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The U.S. CLIVAR CPT Program

by Raffaele Ferrari, Massachusetts Institute of Technology

Numerical models have become essential tools in the study and prediction of natural climate variability and anthropogenic climate change. However the skill of such models in simulating the observed climate variability is still severely limited by (1) numerical approximations in the discretization of the hydrodynamical equations and (2) imperfect parameterizations of the myriad of atmospheric and oceanic processes that happen at scales too small to be explicitly resolved by the model. In the 1960s, at the dawning of the age of numerical modeling, the accuracy of the numerical schemes was the real bottleneck. For example, early models of the ocean generated excessive mixing across density surfaces due to poor numerical discretization. Great strides have been made over the past four decades in overcoming these technical difficulties both through improvement of the numerical codes and through increase in computational power. Currently the major source of model error has become the imperfect or missing parameterization of unresolved processes.

In the U.S. a large fraction of the development and maintenance of IPCC-class models is carried by scientists working at specialized modeling centers. These centers have been successful in improving the numerical kernel of climate models. However the development of effective parameterizations is intellectually more challenging and cannot devolved to a few centers. It demands physical understanding of how the relevant process relate to the overall ocean and atmosphere dynamics, and a careful consideration of issues related to model resolution and numerical formulation. While the modeling centers have the expertise to deal with the latter, progress in basic understanding is typically the result of observations, theory, and idealized studies which involve the broader scientific community. Currently there is little coordination between research at the modeling centers and elsewhere. As a result, parameterizations in atmospheric and oceanic general circulation models do not reflect recent advances in our understanding of the corresponding processes. This is arguably the biggest bottleneck in improving high-end climate models.

Climate Process and Modeling Teams (CPTs) were created in 2003 by the U.S. Climate Variability and Predictability (CLIVAR) program to provide a thorough and efficient forum for improving model parameterizations. CPTs are a small group of observationalists, theoreticians, small-scale modelers, and scientists at the modeling centers to work closely together to improve parameterizations of a particular process in one or more climate models. After a call for proposals, three pilot CPTs have been funded by NSF and NOAA for a three year period: one CPT examining cloud-feedbacks in the atmosphere, and two other CPTs focused on ocean dynamics, one on eddy variability in the upper ocean and the other on gravity currents. The three pilot CPTs are currently being reviewed to evaluate the effectiveness of the new framework. The goal of the three following brief papers is to summarize key results obtained by the CPTs so far and to provide a basis for discussion of the CPT approach within the scientific community.

Motivations for the U.S. CLIVAR's Process Studies and Model Improvement Panel (PSMIP)

by David M. Legler, Director

I had the opportunity to attend the recent Annual AMS Meeting in Atlanta. As usual, there was a wide range of scientific results presented. While it was reassuring to see how far the community has come in various research areas, fundamental challenges such as faithfully representing critical processes in models used to simulate and predict climate still remain. In one high-profile talk at the Meeting, Peter Stone from MIT explored the relationship between critical climate processes and climate model sensitivity (global mean equilibrium temperature response to a doubling of CO_2). Through the use of several diagnostics of coupled climate model runs, he demonstrated how model sensitivity (norms of IPCC model sensitivities are often touted as bellwether indicators) is related to these processes, including those processes that govern heat uptake by the ocean (as expressed in the model through an ocean mixing

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coefficient). His study motivates more careful evaluations of climate models using multiple diagnostics to determine how process parameterizations are linked to model results and their subsequent interpretations. This seems especially critical in the presented results, which suggest climate models have generally been overestimating the rate of mixing of heat into the deep ocean, meaning projections of future surface warming may be too low.

The points raised in the presentation especially motivate the efforts of the U.S. CLIVAR Process Study and Model Improvement Panel (PSMIP). U.S. CLIVAR has historically been strong in promoting and coordinating observational field campaigns and focused modeling activities aimed at improving our understanding and treatment of critical climate processes. In this issue, the three U.S. CLIVAR Climate Process and Modeling Teams (CPTs) describe results that address two sub-grid scale parameterizations of ocean processes that help determine the uptake and distribution of heat, freshwater, and carbon dioxide. A third CPT report on important cloud precesses. Additionally, we report on various other activities of significance to the U.S. CLIVAR community.

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Climate Process Team on Eddy Mixed Layer Interactions:

Eddy-mixed layer interactions in the ocean

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The Climate Process Team on Eddy Mixed Layer Interactions Ocean circulation models used in climate studies typically have mesh grids with a horizontal resolution close to one hundred kilometers, and a vertical resolution transitioning from ten meters at the surface to a few hundreds meters at depth. With such grids all the mesoscale variability (ocean cyclones and anticyclones) and microscale variability (turbulent mixing due to processes such as breaking internal waves and convection) are sub-grid scale and must be parameterized. Although more powerful computers may soon decrease the feasible grid scale to a marginal mesoscale eddy resolution of O(25) km, even finer grids of O(10) km or better are needed to adequately resolve the fluxes produced by mesoscale motions. Thus parameterization of both mesoscale and microscale processes is the only solution for the forseable future.

The CPT on eddy-mixed layer interactions was organized to improve the parameterization suite of sub-grid scale processes in the upper ocean. The decision to focus on the upper ocean was based on two main considerations. First, the Earth's climate is most sensitive to upper ocean dynamics where communication takes place between the atmosphere and the oceanic reservoir of heat, freshwater and carbon dioxide. Second, ocean mesoscale and microscale variability is strongly surface intensified and thus parameterizations have a larger impact on global climate close to the surface.

The upper ocean is typically characterized by a weakly stratified boundary layer (BL) overlying a more stratified thermocline. There is a rich literature on parameterizations of microscale turbulent mixing both in the BL and in the stratified interior. Less is known about mesoscale eddies and their parameterization is the primary focus of the CPT. The current paradigm for ocean eddy parameterization dates back to the work of Gent and McWilliams in the 90s, who realized that eddy fluxes are quasi-adiabatic in the ocean interior and should be represented as an eddy-induced velocity. The Gent-McWilliams (GM) scheme reduced climate drift in coupled ocean-atmosphere models and it has become a standard for climate studies. A major limitation of the GM scheme is that the adiabatic assumption is not valid in the BL where diabatic processes are strong. The common practice in ocean models today is to use ad hoc tapering functions to turn off the adiabatic eddy-induced velocity near the surface, without including any parameterization for the surface eddy fluxes. The tapering approach is at odds with the observational and theoretical evidence that eddy fluxes have a strong impact on the dynamics of the upper ocean. The CPT on eddy-mixed layer interactions used a combination of theory, available observations, and process models to improve our understanding and parameterizations of the eddy processes in the BL. Due to space limitations, we cannot review all the research activities in the team. Instead we briefly list the ongoing research projects and we discuss how they contributed to the development of new parameterizations schemes.

