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Towards Predictability and Predictions

by David M. Legler, Director

One of the core objectives of CLIVAR is predictability and predictions, i.e. characterizing elements of the coupled climate system that are predictable, identifying sources of predictability, and improving our capabilities to predict climate variability on seasons and longer. Much of the research that contributes towards CLIVAR addresses this objective. From teasing out mechanisms that bring about coupled variability to the testing of new prediction system elements, collectively, the CLIVAR predictability/prediction research enterprise must recognize a critical measure of success is the transferal of insight and practical knowledge so it can more effectively be considered and tested in forecast systems used for the routine production of climate forecasts, information, and products. These forecasts and climate information products have inherent value to decision-makers. In this era of increased demand on research programs to demonstrate value by contributing to the decision-making and policy-making processes, it is critical we consider the needs for climate prediction

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The Evolution of the Weak El Niño of 2004-2005

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El Niño episodes differ from one another not only in their relative strengths, but also their seasons of onset, maturity, and demise, as well as the location of their maximum SST anomaly within the tropical Pacific. The peak SST anomaly at the warmest location in the tropical Pacific during an El Niño may exceed 5˚C, as was the case in the great 1997-98 episode, or be only near 2˚C, as in the 1994-95 episode. Of course anomalous SSTs in the tropical Pacific are only one manifestation of El Niño, a phenomenon that owes its existence to the interaction, or coupling, between the ocean and atmosphere. Observational evidence suggests that most El Niño events can be identified by tropical Pacific SST anomalies alone when the latter are of sufficient magnitude, duration, and spatial extent as to likely indicate this coupling is occurring, which, in the atmosphere is revealed through characteristic (and therefore, expected) changes in low level-winds, large-scale shifts in tropical convection and surface pressure patterns, etc. The most recent event, which recently returned to neutral, was weak enough and "non-standard" enough that many experienced oceanographers and climatologists question whether it should be regarded as an El Niño event at all. The answer to this depends upon one's definition, and the issue of an acceptable definition remains nearly as elusive today as it was 10 years ago. In this short piece we examine some aspects of the recent episode's evolution, looking in particular for signs that it was, or was not, an El Niño in terms of what most of us have come to look for in one.

Current predictive capability for the onset of El Niño is still relatively modest, particularly for the onset of weak events, due to a number of factors related to an El Niño's initiation.

The onset of El Niño often occurs during the months of April through July, a period immediately following the time of year when the eastern tropical Pacific normally has its warmest SST. As an El Niño begins, the usual seasonal decline of SST in that part of the Pacific is weakened, and in a very strong El Niño may be nonexistent. El Niño usually matures toward the end of the calendar year, and dissipates during the first five months of the following year for a total lifetime of 8 to 13 months. Current predictive capability for the onset of El Niño is still relatively modest, particularly for the onset of weak events, due to a number of factors related to an El Niño's initiation.

Since El Niño involves coupled interactions between the ocean and atmosphere in and around the tropical Pacific, commonly used definitions tend to be based either on an atmospheric manifestation

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information.

In a previous issue of Variations, experts explored the relative merits of current approaches to predicting El Niño SST anomalies and described the advent of NCEP's Climate Test Bed. In this issue we delve into the somewhat surprising evolution of the recent El Niño and look into how marine ecosystems are impacted by ENSO variability.

As many in the climate research community are aware, U.S. CLIVAR is in the midst of reorganizing. This reorganization will allow US CLIVAR to

- **be more responsive to research agency and US Climate Change Science Program strategic objectives,**
- **stimulate a balanced climate research agenda, and**
- **engage the wider scientific community in pursuit of CLIVAR objectives.**

The details of the reorganization are available on the U.S. CLIVAR web site (http://www.usclivar.org) and are described elsewhere in this issue. In order to provide input to the newly established committees, we seek comment from the community via our web-page. We particularly seek thoughts on the most critical scientific foci these groups should concentrate their efforts towards. The new committees will hold their first meetings in mid-August. Look for reports on these critical meetings in early fall.

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The Evolution of the Weak El Niño of 2004-2005

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(e.g. the Southern Oscillation Index [SOI]—the difference in sea level pressure between Tahiti, French Polynesia and Darwin, Australia) or an oceanic manifestation (e.g. the average SST in an equatorially centered rectangular region such as NINO3 or NINO3.4). There have been attempts to define El Niño using a set of variables from both atmosphere and ocean (e.g. the Multivariate ENSO Index [MEI]). Usually, if an El Niño does not begin to develop by the end of July, it is fairly unlikely to develop during that entire annual cycle, but may do so during April through July of the following year. Occasional exceptions have occurred when an El Niño emerged in August or even September, as for example in 1986. In 2004 the onset of anomalous SSTs of sufficient magnitude as to be indicative of El Niño conditions occurred relatively late in the calendar year, and most climate forecasting centers had all but written off the possibility of one by the time it appeared during the last half of July. For example, in early July the U.S NOAA Climate Prediction Center's ENSO Diagnostic Discussion said "ENSO-neutral conditions are expected to continue for the next 3 months", and the Australian Bureau of Meteorology likewise indicated that the continuation of neutral conditions was most likely. Two weeks later in mid-July, even as the NINO3.4 weekly SST anomaly first exceeded 0.5˚C, the IRI forecasted a 40% probability for El Niño later in the year, a 55% probability for neutral conditions, and 5% for La Niña. In August, all three forecast centers acknowledged that the current instantaneous SST conditions had moved into a range which, if sustained over several months, could likely later be called El Niño SST conditions.

> **…to many people in ENSO-impacted regions, El Niño refers historically to their local El Niño-associated climate condition rather than to the physically governing conditions in the tropical Pacific Ocean.**

The El Niño phenomenon is characterized by mutually enhancing feedbacks between the ocean and the overlying atmosphere, which often keep the episode alive for the better part of one year. Most basically, this feedback involves a close interplay between the SST anomalies along the equatorial Pacific, and the wind and sea level pressure anomalies over that region, such that waxing and waning of the trade winds is associated with mutually reinforcing changes in SST.

Some key factors in the evolution of the 2004-05 El Niño, and the somewhat stronger 2002-03 El Niño, are shown in figure 1. The 2002-03 El Niño was stronger, as shown by the fact that the SST anomalies exceeded 2.5˚C near 170˚W longitude in October 2002, while the anomalies during the 2004-05 El Niño exceeded only 1.5˚C near the dateline in late October and early November 2004. Perhaps more important than the relative strengths of the SST anomalies was that the area of SST exceeding 1°C during 2004-05 never expanded eastward of about 140°W except very briefly in late July when the warming initially developed. Related to this marked limitation to the central Pacific was the fact that the zonal wind anomalies were limited in much the same way, such that the trades were hardly weakened in the eastern Pacific except for a few very short-lived intervals. Westerly wind anomalies were somewhat more broadly observed during middle and late 2002, including an episode of eastward-expanded anomalies in May, preceding a general increase in oceanic heat content and finally a warming of the SST near and eastward of the dateline. Even the 2002-03 El Niño is considered to have been focused in the central, as opposed to east-central, tropical Pacific, and to have been only weak to moderate in intensity.

The zonal wind and heat content

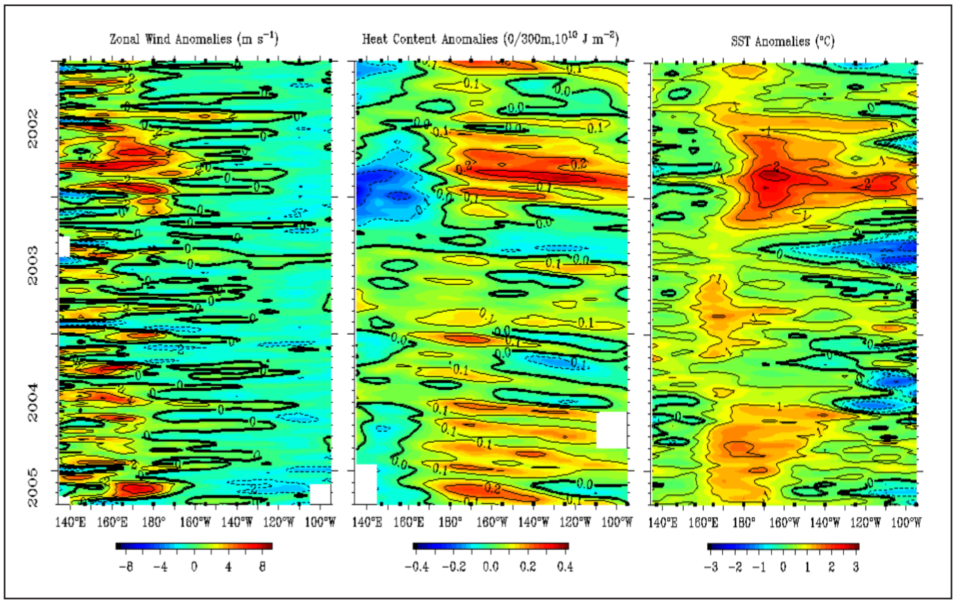

Fig. 1. Time-longitude cross sections across the tropical Pacific. From left to right, anomalies of zonal wind, upper oceanic heat content, and SST. Time marches downward from early 2002 to March 2005, capturing both El Niños. Longitude spans from Indonesia (left side) to somewhat offshore of South America (right) in each panel. Data from TOGA/TAO.

