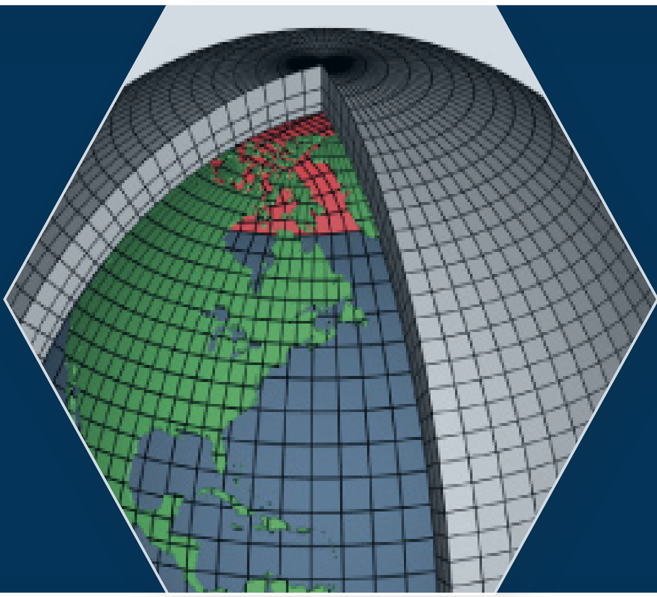

NOAA Technical Report OAR CPO-6

Climate Model Development Task Force Final Report

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Climate Program Office

Silver Spring, Maryland

August 2017

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1 See Appendix B for list of participants.

Executive Summary

The Climate Model Development Task Force (CMDTF; 2014-2017) was formed to bring together representatives from National Oceanic and Atmospheric Administration (NOAA) laboratories, the NOAA National Centers for Environmental Prediction (NCEP), and Climate Process Teams research centers and other projects funded by the NOAA Modeling, Analysis, Prediction and Projections (MAPP) program, with an interest in furthering the coupled modeling capability for sub-seasonal to seasonal and longer time scale prediction. The CMDTF provided a platform to discuss model development efforts and best practices. The CMDTF made contributions to the planning process including defining requirements for the transition from operations to research (O2R) and for future model configurations and output, and defining metrics and a test harness for evaluation of climate models and climate predictions. A number of the projects that were engaged in the CMDTF contributed to designing and developing subgrid-scale and land surface process representations, component models, coupling infrastructure, and multi-model combination strategies. The CMDTF served the functions of both keeping the diverse projects in these categories informed of progress and findings as well as stimulating collaboration among these projects.

Among several contributions from the CMDTF, special emphases were placed on better representing: atmospheric shallow and deep convection, including its initiation, its evolution and magnitude, and its interaction with turbulent and cloud processes; the interactions between clouds, aerosols and radiation; the structure and evolution of ozone concentration in the atmosphere and its interaction with other chemically active species and stratospheric processes in general; soil-hydrology-vegetation interactions, including more accurately initializing soil moisture and better representing the roles of lakes in coupled system prediction; and ocean circulation and the interaction of the upper ocean with the lower atmosphere. The CMDTF also contributed in the areas of software infrastructure for coupling model components, diagnosing and evaluating coupled models and coupled model predictions, and optimally composing multi-model ensembles.

The vigorous CMDTF discussions exposed several critical scientific and organizational challenges that must be addressed as the National Weather Service evolves its long-range weather and climate outlook capabilities. Among the scientific challenges are correcting the relative lack of sensitivity of the atmospheric component to variations in the surface conditions, particularly over continental areas; incorporating atmospheric composition (notably aerosol concentration) into the new atmospheric dynamical core; diagnosing the behavior of the complex coupled Earth system; and addressing several issues associated with increasing spatial resolution of the models, especially, the problems of scale-aware parameterization, trade-offs among resolution choices in different component models, and resolution implications for coupling strategies. Organizationally, the CMDTF recognized that resources to support the transition from research to operations (R2O) are insufficient, including base funding and project grant funds for collaborative research, and high-performance computing resources. There are also important challenges in providing to researchers the appropriate access to model codes and development tools, and ensuring that collaborative groups employ best modern software engineering practices. A chronic issue has been the difficulty in fostering and maintaining communication between rank-and-file NCEP model developers and researchers outside NCEP or NOAA. Finally, the CMDTF clearly indicated the need for a detailed development plan – including a timeline with benchmarks and milestones, and pathways for external partners to contribute – for the next generation coupled Climate Forecast System that goes beyond the planning already in place for the atmospheric component of the Next Generation Global Forecast System (NGGPS).

1. Overview

The Climate Model Development Task Force (CMDTF) was created in 2014 by the Modeling, Analysis, Predictions and Projections (MAPP) program of the Climate Program Office (CPO) in the Office of Oceanic and Atmospheric Research (OAR) of the National Oceanic and Atmospheric Administration (NOAA), based on discussions with Bill Lapenta. Dr. Lapenta was at the time Director of the Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP), National Weather Service (NWS), NOAA, and he sought to have the CMDTF help EMC make progress on Climate Forecast System (CFS) coupled model development. Much of the work of the CMDTF was focused on version 2 of CFS (CFSv2), which became operational in 2011, or its component models.

The CMDTF mission was to coordinate MAPP-funded modeling projects and work in synergy with climate model development efforts in NOAA labs/centers with an emphasis on research contributing to the advancement of the NCEP CFS via activities associated with the NCEP Climate Test Bed (CTB). The MAPP-funded projects included Climate Process Teams (CPT), the Center for Ocean-Land-Atmosphere Studies (COLA) and several individual principal investigator (PI) led activities. The CPTs are small multi-institutional groups of observationalists, theoreticians, small-scale process modelers, and scientists at modeling centers working closely together to improve parameterizations of a particular process in coupled climate or Earth system models.

The Task Force also coordinated these activities with the NWS Office of Science and Technology Integration (STI) Next-Generation Global Prediction System (NGGPS) project, with some of the projects being co-funded with NGGPS. The NGGPS was organized by NWS in 2015 as a means of accelerating progress toward a new global prediction system, in response to recommendations from the University Corporation for Atmospheric Research (UCAR) Community Advisory Committee for NCEP (UCACN). The UCACN had called for a unified modeling strategy initially aimed at the global prediction problem and eventually encompassing all environmental prediction within the purview of NCEP. Toward that end, NWS funded NGGPS sub-projects at NCEP, the Geophysical Fluid Dynamics Laboratory (GFDL), the Earth System Research Laboratory (ESRL) and several entities external to NOAA through a competitive grants program.

In the course of its three-year existence, the CMDTF conducted over 30 monthly conference calls, and developed several initiatives for helping to foster the interaction between the model developers within EMC and the external community. The full Task Force charge is given in Appendix A. A list of projects and PIs participating in the Task Force is given in Appendix B. The sections below provide details of the Task Force activities, contributions to planning and development, opportunities, and challenges.

2. CMDTF Activities

The CMDTF activities included co-leads (see Appendix B) conference calls to discuss the mission and scope of CMDTF and conference call topics and CMDTF monthly conference calls. The monthly conference calls, some with presentations, covered the following topics:

1. Inventories of MAPP funded projects and modeling efforts in other modeling centers, including MAPP-CTB funded projects, MAPP-funded modeling infrastructure projects, and both component development and coupling efforts in other centers.

