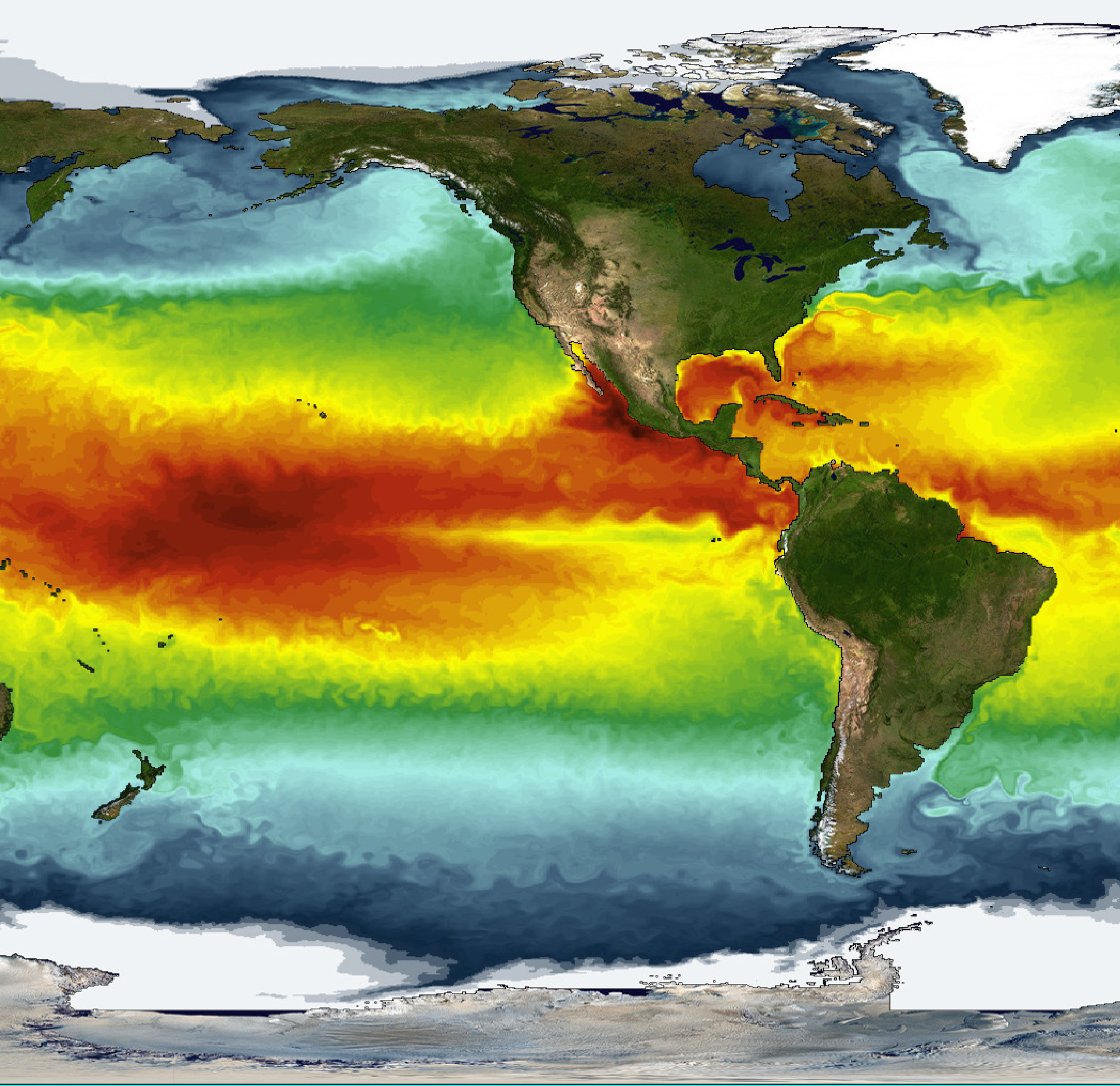

TRANSLATING PROCESS UNDERSTANDNG TO IMPROVE CLIMATE MODELS

A US CLIVAR White Paper

August 2016

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CONTRIBUTORS

Aneesh Subramanian (U. Oxford/U. California San Diego), Caroline Ummenhofer (WHOI), Alessandra Giannini (Columbia U.), Marika Holland (NCAR), Sonya Legg (Princeton U.), Amala Mahadevan (WHOI), Don Perovich (Dartmouth), Justin Small (NCAR), Joao Teixeira (NASA JPL/Caltech), and LuAnne Thompson (U. Washington)

EDITORS

Mike Patterson and Kristan Uhlenbrock, US CLIVAR Project Office

FRONT COVER IMAGE

Sea surface temperature image from GFDL CM2.5, NOAA Geophysical Fluid Dynamics Laboratory

BACK COVER IMAGES

Clockwise from top, then center: Aircraft left to right: NOAA G-IV, NOAA P-3, DOE G-1, Marty Ralph (UCSD/Scripps); RV Sagar Nidhi and bouy, Sean Whelan (WHOI); Sea ice and researchers, Nick Cobbing; ARM facility, Gijs de Boer (U. Colorado, Boulder); Tropical forest canopy and fog, Yadvinder Malhi (U. Oxford); CloudSat Earth observing system, NASA

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1 Introduction

This white paper synthesizes the oceanic, atmospheric, and climate modeling and observational communities' input on the need for a coordinated effort to translate process understanding into climate model improvements. It aims to assess the need for launching a new effort and addresses the questions of what form such an effort ought to take, which areas need to be tackled, and how such an effort might be implemented.

During the past 12 years, the National Science Foundation (NSF) and National Oceanic and Atmospheric Administration (NOAA) have supported Climate Process Teams (CPTs), a concept that was initiated by US CLIVAR to translate process understanding into climate model improvements with the aim of reducing model biases. With the most recently funded CPTs coming to an end, there is a need to review their benefits and devise a plan for future efforts.

In 2015, a steering committee formed by the US CLIVAR Process Study and Model Improvement Panel (PSMIP) conducted a survey of modeling centers, process study groups, enhanced observing projects, recent satellite missions, recent CPTs, and US CLIVAR Working Groups to collect feedback on the utility of CPTs and the continued need for such efforts. The survey specifically targeted the large US modeling centers and a wide range of process studies/ observational efforts (see full list in Appendix D). The results of both surveys confirmed broad community interest for a scoping workshop (Appendix D, E).

A workshop was therefore convened by US CLIVAR (PSMIP), at the encouragement of the US CLIVAR Inter-Agency Group (IAG), to seek input from the observational, modeling, and theoretical communities on how to achieve a translation of process understanding into climate model improvements. The workshop was funded by NSF, NOAA, and the Department of Energy (DOE), with local support from the NOAA Geophysical Fluid Dynamics Laboratory (GFDL). The steering committee organized the workshop, reported to the IAG on its outcomes by means of a short report and teleconference, and has now compiled this white paper to provide feedback to the community.

This open, community-wide workshop was held at GFDL on October 15-16, 2015 with the main goal of discussing possible mechanisms to translate process understanding to model developments and to identify processes for which newly available observational data and understanding could inform future model improvements. Workshop attendance was limited to 90 participants and was quickly filled to capacity, but web streaming made the workshop plenary sessions available to anyone who could not participate in person (which included over 80 remote participants).

Scheduled over two full days, the workshop included invited oral presentations, posters, breakout sessions, and participant discussions. Representatives of modeling centers gave presentations that highlighted model biases and weaknesses. Process study representatives were invited to describe newly developed process understanding from observational and theoretical studies, which could inform model improvement. The goal of these presentations was to be as inclusive and as broad as possible, but the organizers recognize that they could not represent all the interests expressed in the survey due to time constraints.

After much discussion, the organizing committee thought it best to maintain the focus of the workshop on the ocean, atmosphere, cryosphere, and land processes and to encourage discussion on the interaction amongst components of the climate system, which had been identified as important areas for model improvement in the surveys. The agenda for the workshop is available in Appendix C.

2 Need for Process Translation into Model Development

In the past decade, CPTs brought together observationalists, theoreticians, process modelers, and model developers to work closely on improving parameterizations of a particular process in one or more global models. CPTs were initiated in 2003, followed by a second round in 2010, and included funding from both NOAA and NSF, with some involvement from NASA. They focused on improvements in Intergovernmental Panel on Climate Change (IPCC)-class models, particularly at GFDL and the National Center for Atmospheric Research (NCAR)¾used for climate change simulations. Other NOAA-sponsored CPTs were designed to specifically improve NOAA models, including the National Center for Environmental Prediction (NCEP) and GFDL models. Previous CPTs have largely focused on low-latitude cloud processes in the atmosphere and ocean eddy and mixing processes. In addition, two CPTs had a cryospheric focus, as summarized in Table 1.

Following the past experience with CPTs, there is strong recognition from the community that bringing process experts together with climate modelers is a useful means of improving representation of physical processes in large-scale models. The past CPTs have led to important improvements in IPCC-class models; examples include: new cloud parameterizations (e.g., Cloud Layers Unified By Binormals (CLUBB) as implemented in the Community Atmosphere Model; Bogenschutz et al. 2013), new subgrid-scale effects of photosynthetically available radiation in ice-covered waters (Long et al. 2015), new ocean model representations of shear-driven mixing (Jackson et al. 2008), hydraulically controlled flow and mixing in straits (Wu et al. 2007), bottom boundary mixing (Legg et al. 2006), and mixed layer submesoscale restratification (Fox-Kemper et al. 2008). These improvements are included in one or more Coupled Model Intercomparison Project phase 5 (CMIP5) models. Recently, NOAA-sponsored CPTs also led to operational implementations into the NCEP model (e.g., dry eddy diffusivity/mass flux (EDMF) boundary layer parameterization; Han et al. 2016). By focusing in depth on a single problem for a five-year period, CPTs have accelerated scientific understanding of particular processes. For example, the internal-wave driven mixing CPT provided a more complete picture of the ocean internal wave energy distribution and stimulated research into ocean submesoscale processes (Boccaletti et al. 2007). Through involvement in the CPTs, strong and enduring links have developed between specific scientific communities in academia and model developers, such as process experts who were hired as CPT liaisons and have a continuing presence at the modeling centers.

Table 1: Summary of previous CPT efforts, including lead-PI, agency, dates, and modeling centers involved.

CPT Topic	Lead PI	Funding Agency	Dates	Modeling Centers Involved
Ocean eddy mixed layer interactions	Raf Ferrari (MIT)	NOAA/NSF	2003-2008	GFDL, NCAR
Gravity current entrainment	Sonya Legg (Princeton U.)	NOAA/NSF	2003-2008	GFDL, NCAR
Low latitude cloud feedbacks on climate sensitivity	Chris Bretherton (U. Washington)	NOAA/NSF	2003-2006	GFDL, NCAR, GSFC
Improving the subtropical Sc-Cu transition	Joao Teixeira (JPL/ Caltech)	NOAA	2010-2013	NCEP, NCAR
Cloud parameterization and aerosol indirect effects	Vince Larson (U. Wisconsin)	NOAA/NSF	2010-2015	NCAR, GFDL
Ocean mixing processes associated with high-spatial heterogeneity in sea ice	Meibing Jin (U. Alaska)	NOAA/NSF	2010-2013	NCAR, GFDL
Internal wave driven mixing	Jen MacKinnon (Scripps Institution of Oceanography)	NOAA/NSF	2010-2015	NCAR, GFDL
Representing calving and iceberg dynamics in global climate models	Olga Sergienko (Princeton U.)	NOAA	2013-2016	GFDL
Improving turbulence and cloud processes in the NCEP global models	Steve Krueger (U. Utah)	NOAA	2014-2017	NCEP, NCAR
Cloud and boundary layer processes	Chris Bretherton (U. Washington)	NOAA	2014-2017	NCEP, GFDL

These past CPTs have brought together people from modeling and observational communities who otherwise would have had little opportunity for interaction. The US CLIVAR CPTs have typically included 7-12 project investigators (PIs), as well as several postdoctoral researchers, some of whom were placed at the modeling centers. The modeling centers benefited from the exposure to new ideas, the physical insight obtained from observational data, and the involvement of groups looking at the specifics of the process from different angles. Modeling centers funded by different agencies with different missions have been able to pool their resources to tackle a particular scientific problem (e.g., low cloud parameterization problem). The academic community has gained access to modeling center expertise, model and computer resources, and knowledge about the requirements and limitations of climate models. A long-term outcome of such interaction is the synthesis of results from numerous process experiments into forms suitable for reference by model developers. Examples include the “Table of observations,” which condenses observations of oceanic overflows into a convenient reference (Legg et al. 2009), and the synthesis of ocean mixing data (Waterhouse et al. 2014).

