CORC-ARCHES Abrupt Climate Change Program

Consortium on the Ocean's Role in Climate –
AbRupt climate CHangE Studies (CORC – ARCHES)

'building bridges between paleo-observation, climate modeling and modern-observations'

Partner:

- **Lamont Doherty Earth Observatory, Earth Institute at Columbia University**
- ***NOAA's Office of Global Programs***

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Outside Investigators:
Denton (U. Maine), Dickson (CEFAS, UK)

GOAL:

The purpose of the CORC-ARCHES program is to describe, understand and assess the likelihood of abrupt changes in the climate system, and to identify the mechanisms involved.

RATIONALE:

Indications for fast transitions from one climate regime to another have been documented in the earth's history by paleo-observations throughout the globe. The largest and possibly swiftest changes of global climate are found during a cold climate, i.e. ice ages. However, even during the more stable climate of the last 10000 years (the Holocene) rapid swings in temperature and/or precipitation, at least on regional scales, have occurred. None of these events have been fully described. Exactly when they happened? How large and rapid was the climate change? What might have been the trigger? Looking into the future our best estimate of the range of possible scenarios is given to us by climate model simulations under a range of forcing scenarios. All of the models that can be used for such projections have much less climate "noise" compared to what we know from the observed record. Very few models have ever produced an abrupt transition and none of them looked anything like what little information we have from the observed paleo record. What is needed is an integrated approach of modeling, modern and paleo observations to develop and test hypothesis of mechanisms and forcings that can lead to abrupt climate change.

HISTORY:

In 1993 NOAA's Office of Global Programs has initiated a partnership with Columbia University to strengthen their respective programs on Global and Climate Change. After a period of defining the best way forward a focus on abrupt climate change was agreed upon in 1998. Columbia University's research portfolio had the needed breadth of expertise that could generate paleo climate data sets, interpret the records in a dynamical consistent framework and evaluate what additional observations would be needed to detect early warnings of a future abrupt climate change. Columbia University enlarged the reach of the program by working with researchers at other institutions, hosted a series of internationally attended topical workshops, invited outside expertise. In short this effort was instrumental to build the beginnings of an abrupt climate change community. Both partners had always expected that this effort would soon be transformed into a much more significant initiative on abrupt climate change within NOAA. Over the last five years NOAA provided funding at the level of $2M per year.

RESEARCH HIGHLIGHTS:

- Documentation of a systematic freshening through the western basins of the Atlantic Ocean between the 1950s and the 1990s. In essence, the overflow system that ventilates the deep Atlantic Ocean has freshened over a 40-year time span. The results extend a growing body of evidence indicating that shifts in the oceanic distribution of fresh and saline waters are occurring worldwide in ways that suggest links to global warming and possible changes in the hydrologic cycle of the Earth.
- Implemented an ocean time series station in the North Western Weddell Sea to document climate variability and change in one of the sources for Southern Ocean Bottom water.
- Documented a steady increase in subsurface temperatures in the Weddell Sea over the last 20 years.
- The Gulf Stream is not responsible for Europe's milder winters
- By many measures the 1976/77 transition was an abrupt climate change, albeit small, that had serious consequences for climate around the world. ARCHES research has shown that these transitions originate in coupled tropical dynamics and are predictable to a modest degree years in advance.
- Determined that snow-line lowerings during the Last Glacial Maximum, the Younger Dryas, and the Little Ice age are in phase at middle northern and southern latitudes, indicating rapid global teleconnection of climate variability.
- Determined that meridional and zonal gradients of sea surface temperature in the equatorial Pacific Ocean were much less than today during the LGM, implying that either thermal structure of the upper ocean or wind-driven upwelling was substantially different from modern conditions
- Found substantial increase in biological productivity within the Subantarctic zone of the Southern Ocean associated with Heinrich events, the first clear manifestation of these events at high southern latitudes, likely related to reorganization of meridional overturning ocean circulation

CORC-ARCHES IMPLEMENTATION:

The program consists of a paleo-observation component to fill in the sketchy picture of the nature of the abrupt changes documented in the paleo records; a modern observation component to give insight into ocean physics that appears to have a major role in these changes; and a modeling component to test mechanisms proposed to be capable of flipping the climate system into a markedly different state in a remarkably short time (years to a few decades). Obviously, the total task is beyond our small pilot effort, but we are trying to make best use of our skills and the available resources to provide a meaningful core activity on integrated abrupt change research.