   Modeling centers:

   - NOAA/OAR Geophysical Fluid Dynamics Laboratory (GFDL)
   - National Center for Atmospheric Research (NCAR)
   - United Kingdom Meteorological

Office (UKMO)

- European Centre for Medium-range Weather Forecasts (ECMWF)
- NOAA/OAR Global Test Bed (GTB)
  Dates: Several

2. NCEP updates on CFSv3 development strategy/plan/timeline.
   Dates: 4/22/14, 5/27/14, 6/24/14, 8/26/14, 9/23/14, 2/15/15, 8/25/15, and 2/23/16

3. PIs' inputs to NCEP CFS planning process including O2R requirements
   Dates: 10/14/14 (see Appendix C) and 9/22/15

4. Metrics/protocols for evaluating NCEP climate models and forecasts
   Dates: 5/27/14 and 8/26/14

5. Town Hall Meeting: NWS Model Development Forum
   Date: 1/5/15 (95th American Meteorological Society Annual Meeting)

6. Modeling infrastructure/framework
   Dates: 6/24/14, 2/15/15, 3/17/15, 3/29/16, 5/31/16, and 6/24/16

7. Updates on the UCACN Modeling Advisory Committee (UMAC) and EMC plans
   Date: 8/29/16

8. Plans for GFDL contributions to the global prediction capability at NCEP, including the atmospheric dynamical core (FV3) and the ocean model (MOM6)
   Dates: 10/18/16 and 11/29/16

Task Force activities also included a face-to-face Climate Process Team (CPT) meeting with NCEP and a breakout session on modeling and data assimilation in the Climate Test Bed Science Meeting on 11/10/15. The agenda is available at http://www.nws.noaa.gov/ost/CTB/mts-ctb15-d2.htm. Topics discussed in the breakout session were the CFSv3 plan, performance metrics and diagnostics, the NOAA Environmental Modeling System (NEMS), and ways to facilitate external community contributions to CFSv3. In the face-to-face meeting, the leads of individual CMDTF projects discussed with NCEP collaborators issues relating to atmospheric modeling, land modeling, and R2O/O2R.

3. Planning Contributions

The CMDTF included representatives from NCEP, GFDL, several CPTs, COLA, and other projects with an interest in furthering the coupled modeling capability for sub-seasonal to seasonal and longer time scale prediction. The CMDTF provided a platform for funded PIs and modeling centers (e.g., NCEP, GFDL) to discuss model development efforts and best practices. The CMDTF contributions to the planning process included:

- Defining requirements for operations-to-research (O2R) support of researchers
- Defining user (e.g. Climate Prediction Center) requirements for future model configurations and output
- Defining metrics for climate model evaluation
- Defining a test harness for evaluating development milestones in the evolution of a new coupled prediction system (see section 4.10).

Several individuals involved in the CMDTF were also involved in activities of great relevance to the Task Force, notably:

- Developing subgrid-scale physical process representations
- Developing component models at GFDL and other labs
- Developing a coupled modeling capability with

the NOAA Environmental Modeling System (NEMS), based on the National Unified Operational Prediction Capability (NUOPC) and the Earth System Modeling Framework (ESMF)

- Designing a system architecture suitable for both operational prediction on sub-seasonal to seasonal (S2S) time scales and original research on prediction and predictability
- Developing a new multi-model combination strategy to produce an optimized single forecast from ensemble forecasts
- Applying the new strategy to the multi-model ensemble forecasts provided by the international Sub-seasonal to Seasonal (S2S) Prediction Project and the North American Multi-Model Ensemble (NMME) Project to improve S2S forecast skill of North American precipitation and surface air temperature. (Note: A separate project called SubX was solicited and initiated during the period of the CMDTF activities, but was largely outside the purview of the Task Force.)
- Examining specifically how land surface factors contribute to the forecast skill of precipitation and air temperature
- Improving the quality of the land surface initial states and evaluating the impact of land surface initialization on the S2S forecast skill of North American precipitation and surface air temperature

The CMDTF served the functions of both keeping the diverse projects in these categories informed of progress and findings as well as stimulating collaboration among these projects.

4. Key Model Development Contributions

CMDTF projects made several key contributions to EMC model development. These included improvements in the physical parameterization of processes associated to clouds and boundary layer, aerosols, land surface, and lake effects, and the development of the NEMS modeling software infrastructure. Although originally focused on advancing EMC's climate modeling capabilities, these projects ultimately contributed to the overall advancement of the EMC modeling suite, given the current unified modeling approach.

4.1 Soil Moisture Bias

In several sub-projects relating to soil moisture (COLA: Predictability and Prediction of Climate from Days to Decades, J. Kinter), an examination of the behavior of the water cycle in CFSv2 reforecasts and reanalysis revealed that biases in soil moisture grow throughout the duration of forecasts due largely to systematic errors in precipitation (Dirmeyer 2013). The Noah land surface scheme showed the necessary relationships between evaporation and soil moisture for land-driven climate predictability, but CFSv2 cannot maintain the link between precipitation and antecedent soil moisture as strongly as in the real atmosphere, hampering prediction skill (Dirmeyer 2013, Dirmeyer and Halder 2017a). Because the precipitation errors vary or even change sign with lead-time and season, the utility of reforecast programs for bias correction is evident for operational forecast systems.

The National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC), and NCAR global models in uncoupled (land model only), coupled and reanalysis configurations were compared to observations of daily soil moisture from 19 networks over the United States (Dirmeyer et al. 2016). Model soil moistures were evaluated using three metrics: standard deviation in time, temporal correlation (memory), and spatial correlation (length scale). Models do relatively well in capturing large-scale variability of metrics across climate regimes, but they poorly reproduce observed patterns at scales of hundreds of kilometers and smaller. Reanalyses do not outperform free-running models, showing model parameterization is more important than initialization for determining land-atmosphere interaction in models.

Land surface initialization was further evaluated in retrospective forecasts from CFSv2 on sub-seasonal to seasonal time scales (Dirmeyer and Halder 2017a,b). Soil moisture memory is the most broadly important element for significant improvement of realistic land initialization on forecast skill, extending skill of daily forecasts by 1-4 days in most locations, and 5-day means by 1-2 pentads. Importantly, errors in land surface initialization and shortcomings in the parameterization of atmospheric processes sensitive to surface fluxes may have greater consequences than previously recognized, the latter exemplified by the lack of impact on precipitation forecasts even though the simulation of boundary layer development is shown to be greatly improved with realistic soil moisture initialization.

4.2 Representation of Soil-Hydrology-Vegetation Interactions

The overarching goal of this collaborative effort among NCAR (F. Chen and M. Barlage), NCEP (M. Ek, R. Yang, and J. Meng), and the University of Texas at Austin (Z-L Yang), was to improve the CFS forecast skill by enhancing the representation of soil-hydrology-vegetation interactions through the use of the new community Noah[2] with Multiple-Parameterizations (Noah-MP) land surface model (LSM). Soil moisture memory was identified as a key factor in determining seasonal predictability in climate forecast systems. This project leveraged on the previous work of the NCEP/EMC land team on testing Noah-MPv1 in CFSv2, and further evaluated and improved the newly released community Noah-MPv2. Numerous enhancements in Noah-MPv2 were released in April 2016, and this new version has been successfully implemented in CFSv2. The land-cover and soil-texture datasets in CFSv2 were replaced by the new global International Geosphere-Biosphere Programme (IGBP) vegetation-classification data (derived from the Moderate Resolution Imaging Spectroradiometer - MODIS) and global soil type (State Soil Geographic - STATSGO) datasets, which is consistent with recent community efforts to improve the specification of surface characteristics.

