Climate Diagnostics Center

Summary of Climate Dynamics and Experimental Predictions (CDEP) Accomplishments and Plans FY04-05

Overview

CDC research goals supporting the NOAA/OGP CDEP/Applied Research Center (ARC) program include: improving understanding of forcing mechanisms influencing climate variability, particularly from subseasonal to decadal time scales; developing new forecast capabilities for estimating risks of high-impact events based on ENSO or other climate conditions; estimating and fully capitalizing on potential predictability related to ENSO, as well as other modes of variability and non-ENSO related forcing; developing new forecast products to better serve user needs, particularly on regional scales; and ultimately, contributing to the development of new NOAA climate services.

Highlights of CDC Activities for FY04 and Plans for FY05

Global Atmospheric Sensitivity to Tropical SSTs

We continued our comprehensive investigation of the sensitivity of the global atmospheric response to SST anomalies in different parts of the tropical oceans using the NCAR CCM3.10 AGCM. An array of 43 localized SST anomaly patches was specified, and the atmospheric responses were summarized as "Fuzzy Green's Function" sensitivity maps (as described in Barsugli and Sardeshmukh, *Journal of Climate* 2002). Thus far, we have confirmed and extended the results of the Barsugli and Sardeshmukh study in four distinct ways: 1) The sensitivities have now been established with a different AGCM (the NCAR CCM3 instead of the NCEP MRF9) and in all seasons of the year; 2) the opposite sensitivity of many aspects of the global response to SSTs in the tropical Indian and Pacific oceans has been confirmed; 3) the counter-intuitive result that warm SSTs in large areas of the tropics lead to global-mean surface *cooling* and *drying* has also been confirmed; and 4) the significant modification of the remote atmospheric response to tropical SST anomalies through interactions with the underlying sea surface has been demonstrated. Three substantial journal articles describing these results are in preparation. (Sardeshmukh, Barsugli, Shin).

A nodal line of climate sensitivity to tropical SST changes

As part of the larger project described above concerned with estimating atmospheric sensitivity to anomalous SSTs in different parts of the tropical oceans, we conducted a more detailed investigation of the sensitivity of global mean temperature and precipitation to tropical SST forcing. For the DJF season we found that warm SST anomalies in the Indian Ocean lead to a reduction of global mean temperature and precipitation, but warm SST anomalies in the west

Pacific warm pool have the opposite effect. This contrasting behavior is mainly associated with a single circulation response pattern with opposite signs, depending on which side of the "nodal line" between the Indian and west Pacific oceans the forcing lies. The relevance of this nodal line was confirmed when limited portions of the observed tropical 1950-1999 SST trend patterns were used to force the AGCM. The global circulation trend response in these experiments resulted from cancelling responses to the SST trends in these two areas of contrasting sensitivity. The important implication of this result is that regional patterns of climate change, and even the magnitude of the global mean signal, will depend sensitively on the precise spatial pattern of projected SST changes across this nodal line of sensitivity separating the tropical Indian and Pacific Oceans. (Barsugli, Sardeshmukh, Shin)

Extratropical Storm Track Predictability on Seasonal and Decadal Scales

The statistics of extratropical daily weather ("stormtracks") averaged over individual winter seasons, decades, and even longer intervals are not constant but vary substantially from one interval to next. These variations have a random part associated with sampling fluctuations, and a potentially predictable part associated with slow changes of the underlying SSTs and atmospheric composition. In this study, we used very large sets of AGCM runs made at NCAR and NCEP with prescribed observed evolving SSTs during the past 50 years to isolate the SST-forced part of the extratropical stormtrack variations. We found that a significant SST-forced stormtrack signal exists in many winters, but its strength and pattern can vary substantially from winter to winter. The correlation of the SST-forced and observed stormtrack variations over the 50 winters was found to be high enough in the PNA sector to suggest useful predictability. We also showed that most of the predictable stormtrack signal is associated with tropical Pacific SST forcing. Variations from winter to winter of the pattern correlation of the observed and SST-forced stormtrack anomaly fields were generally consistent with variations of the signal strength, and to that extent should be identifiable *a priori* from tropical SST variations. The long-term trend of the Pacific storm track in the 50-yr record was also consistent with the stronger ENSO SST forcing in the second half of the record. A substantial paper describing these and other results was published in the *Journal of Climate*. **(**Compo, Sardeshmukh)

Understanding the 1974-2003 trends in US surface temperature.

Consistent with global warming, there has been a significant surface warming of the U.S over the past 30 years. This warming, however, shows strong seasonal and regional variation. For example, the strongest warming in winter has been over the central US, and the strongest warming in summer over the western US. There has also been no warming in the interior US in spring and summer. To assess how these trend variations might be related to the large upward trend in Indian ocean SSTs over the same period, we generated a 10-member ensemble of 10-yr AGCM simulations with a prescribed time-dependent linear warming of Indian ocean SSTs. The imposed linear trend averaged over the Indian Ocean between 25°N-25°S was +0.1°C/year, so that over the 10 year period of model integration the area-averaged SST increase was +1°C, similar to the observed increase over 1974-2003. The simulated temperature trends over the US were of large enough magnitude to suggest that the Indian ocean warming was likely an important contributor to the US warming. The US temperature response also exhibited dramatic seasonality despite the lack of seasonality in the Indian Ocean warming, and tended to be relatively stronger over the western US, roughly consistent with observations. (Hoerling, Eischeid, Bates, Quan).

Experimental Tropical SST predictions

Monthly and seasonal forecasts of tropical SST anomalies are provided to the Climate Diagnostics Bulletin and the Experimental Long Lead Forecast Bulletin. We have expanded our web services by providing predictions of SSTs in the Indian Ocean and in the vicinity of Hawaii. Our tropical Atlantic forecasts were particularly useful to users during the strong 2004 hurricane season. As pointed out at a meeting of CLIVAR-Atlantic PIs, held in Reading, U.K. in April, 2004 (attended by C. Penland and L. Matrosova), there are very few centers who put out tropical Atlantic SST forecasts since it is difficult to beat persistence as a predictor in that region. During this meeting, we agreed in principle to collaborate with Dr. P. Nobre of IAI in collecting tropical Atlantic forecasts, much as COLA collects tropical El Niño forecasts. Unfortunately, we have not had the funding to follow up on this (Penland, Matrosova).