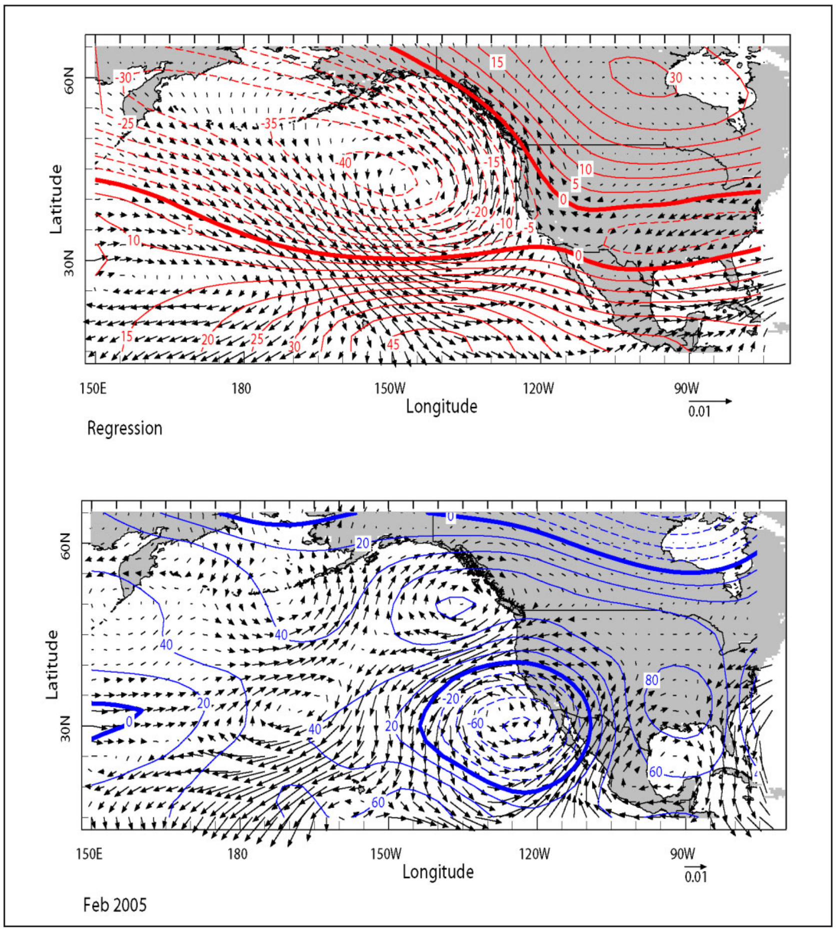

Fig. 2. Top panel: Regression of integrated moisture flux (vectors) and geopotential height anomalies (red contours) onto the NINO3.4 SST index for DJF (1950-1996). Bottom panel: Anomalous moisture flux (vectors) and geopotential height anomalies (blue contours) for February 2005. Data from NCEP-NCAR Reanalysis.

anomalies during the 2004-05 El Niño appear as individual pulses of approximately one month (or less) duration rather than as continuous and broad anomalies as were observed in stronger El Niños such as those of 2002-03 and even more so in still stronger ones. This wave-like feature may be related to the El Niño being supported largely by the westerly wind events associated with the MJO rather than by the slower-acting physics related to a progressive accumulation of anomalous heat in the near-equatorial water volume west of the dateline. While the MJO may play a role in initiating many El Niños, in most cases its role is thought to be catalytic rather than basic. In 2004-05, all three of (1) significant westerly wind anomalies, (2) marked increases in SST, and (3) anomalous convection were limited to near and somewhat westward of the dateline, as opposed to expanding farther eastward through positive feedbacks as observed in more typical El Niño events. Throughout most of the second half of 2004, although the NINO3.4 SST index was high enough to qualify as a weak El Niño, the NINO3 SST and the SOI indices did not differ sufficiently from neutral to categorize the 2004-05 event as an El Niño event. Indeed, due the lack of atmosphere-ocean coupling, only a few of the typical climate teleconnections were observed during the last quarter of 2004 and January 2005—such as below normal rainfall in much of Indonesia and the Philippines, and in part of southeastern Africa and Central America. Earlier, a below average Indian monsoon had occurred just as the Pacific SST was increasing to a weak El Niño level. In February 2005, anomalous convection finally did appear, and strongly, near and just east of the dateline—and the SOI dipped to very low levels just for that month (in fact, reaching its lowest level since the 1982-83 El Niño, and resulting in misleading negative values in running averages of the index). Ironically, the NINO3.4 SST anomaly had returned to neutral levels during February, so that in no month were both the SOI and the NINO3.4 SST above standard El Niño-indicating thresholds. The occurrence of anomalous convection during February and the first 1 to 2 weeks of March was sufficient to induce some global climate impacts that had been absent before

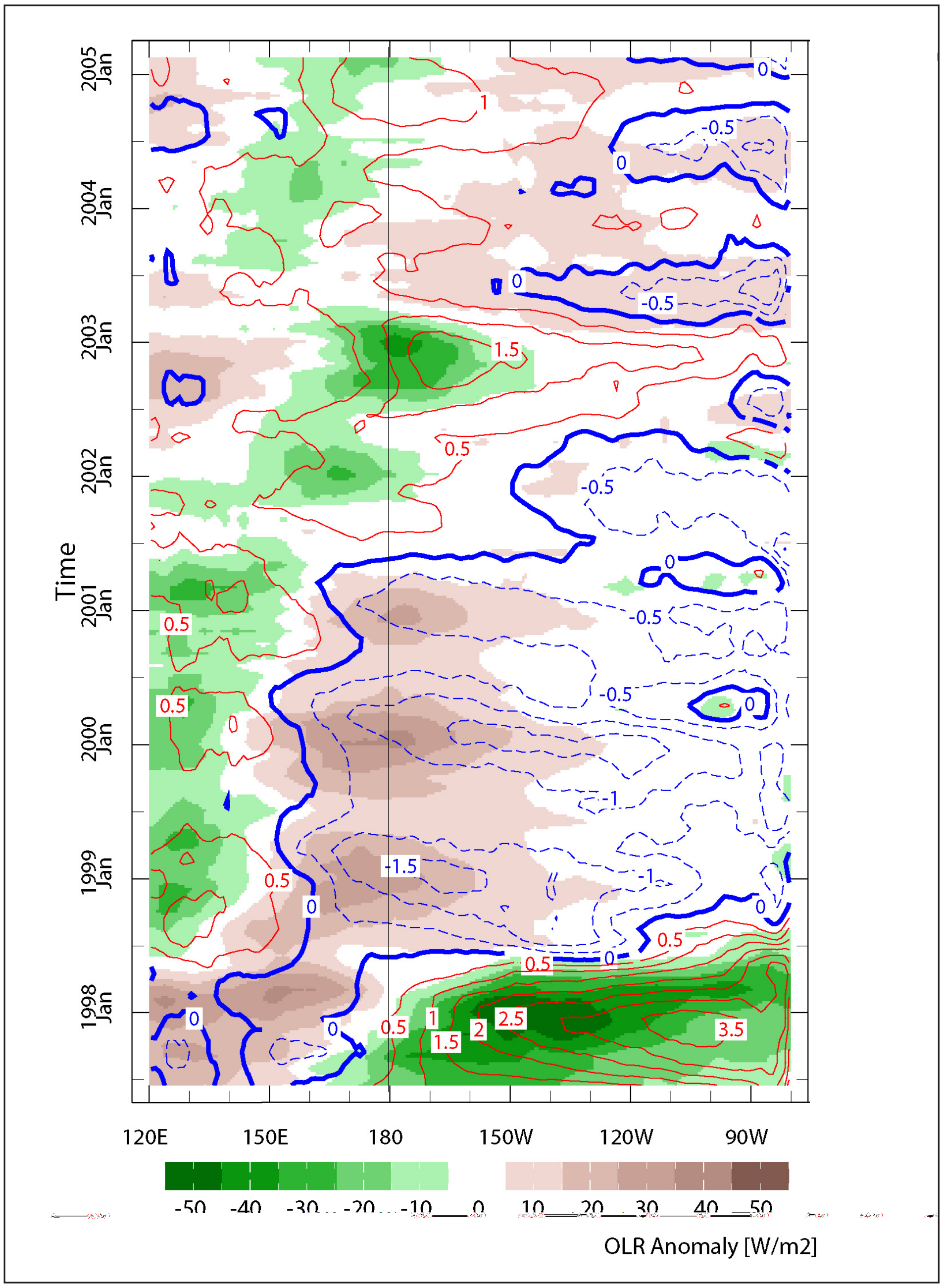

Fig. 3. Longitude-time section of the equatorial Pacific (5S-5N) of anomalous SST (contours) and OLR (shading). Time increases from bottom to top. Corresponding time series of the SOI is shown on the right for both monthly values (bars) and the 5-month running average (line).

February: marked dryness in eastern Australia, deficient rainfall in much of southeastern Africa, a dry start to the rainy season in northeastern Brazil, and heavy rains farther east in the central tropical Pacific itself such as in Nauru and western Kiribati. Heavy rainfall in the southwestern and southern U.S. appears to have been associated with a longwave pattern more reminiscent of a constricted negative PNA-like pattern (Fig. 2, bottom) than the typical, more zonally extensive response to El Niño (Fig. 2, top). Thus, it may have been related more to extratropical processes than to the warmed central tropical Pacific.