The past CPTs have been an effective mechanism to facilitate interaction between process experts and model developers focused around improvements in the representation of particular processes. Nonetheless, the success of the past CPTs does not diminish the need for future activities designed to bring together climate modelers and process experts. Such activities should improve upon the structure of past CPTs, incorporating those elements that have proven successful, while making modifications to enhance their effectiveness and relevance. Only a limited number of processes have so far been targeted with CPTs, as seen in Table 1. Numerous processes and their interactions remain poorly represented in large-scale models, and such models still have many biases that may be improved by better process representation, as detailed in later sections. In many cases, it is the interactions between climate components (e.g., ocean-atmosphere, land-ocean, ice-ocean), processes, and the ways in which parameterizations might interact that remain poorly represented and uncertain in weather and climate models. The experts involved in processes not included in past CPTs may still remain relatively unconnected to climate model developers. Modelers, theorists, and observationalists are generally not collocated, and modeling centers and process study scientists may receive funds from different sources. The ability for different modeling centers to work together to advance science depends on coordination between their different funding agencies. Often, there remains a mismatch between the disparate scientific results obtained from process studies and the information that a model developer can use. For this, synthesis is needed. For example, the numerous process studies of estuaries and river outflows could be synthesized to provide a reference against which to compare climate model representations. Hence, a need for specific mechanisms for coordinated funding to bring together scientists from academia and different modeling centers to focus on particular model improvements still remains.

3

Organizational Approaches for Process Translation Teams

The climate modeling environment has evolved since the first CPTs in 2003. Therefore, one of the objectives of the 2015 workshop was to explore new ways for making these coordinated activities more relevant to the current environment and problems. Breakout sessions were organized to brainstorm alternatives to the past CPT approaches and examine ways in which hurdles to translating understanding to climate model improvement could be overcome.

Aspects of the CPT approach originally supported by NSF and NOAA have now been espoused by other projects and agencies, including DOE, NASA, and the Office of Naval Research (ONR). Between 2011 and 2015, ONR funded a multi-institution five-year Departmental Research Initiative (DRI) on “Unified Physics for Extended-Range Prediction,” which aims to develop generalized physical parameterizations for the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Navy Global Environmental Model (NAVGEM). And in 2016, DOE announced a new funding opportunity for “Climate Model Development and Validation” in the context of its Accelerated Climate Modeling for Energy (ACME) project. NASA’s Modeling, Analysis, and Prediction program is a regular component of the Research Opportunities in Space and Earth Sciences (ROSES) funding call, providing support for development, testing, and improvement of models used by the Global Modeling and Assimilation Office (GMAO) and the Goddard Institute for Space Studies (GISS)

The buy-in of elements of the CPT approach by applied/mission-driven agencies prompts the question of the potential benefit of simultaneously testing novel, process-derived parameterizations in the diversity of models supported by the different agencies against the cost of negotiating different priorities. Realistically, the modeling centers each have their particular strengths, so with more institutions involved, an approach in which individual institutions contribute according to their strengths may be more effective. Differences in agency mission¾ such as NOAA’s interest in seamless prediction from weather to seasonal climate timescales as opposed to NASA’s interest in guiding the design and value of new satellite missions¾could lead each agency to prioritize different processes for improvement.

The survey respondents and workshop participants, however, were clear in their support for future efforts to involve multiple modeling centers. The resulting diversity of expertise and approach leads to better science, and academic experts prefer to enhance the overall state of knowledge rather than tie their efforts to a single agency’s model—especially now that multi-model ensembles have become available from dozens of modeling centers worldwide through the many phases of CMIP. Engagement with the global modeling communities was also encouraged in this regard through involvement of modeling centers and efforts internationally.

A few management issues were brought up as potential concerns when coordinating multiple centers, but the feeling was that the benefits greatly outweigh the disadvantages, given that some of the more macroscopic biases (e.g., in the climatologies of the eastern tropical basins, including the double Intertropical Convergence Zone (ITCZ) in the tropical Pacific, and the Asian-Australian monsoon precipitation climatology) are long-standing problems shared across many models. Logistical challenges for multi-agency, multi-modeling center efforts include a lack of human resources in modeling centers to appropriately engage with a multitude of university investigators, especially face-to-face in meetings; coordination amongst different agencies with different priorities; identification of individuals to lead such an effort and effectively communicate across the diverse group of experts and agencies; and dealing with the different procedures inherent to each agency. A key hurdle for a successful translation of process understanding into models is communication amongst the project participants. This was overcome in the past through regular face-to-face meetings. Another key point was that some of the most useful work that results from the CPTs occurs towards the tail end of the project (e.g., the examination of the impact of Nordic overflow parameterizations on the Atlantic Meridional Overturning Circulation (AMOC) variability, Danabasoglu et al. 2010), or even after the project has officially ended (in terms of funding). Recognition and support for this extended “analysis tail” (where the analysis may be of climate model impacts and parameterization sensitivities, rather than observational data) would help to extract the most value from the project.

A well-conceived scientific focus around specific processes and biases (for some earlier CPTs) was a key factor in the success of past CPTs. However, experience from past CPTs shows that new or improved parameterizations of a process in a climate model do not always lead to a reduction in model biases or improved representation of climate phenomena. This may be due to unpredictable and complex interactions between different physical processes, erroneous parameterizations based on an unrepresentative set of observations/simulations, extrapolating beyond a representative range, or parameterizations that prove to be prohibitively expensive.

In addition to retaining the process-specific focus, some workshop participants and survey respondents suggested that CPTs should also be focused on specific model biases. Candidate problems would be those that required holistic consideration of the coupled ocean-atmosphere-land-ice system, and for which knowledge/understanding of the processes (e.g., from observations or theoretical process studies) was at a sufficiently advanced stage, but had not been translated into climate model applications yet. New approaches to building teams for model improvement, as described below, might allow for more efficient translation of the scientific successes seen in past CPTs to model bias improvements.

It was acknowledged that single modeling center/agency efforts can be an effective mechanism for improving a single model, while the challenges associated with the multi-model, multi-agency approach are considerable. Despite this, the higher payoff to the community as a whole of a multi-model, multi-agency effort warrants the additional efforts and resources required for overcoming these hurdles.

4 Opportunities for Translating Process Understanding to Model Improvements

The workshop included presentations and discussion on biases within climate models, relevant process understanding, and areas where that understanding might be in a suitable state of readiness for translation into climate model developments. Only a subset of the climate science community could attend the workshop, and the topics discussed were naturally dependent on the individuals involved and topics highlighted in the survey results. As such, the opportunities identified at the workshop should be considered illustrative examples of the kinds of topics that could be tackled in future activities.

4.1 Modeling biases/areas requiring improvement

Information on key biases within climate model simulations was provided through a response to a survey questionnaire and talks and breakout group discussions at the workshop. The biases encompass all climate system components, including the ocean, atmosphere, land, and sea ice, and the coupling among them. In many cases, these biases can influence simulated biogeochemistry, the carbon cycle, and the transient climate system response. For example, adequately representing the upper ocean and the mixed layer is important not only for representing short timescale atmosphere-ocean interaction, but also because of its important role in primary productivity.

Many of the highlighted biases have existed through many generations of climate model development. For example, the presence of a double ITCZ, the warm sea surface temperature (SST) biases in eastern ocean boundary upwelling regions, biases in the position and strength of the Gulf Stream and associated SST, sea surface salinity, and surface fluxes of heat are persistent deficiencies in climate models. A number of biases discussed were specific to the atmosphere, such as the generally deficient diurnal cycle of convection and precipitation. Biases are found in aspects of variability, for example the eastward propagation of the Madden-Julian Oscillation (MJO) is, in general, poorly simulated. Biases in the relative proportion of liquid versus ice in mixed phase clouds with large impacts on radiative fluxes, particularly over the higher latitudes, were also discussed. Ocean-specific biases include those associated with water mass transformation in the Southern Ocean and those related to processes driving shelf-open ocean exchange. Cryosphere biases related to poor simulation of snow on sea ice and ice sheet-ocean interactions, particularly in fjords, were also noted. In the case of ice sheet-ocean interactions, current models generally do not even incorporate such coupling, pointing to a need for new model capabilities. Coastal interactions were raised as a concern, including biases associated with estuarine processes and the influence of river runoff on coastal oceans. Finally, there was some discussion of terrestrial biases (e.g., compensating errors in land surface to reduce surface temperature biases of the atmospheric model lead to additional errors, such as weak boundary layer development over agricultural areas).

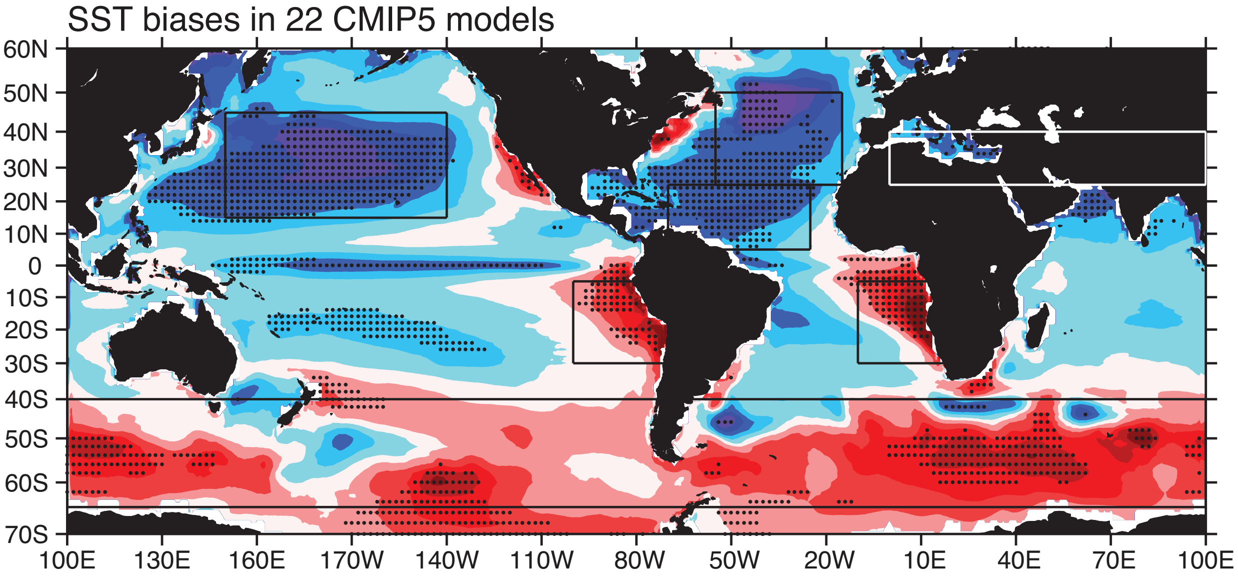

Figure 1: The difference (°C) between the averaged annual mean sea surface temperature (SST) simulated by 22 models participating in CMIP5 and the observational dataset ERSST. The dots denote where at least 18 of 22 models (82%) have the same sign in the SST bias. The boxes highlight regions with high values. Source: Wang et al. 2014.

Some of the noted biases are associated with coarse horizontal resolution. The horizontal resolution in workhorse ocean climate models is typically on the order of 1° with increased meridional resolution in the tropics. This results in resolution that is not adequate to represent baroclinic instability, mesoscale eddies, or coastal estuarine processes. Ocean currents tend to be too weak in mid-latitude boundary currents and often do not have the correct vertical structure. The coarse model resolution results in a poorly simulated Gulf Stream path and associated heat transport, and as a consequence SST biases in the Gulf Stream are amongst the largest in the world's oceans. The Gulf Stream also plays an important role in the AMOC and associated decadal modes of variability. In the atmosphere, coarse resolution adversely impacts the flow over topography, with many consequent impacts and some horizontal transport effects, such as the simulation of atmospheric rivers and high impact extreme events, such as hurricanes and tornadoes. In the tropical Indian Ocean, warm SST bias along the Somali upwelling region is likely due to insufficient representation of air-sea coupled processes in the region, a lack of resolution to represent the East Africa highlands, and the intensity of the Somali jet. Increases in model resolution will likely lead to improvement in some of these simulated aspects. However, given the need to run climate simulations for long timescales and multiple ensemble members, many model simulations will continue to be run at resolutions in which these biases are problematic. The transition to models with the capacity for regional refinement was noted and may alleviate some resolution-dependent issues. This raises the need for parameterizations that are scale-aware and valid for use across a large range of resolutions¾a need that was noted by climate modeling centers and meeting participants.

