Predictability and Diagnosis of Low-Frequency Climate Processes in the Pacific
Final Report to the DOE SciDAC CCPP

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1. Introduction and Relevance to the BER CCRD Long-Term Measure

Predicting the climate for the coming decades requires understanding both natural and anthropogenically forced climate variability. This variability is important because it has major societal impacts, for example by causing floods or droughts on land or altering fishery stocks in the ocean. The work executed here was aimed at increasing our ability to predict climate change and variability, and was organized into three topics.

1) The uncertainties in climate change model projections, including analyzing and diagnosing IPCC AR4 runs for consistency and fidelity in representing observed physical climate processes.

2) Regional predictability of natural and anthropogenically forced changes in climate variability in key areas over western North America, especially focusing on hydrologic variables.

3) Regional predictability of natural and anthropogenically forced changes in climate variability for key areas of the Pacific Ocean, including the California Current, Gulf of Alaska, and adjacent land areas.

The bulk of this work directly addressed the major scientific objective of the BER CCRD, which is “accurate prediction of future climate on decadal to centennial timescales.” Our primary goal was to assess the limits of predictability by identifying the physical processes of climate variability and change, which is necessary for accurate predictions. Both natural variability and the expected changes under anthropogenic forcing were examined in models and observations. This directly addressed the primary purpose of Notice 07-06, which is to “deliver improved climate data and models for policy makers to determine safe levels of greenhouse gases for the Earth system”, which was accomplished via “experiments using existing state-of-the-art global climate models that specifically address and shed insights on uncertainties in current climate change projections.” The work using regional coupled ocean-atmosphere-land models to downscale coarse-resolution GHG-forced climate models helps to “substantially reduce differences between observed temperature and model simulations at subcontinental scales.”
2. Accomplishments

Our results fall broadly into three topics: evaluating global climate model predictions; regional impacts of climate changes over western North America; and regional impacts of climate changes over the eastern North Pacific Ocean; as follows:

2.1 Evaluating Global Climate Model Predictions

A significant amount of effort has been devoted to examining model representations of anthropogenic climate warming, and comparing this to observations in an effort to determine if the model simulations are accurately simulating the observed conditions. The ability to accurately model the historically observed ocean conditions is a prerequisite for any model that will be used to forecast future climate. Part of the motivation for this work is the disparity between different coupled model forecasts of what future warming due to anthropogenic effects should be (IPCC 2001), which makes it difficult to politicians and other planners to anticipate what conditions to plan for. We sought to validate the simulations against measurements of the actual oceans. Of course, some of the disparity in future climate is due to the intrinsically probabilistic nature of climate forecasts, i.e., the actual future climate will be one selection of many possible future climates influenced by unpredictable, chaotic weather events. We addressed this problem by using ensembles of model runs to form probability distribution functions of climate states.

Barnett et al. (2005a) examined the newly-available Levitus ocean temperature data set and two modern coupled ocean-atmosphere general circulation models to see if the models were able to simulate the observed increase in ocean heat content, given realistic anthropogenic forcing. We found that in both model and observations, a distinct warming signal has penetrated into the world’s oceans over the past 40 years. The signal is complex, with a vertical structure that varies widely by ocean. For example, the penetration is much greater in the North Atlantic than in the North Pacific. This can be understood when the various convective regimes of the ocean basins are taken into account; i.e., the presence of deep convection in the North Atlantic carries surface warming into the ocean depths much more quickly than happens in the North Pacific, which lacks deep convective overturning. The warming signal cannot be explained by natural internal climate variability or by solar and volcanic forcing, but is well simulated by the two anthropogenically forced climate models we examined. We concluded that the warming signal is of human origin, a conclusion that is robust to observational sampling fluctuations. The warming is not simply a local 1-D balance; rather, changes in advection combine with surface forcing to give the overall warming pattern. This suggests that future work examining the interaction of ocean warming with changes in circulation could prove fruitful as more regional issues are considered.