The fact that there were no months during which both ocean and atmosphere exhibited El Niño behavior raises the question of whether the 2004-05 episode can be called an El Niño, and whether an appropriate definition of El Niño should involve more than an oceanic index alone or an atmospheric index alone—given that the two usually, but not always, behave consistently due to the coupling process described above. The choice of what index to use for either medium alone presents an additional challenge. In the 2004-05 event, for example, the NINO3.4 SST index held within the weak El Niño range for at least 6 months, but NINO3 did so for only 1 to 2 months. This lack of agreement between SST indices stems from the fact that the strongest SST anomalies were located slightly west of the dateline—quite atypical of an El Niño. There is also choice in the selection of an atmospheric index, as for example the standard Tahiti minus Darwin SOI versus the equatorial SOI. In February 2005, while the standard SOI was very low, the equatorial SOI was much closer to average. Many of these features are exemplified in Fig. 3, a longitude-time section of SST and OLR anomalies (with a 3-month running average applied) for the equatorial Pacific. A time series of the monthly, and a 5-month running average SOI, is also indicated.

In conclusion, the categorization of 2004-05 as a weak El Niño depends on one's definition. The choice of definition, in turn, may depend on which aspects of El Niño create climate responses in the country or region in question. Taking this idea even farther, to many people in ENSO-impacted regions, El Niño refers historically to their local El Niño-associated climate condition rather than to the physically governing conditions in the tropical Pacific Ocean. Because of these differences in understanding, developing a single definition for El Niño remains a complex challenge. Region IV of the WMO has recently adopted NOAA's definition of El Niño[1], a definition that is subject to future revision based on further scientific research. ■

[1] The definition is based on the SST in the NINO 3.4 region (a rectangle covering 120-170°W longitude, 5°N-5°S latitude) being at least 0.5 degrees C above normal, when averaged over three consecutive months. The NINO3.4 region has been previously used to define the ENSO state (Trenberth 1997; BAMS, 78, 2771-2777), and its close connection to the core ENSO phenomenon and its global climate effects has been demonstrated (e.g. Barnston et al. 1997; Atmos. Ocean, 35, 367-383).

El Niño Impacts on the California Current Ecosystem

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1. Introduction

With the recognition that marine populations respond to climate variability, and that climate events such as El Niño (EN) impact the production and distribution of fish stocks in a complex interaction with fishing pressure, NOAA Fisheries scientists and their colleagues have made research in understanding these links a priority. An important facet of EN prediction is the improved ability to anticipate its social and economic consequences, including impacts on fisheries and marine ecosystem productivity.

It was initially believed that EN was principally a tropical phenomenon, and that its ecosystem impacts were limited to near-equatorial waters off western South America. After the 1957-58 EN, scientists began to link a number of major shifts in marine populations in the California Current regional marine ecosystem (CC) to this event (Sette and Isaacs 1960). This was possibly the first time that EN was recognized as a global phenomenon with widespread ecological consequences. At this same time, scientists realized that past EN events had also disrupted the CC ecosystem.

2. The Physical Response of the California Current to El Niño

The physical response of the North Pacific and the CC to EN has been widely documented (Chelton et al. 1982; Emery and Hamilton 1985; Wooster and Fluharty 1985; Mysak 1986; Chavez et al., 2002 and papers therein). From an ecosystem perspective, the primary physical factors of importance are those affecting general biological productivity and availability of food, aggregation for schooling and reproduction, larval dispersal, barriers to migration, physiological effects of extreme conditions, and changes in species composition and interactions.

Figure 1 illustrates how some of these factors have changed during the major EN events of the past half-century. The upper water column warms by 2-3°C during most ENs. The thermocline, an indication of vertical stratification, strengthens and deepens. These are reflections of weaker coastal upwelling, less wind mixing, and a compensating adjustment in alongshelf transport that results in less southward flow, which leads to further warming. Coastal Kelvin waves that may be connected to equatorial Kelvin waves will also contribute to a depressed thermocline during some events.

An important facet of El Niño prediction is the improved ability to anticipate its social and economic consequences, including impacts on fisheries and marine ecosystem productivity.

These changes in water column structure are not the same for each EN event, nor are the ambient conditions the same at the time of each event. There has been a significant trend since 1950 towards enhanced stratification and a deeper thermocline along the California coast (Figure 1; Palacios et al. 2004), as part of a long-term warming trend and subsequent reduction in biological productivity of the CC (Roemmich and McGowan 1995). EN events are impacting the CC against this backdrop of low-frequency climate variability.

3. The Ecosystem Response

Since coastal upwelling is a dominant physical process in the CC and one that is responsible for the system's high biological production, EN influences such as reduced upwelling-favorable winds and stronger vertical stratification will reduce nutrient input to surface waters and lower plankton biomass (Kahru and Mitchell 2000; Bograd and Lynn 2001), and alter production and distribution of many important fish stocks and marine mammals (Sette and Isaacs 1960; Wooster and Fluharty 1985; Chavez et al. 2002; and papers therein).

EN typically means warmer water, which accelerates growth in some species, such as California sardine, but lowers the reproductive capability of rockfish, squid and other species that prefer cooler temperatures. Marine mammal and bird populations are also stressed by warm conditions and reduced food availability, leading to reduced reproduction, starvation and mass mortality of young. EN conditions also create a northward and onshore extension of the range of many populations, including tropical species such as giant squid, barracuda and tunas uncommon to the northern portion of the CC. Highly migratory trans-Pacific pelagic fish, including albacore and other tuna varieties, extend their range and concentrate near the coast, where they prey upon nearshore species, but become easier prey themselves for fishers.

In most EN events, the southward surface transport of the CC is reduced, in part because of geostrophic adjustments to higher coastal sea level. Northward flow of the deeper California Undercurrent over the continental slope is increased, which

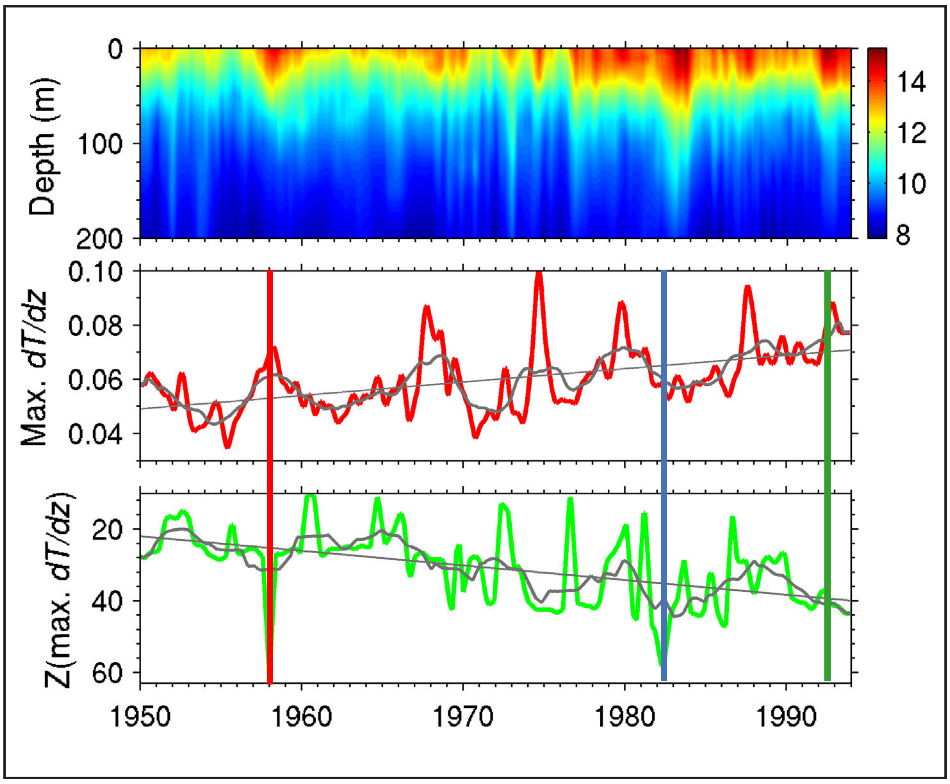

Figure 1: (top) Monthly time series of 0-200 m temperatures from a 1° box centered at 36.5°N, 123.5°W in the California Current. Monthly time series of (b) maximum dT/dz (°C m^{-1}) and depth of the maximum dT/dz (m) derived from the temperature series. The temperatures in (top) are the modeled trend component from a state-space decomposition of observed temperatures from the World Ocean Database (Palacios et al., 2004). Colored curves (bottom) are the monthly series, dark gray curves are the 37-point running averages, and thin gray lines are the regression of each variable on year. Vertical lines mark the approximate times that the El Niño events of 1957-58, 1982-83 and 1991-92 impacted the California Current.

