A White Paper
Resulting from the US CLIVAR Workshop
"Translating Process Understanding to Improve Climate Models"

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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, NSF and 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 currently funded CPTs coming to an end, there is a need to review their benefits and devise a plan for future efforts.

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 modeling centers and a wide range of process studies/ observational efforts (see full list in Appendix). The results of the modeling center survey and the process studies and observational projects survey, available through the embedded links, confirmed broad community interest for a scoping workshop.

A workshop was therefore convened by US CLIVAR (PSMIP) at the encouragement of the US Inter-Agency Group, 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 DOE, with local support from NOAA GFDL. The steering committee organized the workshop, reported to the Inter-Agency Group on its outcomes by means of a short report and teleconference, and has now compiled this white paper to provide feedback to the community.

The community-wide workshop with open participation was held at GFDL, on October 15-16, 2015 to discuss 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 talks available to anyone who could not participate in person (a further ~80 remote participants).

Scheduled over two full days, the workshop included invited oral presentations, posters, breakout sessions, and participant discussions. Oral presentations were solicited from representatives of modeling centers, who were requested to highlight model biases and weaknesses. Process study group representatives were invited to describe newly developed process understanding from observational and theoretical studies, which could inform model improvement. These presentations were solicited to be as inclusive and as broad as possible, but they could not represent all the interests expressed in the survey due to time constraints.

An agenda for the workshop is available online. It targeted the ocean, atmosphere, cryosphere, and land, and the interactions between these climate components. After some discussion early on, and from the feedback of the surveys, it was thought best to maintain the focus of these efforts on physical climate-related 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.

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. The US CLIVAR-sponsored 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 NCAR) used for climate change simulations. Other NOAA-sponsored CPTs were designed to specifically improve NOAA models, including 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., 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 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 by providing a more complete picture of the ocean internal wave energy distribution (CPT website) and stimulating 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, for example through the continuing presence at the modeling center of process experts originally hired as CPT liaisons.

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

Climate process team 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)	NOAA/NSF	2003-2008	GFDL, NCAR
Low latitude cloud feedbacks on climate sensitivity	Chris Bretherton (UW)	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 (UWisc)	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 (SIO)	NOAA/NSF	2010-2015	NCAR, GFDL

Improving turbulence and cloud processes in the NCEP global models	Steve Krueger (U Utah)	NOAA	2014-2017	NCEP, NCAR
Representing calving and iceberg dynamics in global climate models	Olga Sergienko (U Princeton)	NOAA	2013-2016	GFDL
Cloud and boundary layer processes	Chris Bretherton (UW)	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 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, models 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” condensing observations of oceanic overflows into a convenient reference (Legg et al. 2009) and the synthesis of ocean mixing data (Waterhouse et al. 2014).

In summary, 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.

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

3. Format of teams

The CPT approach sought to bring together observationalists, theoreticians, and modelers to improve model representation of targeted processes. Aspects of the CPT approach originally supported by NSF and NOAA have now been espoused by other projects and agencies, including DOE, NASA, and ONR. A number of programs, within the aforementioned agencies, seek to engage the university/research community in model improvement. Between 2011 and 2015, ONR funded a multi-institution five-year Departmental Research Initiative (DRI) on “Unified Physics for Extended-Range Prediction.” DOE has just 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,” and NOAA’s “Climate Test Bed” are regular components of the “Research Opportunities in Space and Earth Sciences” (ROSES), as well as the Climate Program Office’s regular request for proposals.

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 divide up the workload according to their strengths may be more effective. Differences in agency mission, e.g., 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 missions, could thus lead each agency to prioritize the improvement of the representation of different processes.

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.

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) 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 that was emphasized is 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 AMOC variability, Danabasoglu et al. 2010), or even after the project has officially ended (in terms of funding). Recognition and support for this "analysis tail" 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 is due to often unpredictable and complex interactions between different physical processes.

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.

Though the challenges associated with the multi-model/agency approach are considerable, and while single modeling center/agency efforts can be an effective mechanism for improving a single model, the higher payoff to the community as a whole of a multi-model, multi-agency effort encourages the additional efforts and resources required for overcoming these hurdles with planned action.

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. Such an illustrative list is presented in Table 2.

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. Much of this information was provided by several modeling centers themselves with breakout group discussions allowing a wider community perspective. 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 for not only representing short time scale 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, and biases in the position and strength of the Gulf Stream and associated biases in sea surface temperature, sea surface salinity and surface fluxes of heat, are persistent deficiencies in climate models. A number of biases discussed were specific to the atmosphere, for example, 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. Coastal interactions more generally 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, including vegetation biases over the continental United States.

