCAR and ECMWF ERA-40) and their mid-troposphere relative humidity have large differences. Therefore, Kerry Emanuel developed a modified genesis index, which instead of the mid-troposphere relative humidity, per se, the difference between the moist
entropy of the boundary layer and that of the middle troposphere is used. The idea behind this modified index is that the middle troposphere entropy is a function of temperature as well as humidity. While the middle tropospheric temperature varies little in the tropics under the current climate, its variations under climate change may be large enough to be significant to trends in TC statistics.

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

• **Revised Genesis Potential Index**

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

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

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

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

• **Tropical cyclone activity and Quasi-biennial oscillation**

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

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

• **Ideal simulations of hurricanes**

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

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

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

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

Research Progress

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

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

2) **Development of coupled data assimilation procedure.** The first step of our proposed procedure is a reduced space regression between observed SST/SLP fields and a set of model variables that represent the state of the coupled system, based on patterns identified by the Canonical Correlation Analysis (CCA). In practice, using the predetermined CCA prediction matrix, observed SST/SLP data are converted to a "realistic" coupled model state. The latter is then assimilated into the CFS through a weighted nudging method, which can be considered the simplest form of Kalman filters. Since the CFS is already so realistic, we decided after a few group discussions to try direct nudging first. It is now being tested with the CFS and the preliminary results look promising.

3) **Research on ENSO prediction and predictability.** In a recent article, we reviewed the current status of ENSO prediction, discussed different opinions on ENSO’s predictability, and, more importantly, suggested some potential areas for improvement of predictive skill (Chen and Cane, 2008). In particular, based on observational evidence and modeling results, we pointed out that better model initialization and data assimilation, better simulation of surface heat and freshwater fluxes, and better representation of the relevant processes outside of the tropical Pacific, could all lead to improved ENSO forecasts. All of these can be further verified in our present project. We have also studied the inter-decadal variability (Tang et al., 2008) and biological modulation (Zhang et al., 2009) of ENSO.
**Research Goals**

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

**Research Progress**

During the second year of this project we built on the performed earlier systematic intercomparisons of spatial and temporal variability of sea surface heights in satellite altimetry, tide gauges, and ocean model simulations (baroclinic and barotropic components), targeted at constraining short-term and small-scale area of wavenumber-frequency spectra, which controls a component of the observational error due to imperfect sampling and inconsistent averaging. Multi-taper spectra were calculated from these adjusted time series, and then integrated over desired frequency and wavenumber ranges. Using wavenumber and frequency power spectrum estimates, we have computed fields of variance and spectral slopes for sea surface heights. Based on these estimates we produced maps of effective observational error for altimetric observations corresponding to given model grids and assimilation schemes. These maps have a considerable geographical structure. Its interpretation and tuning of error models for the use in data assimilation procedures are underway.
Figure 1. Frequency spectra from daily tide gauge data from 102 island tide gauges in the University of Hawaii Sea Level Center database (thin lines) compared to similar spectra for satellite altimetry (thick lines). Tidal signal was removed prior to computation, and AVISO’s combined atmospheric correction (static and dynamic response to pressure) was applied. Resulting spectra were compared with the average of all Topex frequency spectra within a 2x2 degree box around each tide gauge. Averages separated by Tropical and Extratropical latitudes are shown, suggesting general agreement between the two instruments, and the possibility of simply extrapolating altimetric spectral slopes into high frequencies.
Figure 2. The map of frequency slopes estimated from satellite altimetry. Note a considerable geographic structure. The coherent regions of spectral slope close to -2 red appear to match regions of high eddy activity.
**Research Goals**

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

**Research Progress**

1. **Atlantic SST influences on North American precipitation**

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

2. Assessing the independent contribution of Pacific and Atlantic SST forcing from hindcast experiments

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

Figure 2 (a): The simulated precipitation anomaly for April 1994 from the hindcast runs with the AGCM coupled to a mixed layer ocean over the Atlantic and forced by climatological SST elsewhere. Coupling is turned on at the beginning of November 1993 using the observed SST as the initial state for the Atlantic. Shown is the average of 25 ensemble members. (b): The precipitation anomaly for April 1994 derived from a set of 9-member AMIP runs.
3. Predictability of Dust Bowl drought

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

4. Subtropical drying in future climate

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

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

Research Progress

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

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

Figure 2: First mode of Karhunen-Loève estimate of signal in shelf-ocean heat content (Q; red line) for mooring 1 (in Figure 1) as a function of time, with temperature of $T_{\text{max}}$ (black dotted line) and crosses showing center of transients in Q locations. Coincidence of transients events with spikes in maximum temperature are consistent only with import of nearly pure UCDW, thus suggesting transients are eddies (contributing about 152 Wm$^{-2}$ over the 2008 year).
AWARD NO. NA08OAR4320912
PROJECT TITLE ACCWW: Abrupt Climate Change in a Warming World: Infrastructure
CICAR THEME Themes I, II
PRINCIPAL INVESTIGATORS Peter Schlosser, Robert Anderson
NOAA PROGRAM Climate Variability & Predictability

Highlights

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

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

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

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

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

Research Progress

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

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

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

**Future drying of southwestern North America in paleoclimate context:** The character and causes of IPCC model projected climate change in the southwest has been contrasted with what is known from tree ring records of medieval “megadroughts”. This paper makes the point that these appear to arise from different causes which leaves many questions about the exact nature of long-term climate change. (E. Cook et al. JQS, in press.)
20th Century and future trends in tropical Pacific SSTs: With the release of the newest NOAA SST analysis, all available analyses show an increasing east-west SST gradient over the 20th Century. More notably the SST gradient has been strengthening most during the northern summer through fall season when the cold tongue is best developed and the ocean dynamical thermostat should be most effective. SLP trends show a weakening east-west gradient but little or no weakening in the summer to fall season, broadly consistent with the SST gradients. None of the seasonal changes in gradients are well modeled by the IPCC AR4 models, which, hence, cannot be trusted in this regard for future climate change. (Karnauskas et al., 2009, J. Climate, in press.)