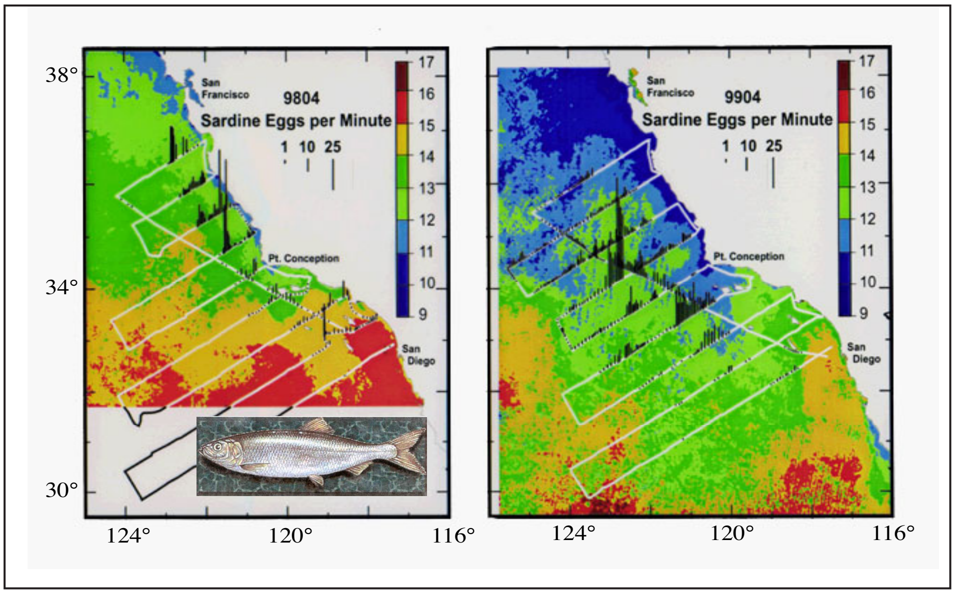

Figure 2: Stick plots of California sardine egg counts per minute from the Continuous Underway Fish Egg Sampler (CUFES) deployed on the (a) April 1998 (El Niño conditions) and (b) April 1999 (La Niña conditions) CalCOFI cruises off southern California, overlaid on satellite-derived sea surface temperature. Adult sardine shown in inset. Courtesy of Ron Lynn and the NOAA Southwest Fisheries Science Center.

may lead to the introduction of unusual warm-water planktonic species to the CC region. These include warm-water krill, pelagic red crab, sedentary bottom-dwelling fishes, and many fish larval and juvenile stages. This anomalous along-shelf advection is a very different process than the warming of surface waters. Because these two processes may not occur in the same EN, the populations they affect will be more influenced during some events than others.

EN effects can be conflicting. For example, the sardine spawning habitat, which is generally defined as the region where SST > 14°C, increased during the 1997-98 EN (Figure 2). However, unusually weak coastal upwelling, indicated by the reduced area of cool SST, led to less food for adults and poor egg production. Record upwelling in 1999 contributed to elevated sardine egg production, despite the more offshore displacement of warmer water. Because of this correspondence between ocean temperature and production, the annual fishery quota of the California sardine is set in part upon recent SSTs. Improving our understanding about climate variability and its biological impacts will allow more examples like the sardine to be incorporated into resource management.

If a consistent relationship between the physical state of a particular El Niño and its ecological response can be found, then we will be able to project which populations are more likely to be affected by future El Niños, thus improving our understanding of climate-ecosystem linkages and the management of living marine resources.

4. Variability between Individual El Niño Events

The CC has a well-documented history of large biotic fluctuations during EN events. However, individual EN events appear to impact specific populations or ecosystem components differently. Recent analysis of the spatial and temporal variability of temperature has identified three dominant types of EN signals in the CC.

The temperature time series in Figure 3, representing the meridional, offshore, and vertical extent of the CC for 1950-93, demonstrate that EN signals extend throughout the CC. They also reflect some of the distinctions between individual El Niño events. These series illustrate the findings of a systematic analysis of upper ocean temperature variability (Mendelssohn et al. 2003) that identified three characteristic patterns of El Niño influence. El Niño events cluster into three distinct patterns with the strongest warm anomalies occurring in the shallow/equatorward, shallow/poleward, and deep/equatorward regions of the CC. Each type is represented by one of the three strongest tropical EN events over this period; 1957–58, 1991–92, and 1982–83, respectively. So, while the 1982-83 EN thermal signal was strongest in the upper thermocline and southern portion of the CCS, the 1991-92 signal was accentuated in surface waters over a broader geographical range. Individual La Niña signals are less spatially variable in the CCS.

These distinct EN types are also likely to have different biological impacts. Specifically, since populations separate spatially with ecosystems (e.g., vertically, meridionally, thermally) as well as temporally (e.g., timing of migration and reproduction), organisms in those regions and times most strongly influenced by a particular EN may also be most impacted. If a consistent relationship between the physical state of a particular EN and its ecological response can be found, then we will be able to project which populations are more likely to be affected by future ENs, thus improving our understanding of climate-ecosystem linkages and the management of living marine resources.

While a comprehensive analysis of the ecosystem response to different EN events is not complete, reports from past major ENs provides evidence that the different spatial physical patterns identified by Mendelssohn et al. (2003) have corresponding regionally distinct biological responses. The primary ecological impact of the 1982-83 EN, which was dominated by a strong thermocline signal and anomalous northward advection, was the northward displacement of coastal bottom-dwelling fishes. In contrast, the 1957-58 and 1997-98 events, which initially featured a broad upper ocean warming, were characterized by a major influx of strong swimming warm-water fish into the CC.

Finally, we must recognize that EN events occur upon longer-term climate

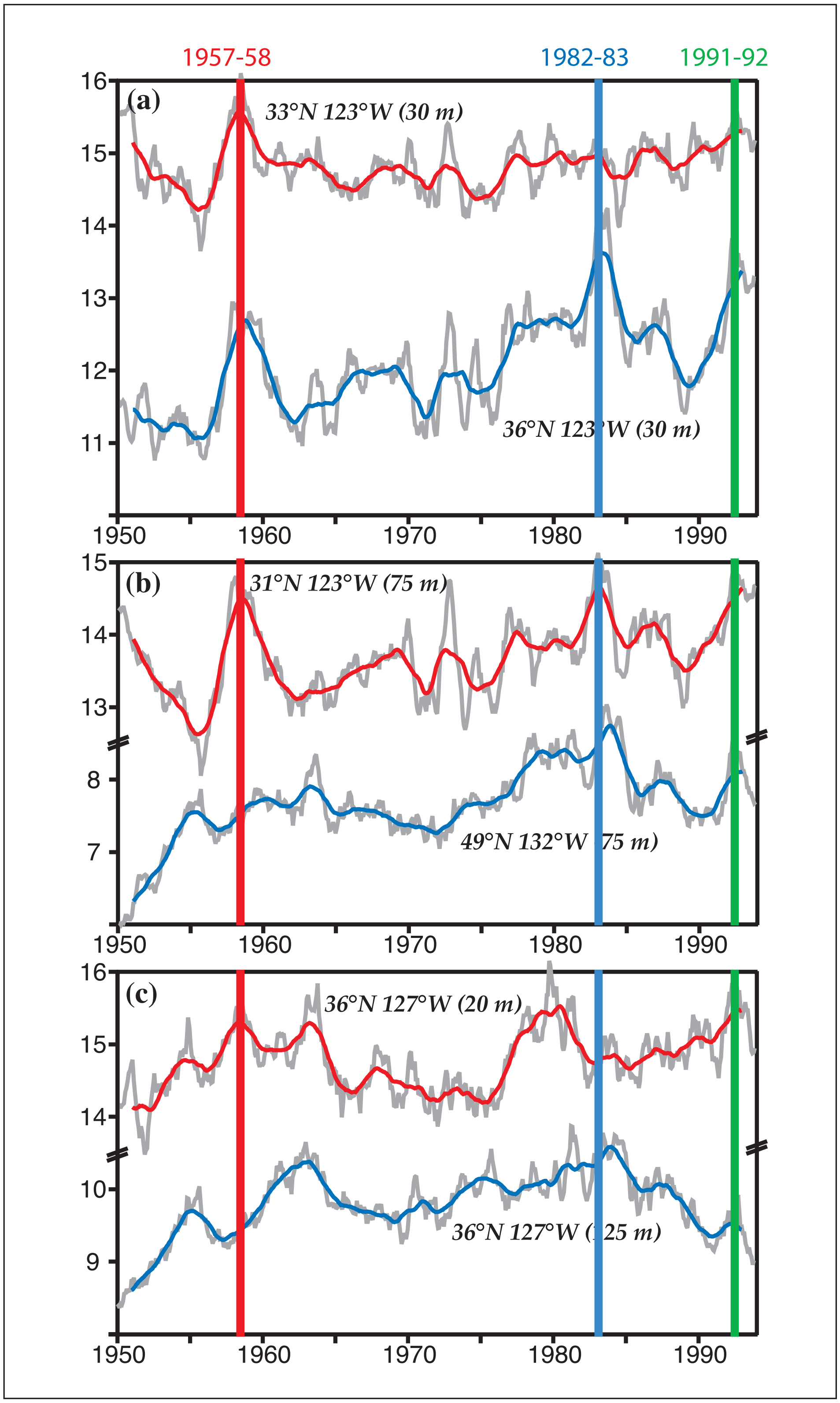

Figure 3: Representative long-term temperature trends from the California Current region derived from a state-space decomposition of observed temperatures from the World Ocean Database (Mendelssohn et al., 2003). These series illustrate the dominant spatial patterns from a common trend analysis of upper-ocean temperatures throughout the California Current: (a) the cross-shore pattern (36°N, 123°W and 33°N, 123°W at 30 m), (b) the alongshore pattern (31°N, 123°W and 49°W, 132°W at 75 m), and (c) the depth pattern (36°N, 127°W at 20 m and 125 m). Light gray curves are the monthly series, and colored curves are the trewess smoother. Vertical lines mark the approximate times that the 1957-58, 1982-83 and 1991-92 El Niño events impacted the California Current.