PALEO SECTION:

There are a number of important questions, which might be answered by further examination of paleoclimate archives. Examples are as follows:
It is important to establish the degree of hemispheric symmetry for the Little Ice Age (LIA), the Younger Dryas (YD) and the Dansgaard-Oeschger events (DO). Our most reliable source of information comes from mountain snowline elevations. The evidence in hand suggests that the timing and extent of snowline lowering for the LIA and YD were probably the same at 40ºS (in New Zealand) as at 40ºN (the Alps and Rocky Mountains). However, both the absolute dating and the snowline elevations must be firmed up. Further, it is important to document the magnitude of the coolings associated with these events both on tropical mountains and in the tropical ocean. The snowline changes associated with the DO events are not likely to be documented in mountain moraines because deposits formed during DO, advances were overrun by the major (i.e., stage 2) glaciation. Rather, evidence regarding the hemispheric symmetry of DO events will have come from alkenone and/or Mg/Ca paleotemperature records from temperate latitude ocean cores. Results obtained by Julian Sachs suggest that the temperature changes at 40ºN in the Atlantic were considerably larger than those at 40ºS in the Atlantic.
While Heinrich events are prominently displayed in the ice rafting records from the northern Atlantic, the climate impacts of these events are not prominently displayed in either Greenland ice or in alkenone paleotempature records. They do however show up clearly in pine events in a pollen record in a Florida lake core, as runoff events in a core off the mouth of the Amazon, and in the chemical composition of rock varnish from the U.S. Great Basin. Also, there appear to be antiphased ice-rafting events in the Southern Ocean. DO events are not seen in these records. It is not clear yet what this is trying to tell us.
Changes in the transport of dust and sea salt through the atmosphere are thought cause albedo changes. Changes in dust transport appear to modulate iron fertilization of the ocean (and consequently atmospheric CO_2 drawdown). While in both Greenland and Antarctica the rain of dust was high during glacial time, the detail in the chronologies of deposition differs. In Antarctica, an abrupt dust demise occurs at the very beginning of each transition from full glaciation to full interglaciation. In Greenland, there is a dustiness pause halfway through the last such transition (i.e., during the Bolling-Allerod [BA]), but dust transport resumed during the YD and thereby did not come to a full halt

until the end of the transition period. For the tropics, it appears that the dust rain terminated at the onset of the BA and did not resume during the YD. Detailed chronologies of dust rain are needed in areas of glacial loess accumulation and off the bulge of Africa. Hopefully at sites in the tropics where dust records are preserved will also be found.

Based on the evidence in hand during glacial time the tropics were less wet and the extra tropics less dry. As the evidence for this pattern remains somewhat sketchy, it is important to expand the geographic coverage of well-dated archives. The sizes of closed basin lakes are especially revealing in this regard.

The geographic coverage of the Holocene record for Bond's 1500-year cycle is almost nonexistent. It is therefore of great importance that the existence (or nonexistence) and the amplitude of this cycle be established at a number of locales. In particular, it is important to document the geographic pattern of the MW-LIA oscillation. This is especially important for Antarctica. Deconvolutions of borehole temperatures at the Taylor Dome show that the MW-LIA cycle is antiphased with respect to that in Greenland. But, in contrast, preliminary analysis of the Antarctic Siple Station record suggests that it is in phase with that for Greenland.

The Mann "hockey stick" temperature reconstruction (based primarily on tree ring widths), while showing a sharp natural warming between 1880 and 1950, shows no temperature shift corresponding to the MW. This apparent disagreement with borehole records must be resolved.