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

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

Other ongoing work: We are revisiting the issue of predictability of the 1976/77 Pacific climate shift, and associated multidecadal change in precipitation across the Americas, using atmosphere model simulations forced by hindcast SSTs. We have also completed an ensemble of atmosphere simulations from 1856 to now with both observed SST changes and changing carbon dioxide and are comparing these to attribute soil moisture changes to SST changes and changes in trace gases. We have also begun to examine and attribute decadal changes in South American hydroclimate.
Figure 1: Model response to Atlantic SST warming. The figure shows the average of 40-year integrations with five different GCMs forced with uniform sign SST anomaly in the Atlantic Basin and climatological SST elsewhere (a pattern associated with Atlantic Multidecadal Variability). In both seasons (winter - top and summer - bottom) the warming leads to enhance precipitation in the north tropical Atlantic (with a maximum in the west), which extends into equatorial Africa. This anomaly is accompanied by reduced precipitation over the US and Mexico, along the entire equatorial Pacific and in the Indian Ocean. This precipitation change in the Atlantic also force lower sea level pressure over the entire North Atlantic Basin and a hemispherically symmetric Pacific pattern of low sea level pressure in the tropics flaked by high pressure anomalies in the extratropics (figure from Kushnir et al, 2009, in review).
Figure 2. Upper three panels: Trends of observed equatorial Pacific SST gradient (went-east) from 1880 to 2005 as a function of calendar month calculated from three different compilations of observations: (a) HadISST1, (b) Kaplan SST, and (c) NOAA ERSST v3. Gray shading denotes 95% confidence intervals based on the nonparametric Sen median slope method. White circles (squares) represent trends significant at the 5% (10%) level based on the nonparametric Mann–Kendall test. The trends in the boreal fall months is significant in all data sets and corresponds to an increasing gradient over time (from Karnasukas et al., 2009). Lower panels: Same as above, but for the east-west sea level pressure gradient based on (a) HadSLP2, (b) Kaplan SLP, and (c) NOAA ERSLP. Note the vertical scale is inverted so that up corresponds to a strengthening of the SLP gradient (DSST), and vice versa. Sea level pressure gradient tends to decrease with time during the boreal spring – indicating a weakening of the trades. However, the trend is weaker or there is no significant change during the boreal fall, when the SST gradient increases.
Theme II: Modern and Paleoclimate Observations

Individual And Collaborative PI Research Projects

CICAR Award # NA03OAR4320179

1. Cook, E., Collaborative Research: Development of a Blended, Gridded Network of Drought Reconstructions of North America
2. Gordon, A., Monitoring the Indonesian Throughflow in Makassar Strait¹
3. Kaplan, A., Multivariate Approach to Ensemble Reconstructions of Historical Marine Surface Winds from Ships and Satellites
5. McGillis, W., Development of an Autonomous System for Direct Measurement of the Flux of CO₂ over the Ocean
6. Takahashi, T., Underway CO₂ Measurements Aboard the RVIB Palmer and Data Management of the Global VOS Program¹

Abrupt Climate Change Studies (ARCHES)

7. Anderson, R., Paleo-Sea-Ice Distributions²
8. Broecker, W., Understanding Abrupt Change and the Glacial to Interglacial CO₂ Record²
9. Denton, G., ARCHES Sub-award: Mountain Snowlines in the Southern Hemisphere
11. Hemming, S., Constraining Changes in Winds, the Conveyor and Local Currents During Periods of Abrupt Climate Change
13. Smethie, W., Tracer Observations of Deep Formation and Circulation in the Southern Ocean

CICAR Continuation Award #NA08OAR4320754

14. Gordon, A., Monitoring the Indonesian Throughflow in Makassar Strait¹
15. Huber, B., Weddell Sea Moorings
16. Takahashi, T., Underway CO₂ Measurements Aboard the RVIB Palmer and Data Management of the Global VOS Program¹

CICAR Shadow Award #NA08OAR4320912

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

Abrupt Climate Change in a Warming World (ACCWW)


¹ Denotes continuation under renewal award number
² No cost extension granted through June 30, 2010
22. Denton, G., *ACCWW Sub-award: Lessons From Holocene Paleo and Modern Instrumental Records, and Model Simulations*
23. Gordon, A., *Fluctuations in Ocean Heat and Freshwater Inventory and of Interocean Exchange*
24. Hemming, S., *Radiogenic Isotope Tracer Paleo-Proxy Scope*
25. Jacobs, S., *Southern Ocean – Ice Sheet Interactions*
27. Schlosser, P., *Synthesis of Tracer Data*
28. Smethie, W., *CFCs*
Research Goals

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

Research Progress

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

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

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

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

![Figure 1](image)

**Figure 1.** Copy of a PowerPoint Slide presented in Session 182 T25: *Terrestrial Response to Climate Variability during the Medieval Warm Period: Lakes, Tree-Rings, and Human Adaptation* at the GSA Joint Annual Meeting held in Houston, TX on October 5-9, 2008. Richard R. Heim, Jr., Russell S. Vose, and Jay H. Lawrimore from NOAA NCDC in Asheville were co-authors of this presentation.
Research Goals

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

Research Progress

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

During the INSTANT periods ENSO was in a weak El Niño state, with a brief La Niña phase occurring in early 2006. The NOAA mooring period spans a time of an overall weak La Niña phase. Except for the Arlindo period, there is no clear correlation of the Makassar Throughflow to ENSO, but it is noted that neither the INSTANT nor NOAA time series recorded during strong ENSO episodes. The December 2006 through May 2009 record displays many of the same attributes as revealed by the INSTANT data: a clear seasonal behavior with maximum flow in August, with minimum flow in November. The particularly weak flow of November 2007 may be a consequence of a strong Kelvin Wave derived from the Indian Ocean. The mean flow within the thermocline and deeper as measured by the NOAA-MAK mooring is strikingly similar (less than 10% difference) to that measured during the INSTANT period. However the flow at 40 meters is notably weaker in the NOAA record, with an average southward speed of 0.3 m/sec versus 0.4 m/sec in the INSTANT 2004-2006 record.
Figure 1: Configuration of the NOAA-ITF Makassar mooring deployed in November 2006 at the Red X in the bathymetry map of Makassar Strait. Recovered 31 May 2009. Redeployed for another ~ two year period.
Figure 2 Meridional speed at Makassar west mooring site 2°51' S; 118°28' E from January 2004 through May 2009. The blue and green lines denote the time series from the first and second deployment of the NSF funded INSTANT program; the red line is from the NOAA funded mooring record.
Research Goals

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

Research Progress

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

1. Analyzed data set development. Recent releases of the International Comprehensive Ocean Atmosphere Data Set (ICOADS) pushed the compilations of marine observations contained in ship reports back to the beginning of the 19th century. The 19th century exhibits dramatic changes in the marine data availability, from the order of 1000 reports