variability. Multi-decadal regime shifts in the North Pacific (Mantua et al. 1997) lead to extended periods of relatively stronger or weaker ENs, depending upon whether these events develop out of a background warm or cool north Pacific regime. The general warming trend of the past century has also resulted in an implied greater overall impact of recent EN events (Mendelssohn et al. 2005). Understanding the interactions between El Niño cycles and other climate variability, and predicting their combined future impact on marine ecosystems and fishery populations, would be an important activity for CLIVAR to consider. ■

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CLIMODE: a mode water dynamics experiment in support of CLIVAR

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1 Introduction

CLIMODE (CLIvar MOde Water Dynamic Experiment) is focused on a region of huge ocean to atmosphere annual-mean heat loss (>200 $W m^{-2}$) which occurs over the separated Gulf Stream in the North Atlantic. The region of most intense wintertime ocean heat loss corresponds to an area with relatively warm surface waters that are carried there by the Gulf Stream, Fig.1. Late winter SST's fall to approximately 18°C as water parcels move east under this cooling. The associated buoyancy loss from the ocean is believed to trigger ocean convection on the northern rim of the subtropical gyre to form what is known as Eighteen Degree Water (EDW) – Worthington (1959; 1976) – the North Atlantic Subtropical Mode Water. The wedge of weakly stratified water spanning temperatures between about 17°C and 19°C characteristic of mode water are clearly evident in the Gulf Stream section shown in Fig.2.

The region of EDW formation is particularly relevant to wider CLIVAR goals because, first, the annual mean ocean to atmosphere heat flux over the EDW formation region might be crucial for the maintenance of the Atlantic Storm track (Hoskins and Valdes, 1990). Second, EDW and the associated Gulf Stream recirculation and thermal structure is a key region where oceanic timescales can possibly imprint themselves on the atmosphere. Seasonal to interannual timescales are introduced by the thermal inertia of the ocean mixed layer/EDW layer system, whose evolution through the annual cycle is strongly connected to the re-emergence of SST anomalies from winter to winter (Alexander and Deser, 1995; de Coëtlogon and Frankignoul, 2003). On longer timescales the intensity and path of the Gulf Stream affects air-sea exchange and mode water formation through interannual variations in low-frequency flow as well as lateral eddy heat fluxes – Marshall et al (2001), Czaja and Marshall (2001), Dong and Kelly (2004). How exactly such oceanic influences on climate work is a subject of great importance, controversy and subtlety. Finally, CLIMODE should also be seen as making an important contribution to tying down the basin scale air-sea heat budget and, by implication, quantifying the meridional transport of heat in the Atlantic basin.

CLIMODE is motivated by the fact that there is presently a major disconnect between the best available estimates of EDW formation rates based on air-sea fluxes and what we (think we) know about likely dissipation rates. Either our air-sea flux estimates are grossly in error and/or there is 'missing physics' involved in the basic mechanism of mode water formation, which is not represented in our models. CLIMODE is designed to get to the bottom of this conundrum. A prime candidate for the missing physics is lateral, diabatic exchange through the mixed layer by mesoscale eddy processes which, we argue below, play an order one balance in the buoyancy budget.

Our working hypothesis in CLIMODE is that the onset of late winter convection, when combined with Gulf Stream heat transport, intensifies the meridional slopes of near surface isopycnals, resulting in an explosion of baroclinic instability in the ocean. The northward heat flux so generated is envisioned as balancing much of the heat loss due to air-sea interaction as sketched in Fig.3 (right). In ocean climate models which do not resolve the eddies, this process must appear as some sort of eddy advective/diffusive transport directed laterally through the mixed layer. But it is not yet at all clear how to parameterize this process.

As the ocean surface is approached, eddy fluxes must develop a diapycnal component because density is maintained vertically homogeneous by strong surface boundary layer mixing whilst, as sketched in Fig.3 (left), largescale eddying motions are constrained to be horizontal by the upper boundary. We call this transition layer between the mixed layer and the adiabatic interior, in which isopycnals are intermittently in contact with the turbulent mixed layer, the 'surface diabatic zone'. We believe that this zone is likely to play a key role in mode water formation and dissipation. It is a key focus in CLIMODE.

The evidence that lateral eddy fluxes play an important role in the dynamics of the upper ocean has only recently come to the attention of the modeling community. It was in recognition of the importance of near-surface mixing in climate models that the Climate Process Team (CPT) EMILIE (EddyMIxed-Layer Interactions–see the Emilie web site maintained by Raf Ferrari: http://cpt-emilie.org/) was set up to foster our understanding of the effect of transient eddy motions in the upper ocean and to develop parameterizations of these effects for IPCC-class climate models. CLIMODE's focus on the role of the surface diabatic zone in the cycle of mode-water formation provides a specific context in which the general issues of upper-ocean mixing can be addressed.

In this short article we briefly review the science questions that motivate CLIMODE and the observational and modeling plan designed to tackle it. In section 2 we return to the central conundrum of reconciling EDW formation and dissipation rates that is at the heart of our experiment. In section 3, we summarize the observational and modeling elements that have been brought together to tackle the problem. Contact information is in Section 4.

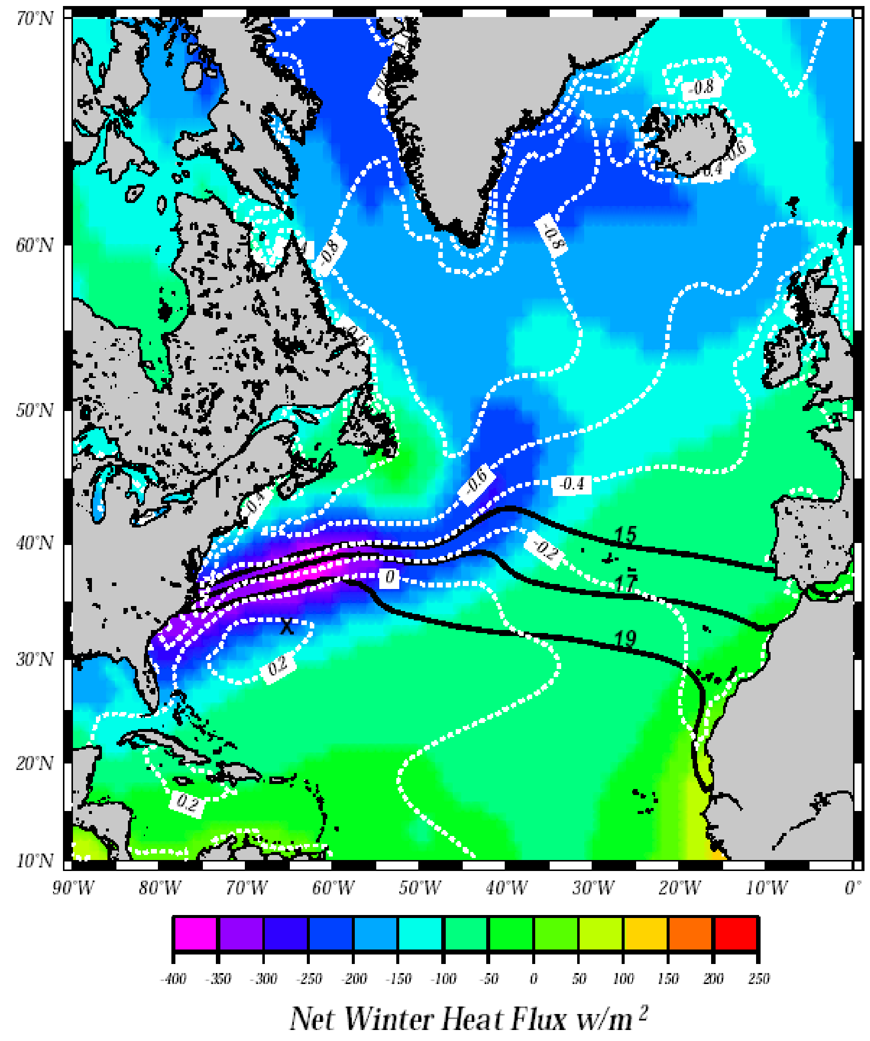

Figure 1: Wintertime net heat flux (colors in W/m^2– COADS), selected SST outcrops (black lines) and dynamic height field (dotted lines, provided by the ECCO data assimilation scheme using the MIT ocean model). The black cross marks Bermuda.

2 Reconciling EDW formation and dissipation rates

EDW is formed very close to or within the Gulf Stream where surface heat loss is large. Based on air-sea flux integrations using Walin's (1982) framework, Speer and

Tziperman (1992) estimated a formation rate of 15 to 20 Sv of EDW - see Fig.2 (right). The fundamental problem we are addressing is why this rate is so much larger than the order 5 Sv inferred from seasonal changes based on profiling floats (e.g. Kwon and Riser, 2005) and implied by thermocline diapycnal mixing rates.