CORC-ARCHES paleoclimate research addresses these issues, and more. Denton's work in New Zealand and South America will better constrain the interhemispheric phasing of rapid climate change. Each of the components of the proposed paleo work will contribute to a better understanding of the global footprint of Heinrich events, as well as their regional characteristics. Hemming and Goldstein will establish the chronology of dust fluxes to the South Atlantic where, presumably, the principal source is Patagonia, as it is for central Antarctica. Working in the South Atlantic, much closer to the source of the dust, will enable ARCHES investigators to determine whether the early demise of dust in Antarctica reflects a reduction in the dust source, or a change in winds leading to a reduction in transport of dust to Antarctica. Sea ice reconstructions (Anderson and Burckle) will improve our understanding of the boundary conditions influencing the intensity and pattern of atmospheric circulation which, in turn, regulate both the sources and the transport of dust. Reconstructing past changes in sea surface temperature (SST) of the eastern tropical Pacific (Lynch-Stieglitz) will reveal if and when the region became locked in sustained El Niño or La Nina modes. Combining these SST reconstructions with modern relationships between regional patterns of precipitation and the phase of the ENSO cycle will provide valuable insights into the origin of the climate-related changes in precipitation that are evident in various paleo records. Bond's work will improve our understanding of the origin, distribution, and regional characteristics of the 1500-year cycle that pervades all phases of Earth's climate and which may serve as a trigger for abrupt climate change.

MODERN OBSERVATION SECTION:

Changes of global climate in the past seem to have always involved the large-scale ocean circulation either as an active element, amplifier, or global communicator of climate change. The oceans transport large amounts of heat from the tropics to higher latitudes and between basins. Some of this heat transport is due to the horizontal wind driven circulation. However, most of it is facilitated by the density-driven, thermohaline circulation.

Modern climate/ocean observations are needed to describe the present state and the future evolution of the system. Such observations, in conjunction with synthesis efforts including data assimilation form the basis from which to attempt climate predictions and abrupt change scenario assessments. Presently a number of international planning efforts are underway within the GCOS/GOOS and CLIVAR framework to design a cost-effective, integrative global ocean observing system. Our abilities to successfully predict aspects of the coupled ocean-atmosphere climate system on seasonal to interannual time scales in the tropics drives the design, optimization and internationalization of upper ocean tropical observing systems (TAO, PIRATA, etc.). Studies of the thermohaline circulation of the ocean are not far enough along to assess its predictability. However, even in the absence of a demonstrated predictive capability for the thermohaline circulation, the anticipated dramatic and possibly long-lasting effects of a major change in the oceans meridional overturning circulation on the planet's climate demand an adequate amount of observational effort of the deeper portions of the ocean. It is expected that the currently planned and implemented ocean observing systems will be critically evaluated once all data can be assimilated into a predictive ocean circulation model. In the mean time, we can already point to a number of sites that very likely will remain key regions for any truly global ocean observing system for climate.

Air-sea cooling in the high latitudes raises the surface density and causes the ocean mixed layer to deepen. At some places this convective process reaches to great depth in the ocean (e.g. Greenland Sea, Labrador Sea). In the southern hemisphere, however, the bathymetry of the ocean and land sea distribution prohibits effective open ocean deep convection and dense water mostly forms on the vast shelf regions. From there it needs to cross the shelf-break front to penetrate into the deep ocean. This happens by a whole range of complex processes such as bottom flows within canyons, meso-scale eddies and tidal processes. Once the dense water has reached the shelf break it ascends to great depths entraining lighter ambient waters on its way. In contrast to large scale open ocean convection shelf convection happens at many places and on small spatial scales. This poses a significant challenge to quantify its mean formation rate, as well as the variability of properties and formation rates in the source regions.

In the North, long-term observations in the center of the Labrador and Greenland Seas were started during the era of weather ships (1950-1975) and are now obtained by an internationally coordinated program with participation from several European countries, Canada and the US (VEINS and CLIVAR programs). In particular, efforts to measure the flow through Denmark Strait are the observational cornerstones to document the current state of dense water formation and density driven ocean overturning within the Atlantic sector. These efforts have been supported by CORC from its very beginning through partial funding of Dickson's current meter arrays. Meanwhile, the existing current meter records show intriguing signals that suggest linkages between the properties of the overflowing waters and those in the waters flowing into the Nordic seas.

In the South, around the Antarctic continent, observations are much sparser than in the north and time series hardly exist. In addition to logistical issues sea ice and the existence of several geographically widely separated deep-water formation regions poses a real challenge to any observational program. However, the Weddell gyre offers a unique setting for monitoring one of the major, if not the single most important, sources of Southern Ocean deep water in that it has a well developed gyre circulation. The western part of the gyre collects newly formed deep and bottom waters and advects them via a western boundary current northward along the Antarctic Peninsula towards the South Orkney plateau.