In many cases, studies have provided insights on the causes for model biases. New diagnostic capabilities have become available, such as satellite simulators within climate models that ensure consistent comparisons to satellite observations. These are aiding our understanding of the underlying causes and consequences of certain model biases. Process knowledge and observational data have advanced in many areas, providing the potential for translation into model improvements. Below we outline some example processes that impact specific model biases and are in a state of readiness for translation into climate model developments. The list is by no means exhaustive. Many other candidate topics are possible. However, working through these topics does give some indication of common requirements that are needed to make advancements.

4.2 Process understanding in a state-of-readiness for implementation in climate models

A series of talks and breakout sessions targeted areas where advances in process knowledge and observational information have been made that could be used to address some climate model biases. These processes spanned the climate system, including aspects of different climate components and the coupling between them[1]. In some cases, the processes mapped directly on to the climate model biases presented. However, even when this was not the case, it was generally thought that improved process representation in many areas would lead to improved and more reliable models.

In addition to improving specific processes within the model, there was a stated need to incorporate new model capabilities, such as the inclusion of estuary and fjord modules to better represent riverine or glacial discharge and coupling to the ocean. In order to capitalize on fjord modules, new developments would also be needed to simulate ice sheet/ocean interactions, with potential implications for AMOC variability. There was also recognition that some key issues in atmospheric model physics are presently related to the connections between the different parameterizations, highlighting the need for unified parameterizations (e.g., unified boundary layer and moist convection parameterizations). The importance of focusing on processes occurring at the interfaces (e.g., air-sea interaction, land-sea interaction, ice sheet-ocean interaction) was also highlighted.

The breakout groups focused at length on the state-of-readiness of specific processes for translation into climate model improvements. In general, this included processes that are thought to significantly impact important climate model biases, have significant process knowledge, and have observational constraints that would facilitate parameterization/process model developments. Below we address in more detail some example topics including the biases or phenomena that might be impacted, the data and understanding that exist, and how the translation of that information could be used to improve models. The example topics span the atmosphere, ocean, cryosphere, and coupled system, but by no means represent an exhaustive list. Indeed the workshop highlighted numerous candidate topics of this type and undoubtedly even these are just a subset of the possible processes in a state-of-readiness to be improved in models through coordinated activities. The examples discussed below were not chosen based on their relative importance or readiness relative to other candidate topics, but instead because adequate information existed from the workshop materials to more fully flesh them out. We

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[1] A list of examples of some of the types of processes that were discussed, including information on the motivation for addressing them is provided on the workshop website.

provide these examples primarily because they allow insights on the factors that determine the readiness of processes for incorporation into models.

4.2.1 Atmosphere example - Moist convection

Moist convection (in the boundary layer, shallow and deep) plays a crucial role in the climate system. A realistic representation of moist convection in weather and climate models is essential for the accurate prediction of a variety of phenomena, from weather to seasonal and climate change prediction¾for example, the diurnal cycle of convection and precipitation over land and ocean, severe storms, MJO, the monsoon, El Niño-Southern Oscillation (ENSO), and cloud-climate feedbacks.

Unfortunately, moist convection is notoriously difficult to parameterize in weather and climate models. The complexity of the convective processes and how they interact with the global climate system is seen in Figure 2. A variety of moist convection parameterizations have been developed over the last few decades (since the start of numerical weather and climate prediction in the 1960s), but many problems in its representation still need to be resolved. Even with the advent of global cloud resolving models (with horizontal grid resolutions from 1-10 km, capable of at least explicitly representing cluster/mesoscale dynamics), the community will need to develop improved moist convection parameterizations—not only for shallow convection and the transition to deep convection, but for deep convection as a whole—since at these resolutions, the resolved dynamics part is not able to explicitly represent key processes such as turbulent lateral entrainment.

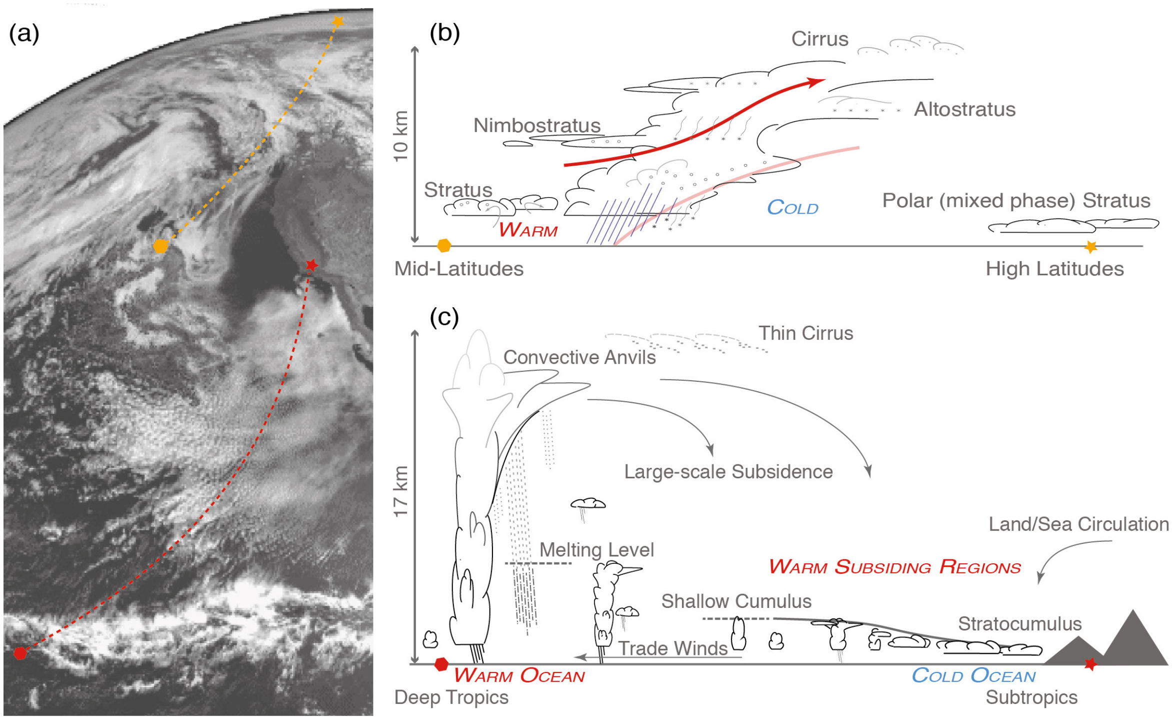

Figure 2: Two schematic cross-sections of the atmosphere—from the (b) high- to mid-latitudes and from the (c) subtopics to the tropics—highlighting the crucial role of different types of moisture convection and the need for unified parameterizations of all types of convection in atmospheric models. Source: IPCC AR5 Chapter 7 Fig. 7-04.

The development of moist convection parameterizations relies heavily on high-resolution (limited domain) models such as large-eddy simulation (LES) models (with resolutions of 10 to 100 m); on satellite observations (e.g., CloudSat); on *in situ* observational programs (e.g., DOE Atmospheric Radiaion Measurment (ARM) program); and on field experiments (e.g., RICO, TWP-ICE, DYNAMO).

An important modern topic of parameterization research is the development of unified parameterizations of all turbulent and convective processes in the Earth's atmosphere (including shallow and deep moist convection). In fact, the last few years have seen the advent of different approaches to solve this unification problem, which are being implemented in operational weather and climate prediction models. In particular, much work has been performed on approaches based on assumed probability density functions (PDFs; e.g., Bogenschutz et al. 2013) or on optimal blends of eddy-diffusivity (ED), typically used to parameterize more local mixing, and mass-flux (MF), typically used for moist convection (EDMF; e.g., Siebesma et al. 2007). Although versions of PDF and EDMF parameterizations have been tested and implemented with some success recently, it is fair to say that no parameterization that fully unifies the representation of all turbulent and convective processes has yet been implemented in atmospheric models.

Extending these new approaches to deep convection, which would allow realistic representation of the transition from shallow to deep convection for example, is perceived as crucial for the development of more accurate weather and climate models. A particularly important topic in this respect is the representation (parameterization) of the more complex convective structures that exist when moist convection gets deeper than the boundary layer and cloud microphysics start to play a key role in the dynamics and thermodynamics. Over the last several years much work has been done using multi-scale modeling framework (MMF) approaches, where 2D cloud resolving models (CRMs) are embedded in a climate model grid-box (e.g., Randall et al. 2003). MMF approaches can be useful to improve understanding of the interactions between deep convection and the large-scale dynamics. However, MMF approaches are still too (computationally) expensive and often suffer from similar parameterization issues as regular weather and climate models (e.g., clouds, boundary layer, and shallow convection all still need to be parameterized in these CRMs).

Multiple-plume convection parameterizations (e.g., Suselj et al. 2013) have grown in popularity in recent years to try to represent the complexity of moist convection and its interplay with the surrounding environment. But fully unified convection parameterizations, extending from boundary layer and shallow convection to deep convection, still need to address significant challenges. These include: the coupling of convection parameterizations to cloud micro and macrophysics parameterizations, downdraft parameterizations, and the role and representation of cold pools.

A clear advantage of unified parameterizations of boundary layer mixing and moist convection (as opposed to the more traditional parameterization modularity) is that the interaction of moist convection with the sub-cloud layer occurs in a much more natural (continuous) manner without the need for ad hoc cloud base closures, for example. In addition, it should also improve the representation of the interaction of moist convection with the land and ocean surface. In this context, particular attention should be paid to air-sea flux parameterizations and the interaction with ocean mixing, the triggering of convection over land by heating versus moistening (dry-versus wet-soil advantage; Findell and Eltahir 2003, Tawfik et al. 2015), subseasonal and higher frequency air-sea coupling, and the interaction of moist convection with sub-grid orography and gravity waves.

Important modern topics of research in numerical weather prediction, such as data-assimilation, ensemble prediction, and (global and mesoscale) high-resolution modeling (with horizontal resolutions of the order of 1 to 10 km), have major implications for the development of future convection parameterizations. In particular, the development and successful implementation of stochastic and scale-aware convection parameterizations will be crucial to improve the accuracy and reliability of weather, seasonal, and climate prediction.

4.2.2 Ocean example – Mesoscale eddy life cycles

Ocean mesoscale eddies, generated through baroclinic instability in regions of strong horizontal density gradients, are smaller than the grid-scale of most global models that are routinely used for climate-scale simulations. The horizontal model resolution needed to resolve the largest eddies in different regions around the globe is shown in Figure 3. The effect of such eddies on buoyancy transports and restratification has typically been represented by variants of the

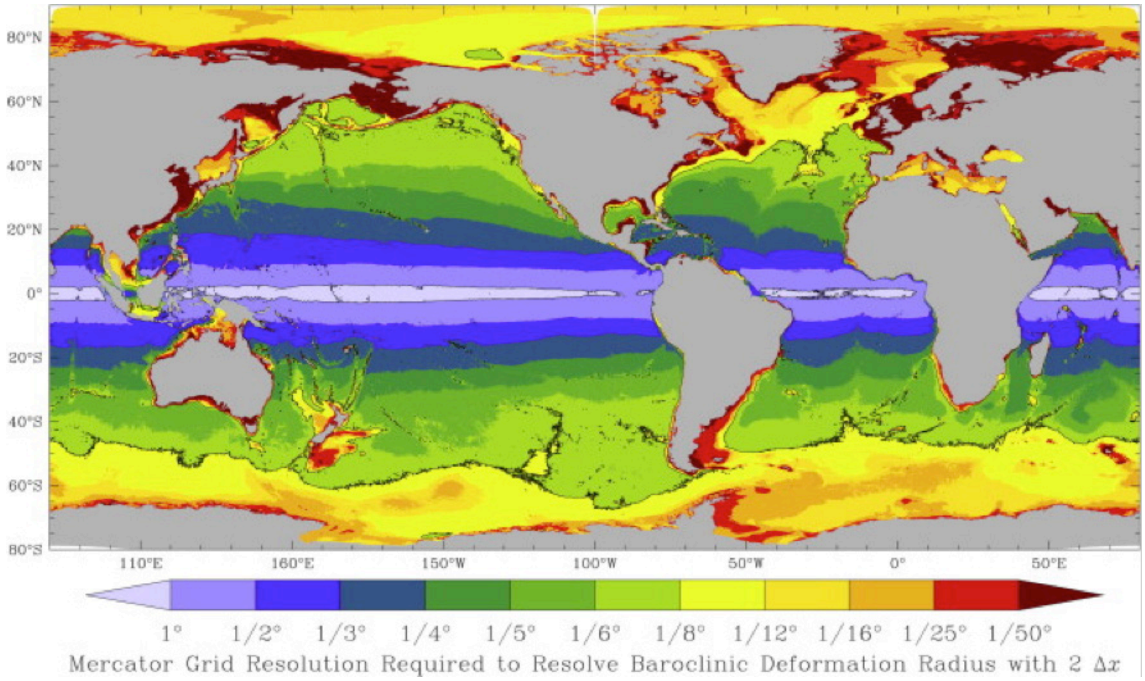

Figure 3: This figure shows an ocean model horizontal resolution required for the baroclinic deformation radius to be twice the grid spacing, based on a nominally eddy permitting ocean model after one year of spin-up from climatology. At the coarse resolution that is typical of the ocean components of CMIP5 coupled climate models (nominally 1° resolution), an ocean model only resolves the deformation radius in deep water in a narrow band within a few degrees of the equator; any important extratropical eddy effects will need to be parameterized. At a much higher resolution, such as a 1/8° Mercator grid, the deformation radius is resolved in the deep ocean in the tropics and mid-latitudes, but even in this case eddies are not resolved on the continental shelves or in weakly stratified polar latitudes. Source: Hallberg et al. 2013.