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 and mesoscale eddies. 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 Atlantic Meridional Overturning Circulation (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. 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. However, this raises the need for parameterizations that are scale-aware and valid for use across a large range of resolutions; a 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. In some cases, the processes mapped directly on the climate model biases presented. However, even when this was not the case, it was generally felt that improved process representation in many areas would lead to improved and more reliable models.

Table 2 contains a list of some of the processes that were discussed, including information on the motivation for addressing them. 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 discharge and coupling to the ocean. 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) was also discussed in some detail.

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 were felt 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 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 and 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 prediction, e.g., 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. 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 to 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 as well—since at these resolutions the resolved dynamics part is not able to explicitly represent key processes such as turbulent lateral entrainment.

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 starts 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 particularly 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, 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 tackle 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, 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 high-resolution modeling (with horizontal resolutions of the order of 1 - 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 effect of such eddies on buoyancy transports and restratification has typically been represented by variants of the Gent and McWilliams (1990) parameterization. New global models are increasingly becoming eddy permitting, at least at low latitudes. 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.

Improved representation of the full life cycle 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., 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). Jansen et al. (2015b) and Eden and Greatbatch (2008) 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 interaction 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 involve 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

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. 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 et al. 2014). They also generally exclude factors, such as blowing snow and snow metamorphosis, which impacts 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. 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 of CLIVAR: http://www.clivar.org/research-foci/upwelling.

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 much 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 (Small 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 et al. (2015). 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 UCLA ROMS group and others have extensively explored non-linear ocean dynamics, including eddies, frontal filaments, and submesoscale vortices (Capet et al. 2008, references therein).

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, http://preface.b.uib.no/) 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 (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.
- Ocean parameterizations to mimic the effect of narrow coastal upwelling and coastal oceanic jets 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. These opportunities are summarized in Table 2, but 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.

Table 2. Processes/phenomena identified at the workshop that participants felt were in a reasonable state of readiness for translation into climate model improvements.

Process / Phenomenon	Potential Bias Improvement	Motivation	References
Estuarine/fjord – ocean interactions	Salinity near estuaries and rivers; coastal ocean stratification	Allows for riverine nutrient & heat transport; impacts coastal biogeochemistry	Geyer and MacCready (2014)
Atmospheric boundary layer and land surface interaction	Forecast biases on sub-seasonal timescales	Improvements in soil moisture coupling to atmospheric boundary layer	Kumar et al. (2014)
Equatorial mixing	Cold tongue bias	Can influence simulated variability (ENSO), surface coupling	Sasaki et al. (2013)
Eddy life cycle and energetics	Mixed layer depth; primary production	Controls on vertical ocean exchange, upper ocean stratification	Jansen et al. (2015b)
Eastern boundary upwelling	Warm regional SST bias	Improve coupled interactions and feedbacks; impacts on BGC	Small et al. (2015)
Western boundary currents	SST, surface heat fluxes, and oceanic heat transport	Potential links to AMOC, decadal variability	Carton et al. (2014), Hu et al. (2015)
Swell	Southern ocean mixed layer bias	Potentially influence ocean transient response	Fan and Griffies (2014)
Shelf-open ocean exchange	Ocean water mass and density structure	Potential influence on shelf biogeochemical processes including upwelling driven primary production, hypoxia, and low pH events	Bryan et al. (2015)
Gravity wave drag	Large-scale circulation	Improved wind stress and coupling	Geller et al. (2013)
Atmospheric moist convection	Diurnal cycle of precipitation	Improvements to tropical climate and variability	Pearson et al. (2014)
Mixed-phase clouds	Radiation biases, precipitation biases	Potential influence on cloud feedbacks	Pithan et al. (2014)
Snow on sea ice	Snow and albedo biases	Influences polar feedbacks	Hezel et al. (2012)

5. Pathways to future teams

While there was consensus on the success and effectiveness of the current CPT format, a long 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. 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 and should not be exclusively tied to a specific improvement in model fidelity.

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 oceans 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 has 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 (LES) can adequately resolve processes missing in climate models, satellite data rarely possesses 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 of optimal combinations of high-resolution modeling, *in situ,* 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. Past CPTs have led to significant model improvements and helped develop strong and enduring links between specific scientific communities in 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, theory, and modeling communities and form dedicated teams that achieve synergy in improvement of 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 gave 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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Appendices to be included in final report:

1. *Modeling Center Survey Responses*
2. *Process Study Survey Responses*
3. *List of workshop attendees*
4. *Workshop agenda*
5. *List of acronyms*