Team activities

The CPT on eddy-mixed layer interactions is composed of 15 principal investigators work- ing at 9 different institutions: three observationalists who lead numerous upper ocean studies (D. Rudnick, Scripps; K. Speer, Florida State University; R. Weller, WHOI), seven theoreticians with expertise in the study and parameterization of upper ocean processes (R. Ferrari, G. Flierl, and J. Marshall, MIT; J. McWilliams, UCLA; A. Tandon, University of Massachusetts at Dartmouth; L. Thomas, WHOI; G. Vallis, Princeton), and five scientists working at two modeling centers (G. Danabasoglu, P. Gent and W. Large, NCAR; R. Hallberg and S. Griffies, GFDL). Funding is used to partly support postdoctoral researchers at each participat-

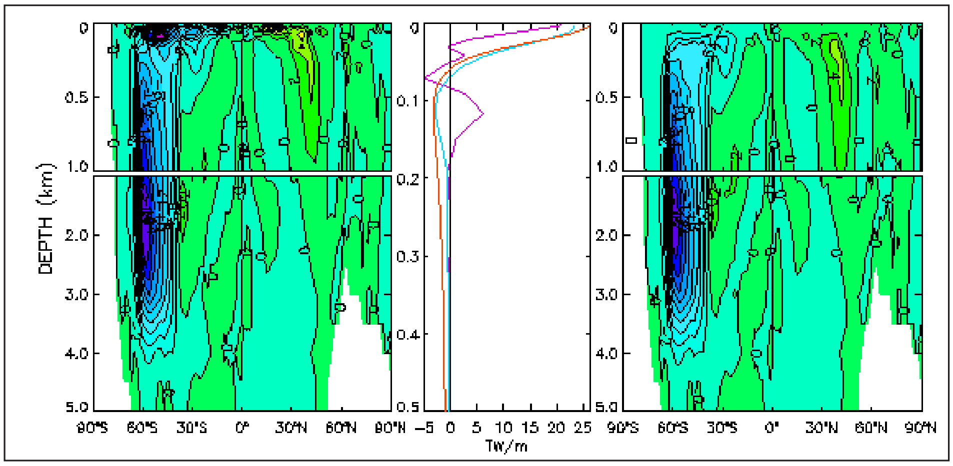

Fig. 1. Time-mean eddy-induced meridional overturning streamfunction produced with CCSM3 (NCAR). Output from a control simulation with the GM eddy parameterizations (left panel) and from a run using the new parameterization developed by the CPT (right panel). Contour interval is 2 Sv. The positive and negative values indicate clockwise and counter-clockwise circulations. The center panel shows the zonally averaged heat flux across 47° S in the upper 1000 m from the control run using the GM parameterization (purple line), the run using the new parameterization (cyan line) and a 1/8° global eddy resolving simulation run with the MITgcm (red line).

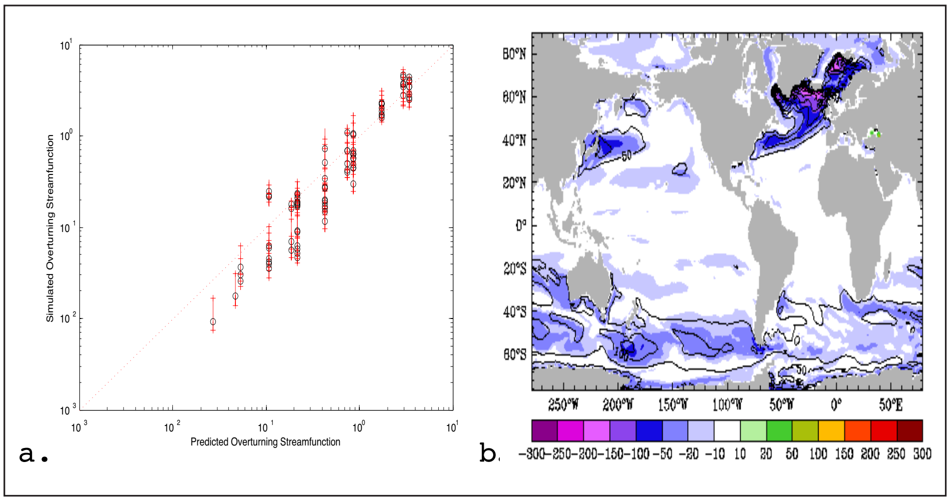

Fig. 2. a) Parameterized versus resolved submesoscale eddy overturning streamfunction generated by simulations of a slumping horizontal front in a turbulent boundary layer subject to diurnal surface fluxes. The simulations are run with the MIT general circulation model and differ for front strength and width, vertical stratification and turbulent boundary layer scheme (see movies at http://cpt-emilie.org/). b) 5-year mean surface mixed layer depth changes after 10 years between control run and a run with the parameterization for submesoscale restratification. Simulations were run at GFDL with the HIM model at 1° resolution. The submeso-scheme substantially reduces the boundary layer depth at high latitudes in winter.

ing institution. R. Ferrari has overall responsibility for the CPT program, coordinating the theory, modeling and observational activities, organizing investigator meetings, and promoting the CPT participation in relevant ongoing observational programs. With PIs distributed across the us, yearly workshops were extremely useful to coordinate research activities and spin off new collaborations. A web-site (http://cpt-emilie.org/) has been created to disseminate results and workshop activities. Finally, the CPT work will be presented in a special session at the Ocean Sciences Meeting in February 2006.

The focus of the CPT is on eddy variability in the upper ocean. There are two separate classes of eddies in the upper ocean: mesoscale eddies generated through baroclinic instability of the full water column with scales close to the internal deformation radius (50 km) and submesoscale eddies generated through ageostrophic baroclinic instabilities within the Boundary Layer with scales close to the BL deformation radius (1 km). Neither class is currently parameterized in climate models. The team made progress toward the understanding and parameterization of both classes of eddies. Detailed results are reported in the CPT publication list at the end of the paper.

Mesoscale eddies control the subgrid lateral transport of tracers in the surface BL and the subgrid exchange of properties between the BL and the stratified interior. Both processes are important for the Earth's climate, especially on decadal and longer timescales. Mesoscale eddies transport large amounts of heat in the Southern Ocean and in the Gulf Stream and Kuroshio Current regions. Eddy formation of mode waters strongly modulates air-sea fluxes in mid-latitudes. As a result of the tapering of parameterizations in the surface BLs, these effects are missing in ocean models.

A major challenge in the parameterization of submesoscale eddies is to identify and predict the transition region where fluxes develop a diabatic component. The observationalists in the team used a database of $> 70,000$ km of SeaSoar temperature and salinity data and ADCP measurements to estimate statistics of this transition layer. They found that the transition layer thickness is typically of the order of 10% the boundary layer depth and it is associated with enhanced shears and turbulence. These results, together with analysis of high resolution numerical simulations carried out at MIT, Princeton, and UCLA provided the basis for the parameterization scheme described in the next section.