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

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

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

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

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

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

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

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

6.2. Tropical Pacific

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

6.3. ENSO impact on North Atlantic

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

6.4. Interpretation of a tropical Atlantic paleorecord

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

6.5. Southeastern U.S. precipitation and Bermudan High

In the studies involving the paleodata, Anchukaitis et al. (2006) identified the strength of the Bermuda high-pressure area as a controlling factor on the type of local climate influence on the tree growth in the southeastern United States. Specifically, the reduction in the summer rainfall in this area, apparently associated with the weakening of the Bermuda High in the last century, starting from 1970s has caused the major stress factor in the tree growth to shift from the spring coldness to the summer drought.
El Niño of 1877-1878 in analyzed anomalies

Figure 1. Anomalies of 1877-1878 El Nino illustrated by univariate reduced space analyses.
Figure 2. Intercomparison of ENSO indices: NINO3, degree C, by Kaplan et al. [1998]; Darwin station SLP, mb, [Allan et al., 1991]; Darwin area SLP estimate from ship-based RSOI, mb, [Kaplan et al., 2000]; and Central Equatorial Pacific zonal wind anomaly (5S-5S,160E-120W), 5m/s from the ongoing CICAR project. Pressure and wind data are 5 month running means. [Adapted from Evans and Kaplan, 2004].
Figure 3. Lagged correlation coefficients in the zonal wind anomalies from the NCEP-NCAR reanalysis (160E-120W averages) show highly significant temporal persistence for the period of six months and beyond within 10 degrees latitude of Equator. This persistence has a potential as a statistical constraint to support the analyses of historical wind fields, when the observational data coverage is poor.
Figure 4. ENSO influence over the North Atlantic. (left) Regression patterns of wind vectors from the specified product, smoothed by a 3-month running average, on the NiNO3 index, normalized to unit variance. Units of regression coefficients are given per standard deviation of the index. (right) Corresponding correlation patterns, shown for the meridional component only. (a) GFDL H1 surface wind stress regression. (b) GFDL H1 meridional wind stress correlation. (c) POGA-ML surface wind stress regression. (d) POGA-ML meridional wind stress correlation. (e) Analysis of ICOADS data, surface wind regression. (f) Analysis of ICOADS data, meridional wind correlation. [From Emile-Geay et al. 2007]
Research Goals

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

Research Progress

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

Preliminary testing in the laboratory also provides a motion free environment. Optimized for the ocean, it was tested in sea trials.

1. High volume in situ air sampling included in the autonomous system was used with CO2 detectors in environmental enclosures. Remote air-pumps ensure continuous sample delivery over month-long periods, despite heavy aerosol loads in samples.

2. The in-line null pCO2 sensor is used to quantify motion contamination. The atmospheric sample is mixed and sent through a second sensor measured simultaneous with the vertical wind velocity. The carbon dioxide fluctuations are removed and the flux signal from this system will be assessed as the motion bias.

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

Figure 1: Bow mast of the Ronald H. Brown showing the meteorological package for testing of the CO$_2$ autoflux system. Three sonic anemometers, five open-path 7500-CO$_2$/H$_2$O detectors, two RH/T, and intake lines for three closed-path CO$_2$/H$_2$O detectors are shown. The 7500-CO$_2$ sleeved detectors are on the right. The one connected to the blue-hose air sampler pulls bow air at 5 lps. The other 7500-CO$_2$ sleeved detector draws air in at .05 lpm. The low flow provides air samples of the ambient environment with damped high frequency fluctuations to determine the effect of motion on the carbon dioxide flux measurements.

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

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

The primary objective of this program is to observe and document the space-time distribution of the sea-air pCO2 difference and to estimate sea-air CO2 flux over the regional and global oceans in seasonal, annual and interannual time scales. We operate shipboard underway pCO2 systems installed aboard RVIB Palmer and other research and commercial ships participating the NOAA/VOS program. The data obtained under the NOAA/VOS program by participating members are processed and interpreted at Lamont-Doherty Earth Observatory, and the processed data are archived at and distributed to the public by the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN.

**Research Progress**

Approximately 3.6 million observations for the surface water pCO2 have been assembled during this project. This database includes the pCO2 observations made before 2006, and are accompanied with date, time, positions, seawater temperature, salinity and barometric pressure. The processed data (Version 1.0) are archived at and distributed to the public by the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN.


Climatological mean air-sea CO2 flux for the contemporary global ocean is estimated using the sea-air pCO2 difference observations and the air-sea gas transfer rate that is parameterized as a function of (wind speed)^2 and the 1979-2005 NCEP-DOE AMIP-II Reanalysis (R-2) wind speed data. The equatorial Pacific (14°N-14°S) is the major source for atmospheric CO2, emitting about +0.44 Pg·yr⁻¹, and the temperate oceans between 14° and 50° in the both hemispheres are the major sink zones with an uptake flux of -0.64 Pg·C·yr⁻¹ for the northern and −0.98 Pg·C·yr⁻¹ for the southern zone. The high latitude North Atlantic, including the Nordic Seas and portion of the Arctic Sea, is the most intense CO2 sink area on the basis of per unit area, with a mean of −2.3 Tons·C·month⁻¹·km⁻² (1 Ton = 10⁶ grams). This is due to the combination of the low pCO2 in seawater and high gas exchange rates. In the ice-free zone of the Southern Ocean (50°S-62°S), the mean annual flux is small (-0.06 Pg·C·yr⁻¹) because of a cancellation of the summer uptake CO2 flux with the winter release of CO2 caused by deepwater upwelling.
The annual mean for the contemporary net CO$_2$ uptake flux over the global oceans is estimated to be $-1.4 \pm 0.7$ Pg-C yr$^{-1}$. Taking the pre-industrial steady state ocean source of $0.4 \pm 0.2$ Pg-C yr$^{-1}$ into account, the total ocean uptake flux including the anthropogenic CO$_2$ is estimated to be $-1.8 \pm 0.7$ Pg-C yr$^{-1}$ in 2000.