It has become increasingly obvious to the ocean/climate modeling community that issues of sampling variability and evaluation of the level of natural internal variability in the coupled climate models and real oceans are difficult ones that require careful attention. For example, there are sessions exploring this at the AGU fall meeting (2006) and EGU spring meeting (2007). Pierce et al. (2006a) addressed many of
these issues in a detailed examination of the simulations of PCM and HadCM3. In our model-observed comparisons we sampled the models at the same locations as the gridded yearly observed data, a key step that makes possible a direct comparison of the warming of the model oceans and the real oceans. When this is done correctly, we find that in the top 100 m of the water column the ocean warming is well separated from natural variability, both internal and that arising from solar and volcanic fluctuations. Between 125 and 200 m the agreement between the model and observed warming is not statistically significant, a finding that should be studied further, and suggests the importance of correctly accounting for thermocline variability in the comparison. The agreement between model and observed warming then increases below 200 m and remains significant down to 600 m. Analysis of the model’s heat budget indicate that the warming is driven by an increase in net surface heat flux that reaches 0.7 W/m² by the 1990s; the downward longwave flux increases by 3.7 W/m², which is not fully compensated by an increase in the upward longwave flux of 2.2 W/m². Latent and net solar heat flux each decrease by about 0.6 W/m². An interesting finding was that the changes in the individual longwave components are distinguishable from the pre-industrial mean by the 1920s, but due to cancellation of components, changes in the net surface heat flux do not become well separated from zero until the 1960s. Changes in ocean advection also play an important role in local warming, depending on the location. The observed sampling of the ocean temperature is highly variable in space and time, but sufficient to detect the anthropogenic warming signal in all basins, at least in the surface layers, by the 1980s. We also examined whether the likely biased seasonal sampling (i.e., more ocean observations in local summer than in local winter) is enough to affect our conclusions, and found that it was not. In AchutaRao et al. (2006), the variability of ocean heat uptake in 22 different coupled climate models in the IPCC database was compared, rounding out our detailed analysis of two models. Again, special attention was paid to the issue of correctly accounting for the effect of large year-to-year changes in the actual sampling of the oceans, and how this can be reasonably compared to model results. One interesting result from this analysis was the importance of including observed volcanic forcing over the historical era; models that lacked historical volcanic forcing tended, as a group, to produce too much ocean warming.

One implication of the ocean warming that has received considerable attention is its possible effect on hurricane development. Previous work had identified links between changes in ocean surface temperature and the intensity of hurricanes. We contributed to this work in the study of Santer et al. 2006, which examined the causes of the increase in SST in the North Atlantic and Pacific tropical cyclogenesis regions. The observed SST increases in these regions range from 0.32 C to 0.67 C over the 20th century. Results from the 22 climate models examined suggest that century-timescale SST changes of this magnitude cannot be explained solely by unforced variability of the climate system. Model simulations of natural internal variability indicated that there is an 84% chance that external forcing, including anthropogenic gasses combined with aerosols, explains at least 67% of the observed SST increases in the two tropical cyclogenesis regions. Model simulations of the 20th century are, in fact, generally capable of
replicating the observed SST increases when they are forced by combined anthropogenic and natural factors. Experiments in which forcing factors were varied individually rather than jointly showed human-caused changes in greenhouse gases were the main driver of 20th-century SST increases in both tropical cyclogenesis regions.

Another implication of general climate warming is the impact on snowpack and the hydrological cycle. Part of this important subject is addressed elsewhere in this proposal, with an emphasis on the arid western U.S., which is dependent on storage of winter precipitation in mountain snow pack for summer water supplies. In the review article of Barnett et al. (2005b), it was pointed out that all currently available climate models predict a near-surface warming trend under the influence of rising levels of GHG in the atmosphere. In addition to the direct effects on climate – for example, on the frequency of heat waves – this increase in surface temperature has important consequences for the hydrological cycle in regions all over the world where water supply is dominated by melting snow or ice. In a warmer world, less winter precipitation falls as snow and the melting of winter snow occurs earlier in the spring. Even without any changes in precipitation intensity, both of these effects lead to a shift in peak river runoff to winter and early spring, away from summer and autumn when demand is highest. Where storage capacities are not sufficient, much of the winter runoff will be immediately lost to the oceans. With more than one-sixth of the Earth’s population relying on glaciers and seasonal snow pack for their water supply, the consequences of these hydrological changes for future water availability – predicted with high confidence and already diagnosed in some regions – are likely to be severe.