Gent and McWilliams (1990) parameterization. New IPCC-class global models are increasingly becoming eddy permitting, at least at low latitudes or in some cases even eddy resolving (McClean et al. 2011, Griffies et al. 2015). Yet, they are unable to represent the full range of mesoscale eddy activities, including their feedback on surface mixed layers, surface fluxes, large-scale current structure, and the processes by which eddies dissipate or transfer energy to larger scales. Contemporary ocean models thus need parameterizations of unresolved mesoscale processes that can co-exist with the resolved, or partially-resolved, mesoscale features without compromising the resolved dynamics.

Improved representation of the full lifecycle of mesoscale eddy energy would impact two major biases in climate models: western boundary currents (which in turn impact SST biases, AMOC, and decadal variability), and Southern Ocean and subpolar North Atlantic mixed layers (which in turn impact primary productivity and carbon uptake). Progress in improving the representation of these processes would be facilitated by the analysis of new high-resolution (up to 1/50°) simulations and by making use of new potential vorticity budget diagnostics (e.g., as recently implemented in CESM).

Several new parameterization ideas have shown promise in tests, including resolution-dependent mesoscale eddy parameterization (Hallberg 2013), the addition of stochastic backscatter (Jansen et al. 2015a), and use of negative viscosity or non-Newtonian visco-elastic dynamics (Mana and Zanna 2014). The loss of energy from mesoscale eddies to lee waves—and hence to diapycnal mixing—has been explored by Nikurashin and Ferrari (2011), and the impact of this lee-wave drag on the energy budget has been quantified in an eddy-resolving ocean model by Trossman et al. (2013). Eden and Greatbatch (2008) and Jansen et al. (2015b) have developed frameworks for accounting for the full mesoscale eddy energy budget.

New observational and process modeling efforts that are underway (ONR DRI including FLEAT, LatMix, and ASIRI) will likely provide new insights for understanding the evolution of eddies and fronts, and the important role that they play in controlling near-surface stratification. Other recent observations (DIMES; Gille et al. 2012) have focused on the interaction between eddies, topography, and diapycnal mixing. In both the upper and deeper ocean, these observations allow for a better understanding of the interactions between internal waves and eddies.

In summary, better representation of the eddy energy lifecycle is possible by synthesizing several new parameterization ideas—incorporating the loss of eddy energy to upscale transfer and dissipation at bottom topography—with new understanding from recent field programs, thereby improving representation of the impact of mesoscale eddies on mixed layers, surface fluxes, and large-scale energetic currents. Such a synthesis would involve theory (e.g., geostrophic turbulence inverse energy cascade), observations, high-resolution modeling, and interactions between different parameterization components (e.g., interactions between mesoscale eddy parameterizations and abyssal mixing via the generation of lee waves, interactions between mesoscale eddies and mixed layer parameterizations via re-stratification).

4.2.3 Cryosphere example – Snow on sea ice

Figure 4: Researchers collect samples of snow on sea ice, revealing its high spatial heterogeneity and redistribution by wind. Source: Donald Perovich, CRREL.

For much of the year, sea ice has an extensive and highly variable snow cover. This snow exhibits high-spatial heterogeneity and is greatly impacted by factors such as wind redistribution (Figure 4). Snow on sea ice is a highly insulative material (Sturm et al. 1998, 2002) with one of the highest albedos of all natural materials (Perovich et al. 2002). These aspects of the snow play a primary control on sea ice mass budgets and coupled interactions. The snow cover greatly attenuates light transmission to the ice and ocean with consequent impacts on ice and ocean biota. The relative importance of different snow impacts varies by season and is likely to change with changing climate conditions. For example, in winter snow insulates and slows ice growth, while in summer, the highly reflective snow reduces surface melt. As such, the state and variability of snow conditions on sea ice has implications for coupled climate feedbacks and the transient response of sea ice to changing forcing.

Climate models simulate large discrepancies in the snow conditions on sea ice (Hezel et al. 2012; Light et al. 2015). This influences the climate response to perturbations in forcing and the strength of the surface albedo feedback in future climate projections (Holland and Landrum 2015). The physical treatment of snow processes in climate models is quite simple and has remained largely unchanged over multiple model generations. For example, climate models typically assume a constant density snow pack with no liquid water content (e.g., Hunke 2014). They also generally exclude factors such as blowing snow and snow metamorphosis, which impact the snow mass budgets, its spatial heterogeneity, thermal properties, and surface reflectivity.

While the climate model representation of snow on sea ice has remained quite simple, considerable advances have been made in understanding the processes driving variations in snow conditions. Observational data indicate important changes in the thickness of the snow cover (e.g., Webster et al. 2014) that are coupled to and likely feedback on the changing sea ice state. Observations have also provided insights on what influences blowing snow and its redistribution (e.g., Dery and Tremblay 2004; Leonard et al. 2008), factors that influence snow metamorphosis (e.g., Sturm and Massom 2010), and how snow modifies the coverage and location of melt ponds (Perovich and Polashenski 2012). In some cases, aspects of this knowledge have been encapsulated in process models (e.g., Dery and Tremblay 2004; Lecomte et al. 2011) that can provide avenues for parameterization developments for large-scale climate models. New observations, for example from Operation IceBridge surveys (Kurtz and Farrell 2011), are also providing a larger scale perspective on varying snow conditions. The wealth of observations and process knowledge available should allow for significant advances in the process representation for snow on sea ice within climate models. This would improve simulated feedbacks with important implications for the projected climate response.

4.2.4 Coupled system example – Eastern boundary upwelling systems

Eastern boundary upwelling systems are regions of high biological productivity and play an important role in the carbon cycle. The dynamics of the processes controlling these regions are highly coupled and dependent on wind forcing, cloud processes, and ocean dynamics (Figure 5). SST biases at eastern boundaries are a longstanding problem with climate models. Various hypotheses have been proposed for their existence, including inadequate stratocumulus cloud representation, weak upwelling and coastal currents, and teleconnection of errors from remote (equatorial) regions. The SST biases are important to climate variability and predictability in these regions, and upwelling biases are important to projections of how coastal ecosystems respond to changing climate, including fishery and other impacts. Consequently, upwelling is one of the research foci for international CLIVAR .

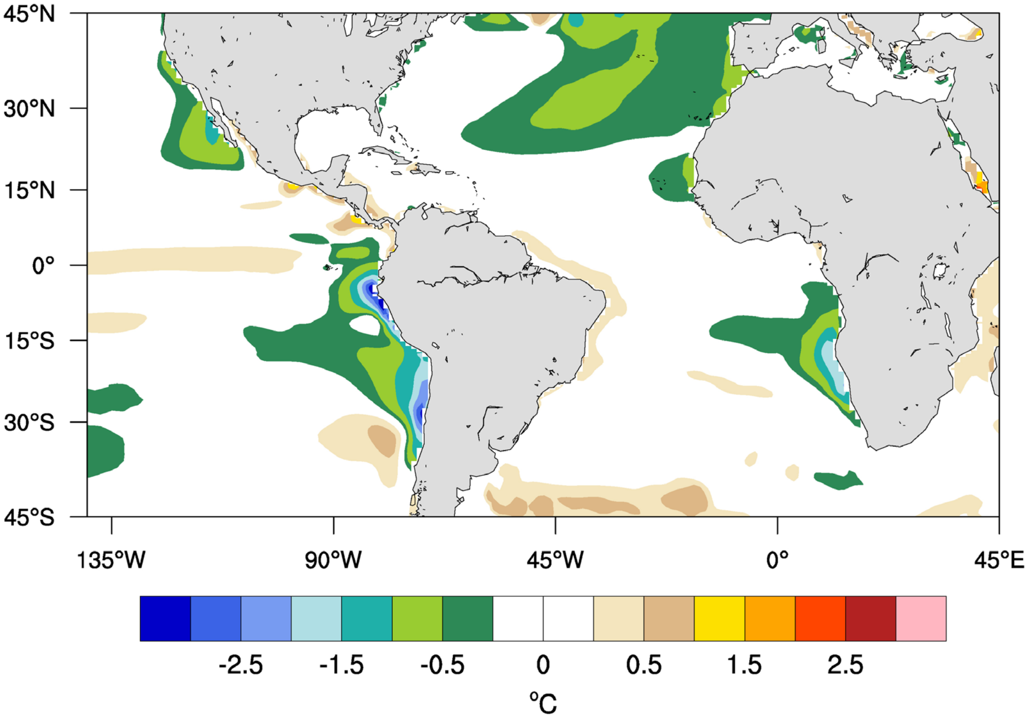

Figure 5: The impact of improving atmosphere resolution on global climate model SST. The figure shows SST in the Community Climate System Model (CCSM4) with a 0.5° atmosphere resolution, compared to CCSM4 with 1° atmosphere resolution. The plot is for boreal summer (June-July-August average) and shows a reduction of SST notably along the eastern boundaries of the Pacific and Atlantic oceans. The reductions off California and Baja California, off Peru and Chile, and off the South-west Africa coast act to improve the typical climate model warm biases in these regions. The improvements are due mainly to enhanced upwelling, more Equatorward surface flow, and changes to low level clouds.

The interactions between clouds and SST (i.e., the coupling between atmospheric and ocean physics) play a key role in modulating both the cloud properties and the SST. It is well known that the SST biases extend far beyond the upwelling regions and many of these biases can only be accounted for by biases in cloud cover and liquid water. There is a potential positive feedback in this tight coupling problem: Cloud biases lead to SST biases, which in turn lead to even more marked cloud biases, and so on. Biases in cloud cover and liquid water are, to first degree, a manifestation of issues in the vertical thermodynamic structure of the atmospheric boundary layer. New and improved parameterizations of the atmospheric boundary layer turbulence and convection (e.g., PDF-based, EDMF) are essential for the improvement of these cloud and SST biases.

Recent work has confirmed that the representation of physical processes in the eastern boundary of ocean basins in models is resolution-dependent in a significant manner. Higher atmosphere horizontal resolution is key to simulating atmospheric jets and obtaining a coastal SST bias reduction (Gent et al. 2010). High-vertical resolution, particularly within the planetary boundary layer, can improve coupled model biases (Harlaß et al. 2015). Higher ocean resolution (to at least 0.1°) is needed to resolve coastal currents/fronts and upwelling (Small et al. 2015).

The theory controlling features relevant to the SST biases have been explored in a number of studies. The dynamics of the atmospheric coastal jet have been examined in the framework of hydraulic theory (Samelson 1992), which has been applied to the California Jet. Validity of the theory is being tested for the Benguela Jet (Patricola et al. 2015), but what key parameters control the jet structure remains to be explored. The linear dynamics of coastal upwelling have been extensively explored in McCreary et al. (1987), Fennel et al. (2012), and Junker (2014). These dynamics were found by Small et al. (2015) to explain much of the errors in one particular climate model (NCAR's CCSM4) due to the biased off-coast structure of wind forcing. The University of California Los Angeles Regional Oceanic Modeling System (ROMS) group and others have extensively explored non-linear ocean dynamics in ocean-only simulations, including eddies, frontal filaments, and submesoscale vortices (Capet et al. 2008, references therein). Coupled high-resolution regional models (Jin et al. 2009; Renault et al. 2016; Seo et al. 2016) further provide insight on feedback processes operating in the upwelling zone.

Extensive observations also exist for the three most biased regions in the world, namely the southeast Atlantic/Benguela system, the southeast Pacific/Humboldt current and the northeast Pacific/California Current. For example, the Coastal Ocean Dynamics Experiment (CODE) collected some very useful data for the California Jet, the VOCALS campaign (Mechoso et al. 2014) took extensive observations for the southeast Pacific and Humboldt current system, and the ongoing PREFACE (Prediction of Tropical Atlantic climate and its impacts), campaign is gathering extensive data of the oceanographic dynamics of the southeast Atlantic/Benguela current system. Additional existing data can be brought to bear on understanding the relative controls on SST conditions in these regions.