"Scenario experiments" to inform operational seasonal forecasts

CDC scientists continue under an ongoing CDEP project to develop an experimental seasonal forecast tool for North America based on multi-GCM ensemble responses to observed historical patterns of anomalous SST forcing. We generate real-time experimental predictions with this tool to contribute to the routine monthly dialogue between CDC and NWS operations. The tool is available online to researchers and forecasters at http://www.cdc.noaa.gov/seasonalfcsts/. We are currently documenting its performance characteristics, and are also using it to make general assessments of seasonal predictability. We also plan to generate seasonal US temperature and precipitation hindcasts for 1981-2003, and compare them with the new CFS hindcasts, to provide a Climate Test Bed (CTB) benchmark for the NWS's new coupled forecast system.

A second activity, directed at CDEP clients at CPC, is the production of S/I "scenarios on demand". Following CPC's official declaration of an El Niño event in late summer of 2004, we partnered with CPC scientists to explore the possible impacts of this event on the US winter of 2004/05. Specifically, we addressed the issue of how the canonical El Niño signal over the US might be affected by the recent cooling trend in the Indian ocean. To this end, we performed ensemble AGCM integrations with idealized 1K anomalies in the tropical eastern Pacific and Indian oceans, and found that that the North American response to a 1K Indian ocean cooling was remarkably similar in magnitude and structure to the 1K east Pacific warming, and thus in the sense of strongly reinforcing the canonical El Nino signal over North America (Hoerling, Eischeid, Bates, Quan)

A critique of the dynamical "two-tier" method of seasonal prediction.

Dynamical predictions of Asian monsoon rainfall have little or no skill. These predictions are typically made using a "two-tier" procedure in which seasonal forecasts of tropical (and sometimes global) SSTs are first made using statistical or coupled dynamical models, and the predicted SSTs are then used to drive uncoupled AGCMs. The poor monsoon forecasts could thus be due either to poor SST forecasts or to the two-tiered strategy itself being fundamentally flawed. We believe the latter to be the case, because the skill of monsoon hindcasts made by driving 10 different uncoupled AGCMs with even perfectly predicted (i.e observed) SSTs remains poor. We examined the monsoon hindcast skill of partially coupled GCMs in which SSTs were prescribed in the central and eastern tropical Pacific but were allowed to evolve elsewhere through coupled interactions with the oceanic mixed layer. The skill of these hindcasts was significantly higher than that of the fully uncoupled hindcasts. The coupling over the tropical warm pool was crucial for this improvement. We have further confirmed the flaw in the two-tiered prediction approach by examining the 1-season lead monsoon hindcast skill over 1959-2001 of 7 different fully coupled models participating in the DEMETER project. The median skill of these hindcasts is also higher than those of the uncoupled hindcasts. This is remarkable, considering the SST hindcast biases of the DEMETER models which are absent in the uncoupled model hindcasts by design. (Krishna Kumar, Hoerling, Rajapolan).

Monitoring of ENSO conditions with the Multivariate ENSO Index

We have continued to provide a monthly discussion of the state of ENSO and its expression in the Multivariate ENSO Index (MEI) at http://www.cdc.noaa.gov/~kew/MEI/. This web page includes widely used comparison figures for the biggest El Nino and La Nina events of the last half century. Related input was also provided to the monthly ENSO Advisory issued from the Climate Prediction Center (CPC) (Wolter).

Isolating non-ENSO variability

The global response to ENSO is best investigated in models in which one has the ability to specify SSTs with and without the El Nino signal. Unfortunately, it has proved difficult to eliminate the ENSO signal from historical data sets without eliminating all variability in the interannual frequency band, regardless of whether or not it is ENSO-related. At CDC we have developed a method, based on the observed statistical patterns associated with ENSO SST variability, to identify and remove most of the evolving El Nino signal while retaining the broadband frequency signal not associated with ENSO. It is distinctive in that it defines ENSO as an evolving superposition of three complex mode pairs rather than just the SST in say the Nino 3.4 region. Among many applications, we propose to use this filter to investigate the relations between the interannual and interdecadal components of tropical variability.

Interesting results using this filter have already been obtained, and an article, “El Niño and Interdecadal Variability in Tropical Sea Surface Temperatures” will soon be submitted to the *Journal of Climate.* In this manuscript, we show that the leading EOF of the filtered (i.e. the "non-ENSO") SST data shows large similarities to the global trend pattern recently identified by Livezey and Smith. The time series coefficient of our EOF pattern, however, is very smooth and can be related to the observed trend in tropical SSTs, as well as trends in such quantities as Sahelian rainfall and the frequency of tropical Atlantic hurricanes. Further, we have shown this interdecadal background trend to be strongly related to the non-normal growth of mature El Niño patterns (Penland, Matrosova).

Tropical Forcing of extratropical SST anomalies via the "Atmospheric Bridge"

ENSO-induced atmospheric changes can force the ocean far from the equatorial Pacific. As a result, the atmosphere can act like a bridge connecting ENSO-related SST anomalies with those in other parts of the world. We have used several data sets to understand the atmospheric bridges between different ocean basins, with particular emphasis on the formation of large-amplitude North Pacific SST anomalies in the summer before ENSO peaks. Over the western North Pacific, the southward displacement of the jet stream and storm track in summer changes the surface insolation and latent heat fluxes, resulting in anomalous cooling (and deepening) of the oceanic mixed layer at ~40N. The SST anomalies exceed 1C in Aug-Sep, one of the largest "bridge"-related SST signals over the globe. These results have been published as a chapter in forthcoming AGU Monograph (Alexander, Scott).