A hydrographic section south of the South Orkney Islands seems to be the best place for a long term observing effort. The sea ice is relatively light and the distance to the US Palmer station still acceptable. The combination of a few moored sensors within the 500m thick dense water plume from the bottom at a water depth between 2500-4500m and annual or biannual hydrographic sections has proven to be a cost effective approach. Measurements of currents, temperature, salinity and oxygen as well as CFCs, tritium and helium isotopes allow to effectively detect changes in the amount and properties of deep waters formed in the Weddell sector of the Southern Hemisphere. We envision this site to become the "Denmark Strait overflow index" of the Southern Hemisphere.

It is important to continue the by now 4 year long time series for several more years in order to find out if and how the Southern ocean density driven circulation changes during "global warming". We need to optimize the distribution of sensors and experiment with new instruments such as a moored water sampler to obtain a weekly time series of CFCs and other trace elements.

Although there are only one or two places where observations were obtained systematically before we need to collect all available in situ and remotely sensed data and analyze them in conjunction with the new data sets. We also need to pay attention to changes in the atmospheric circulation such as the Antarctic annular mode and the Antarctic circumpolar wave. How are they connected to the varying amount and properties of deep waters formed.

Basin-scale synthesis of the amount of trace elements such as CFCs and tritium/helium will also help to set bounds on the mean rate of deep-water production and its variability. These studies will also help to resolve the recent controversy about the ratio of deep-water formation between the northern and southern hemispheres.

In the long term our observations will help to improve ocean models, in particular with regards to slope convection, which then can be used to explore which aspects of the density driven circulations might be predictable.

MODELING SECTION:

"It is tough to make predictions, especially about the future". Any climate scientist with even a touch of humility would agree with Sam Goldwyn's aphorism. Yet, the impact of anthropogenic forcings on the climate system now makes it imperative that we forecast the future. Perhaps we in the developed countries will have little difficulty adjusting to a gradual global warming, but even for us the prospect of abrupt changes might cause some alarm. At present, the models we might hope to use for prediction do not produce large amplitude abrupt changes, a reflection of our lack of understanding of this dangerous aspect of the climate system.

The first task of an abrupt change modeling program must be to explain what initiates abrupt climate changes and what feedbacks accomplish the sizeable task of converting modest or regional signals into large global responses. Success in this task would be demonstrated by simulating at least some of the past abrupt change events.

Had these abrupt climate changes been purely regional, perhaps centered around the North Atlantic basin, then there would be no need to invoke impressive climatic feedback mechanisms and, from a theoretical point of view, their interest is as limited as their impacts. On the other hand if they are global, as increasing evidence seems to suggest, then it almost beggars belief to see how the planet's climate could change so drastically and so rapidly. In this case powerful climate feedback mechanisms that involve some large-scale reorganization of the workings of the climate system must be invoked. The leading ideas at present for the triggers of this reorganization are either the tropics, or the North Atlantic role in the thermohaline circulation. If the tropics are the ringmaster then global synchroneity of climate changes might be expected. But can the necessary amplitude be attained? On the other hand, if the North Atlantic Ocean is driving, then we need to find feedbacks that can alter a regional climate change into a global change.

To achieve such rapid climate changes requires not just a shift in the patterns of atmosphere or ocean heat transport but a change in the planetary radiation budget. Global, annual incoming solar radiation at the top of the atmosphere remains essentially unchanged as these abrupt climate changes occur and, therefore, so must the sum of outgoing long wave radiation and reflected solar radiation. An abrupt change in the planetary albedo or greenhouse trapping is required.

The planetary albedo is primarily controlled by the distribution of ice, snow and cloud. Water vapor and clouds primarily control greenhouse trapping. How can the distributions of snow, ice, clouds and water vapor be altered so drastically and so quickly? One possible explanation is that the atmosphere-ocean circulation responds to small perturbations, or internally reorganizes itself, in a threshold kind of manner: either sides of the threshold are associated with radically different distributions of reflectors and absorbers associated with different patterns of circulation, convection, subsidence and heat transport. An abrupt change modeling program must concern itself with the factors controlling the planet’s heat balance: what mechanisms enable rapid changes in water vapor, cloud, land snow and ice, sea ice?

In this phase of the Consortium on the Ocean's Role in Climate we plan an extensive investigation into the mechanisms of abrupt climate change. Using numerical models and modern and paleo observations, we aim to identify the processes within the climate system that are capable of turning small perturbations into large responses.