Scripps M.S. student Gino Passalacqua, advised by Miller and Pierce, analyzed the effects of future changes in ENSO in ensembles of GHG-forced PCM runs. Although the changes tended to be small, the altered teleconnections may significantly impact the physical oceanography, atmospheric climate, and oceanic fisheries along the western coasts of South and North America (Passalacqua, 2007).

Moving to decadal time scales, we investigated the predictability of North Pacific processes using the CCSM3 model. Many studies have shown the strong effect of the Pacific Decadal Oscillation on climate over North America. Important contributions in this area have been done by the PIs under previous DOE support. Our new work in this area has addressed the predictability of these phenomena. One way to approach this is by evaluating the so-called “potential predictability” of the system. This can be done by determining what part of the total climate variability is not well described by the simple linear stochastic model of Hasselmann (1976), with the idea that departures from this model are presumably related to more interesting, and potentially predictable, physics. A complementary view of the problem is to evaluate what fraction of the 5-yr averaged variance in a climate variable of interest, for example SST, is unlikely to have arisen from sampling fluctuations in short-timescale weather noise. The idea here is that climate variability not explainable as sampling variations of unpredictable weather forcing might arise from physical processes that could be predictable. These techniques have been described in Pohlmann et al. (2004), Boer (2000, 2004), and Collins (2002). We applied them to CCM3, and used both T42 and
T85 runs to additionally investigate the effect of model resolution on the results. An example result is shown in Figure 1. The top panel shows places where variability is not well represented by a simple Hasselmann-type climate relationship. For example, in the tropical Pacific, there is a 99% chance that climate variability arises from more than simple Hasselmann-type damped stochastic forcing. Other regions are identified in the North Pacific, North Atlantic, Southern Ocean, and Arctic Sea. The lower two panels of Figure 1 show the fraction of 5-yr (middle panel) and 10-yr (bottom panel) mean SST variability that is unlikely to have arisen from sampling fluctuations of chaotic weather noise. It is found that 20-30% of the interannual to decadal variability cannot be explained by weather noise in the North Pacific and North Atlantic, and thus arises from physics that may be potentially predictable.

2.2 Regional Impacts of Climate Changes over Western North America

The water resources of the western U.S. depend heavily on snowpack to store part of wintertime precipitation into the drier spring and summer months. Stewart, Cayan and Dettinger (2005) investigated a shift towards earlier runoff in recent decades. In documenting this shift, changes in the timing of snowmelt-derived streamflow from 1948 to 2002 were investigated in a network of 302 western North America gages by examining the center of mass for flow, spring pulse onset dates and seasonal fractional flows through trend and principal component analyses. Widespread and regionally-coherent trends towards earlier onsets of springtime snowmelt and streamflow have taken place across most of western North America, affecting an area that is much larger than previously recognized. These timing changes have resulted in increasing fractions of annual flow occurring earlier in the water year by 1-4 weeks. The immediate (or proximal) forcings for the spatially coherent parts of the year-to-year fluctuations and

\textbf{Figure 1. Diagnostic Potential Predictability for CCSM3 (see text for explanation). Pierce (2007)}
longer-term trends of streamflow timing have been higher winter and spring temperatures. Although these temperature changes are partly controlled by the decadal scale Pacific climate mode (PDO), a separate significant part of the variance is associated with a springtime warming trend that spans the PDO phases.