**Figure 1.** Climatological 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-tons Carbon per year. (Takahashi et al., DSR-II, 2009)
Research Goals

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

Research Progress

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

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

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

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

Together with postdoctoral fellow Jimin Yu, we are attempting to reconstruct variations in carbonate ion concentration in the deep sea over the last 150,000 years as a means of constraining the causes of the changes in atmospheric CO$_2$ content which occurred during this time interval.
Research Goals

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

Research Progress

The detailed 10Be exposure-age chronology for moraines alongside Lake Pukaki (Fig. 1) was completed with field work carried out in January and February of 2009, followed by laboratory work and dating. Figures 2 and 3, given below, show the Pukaki moraine system with all of the dates plotted on the map. This figure is an updated version of a similar one shown in the progress report of a year ago, but with the addition of all of the new dates. Together with a similar chronology previously developed with NOAA funding for the adjacent Ohau moraine system (Figs. 2 and 4), these results give the most complete chronology for Last Glacial Maximum moraines anywhere in the world. They show a prolonged LGM represented by the youngest moraine set. Near-maximum glacier extent was held between about 34,000 and 18,000 years ago. The last termination set in very close to 18,000 years ago, with rapid ice recession. The deglaciation was stalled during a climate reversal in which glaciers halted their recession and underwent a minor advance that culminated at 13,000 years ago. Deglaciation resumed thereafter.
A critical issue in constructing our moraine chronologies is to determine an accurate local production rate $^{10}\text{Be}$ on boulder surfaces. Therefore we dedicated considerable time and effort in establishing a local calibration site in Macauley Valley, located near lakes Pukaki and Ohau. Here a debris flow from a tributary valley buried a scrub forest growing on the valley floor about 9000 years ago. We established the age of the debris flow from radiocarbon dates of the crushed trees. We then measured the $^{10}\text{Be}$ concentration on the surfaces of boulders embedded in the surface of the debris flow. Because the emplacement of the debris flow was essentially an instantaneous event, we could then calculate a local production rate by comparing the two sets of data. The resulting production rate was checked at another site in the Lake Pukaki basin where a moraine surface was associated with radiocarbon and $^{10}\text{Be}$ samples. Both sites gave consistent results, which were then used to determine the moraine ages plotted in Figures 3 and 4.

Field work was also carried out in the Lago Argentino area alongside the Southern Patagonian Icefield in the austral summer of 2009. A radiocarbon chronology was completed for the late-glacial Puerto Bandera moraines deposited by outlets of the Southern Patagonian Icefield. The results show that the Puerto Bandera late-glacial moraines are of the same age as the Birch Hill moraines alongside Lake Pukaki in Figure 3.
Figure 2. Glacial geomorphic map of the Mackenzie Basin, South Island, New Zealand. Red features are moraines deposited during the LGM, and moraines deposited during earlier glacial periods are colored green. Tan colors depict outwash associated with the LGM (dark) and Holocene (light). Black boxes outline the field areas targeted for surface exposure dating, detailed in Figs. 3 & 4. General index map of the South Island is included as inset.
Figure 3. Glacial geomorphic map of the Lake Pukaki region. Symbols and colors are as described for Fig. 2. $^{10}$Be surface-exposure ages determined from the moraine landforms are given in white boxes, and lines with dots designate their locations on the map. We note that this figure has been updated to reflect several new $^{10}$Be ages, including those determined from the Boundary Stream moraines (lower inset box), and the Birch Hill late glacial moraines (upper inset box).
Figure 4. TOP: Glacial geomorphic map of the Lake Ohau LGM terminal moraine system. Features are as defined in Fig. 2. $^{10}$Be surface-exposure dates are given in white boxes and lines with dots denote sample locations. BOTTOM: Probability distribution plots of $^{10}$Be ages from the Ohau moraine belts. Red numbers above boxes are the mean landform ages ($\pm 1\sigma$, in thousands of years) and yellow bands represent the $1\sigma$ uncertainty range. Statistical information occurs as insets.
Figure 5. **LEFT:** Panel A: EPICA Dome C (EDC) deuterium record (Monnin et al., 2004). Panel B: EDC \( \text{CO}_2 \) record (Monnin et al., 2004). Panel C: GISP2 oxygen isotopes (Stuiver and Grootes, 2000). Panel D: Chinese monsoon records reconstructed from speleothems (Wang et al., 2001; Yuan et al., 2004). Panel E: methane curve from the GISP2 record (Brook et al., 2000). Panel F: magnetic susceptibility (MS) and ice-rafted detritus (IRD) from marine sediments located off the coast of Portugal (Bard et al., 2000), where IRD is expressed as the number of grains per gram for the size fraction greater than 150 microns. ‘H-1’ is ‘Heinrich Event 1’. Panel G: sea-surface temperatures based on alkenone unsaturated ratios from North Atlantic marine sediment core SU-8118 (Bard et al., 2000). Panel H: \(^{231}\text{Pa} / ^{230}\text{Th} \) ratios from core GGC5 off the Bermuda Rise (McManus et al., 1999).

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

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

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

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

**Research Progress**

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

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

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

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

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

![Figure 1](image.png)

**Figure 1.** Location of the Weddell Sea moorings (red dots) and repeat CTD/Tracer line (dashed line). Shown schematically are the pathways of deep and bottom waters formed by interaction of WDW with continental and ice shelf waters.
Figure 2. M3 temperature and bottom speed time series, 1999 to 2007.
Research Goals

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

Research Progress

We have used the resources provided by this grant to characterize the behavior and role of northern hemisphere ice sheets in the climate system, a key goal of our research has been application of high resolution records of changes in deep water and intermediate water mixing in the South Atlantic in the context of rapid climate changes. Kissel et al. (2008) used detailed correlation, allowed by magnetic paleointensity, between cores in the North Atlantic with magnetic evidence for changes in the vigor of NADW overflow across the Nordic sills and cores in the South Atlantic with detailed Nd isotope records. We have found a remarkable correlation between the two records, but careful evaluation leads to a several hundred-year lag between evidence for reduced vigor in the North Atlantic and evidence for reduced NADW contributions in the deep South Atlantic. Alex Piotrowski et al. (2009) have used the combined high resolution benthic and planktonic stable isotopes and Nd isotope records from South Atlantic cores to examine in detail the relationships among these proxies to better understand the responses of both northern and southern source deep water formation during rapid climate changes. One of the implicit conclusions from our results and interpretations is that, while the North Atlantic and Pacific end members do not appear to have changed appreciably, the Southern Ocean end member most likely changed as a result of the reduced input from the NADW.

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

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

Improve understanding of deep water formation in the Southern Ocean and in the North Atlantic, including its variability.