Various CFS sensitivity experiments were conducted with the climatology green vegetation fraction (GVF) replaced by near real-time satellite observations, and with the Noah-MP dynamic vegetation model to generate inter-annual GVF and leaf area index (LAI) variability. To examine these effects on CFS prediction skill, T126 CFS reforecast experiments were carried out for 11 selected years (1982, 1987, 1996, 1988, 2000, 2007, 1986, 1991,1999, 2011, 2012) with 4 ensemble members (00z of May 1 to May 4). The 11 years are composed of 3 years with cold El Niño and the Southern Oscillation (ENSO) states, 3 ENSO-warm, and 5 neutral years. The experimental CFS with the Noah-MP dynamic vegetation model improves the summer seasonal precipitation anomaly-correlation scores over the western states with sparse vegetation and over the central Great Plains where the soil moisture memory and land-atmospheric coupling strength showed significant impacts on seasonal precipitation prediction. The CFS with satellite GVF showed improvement over most of the U.S., indicating the important role of vegetation characteristics in Noah. Compared to the CFS operational setting with the Noah LSM, the hindcast with Noah-MP significantly improved the precipitation prediction skill over the Pacific Northwest and the Gulf states, and the CFS with Noah-MP dynamic vegetation had the best performance over the central Great Plains. Similarly, the CFS coupled to Noah-MP performed better in predicting 2m temperature anomalies.

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2 http://www.emc.ncep.noaa.gov/mmb/gcp/noahlsm/Noah_LSM_USERGUIDE_2.7.1.htm

4.3 Lake Process Modeling

This project (J. Jin, Utah State University; M. Ek and Y. Wu, EMC/NCEP) was to incorporate a numerically efficient, physically based lake model into NCEP's operational CFSv2 in order to advance climate prediction at intraseasonal to interannual (ISI) time scales in North America. North America has the largest total lake volume and surface area of any continent on Earth. Some lakes (e.g., the Great Lakes) also trigger severe storms during early winter and spring. However, in CFSv2, running at approximately 100-km resolution, lake processes and their interactions with the atmosphere are largely neglected, degrading climate forecasting skill.

An existing physically based lake model was coupled to CFSv2 in order to dynamically predict lake processes and their effects on climate in North America at ISI time scales. The lake model selected was the freshwater lake (FLake) model, which is a one-dimensional, two-layer energy and mass balance model. It includes parameterizations of lake thermocline, lake ice and snow, and surface momentum, water, and heat fluxes. FLake has been implemented in several operational and research climate models across the world, resulting in improved predictions of lake-atmosphere interactions and thermal conditions for different-sized lakes at hourly to interannual time scales. However, as shown in Fig. 1, the original offline FLake model is unable to accurately reproduce the seasonal cycle of lake surface temperature (blue line). Essentially, the errors result from the oversimplified model structure of FLake with only two model layers. For this project, FLake was modified by adding one additional model layer to better capture the vertical lake temperature profile. The three-layer FLake model significantly improved lake surface temperature simulations (red line) when compared to buoy station observations (solid dark line) and the MODIS data (dashed dark line).

The original and improved FLake models was also applied to simulating lake ice in the Great Lakes (Fig. 2). The observations are for ice fraction, but the simulations are for ice thickness. Although these two variables are not directly comparable, one can examine their spatial distribution. Figure 2 shows that the original FLake greatly underestimates the lake ice. With the modified Flake model, the spatial distribution of the simulated lake ice is significantly improved. Thus, it was concluded that the change in the FLake model structure contributed to better predictions of lake processes in the climate system.

Currently, retrospective forecasts with the coupled CFS-FLake model are being performed for historical periods on a high-performance computing platform and will be quantitatively evaluated using standard NCEP metrics for model evaluation with a focus on lake-related processes. The coupling work will provide a framework for the next CFS (version 3). The biggest challenge for this project is to generate sufficient ensemble members for a long-term period to objectively evaluate the performance of the coupled model and accurately identify the role of the lakes in North America in the climate system.

4.4 Ocean Circulation Model Codes at NCEP

Ocean circulation modeling at NCEP has traditionally made use of two codes: MOM from NOAA/GFDL and the Hybrid Coordinate Ocean Model (HYCOM) from the US Navy. These models serve complementary roles, with MOM in use for seasonal predictions, and HYCOM being used for shorter range coastal and weather forecasting. With the release of MOM6, this split between two ocean models at NCEP is being reconsidered, since MOM6 incorporates many of the numerical features formerly unique to HYCOM. The MOM6 project is led by GFDL scientists Alistair Adcroft, Robert Hallberg, and Stephen Griffies, in collaboration with other GFDL scientists and engineers, as well as a growing national and international community of developers.

Recent discussions involving GFDL, NCEP, Navy, and university PIs have led some to consider merging key features of HYCOM into MOM6. These discussions originated from a meeting at NCEP on 3-4 October 2016, where a number of key U.S. ocean model developers discussed the pros and cons of various numerical methods for ocean modeling. As a result of that meeting, it became clear that MOM6 offered the optimal baseline to serve the many needs of operations and research.

MOM6 has been chosen by the National Science Foundation (NSF) sponsored Community Earth System Model (CESM) leads to serve as the ocean code for their new climate model development for CESM version 3 - to occur after the Coupled Model Inter-comparison Project, phase 6 (CMIP6) is completed. Consequently, there are a number of distinct U.S. modeling threads that are aligning with the development and use of MOM6.

In addition to the above developments of ocean code, GFDL and NCEP/EMC are participating in a two-year (Aug 2016 to July 2018) MAPP-funded project to incorporate WAVEWATCH III into MOM6 as part of the development of new weather and seasonal prediction models at NCEP. The PIs for this project are Stephen Griffies, Alistair Adcroft and Robert Hallberg at GFDL; Arun Chawla, Suranjana Saha, and Hendrik Tolman at EMC; and Stephen Penny at University of Maryland. This project offers a further strong link between GFDL and NCEP, thus complementing the atmospheric modeling links facilitated by the use GFDL FV3 atmospheric dynamical core for the new NCEP weather forecasting model.

4.5 Triggering Convection

The conditions necessary for convection to be initiated in the atmospheric component of a coupled model are referred to as the triggering conditions. In this project (Kinter, COLA/GMU), a hypothesis was formulated that the triggering conditions in various versions of the NCEP global models (CFSv2, the Global Forecast System - GFS and the Global Ensemble Forecast System - GEFS) were responsible for some of the bias in precipitation, notably, the intensity of rainfall. A series of tests were made with alternative versions of the triggering conditions by COLA (Bombardi et al. 2015; 2016). In particular, the Heated Condensation Framework (HCF; Tawfik and Dirmeyer 2014; 2015a; 2015b) was inserted in CFSv2 and several re-forecast experiments were run. In one set of experiments (Bombardi et al. 2015), the HCF trigger was used in addition to the trigger applied in the original convection scheme of CFSv2 (Simplified Arakawa-Schubert, SAS; Arakawa and Schubert, 1974; Pan and Wu 1995; Han and Pan 2011), which has the effect of allowing convection to occur more frequently, which improves the rainfall amounts in monsoon regimes such as the Indian summer monsoon (Fig. 3).

In another set of experiments (Bombardi et al. 2016), the HCF trigger was applied to the updated SAS scheme (new-SAS) as a means of restricting the initiation of convection. By causing the convection to occur less frequently, the atmospheric column has the opportunity to build up instability, so that when convection occurs, the rainfall intensity is increased. This is an improvement in tropical regimes (Fig. 4), but it can exacerbate the error in extratropical regimes. It was determined that the HCF trigger could be tuned together with the representation of shallow convection to reduce rainfall bias, suggesting a way forward in the further development of global models that must parameterize cumulus parameterization.