Given the importance of the SST biases in these regions, advances in theoretical understanding, and extensive observations that exist, model developments are both needed and possible. A number of possible approaches to address this issue include:

- Enhancements in atmospheric horizontal resolution to at least 0.5°, which are currently being run in some models and appear sufficient to reduce the SST bias in some regions (Gent et al. 2010; Small et al. 2015);
- Mesh-refined atmosphere and/or ocean components, which are becoming available in some models and can provide regional refinement in coastal zones;
- Atmospheric parameterizations to better represent the boundary layer turbulence, convection, clouds (e.g., PDF-based, EDMF), and coastal jets; and
- Ocean parameterizations to mimic the effect of narrow coastal upwelling, coastal oceanic jets, and topographically influenced filaments and eddies in coarser resolution models.

4.3 Implementation-ready processes likely to benefit model improvement

The workshop identified many different opportunities for model improvement by incorporating new process understanding. Any future activities should not be limited to the topics discussed in this document or at the workshop given that the interests of only a subset of the community have been considered thus far. As highlighted in discussions at the workshop and illustrated by examples above, there are some common elements for relevant implementation-ready processes. These include:

1. Processes that have an important influence on the simulation characteristics. This can include processes for which improved representation ameliorates biases in the simulated climatological state or—just as importantly—increases the realism of climate variability and feedbacks or influences the simulated biogeochemistry and carbon cycle.
2. Processes that have an adequate level of understanding. This understanding should be informed by theoretical considerations and observational analysis.
3. Adequate human capital (e.g., theoreticians, observers, modelers) that can synthesize and enhance the relevant process knowledge to enable translation into model improvements.

5 Pathways for Future Teams

While there was consensus on the success and effectiveness of the current CPT format, extensive discussion focused on possible improvements to the structure of future teams. While many of the current and past CPTs have successfully focused on specific processes, there is the realization that new efforts could be focused on questions related to the interactions between different components of the climate system. An example includes the physics of the coupled ocean-atmosphere system in upwelling regions giving rise to SST biases. A coupled CPT would draw on members of two or more disciplines to improve representations of a coupled process. The highly focused approach of CPTs could be extended to include specific climate phenomena, which emerge from multiple interacting processes. These efforts have merit from a "pure" scientific angle; potential climate simulation improvements may not be obvious until functioning representations of the processes can be studied in a connected system.

It would be useful to explore process translation themes that would attract interest from multiple modeling centers and agencies, including both weather and climate prediction centers. In this context, data-assimilation is a tool that could help bridge the gaps between these different communities. Ensemble prediction has not been studied in detail by previous CPTs and brings slightly different challenges in terms of parameterization (e.g., stochastic physics). Sensitivity experiments (e.g., model resolution or parameter uncertainty in parameterizations) could also be used to better identify parameters and processes responsible for coupled biases.

New computational capabilities now allow for experimental global simulations with ultra high-resolution (order of a few km, even if only for a few days) for both the ocean and atmosphere. These new revolutionary global simulations are unique tools to understand atmospheric and oceanic processes at scales between 1 km and the more commonly used grid resolutions of 50-100 km in climate model simulations. In particular, in the atmosphere, these models will provide unique insight into the role of deep convection and mesoscale dynamics and novel ideas on how to move forward with parameterizations of moist convection in climate and weather models.

In terms of new observational capabilities, large datasets (e.g., from new autonomous underwater vehicle capabilities, satellite data) and data mining capabilities (making use of big data) could potentially lead to new developments. In particular, satellite observations, which often provide a global view of certain variables and processes, have not been at the core of previous CPTs. However, satellite data have been used for data assimilation and validation of weather and climate models. While *in situ* observations or high-resolution models, such as large-eddy simulation, can adequately resolve processes missing in climate models, satellite data rarely possess the spatial and temporal resolutions to completely represent these physical processes. However, satellite observations offer comprehensive, nearly global datasets that have yet to be completely exploited in parameterization development endeavors. Recent examples (e.g., Suzuki et al. 2013) on how to successfully use satellite observations to improve specific physical processes in climate models offer significant promise in this respect. Focused efforts for parameterization development should be encouraged that take advantage of satellite observations and optimal combinations of high-resolution modeling, *in situ* observations, and satellite observations.

In summary, there are a variety of exciting challenges and opportunities, from focusing on process-interaction to exploiting new computational capabilities and satellite datasets, which will help shape new CPT projects.

6 Summary and Conclusions

The workshop highlighted key current biases across the plethora of climate and weather models developed and maintained by seven different modeling centers in the US. It also showcased how past CPTs have led to significant model improvements, while developing strong and enduring links between academia and model developers. The success of past CPTs does not diminish the need for future activities in this arena, as numerous processes remain poorly represented. Better representations of specific processes—as well as the complex interactions between processes—and between ocean, atmosphere, land, and cryosphere components, are likely to reduce still pervasive model biases. Hence, there is consensus on the need for future efforts to harness expertise from the observational, theoretical, and modeling communities and form dedicated teams that achieve synergy for improving climate models.

The workshop participants strongly recommend such activities continue in the future. There is consensus that new activities should retain many aspects of the past CPTs. These include the formation of teams involving modelers, observationalists, and theoreticians, based in both modeling centers and academia, and the funding of postdocs dedicated to the task. Workshop participants also give strong support to multi-modeling center, multi-agency approaches, well-suited to deliver sustainable and comprehensive improvements to climate models. Recommendations for new developments include enlarging the scope of such activities to consider not only teams built around the theme of improving the representation of a specific process, but also new teams focused on coupled processes and model component interactions to address specific biases or climate phenomena. New activities must consider the emerging computational and expanded observational capabilities, as well as the challenges associated with the growth in observational and model data. Future mechanisms to facilitate the translation of process understanding to improvements in climate models will be broadly welcomed by the climate science community.

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Appendix A: Workshop Organizers

Scientific Steering Committee

Alessandra Giannini, Columbia University

Marika Holland, National Center for Atmospheric Research

Sonya Legg, Princeton University

Amala Mahadevan, Woods Hole Oceanographic Institution

Aneesh Subramanian, University of Oxford / University of California San Diego (chair)

Joao Teixeira, NASA Jet Propulsion Laboratory / Caltech

Caroline Ummenhofer, Woods Hole Oceanographic Institution

Program Organzing Committee

Mike Patterson, US CLIVAR

Jill Reisdorf, University Corporation for Atmospheric Research

Kristan Uhlenbrock, US CLIVAR

Appendix B: Workshop Participants

Name	Institution
Abernathey, Ryan	Lamont Doherty Earth Observatory/Columbia University
Adcroft, Alistair	Princeton University/NOAA Geophysical Fluid Dynamics Laboratory
Alford, Matthew	University of California, San Diego
Annamalai, H	University of Hawaii
Arbic, Brian	University of Michigan
Bamzai, Anjuli	National Science Foundation
Barrie, Daniel	NOAA Climate Program Office
Bombardi, Rodrigo	George Mason University
Bretherton, Christopher	University of Washington
Burls, Natalie	George Mason University
Cabre, Anna	University of Pennsylvania
Carton, James	University of Maryland
Cesana, Gregory	NASA Jet Propulsion Laboratory/Caltech
Chassignet, Eric	Florida State University
Danabasoglu, Gokhan	National Center for Atmospheric Research
De Boer, Gijs	University of Colorado, Boulder
DeWeaver, Eric	National Science Foundation
Dirmeyer, Paul	George Mason University
Dunne, John	NOAA Geophysical Fluid Dynamics Laboratory
Edson, James	University of Connecticut
Fedorov, Alexey	Yale University
Flatau, Maria	Naval Research Laboratory
Fox-Kemper, Baylor	Brown University
Giannini, Alessandra	Columbia University
Giddings, Sarah	Scripps Institution of Oceanography
Gnanadesikan, Anand	Johns Hopkins University
Griffies, Stephen	NOAA Geophysical Fluid Dynamics Laboratory
Groeskamp, Sjoerd	Lamont-Doherty Earth Observatory/Columbia University
Grooms, Ian	University of Colorado

Hagos, Samson	Pacific Northwest National Laboratory
Hallberg, Robert	NOAA Geophysical Fluid Dynamics Laboratory
He, Feng	University of Wisconsin-Madison
Held, Isaac	NOAA Geophysical Fluid Dynamics Laboratory
Hewitt, Helene	UK Met Office
Holland, Marika	University Corporation for Atmospheric Research
Itsweire, Eric	National Science Foundation
Jansen, Malte	The University of Chicago
Jiang, Xianan	University of California, Los Angeles
Koch, Dorothy	Department of Energy
Krueger, Steven	University of Utah
Legg, Sonya	Princeton University
Leung, Ruby	Pacific Northwest National Laboratory
Lindsay, Keith	National Center for Atmospheric Research
Liu, Zhiyu	Xiamen University
Lubin, Dan	Scripps Institution of Oceanography
Lucas, Sandy	NOAA Climate Program Office
Mahadevan, Amala	Woods Hole Oceanographic Institution
Martin, Andrew	Scripps Institution of Oceanography
Maslowski, Wieslaw	Naval Postgraduate School
Mechoso, Carlos	University of California, Los Angeles
Ming, Yi	NOAA Geophysical Fluid Dynamics Laboratory
Patricola, Christina	Texas A&M University
Patterson, Michael	US CLIVAR Project Office
Pawson, Steven	NASA GSFC - GMAO
Pene, Chrystal	University Corporation for Atmospheric Research
Penny, Steve	University of Maryland
Perovich, Don	Dartmouth College
Pirani, Anna	International CLIVAR Project Office
Ralph, Marty	Scripps Institution of Oceanography
Randall, David	Colorado State University
Reynolds, Carolyn	Office of Naval Research
Richards, Kelvin	University of Hawaii
Ridout, James	Naval Research Laboratory
Romanou, Anastasia	Columbia University/NASA Goddard ISS
Shevliakova, Elena	NOAA Geophysical Fluid Dynamics Laboratory

Singh, Bohar	George Mason University
Small, Richard	National Center for Atmospheric Research
Smyth, William	Oregon State University
Solomon, Amy	NOAA/University of Colorado
Stephens, Graeme	Colorado State University
Straneo, Fiammetta	Woods Hole Oceanographic Institution
Subramanian, Aneesh	University of Oxford / University of California, San Diego
Teixeira, Joao	University of California, Los Angeles
Thompson, Andrew	California Institute of Technology
Thompson, LuAnne	University of Washington
Tolman, Hendrik	NOAA National Centers for Environmental Prediction
Trossman, David	NASA GESTAR/Johns Hopkins University
Tselioudis, George	NASA/Goddard Institute for Space Studies
Uhlenbrock, Kristan	US CLIVAR Project Office
Ummenhofer, Caroline	Woods Hole Oceanographic Institution
Wang, Shugang	Columbia University
Winton, Michael	NOAA Geophysical Fluid Dynamics Laboratory
Xu, Xiaobiao	Florida State University
Zeng, Zhen	COSMIC/University Corporation for Atmospheric Research
Zhang, Chidong	University of Miami
Zhao, Ming	NOAA Geophysical Fluid Dynamics Laboratory
Zuidema, Paquita	University of Miami

Appendix C: Agenda

Thursday, October 15

7:30-8:00	Registration/breakfast	
8:00-8:15	Introduction	Aneesh Subramanian, U. Oxford
8:15-9:55	**Modeling Center Presentations (15 mins + 5 min discussion each)** **Chair: Sonya Legg**	
8:15	Key issues arising in CM4 development at GFDL	Isaac Held, NOAA GFDL
8:35	Biases and development needs for CESM	Marika Holland, NCAR CESM
8:55	Improvements in the GISS climate model and process based evaluation	Anastasia Romanou, NASA GISS
9:15	DOE's Accelerated Climate Model for Energy (ACME): Plans for Version 1 and Beyond	Dorothy Koch, DOE
9:35	Moving to a simpler NCEP production suite; moving to unified coupled global modeling	Hendrik Tolman, NOAA NCEP
9:55-10:15	Break	
10:15-11:20	**Modeling center talks continued (15 mins + 5 min discussion each)**	
10:15	US Navy coupled system research and development under Earth system prediction capability	Carolyn Reynolds, NRL
10:35	Observation-driven studies using the GEOS-5 Earth System modeling and analysis: Some examples	Steven Pawson, NASA GMAO
10:55	Discussion with modeling center presenters	
11:20-12:00	**Current status of process understanding (15 mins + 5 min discussion each)** **Chair: Joao Teixeira**	