2.1 The Walin framework

Walin considered the volume budget of an isopycnal layer outcropping at the sea surface, integrated across the ocean from one coast to the other, as sketched in Fig.3 (middle). He showed that even in a time-dependent, eddying ocean, A, the diapycnal volume flux across σ, could be expressed precisely in terms of the diffusive fluxes, 'D', acting across the surface of the control volume, and air-sea fluxes

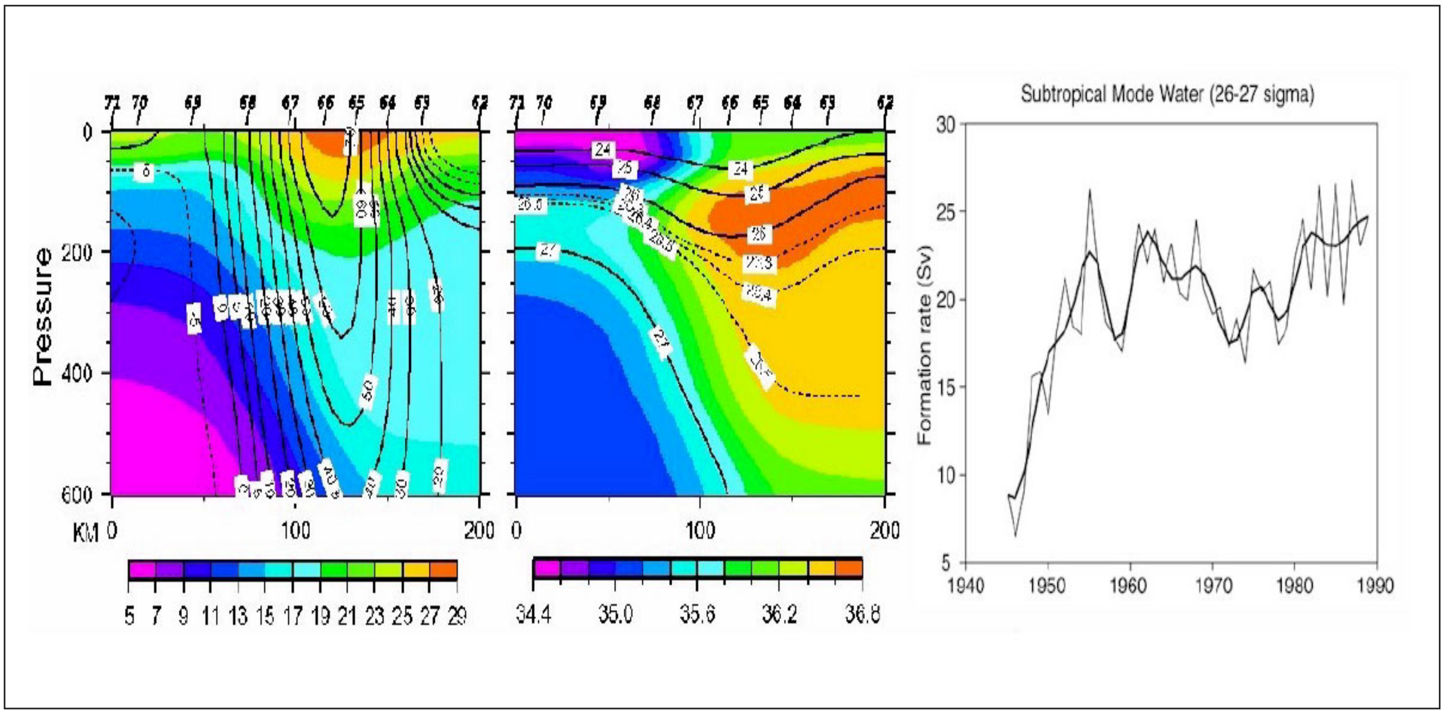

Figure 2: (left) Meridional section looking eastward across the Gulf Stream taken in the summer of 1997 using CTD & LADCP stations (station locations shown) along 66°W. Temperature and zonal velocity: contours in cm/s taken from Joyce et al, 2001a are shown, (middle) salinity and $\sigma\theta$ contours. (right) Annual average transformation rate $\partial F/\partial\sigma$ (in Sv) by air-sea fluxes in the $\sigma = 26 - 27$ range(thin); smoothed over 3 years (thick). From Speer (private communication, 2002).

'F', thus (using Garrett et al's (1995) terminology):

$$\underbrace{A}_{\text{diap vol flux}} = \underbrace{F}_{\text{air-sea flux}} - \underbrace{\partial D/\partial\sigma}_{\text{diffusive flux}} \quad \text{'transformation'} \quad (1)$$

(Fig.3: middle). Here:

$$F = \frac{\hat{B}}{\ } \text{ where } \hat{B}$$

is the integral of the air-sea buoyancy flux over outcrop windows. The Walin framework has been discussed and applied to water mass transformation in the recent review by Large and Nurser (2001).

The annual formation rate of EDW (in the density range 26–27σ) implied by climatological air-sea buoyancy fluxes alone (i.e obtained by neglecting mixing in Eq.(1), thus setting $A = F$, and computing the difference $A_{27} - A_{26}$) is some 15 to 20Sv - see Fig.2 (right). If the volume of EDW is to remain steady over long timescales this suggests that some 15Sv or so must be dissipated. However, the mixing-induced EDW loss in the interior is estimated, using mean values of an accepted diapycnal velocity, to be ~1.5Sv, an order of magnitude less than the transformation rate inferred from climatological outcrops and air-sea buoyancy fluxes.

2.2 The hypotheses to be tested in CLIMODE

The most likely possibility for the disconnect between estimates of mode water formation and dissipation rates described above are we believe: (a) neglect of eddy processes acting in the mixed layer in and near the Gulf Stream which result in significant lateral transport and (b) incorrect estimates of air-sea fluxes. We treat these briefly in turn.

a. Partial balance of air-sea buoyancy loss by lateral eddy processes.

As sketched in Fig.3 (right), in an eddying ocean lateral, diapycnal eddy buoyancy fluxes due to mesoscale variability, D_{eddy}, may balance a significant fraction of the air-sea buoyancy loss. Evidence for the likely role of eddies in EDW formation can be seen in the remarkable SST maps prepared by Kathie Kelly in Fig.4 (top). As the winter proceeds the entire region south of the Gulf Stream has eddying fluid in the range 18-19°C encroaching into warmer waters. An estimate of the diapycnal eddy term can be made, making some assumptions about eddy diffusivity and mixing volumes. Using the Levitus climatology and integrating over isopycnal areas, D_{eddy} is of the same order as, and of opposite sign to, the transformation implied by air-sea fluxes. Lateral eddy fluxes thus emerge as a candidate to abate our dilemma.

b. Uncertainties in evaluation of the formation rate, F.

The statistics of the air-sea buoyancy flux are likely to be highly variable in space and time, making computations of F based on climatologies somewhat problematical. Moreover F involves integrating buoyancy fluxes across outcrop windows which are also time-dependent - see Fig.4 (top). It is thus possible that the total 15-20 Sv formation number (based on climatologies) is itself not representative of the true formation rate implied by air-sea fluxes. Indeed, an independent measure of EDW formation rates was recently given by Kwon and Riser (2005) using WOCE float

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Calendar of CLIVAR and CLIVAR-related meetings

Further details are available on the U.S. CLIVAR and International CLIVAR web sites: www.usclivar.org and www.clivar.org

Seasonal to Interannual Climate Variability: its Prediction and Impact on Society - NATO Advanced Study Institute (ASI)

23 May – 3 June 2005
Gallipoli, Italy
Attendance: Open
Contact: Alberto Troccoli

AMS joint conference on Atmospheric and Ocean Fluid Dynamics, Middle Atmospheres and Climate Variability

13-17 June 2005
Boston, MA
Attendance: Open
Contact: www.ametsoc.org

Pan WCRP Monsoon Workshop

15-17 June 2005
Irvine, CA
Attendance: Invited
Contact: icpo@soc.soton.ac.uk

International GEWEX Workshop

20-24 June 2005
Orange County, CA
Attendance: Open
Contact: www.gewex.org/5thconf.html

10th Annual CCSM Meeting

21-23 June 2005
Breckenridge, CO
Attendance: Limited
Contact: www.ccsm.ucar.edu

Modes of Variability in the Southern Ocean Region

27-28 June 2005
Cambridge, United Kingdom
Attendance: Invited
Contact: www.clivar.org

"The Ocean Carbon System: Recent Advances and Future Opportunities" An Ocean Carbon and Climate Change Workshop

1-4 August 2005
Woods Hole, MA
Attendance: Open
Contact: www.ioc.unesco.org/ioccp

The International Association of Meteorology and Atmospheric Sciences (IAMAS) Biennial Scientific Assembly

2-11 August 2005
Beijing, China
Attendance: Open
Contact:
http://web.lasg.ac.cn/IAMAS2005

PAGES 2nd Open Science Meeting

10-12 August 2005
Beijing, China
Attendance: Open
Contact: http://www.pages2005.org

U.S. CLIVAR Summit

15-18 August 2005
Keystone, CO
Attendance: Invited
Contact: www.usclivar.org

Joint assembly of the International Association of Geodesy, International Association for Physical Sciences of the Oceans and the International Association for Biological Oceanography

22-26 August 2005
Cairns, Australia
Attendance: Open
Contact: info@dynamicplanet2005.com

CLIVAR/OOPC/GOOS/ARGO Workshop on the South Pacific

11-14 October 2005
Concepcion, Chile
Attendance: Limited
Contact: CLIVAR Office
(icpo@soc.soton.ac.uk)

Tropical Atlantic Variability Workshop

17-19 October 2005
Venice, Italy
Attendance: Invited
Contact: Paola Malanotte-Rizzoli
(Rizzoli@mit.edu)