In the BLs eddies develop also at the submesoscale along density fronts generated by sudden changes in surface fluxes or by stirring of the large scale temperature and salinity gradients. The dynamics are quite simple. Once formed, these lateral fronts slump under the action of gravity with denser water flowing under lighter water. The slumping process is modified by rotation and generates eddies with scales close to the BL deformation radius of a few kilometers. Even though anecdotal evidence of submesoscale features pervades the upper ocean literature, there was no comprehensive study of their effect on BL dynamics. The CPT found that the slumping fronts efficiently restratify the BL and have a substantial impact on BL depth and sea-surface temperatures, two key dynamical variables for climate variability on timescales from days to decades and beyond. A parameterization for submesoscale eddies was developed using a hierarchy of high resolution numerical models at MIT and UCLA, and it is now being tested versus mooring observations. Preliminary results are discussed below.

The results obtained to date demonstrates that CPTs are a viable framework to climate model improvement. Some of the research carried out by members of the CPT on eddy-mixed layer interactions would have happened regardless of the creation of a CPT, the development of a full set of parameterizations for IPCC-class models would still be years away, because it relied on the close collaboration of scientists that were unlikely to interact outside the CPT. The team has been more than the sum of its members.

Parameterization of mesoscale eddies in the upper ocean

A new parameterization has been developed to represent the transition from adiabatic, isopycnally oriented mesoscale fluxes in the interior to diapycnal, along-boundary mesoscale fluxes near the boundaries (Ferrari and McWilliams, 2006). The parameterization stems from ideas first proposed by Treguier and Held at the end of the 90s and it is constructed as follow:

- In the ocean interior the closure scheme is essentially equivalent to the GM parameterization.
- In the turbulent BL, the parameterization is composed of two terms. An eddy induced velocity with zero shear, in the spirit of well-mixed BL models. And an along-boundary down-gradient flux of density that represents the diabatic nature of mesoscale eddies in the BL.
- The interior and boundary layer parameterizations are matched by linearly interpolating through a transition layer, whose thickness depends on the slope of density surfaces below the BL base.

The new parameterization is supported by high resolution numerical simulations run by members of the CPT (Kuo et al., 2005) and has been implemented in the ocean component of the NCAR Community Climate System Model (CCSM3) and in the MITgcm Ocean Model at MIT. Here we report on results with a 3° resolution simulation with CCSM3. The most prominent and significant effects of the new scheme occur in the Southern Ocean where the mesoscale activity is expected to be the highest and in deep water formation regions of both hemispheres. The time-mean eddy-induced meridional overturning streamfunction distributions from the new scheme are compared with the original one in Fig. 1; the new scheme results in the elimination of the spurious near surface circulations whose strengths strongly depend on the ad-hoc tapering function of the original scheme. The result is a dramatic improvement in the vertical structure of the of heat flux as compared with eddy-resolving simulations (Fig. 1), inverse models (Lumpkin and Speer, 2005), and estimates from mooring observations in the Southern Ocean. The diapycnal eddy mixing in regions where the boundary layer is deep largely eliminates the warm biases of the control case at high latitudes. These results are very encouraging, and the CPT is now testing the robustness of the sensitivities observed and planning experiments to estimate the climate implications of these results.

Parameterization of submesoscale eddies in the upper ocean

Fox-Kemper and Ferrari (2006) formulated a parameterization for submesoscale restratification. The basic idea is that in the presence of a horizontal density gradient $\nabla_H \rho$, an overturning streamfunction develops which represents the slumping of

$$\psi = c_e f^{-1} z(z+H)\hat{z} \times \nabla_H \bar{b},$$

where H is the BL depth, f the inertial frequency, and c_e an efficiency factor of order one. The parameterization has been tested versus idealized simulations exploring the parameter regime relevant for the ocean surface BL (Fig. 2a). This parameterization is readily applied to climate models, and preliminary tests have been run at GFDL with the Hallberg Isopycnal Model (HIM) in coupled ocean-atmosphere simulations. The main impact on model output is a strong reduction of the mixed layer depth (of order 30% in mid-latitudes) after mixing events (e.g., after a winter convective event) leading to a noticeable decrease in the time-mean mixed layer depth when compared to a control simulation (Fig. 2b). The dominant signal is accentuated in regions of strong gradients (e.g., western boundary current extensions) and deep convection (e.g., the Nordic Seas). The CPT is now pursuing a comparison of these results versus available climatologies of ML depth. The next step will be to test the climate sensitivity to the reduction in ML depth.

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Gravity Current Entrainment Climate Process Team

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The goal of the Gravity Current Entrainment Climate Process Team is to improve the representation of dense gravity currents or overflows in ocean-climate models. Dense waters formed in marginal seas or on coastal shelves enter the open ocean by flowing through narrow channels and down the continental slope, entraining and mixing with overlying water. Present climate models have insufficient resolution to capture these mixing processes or even in some cases the small scales of the important topographic channels. Therefore the models cannot correctly simulate the dense water masses which result, some of which (e.g. North Atlantic Deep Water, Antarctic Bottom Water) play very important roles in the large-scale ocean circulation.

The Gravity Current Entrainment Climate Process Team was established by U.S. CLIVAR, and funded by NSF and NOAA, to foster the collaboration between climate model developers and those conducting observational, numerical and laboratory process studies in order to facilitate the timely development of improved model representation of overflows.