11:20	Atmosphere-ocean boundary layers and fluxes	Baylor Fox-Kemper, Brown U.
11:40	Improved parameterization of heat, mass and momentum exchange for process studies in numerical models	Jim Edson, U. Connecticut
12:00	Lunch	
1:00-3:00	**Current status of process understanding: continued (15 mins + 5 mins discussion each)**	
1:00	Recent advances in understanding glacier-ocean interactions	Fiamma Straneo, Woods Hole Oceanographic Institute
1:20	Radiation, clouds and aerosols	Graeme Stephens, Colorado State U.
1:40	Gliding into the Grey Zone: The quest for resolution-independent physics	Dave Randall, Colorado State U.
2:00	Capturing the dynamics of ocean-estuarine interactions across multiple spatial and temporal scales	Sarah Giddings, Scripps Institution of Oceanography
2:20	Land-atmosphere interactions - A coupled modeling problem	Paul Dirmeyer, George Mason U.
2:40	Discussion with process understanding speakers	
3:00-3:15	Break	
3:15-5:00	**Breakout session 1:**	
Room 1: Ocean | Lead: LuAnne Thompson; Rapporteur: Malte Jansen		
Room 2: Atmosphere | Lead: Steven Krueger; Rapporteur: Rodrigo Bombardi		
Room 3: Atmosphere | Lead: Don Perovich; Rapporteur: Amy Solomon		
Room 4: Air-Sea | Lead: H. Annamalai; Rapporteur: Natalie Burls		
5:30 - 7:30	**Poster session & networking event; Brush Gallery, Princeton Campus**	

Friday, October 16

8:00-8:30	Breakfast	
8:30	Introduction	Aneesh Subramanian, U. Oxford
8:35-9:05	Agency perspective	
	Sandy Lucas (NOAA) Dorothy Koch (DOE) Dan Eleuterio (ONR) Eric Itsweire, Eric DeWeaver, Anjuli Bamzai (NSF)	
9:05-10:00	**Some past Climate Process Team examples: Lessons learned** **Chair: Marika Holland**	
9:05	Has a decade of Climate Process Teams strengthened US climate model development?	Chris Bretherton, U. Washington
9:20	Ocean climate process teams: Successes and lessons learned	Sonya Legg, Princeton U.
9:35	Discussion	
10:00-10:20	Break	
10:20-10:40	Summary of breakout session 1	Leads for each breakout session
10:40-12:00	**Breakout session 2:**	
Room 1: Tropical biases | Lead: Xianan Jiang; Rapporteur: Gregory Cesana		
Room 2: Mid-latitude biases | Lead: Richard Small; Rapporteur: Ryan Abernathy		
Room 3: High-latitude biases | Lead: Wieslaw Maslowski; Rapporteur: Gijs De Boer		
12:00-1:00	Lunch	
1:00-2:30	**Future prospects for observations/modelers (10 mins. each + discussion)** **Chair: Caroline Ummenhofer**	
1:00	Air-Sea Interaction Regional Initiative (ASIRI) in the Northern Indian Ocean	Amala Mahadevan, Woods Hole Oceanographic Institution

1:10	From DYNAMO to YMC: How field campaigns help understand processes of tropical deep convection and its interaction with the ocean	Chidong Zhang, U. Miami
1:20	The CalWater Field Experiment: Overview of objectives and data collected	Marty Ralph, Scripps Institution of Oceanography
1:30	Smoke and clouds above the southeast Atlantic: Combined observational and modeling strategies to probe absorbing aerosol's impact on climate	Paquita Zuidema, U. Miami
1:40	The Oliktok Point Observational Facility	Gijs De Boer, U. Colorado
1:50	Update on CMIP6	Gokhan Danabasoglu, NCAR
2:00	Developing ocean and sea ice components of UK coupled models for seamless prediction	Helen Hewitt, UK Met Office
2:10	Discussion	
2:30-2:45	Break	
2:45-3:05	Summary of breakout session 2	Leads for each breakout session
3:05-4:30	**Breakout session 3: Mechanisms for future activities that bridge process studies and modeling centers**	
Group 1 | Lead: Andy Thompson; Rapporteur: Andrew Martin		
Group 2 | Lead: Maria Flatau; Rapporteur: Sjoerd Groeskamp		
Group 3 | Lead: Alistair Adcroft; Rapporteur: David Trossman		
4:30	Break	
4:45-5:30	**Summary session: next steps** **Chair: Amala Mahadevan/Alessandra Giannini**	
5:30	Workshop adjourns	

Poster Presentations

Isopycnal Mixing and Ventilation Controlled By Winds	Ryan Abernathey	Columbia University
The Calving and Icebergs CPT	Alistair Adcroft	Princeton University/ NOAA GFDL
Systematic errors in monsoon simulation: A way forward	H. Annamalai	University of Hawaii
The internal gravity wave spectrum: A new frontier in global ocean modeling	Brian Arbic	University of Michigan
Implementing a New Convective Trigger function in the NCEP Climate Forecast System version 2	Rodrigo Bombardi	George Mason University
Extra-tropical origin of equatorial Pacific cold bias in climate models	Natalie Burls	George Mason University
Southern Ocean open-sea convection teleconnections	Anna Cabre	University of Pennsylvania
Evaluation of Cloud and Heating Rate Profiles in Eight GCMs Using A-train Satellite Observations	Gregory Cesana	NASA JPL/Caltech
Sensitivity experiments with HYCOM-CICE during the CORE-II project	Eric Chassignet	Florida State University
Impact of isopycnal mixing on the amplitude of El Nino	Anand Gnanadesikan	Johns Hopkins University
Global ocean circulation and mixing strengths deduced from observations	Sjoerd Groeskamp	Columbia University
AMIE/DYNAMO/CINDY: From process level understanding to model evaluation and improvement	Samson Hagos	Pacific Northwest National Laboratory
Parameterizing subgrid-scale eddy effects using energetically consistent backscatter	Malte Jansen	The University of Chicago
Exploring Key Processes in Modeling the Madden-Julian Oscillation	Xianan Jiang	University of California, Los Angeles
An Economical PDF-Based Turbulence Closure Model for Cloud-Resolving Models and Global Climate Models	Steven Krueger	University of Utah

Atmospheric Rivers From a Hierarchy of Climate Simulations	L. Ruby Leung	Pacific Northwest National Laboratory
The ARM West Antarctic Radiation Experiment (AWARE)	Dan Lubin	Scripps Institution of Oceanography
Evaluating Kinematic and Thermodynamic Structure of Modeled Atmospheric Rivers using Airborne In-Situ Observations	Andrew Martin	Scripps Institution of Oceanography
Improving understanding and modeling of Arctic climate change with process resolving climate models	Wieslaw Maslowski	Naval Postgraduate School
Coupled Air-Sea Interactions in Coastal Upwelling Regions: Atmospheric Low-level Coastal Jets and Marine Stratocumulus Clouds	Christina Patricola	Texas A&M University
The Hybrid Global Ocean Data Assimilation System at NCEP	Steve Penny	University of Maryland/ NCEP
Sunlight and Sea Ice	Don Perovich	Dartmouth
The CalWater Field Experiment	F. Martin Ralph	Scripps Institution of Oceanography
Shear driven turbulence in the natural environment	Kelvin Richard	University of Hawaii
Bimodal Representation of Convection with a Modified Kain-Fritsch Cumulus Scheme	James Ridout	Naval Research Laboratory
Wind driven currents in the Benguela upwelling system and the success of climate models	Richard Small	NCAR
Short-term sea ice forecasts with the RASM-ESRL coupled model: A testbed for improvign simulations of ocean-ice-atmosphere interactions in marginal ice zone	Amy Solomon	University of Colorado/ NOAA-ESRL
Improving modeling of diurnal variability in upper ocean processes and surface fluxes using satellite and in-situ observations	Aneesh Subramanian	University of Oxford
Stochastic multi-scale modeling for weather and climate prediction	Aneesh Subramanian	University of Oxford
Open-ocean submesoscale motions: Seasonal variations in mixed layer instabilities from gliders	Andy Thompson	CalTech
Metrics for position, strength and variability of the Gulf Stream	LuAnne Thompson	University of Washington

Revelations about parameterizing lee waves in ocean models	David Trossman	NASA GSFC/Johns Hopkins
A GEWEX Process Evaluation Study (PROES) of water and energy cycles in mid-latitude storms	George Tselioudis	NASA/GISS
Temperature-Salinity Structure of the North Atlantic Circulation and Associated Heat/ Freshwater Transports	Xiaobiao Xu	Florida State University
Cloud-radiative feedback in the DYNAMO MJO events	Shuguang Wang	Columbia University
Remote Sensing of the Thermal Structure of Marine Boundary Clouds in the Southeast Pacific using COSMIC, CALIOP, and Radiosonde	Zhen Zeng	UCAR/COSMIC
Shallow Cloud at Manus in Observations and GCM Simulations	Chidong Zhang	University of Miami

Appendix D: US CLIVAR Climate Process Team Survey Summary of Process Study/Observing Program/ Prior Team Responses

In spring 2015, the scientific organizing committee for the US CLIVAR Workshop on Translating Process Understanding to Improve Climate Models developed a survey to collect feedback on the CPT approach and to identify processes for which newly available observational data and understanding could inform future model improvements from the perspective of process studies, enhanced observing projects, recent satellite missions, recent Climate Process Teams (CPTs), and US CLIVAR Working Groups. The input was used to inform the scope and agenda of the workshop. The survey was sent to 61 such efforts and the committee received responses from the 43 listed on the next page. A single completed survey was provided by the respondent listed on behalf of each effort. The survey was also promoted through the US CLIVAR and monthly newsgram to solicit input from individual scientists. An additional eight responses were received. This document summarizes the responses provided by the 51 respondents and their collaborators.

The organizing committee expresses appreciation to the respondents and contributors for their input. The individual responses of the survey are available on the US CLIVAR website.

Individuals who contributed to survey responses:
Matthew Alford, Matt Barlow, Rob Black, Peter Bogenschutz, Michael Bosilovich, Chris Bretherton, David Bromwich, Maarten Buijsman, Antonietta Capotondi, Luca Centuroni, Ming-Huei Chang, Ping Chang, Tom Cowton, Gijs de Boer, Charlotte DeMott, John Dunne, David Farmer, Tom Farrar, Oliver Fringer, Ke-Hsien Fu, Patrick Gallacher, Sasha Gershunov, Sarah Gille, Hans Graber, Richard Grotjahn, William Gutowski, David Gutzler, John Gyakum, Weiqing Han, Patrick Heimbach, Karl Helfrich, Shu-Peng (Ben) Ho, George Huffman, Steven Jachec, Chris Jackson, Sen Jan, Steven Jayne, Meibing Jin, Bill Johns, Shaun Johnston, Nicole Jones, Terry Joyce, Kris Karnaukas, Kathryn Kelly, Sam Kelly, Jody Klymak, Pavlos Kollias, Steven Krueger, Young-Oh Kwon, Gary Lagerloef, Vince Larson, Sonya Legg, Ruby Leung, Ernie Lewis, Ren-Chieh Lien, John Lillibridge, Young-Kwon Lim, Susan Lozier, Dan Lubin, Andrew Lucas, Jennifer MacKinnon, Amala Mahadevan, Eric Maloney, John Marshall, Greg McFarquhar, Roberto Mechoso, Brian Medeiros, Chris Meinen, Dimitris Menemenlis, Mark Miller, Shrinivas Moorthi, Jim Moum, James Moumand, Ruth Musgrave, Jonathan Nash, Peter Nienow, Theresa Paluszkiewiczx, Jae-Hun Park, Tom Peacock, Steve Penny, Renellys Perez, Andy Pickering, Robert Pincus, Rob Pinkel, Al Plueddemann, Steve Price, Luc Rainville, Steve Ramp, Jens Redemann, Dan Rudnick, Lynn Russell, Sutanu Sarkar, Ray Schmitt, Russ Schumacher, Alberto Scotti, Olga Sergienko, Toshiaki Shinoda, Emily Shroyer, Harper Simmons, Gail Skofronick-Jackson, Emily Shroyer, Donald Slater, Justin Small, Bill Smyth, Andrew Sole, Amy Solomon, Janet Sprintall, Lou St. Laurent, Fiamma Straneo, Peter Strutton, Amit Tandon, T-Y Tang, LuAnne Thompson, Martin Truffer, Johannes Verlinde, Andreas Vieli, Andrew Vogelmann, Duane Waliser, Chunzai Wang, Wanqiu Wang, Yu-Huai Wang, Amy Waterhouse, Michael Wehner, Bob Weller, Rob Wood, Y-J Yang, Chidong Zhang, Zhongxiang Zhao, and Paquita Zuidema.