4.6 Improving Turbulence and Cloud Processes

One of the CPTs (Lead PI: Steven Krueger, University of Utah), which is now in its last year, was intended to (1) unify the representation of sub-grid scale (SGS) deep convective precipitation and grid-scale precipitation as the horizontal resolution decreases by implementing (installing) the Arakawa-Wu unified parameterization (UP) in the GFS, (2) unify the representation of turbulence and SGS cloud processes by implementing (installing) SHOC (Simplified Higher-

Order Closure) into the GFS, and (3) improve the representation of cloud, radiation, and microphysics interactions.

The Arakawa-Wu UP grows individual clouds when/where the resolution is high, parameterizes convection when/where resolution is low, with continuous scaling in between, one set of equations, one code. The version implemented (installed) into and tested in the GFS is based on the Chikira-Sugiyama cumulus parameterization, which allows multiple cloud types and predicts the updraft vertical velocity for each cloud type. Remaining tasks include coupling with SHOC and radiation.

SHOC is now incorporated into NEMS as well as operational versions of the GFS. In these models, SHOC replaces the boundary layer turbulence and shallow convection parameterizations, calculates the cloud fraction, and adds a new prognostic scalar, sub-grid-scale (SGS) turbulent kinetic energy. The radiative transfer scheme currently uses cloud fraction and condensate computed by SHOC. The current challenge is to allow condensate detrained from parameterized deep convection to affect the SGS variability of total water. To do this, prognostic variance of total water that includes a source due to detrainment from deep convection was added.

There is current work to couple both “stratiform” (grid-scale) and parameterized deep convective clouds to radiation through McICA (Monte Carlo Independent Column Approximation) sampling. Grid-scale clouds are coupled by sampling the SGS distributions of liquid or ice concentration at each level obtained from SHOC to represent SGS structure in cloud properties. The initial focus is on SHOC clouds first. An important challenge is representing the clouds without having to compute too many expensive random numbers. The SHOC PDF is able to be reproduced using 4.5 random numbers per cell (compared to 1 for current GFS).

4.7 Cloud and Boundary Layer Processes

A MAPP-funded CPT (C. Bretherton, University of Washington; J. Teixeira, NASA Jet Propulsion Laboratory; H. Pan, NOAA EMC; C. Golaz and M. Zhao, NOAA GFDL) worked to improve cloud and boundary layer processes in NCEP’s Global Forecast System (GFS) and Climate Forecast System (CFS) models, as a sequel to a MAPPfunded CPT on the subtropical stratocumulus to cumulus transition. The primary goal was to simultaneously improve the cloud climatology, energy budget, and operational forecast skill of the GFS and the nextgeneration CFS. A secondary goal was to identify weather regimes where clouds are either forecast much better or much worse by GFDL global climate models vs. GFS, as a step toward improving cloudrelated parameterizations in both models.

The earlier work found that both the operational GFS and CFS severely underpredict cloud amount, water content, and cloud radiative impact over most of the globe, producing unacceptably large global and regional biases in the net topofatmosphere and surface energy budgets. Reducing these biases would provide a strong foundation for reducing systematic errors in extendedrange and seasonal forecasts. This project developed a portable singlecolumn version of the operational GFS, which was used to improve the boundarylayer and shallow cumulus parameterizations, modestly improving global cloud distributions. A new cloud fraction parameterization was also developed that somewhat increases GFSsimulated global cloudiness, and a new eddydiffusivity massflux scheme for GFS that combines the simulation of turbulence and shallow cumulus convection. The project sought to advance these first steps into a GFS version that has clouds whose radiative properties are simulated as skillfully as in leading climate models, while at the same time maintaining or improving conventional measures of weather forecast skill. The strategy involved careful testing and improvement of the microphysics and precipitation parameterizations, singlecolumn and global analysis of the fidelity of parameterized interactions among clouds, turbulence and precipitation in the revised GFS, and detailed comparisons of cloud simulations in hindcasts by GFS and two GFDL models, AM3 and HiRAM.

4.8 Representation of Aerosol Processes

In another CPT project (S. Lu, SUNY-Albany; Y-T Hou, NCEP/EMC; A. da Silva, NASA/GMAO), improving the representation of aerosol processes, cloud microphysics, and aerosol-cloud-radiation interaction in NCEP global models was targeted. The project advanced the physical parameterization suite in the NEMS-based Global Spectral Model (GSM) by:

- Implementing a multimodal and double-moment modal aerosol module
- Implementing a double-moment cloud microphysics scheme (developed in a separate project – S. Moorthi)
- Coupling among cloud micro- and macro-physics, radiation, aerosol physicochemical properties, and cloud properties
- Updating the aerosol optical properties look-up-tables
- Adding the option to determine aerosol optical properties and cloud condensation nuclei and ice nuclei (CCN/IN) activation from prescribed aerosol distributions
- Enabling NEMS GSM to output additional cloud diagnostic fields, including liquid cloud water path, ice cloud water path, cloud optical depth, and cloud emissivity

Tests of the physics upgrades were conducted individually (uncoupled) initially. Experiments to test these upgrades interactively (coupled) are in progress to investigate aerosol direct and indirect effects in NEMS GFS. Sensitivity experiments have been conducted for selected cases, e.g., the 2016 Louisiana flooding and Hurricane Matthew, and the results were compared with in situ observations, satellite retrievals, and reanalysis. The new implementation results in a general model improvement in cloud fields (e.g., cloud fraction, cloud optical depth). However, the impact of the physics upgrade on precipitation is insignificant. Additional tuning and adjustments will be necessary to ensure the physics upgrades indeed lead to better weather forecast and climate prediction. The need for model refinement in turn calls for the need to enhance the model evaluation/verification package (see Section 5).

4.9 Software Modeling Infrastructure

A MAPP-funded infrastructure project (Lead PIs: C. DeLuca, U. of Colorado; J. Kinter, COLA; V. Balaji, GFDL) collaborated with NCEP EMC, NCAR, and other partners to design, implement, and test a prototype coupled model (the Unified Global Coupled Model; UGCS) that targets seasonal time scales. Constituent science components of the prototype include the NCEP/EMC GSM, the Los Alamos sea ice model (CICE), and MOM5. This coupled model, possibly with different science components, is being evaluated as a successor to CFSv2.

A principal task was to develop a flux coupler based on the ESMF and NUOPC community standards (Theurich et al. 2016), and ensure that field exchanges through the coupler were operating correctly. This activity evolved and extended the NEMS infrastructure initiated by NCEP/EMC developers several years before. The MAPP-funded collaborators created infrastructure suitable for a NEMS-based unified modeling system, spanning multiple time scales, spatial scales, and predictive targets. An important new construct was the “application” or “app,” a set of coupled components associated with a specific predictive target. Different apps (e.g. seasonal, regional nest, etc.) can share components and infrastructure in a controlled manner. Also added to NEMS were “component sets” or “compsets”, a labeling system used by the CESM project for many years to simplify the description of coupled runs.

Several milestone releases of UGCS-Seasonal were delivered. The most recent, UGCS-Seasonal 0.4 (in Feb. 2017), is a three-way coupled system with a full set of field exchanges, that shows Earth-like behavior and runs on multiple NOAA computing platforms including Theia and Gaea. Test runs were initialized using a cold start run sequence using Climate Forecast System Reanalysis (CFSR) data. An end-to-end workflow for testing this model is now being implemented by NCEP/EMC.

Other work under this MAPP-funded infrastructure project was to establish the Earth System CoG, a wiki for hosting projects and accessing distributed data, as the new user interface to the Earth System Grid Federation (ESGF), in support of CMIP6. This process is complete. A questionnaire for collecting CMIP6 metadata was also developed but has not yet been deployed.