The work will involve two components. The first will use a range of models, from simple to fully complex coupled general circulation models, to examine the means whereby abrupt climate changes can be triggered by changes in cloud cover and albedo, water vapor, sea ice and the atmosphere and ocean circulation. This can be done in the context of easily understood, controlled experiments, such as changes in the distribution of incoming solar radiation, the solar constant, specified ocean heat transport (in the case of a mixed layer ocean) and so on. Such experiments will minimize the processes forcing a climate change and, therefore, the complexity of the response. The aim is to allow identification off which feedbacks are important.

The second component will involve an attempt to explain the origins of one example of abrupt climate change: the Younger Dryas cooling that interrupted the most recent deglaciation. Increasing evidence suggests that this event effected large regions of the globe, not just the North Atlantic region where its existence is most obvious. It has been suggested that the Younger Dryas was initiated by a sudden release of meltwater from the Laurentide ice sheet that weakened the North Atlantic overturning circulation. An alternative explanation has been advance that the event was initiated by an orbitally forced change in the operation of the El Niño -Southern Oscillation. At that time the orbit was just such that the seasonal cycle of the tropical Pacific was altered so as to make the coupled system near stable to interannual variability and ENSO variously was absent, and the Pacific adopted a La Niña like state, or flickered on and off.

Changes in the North Atlantic or the tropical Pacific will cause local and remote changes. Which can best account for the reconstructed pattern of Younger Dryas climate change? We will use numerical models to examine the global impacts of long-term changes in the thermohaline circulation and ENSO and compare these against the reconstructed pattern of Younger Dryas climate change. Which can best account for the observed change? Are changes in ENSO required to account for the reconstructed climate changes far from the North Atlantic? Can a shutdown or weakening of ENSO, and its replacement by a more La Niña like steady seasonal cycle, explain these changes? To what extent are other reorganizations of the tropical climate system (e.g. the tropical Atlantic and monsoons) important?

While the Younger Dryas may not be typical of abrupt climate changes we feel that understanding a single abrupt change will be a great advance over our current situation. Furthermore, the feedbacks that amplified either tropical Pacific or North Atlantic changes into a global or near global response are likely to operate in other abrupt changes too. Also, current coupled GCMs provide increasing evidence that long-term changes in ENSO will accompany greenhouse warming. Examining past changes in ENSO, and the feedbacks that amplify them into global signals, which can be verified against existing data, however sparse, is critical in efforts to quantify, and have confidence in, the predicted impacts of anthropogenic changes in ENSO.

CORC ARCHES RESEARCH ACCOMLISHMENTS

Modern Observations

Dickson (collaborator UK): showed that the overflow system which ventilates the deep Atlantic had freshened for 40 years---- by tracking the freshening south through the deep basins of the North and South Atlantic and discovering that the change in the distribution of salinity between the 1950s-60s to 1980s-90s resembles the sort of change expected by an acceleration of the Global Water Cycle, an expected accompaniment of global warming.

Gordon/Visbeck/Smethie/Schlosser: established a time series (1999-today) in the outflow region of the Weddell Sea, a major deep water formation area in the Southern Ocean. The site is instrumented by current meter moorings and hydrography/tracer sections are occupied during recovery/deployment cruises. First results are being processed for presentation and publication.

Gordon/Visbeck: assembled and inspected all historical hydrographic data from the regions of deep and bottom water formation in the Southern Ocean and will make them available to the wider community.

Schlosser/Smethie: studied water/glacial ice interaction in the Ross Sea (Ross Ice Shelf). Determined fractions of glacial meltwater and are working on estimates of melt rates underneath the Ross Ice Shelf, as well as the related freshwater fluxes. Studies of circulation patterns of Ice Shelf Water in the Ross Sea are underway.

Schlosser: completed study of shelf water interaction with glacial ice in the Amundsen and Bellingshausen seas. Calculated freshwater fluxes and melt rates of glacial ice sheets.

Modeling

The Gulf Stream is not responsible for Europe's mild winters

By many measures the 1976/77 transition was an abrupt climate change, albeit small, that had serious consequences for climate around the world. ARCHES research has shown that these transitions originate in coupled tropical dynamics and are predictable to a modest degree years in advance.