Recent and Planned Process Studies

		Field Years	Respondent	Institution
ACAPEX	ARM Cloud Precipitation Experiment	2015	Ruby Leung	PNNL
ASIRI	Air-Sea Interaction in the Northern Indian Ocean – Regional Initiative	2013-2014	Emily Shroyer	Oregon State U.
AWARE	ARM West Antarctic Radiation Experiment	2015-2016	Dan Lubin	SIO
CLIMODE	CLIvar Mode Water Dynamic Experiment	2005-2007	Terry Joyce	WHOI
DIMES	Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean	2009-2014	Sarah Gille	SIO
DYNAMO	Dynamics of the MJO	2011-2012	Eric Maloney	U. Miami
IASCLIP	InterAmericas Study of Climate Processes	N/A	Chunzai Wang	NOAA AOML
IWISE	Internal Waves in Straits Experiment	2011	Matthew Alford	U. Washington
KESS	Kuroshio Extension System Study	2004-2006	Steven Jayne	WHOI
LASIC	Layered Atlantic Smoke Interactions with Clouds	2016-2017	Paquita Zuidema	U. Miami
MAGIC	Marine ARM GPCI Investigation of Clouds	2012-2013	Ernie Lewis	BNL
ORACLES	Observations of Aerosols above Clouds and their Interactions	2016-2018	Jens Redemann	NASA-Ames
SOCRATES	Southern Ocean Clouds, Radiation, & Aerosol Transport Experimental Study	2016-2019	Greg McFarquhar	U. Illinois
SPICE	Southwest Pacific Ocean Circulation and Climate Experiment	2008-2015	Janet Sprintall	SIO
SPURS	Salinity Processes in the Upper Ocean Regional Study (First & Second)	2012-2013 2016-2017	Ray Schmitt	WHOI
TTide	Tasman Tidal Dissipation Experiment	2015	Rob Pinkel	SIO
VOCALS	VAMOS Ocean-Cloud-Atmosphere-Land Study	2008	Roberto Mechoso	UCLA

Enhanced Observations Projects

		Period	Respondent	Institution
AMOC	Atlantic Meridional Overturning Circulation Observing System			
	RAPID/MOCHA: Meridional Overturning Circulation and Heatflux Array	2004-2020	Bill Johns	U. Miami
	OSNAP: Overturning in the Subpolar North Atlantic Program	2014-2018	Susan Lozier	Duke U.
	SAMOC: South Atlantic Meridional Overturning Circulation	2009-	Chris Meinen	NOAA AOML
ARM	Atmospheric Radiation Measurements Climate Research Facility			
	Eastern North Atlantic	2013-	Rob Wood	U. Washington
	North Slope of Alaska	1997-	Gijs de Boer	U. Colorado
OOI	Ocean Observatories Initiative			
	Pioneer Array: Northeast Coast	2013-	Al Plueddemann	WHOI
	Global Nodes: Irminger Sea, Station Papa, Argentine Basin, Southern Ocean	2014-	Bob Weller	WHOI

Recently Deployed Satellite Missions

		Period	Respondent	Institution
Aquarius	Aquarius Sea Surface Salinity Mission	2011-	Gary Lagerloef	ESR
COSMIC-2	2nd Constellation Observing System for Met, Ionosphere, & Climate	2016-	Ben Ho	UCAR
GPM	Global Precip. Measurement (& Tropical Rainfal Measuring Mission)	2014-2017	George Huffman	NASA GSFC
JASON-3	3rd JASON Altimetry Mission	2015-	John Lillibridge	NOAA NESDIS

CPT and CPT-like Projects

		Period	Respondent	Institution
US CLIVAR	Ocean Eddy Mixed-Layer Interactions	2003-2008	Dan Rudnick	SIO
US CLIVAR	Gravity Current Entrainment	2003-2008	Sonya Legg	WHOI
US CLIVAR	Ocean Mixing Processes Associated w/ High Spatial Heterogeneity in Sea Ice	2010-2015	Meibing Jin	U. Alaska
US CLIVAR	Cloud Parameterization and Aerosol Indirect Effects	2010-2015	Vince Larson	U. Wisconsin
NOAA MAPP	Improving Turbulence and Cloud Processes in the NCEP Global Models	2013-2016	Steven Krueger	U. Utah
NOAA MAPP	Representing Calving and Iceberg Dynamics in Global Climate Models	2013-2016	Olga Sergienko	Princeton U.

Working Groups

		Period	Respondent	Institution
US CLIVAR	MJO WG	2006-2010	Duane Waliser	NASA JPL
US CLIVAR	Drought WG	2006-2009	David Gutzler	U. New Mexico
US CLIVAR	Western Boundary Current WG	2007-2010	Kathryn Kelly	U. Washington
US CLIVAR	Decadal Variability WG	2009-2013	Amy Solomon	U. Colorado
US CLIVAR	Greenland Ice Sheet-Ocean Interactions Working Group	2010-2014	Patrick Heimbach	U. Texas-Austin
US CLIVAR	Eastern Tropical Ocean Synthesis WG	2012-2015	Paquita Zuidema	U. Miami
US CLIVAR	ENSO Diversity WG	2012-2015	Antonietta Capotondi	U. Colorado
US CLIVAR	Extremes WG	2012-2015	Richard Grotjahn	U. Cal-Davis
US CLIVAR	Ocean Carbon Uptake	2012-2015	John Dunne	NOAA GFDL

Does your effort address interactions between components of the climate system (e.g. ocean-atmosphere, land-ocean, cryosphere-hydrosphere) or can it be used to throw light on such interactions?

Atmosphere-ice:	2
Atmosphere-only:	3
Coupled:	1
Land-atmosphere:	1
Ocean-atmosphere:	22
Ocean-atmosphere-ice:	1
Ocean-atmosphere-land:	2
Ocean-ice:	3
Ocean-only:	3

What benefits do you see from an observational/theoretical point of view for participating in a team (that would involve climate modelers) for translating your results to climate models?

- Down- and upscaling observations and process-understanding across spatial and temporal climate-relevant scales
    - Ability to use climate models to estimate metrics of interest (e.g. AMOC strength) in periods prior to and after the observing system is in place
    - Ability to interpret regional signals in a longer/broader climate-relevant context: observationalists and regional modelers would welcome an opportunity to improve their knowledge of how the "regional downscaling" of climate variability is influencing local processes
    - "Much more aware of the issues, scales involved, constraints and even language of climate models, and how different they are from what we small-scale observationalists are used to"
    - "Appreciation [of] what scales can and cannot be resolved in climate models, development of the most fundamental representations of specific physical processes and reassessment of theoretical assumptions in a context of several components of the climate system"
- Assess dynamical links within the modeled system
    - "Observational researchers can assess the relationships between components, but do not necessarily know what the dynamical link is, whereas the theorists hypothesize links, but don't know how robust they are. Neither group necessarily understands the practical limitations of the models, but have ideas about what needs to be included in a climate model to reproduce what is observed. As an observationalist working with a model, it is gratifying to see a dynamical system modeled to understand the links between components. Modelers seem to focus excessively on removing the biases of the models rather than reproducing the accuracy of the component interactions (sensitivity of each component to input)."
    - "Opportunity to synthesize and analyze available observations in a context of multiple components of the climate system, and by virtue of that to better understand specific physical processes"
    - "Each discipline is limited in their ability to assess the system and its controls as a whole ; only through integration can one start to build a consistent physical model"

- Help promote predictive capabilities, including seamless prediction
- Broader impact of the results from observational and theoretical studies à helps provide motivation for future studies

Have you participated in a CPT before? Why/why not?

Yes: 12 No: 23 Informal: 4

- Reasons for "no": No relevant CPT call; no funding success; not invited to participate; lack of organization in the community; no topical fit within CPT parameters

What do you see as the strengths/weaknesses of the current (or past) CPT efforts?

Strengths:

- Bringing modelers/observationalists/theoreticians together
    - Improving communication, in-depth discussion
    - Interdisciplinary groups form new research communities
    - Exposes modeling centers to new ideas, physical insight obtained from data, involvement of groups looking at the specifics of the process from different angles
    - Community learns of problems facing climate models, what their inherent limitations are, and what modelers need for model verification and improvement
    - Community gets access to modeling center scientists, models, and resources
- Achieve significant model improvement by focusing on a specific climate process
    - Clear goal and model-ready parameterizations
    - Timeline and expected results: motivation for the team to work together
    - Bring a parameterization problem to closure
- Funding for postdocs
    - Postdocs can be dedicated to the tasks needed to bring parameterization schemes to fruition, where observations and essential theory already exist, which might otherwise be crowded out by other obligations

Weaknesses:

- Timeline allotted to CPT is not always sufficient to accomplish goals
    - Important not to overpromise
    - It may take longer than 3-5 years to complete work, starting from quality control of observations, to iteration on different parameterization ideas, to finally assess parameterizations in climate models.
- More communication needed
    - More frequent in-person workshops
    - Communication can tail off toward end of project
    - Need to maintain communication between workshops, but no specific funding for management of websites, telecommunication, etc.
- Obstacles to interaction with modeling centers
    - Modeling centers have to contend with competing demands (e.g. IPCC schedules)
    - Some modeling centers are not organized for external collaboration
- Need to ensure CPTs lead to lasting model improvements
    - Parameterizations should be physically based
    - Parameterizations should be implemented and evaluated in key climate models
    - Common code repository for resulting parameterizations needed

- Insufficient focus
    - Key is to choose the right problem
- Lack of international participants
- Ongoing feedback needed during lifetime of CPT, to allow adjustment for key gaps in expertise, unforeseen problems
- Not always clear how interested people, especially observationalists, could participate

What information/outcome from your effort or from other studies known to you, can be used toward development of the next generation of Earth System Models?

- New parameterization schemes:
    - sub-grid-scale ocean mixing
    - next-generation parameterization of internal wave mixing
    - representation of calving and icebergs
    - gravity currents
    - cloud parameterization (CLUBB)
    - representation of clouds and turbulence
    - cloud/aerosol interaction parameterization
- Datasets:
    - ground-truthing for N. Atlantic and S. Atlantic overturning (OSNAP & SAMOC);
    - obs. from high-wind regimes, air-sea fluxes (KESS)
    - measurements of clouds, aerosols, radiation. (ARM North Slope of Alaska)
    - PBL measurements (SOCRATES)
    - Shelf/slope exchange, carbon fluxes (Pioneer array)
    - MJO processes (DYNAMO)
    - Antarctic cloud microphysics, aerosol chemistry (AWARE)
    - Sea surface salinity (Aquarius)

    - radar and lidar obs.(ARM Eastern N. Atl.)
    - aerosols and clouds, Southeast Pacific and Atlantic (VOCALS-Rex dataset; ORACLES and LASIC future datasets)
    - freshwater and mixed layer processes (ASIRI)
    - equatorial surface mixing processes
    - cloud/aerosol/radiation (MAGIC)
    - radio occultation estimates of marine boundary layer height (COSMIC)
    - precip/latent heat estimates (GPM & TRMM).
- Model techniques:
    - data assimilation available to identify model biases and observational outliers
    - increased horizontal and/or vertical resolution
    - ocean hybrid coordinates
- Model diagnostics/metrics:
    - MJO diagnotics
    - Large-scale meteorological patterns associated with extremes
- Process understanding:
    - western boundary currents
    - Intra-Americas Seas region
    - cloud-atmosphere interactions in Arctic
    - eastern upwelling regions
    - glacier/ocean interaction

Which process(es) do you think are 'ready' for implementation as a new or improved parameterization in climate models? List specific climate process (or interaction among climate processes), whose representation in climate models could be significantly improved in 3-5 years.