4.10 The CFS Test Harness

A MAPP-funded project (Saha, NOAA EMC) was undertaken to define, conduct, and publically release a test harness for coupled climate runs and possibly, conduct next-generation coupled prediction experiments as part of a CFS test harness. The NCEP CFSv2 became operational in March 2011. There have been many developments that can be utilized to make a significant advance from CFSv2 and there is an urgent need to quickly develop, test and implement a new and improved CFSv3 into operations. NCEP/EMC put a team together to develop and test the next generation of CFS. In anticipation of a working version of the coupled system available in NEMS, the development of a test harness and associated validation for coupled model runs was initiated using existing output from the archive of CFSv2 retrospective forecasts (spanning the period from 1982-present). As soon as working versions of CFSv3 become available, experimental runs will be made to ensure that all process-oriented validation procedures work satisfactorily. The MAPP support to this project aimed at speeding up EMC CFSv3 development and coordinating this development with MAPP's Climate Model Development and Model Diagnostic Task Forces as well as with the Climate Test Bed (CTB) activities.

4.11 Prognostic Ozone Parameterization

A MAPP-funded project (G. Compo, CU/CIRES and NOAA ESRL; J. Whitaker ,NOAA ESRL; P. Sardeshmukh ,CU/CIRES and NOAA ESRL; C. Long, NOAA CPC; S. Moorthi, NOAA EMC; S. Lu, NOAA EMC; J. McCormack, NRL) aimed to improve the representation of stratospheric ozone (O3) and water vapor in NOAA's climate reanalyses in order to improve NOAA's simulation, analysis, and forecasting of weather and climate variability, including forecasts of UV radiation to protect public health. A complete treatment of O3 photochemistry is too computationally intensive for current models. Therefore, a parameterization is included in the current NCEP GFS atmosphere/land model used in the 20th Century Reanalysis and operational forecasts, and also used in the CFS Reanalysis and operational CFSv2. The GFS parameterization for the time tendency of O3 is based on parts of NRL's CHEM2D Ozone Photochemistry Parameterization (CHEM2DOPP). It includes terms representing net production and loss and a dependency on the ozone mixing ratio itself. It is based on gasphase chemistry of the late20th century, which includes the depletion of ozone by chlorofluorocarbons (CFCs). For climate reanalyses and climate modeling extending back to the early 20th century or earlier, before large quantities of CFCs began to be released into the atmosphere, a new version of this parameterization was needed to represent preCFC stratospheric O3 chemistry. To understand, analyze, and predict atmospheric variability in the 21st century, the parameterization should utilize additional interactions included in CHEM2DOPP that affect stratospheric

O3. Stratospheric water vapor is also an important radiative constituent. Its representation in the GFS was also improved, paving the way for improved assimilation of satellite radiances and for interactive chemistry.

A more advanced O3 parameterization using the full CHEM2DOPP and an improved treatment of stratospheric water vapor was implemented for use in new versions of the GFS, CFS, and next generation NOAA climate reanalysis systems. The O3 parameterization included the effect of changes in temperature, changes in the vertical distribution of O3, and the timevariation of CFCs. As a first step, the parameterization was tested with two modes, one for times before CFCs and one for times after CFCs began to be released in large quantities. The team also implemented a new stratospheric H2O climatology as a necessary first step toward future implementation of parameterized H2O photochemistry. The upgraded parameterization and new climatology were tested in climate reanalyses and weather and climate simulations. The impact of the new O3 and water vapor treatments on reanalysis, GFS medium-range forecast skill, and CFS climate simulations was evaluated using comparisons with both historical and modern O3 and temperature observations throughout the troposphere and stratosphere as well as with UV radiation observations.

4.12 Advanced Ocean Data Assimilation

A MAPP-funded project (J. Carton and E. Kalnay, University of Maryland, D. Behringer and Hendrik Tolman, NOAA/NCEP) has been upgrading NCEP's Global Ocean Data Assimilation System (GODAS) from the current 3DVar system implemented in 2003 to the ensemble Local Ensemble Transform Kalman Filter (LETKF). GODAS serves as the ocean component of the integrated atmosphereocean analysis system, in turn providing the initial conditions for NCEP's atmosphere/ocean Climate Forecast System, version 2, (CFSv2). The project also has been combining the 3DVar and LETKF systems to form a hybrid version of GODAS for exploring the effectiveness of this hybrid system to represent time-evolving local correlations due, for example to fronts or currents, while at the same time maintaining largescale correlations. The computational efficiency of the hybrid filter relative to its 3DVar and LETKF alternatives has been examined.

The proposal brought together researchers from the University of Maryland experienced in the development and use of LETKF with NCEP researchers who have overseen development of 3DVarGODAS and the first two versions of the CFS. The rationale for proposed work is to: 1) Provide an upgrade of the ocean analysis system to one that will be analogous to NCEP's 3DVar-hybrid Gridpoint Statistical Interpolation system (GSI) used for atmospheric analysis. This upgrade will allow the next generation CFS to gain the benefit of a more integrated atmosphereoceanland analysis system in which both ocean and atmosphere components use coupled ensemblebased estimates of flux error at the interface. 2) The implementation of LETKF in GODAS provides NCEP with a more flexible ocean analysis system, for example simplifying the inclusion of new observational data sets like sea surface salinity and providing an error estimate for the ocean state. This flexibility is important to allow NCEP to implement assimilation upgrades to both GODAS (using a MOM-based model) and the eddyresolving RealTime Ocean Forecast System (RTOFS) (using a HYCOMbased ocean model). The work was carried out in NCEP's computing environment thus facilitating the integration of the resulting system into operations.

4.13 Stratospheric Processes

The primary purpose of the reanalysis effort is to advance climate studies by eliminating fictitious trends caused by model and data assimilation changes that occurred in real time. Reanalyses are to represent the observations as closely as possible and could be used as surrogates where observations are not available.

Each generation of reanalyses has improved upon its predecessor in many ways by: reduction of errors, increased spatial and vertical resolution, and addition of more variables. The current generation of reanalyses provides more information about the stratosphere than previous versions. This is important for monitoring the impacts of climate change and ozone depletion on the stratospheric circulation and the stratospheric interactions with the troposphere. Assessments of the stratosphere in the latest generation of reanalyses revealed several issues that may hinder the full use of these reanalyses for climate studies. This was particularly true for the NOAA Climate Forecast System Reanalysis (CFSR). This reanalysis contains jumps in data records during stream transitions, warming trends in the upper stratosphere between streams, poor representation of the Quasibiennial Oscillation (QBO) winds, ozone observations not being assimilated in the upper stratosphere, and poor representation of water vapor above the tropopause. It is important to rectify these issues before the next NOAA reanalysis effort.

This MAPP-funded project (C. Long, NOAA CPC; J. Perlwitz CU/CIRES and NOAA ESRL; F. Sassi, NRL) addressed the climate objectives outlined in the NOAA Next Generation Strategic Plan (NGSP) and a major CPO/Modeling, Analysis, Predictions, and Projections (MAPP) Program priority: Research to Advance Climate Reanalysis, particularly “issues with the quality of reanalyses in the stratosphere” by improving the characterization of the stratosphere in reanalysis by building upon research conducted following the CFSR. We propose to: reduce the impacts of data inhomogenuity on temperature and ozone, to improve the thermal structure of the upper stratosphere, improve the representation of the QBO winds and residual circulation in the tropics, and improve the depiction of ozone and water vapor in the stratosphere. Success in providing these improvements will lead to a better characterization of the stratosphere. A well characterized stratosphere may enable better weather and climate research and services by: 1) providing a more accurate depiction of past weather and climate conditions, 2) improving the monitoring of current climate conditions, and 3) enabling the attribution of climate variations and change by comparison with past conditions.