CRCES Workshop on Decadal Variability

17-20 October 2005
West Virginia, USA
Attendance: Open
Contact: http://www.crces.org

NOAA Climate Diagnostics and Prediction Workshop / Climate Test Bed Meeting

24-28 October 2005
State College, Pennsylvania
Attendance: Open
Contact: www.cdc.ncep.noaa.gov

AGU Fall Meeting

5-8 December 2005
San Francisco, CA
Attendance: Open
Contact: http://www.agu.org/meetings/

13th Ocean Sciences Meeting, a joint meeting of ASLO, TOS and AGU

20-24 February 2006
Honolulu, HI
Attendance: Open
Contact: http://www.agu.org/meetings/

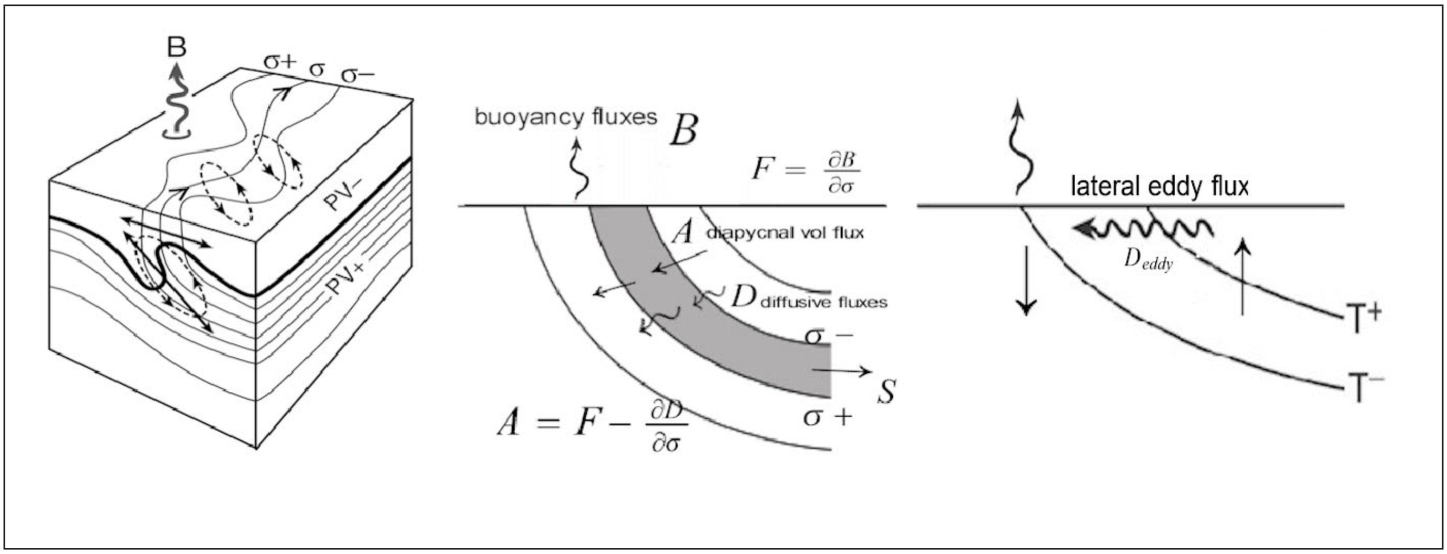

Figure 3: (Left) Schematic diagram showing the interaction of a mixed layer (low PV) and the stratified interior (high PV) in a strong frontal region with outcropping isopycnal surfaces, σ, undergoing buoyancy loss, B. Eddies forming along the front play a central role in controlling horizontal fluxes through the mixed layer and two-way quasi-adiabatic exchange between the mixed layer and the interior. (Middle) Application of the formalism due to Walin (1982): lateral diapycnal volume flux, A, whose divergence drives subduction, is related to 'diffusive' fluxes, D, acting across the boundary of the shaded control volume (which includes small-scale and diapycnal eddy fluxes) and air-sea buoyancy fluxes acting across the upper surface, $F = \partial B/\partial\sigma$. (Right) Air-sea buoyancy loss triggering convection and EDW formation may be largely balanced by lateral diabatic eddy fluxes associated with mesoscale variability seen in Fig.4 (top). The sense of the eddy-induced flow in the ocean is also marked.

Continued from Page 10

data by monitoring the seasonal cycle of low PV waters. From the autumn to spring volume difference, the implied annual EDW production rate is 7.3 (float) or 3.5 (climatology) Sv, much less than that implied by air-sea fluxes.

3. The elements of CLIMODE

Of the two likely ameliorating influences, which can remedy the apparent imbalance between EDW production and dissipation, i.e. (1) lateral eddy fluxes in the mixed layer, (which have only been subject to rather coarse estimation), and (2) the inaccuracy of the estimation of transformation air-sea flux using climatological air-sea flux and SST data, we suspect the former is more important, but CLIMODE is designed to address both processes.

Our working hypothesis in CLIMODE is that the onset of late winter convection, when combined with Gulf Stream heat transport, intensifies the meridional slopes of near surface isopycnals, resulting in an explosion of baroclinic instability in the ocean.

CLIMODE has been constructed around a two-year period of field measurements (2006, 2007) with particular emphasis on the late-winter/early-spring periods, times when EDW 'formation' is highest. Observations will be collected at high spatial resolution over the top 500 m of the ocean to capture the processes associated with mode water formation in the context of the meandering front. Simultaneously, we will measure the evolving marine boundary layer above and document the air-sea fluxes that drive the two fluids. On longer time scales, the subsequent capping and initial injection of the mode water into the subtropical thermocline will also be observed, as well as its eventual dispersal.

A variety of measurements and modeling activities will be carried out under CLIMODE. Fig.4 (bottom) and Table 1 provide an overview. For the two-year observation period, moorings (one surface, two subsurface) will be maintained in the EDW transformation region surrounded by an array of profiling floats. Continuous remote sensing of the ocean surface properties (SST, winds, sea level anomalies) will also be carried out, in conjunction with an array of surface drifting buoys. Extensive discussion of the observational component of CLIMODE can be found at: http://www.climode.org/cruises.html.

In parallel with the observational program, modeling and theoretical studies will be carried out. The modeling component of CLIMODE is directed at testing the hypotheses that underlie the program discussed above, and, at the same time, will encourage transfer of understanding to the large-scale models used in climate research. A combination of regional and process ocean models will be used to address the phenomenology of EDW formation and dissipation. We are fortunate in having a strong common interest with the CPT-EMILIE (http://cpt-emilie.org) in upper-ocean mixing. In conjunction with that program we plan to explore the whole range of scales with a hierarchy of numerical models of increasing complexity.

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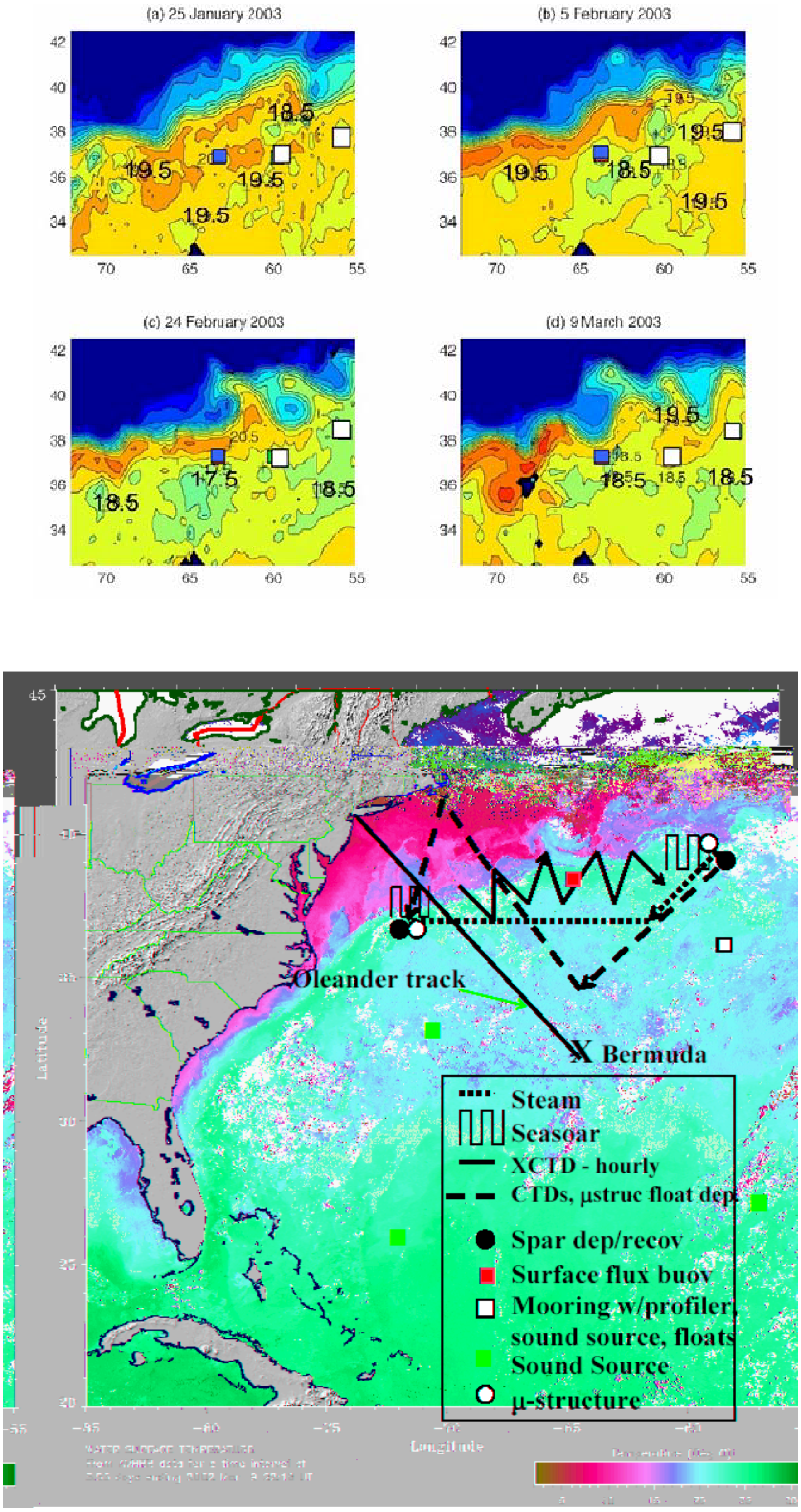