A coupled AGCM-mixed layer model with Ekman transports

Given the intractable biases of most fully coupled climate models, it is now increasingly evident that the major benefits of coupling are already realized in AGCMs coupled to simpler mixed layer (ML) ocean models. As a further refinement of this simpler set-up for investigating climate variability, we have extended a coupled AGCM-ML model to include anomalous oceanic Ekman heat transports in the model's SST equation. To assess the impact of these transports, we recently generated an ensemble of 10 integrations for 1950-99 with prescribed observed SSTs in the tropical Pacific (15N-15S, 172E to the South American coast) and with a grid of variable-depth ML models over the rest of the global ocean. Preliminary results indicate that the Ekman transports significantly enhance the extratropical SST anomalies forced from the tropics via the atmospheric bridge and possibly influence the feedback of these SST anomalies on the atmosphere. (Alexander, Scott).

Diagnosis of decadal variability in the extratropical and tropical Pacific

To examine variability driven by ocean dynamics in both the extratropical and tropical Pacific, we examined fields from an NCAR OGCM driven by observed surface fluxes over 1958-1997. Our analyses indicated a shoaling of the pycnocline in the central part of the Gulf of Alaska after the mid-1970s, and a deepening in a broad band along the coast. The deepening was particularly pronounced in the western part of the Gulf of Alaska, to the southwest of Kodiak Island, where the pycnocline deepened by 25-30 m after 1976. The surface forcing responsible for these changes was local Ekman pumping over much of the Gulf of Alaska, plus ocean advection and coastally-trapped waves along the west coast of North America. In the tropics, we have examined the evolution of the different branches of the subtropical cell - a shallow overturning circulation with polar flow at the surface and equatorward flow within the pycnocline. The pycnocline transport simulated by the model is consistent with previous observational analyses, and helps confirm that off-equatorial transports influence SSTs on decadal scales. The subtropical cell changes, driven by subtropical winds, do not occur uniformly across the basin but rather are tied to baroclinic adjustment through Rossby wave propagation. (Alexander, Capotondi).

Evaluation of extratropical Atmosphere-Ocean variability in the NCAR Community Climate System Model (CCSM3)

CDC scientists are leading an effort to evaluate extratropical atmosphere-ocean variability in the CCSM3, NCAR's recently released climate system model. More generally, we are seeking a better understanding of the mechanisms of extratropical SST anomaly generation and to what they are misrepresented in the CCSM3. To this end we have examined storm tracks and their relation to SST anomalies; summertime cloud formation; the dominant patterns of atmospheric and oceanic variability, including the NAO and PDO; the upper ocean thermal structure including the winter-to-winter recurrence of SST anomalies; and the pycnocline variability and upper ocean current structure. Many of these phenomena are well simulated by the model although deficiencies clearly exist. Perhaps the most prominent is the underestimation of extratropical-tropical connections in both the atmosphere and ocean. A paper describing these results is being prepared for a special issue of *Journal of Climate* devoted to the CCSM3. (Alexander, Capotondi, Scott)

ENSO-Forced Variability of the Pacific Decadal Oscillation

In a *Journal of Climate* paper (by Newman, Compo, and Alexander) published last year, we showed that North Pacific SST anomalies forced by ENSO via the "atmospheric bridge" peak a few months after the ENSO maximum in tropical Pacific SSTs. Furthermore, North Pacific SSTs also "remember" the previous winter's SSTs: deep oceanic mixed layer temperature anomalies from one winter become decoupled from the surface in summer and then “re-emerge” through entrainment into the mixed layer the following winter. Thus over the course of years the North Pacific integrates the effects of ENSO. Guided by these considerations, we constructed the simplest possible model of the "Pacific Decadal Oscillation" (PDO), using the annually averaged SST anomalies in the central North Pacific as a PDO index, as $P_n = 0.58P_{n-1} + 0.58E_n + \mathrm{h}_n$, where P is the model PDO index, E is the observed ENSO index, n is time (in yrs), and h is uncorrelated noise. Model forecasts of the PDO index had a correlation of 0.74 with observations. This showed that to first order the PDO may be considered a red response to atmospheric noise as well as to ENSO, resulting in more decadal variability than both.This null hypothesis should be kept in mind when diagnosing and modeling “intrinsic” North Pacific decadal variability.

Following up on this research, we have built a more sophisticated 9-component Linear Inverse Model (LIM) of decadal tropical-extratropical variability. The 9 components represent 7 EOFs of tropical Indo-Pacific and 2 EOFs of North Pacific annual mean (July to June) SST anomalies. The model is trained on 1-yr lag correlations; nevertheless its cross-validated one-year anomaly correlation forecast skill is about 0.6 for the leading PCs of both tropical and North Pacific SSTs. When integrated in "climate" mode, the model yields power spectra in good agreement with observed PDO spectra. Similar LIMs constructed from CMIP2 coupled-GCM output (from 10 different modeling centers) suggests that the coupled models probably misrepresent decadal North Pacific SST variability because they incorrectly simulate ENSO and/or the atmospheric bridge. That is, both the "bridge" between the Tropical and North Pacific SSTs, as well as the decadal Tropical SST variability itself, are weak in these models compared to observations. By underestimating the tropically forced portion through these biases, the coupled models thus overemphasize the "internally generated" portion of decadal North Pacific SST variability.

SST influences on the NAO

We have completed a study of the extratropical and tropical Atlantic SST forcing of the NAO. It suggests that the observational relationship between the fall North Atlantic horseshoe (NAH) SST anomaly and the subsequent winter NAO, as identified in recent studies, cannot be accounted for by the NAH SST forcing of the NAO. Instead, this relationship may result from the seasonal march of extratropical coupled responses to persistent tropical SST forcing. An article describing these findings has been accepted for publication in J. Climate (Peng et al. 2005). To determine the effects of Ekman transports on the extratropical coupled response to tropical SST forcing, we have developed a new coupled model (AGCM_EML) by including the Ekman advection in the slab mixed-layer ocean. Large ensembles of experiments with the AGCM_EML forced by the same tropical SST anomaly have been conducted. The results show that with the Ekman advection included, the tropical forcing induces a coupled NAO-SST tripole response earlier in the season, in comparison with that in the AGCM_ML (NDJ vs. FMA). As a result, the seasonality of the NAO response in the AGCM_EML is more consistent with observations. (Peng)

ENSO as a regulator of the mean tropical climate

We have continued refining our theory of ENSO as a planetary scale "heat pump". According to the theory, La Niña is a mechanism by which the subsurface equatorial Pacific ocean stores excess solar heat, and El Niño acts a ventilator to transport that excess poleward. ENSO is thus a regulator of the tropical Pacific climate. We have shown that the observed variations of the tropical Pacific heat balance over the last 20 years are consistent with this view. Numerical experiments with a coupled atmosphere-ocean model consisting of an empirical atmospheric model coupled to an NCAR Pacific basin ocean model also support this view. The anomalous ENSO activity observed over the last two decades could thus be a response to enhanced radiative heating of the tropical Pacific, consistent with the anomalously high warm-pool SSTs observed in this period. By underscoring the importance of ENSO in regulating the mean climate, the heat pump view suggests caution in accepting predictions of mean climate changes by models that misrepresent ENSO variability.