4.14 Next Generation Reanalysis

The fidelity of new reanalysis datasets (MERRA, 20CR, CFSR, ERAInterim) at representing climate variability of the 20th century has enabled significant advances in climate research. In a MAPP-funded project (A. Kumar, NOAA CPC; G. Compo, CU/CIRES and NOAA ESRL; J. Whittaker, NOAA ESRL; P. Sardeshmukh, CU/CIRES and NOAA ESRL; R. Vose, NOAA National Climatic Data Center, now National Environmental Information), investigated known shortcomings of these datasets, while developing a framework for a new NOAA Climate Reanalysis (NCR) system to ameliorate them. The NCR will eventually have four “streams” to meet the various user needs for reanalysis information:

- Stream 0: Boundaryforced, 1850present “AMIP” simulation with large ensemble
- Stream 1: Historical, 1850present using only surface data
- Stream 2: Modern, 1946present using only surface and conventional upper air data
- Stream 3: Satellite, 1973present using quality-controlled satellites, Global Positioning System Radio Occultation, and surface and conventional upper air data.

One of the foci of this research has been to use observing system experiments. In these, the 2000--2010 observing system is reduced to that of selected historical periods to investigate the impact on the timevarying quality and density of the observing system and determine ways to reduce this impact. The project employed innovative methods to assess the relative importance and impact of model errors and observational errors on the quality and homogeneity of the reanalysis fields, with particular attention to reducing or eliminating spurious jumps and trends. The framework for the NCR system leveraged recent advances in operational data assimilation for global weather prediction, as well as newly digitized observational datasets and global model improvements. While initially focusing on the atmosphere to develop the NCR framework, this project could serve as the basis for further NCR efforts, incorporating advancements generated by other projects supported by MAPP, such as integration of ocean, chemistry, and land components and the treatment of observational and model biases. International coordination and data sharing with NOAA's reanalysis partners at NASA, ACRE, ECWMF, and JMA and synergies from the NOAA Reanalysis Task Force were important parts of the project.

4.15 Surface Fluxes in Global Energy and Water Budgets

This MAPP-funded project (L. Yu, Woods Hole Oceanographic Institution; Y. Xue, NOAA CPC) aimed to provide a comprehensive assessment of the partially coupled Climate Forecast System Reanalysis (CFSR) in representing airsea heat, freshwater, and momentum fluxes in the context of the global energy and water budgets. The CFSR is the first and only reanalysis that incorporates a coupled atmosphereocean-land climate system with an interactive seaice component, and has the finest spatial resolution (~0.5°). There are clear advantages of the finerresolution coupled CFSR reanalysis in characterizing air-sea fluxes at regional and global scales, but biases/errors in the CFSR flux components at various temporal scales have also been found. The biases/errors appear to have significant impact on the estimates of the energy and water budgets over the global oceans. Currently, the CFSR produces a global energy imbalance of 15 Wm2, which is about 10 Wm2 higher than estimates from earlier NCEP reanalyses. Balancing the global energy/water budgets has long been a challenge, with global energy budgets differing considerably, from 2 to 30 Wm2, when computed using reanalyzed, ship-, and satellitebased flux products. However, the global energy/water budgets are central to the understanding of climate variability and climate changes produced by the reanalyses. A good knowledge of the impact of biases/errors in surface flux components on the global budget estimates will be highly beneficial to not only the users of CFSR products but also the developers for the nextgeneration Earth System reanalysis. This study analyzed the biases/errors in the CFSR surface fluxes in the context of the global energy/water budget and also compared the CFSR with other reanalyses.

The approaches included: (i) in situ validation, in which a database consisting of more than 130 flux buoys was used as ground truth for identifying and quantifying biases/errors in flux products; (ii) spectral analysis, in which ship and satellitebased global flux analyses were used as reference to evaluate and characterize the regional and global spectral structures of flux products, and (iii) dynamical diagnosis, in which dynamic constraints (such as energy and freshwater budgets in an enclosed volume) were used to test the physical consistency of flux products with ocean state variables (temperature and salinity).

The primary objectives of the proposed research were to (i) identify the strength and weakness of the CFSR surface flux components by comparison with in situ flux measurement, satellitebased analyses and other reanalyses and tounderstand the sources of biases, (ii) examine the effect of spatial resolution in improving the accuracy and spatial structure of CFSR fluxes on regional and global scales, and (iii) investigate the use of physical constraints together with ocean state variables to diagnose and understand the uncertainties in CFSR airsea fluxes.

4.16 Multi-Model Ensembles

A new multi-model combination strategy has been developed to produce an optimized single forecast from multi-model ensemble forecast and the forecast has been evaluated against the observations. Preliminary results suggest that the new methodology outperforms individual models and can increase the one-month lead forecast skill of surface air temperature by 50% over the simple multi-model average across much of the area of focus.

5. Opportunities and Critical Challenges

The discussions of the CMDTF have exposed a number of critical challenges for future collaborative development of operational prediction systems, such as are envisioned by NCEP and the Next Generation Global Prediction System (NGGPS) project. Addressing these critical challenges is a necessary, but not sufficient, condition for making progress toward the community modeling paradigm currently being discussed in strategic planning at NCEP. These challenges are both scientific and organizational.

Scientific challenges:

- Although there is clear responsiveness of surface heat fluxes, near surface temperature, humidity and daytime boundary layer development to variations in soil moisture over much of the globe, precipitation in CFSv2 is unresponsive. Failure to realize potential predictability from land surface states is undoubtedly connected to piecewise model development practices, where land and atmosphere models are not developed and tested in coupled configurations (Dirmeyer et al. 2015). Consideration of surface-atmosphere interactions are critical for realistic simulation of boundary-layer development and convective initialization (Tawfik and Dirmeyer 2014; Tawfik et al. 2015a,b).
- NCEP is now evolving toward a unified modeling framework with the FV3 dynamic core. An important challenge is incorporating prognostic aerosols into that unified modeling system. Specifically, NCEP will need to determine how atmospheric composition (aerosols) should be integrated into the unified model architecture. This is an active area of discussion among the NGGPS system architecture, infrastructure, and physics working groups.
- There is a need for an observation-based diagnosis package, with well-defined metrics, to examine whether a given model change makes a significant improvement. A more process-oriented diagnostic approach is needed to evaluate physically-based parameterization schemes. For example, an observation-based diagnosis package is needed to determine whether the model with an improved aerosol-cloud package can better represent aerosol/cloud properties and the processes relevant to aerosol-cloud-radiation interaction.
- As spatial resolution in component models increases, there is a need for evaluating the impact on long-standing issues such as bias, variability and coupling (e.g. ocean eddies – see bullet below). Any discretization or filtering scheme either explicitly or implicitly discriminates between resolved and unresolved scales such that features with a size of 5-10 ΔX and larger are considered “resolved”. The rectified effects of processes occurring on unresolved scales – which can be first-order in the resolved scales due to increasing entropy, irreversible processes and dynamical nonlinearity – must be parameterized. In order to preserve numerical stability, parameterizations are generally local, diffusive and equilibrium-restoring; hence, they do not adequately represent processes that are non-local, latent, up-gradient, or locally unstable. A related issue concerns the utility of parameterizations that are aware of the resolved scales. Ideally, such scale-aware schemes (e.g., the Smagorinsky viscosity scheme) require minimal retuning as model resolution is altered. Scale-aware methods are challenging to develop, but they offer

important payoffs that warrant continued research.