Offered prediction that the 1997/98 El Nino ended the post 1976 tropical Pacific warm period heralding cold conditions and, for example, drier conditions in the South West and Great Plains.

Explained why during El Nino events the mid-latitudes of each hemisphere get cool.

Unraveled the mechanisms whereby the tropical Pacific forces hemispherically and (fundamentally) zonally symmetric temperature and precipitation variability.

Analyzed and modeled the mechanisms whereby the tropical Pacific influences precipitation in the Southwest and the Great Plains, with relevance to the Dust Bowl and past dramatic changes in continental hydrology.

Enhanced understanding of stratospheric influence on troposphere with relevance to trends in the Arctic Oscillation.

Advanced understanding of basic tropical climate dynamics and climate feedbacks, especially in relation to the origin and characteristics of the tropical warm pools which play large role in regulating the global climate.

Provided a reassessment of why the downwelling branch of the thermohaline circulation is in the North Atlantic and not the North Pacific. Atmospheric freshwater fluxes linked to the Asian monsoon are advanced as the reason.

(3) Paleo studies

Bob Anderson and Lloyd Burckle

1) Developed a stratigraphic method based on the relative abundance of *Eucampia antarctica* (as percentage of total diatoms) to correlate high-resolution paleoclimate records among sediment cores from the Southern Ocean, and between sediment cores and Antarctic ice cores. A diatom-based stratigraphic method is vital for paleoceanographic work in the Southern Ocean where calcium carbonate (e.g., foraminifera) normally used for sediment stratigraphy is poorly preserved.

2) Demonstrated that the abundance of ice-rafted debris (IRD) in cores separated by as much as 800 km in the Atlantic sector of the Southern Ocean can be correlated throughout the last glacial cycle. This work was made possible through application of the new stratigraphic method mentioned above. The spatial extent of correlative IRD events will be examined in future work. Whether these features reflect surges in the Antarctic ice sheet, analogous to those that dominated abrupt climate changes in the North Atlantic Ocean during the last glacial period, or changes in sea surface temperature that influenced the distribution of icebergs, will also be the subject of future investigation.

Gerard Bond

1) Identified for the first time a millennial scale climate cycle (not necessarily periodic) running through the entire Holocene and into the late glacial spanning ~0 to 25,000 years calendar age. The evidence came from IRD proxies in sediments from the North Atlantic.

Mean pacing of the cycle was found to be 1470 ± 500 years in both late glacial and Holocene. That finding suggested that the cycle pacing of about 1500 years is independent of the climate state (glacial and interglacial).

2) Documented a close connection between proxies for changes in solar activity (fluxes of atmospheric 14C as measured from tree ring data and 10Be as measured in polar ice cores) and a much higher resolution record of Holocene variability in the North Atlantic than previously published. Cycles with both multi-centennial (400 to 500 years) and millennial (900 to 1100 years) duration were identified. Cold phases of those cycles correlated with reductions in solar activity. The range in cycle variability of the millennial cycle falls within the 1 sigma range of the 1500 year cycle, suggesting that in some way variations in solar activity might underlie both the Holocene and the glacial parts of the 1500 year cycle.

3) Analyzed sediment from sediment traps moored beneath the main routes of sea ice leaving the Arctic Ocean via Fram Strait (in collaboration with Eduard Bauerfeind of the Alfred Wegener Institute). These analyses have demonstrated that sediment-bearing multi-year sea ice carries large amounts of lithic grains in the size range taken in most studies as glacier derived IRD. In addition, around 20% of the sea ice-borne lithic gains are stained with hematite, suggesting that the Arctic is the ultimate source of the hematite-stained grain signal we have identified in the subpolar N. Atlantic and correlated with proxies of solar variability.

Wally Broecker

1) Demonstrated that an empirical algorithm based on the shell weights of planktonic foraminifera used in previous studies to estimate past changes in the carbonate ion concentration in deep waters suffers from overprints caused by other environmental factors. Proxy records to reconstruct past changes in the carbonate ion content of deep waters have long been sought by paleoceanographers as a strategy to constrain the mechanism(s) by which ocean processes have regulated climate-related changes in the carbon dioxide concentration of the atmosphere. All such proxy methods have been found to suffer from artifacts. Future work will examine ecological factors that influence the thickness and weight of foraminifera shells to determine whether or not there is any promise in pursuing this method further.