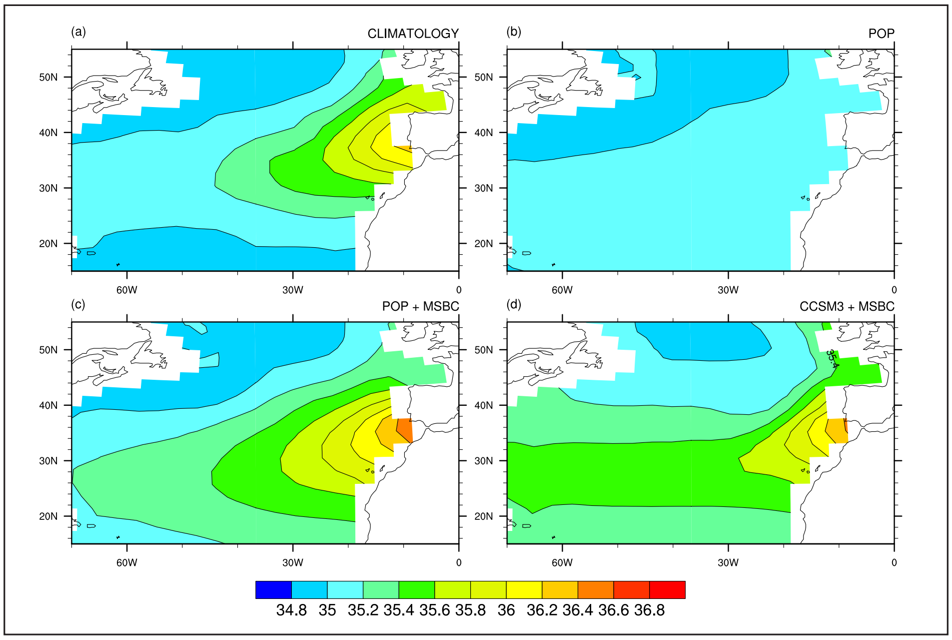

Figure 1: Comparison between observed and modeled salinities in the vicinity of the Mediterranean outflow plume, at 1100m depth. Top left: World Ocean Atlas 1998 climatology; top right: ocean-only model results without Marginal Sea Boundary Condition; bottom left: ocean-only model results including the Marginal Sea Boundary Condition at Gibraltar; bottom right: Coupled model results including the Marginal Sea Boundary Condition at Gibraltar. Model results are averaged over 1 year, after 250 years of integration. (Wanli Wu, William Large and Gokhan Danabasoglu, NCAR).

The Structure of the Climate Process Team

Our climate process team consists of groups from two of the modeling centers, NCAR and GFDL, observationalists at WHOI, LDEO and Miami, process modelers from WHOI, Princeton and Miami, and additional model developers at Miami. The bulk of our funding has gone toward fulltime postdocs at WHOI and Miami, a halftime postdoc at GFDL and a halftime researcher at NCAR, both of whom are shared with the other ocean CPT. Annual workshops have been the principal mechanism for establishing our collaboration, with important follow-up at other conferences and meetings and through email and our webpage http://www.cpt-gce.org. The workshops have also been an important route for interacting with other members of the community, and have included presentations from many other observationalists and process modelers. The project is now partway through its third year, and we have applied to NSF for 2 more years of funding.

Results

Our results can be separated into 2 broad classes, defined by the model vertical coordinate. Whereas height-coordinate models at coarse climate model resolution have great difficulty moving dense fluid down a slope without introducing excessive mixing, isopycnal-coordinate models have no diapycnal mixing unless explicitly parameterized. The issues therefore become: (a) For z-coordinate models, how do we move dense fluid down the slope while limiting diapycnal mixing? (b) For isopycnal-coordinate models, what is the correct parameterization of mixing? An important step in determining the areas to focus on and evaluating new model developments has been a careful intercomparison of current model capabilities for idealized overflows (Legg, Hallberg and Girton, 2006; Anderson, 2005; Ezer and Mellor, 2004; Ezer, 2005) and comparison of regional model simulations with observations (Riemenschneider and Legg, 2006; Xu et al, 2006; Chang et al, 2006; Ezer, 2006). We continue to extend our understanding of the mixing in overflows through nonhydrostatic simulations of the effects of complex bottom topography and ambient stratification on overflow entrainment (Ozgokmen et al, 2004b, 2006) and review of observations (http://www.cpt-gce.org/Table_of_observations.htm).

The Marginal Sea Boundary Condition

For coarse resolution models an attractive approach is to parameterize all the sub-grid-scale physics and topography involved in an overflow. A promising basis for such a parameterization is the Marginal Sea Boundary Condition, developed by Price and Yang (1998). While they included it in idealized ocean models,

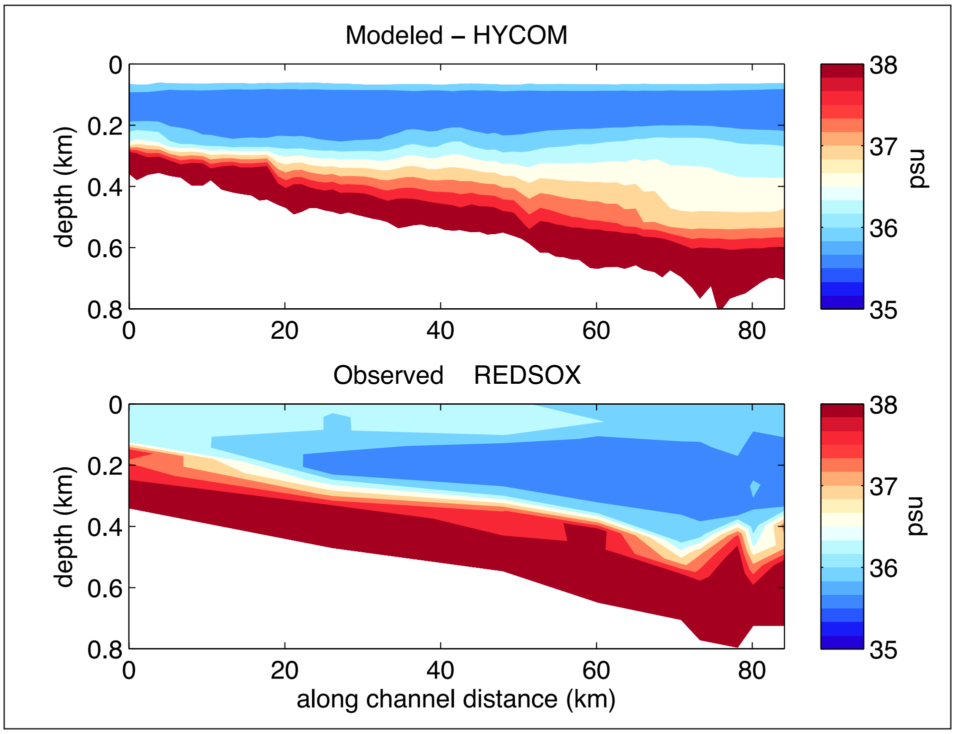

Figure 2: Comparison of the salinity distribution modeled by HYCOM with that from REDSOX-1 observations (Peters et al., 2005) along the ``Northern channel", which is a narrow (3-5km wide) channel transporting approximately half of the Red Sea overflow water after the overflow bifurcates shortly downstream of the Bab-el-Mandep strait. The model has a horizontal resolution of 1 km and 12 vertical layers, and uses the version of the Turner (1986), Hallberg (2000) parameterization tuned by Xu el al. (2006) (Yeon Chang, Tamay Ozgokmen, Hartmut Peters and Xiaobao Xu, U. Miami).

through the CPT the NCAR team has incorporated the MSBC into a full ocean climate model (the CCSM) for the first time (Wu et al, 2006). In the first stage of implementation, it completely determines the transports, tracer properties and depths of the inflows and outflows associated with exchanges between the modeled Mediterranean Sea and North Atlantic, where a realistic Mediterranean salt tongue is generated (figure 1). The next stage, a Nordic overflow implementation, is underway. The goal is to include all the climatically important overflows. This endeavor is being assisted by (i) a comparison table of observations of overflows produced by observational members of our team, which gives some of the input parameters needed for the MSBC, and is available on the CPT webpage; (ii) high resolution regional simulations, especially of the Nordic overflows, produced by Ulrike Riemenschneider which provide guidance on aspects of the flow such as where entrainment occurs; (iii) improvements to the MSBC being pursued by Price and Yang, to make it more suitable for time-varying flows.