- In addition to increasing computational cost and exerting pressure on operational prediction schedules, the trend toward higher spatial resolution in coupled models requires an evidence-based assessment of the tradeoffs involved in increasing resolution in individual component models. For example, how closely does the resolution in the atmospheric and oceanic component models have to match to avoid errors in the representation of the effects of small-scale features in, say, the atmospheric component on the response in the oceanic component? Similarly, there are scientific issues associated with mismatched horizontal and vertical resolution in the atmosphere and the extent of the domain (e.g. well-reserved stratosphere or inclusion of deep atmospheric effects on troposphere).
- As prediction models refine their ocean resolution, transient mesoscale eddies appear and can have an impact on the atmospheric variability that goes beyond that seen with coarser resolution ocean models. Recent research suggests that these fine scale air-sea interactions have particular importance for storm tracks and tropical cyclones. A major challenge in prediction models will be to incorporate realistic boundary layer models, using refined vertical and horizontal resolutions, in both the ocean and atmosphere to ensure accurate representation of the physical processes. Stimulated by the work done by CMDTF, many of these topics were discussed during the MAPP Webinar Series on 13 March 2017: High-resolution modeling: working toward improved process representation and simulations of the Earth system.
- The traditional paradigm for coupling sea ice models to ocean models has its limitations, particularly when moving to finer resolution models where numerical instabilities manifest due to mismatches between fluxes transferred across the model components. These limitations are overcome when embedding the sea ice dynamics into the ocean dynamics, which is a project that is ongoing at GFDL based on the MOM6 ocean and SIS2 sea ice models (R. Hallberg, personal communication). This work is also critical as climate models consider the additional complexities associated with coupling with interactive ice shelf models, with such coupling a necessary aspect of unraveling questions about sea level rise.

Organizational challenges:

- There is currently insufficient operations-to-research support for model developers, both inside and outside NCEP, which has greatly slowed the progress of MAPP-funded projects whose goals include improving operational models.
- The access to high-performance computing (HPC) has been slow or limited for some projects and individuals due to protracted authorization procedures and security issues.
- PI access to model codes and development tools (e.g., the hierarchy of model components, run scripts, diagnostic codes, documentation etc.) for experimentation is a critical requirement that is currently inadequate.
- Modern software engineering practices, including version control to manage code, are still lacking.
- Despite the contribution of the CMDTF, communication between NCEP developers and externally-funded PIs is still an issue and needs to be facilitated even more strenuously, including the clear definition of NCEP staff involvement.
- There has not been a clear EMC-CFS development plan, with a timeline, definition of benchmarks and milestones, and pathways for external partners to contribute.

6. Conclusion

The Climate Model Development Task Force 3-year term ended in January 2017. During its lifetime, the Task Force organized by the MAPP program has engaged with NCEP staff to provide strategic and technical input to its planning activities. Task Force contributions to NCEP model development include the testing of new process parameterizations for convection, aerosols and land via the Climate Test Bed, as well as progress in data assimilation and in model infrastructure as part of NEMS development. Activities have been carried out in coordination with the NGGPS program. A number of mainly organizational challenges were identified and are being addressed by EMC in coordination with the MAPP and NGGPS programs. In order to advise on how to facilitate community engagement in model development, the Task Force developed the following suggestions:

- *Communication.* The information exchange afforded by monthly conference calls of the CMDTF were effective at keeping a diverse set of relevant researchers informed about each other's progress. There was a general feeling, however, that these calls were not sufficient to provide the sort of tight coordination that would be needed to accelerate progress. To its credit, building on the work of the CMDTF, NOAA's National Weather Service and other line offices have developed a Strategic Implementation Planning (SIP) process, in conjunction with the Next Generation Global Prediction System (NGGPS) project that includes the formation of several working groups that have been very effective at fostering communication among model development groups and individuals.
- *Observations.* The concept of the CPTs – to bring together experts in relevant processes with experts in model development – was successful within the limited scope in which it was applied. We thus suggest that a more robust program involving process-oriented metrics be routinely applied to models in development in order to scientifically confront models with observations in a scientific way is suggested.
- *Support.* Several participants expressed the view that a more robust level of support for developers and users of operational models would go a long way to accelerating progress. Such support would include documentation, HPC resources, automation of routine tasks such as model setup, testing and diagnosis, and the formation of short-term expert teams ("tiger teams") to address specific issues.
- *Testing.* While NCEP operations has a number of standard tests with standard metrics and benchmarks, largely driven by Government Performance and Results Act (GPRA) strictures, there are many other tests and metrics that could be used to advance climate model development. A more comprehensive system for gathering and implementing these tests is needed that can be accessible to both the EMC and external developers and analysts.
- *Planning and best practices.* The CMDTF spent considerable time discussing potential pathways for development without the benefit of a concrete modeling plan. It is critically important, as emphasized in several UCACN and UMAC reports, that a strategic plan be developed by EMC to guide implementation and collaborative development

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Appendix A: Charge to Climate Model Development Task Force

The following is the charge to the Climate Model Development Task Force from the Modeling, Analysis, Prediction and Projections (MAPP) program of the Climate Program Office (CPO) of the Office of Oceanic and Atmospheric Research (OAR) of the National Oceanic and Atmospheric Administration (NOAA), issued in December 2013 for a three-year Task Force period of performance commencing on 1 January 2014:

The Climate Model Development Task Force is an initiative of NOAA's MAPP Program in partnership with the Climate Test Bed to achieve significant advances in NOAA's climate models in support of improved predictions. The Task Force brings together scientists from universities, research laboratories, and NOAA's centers and labs and builds-on MAPP funded research activities. It is envisioned that the Task Force will work in synergy with internal climate model development efforts at NOAA's research laboratories and centers and will emphasize research contributing to the development of the next-generation operational climate forecasting system via Climate Test Bed activities. Research objectives of the Task Force will contribute to advance NOAA's next-generation climate modeling capability in the broader weather-to-climate modeling context addressing improvements in the representation of physical processes, coupling of model components and software infrastructure. Research activities will build on MAPP projects that include improving the representation of atmospheric convection, land and hydrology, ocean processes, coupling of various components and modeling infrastructure. The Climate Model Development Task Force will coordinate with the Climate Reanalysis Task Force on aspects relating to model improvement and initialization. Research will be done in coordination with other relevant national and international climate modeling activities in the context of USGCRP and WCRP.