To further investigate the role of ENSO as a tropical climate regulator, we conducted pairs of perturbation experiments in a coupled model with ENSO turned on and off. Perturbations were introduced through either enhancing tropical heating or subtropical cooling. Regardless of the perturbation method, the time mean value of Tw -Tc (the temperature difference between the warm-pool SST and the characteristic temperature of equatorial thermocline water) was much smaller with than without ENSO. In the enhanced tropical heating case, ENSO mixed surface heat down to the thermocline, whereas in the enhanced subtropical cooling case the same downward mixing reduced the equatorial thermocline cooling induced by the subtropical cooling through subsurface transports. To the degree that the value of Tw-Tc controls the stability of the tropical Pacific climate system, these numerical experiments provide further confirmation of ENSO as a regulator of the tropical climate. (Sun)

Understanding the differences between the mid-Holocene and present climates

One way to build confidence in future climate projections is to assess our ability to simulate past climate changes, for which, unlike the future, at least some observational paleoclimatic verification data are available. For example, the paleoclimatic evidence suggests that during the mid-Holocene epoch (about 6000 years ago) North America and North Africa were significantly drier and wetter, respectively, than at present. Modeling efforts using fully coupled climate models to attribute these differences to differences in orbital forcing and greenhouse gas levels have had limited success, especially over North America. In this study, the importance of a possibly cooler tropical Pacific ocean during the epoch (akin to a permanent La Nina-like perturbation to the present climate) in causing these differences was investigated. Systematic sets of AGCM experiments, with prescribed SSTs in the tropical Pacific and coupling to a mixed-layer slab ocean elsewhere, were performed. Our simulated responses to these changes were generally consistent with the available paleoclimatic records. We concluded that the net response to the orbital changes was to shift the North Atlantic ITCZ northward and make North Africa wetter. The response to the reduced greenhouse gas levels opposed but did not eliminate these changes. The northward shifted ITCZ also blocked the moisture supply from the Gulf of Mexico into North America. This drying tendency was greatly amplified by the local response to La Nina-like conditions in the tropical Pacific. Local soil-moisture feedbacks further amplifed the drying. Consistent with the paleoclimatic evidence, the simulated North American drying was also most pronounced in the growing (spring) season. A paper describing these results is in preparation (Shin, Sardeshmukh, Webb, Oglesby, Barsugli).

Tropical Climate Regimes and Global Climate Sensitivity in a Simple Setting

Most current climate models have trouble simulating tropical rainfall. In particular the Pacific ITCZ varies considerably from model to model. Even the zonal mean rainfall fields show large *structural* uncertainties with some models exhibiting a distinct “double ITCZ”. Many of these models also have 1-2K biases in tropical SSTs. To better understand the connection between the two, we forced an AGCM coupled to a global slab ocean with globally uniform insolation. To our surprise, we found multiple tropical climate regimes with radically different ITCZ structures for different values of the insolation. In order from the coldest to the warmest climates these were: a symmetric double ITCZ, a near-symmetric equatorial ITCZ, a transient asymmetric ITCZ, and a stable, strongly asymmetric ITCZ. Further diagnosis showed that air-sea coupling was essential for the establishment and maintenance of the strongly asymmetric ITCZ. Wind-evaporation-SST feedback, as well as the longwave radiative effects of clouds and water vapor on SSTs, were all important in maintaining the asymmetric regime. This demonstration of the existence of multiple regimes even in a single AGCM, and their dependence on SST feedbacks, may have a bearing on the ITCZ errors of current coupled climate models. Their existence also complicates the notion of a constant global mean surface temperature sensitivity to climate change, because climate sensitivity measured across a regime transition can be much larger than the sensitivity within a single regime. These results will appear in an article in the *Journal of Atmospheric Sciences*. (Barsugli, Shin, Sardeshmukh).

Understanding the causes of the cold-tongue bias in coupled models: the role of climate feedbacks

A cold bias in the central equatorial Pacific cold tongue region is common to many coupled climate models. To diagnose its causes, climate feedbacks in the equatorial Pacific in 7 leading AGCMs have been quantified and compared with observations. The AGCMs are the NCAR CAM1, CAM2, and CAM3; the Hadley Center Model, the NASA/NSIPP AGCM, and the GFDL AM2p10 and AM2p12. With the exception of the GFDL models, all of these AGCMs produce an excessive cold tongue when coupled to OGCMs. In all of them, the net feedback from the atmosphere on SST is less negative over the region than in observations. In other words, all of these model atmospheres over the cold tongue have a weaker regulating effect on the underlying SST than does the real atmosphere. We have determined that this is basically because the negative cloud albedo and atmospheric transport feedbacks are underestimated and the positive water vapor feedback is overestimated. The GFDL models do relatively well in this regard, but they too have cold biases in coupled mode. This suggests that a weaker regulating effect from the atmosphere is an important but not the only factor responsible for the excessive cold tongues in coupled models. The need to validate feedbacks from oceanic transports is therefore highlighted (Sun, Covey, Chou, Collins, Hack, Held, Klein, Kiehl, Meehl, Suarez)

Numerical implementation of stochastic terms in NWP and climate models

We have developed a new method for adapting existing GCM and NWP model codes to handle stochastic forcing arising from random errors in the model's physical parameterization tendencies at each time step. Its chief virtue is that it satisfies well-known numerical convergence criteria without requiring extensive rewriting of the code. We have also shown how a naive application of standard deterministic numerical methods to handle stochastic forcing can cause severe errors, particularly in systems with multiple dynamical regimes A paper describing these results was published in *Monthly Weather Review*. A follow-up note on efficient approximation techniques for integrating stochastic differential equations has been submitted. Current research includes proving a conjecture on converting deterministic numerical schemes to stochastic ones made in the note, and introducing stochastic integration components in the GFDL ocean model's dynamical core. This last project will be done in collaboration with colleagues at Texas A&M University (Penland).