Research Progress

The goals for this funding period included evaluation of data sets previously collected as part of ARCHES, specifically the data in the Ross Sea and the global $^3$He distributions. The data set from the AS2K cruise in 2000 along the Ross Ice Shelf will provide insight into the interaction between shelf waters and glacial ice, the global $^3$He data set will be used to study the principal return flow of deep waters in the global ocean. For the latter activity, a collaboration has been started between the LDEO tracer group and the groups of Jorge Sarmiento (Princeton University) and Anand Gnanadesikan (GFDL). This collaboration led to a proposal to the National Science Foundation on studies of the deep ocean circulation using a combination of models and tracers. We made progress on the Ross Sea data by adding water mass inversions to address the problem of melt water fractions and fluxes in water flowing out from underneath the floating ice shelf. We also moved towards completion of the global $^3$He data set, mainly in terms of quality control and plotting capabilities.
Example of the results from the global $^3\text{He}$ distribution work: Distribution of $d^3\text{He}$ at 2500m depth in the global helium isotope data set presently being compiled by the Lamont group. High values are associated with ridge systems such as the Galapagos Rise. Similar plots can be produced for any desired depth or isopycnal surface.
**Research Goals**

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

**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.
Research Goals

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

Research Progress

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

During the INSTANT periods ENSO was in a weak El Niño state, with a brief La Niña phase occurring in early 2006. The NOAA mooring period spans a time of an overall weak La Niña phase. Except for the Arlindo period, there is no clear correlation of the Makassar Throughflow to ENSO, but it is noted that neither the INSTANT nor NOAA time series recorded during strong ENSO episodes. The December 2006 through May 2009 record displays many of the same attributes as revealed by the INSTANT data: a clear seasonal behavior with maximum flow in August, with minimum flow in November. The particularly weak flow of November 2007 may be a consequence of a strong Kelvin Wave derived from the Indian Ocean. The mean flow within the thermocline and deeper as measured by the NOAA-MAK mooring is strikingly similar (less than 10% difference) to that measured during the INSTANT period. However the flow at 40 meters is notably weaker in the NOAA record, with an average southward speed of 0.3 m/sec versus 0.4 m/sec in the INSTANT 2004-2006 record.
Figure 1: Configuration of the NOAA-ITF Makassar mooring deployed in November 2006 at the Red X in the bathymetry map of Makassar Strait. Recovered 31 May 2009. Redeployed for another ~ two year period.
**Figure 2** Meridional speed at Makassar west mooring site 2°51' S; 118°28' E from January 2004 through May 2009. The blue and green lines denote the time series from the first and second deployment of the NSF funded INSTANT program; the red line is from the NOAA funded mooring record.
Research Goals

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

Research Progress

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

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

Mooring M3 was replaced with a full suite of instruments, and a mix of spare flotation and floats borrowed from other groups on board the vessel. We do not yet have enough instruments and mooring gear to sail with complete backup, so mooring M2 was redeployed in a reduced configuration, with only a single release, and instruments in the lower 250 m instead of the usual 500 m instrument string.
Mooring work was accompanied by more than 200 Conductivity/ Temperature/ Depth/ profiles (CTD) including a high-resolution section across the Orkney Passage. As SHACKLETON is not a research vessel, the CTD system had to remain on deck throughout the cruise, unprotected from the weather. This resulted in large offsets in measured salinity. These will require additional effort to correct, using salinities derived from water samples collected during the cast. Thus, the data are not yet available. Analysis of the first 8 years of the Weddell time series has been prepared for presentation at international meetings and publication. In January 2009 two abstracts were written, and in March 2009 accepted, for presentation at the MOCA09 meeting in Montreal CA.

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

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

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

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

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

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

Research Progress

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

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


Figure 1. The rates of increase in the surface water pCO₂ during the three winter months over the subpolar Southern Ocean, 45°S-55°S. The data for three of the six zonal SST bands around Antarctica are shown. A) 0.8°C <SST< 1.50°C; B) 1.50°C <SST< 2.50°C; C) 4.50°C <SST< 5.50°C. The mean rate of increase for all six zones studied is 2.1 ± 0.6 uatm/yr. (Takahashi et al., 2009, DSR-II). This suggests that the rate of deep water upwelling has been increasing and the CO₂ sink intensity has been decreasing.
The first partial year of the PR-Challenge was primarily used to explore and develop hardware and software options for data preparation, dissemination to the participants and subsequent retrieval of the reconstruction that make up the full chain of PR-Challenge steps. To support this effort, we hired Laura Landrum (PhD) at 0.5 FTE in January 2009. Her expertise is oceanography and ocean chemistry, but over the past years she has worked extensively in GIS-based data preparation and distribution to various user groups of the US Department of Agriculture's Agricultural Research Service.

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

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

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

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

1.1 Data

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

- an advanced way to provide data and openly stimulate careful evaluation of the proxies
- provide realistic process models for development of useful pseudo-proxies

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

Figure 2: Illustration of selected network in a visual way. The front end of this interface could be ARC-GIS Server that provides all tools to zoom and select, interface proxy-layer with other spatial information (elevation, climatic zones, instrumental data, etc.)

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

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

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

1.2 Reconstruction

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

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

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

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

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

![Diagram of Model-based Experiments](image)

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

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

2- Evaluation of software infrastructure and evaluation of hardware logistics

So far we have identified an elegant way using ARC-GIS Server as the front end. Detailed discussions are ongoing with NOAA and NCAR (Laura as the GIS specialists as well as members of the GIS group at NCAR). The current goal is to have a demonstration ready at the PAGES Open Science Meeting in July in Corvallis.
A second option is under consideration for the PR-Challenge to get underway more quickly. This option is under discussion with Don Middleton and the NCAR Earth System Grid (ESG). Although this might not be based on a GIS frontend interface because the new generation of ESG provides an alternative way of interacting with the user, all the background scripts and procedures would remain identical. The ESG solution has both full NCL capabilities in the background, and, most importantly, it is designed to work with large data volumes (for CMIP!). This solution might be the most efficient because it offers a simple upload capability. Going online with the new ESG system is planned for July 1.

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

3- PR-Challenge start at PAGES Open Science Meeting

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

Subsequently to the start with first exercises ready (first examples are resolution of network and various noise colors in the pseudo-proxy data), we will hold a workshop to evaluate what advanced process models could be used and designed for use in the PR-Challenge. This is an ongoing effort of us to stimulate the community to describe and test process-based proxy models.
Research Goals
The primary goal for this project is to determine the variability in wind-driven upwelling in the Southern Ocean during the Holocene. This project builds on our NOAA-ARCHES work in which changes in upwelling in the Southern Ocean were assessed using an opal flux proxy for upwelling. Results of that work indicate that a reorganization of global wind systems is the primary mechanism linking manifestations of past abrupt climate changes found at many locations worldwide, and we seek to establish whether or not the Southern Ocean has experienced significant variability in wind-driven upwelling during the Holocene period.