To investigate a possible mechanism leading to the snowmelt streamflow timing advances, we investigated a trend toward more precipitation falling as rain instead of snow. Knowles, Dettinger and Cayan (2006) used a large set of weather station histories to document a regional trend during the period 1949-2004 toward smaller ratios of winter-total snowfall water equivalent (SFE) to winter-total precipitation (P). The most pronounced reductions in this ratio (Figure 2) have occurred in the Sierra Nevada and the Pacific Northwest, with more varied changes (but still predominantly reductions) in the Rocky Mountains. Trends in this ratio correspond to shifts toward less SFE rather than to changes in total precipitation, except in the Southern Rockies where both snowfall and precipitation have increased. The trends toward reduced SFE are a response to warming across the region, with the most significant reductions occurring where winter-average wet-day minimum temperatures were warmer than −5°C. Most of the SFE reductions were associated with winter wet-day temperature changes between 0 and +3°C during the study period. Warming of this (limited) magnitude has occurred primarily at warmer, lower elevation stations where precipitation form is particularly sensitive to temperature. Stations at elevations above about 1800m are cooler on average and thus precipitation form has been less vulnerable to recent trends. These higher stations have not exhibited SFE shifts, even though many of them have warmed more than those at lower elevations. At the monthly scale, trends toward reduced SFE/P have been most pronounced in March regionwide, although near the west coast trends have also been pronounced in January. These monthly SFE/P trends correspond to monthly warming trends in wet-day temperatures that have been most widespread in Januaries and Marches. Mean temperatures were colder in January at higher elevations, restricting SFE/P impacts to the lower elevations near the west coast, whereas warmer mean temperatures in March allowed the recent warming to produce SFE/P declines all across the region.

Figure 2. Less snow and more rain since 1950 is a symptom of a warmer winter and spring Climate. Plotted are Winter (Nov-Mar) SFE/P trends: symbol area is proportional to study-period changes, measured in standard deviations as indicated; circles indicate high trend significance (p<0.05), squares indicate lower trend significance (p>0.05). Knowles et al. (2006)
To investigate possible future climate changes in California, a set of climate change model simulations was selected and evaluated. Cayan et al. (2007) describe this work, which will appear in a special volume of *Climatic Change* devoted to a multifaceted assessment of climate change impacts on resources, ecosystems, agriculture, human health and other aspects in California. From the IPCC Fourth Assessment, simulations of 21st century climates under a B1 (low emissions) and an A2 (medium-high emissions) emissions scenarios were evaluated, along with occasional comparisons to the A1 (high emissions) scenario. The climate models whose simulations were the focus of the present study were from PCM1, and the NOAA GFDL CM2.1 model. These emission scenarios and attendant climate simulations are not “predictions,” but rather are a purposely diverse set of examples from among the many plausible climate sequences that might affect California in the next century. Temperatures over California warm significantly during the 21st century in each simulation, with end-of-century temperature increases from approximately +1.5ºC under the lower emissions B1 scenario in the less responsive PCM1 to +4.5ºC in the higher emissions A2 scenario within the more responsive GFDL model. Three of the simulations (all except the B1 scenario in PCM1) exhibit more warming in summer than in winter. In all of the simulations, most precipitation continues to occur in winter, and relatively small (less than ~10%) change in overall precipitation is projected. The California landscape is complex and requires that model information be parsed out onto finer scales than GCMs presently offer. When downscaled to its mountainous terrain, warming has a profound influence on California snow accumulations, with snow losses that increase with warming. Consequently, snow losses are most severe in projections by the more responsive model in response to the highest emissions.

### 2.3 Regional Impacts of Climate Changes in the North Pacific Ocean and Western North America

Current global climate models of future conditions are unable to resolve coastal oceanic processes associated with coastal upwelling and mesoscale eddy variability. Towards understanding how the coastal ocean may be modified under GHG warming conditions, we have been studying the current climate variations in the California Current System (CCS) and Gulf of Alaska (GoA), as well as GHG-forced global GCM predictions of these regions.

Kim and Miller (2007) analyzed observed hydrographic profiles in the CCS region from the CalCOFI hydrographic surveys to attempt to better understand the spatial structure of stratification changes observed across the 1976-77 climate shift (e.g., Miller et al., 1994; McGowan et al., 2004). The 55-year dataset in the southern CCS revealed (Figure 3) a significant surface-intensified warming and stratification (buoyancy frequency) change across the 1976-77 climate regime shift. Surprisingly, however, the average depth of the thermocline, defined as the maximum gradient of temperature, did not change significantly across the regime shift. The maximum-gradient criterion for thermocline depth may therefore be more appropriate than following an isotherm because the isotherm necessarily deepens in the presence of surface-intensified warming. As the surface heating changed the strength of stratification, it
also changed the slope of the nitrate-temperature relation for the middepth waters (roughly 30m to 200m). Thus, the quality of upwelled water may have been fundamentally altered after the shift. These results also apply to the pycnocline and when considering nearshore versus far-offshore regional changes. Understanding how these physical changes directly influence primary production is another step we are taking, using eddy-resolved ocean models with simple biological components (or tracers).