- Atmosphere:
  - More unified parameterizations of subgrid clouds, turbulence, aerosols, and radiative processes; will advance rigor and consistency of parameterizations
  - Improved prognostic cloud formulations and aerosol-cloud interactions
  - Organization of tropospheric water vapor plumes ("atmospheric rivers")
  - Stochastic physics and scale-aware parameterizations of clouds and convection
  - Convection parameterization that better controls entrainment into convective cores
  - Large-scale dynamic/thermodynamic structures that facilitate the production of temperature and precipitation extremes
  - Representation of cloud phase (cloud microphysics schemes esp. in the high latitudes)
  - Ice nucleation parameterizations and aerosol-cloud-precipitation interactions using data from ACAPEX and other field campaigns
  - Parameterizations to help improve representation of atmospheric coastal jets
  - Precipitation formation incorporating turbulent redistribution of precipitating hydrometeors
  - Representation of continental cumulus convection and the associated diurnal cycles of cloud, radiation and precipitation
- Ocean:
  - Parameterization of frontal processes such as distribution of surface buoyancy gradient, submesoscale vertical mixing, air-sea buoyancy and momentum fluxes at fronts and restratification.
  - Representation of small scale heterogeneity in turbulence penetrative depths and frontally associated local horizontal gradients to improve mechanisms of sub-mixed layer ocean stratification
  - Mixed-layer processes and parameterization (surface waves effects and the transition layer in KPP model)
  - “deep cycle” turbulence found just below the surface mixed layer
  - Improvements to air-sea flux parameterizations
  - Representations of property exchange between the continental shelf and open ocean
  - Parameterization of submarine melting, sub glacial discharge and freshwater export from fjords
  - Processes that affect the depth, intensity, and compactness of the equatorial thermocline (diffusion of heat from the surface, diurnal cycle of vertical mixing, entrainment of cold water from below)
  - Up gradient potential vorticity fluxes and the resulting acceleration of the jet
- Land:
  - Vegetation & carbon fluxes over continents
  - Subsurface processes such as groundwater table dynamics and plant hydraulics processes can improve simulations of ET and land-atmosphere interactions
- Ice:
  - Fast sea ice
  - Ice-albedo feedback associated with sea ice (polynyas etc.) and with continental snowpack decline
  - Effects of heat and freshwater flux anomalies on local sea-ice formation

- Coupled:
    - Mixed-layer diurnal variability in coupled climate models with better representation of the diurnal cycle of heat, salinity and momentum
    - Parameterization of diurnal skin layer in climate models to improve the MJO simulation
    - Air-surface exchanges at high latitudes
    - Ice-shelf/sea ice interaction
    - Water and heat fluxes over continents, partition E vs T in evapotranspiration (ET) fluxes, leading to questions about the relative roles of soil moisture vs plant transpiration in generating ET
    - Updated COARE flux algorithm for air-sea flux exchange
    - Representation of linkages between SSS and soil moisture

Do you envision a need for inter-disciplinary teams to translate process understanding into climate models? Comment on how they can be most effective.

Yes: 21 No: 4

- To be most effective, interdisciplinary teams should:
    - Focus on specific (well-defined) problem
    - Focus on problems with sufficient knowledge/understanding of the processes (eg. from observations or theoretical process studies), but that knowledge has not been translated into climate model applications
    - Target processes likely to lead to a significant impact on climate models, and benefit multiple climate modeling efforts à participants from multiple modeling centers
    - Be more effective when focusing on one climate model only
    - Encompass interaction between observation teams, key personnel in the modeling centers, and data assimilation personnel from the operational centers à data assimilation as ‘stepping stone’ between other two communities
    - Be coupled CPTs, rather than atmosphere-only or ocean-only CPTs
    - CPTs as important strategy for raising profile of particular issues & provide internal modeling center support for model development
    - Have limited team size
    - Have more interaction btw university-based academics & modeling centers
    - Allow for effective planning, requiring long enough lead times to coordinate diverse teams (eg. wrt funding calls)
    - Have more funding for model development at national level (and better (coordinated) management of available funding)
- Reasons for “no”: too premature; priority should be within realms/model components to improve process-representation in models (only exception is ocean-sea ice-atm, which is ready for interdisciplinarity)

A workshop on "Translating Process Understanding to Improve Climate Models" is being planned to facilitate engagement and interaction of modeling center and community expertise (across observations, process modeling, and theory) and explore prospects for model improvement. Are you (or representatives from your group) interested in attending the workshop? Why/why not?

Attend – yes: 24 Attend – maybe: 12 Attend – no: 3

Yes: ACAPEX, ARM research facilities, ASIRI, AWARE, COSMIC, decadal variability WG, DYNAMO, ENSO WG, ETOS WG, extremes WG, GCE CPT, GRISO WG, IWISE, ocean carbon WG, OSNAP, OSTST, Pioneer array (OOI), SAMOC, SOCRATES, turbulence & cloud processes CPT, VOCALS

- Reasons for "maybe" responses: lack of funds; conflicting schedule
- Reasons for "no" responses: too premature; too prescriptive, CPT formation should emerge from bottom-up approach, not top-down by US CLIVAR

What was your experience in participating in a CPT?

- "Learned a lot from the group of PIs, both from gaining knowledge from each other and training of managing a big project"
- "It was great fun in that we assembled a large group of great people working on cloud problems, and some interesting work came out of the CPT. Personally, I wound up not having much more collaboration through the team than I might have otherwise. … but I think we had essentially zero impact on the modeling centers."
- "Postdoc from that CPT is now a researcher at my institution" à recruitment tool

Do you like their present structure and organization? (Please comment only on the structure and not on specific science or individuals).

Like: 8 Dislike: none

- "I think the CPT structure is genius. My European colleagues have been extremely envious when I have described some of the efforts with which my institution has been involved."
- "Allowing for international participants will be very beneficial"
- "Success of any CPT hinges on its leadership" à not necessarily best for early-/mid-career scientists, unless advised by senior mentor
- In-depth communication is key, currently facilitated by workshops; more frequent communication between workshops desirable through funded support staff
- "Well-organized with monthly group telecons and a well-organized reporting and communicating structure using wiki-based software"
- "It might be useful to form CPTs that work on only one climate model, rather than two."

Appendix E: US CLIVAR Climate Process Team Survey Summary of Modeling Center Responses

With the completion of the current cycle of US CLIVAR Climate Process Team (CPT) projects in 2015, the US CLIVAR Process Study Model Improvement Panel is undertaking a review to assess:

- Effectiveness and lessons learned from the CPT approach
- Main sources of errors/biases in models
- Opportunities for future model improvement based on new observations and process understanding
- Potential payoff for possible future collaborative projects (e.g., CPTs)

To inform the review and help scope and agenda for the October 2015 Workshop on Translating Process Understanding to Improve Climate Models, the organizing committee for the review and workshop developed a questionnaire to gather input from US climate modeling centers on the strength/weaknesses of current or previous CPTs (for those who participated in them) and to assess the status of various components of the models and the main sources of errors and biases – for an expanded list of modeling centers who may participate in future projects. The questionnaire also explored interest in expanding beyond the prior focus on ocean and atmosphere component models to potentially include crysophere, land surface, and biogeochemistry. Questions were purposefully open-ended so as not to direct or limit the responses. A single coordinated response from each center was requested.

The list of centers that completed the survey include:

- NSF National Center for Atmosphere Research (NCAR)
- NOAA Geophysical Fluid Dynamics Laboratory (GFDL)
- NOAA National Centers for Environmental Prediction (NCEP)
- NASA Goddard Institute for Space Studies (GISS)
- NASA Global Modeling and Assimilation Office (GMAO)
- DOE Accelerated Climate Modeling for Energy (ACME)
- ONR Naval Research Laboratory (NRL)

The following pages provide a summary of the responses to the questionnaires. The organizing committee expresses appreciation to the respondents for coordinating the responses on behalf of their center. The individual responses of the survey are available on the US CLIVAR website.

Lessons from Past CPTs

Strengths:

- Coordinated multi-institutional and multi-agency research efforts (envy of intl community)
- Provides pathway for translating observationally, theoretical and numerically derived

process understanding for improving models (à effective in leveraging costly observational programs); topic choice for CPT determined by ‘readiness’ of process understanding from community, rather than by modeling center needs
- Encourages multiple different approaches/ideas within a team, which mitigates risks, explores innovative approaches, and facilitates cross-fertilization; effective in building bridges between modeling centers and broader community
- Collaboration between centers, rather than competition, building bridges among the community and modeling centers
- Goes beyond diagnosing model problems/biases, but seeks connection between biases and model physics, which is difficult and time consuming; process-focused, not bias-focused
- Early-mid career CPT leaders and dedicated postdoc personnel (the latter kept things going between meetings), both clearly invested in success of CPT, but providing them also with effective training
- Annual workshop crucial for enhancing/establishing (new) collaborations; such exchange leverages more than what is directly funded
- Most support going to community, not modeling center

Weaknesses:

- Funding asymmetries between funding agencies lead to asymmetries in team focus
- Hard to include international collaborators
- With thematically/temporally overlapping CPTs, key model center personnel can be over-taxed
- Overly narrow proposal categories can lead to funding of weak CPTs
- Productivity, as measured by publication output, potentially not so great (à publication count should not be the ‘metric’ for success for CPTs)
- Challenge to keep collaborations going after CPTs

How to make CPTs more effective:

- Encourage budgeting for dedicated project manager and technical support (e.g., website, cross-group communication, timely exchange of data, outreach, organizing conference session) to allow the lead-PI to focus on CPT topic. Such a model ensures success/lasting legacy of CPT, rather than funding a collection of loosely connected individual projects.
- Ensure support for annual workshops
- Allow international collaborators to be funded (strongly suggested by GFDL)
- Think about funding mechanisms for non-center participants and ensure equal engagement with all centers involved despite potential funding asymmetries by different agencies
- Steady supply of funds, rather than a one-time fund injection (perhaps internal to NOAA)
- Ensure CPTs have focused scientific goals/models, without narrowly confining proposal categories
- There are many more ways that changes could make CPTs less effective and diluted, rather than more effective. Care is needed to build on demonstrated strengths.

Model Improvement Needs and Opportunities

Expansion of CPTs to encompass the cryosphere, land surface, and biogeochemistry:

- In principle supportive, but not through single CPT solicitation (too broad/diluted); agencies should be focused in CPT solicitation to make meaningful contributions to programs/ constituents; process-understanding in some realms possibly not ready for CPT, yet
- ESM aspects requiring most attention often cite processes at interface between different realms, e.g.,:
    - Coupling/consistent and scale-insensitive parameterization of subgrid scale processes, fluxes/exchange between different model system components
    - Ice-ocean interactions and sea-ice dynamics (glacier-fjord models, sea-ice thermodynamics)
    - Air-sea interactions (atmospheric boundary processes, near-surface ocean processes)
    - All aspects of hydrological cycle and convective parameterization (snow and aerosol models)
    - Coastal/marginal sea processes (e.g., estuarine mixing, coastal upwelling)
    - Vertical transports and surface processes in ocean (e.g., overturning, upwelling, waves)
    - Polar feedbacks (e.g., ice-albedo, cloud radiative)
    - Biogeochemistry (e.g., carbon cycle and climate feedbacks, ocean biology, dynamic vegetation)
    - Interaction between land (canopy) and atmosphere

Strongest model biases:

- Double ITCZ, precipitation intensity distribution across all spatiotemporal scales, tropical cyclones
- Ocean heat uptake, storage, and redistribution; biases in tropical ocean SST
- ENSO (e.g., amplitude, periodicity), MJO and other modes of climate variability (PNA, NAO, AO)
- Coastal upwelling and stratus decks (eastern boundary regions, including ocean biogeochemistry)
- Clouds (e.g., aerosol-cloud interactions, low-level clouds, liquid/ice water content)
- Diurnal cycle over land and ocean
- Subtropical cloud radiative effects in the Southern Ocean
- Ice-sheet dynamics and discharge

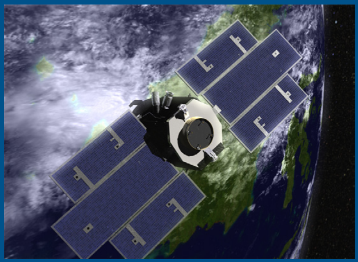
Challenges with modeling climate variability:

- Problems seen as emergent phenomena in climate system/model arising from difficulty in simulating specific processes; challenging phenomena include internal climate variability (e.g., AMO, ENSO, MJO, monsoon) and distinguishing the variability signal from the model trend; not enough observations for describing long term climate variability

Specific climate processes with potential to improve models in 3-5 years:

- Meso- and submeso-scale mixing in ocean (waves, tidal mixing); Southern Ocean mixing
- Cloud microphysics (including aerosols), atmospheric turbulence, aspects of convection modeling (such as convective detrainment, cold pool triggering), cloud-radiation interaction
- Interaction between marginal seas and open ocean (including freshwater discharge)

- Upwelling (coastal, equatorial) and links to stratus decks (clouds)
- Multi-decadal internal climate variability (AMO), and QBO to be resolved in the stratosphere
- Increased model resolution and scale-aware parameterizations for various processes
- Diurnal-to-annual surface processes (land and ocean)
- Ice-sheet atmospheric interactions, ice-sheet dynamics, ice-ocean interactions
- Terrestrial carbon stores and land surface (surface/subsurface hydrological processes, Land Use and Land Cover Change)



US Climate Variability &
Predictability Program
1201 New York Ave NW, Suite 400
Washington, DC 20005
www.usclivar.org
uscpo@usclivar.org
twitter.com/usclivar

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