Refining techniques to account for sub-grid scale variability of cloud properties and radiative fluxes in GCMs

CDC scientists have been working for several years on accounting for the effects of subgrid-scale variations of cloud and water vapor in large-scale models by treating each large-scale model column as a series of subcolumns. Each subcolumn is homogeneous, but the statistical properties of the population of subcolumns reproduces the large-scale model state. If a particular layer in the large-scale column has cloud fraction 50%, for example, then half of the subcolumns will have cloud in that layer. Nonlinear process rates (e.g. radiation and precipitation fluxes) can be computed in each subcolumn and the results averaged; this has been shown to remove biases, especially in radiation. These ideas have been implemented in the GFDL AM2 model. The AM2, like most models, assumes that clouds within a grid box are homogeneous, so our effort focused on using the subcolumns to represent cloud overlap. We built a subcolumn generator and tied this to the model's radiation code (which was modified to use the Monte Carlo Independent Column

Approximation) and to the diagnostics package, most notably the ISCCP simulator. This treatment of cloud overlap and the necessary radiation code will be incorporated into the default model once GFDL's IPCC runs are completed (Pincus).

Developing stochastic climate simulators for diagnosing climate model errors and climate sensitivity

In two papers published recently in the *Journal of Climate*, we investigated the viability of using atmospheric single column models (SCMs) to diagnose observed and GCM-simulated climate variations. A fundamental weakness of SCMs stems from their decoupling of adiabatic and diabatic tendencies, which often leads to explosive spurious instabilities. To correct this weakness, we developed a simple coupling scheme that effectively stabilizes the SCM. This helps it maintain a realistic climate in long integrations, reduces error growth in short integrations, and reduces growth of ensemble spread in ensemble integrations. Our results imply that the decoupled SCM framework is itself a significant source of error that can easily mask the physical parameterization errors that are the real targets of SCM diagnosis.

Additionally, because our coupled SCM is stable, it provides the foundation for developing more sophisticated diagnostic models. In this vein, we have extended the coupled SCM to include additional corrective and stochastic forcings. These forcings can be specified in such a way as to reproduce either the observed or a GCM's climate variability at any gridpoint of interest. Such a flexible diagnostic tool clearly has wide application. We recently constructed and tested a prototype based on the NCAR SCM (CCM3.6 and CAM2.0) physics on temperature and humidity fluctuations observed during TOGA COARE. The results were encouraging: the stochastically forced SCM maintained a stable climate in long (1000 day) runs and produced temperature and humidity variations with realistic amplitude and vertical structure. (Bergman, Sardeshmukh, Penland)

Studies of Subseasonal Predictability

Last year we published in *Monthly Weather Review* a detailed study (by Newman, Sardeshmukh, Winkler, and Whitaker) of the potential and actual predictability of 7-day mean atmospheric variations anomalies at the Week 2 and Week 3 forecast ranges using simple statistical and comprehensive NWP models. It is interesting and important that the skills of the statistical and NWP models are comparable at these ranges. This work has been presented at many conferences and symposia. It has been influential in rekindling interest in Week 2 and Week 3 predictability and has helped make Week 2 Predictability an important research theme of THORPEX. This year we were awarded a new 3-yr Clivar-Pacific grant (PIs: Sardeshmukh, Newman, Penland) to further develop our linear inverse model of tropical variations by explicitly considering the vertical structure of the diabatic heat sources and moisture sinks and coupled interactions with the underlying SSTs.

A stochastic perspective on atmospheric regime behavior

Atmospheric circulation statistics are not strictly Gaussian. Small bumps and other deviations from Gaussianity of the probability distributions are often interpreted as implying the existence of distinct and persistent nonlinear circulation regimes, with potentially higher than average levels of predictability. We have recently shown that such deviations can, however, also result from stochastically perturbed linear dynamics with multiplicative (i.e., state-dependent) noise statistics, but are associated with much lower predictability. Multiplicative noise is generally identified with state-dependent variations of stochastic feedbacks from unresolved system components, and may be treated as stochastic perturbations of system parameters. We have shown that including such perturbations in the damping coefficient of large-scale linear Rossby waves can produce deviations from Gaussianity very similar to those seen in the joint probability distribution of the first two Principal Components (PCs) of observed weekly-averaged 750 hpa streamfunction data of the past 52 winters. A closer examination of the Fokker-Planck probability budget shows that the observed deviations are indeed consistent with multiplicative noise, and are unlikely the result of slow nonlinear interactions of the two PCs. Thus the observed non-Gaussian probability distributions do not necessarily imply the existence of persistent nonlinear circulation regimes, but are rather more consistent with the expected distributions for a linear system perturbed by multiplicative noise. A paper describing these results is due to appear in the *Journal of the Atmospheric Sciences*. (Sura, Newman, Penland, Sardeshmukh)

Improving Week 2 Forecasts using Retrospective Ensembles

CDC has produced a 23-year dataset of retrospective 2-week ensemble forecasts using a reduced-resolution version of the NCEP Medium-Range Forecast (MRF) model. This retrospective forecast database was used to develop statistical corrections to real-time ensemble forecasts. We found that the uncorrected ensemble forecasts had little skill at Week 2, but after statistical correction, were much more skillful than NCEP's operational Week 2 forecasts in the winters of 2001 and 2002, We established that most of this improvement could have been achieved with a shorter 10-yr forecast training dataset. Based on these results, we recommend that operational forecasting centers invest in generating such datasets on a regular basis to obtain reasonably accurate statistics of their forecast errors before implementing new model versions. (Hamill, Whitaker)