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

Also, during the past year we were informed that NOAA will no longer fund paleoceanographic work after the current two-year period is complete. Therefore, we intend to make use of our remaining resources to produce results with the greatest possible scientific impact. Although we intend to complete a Holocene study of upwelling in the Southern Ocean, we also intend to test the hypothesis that the primary site of deepwater formation during the peak of the last glacial period was located in the Ross Sea. Deepwater formation, and its link to the ocean’s overturning, represents a fundamental component of Earth’s climate system. There has long been speculation about the location and mechanism of deepwater formation under glacial boundary conditions. If the hypothesis is correct, then the near-exclusive formation of deep water in the Ross Sea would represent a mode of ocean overturning circulation heretofore not envisioned, and certainly not depicted in any climate models. If new evidence supports this hypothesis, then it would represent a unique new data set that will be of great value in improving climate models.
Research Goals

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

Research Progress

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

We also find that periods of alternating wet and dry conditions occurred during the 6 kyr\ interval of deglaciation. From 17.5 to 16.0 kyrs and from 14.5 to 12.7 kyrs the lands in the 35° to 40° N zone were unusually dry and from 16.0 to 14.5 kyrs and from 12.7 to 11.4 kyrs they were unusually wet. The opposite set of situations was experienced in China and on the Altiplano of South America. We tentatively attribute this alternation of conditions to changes in the interhemispheric temperature difference resulting from the changes in extent of sea ice cover in the northern Atlantic relative to those in the
Southern Ocean. This is of interest because the extent of global warming will likely be
greater in the northern hemisphere than in the southern hemisphere.
Research Goals

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

Research Progress

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

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

The potential for reconstructing drought over the Old World from tree rings is clear. However, the tree-ring chronologies that we will use for the OWDA will all have to be recreated from their raw measurements to guarantee that they are estimated in the best way possible to preserve low-frequency variance due to climate. This is due to important recent advances in the methods used to develop tree-ring chronologies for the reconstructions of past climate. The processing of the chronologies will require revisiting all of the primary ring-width measurement series and applying the newest state-of-the-art
“signal free” methods of tree-ring standardization (detrending) developed by Dr. Briffa and his former PhD student Dr. Tom Melvin to preserve as much low-frequency information as possible in the chronologies. This of course is critical if we wish to determine the degree to which megadroughts (droughts of exceptional duration) have occurred in the past over Europe, North Africa, and the Middle East, as they have occurred over North America. E.R. Cook has committed four months time to work off-campus at the Climatic Research Unit with Briffa and Melvin to accelerate the acquisition and processing of the tree-ring data for this OWDA project.

During the time leading up to this progress report, I have also been working on incorporating ways of estimating uncertainty in the drought reconstructions that are not tied to the biased calibration period statistics. The procedure I will use is based on the bootstrap. It will assume a random (versus fixed) model formulation in its resampling scheme to allow for as much uncertainty as possible to be incorporated into the estimates. The bootstrap is also relatively easy to employ and also relatively fast given the thousands of 0.5° grid points of PDSI that will be reconstructed. The bootstrap uncertainties will vary over time depending on the properties of the tree-ring predictors and will cover the full lengths of the reconstructions.
Research Goals
The year 1 results were very encouraging and so we plan to continue this work into Year 2 with a detailed AMS radiocarbon stratigraphy for core GC-13 from the NW Atlantic and additional cores off Greenland and new sediment cores from the NW African margin. The goal will be to develop detailed, multidecadal-resolution records of SST variability spanning two periods from 0-1500 years BP and 2500-3000 years BP. The reason for these two windows is that the 14C production peaks, that indicate changes in solar irradiance, have the largest amplitudes in these windows and thus provide the best opportunity to extract SST sensitivity to solar forcing.

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

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

Over the first year of this project we completed detailed oxygen isotopic and Mg/Ca ratio analyses of planktonic foraminifera at two core sites between 0-3000 years BP, one from the Laurentian Slope (GC-13) and another off the Carolina Margin (Site 1055). Both of these cores have very high Holocene accumulation rates (40 cm/ka) and so the 2cm sampling interval was equivalent to about 50 years. Preliminary AMS radiocarbon chronologies indicated that both cores have bomb 14C coretops and thus were suitable for the more detailed AMS 14C analyses of this project. The oxygen isotopic and Mg/Ca analyses indicated that the Little Ice Age section of the cores exhibited an anti-phase relation, with the northern Laurentian slope site indicating cooler conditions (1-2°C) and the southern Carolina Margin Site 1055 indicating warmer conditions, suggestive of an NAO-like spatial pattern.

At Site 1055 we conducted detailed AMS 14C analyses on every 2-cm sample between 0-60 cm, or the last 150 years BP. These analyses were conducted in collaboration with Scott Lehman at Univ. Colorado, Boulder and John Southon at Univ. California, Irvine. Impressively, the downcore 14C analyses reveal the expected radiocarbon plateaux evident in the atmospheric tree-ring 14C record. The presence of these plateaux allowed...
the development of a **calendric** age scale for the Site 1055 core and its d18O stratigraphy. These results unequivocally illustrate that conditions at Site 1055 were warmer during the LIA and during the associated minima in solar irradiance at this time.
Research Goals

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

Research Progress

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

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

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

New 10Be chronology of the Cameron Glacier moraine system in the Southern Alps reveals that the glacier extent has decreased steadily throughout the Holocene, implying an increase in summer temperature that has reached its warmest value within the past 20
Figure 1. Glacial geomorphic map of the Mueller and Hooker Glacier Holocene moraine systems, Mount Cook/Aoraki National Park, Southern Alps, New Zealand. Purple features are moraine ridges and yellow shading depicts Holocene alluvium and glaciofluvial outwash terraces. Dark purple represents moraine and moraine ridges deposited during historical time. Glacial ice is represented by crosshatched blue pattern. $^{10}$Be surface-exposure ages are given in white boxes, and sample locations are marked by yellow dots.
Figure 2. Glacial geomorphic map of the Cameron River valley Holocene moraines, Arrowsmith Range, Southern Alps, New Zealand. Geomorphic features are detailed as in Figure 1, and additional geomorphic features are described in inset figure legend. Bold line outlines the AD1863 position of the Cameron Glacier terminus. $^{10}$Be ages are in white boxes, and yellow dots mark sample locations.
Research Goals

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

Research questions that were developed in ACCWW year 1 include:

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

Research Progress

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

1. The Weddell Sea time series:

The bulk of Antarctic Bottom Water [AABW] is derived from the continental margins of the Weddell Sea. Since April 1999 the AABW outflow from the Weddell Sea has been recorded with NOAA funding. Since 2008 the observational program funding was shifted over to NOAA/OCO, with the data analysis continuing within ACCWW. The following is the abstract of a presentation to be made at the MOCA-09 [IAMAS-IAPSO-IACS 2009 Joint Assembly] meeting in Montreal in July 2009 based on the ACCWW supported data analysis:

Arnold L. Gordon, Bruce Huber. “*Seasonal and interannual fluctuations of Weddell Sea Bottom Water outflow*” An 8 year record (April 1999 to February 2007) of the currents and T/S stratification within the lower ~500 m of the water column, within the outflow of dense Weddell Sea Bottom Water south of the South Orkney Islands, reveals strong T/S seasonal and interannual variability. A cold bottom water pulse is evident in the May-July period, though the precise timing and duration varies with year. Intensification of the near
bottom stratification is observed as the bottom water attains its coldest values. The coldest bottom events occurred in 1999 and 2002, while in 2000 it was absent, with slow warming since 2002. At bottom temperatures <-0.8°C the salinity variability makes for a ‘fan-like’ appearance in T/S space suggesting a varied source of dense shelf water, with the coldest bottom water associated with the saltiest water, indicating a southwest Weddell Sea origin. In consideration of the isobath following distance from likely source to the mooring array, at typical bottom speed of 10-15 cm/sec, we determine that the export of the dense shelf water occurs during the austral summer (as also observed in the Ross Sea). Relationship of the behavior of the shelf water export to the strength of the Weddell Gyre and to SAM is proposed. The existing Weddell Sea Bottom Water outflow mooring array continues to extend this important time series that detects changes in the Southern Ocean MOC.

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


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

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

During the ACCWW year 1 the trends of SSS of the North Atlantic subtropical have been investigated.
The SSS anomaly (anomaly within 2 by 2 lat/long boxes from the long term mean within that box) within the North Atlantic subtropical regime reveals a long-term trend of increasing values from the 1950s into the 1990s (Fig. 2). This trend is interrupted by brief periods of reduced SSS of the mid-1970s and mid-1980s. Since 2004, another period of lower SSS is observed (also see Gordon and Giulivi, 2008).

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

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

Figure 1b. Long-term average (1958-2001) of the vertical integral of the divergence of moisture flux (color; units= kg m^-2 s^-1 x 1000) computed from monthly ECMWF ERA-40 data. Evaporation -precipitation (contours; units in m yr^-1) estimated from ERA-40 monthly surface large scale and convective precipitations and evaporation data.

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

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

Research Progress

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

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

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

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

**Research Progress**

During the foreshortened initial project year we continued work on two manuscripts and a primary ocean data set acquired in the Amundsen and Ross Seas. Key elements of that processed data have now been forwarded to the National Oceanographic Data Center, and made available to collaborators on the specific cruise (NBP07-02). The data have also added to the time series reported in Jacobs & Giulivi 2009, which documented strong salinity declines extending from the IGY to the IPY in and downstream of the Ross Sea. That freshening appears to be linked to change in the large-scale atmospheric circulation and to an accelerating rate of ice shelf melting and glacier advance upstream in the Amundsen Sea. The second paper, by Loose et al., applied multi-parameter analysis to three ocean data sets to infer melting rates of 33-50 km3/yr at the base of the Ross Ice Shelf, consistent with prior estimates. Whether chemical samples still in the processing queue and a higher-resolution sampling pattern can detect melt rate change remains to be determined.
Figure 1. The variability of shelf water temperature and salinity since the IGY in the SW Ross Sea. Temperatures are referenced to the sea surface freezing point, ~1.91°C at a salinity of 34.8. These profiles are located north (solid lines) and west of Ross Island, mostly in a continental shelf depression filled with dense shelf water formed during winter sea ice formation. A long-term drift toward lower salinity (~0.03/decade for >50 years) is responding mainly to larger freshening in lower-salinity surface water transported into the Ross Sea by the Antarctic Coastal Current. From Jacobs, S. & C. Giulivi, 2008: Variability and change in Ross Sea shelf waters. In: Antarctic Climate Change and the Environment, J. Turner et al., (eds), http://www.antarctica.ac.uk/met/SCAR_ssg_ps/ACCE.
Research Goals

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

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

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

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

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

Research Progress

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

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

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

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

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

- The Greenland Sea is still in a state of low deep water formation and the deep circulation scheme has changed considerably. A major follow-on question emerging from these studies is the link of the changes in the Nordic seas to those in the Arctic and the North Atlantic.
• The presence of radiogenic helium indicates interaction between the Ross Ice Shelf and subsurface waters at the grounding line. This could be a very important process for the stability of the Ronne Ice Shelf.

• The best estimate for the basal melt rate of the Ross Sea Ice Shelf (based on CFC budgets and oxygen and helium isotope measurements) is 33 km³/yr in 1994 and 50 km³/yr in 2000.
Research Goals

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

Research Progress

The funding for this project was delayed until early 2009, so we have just begun work. We have acquired much of the WOCE and CLIVAR hydrographic and CFC data from the Atlantic and Pacific oceans that will be needed for calculation of CFC inventories and comparison of repeat lines for changes in deep water properties. We have continued to examine the temporal variability (seasonal and interannual) of CFCs in conjunction with temperature and salinity in Denmark Strait Overflow Water in Denmark Strait to better establish the boundary condition for CFC input into the deep North Atlantic Ocean by this water mass. We have completed our study of glacial melt from the Ross Ice Shelf based on optimal multi-parameter analysis of helium isotopes, neon, oxygen, oxygen isotopes, temperature and salinity, and water residence times beneath the ice shelf based on CFC measurements, from cruises to the Ross Sea in 1994 and 2000. This work was begun and supported primarily with funding from ARCHES: Tracer Observations of Deep Formations. It is in press (Loose et al., 2009). The basal melt rate was calculated to be 33 km3/yr in 1994 and 50 km3/yr in 2000.

We will continue to acquire high quality CFC data sets collected from various regions of the world ocean. Subsets of these data will be used to determine CFC inventories for North Atlantic Deep Water for the 2003-2005 time period, which in turn will be used to calculate its rate of formation. The CFC inventory method yields an integrated formation rate over the time interval between observations. The NADW formation rate based on the 2003-2005 data will be compared to CFC inventory based rates we calculated for 1990 and 1997 to investigate variability in the deep Atlantic limb of the MOC. In addition, these data will be used for comparing WOCE and CLIVAR repeat lines to document water mass property changes in the most recently ventilated deep water, which will be identified using CFC data. We have also begun a project to investigate saturation of CFCs in the surface ocean as a function of time and location and will use the upper ocean data from these stations for this. This is important to establish the concentration boundary condition for uptake of CFCs by the ocean, which is used in OGCMs and in calculating the fossil fuel CO2 uptake by the ocean.
The best estimate for the basal melt rate of the Ross Sea Ice Shelf (based on CFC budgets and oxygen and helium isotope measurements) is 33 km3/yr in 1994 and 50 km3/yr in 2000.
Theme III: Applications Research

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

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

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

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


5. Schlosser, P., ACCWW: *Infrastructure*
Research Goals

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

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

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

Students also were shown state-of-the-art flux measurement and air-sea surface process systems, used in studies of heat, momentum, and gas exchange.