Mixing Parameterizations in layered ocean models

In models where the vertical coordinate is based on density, explicit parameterizations of mixing are needed to generate the observed modifications to the dense water masses. At the onset of the Climate Process team, there were two parameterizations of interior mixing available in such models: a parameterization based on the entrainment formula of Ellison and Turner (1959), implemented in layered models by Hallberg (2000); and a diffusivity based on the Pacanowski-Philander parameterization, employed as the interior mixing parameterization in the KPP vertical mixing scheme of Large et al (1994).

The CPT has lead to the following results and improvements for mixing parameterizations in isopycnal and hybrid coordinate models:

i.) The Ellison-Turner type parameterization, with non-dimensional constants originally determined from laboratory measurements of the entire dense layer, has been calibrated by Miami researchers for implementation in the Hybrid Coordinate Ocean Model (HYCOM), by comparison with idealized non-hydrostatic overflow simulations by Ozgokmen et al. (2004a). Good agreement is found with observations when the parameterization is used in regional HYCOM simulations of real overflows such as the Red Sea and Mediterranean provided resolution is sufficient to capture the narrow channels (Figure 2) (Xu et al, 2006; Chang et al, 2006).

ii.) A parameterization of mixing due to bottom friction has been developed by Robert Hallberg, following comparison between non-hydrostatic MITgcm simulations and HIM isopycnal model simulations (Legg et al, 2006), stimulated by discussion with Hartmut Peters concerning the different mixing in bottom and interfacial layers of the Red Sea overflow. This parameterization eliminates spurious splitting of the dense plume, and greatly improves simulations of the Mediterranean overflow when implemented in the Hallberg Isopycnal model, combined with the Hallberg (2000) implementation of the Ellison and Turner scheme.

iii.)To the extent that mixing in overflows is driven by the shear, one might expect existing parameterizations of shear-driven mixing to be suitable for representing mixing in overflows. However, Miami researchers have shown that one such parameterization, the KPP interior mixing component, gives too little mixing for overflows (Chang et al., 2005), having been originally calibrated for the equatorial undercurrent. Similarly Ellison-Turner type parameterizations give too much mixing in the equatorial undercurrent when calibrated for overflows. A new parameterization of shear-driven mixing is clearly needed for use in global models. Laura Jackson and Robert Hallberg are developing such a parameterization, with an eddy diffusivity κ, which satisfies

$$\frac{\partial^2 \kappa}{\partial z^2} - \frac{\kappa}{L_B^2} = -2SF(Ri)$$

where S is the vertical shear of the resolved horizontal velocity, and $L_B = Q^{1/2}/N$ is the buoyancy length scale (the scale of the overturns) with Q the turbulent kinetic energy (TKE) found from an energy budget and $F(Ri)$ is a function of the shear Richardson number Ri. The parameterization is being calibrated against direct numerical simulations and LES from GFDL and Miami, with initial results looking promising.

Ongoing and future work

CPT Researchers are continuing to implement the new and improved parameterization schemes in global climate models at NCAR, GFDL and Miami, and examine the sensitivity of ocean-only and coupled climate simulations to the representation of overflows. If the CPT is extended, a major emphasis will be on the treatment of straits narrower than the climate model resolution, with possible methods of dealing with this problem including high-resolution regional simulations for each overflow, 2-way nested models, or partially open barrier algorithms.

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* *Results of the CPT initiative*

The Climate Process Team on Low-Latitude Cloud Feedbacks on Climate Sensitivity

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Introduction

The Climate Process Team on Low-Latitude Cloud Feedbacks on Climate Sensitivity (cloud CPT) includes three climate modeling centers, NCAR, GFDL, and NASA's Global Modeling and Assimilation Office (GMAO), together with 8 funded external core PIs led by Chris Bretherton of the University of Washington (UW). Its goal has been to reduce uncertainties about the feedback of low-latitude clouds on climate change as simulated in atmospheric general circulation models (GCMs). To coordinate this multi-institution effort, we have hired liaison scientists at NCAR and GFDL, had regular teleconferences and annual meetings, and developed special model output datasets for group analysis. The cloud CPT web site www.atmos.washington.edu/~breth/CPT-clouds.html provides links to all its publications and activities. The cloud CPT has had many interesting subplots; here we focus on two of interesting recent results and its future plans. The results showcase a key CPT strategy - gaining insight from the use of several complementary modeling perspectives on the cloud feedbacks problem.

Two recent findings of the cloud CPT

(1) *The world's first superparameterization climate sensitivity results show strong negative cloud feedbacks driven by enhancement of boundary layer clouds in a warmer climate.*

Superparameterization is a recently developed form of global modeling in which the parameterized moist physics in each grid column of an AGCM is replaced by a small cloud-resolving model (CRM). It holds the promise of much more realistic simulations of cloud fields associated with moist convection and turbulence. Superparameterization is computationally expensive, but multiyear simulations are now feasible. The Colorado State University and UW cloud CPT groups collaborated on the first climate sensitivity analysis of a superparameterized AGCM (Wyant et al. 2006b). The Khairoutdinov-Randall (2001, 2005) superparameterized CAM3, hereafter CAM-SP, was used. Each CRM in CAM-SP has the same vertical levels as CAM3, 4 km horizontal resolution, and one horizontal dimension with 32 horizontal gridpoints.

Following Cess et al. (1989), climate sensitivity was assessed by examining the TOA radiative response to a uniform SST increase of 2K, based on the difference between control and +2K 3.5 year CAM-SP simulations. Fig. 2 compares the results to standard versions of the NCAR CAM3, GFDL AM2 and GMAO

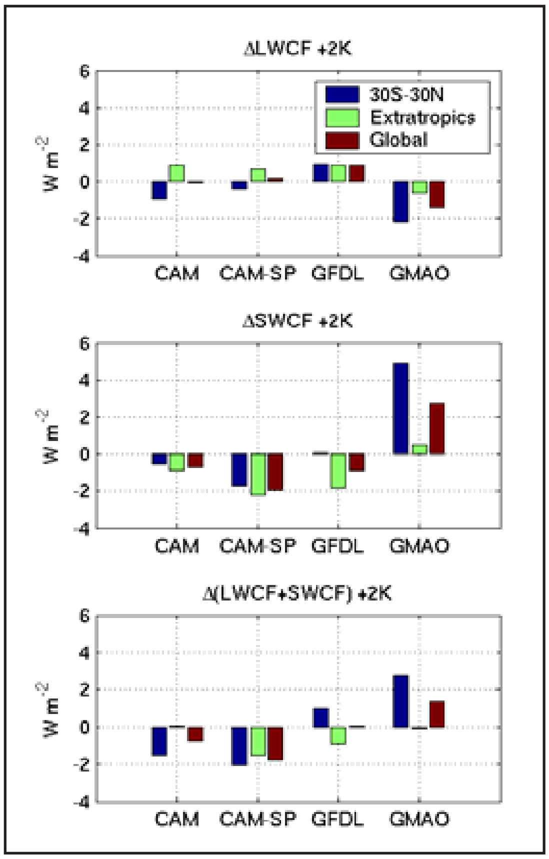

Figure 1. Comparison of global sensitivities (Delta Long-Wave cloud forcing (DLWCF), Delta short-Wave cloud forcing (DSWCF) and combined cloud forcing) for the NCAR-CAM Super-Parameterized (CAM-SP), NCAR-CAM, GFDL AM2 and NASA GMAO atmospheric general circulation models to imposed (Cess type) +2K heating of SST.