Figure 4: (top) Wintertime SST from the AMSR-E microwave sensor, courtesy of Remote Sensing Systems; contour interval 1 degree. Positions of the surface (blue) and subsurface (white) moorings are indicated. Note the warm core of the Gulf Stream and the irregular opening of the EDW ventilation window (classically between about 17.5 and 18.5˚C). Bias errors of up to 0.5˚C may be present in these newly available data. (bottom) Schematic of CLIMODE fieldwork. Shown are nominal beginning and ending locations for the spar drifts, the SeaSoar and XCTD survey patterns, a subset of microstructure sampling sites, and two hydrographic section lines. Positions of the surface and subsurface moorings and two of the sound sources are also indicated.

Table 1.
Overview of measurement and modeling activities within CLIMODE

CLIMODE	Air-sea fluxes F Edson, Weller, Kelly	Eddies and mixing D Joyce, Gregg, Toole, Lumpkin	Subduction, dispersal A Fratantoni, Sloyan, Straneo, Talley
Observations	Direct air-sea fluxes Moored atmosphere boundary layer observations Remote sensing of SST, winds, sea level anomalies	Ocean μstructure profiles Fine-scale Gulf Stream frontal surveys Lagrangian observations of surface, upper ocean velocity T/S	Lagrangian & Eulerian observations of stratification and bolus flux EDW volume observations
Models	Regional atmospheric model Samelson, Skyllingstad	Process/regional ocean model Dewer, Ferrari, Marshall	Process regional ocean model Dewer, Ferrari, Marshall

Continued from Page 12

4. Contact information and timetable

Terry Joyce (WHOI) and John Marshall (MIT) have overall responsibility for the CLIMODE program. Terry Joyce is overseeing the observational element; John Marshall is coordinating the theory and modeling activities and the interaction of CLIMODE with the CLIVAR Ocean-Mixing CPT. The seagoing element of CLIMODE begins in the November of 2005, when moorings and floats will be deployed. The intensive winter observational periods follow in February 2006, 2007. Floats will track dispersal of mode waters in subsequent years autonomously.

Many more details and latest information can be found from the CLIMODE website (http://www.climode.org/).

5. Acknowledgements

We thank the Physical Oceanography program of NSF, and particularly its director Eric Itsweire, for their support of CLIMODE. We would also like to acknowledge the support and advice of the Atlantic and US CLIVAR committees.

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U.S. CLIVAR Reorganization

by David M. Legler Director, U.S. CLIVAR

U.S. CLIVAR has enjoyed a period of five plus years marked by numerous successes in implementing its vision for the climate variability and predictability research enterprise. After such a period of time, new scientific advances, new ways of organizing research, as well as changes in the programmatic and budget landscape motivated an evaluation of our organizational structure. After considering a number of inputs and to insure U.S. CLIVAR is well-suited to meet its objectives over the next decade, U. S. CLIVAR is changing the way in which it is organized. This change in infrastructure will allow US CLIVAR to

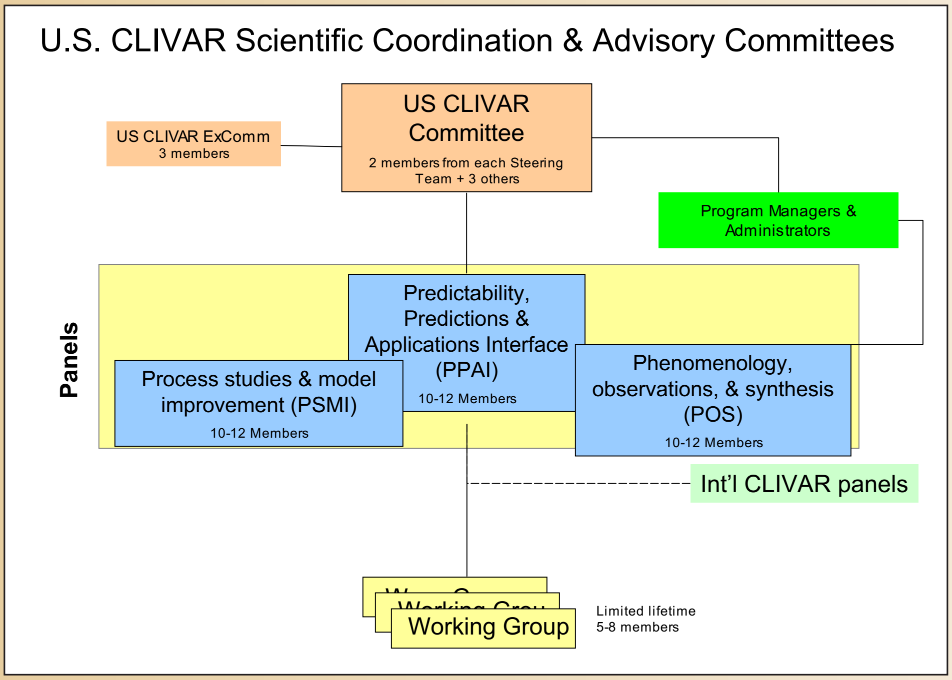
- carefully plan, implement, and coordinate activities that are more responsive to research agency and US Climate Change Science Program strategic objectives,
- stimulate a balanced climate research agenda that includes improving our understanding, prediction capabilities, and communication with and linkages to users of climate information, and
- engage more of scientific community in pursuit of CLIVAR objectives.

The details of the reorganization are available on the U.S. CLIVAR web site (http://www.usclivar.org). The new three-tier structure (Figure 1) consists of an overarching U.S. CLIVAR Committee that will steer the U.S. CLIVAR research enterprise, three new Panels (committees) to guide and implement the program in the broad functional goals of predictability/prediction; process and model improvement, and phenomena/observations/synthesis, and a third tier of limited term Working Groups that will be on the front lines of coordinating and implementing focused components of the climate variability/predictability research enterprise. The Panels will develop and coordinate research plans and activities, and provide input to agency programs. In response to increased demands on research programs to document progress, these Panels will also be asked to consider how best to describe their plans and assess achievement using measurable performance metrics (e.g. milestones).

In transitioning from a basin-centric framework to one arranged around broad functional goals of U.S. CLIVAR, we are working to avoid delaying project plans and proposals already being considered; making the transition process and the functioning of the new organization transparent to the community, and eliminating duplication of effort. Moreover, we recognize strong linkages to the international CLIVAR regional implementation panels must continue. Lastly, we are planning annual collective meetings to facilitate communication between the U.S. Panels, Working Groups, and others interested in the U.S. CLIVAR research program. The first such annual "Summit" meeting of all the new Panels and U.S. CLIVAR Committee is scheduled for mid-August.

We encourage community contributions towards CLIVAR planning and implementation. As a first step, we have placed our reorganization plans online (www.usclivar.org). We request your feedback on the scope of our efforts and particularly scientific areas where the new Panels should focus their energies, e.g. what are the topical areas of greatest potential payoff that could be realized with more coordination and focus? Such feedback should be submitted through a link on the reorganization webpage. All input will be provided to the new U.S. CLIVAR committees in advance of the August Summit.

We will report on the Summit in future issues of Variations and through other publications. ■



CLIVAR/IPCC Workshop on Analysis of Climate Model Simulations for the IPCC AR4

On March 1, 2005 the U.S. CLIVAR in association with the Intergovernmental Panel on Climate Change (IPCC) convened a workshop at the International Pacific Research Center (IPRC) in Hawaii. The goals of the workshop included examining what analyses were being done, understanding the results emerging from the analyses, and determining where these analyses fit into the IPCC's 4th Assessment Report (AR4). This was the largest coordinated international global climate model analysis attempted.

Approximately 150 international scientists attended the workshop including those awarded grants under the U.S. CLIVAR Climate Model Experiment Program. Topics ranged from monsoons and ENSO, to mid and high latitude phenomena, clouds and radiation, downscaling and regional events, climate sensitivity, 20th century simulations, and ocean and land surface modeling. As a result of the workshop, the AR4 lead authors were able to discern what is being assessed for their IPCC chapters. Likewise, the scientists now understand where and how their results will fit into the AR4.

Additional information regarding the workshop (including presentations and results) can be found at: http://ipcc-wg1.ucar.edu/meeting/CMSAW.

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