An Experimental MJO Prediction Website

Improved predictions of the Madden-Julian Oscillation (MJO) offer the possibility of increasing tropical and extratropical forecast skill at lead times of 1-4 weeks. Unfortunately, current GCMs have difficulty in representing the MJO and its associated multi-scale interactions of convection and circulation. Acting on recommendations from two recent NASA/NOAA workshops on subseasonal variability, CDC agreed to host a website where real-time and experimental MJO forecasts could be objectively evaluated, and feedback provided to the forecasters. A preliminary version of the website became operational in November 2003. Substantial additions to the site have since been implemented. Forecast contributions now number five statistical models, two GCM ensembles and a coupled ocean-atmosphere model, with more contributions pending. Forecasts of five different variables are displayed in a common graphical format for easy comparison. Week 1 and 2 forecasts are being emphasized at this stage, but eventually will be extended to Weeks 3-4 if feasible (e.g., the ECMWF 51-ensemble member forecast out to 30 days is available weekly). Forecasts are being verified in real time using spatial anomaly correlations. Results confirm that both the statistical and numerical prediction models have only marginal skill at Week 2, even for planetary scale variables like 200 mb velocity potential. The forecast skill of tropical precipitation is poor for all the available GCMs. (Weickmann).

Feasibility of atmospheric circulation Reanalyses before the radiosonde era

For a reconstruction of weather maps of the past 100 years, no upper level radiosonde wind observations are available for the early part of the record (pre-1948). However, some surface pressure observations are available. In this study, the feasibility of reanalyzing this early record using an ensemble square-root filter (EnSRF) was examined. Real surface pressure observations for 2001, sub-sampled to resemble observation densities in 1895, 1905, 1915 and 1935 were used. Analysis errors were defined relative to a three-dimensional variational (3DVar) analysis performed using current observation densities. Results obtained with an improved EnSRF algorithm led us to conclude that a tropospheric northern hemisphere reanalysis of the 20th century is feasible even using only surface pressure observations. The expected analysis errors at 850 and 300 mb of geopotential heights and zonal and meridional winds would be similar to current 1 to 2 day forecast errors, and 2 to 3 day forecast errors, respectively, at those levels. A similar tropospheric reanalysis of the southern hemisphere, and of the northern hemisphere in the late 19th century, will also be feasible after more observations become available. Our next step is to produce an actual reanalysis of 1938-1948 using the EnSRF and available surface pressure observations. (Compo, Whitaker, Hamill, Sardeshmukh)

Advanced techniques for climate data assimilation.

CDC scientists have developed an experimental climate data analysis system based upon the ensemble Kalman filter. The system utilizes an ensemble of forecasts from a global atmospheric model to estimate the uncertainty in the first-guess fields used in the analysis. The flow-dependant nature of this uncertainty estimate allows the system to make much better use of sparse observations, compared to current analysis systems that use static first-guess uncertainty estimates. This makes the scheme particularly well suited for a reanalysis of the first half of the twentieth century. We published a paper (Whitaker, Compo, Hamill) in *Monthly Weather Review* this year demonstrating the performance of the scheme for a simulated 1915 network of only surface pressure observations. Analyses at 500 mb for this case were roughly as accurate as current 60-hr forecasts. We have since refined the EnSRF algorithm further, and plan to use it this year to produce a pilot reanalysis of the 1938-48 period using only surface pressure observations.

Develoment of a South American precipitation dataset

CDC, in conjunction with scientists from the University of Buenos Aires, has archived daily precipitation data from more than 30 sources in South America, resulting in data from more than 8,000 stations. Unfortunately, these observations are not evenly distributed but are concentrated east of the Andes Mountains, with highest density near the coast of Brazil. Nonetheless, they have proved to be valuable for model validation and diagnosis of climate variability. For example, we have used these data to investigate the relationship between extremes of daily precipitation and episodes of strong northerly low-level flow east of the Andes. The problem is of practical interest, because the low-level jet transports most of the water that ultimately ends up as precipitation in the Rio de la Plata basin, the most agriculturally intensive and densely populated basin of South

America. We have also examined the relationship between variations of the low-level jet strength and those in the vicinity of the South Atlantic convergence zone, a band of precipitation extending southeastward from the Amazon Basin into the Atlantic Ocean. The two are out of phase on many time scales. On the synoptic scale, activity in one and suppression of the other depends on the phase of the synoptic midlatitude wave train as it crosses the Andes and curves northward into South America. There is also a preference, albeit weak, for the phase of the synoptic wave to be determined by the phase of the MJO. This provides some hope of improving long-range (greater than two weeks) forecasts over the region. Future work will focus on understanding relationships between the MJO and precipitation over all of South America, as well as the dominant dynamics responsible for those relationships. As a service to the community, we have put these data onto grids and made them available via the World Wide Web. A manuscript describing the dataset is due to appear in the *Bulletin of the American Meteorological Society*. (Liebmann).

Trends in South American rainfall

Some long-term trends in South American precipitation have been identified. Of particular interest is a positive trend in Southern Brazil, which contributes to rainfall in the Paraná River Basin that is part of the Rio de la Plata system. The trend is observed in the January – March season, and from 1976-1999 explains more than 30% of the interannual variance. It results from an increase in the number of rainy days in the wet season (which has not increased in length), and an increase in the amount per rainy day. The trend is also apparently related to the SST trend off the Brazilian coast, although perhaps not causally. The SST trend is linked to a systematic decrease in the strength of the South Atlantic High, which has resulted in reduced coastal upwelling and less mechanical stirring. The cause of the precipitation trend is being investigated. It is interesting and important that this trend is generally absent in AGCM simulations of the second half of the 20th century with prescribed observed SSTs. A paper describing these results was published in the *Journal of Climate*. (Liebmann).