In the second week, students gave oral presentations before all of the participants. Many students were able to incorporate techniques that they learned during the previous week’s workshops to give an articulate and concise overview of his or her work and present a poster based on research that they had performed previously.
**Education Goals**

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

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

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

Day 2 will focus on gas exchange processes including large-scale determination of gas exchange coefficients and micrometeorology; the 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 bio-diversity of the sea, including the chemical fluxes associated with different species. We will explain how biological processes can be represented in numerical models, and how satellites and data assimilation can be used to quantify the different fluxes of gases at the air-sea interface.

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

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

Day 9 will focus on atmospheric processes such as the formation and transport of dust and marine particles and gas phase reactions, the various chemical reactions that occur at the sea surface, and the turnover time of chemicals in the atmosphere.
Day 10 will focus on integrative research in the complex area of marine particles and the cycle of sulfur and its potential impact on DMS and atmospheric chemistry.

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

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

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

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

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

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

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

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

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

Research Progress

Details of the Curriculum

The study of surface ocean-lower atmospheric processes requires a thorough knowledge of the state and variability of (1) marine biogeochemistry, (2) air-water gas exchange rates, (3) atmospheric trace gases and particles, and (4) climate. In the past, these fields of research have mostly progressed in parallel and the state of the art in each of these fields is separately reviewed. The challenge of SOLAS and the value of the SOLAS Summer School is to bring scientists from these different backgrounds together to work collaboratively.

Marine biogeochemistry consists of the state of ocean physics, chemistry, and marine biology that determines the oceanic conditions triggering a transfer of gas or particles to and from the atmosphere. Marine biological productivity occurs at the ocean surface, but as organisms die and sink to the deep ocean, trace elements are transported away and become isolated from the atmosphere (this mechanism is known as the "biological pump"). Biological productivity is sustained by the input of nutrients from the atmosphere, rivers and continental margins, and the deep ocean. Whereas nitrate and phosphate are the most common limiting nutrients, recent experiments have demonstrated that iron may also limit biological productivity over large regions of the ocean (Martin et al., 1994; Coale et al., 1996; Boyd et al., 2000). These studies highlight the role of different phytoplankton groups in the efficiency of the biological pump. Efforts are underway to characterize specific properties of the main phytoplankton groups (see for example the iron addition experiments). Biological processes determine the concentration of atmospheric CO₂ on time scales of a few thousand years, while contributing to regional patterns of air-sea CO₂ fluxes on shorter time scales. Biological processes also affect the sulfur cycle. Process studies have established a general link between phytoplankton and dimethylsulphide (DMS) levels, although the exact mechanisms responsible for DMS production are not fully understood. DMS is a direct feedback on climate through its radiative forcing, and an indirect feedback because it is a source of cloud condensation nuclei, and thus can change cloud properties.

The physics of gas exchange governs the transfer of greenhouse gases at the air-sea interface. Gas exchange rates have either been extrapolated from laboratory measurements or measured in the field. Laboratory measurements have proven useful in elucidating the fundamental physicochemical mechanics of gas exchange. For example, studies in wind tunnels defining the impact of synthetic and natural surfactants on wave slope and gas exchange rates have provided insights into underlying processes. However, some field measurements using the dual tracer technique seem to contradict these findings (for example, Nightingale et al., 2000) and more fieldwork is clearly needed. At
higher wind speeds the challenge of making useful measurements of near-surface and interfacial processes increases. Acoustical methods have proven helpful in the study of wave breaking and in delineating bubble distributions. The size distribution depends on the prior life history of the bubbles, from their formation in breaking waves, through turbulent mixing, advection and loss by buoyancy and dissolution. Measurements of bubble sizes in the context of these processes provide a sensitive diagnostic basis for exploring the detailed physics of the upper ocean boundary layer.

In the atmosphere, sea-salt particles are a major reactive medium and precursors for volatile reactive halogens as well as a significant source of atmospheric alkalinity and organic material. The production of several classes of compounds as well as the chemical processing and deposition of important sulphur and nitrogen species are directly tied to sea-salt cycling. Sea salt is also an important source of condensation nuclei and thus can change cloud properties including the radiation effects of clouds. In some regions, reactive halogen compounds (Cl, Br, and I) play major roles in the photochemical processing of air in the marine boundary layer. Currently organo-halogen gases contribute about 25% of the equivalent chlorine to the stratosphere and contribute significantly to the loss of stratospheric O\textsubscript{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\textsubscript{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.
Research Goals

Per request of the principal investigators of the *Abrupt Climate in a Warming World* (ACCWW) project, the Columbia Climate Center solicited proposals to meet the goal of linking the physical science in ACCWW with decision makers and the general public. It was recognized that social scientists must be engaged to make that connection in a more meaningful way. Two projects were chosen: *Impacts of a Changing Climate on Water Allocation Rules in the SW United States* (Heikkila, Schlager and Siegfried) and *Bridging Social and Physical Sciences, Outreach and Communication* (Carr and Marx). These projects were chosen in January of 2009, thus the period of performance has been shorter than other parts of the ACCWW project.

The goal of *Impacts of a Changing Climate on Water Allocation Rules in the SW United States* is to understand the interaction between climate information and interstate water allocation rules and how water laws and institutions might cope under different climate change scenarios. There are three project components: 1) a survey of water managers in the Southwest to identify how climate information is used and shared, 2) an analysis of policy changes in southwestern states to better assess how policies change and respond to drought conditions, 3) a model of the performance of interstate water allocation rules under different scenarios of climate change and water allocation.

The goal of *Bridging Social and Physical Sciences, Outreach and Communication* is to enhance the outreach and communication of the research team of the ACCWW project by taking advantage of expertise on how information is understood and how decisions are made.

Research Progress

Progress has been made in Year 1 on all three components. The Rio Grande Basin has been chosen as the optimal test case as a study site. Questions for the survey of water managers in the Upper Rio Grande watershed are being developed using information from a prior governance study (component 1). A database of water laws passed each year since the 1930s throughout the three states in the Rio Grande Basin -- Colorado, New Mexico and Texas -- has just been completed and will be the basis of the analysis of how policymakers have responded to periods of severe or extended drought in the past (component 2). The agent-based model (component 3) is being adapted to the Costilla Creek watershed, an interstate tributary to the Rio Grande.

Year 1 has also seen the design of a dedicated webpage; there have been various blog postings on abrupt climate change in the CCC blog at:
http://blogs.ei.columbia.edu/climate/ and ACCWW project team members have been active participants at various CCC events, which always include researchers from broad disciplines and are very well attended.