2) Identified highly-discordant radiocarbon ages in samples of monospecific planktonic foraminifera taken from a common sediment sample. Samples taken from different species are expected to give the same age within analytical uncertainty, yet radiocarbon ages for different species sometimes differed by in excess of 1000 years. Uncertainties this large make it impossible to correlate millennial-scale climate features recorded in different marine sediment cores. Therefore, it is vital that the cause of these discordant ages be identified, and that a method to overcome the discrepancies be found. Ongoing work is directed toward resolving this problem.

George Denton (University of Maine collaborator)

1) Completed glacial-geologic maps of the McKenzie Basin of New Zealand's Southern Alps, which were then digitized at the Crown Institute of Geological and Nuclear Sciences (IGNS) in Dunedin, New Zealand. These maps have now been posted on an IGNS website (http://wyvern.gns.cri.nz/website/csigg/) for review and possible correction by all interested New Zealand geologists. They now form the basis for all associated paleoclimatic studies in New Zealand, including palynology, chironomids, and equilibrium-line attitudes (ELA's).

2) Calculated former ELA's in the Ben Ohau Range of the Southern Alps. When combined with radiocarbon and exposure-age dates (in progress), the timing and amplitude of snowline changes in the southern hemisphere will be compared to contemporary features in the northern hemisphere to elucidate the mechanisms underlying past climate change.

3) Identified a late-glacial readvance in the Argentine Lake District, dated at 11,150 radiocarbon years before present.

Sidney Hemming/Steve Goldstein

1) Identified a stunning correlation between the isotopic composition of neodymium held within the authigenic fraction of sediments in the SE Atlantic Ocean and the temperature record held within Greenland ice cores. This correlation is found to hold throughout the past 60,000 years. Changes in neodymium isotope composition are interpreted to reflect changes in formation of North Atlantic Deep Water, which carries a distinct neodymium isotopic signal. This information, in turn, helps to understand the linkages between ocean circulation and abrupt climate change.

2) Characterized the strontium and neodymium isotopic composition of lithogenic material throughout the South Atlantic Ocean to use the isotopic compositions of these phases as a proxy for their provenance. Climate-related changes in the isotopic composition of lithogenic phases is observed in South Atlantic sediment cores. Combined with the new provenance information, these records will aid in reconstructing past changes in ocean currents that delivered the sediment to the core sites.

Jean Lynch-Stieglitz

1) Demonstrated, using various proxies for sea surface temperature, that both zonal and meridional temperature gradients in the equatorial Pacific Ocean were lower than today during the Last Glacial Maximum. These findings are interpreted to indicate weakened Hadley and Walker circulation, a southward shift in the Intertropical Convergence Zone, and a predominant El Nino-like pattern in the equatorial Pacific Ocean during the LGM.

2) Documented an early and mid-Holocene cooling in the eastern Pacific cold tongue suggestive of a predominant La Nina-like pattern with enhanced sea surface temperature gradients and strengthened Trade Winds.

CORC-ARCHES TOPICAL CONFERENCES

TITLE	**DATES** Start	End	**Attendance Estimate**	**NOTES**
Deep-Sea Carbonate Dissolution	8/30/99	8/31/99	40-50	
The Role of Sea Ice in Present and Past Southern Ocean Climate Variability	9/23/99	9/25/99	90-100	Annual Meeting
Little Ice Age Miniconference	3/30/00	3/31/00	50 -60	
Southern Ocean	8/24/01	8/24/01		Mainly LDEO & Princeton PIs as participants
Heinrich Events	10/11/01	10/12/01	50-60	It was a great success and resulted in one publication (Broecker and Hemming, *Science*, December 14, 2001)
Ocean and Climate Linkages between the Southern Ocean and the Tropics	11/26/01	11/28/01	75-100	Annual Meeting
Surface Exposure Dating in Modern Earth Sciences	3/17/02	3/19/02	20-30	
Workshop on Marine CaCO3 Cycle	10/24/02	10/25/02	40-50	
Reorganization of Atmsopheric Circulation as a Cause of Abrupt Climate Change	11/6/02	11/8/02	75-100	Annual Meeting
PLIocene Workshop	3/19/03	3/21/03	30-50	Co-sponsored with the Climate Center
Sea Level Miniconference	10/22/03	10/23/03	40-50	

CORC-ARCHES VISITOR PROGRAM