Some other CDEP Activities

An effort has been made to post weather-climate forecast discussions on a quasi-regular basis since December 2003. The discussions evaluate the real time global atmospheric circulation anomalies, utilize forecasts of the MJO available on the CDC website and make experimental subjective predictions of US temperature and precipitation for weeks 1 through 3. They also seek to link midlatitude synoptic events with the more slowly evolving MJO and teleconnection patterns with an emphasis on extreme events and circulation transitions. A subseasonal synoptic-dynamic model provides a framework for evaluating the prediction models and for forecasting circulation and USA temperature/precipitation anomalies (Weickmann)

CDC continues to provide scientific support to the OGP-funded regional assessment on the effects of climate variability on water resources in the Interior West ("Western Water Assessment", or WWA). CDC scientists continue their frequent interactions with other federal and state agencies such as Department of the Interior, including the Bureau of Reclamation and the Fish and Wildlife Service, and other user groups, such as the Denver Water Board, Colorado River Water Conservation District, and Colorado Drought Task Force. An important objective of this research is to learn how to better incorporate climate information and forecasts into water resource decisions in this highly water-sensitive region. CDC also continues to work closely with NCEP, particularly with EMC on the coupled model project and with CPC on week-two and seasonal climate forecasts. A CDC scientist will spend six months at EMC in FY05 helping implement stochastic parameterizations in the NCEP models. In collaboration with the IRI, CDC conducts diagnostic and predictability analyses with models that are used for predictive purposes by the IRI and its partners.

CDC also continues its strong tradition of public outreach and service to the broader scientific community. CDC staff, in collaboration with CPC staff, developed a week-long NWS/SOO training course that has so far been given six times in the spring and fall seasons of 2002, 2003 and 2004. CDC staff continue to provide numerous media interviews and specialized climate briefings. The CDC web site contains links to many experimental and applied climate products that were developed at CDC under the support of the CDEP/ARC program. Some examples were already highlighted in the main body of this report. Other examples of available products include prototype global risk assessments; climate probability distributions; interactive pages for calculating and displaying composite fields and correlations from NCEP Reanalysis data; operational analyses, US climate division data, ENSO climate risk pages, and a climate products information page that includes a broad range of operational and experimental climate products, particularly those developed by NOAA and its partners. CDC continues to serve as a primary redistribution point for the NCEP Reanalysis data set, providing netCDF versions of the reanalysis fields via the web or via tape (for larger requests) to users throughout the world. CDC is a core NOAA partner, with NCEP, NCDC, GFDL, and PMEL, in the NOAA Operational Model Archive and Distribution System (NOMADS) being developed to provide seamless access to geographically distributed climate model outputs.

CDC was heavily involved in two NASA-sponsored workshops held in Spring 2002 and 2003 that explored the potential for improving forecasts of weather and short-term climate variability on subseasonal time scales. The CDC MJO website is a direct outcome of these workshops. The website has already facilitated discussion in the weekly CPC hazards assessment calls. Our goal in participating in these calls is to explore the possibility of extending skillful predictions of extreme weather events into the week 2 timeframe. (Dole, Weickmann, Newman, Sardeshmukh, Whitaker).

CDC continued updating and improving the recently renamed International Comprehensive Ocean-Atmosphere Data Set (I-COADS), under a cooperative project with NCAR and NOAA/NCDC. The new name recognizes the multinational input to the database, while maintaining continuity of identity with COADS, which has been widely used and referenced. Updated data products, together with 1° monthly summaries, are included in the new real-time (I-COADS.RT) archive. (Woodruff)

CDC-CDEP General Research Objectives, FY05

Most of the projects described in the previous sections are ongoing research efforts, and as such will continue into FY05. CDC's overall research emphasis will continue to be on applying its unique diagnostic expertise to help achieve CDEP's primary goal of improving the skill and usefulness of climate forecasts, in support of the IRI, NCEP, and regional assessments. Stronger collaborations continue to be developed with the IRI to support global seasonal predictions, as well as with GFDL on climate model diagnosis. We are working with GFDL to bring the Flexible Modeling System (FMS) and AM2 climate model to CDC. This will allow CDC scientists to do research and develop diagnostics using the same model that NOAA will use for making its contributions to the IPCC Fourth Assessment. Several CDC scientists are also preparing to evaluate and diagnose the new NCEP atmospheric (GFS) and coupled (CFS) forecast systems.

CDC will continue major efforts in diagnostic and predictability research to further NOAA's capabilities in extreme events risk predictions; describing relationships between intraseasonal variations such as the MJO and seasonal-to-interannual climate predictions and predictability; clarifying ocean-atmosphere interactions on longer than ENSO time scales; assessing extratropical ocean-atmosphere processes and related prospects for predictability; establishing improved measures to estimate the confidence of climate forecasts; and developing the means to better communicate climate information to the public and decision makers. Specific research foci will include:

- Assessing effects of coupled processes on large-scale teleconnections
- Identifying impacts of decadal variability and long-term trends on climate predictability

* Improving methods of ensemble prediction and ensemble data assimilation
* Developing Linear Inverse Modeling (LIM) methods of diagnosis and prediction
* Developing stochastic approaches to modeling and parameterizations
* Improving probability forecasts through estimation of future probability distribution functions (PDF's) through large ensembles, multi-model approaches and other techniques
* Evaluating links between weather and climate for applications in climate forecasts (e.g., improved estimates of extreme event risks)
* Diagnosing physical processes using observations and a hierarchy of simple models

CDC will continue to provide a sustained infrastructure that enables NOAA to better meet current and emerging needs of users for climate data and forecasts. Examples include developing web-based products to improve access to available climate information, and simplifying interactive uses of climate data and forecasts. Such activities help to support the missions of the IRI, NCEP, and projects supported by OGP under its regional assessments and human dimensions programs.