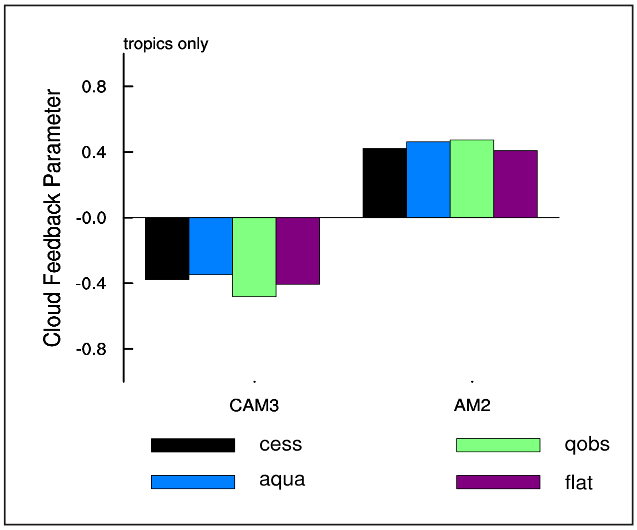

Figure 2. Tropical-mean cloud feedback parameter for +2K SST changes from realistic ('Cess') and three aquaplanet mean states.

AGCMs. All these models have similar clear-sky responses, so we just plot the +2K changes in longwave (greenhouse) and shortwave (albedo) cloud radiative forcings (DLWCF and DSWCF). Since DSWCF tends to be larger than DLWCF. boundary-layer cloud changes (which have little greenhouse effect compared to their albedo enhancement) appear to be particularly important.

The CAM-SP shows strongly negative net cloud feedback in both the tropics and in the extratropics, resulting in a global climate sensitivity of only 0.41 K/(W m^{-2}), at the low end of traditional AGCMs (e.g. Cess et al. 1996), but in accord with an analysis of 30-day SST/SST+2K climatologies from a global aquaplanet CRM run on the Earth Simulator (Miura et al. 2005). The conventional AGCMs differ greatly from each other but all have less negative net cloud forcings and correspondingly larger climate sensitivities than the superparameterization.

The coarse horizontal and vertical resolution of CAM3-SP means that it highly under-resolves the turbulent circulations that produce boundary layer clouds. Thus, one should interpret its predictions with caution. With this caveat, cloud feedbacks are arguably more naturally simulated by superparameterization than in conventional AGCMs, suggesting a compelling need to better understand the differences between the results from these two approaches.

(2) *The tropical cloud feedback differences between the NCAR and GFDL models are qualitatively captured in simplified settings, including single-column and aquaplanet models, and seem strongly tied to the models' cumulus parameterizations.*

Globally-important cloud feedbacks are much more easily understood if they can be reproduced in simpler contexts. The cloud CPT has been exploring two such contexts. One is an aquaplanet with zonally symmetric SST. Aquaplanet simulations provide a climate that is different yet similar to the real Earth and hence may be useful for testing the robustness of proposed cloud feedback mechanisms. Their zonal symmetry and simple lower boundary condition makes for comparatively easy interpretation of results.

UCLA CPT investigator Bjorn Stevens, his graduate student Brian Meideiros, and the cloud CPT modeling centers compared the response of fully realistic AGCM simulations to a near-global 2K SST increase with various aquaplanet configurations, following when possible the protocols of the Aqua-Planet Experiment intercomparison project (APE, www.met. rdg.ac.uk/~mike/APE/). Fig. 2 compares the 30S-30N average cloud feedback parameter of the NCAR CAM3 and the GFDL AM2 in response to the SST increase, starting from four mean states. These states are the model with fully realistic geography and SST ("Cess") and aquaplanet configurations with three different zonally symmetric SST patterns of varying degrees of flatness across the Tropics ("aqua," "qobs" and "flat"). For each climate perturbation, the cloud feedback parameter is defined as the ratio of the change in total cloud radiative forcing to the total change in radiative forcing. For each model, the cloud feedback parameter is very similar for all four mean initial states, with the GFDL AM2 exhibiting a large positive tropical cloud feedback and the NCAR CAM3 having a strong negative feedback. Thus,