Figure 3. Probability density functions of the thermocline depth (left) and buoyancy frequency (right) for offshore stations of CalCOFI before (blue) and after (red) 1976-77 climate shift. Kim and Miller (2007).

Auad, Miller and Di Lorenzo (2006) evaluated the potential impact of global warming on the oceanic circulation off the coast of California using an eddy-permitting ocean model that had been previously studied by Di Lorenzo, Miller, Schneider and McWilliams (2005) under current climate-change conditions. The simulation was forced with wind stresses, heat fluxes and open boundary conditions obtained from the PCM forced by increased GHG. These atmospheric fields were downscaled using RSM by Han and Roads (2004) to provide forcing functions from two decades, 1986-1996 and 2040-2050, which are then used to drive forecasts of future oceanic conditions in the California Current System. Oceanic boundary conditions are interpolated from the PCM oceanic grid. The scenario leads to increased upper-ocean temperatures, and increased stratification along the coast. The vertical structure of the thermal response is in general good agreement with recent studies of global warming trends. This temperature change is, however, not strong enough to suppress the effect of increased upwelling-favorable winds (wind stress and wind stress curl), which increase upwelling in the coastal ocean (Figure 4), suggesting increases in nutrient fluxes to the surface. This provides an interesting contrast with the modeling results of Di Lorenzo et al. (2005) which indicate that, over the past 50 years of warming observed in the CalCOFI data, the increase in stratification is strong enough to suppress increased upward fluxes of nutrient proxies thereby potentially reducing productivity. Understanding why these two scenarios differ is a focus of our proposed research.
We also published a suite of papers aimed at understanding the physical oceanographic changes in the Gulf of Alaska that may have precipitated important ecosystem changes (e.g., zooplankton, Steller sea lions, etc.) across the 1976–77 climate shift. Miller et al. (2005) used an eddy resolving model of the GoA to demonstrate that strong changes in the western Gulf can occur, with only weak changes in the eastern Gulf, which matches the spatial structure of Steller sea lion declines (in the west, but not in the east). Capotondi et al (2005) and Alexander et al. (2007) used coarse resolution physical and biological ocean models to provide the large-scale context of these eddy-resolved runs. Since the Gulf of Alaska is such an economically and socially important area, we plan to continue these studies using estimates of future climate conditions as forcing functions.

We also developed the Scripps Coupled Ocean-Atmosphere Regional (SCOAR) model (Seo, Miller and Roads, 2007a), which includes the Regional Spectral Model for the atmosphere (Juang and Kanamitsu, 1994) and the Regional Ocean Modeling System (ROMS) for the ocean (Haidvogel et al. 2000; Shchepetkin and McWilliams 2005). SCOAR has been remarkably successful in simulating mesoscale ocean-atmosphere coupling for Pacific tropical instability waves (TIW’s), mesoscale eddies in the California Current System (Figure 5), and gap winds along the Central American Coast (Seo et al., 2007a). These phenomena were modeled for the first time using high resolution and full coupling, with key aspects of model variables compared favorably with observations.

Seo et al. (2006) also used SCOAR to investigate the effect of oceanic mesoscale features on the mean climate of the tropical Atlantic. They showed that, compared to a non-eddy resolving ocean model, resolving oceanic mesoscale variability leads to a cooler mean equatorial cold tongue and a cooler coastal upwelling zone, which changes the meridional SST gradient and mean rainfall of the ITCZ. [This paper won the 2006 Frieman Prize for Best Graduate Student Paper at Scripps.] Seo et al. (2007b) show how the feedbacks in the tropical Atlantic alter the key properties of TIW’s.
Figure 5. Model 30-day-ave fields (left) anomalous wind stress divergence ($WSD$) with contours of downwind SST gradient (ddT) and (right) anomalies of wind stress curl ($WSC$) with contours of crosswind SST gradient (cdT) showing the effects of mesoscale eddy SST anomalies on surface wind stress, which has been observed in satellite observations by Chelton et al. (2007).
References

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