Refereed Journal Articles by CDC Scientists (Jan-Nov 2004)

Alexander MA, Bhatt US, Walsh JE, et al.
The atmospheric response to realistic Arctic sea ice anomalies in an
AGCM during winter.
JOURNAL OF CLIMATE 17 (5): 890-905 MAR 2004

Bergman JW, Sardeshmukh PD
Dynamic stabilization of atmospheric single column models
JOURNAL OF CLIMATE 17 (5): 1004-1021 MAR 2004

Bister M, **Mapes BE**
Effect of vertical dipole temperature anomalies on convection in a cloud model.
JOURNAL OF THE ATMOSPHERIC SCIENCES 61 (16): 2092-2100 AUG 2004

Bradley RS, Keimig FT, **Diaz HF**
Projected temperature changes along the American cordillera and the
planned GCOS network.
GEOPHYSICAL RESEARCH LETTERS 31 (16): Art. No. L16210 AUG 28 2004

Carvalho LMV, Jones C, **Liebmann B**
The South Atlantic convergence zone: Intensity, form, persistence, and
relationships with intraseasonal to interannual activity and extreme rainfall.
JOURNAL OF CLIMATE 17 (1): 88-108 JAN 2004

Compo GP, Sardeshmukh PD
Storm track predictability on seasonal and decadal scales
JOURNAL OF CLIMATE 17 (19): 3701-3720 OCT 2004

Ewald B, **Penland C**, Temam R
Accurate integration of stochastic climate models with application to El nino
MONTHLY WEATHER REVIEW 132 (1): 154-164 JAN 2004

Flugel M, Chang P, **Penland C**
The role of stochastic forcing in modulating ENSO predictability
JOURNAL OF CLIMATE 17 (16): 3125-3140 AUG 2004

Hamill TM, Whitaker JS, Wei X
Ensemble reforecasting: Improving medium-range forecast skill
using retrospective forecasts MONTHLY WEATHER REVIEW 132 (6): 1434-1447 JUN 2004

Hoerling MP, Hurrell JW, **Xu T**, et al.
Twentieth century North Atlantic climate change. Part II: Understanding the effect of Indian Ocean warming
CLIMATE DYNAMICS 23 (3-4): 391-405 SEP 2004

Hurrell JW, **Hoerling MP**, Phillips AS, et al.
Twentieth century North Atlantic climate change.
Part 1: assessing determinism
CLIMATE DYNAMICS 23 (3-4): 371-389 SEP 2004

Jakob C, **Pincus R, Hannay C**, et al.
Use of cloud radar observations for model evaluation: A probabilistic approach
JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES 109 (D3): Art. No. D03202 FEB 5 2004

Kerwin MW, Overpeck JT, **Webb RS**, et al.
Pollen-based summer temperature reconstructions for the eastern
Canadian boreal forest, subarctic, and Arctic
QUATERNARY SCIENCE REVIEWS 23 (18-19): 1901-1924 OCT 2004

Lee MI, Kang IS, **Mapes BE**
Impacts of cumulus convection parameterization on aqua-planet
AGCM Simulations of tropical intraseasonal variability
JOURNAL OF THE METEOROLOGICAL SOCIETY OF JAPAN 81 (5): 963-992 OCT 2003

Li SL
Impact of northwest Atlantic SST anomalies on the circulation
over the ural mountains during early winter
JOURNAL OF THE METEOROLOGICAL SOCIETY OF JAPAN 82 (4): 971-988 AUG 2004

Liebmann B, Kiladis GN, Vera CS, et al.
Subseasonal variations of rainfall in South America in the vicinity of the low-level jet east of the Andes and comparison to those in the South Atlantic convergence zone
JOURNAL OF CLIMATE 17 (19): 3829-3842 OCT 2004

Lin JL, Mapes B
Wind shear effects on cloud-radiation feedback in the western Pacific warm pool
GEOPHYSICAL RESEARCH LETTERS 31 (16): Art. No. L16118 AUG 31 2004

Lin JL, Mapes BE
Radiation budget of the tropical intraseasonal oscillation
JOURNAL OF THE ATMOSPHERIC SCIENCES 61 (16): 2050-2062 AUG 2004

Lin JL, Mapes B, Zhang MH, et al.
Stratiform precipitation, vertical heating profiles, and the Madden-Julian oscillation
JOURNAL OF THE ATMOSPHERIC SCIENCES 61 (3): 296-309 FEB 2004

Mangan JM, Overpeck JT, **Webb RS**, et al.
Response of Nebraska Sand Hills natural vegetation to drought, fire, grazing,
and plant functional type shifts as simulated by the century model
CLIMATIC CHANGE 63 (1-2): 49-90 MAR 2004

Mapes BE
Sensitivities of cumulus-ensemble rainfall in a cloud-resolving
model with parameterized large-scale dynamics
JOURNAL OF THE ATMOSPHERIC SCIENCES 61 (18): 2308-2317 SEP 2004

Mapes BE, Warner TT, Xu M
Comparison of cumulus parameterizations and entrainment using
domain-mean wind divergence in a regional model
JOURNAL OF THE ATMOSPHERIC SCIENCES 61 (11): 1284-1295 JUN 2004

Otto-Bliesner BL, Brady EC, **Shin SI**, et al.
Modeling El Nino and its tropical teleconnections during the
last glacial-interglacial cycle
GEOPHYSICAL RESEARCH LETTERS 30 (23): Art. No. 2198 DEC 5 2003

Peng SL, Robinson WA, **Li SL**
Mechanisms for the NAO responses to the North Atlantic SST tripole
JOURNAL OF CLIMATE 17 (15): 3055-3055 AUG 2004

Seth A, Rojas M, **Liebmann B**, et al.
Daily rainfall analysis for South America from a regional
climate model and station observations
GEOPHYSICAL RESEARCH LETTERS 31 (7): Art. No. L07213 APR 14 2004

Shinoda T, Hendon HH, **Alexander MA**
Surface and subsurface dipole variability in the Indian Ocean and its relation with ENSO
DEEP-SEA RESEARCH PART I-OCEANOGRAPHIC RESEARCH PAPERS 51 (5): 619-635 MAY 2004

Shinoda T, Alexander MA, Hendon HH
Remote response of the Indian Ocean to interannual SST variations
in the tropical Pacific
JOURNAL OF CLIMATE 17 (2): 362-372 JAN 2004

Sun DZ, Zhang T, Shin SI
The effect of subtropical cooling on the amplitude of ENSO: A numerical study
JOURNAL OF CLIMATE 17 (19): 3786-3798 OCT 2004

Wang XG, Bishop CH, Julier SJ
Which is better, an ensemble of positive-negative pairs or a
centered spherical simplex ensemble?
MONTHLY WEATHER REVIEW 132 (7): 1590-1605 JUL 2004

Whitaker JS, Compo GP, Wei X, **Hamill TM**
Reanalysis without radiosondes using ensemble data assimilation
MONTHLY WEATHER REVIEW 132 (5): 1190-1200 MAY 2004