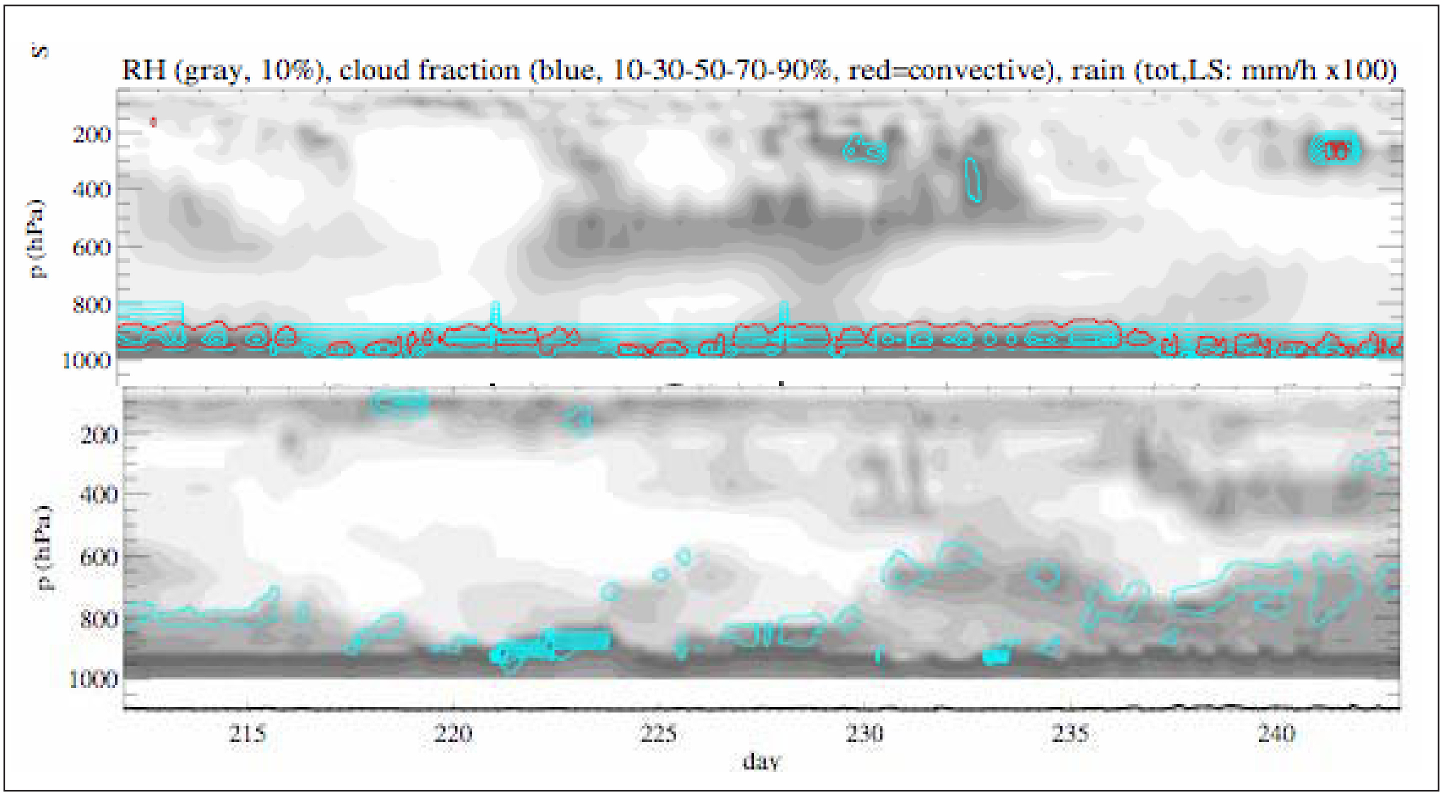

Figure 3. October time-height sections of relative humidity (shadeing, darker grey = more humid) and cloud fraction (blue contours every 10%) at 85W, 20S in the SE Pacific stratocumulus regime from climatological CAM3 (top) and AM2 (bottom).

the aquaplanet configurations capture the gross cloud feedback of the full model in a simpler context.

Another simplified analysis framework is single-column intercomparison. This allows a detailed diagnosis of how individual parameterizations in single-column versions of the three models contribute to the mean characteristics and climate sensitivity of their simulated clouds. The cloud CPT liaison scientists, Cecile Hannay of NCAR and Ming Zhao of GFDL, archived output profiles at selected grid columns from the CAM3 and AM2.12b for each time step of a simulated year. Fig. 3 compares sample October time-height slices of relative humidity and cloud fraction from CAM3 and AM2 at a location in the heart of the SE Pacific stratocumulus regime. Although both models produce similar net cloud radiative forcings, their simulated cloud fields are quite different. with CAM3 having an overly shallow persistent stratocumulus layer, and AM2 having a deeper boundary layer, but spurious outbreaks of mid-level cumulus convection.

Clouds CPT investigator M. Zhang (Stony Brook) initiated a intercomparison of single-column versions of the three participating GCMs using steady forcings idealized from a subtropical trade wind regime with mean subsidence and 296 K SST, capped by a free troposphere with 15% relative humidity and a moist-adiabatic lapse rate tied to a warmer ITCZ SST of 300 K. Fig. 4 shows results for the CAM3, AM2 and GMAO SCMs run to equilibrium with these forcings. This took 50-100 days due to slow but persistent radiative feedbacks of the cool cloudy CTBL on the free-tropospheric temperature. The key point is that the SCMs exhibit similar cloud biases to their full AGCM counterparts, with the CAM3 SCM forming a shallow stratocumulus layer and the AM2 SCM producing unrealistically deep mid-level cumuli, and the GMAO model produced an even deeper and much thicker mid-level cloud layer. Different cloud responses led to different steady-state thermodynamic profiles, amplifying the model differences. An SCM climate sensitivity test in which local and ITCZ SSTs were raised by 2K also gave results qualitatively similar to the full AGCMs

Adiagnosis of the CAM3 SCM showed the cloud layer was maintained by a complex cycle with a few hour period in which different moist physics parameterizations take over at different times in ways unintended by their developers. A surprise was the unexpectedly large role of parameterized deep convection even though the cloud layer does not extend above 800 hPa. This emphasizes that an AGCM is a system whose mean behavior can reflect unanticipated and unphysical interactions between its component parameterizations.

Cloud CPT future plans

The focus of the cloud CPT will narrow to low-latitude boundary layer clouds, driven by recent findings by the CPT and other international groups (Wyant et al. 2006a, Webb et al. 2005; Bony and DuFresne 2005) that the net radiative feedbacks of these clouds on a climate perturbation are particularly large and uncertain. We are using our simplified frameworks to develop a process-level understanding of how changed parameterizations in current development versions of the three AGCMs and the superparameterized CAM affect their boundary layer cloud feedbacks.

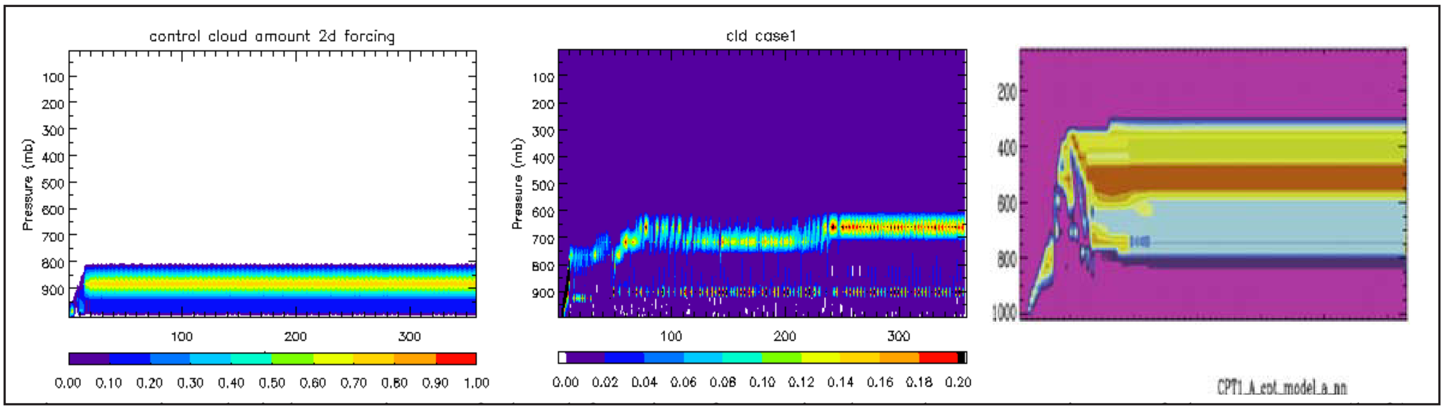

Figure 4. Time-height sections of cloud fraction from single-column version of the CAM3 (left), AM2 (middle, different color scale), and GMAO (right; purple = 0 and brown > 0.9). Time is in days. GMAO simulation runs out to 300 days.

One interesting preliminary finding in this direction, from Ming Zhao and Isaac Held of GFDL, is that the climate sensitivity of AM2 is considerably lowered by changing only its parameterization of shallow cumulus convection to a UW scheme (Bretherton et al. 2004).. We are also pioneering the testing and improvement of cloud-related parameterizations through analysis of AGCM simulations in weather forecast mode, in close collaboration with the CCSP-ARM Parameterization Testbed (CAPT), a Department of Energy project housed at Lawrence Livermore National Laboratories (www-pcmdi.llnl.gov/projects/model_testbed.php; Phillips et al. 2004).

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North American Monsoon Experiment (NAME) Update

The North American Monsoon Experiment (NAME) is currently in an analysis phase after the extensive field campaign from June-September 2004. Current and future studies include assessing global and regional model simulations of the 2004 monsoon, evaluating the impact of changes in model parameterization schemes, and measuring improvements in model simulations of monsoon onset and variability. An article highlighting the NAME 2004 field campaign and its modeling strategy can be found in the January 2006 issue of the *Bulletin of the American Meteorological Society*. In addition, there will be a special issue of the *Journal of Climate* in 2006 highlighting NAME results. UCAR/JOSS maintains a comprehensive list of archived data, NAME forecasts and modeling strategy (www.joss.ucar.edu/name).

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

SEAFLUX Meeting
2-3 March 2006
Tallahassee, FL
Attendance: Open
Contact: http://gfdi.fsu.edu/SEAFLUX/

2nd ARGO Science Meeting
13-18 March 2006
Venice, Italy
Attendance: Open
Contact:
http://www.argo.ucsd.edu/FrSecond_Science_Work.html

The 36th Annual Arctic Workshop
16-18 March 2006
Boulder, Colorado
Attendance: Open
Contact: http://instaar.colorado.edu/meetings/AW2006/

NOAA Climate Prediction Applications Science Workshop
21-24 March 2006
Tucson, Arizona
Attendance: Open
Contact:
http://cals.arizona.edu/climate/CPASW2006/index.htm

Workshop on Tropical Cyclones and Climate
27-29 March 2006
Palisades, New York
Attendance: Open
Contact: iri.columbia.edu/outreach/meeting

DOE ARM Meeting
27-31 March 2006
Albuquerque, New Mexico
Attendance: Open
Contact: http://stm.arm.gov/

European Geosciences Union General Assembly
2-7 April 2006
Vienna, Austria
Attendance: Open
Contact:
http://meetings.copernicus.org/egu2006/

NSTC Joint Subcommittee on Ocean Science and Technology (JSOST) Workshop
19-21 April 2006
Denver, Colorado
Attendance: Open
Contact:
http://ocean.ceq.gov/about/jsost.html

International CLIVAR SSG-14
18-20 April 2006
Buenos Aires, Argentina
Attendance: Invited
Contact: www.clivar.org

PICES/GLOBEC Symposium on Climate Variability and Ecosystem impacts on the North Pacific
19-21 April 2006
Honolulu, Hawaii
Attendance: Open
Contact: http://www.pies.int/meetings/international_symposia

CLIVAR 9th VAMOS Panel Meeting
22-23 April 2006
Foz do Iguacu, Brazil
Attendance: Invited
Contact: www.clivar.org

8th International Conference on Southern Hemisphere Meteorology and Oceanography
24-28 April 2006
Foz do Iguacu, Brazil
Attendance: Open
Contact:
http://www.cptec.inpe.br/SH_Confernece/index.shtml

SAMOS/GOSUD Meeting
2-4 May 2006
Boulder, Colorado
Attendance: Open
Contact: http://www.coaps.fsu.edu/RVSMDC/marine_workshop3/announcement.html

U.S. CLIVAR Salinity Workshop
8-10 May 2006
Woods Hole, Massachusetts
Attendance: Open
Contact:
http://www.usclivar.org/Organization/Salinity_WG/Salinity2006.html

Aquarius/SAC-D Workshop
10-12 May 2006
Woods Hole, Massachusetts
Attendance: Open
Contact: http://www.aquarius.gsfc.nasa.gov

NOAA Climate Observation Program – 4th Annual Review
10-12 May 2006
Silver Spring, MD
Attendance: Open
Contact: http://www.ocoreview.noaa.gov

Understanding Sea-level Rise and Variability
6-9 June 2006
Paris, France
Attendance: Open
Contact:
http://copes.ipsl.jussieu.fr/Workshops/SeaLevel/index.html

Holivar 2006 Open Science Meeting on Natural Climate Variability and Global Warming
12-16 June 2006
London, England
Attendance: Open
Contact: http://www.holivar2006.org

ECMWF Reanalysis Workshop
19-22 June 2006
Reading, England
Attendance: Open
Contact: http://www.ecmwf.int/newsevents/meetings

CCSM Meeting
20-24 June 2006
Breckenridge, Colorado
Attendance: Limited
Contact: http://www.ccsm.ucar.edu/

Arctic/Subarctice Ocean Fluxes (ASOF) Science Conference
28 June – 1 July 2006
Faroe Islands
Attendance: Open
Contact: http://asof.npolar.no/

U.S. CLIVAR Summit
26-28 July 2006
Breckenridge, Colorado
Attendance: Invited
Contact: http://www.usclivar.org

U.S. CLIVAR Town Hall Meeting

U.S. CLIVAR held an open Town Hall meeting at the Annual AMS Meeting in Atlanta in late January. The Town Hall meeting was designed to present to the community how U.S.CLIVAR reorganized and what scientific and coordination activities its three new Panels have proposed as near-term foci. Building on the vision and activities developed and coordinated by U.S. CLIVAR over the past six years, new foci include developing predictive understanding of extreme events such as drought; prediction systems for climate impacts on ecosystems; enabling use of CLIVAR science for improved decision support; understanding of climate variability mechanisms and structure in the past, present, and future; sustaining, improving, and exploiting existing climate observing systems; developing consistent ocean-land-atmosphere data sets and analyses; and characterizing and reducing systematic biases and uncertainties of climate models. The Town Hall presentations can be obtained through the U.S. CLIVAR web site (www.usclivar.org).

Following the presentations, the floor was opened for comments and questions from the dozens of scientists in attendance. The questions addressed the scope of the proposed foci, interactions with GEWEX (they are increasing), engagement of the federal research agencies that support U.S. CLIVAR (they are very supportive, but overall national funding constraints will limit new activities), and how U.S. CLIVAR will engage decision makers (we will work through centers and on-going research programs that are interacting directly with user communities).

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