Appendix B: Projects and Participants in the Climate Model Development Task Force

CMDTF Projects

Model Development

- A CPT for Improving Turbulence and Cloud Processes in the NCEP Global Models
  PI: Krueger (MAPP-CTB)
- A CPT to improve cloud and boundary layer processes in GFS/CFS
  PI: Bretherton (MAPP-CTB)
- Improving the Prognostic Ozone Parameterization in the NCEP GFS and CFS for Climate Reanalysis and Operational Forecasts
  PI: Compo
- Improving the NCEP Climate Forecast System (CFS) through Enhancing the Representation of Soil-Hydrology-Vegetation Interactions
  PIs: Chen and Ek (MAPP-CTB; co-supported by NGGPS)
- Advances in Lake-Effect Process Prediction within NOAA's Climate Forecast System for North America
  PIs: Jin, Chen and Ek (MAPP-CTB; co-supported by NGGPS)
- Improving cloud microphysics and their interactions with aerosols in the NCEP Global Models
  PI: Lu (MAPP-CTB; co-supported by NGGPS)

Software Modeling Infrastructure

- Software modeling infrastructure: Couple NCEP EMC NEMS to MOM5/ice for more capable CFSv3 and single framework for EMC/CPC
  PI: DeLuca

Data Assimilation

- Exploration of advanced ocean data assimilation schemes at NCEP
  PI: Carton
- Strategies to Improve Stratospheric Processes in Climate Reanalysis
  PI: Long
- Research towards the next generation of NOAA Climate Reanalyses
  PIs: Kumar and Compo
- Improving the land surface components of Climate Forecast System Reanalysis (CFSR)
  PI: Ek

Model/Analyses Evaluation

- COLA: Predictability and Prediction of Climate from Days to Decades
  PI: Kinter
- Evaluating CFSR Air-Sea Heat, Freshwater, and Momentum Fluxes in

the context of the Global Energy and Freshwater Budgets
PIs: Yu and Xue

CMDTF Participants

Co-Leads

- Stephen Griffies, Geophysical Fluid Dynamics Laboratory (NOAA)
- James Kinter, Center for Ocean-Land-Atmosphere Studies, George Mason University
- Suranjana Saha, Environmental Modeling Center, National Centers for Environmental Prediction (NOAA)

All Participants[3]

Donifan Barahona	NASA Goddard
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Tony Craig	NEMS/NOAA
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Arlindo da Silva	NASA Goddard
Cecelia DeLuca	CIRES / NESII/ESRL/NOAA
Paul Dirmeyer	COLA/George Mason University
Michael Ek	EMC/NCEP/NOAA
Chris Golaz	GFDL/NOAA
Stephen Griffies (Co-Lead)	GFDL/NOAA
Jongil Han	CPC/NCEP/NOAA
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Sarah Lu	State University of New York at Albany
Jesse Meng	EMC/NCEP/NOAA
Qilong Min	State University of New York at Albany

3 Note: At the request of EMC management, the Task Force also included several NCEP scientists not directly funded by the MAPP program.

Kingtse Mo	CPC/NCEP/NOAA
Shrinivas Moorthi	EMC/NCEP/NOAA
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Jun Wang	EMC/NCEP/NOAA
Wanqiu Wang	CPC/NCEP/NOAA
Jack Woollen	EMC/NCEP/NOAA

Appendix C: User Requirements

In October 2014, members of the CMDTF engaged with model developers and users to generate two lists of requirements. One is a set of operational requirements articulated by the Climate Prediction Center. The other is a list of characteristics that emerged from the workshop held at that time.

CPC Operational Requirements/Metrics

A) Climate Forecasts

1. Essential
   - 1.1. Intra-seasonal
     - 1.1.1 A daily higher resolution coupled ensemble forecast system, and ensemble size similar to GEFS, is needed for intra-seasonal forecasts out to at least 32 days. (perhaps even longer for multi-day lead forecasts)
     - 1.1.2 Intra-seasonal forecast system needs to be upgraded more frequently (every two years or less) than the seasonal forecast system.
     - 1.1.3 Reforecasts for the intra-seasonal forecast system needs to have at least 20 years of reforecasts for bias correction and calibration and needs to be performed every time there is an upgrade.
     - 1.1.4 Reforecasts should include at least 6 members.
     - 1.1.5 Consistent ensemble generation methods for both the reforecasts and the realtime forecasts.
     - 1.1.6 Realtime forecasts generated at least two times per week.
   - 1.2 Seasonal
     - 1.2.1 A seasonal forecast system is needed for forecasts out to 15 months.
     - 1.2.2 Forecast frequency of at least once every 5 days.
     - 1.2.3 Reforecasts for the seasonal forecast system need to have at least 30 years (1981- present) of reforecasts for bias correction and calibration.
     - 1.2.4 Skill for key variables (sea ice, ENSO, MJO, and surface temperature and precipitation over the US) should be better than the current system.
     - 1.2.5 A lower resolution version of the seasonal forecast model should be available for sensitivity and attribution studies
     - 1.2.6 Proper analysis/coupling of the ocean mixed layer, air-sea fluxes, sea ice, and ocean currents.
     - 1.2.7 Realistic simulation of the Atlantic Meridional Overturning Circulation.
   - 1.3 All time-scales
     - 1.3.1 The forecast model used to generate the initial conditions must be the same for hindcasts and real-time forecasts.
     - 1.3.2 Temporal consistency in the initialization of ocean, soil moisture, sea-ice across hindcast and real-time forecasts (to avoid issues with discontinuity and bias correction).
     - 1.3.3 Coupling of atmosphere with ocean, land, sea ice models is preferred but left to the discretion of EMC.
     - 1.3.4 Adequate spin up for land surface and ocean conditions.

1.3.5 A realistic QBO produced by an improved gravity wave parameterization.

1.4 Output Format: Hourly (at least 3-hrly) output of surface flux fields including precipitation variables.

2. Metrics:

2.1 Relationships between CPC & EMC need to be promoted to interact on development and validation of CFS forecasts and reanalysis.

2.2 Operational: to be evaluated on the entire hindcast history (instead of one month at a time) or all relevant spatial and temporal scales:

2.2.1 Precipitation

2.2.2 2-meter max/min air temperature

2.2.3 SST (ENSO)

2.2.4 MJO

2.2.5 Sea ice

2.2.6 Streamflow

2.2.7 QBO

2.2.8 Radiation balance

2.3 Developmental: to be evaluated on specifically designed experiments while conducting experimental research on process-oriented physics, etc. Climate "scorecard" of basic indices such as ENSO, MJO, NAO, etc. to be developed by the NMME group in CPC.

2.4 Test "harness" for quicker evaluation during development.

B) Climate Reanalysis

1. Essential

1.1 Sufficient (i.e. multi-year) spin up to create the reanalysis.

1.2 Resolution in the horizontal and vertical is comparable to the Climate Forecast System.

1.3 Forecast model must stay consistent with that used to generate hindcasts.

1.4 Minimize jumps during transitions in observations.

2. Ideal

2.1 One stream

2.2 A low-resolution pilot run of the entire reanalysis to check for trends and discontinuities.

2.3 Make this run available for users to evaluate.

2.4 Replacement for R1 (i.e. a reanalysis back to 1948)

3. Metrics

3.1 Validation against non-assimilated data sets AND other available reanalyses

3.2 Mechanism to determine unwanted trends in reanalysis.

Characteristics of Next Generation Coupled Climate Forecast System

1. CFSv3 Planning and Development Process

1.1 Need to provide the basis (scientific facts, drivers and boundary conditions) and process for making the choices of the model physics, dynamics, and resolutions.

1.2 Need to survey what's in place in other NOAA programs (e.g. NGGPS) and other operational modeling centers, and the state of the science.

1.3 Need to clarify meaning of ‘requirements”, “predictands”, “metrics”, and “constraints” so that the Task Force members will know how to provide inputs to the requirements and metrics documents.

1.4 Need to better define the governance of the CFSv3 development, such as, engagement process, decision-making authority and process, the role of CPC in CFSv3 development.

1.5 The above processes should be transparent to everyone, including the external community.

1.6 The CFS development team should be responsible for implementing the CFSv3 plan and be the POC within NCEP and with the external community.

2. Technical comments

2.1 Coupling of six model components should be addressed in a scientific context.

2.2 Although NEMS cannot replace basic research, NEMS is a necessary infrastructure to ensure the system components are compatible and structured efficiently.

2.3 Development and cal/val should be done for both component models and 3-D coupled system in NEMS.

2.4 Additional wish list for CFSv3 includes energy conservation, avoiding spin-up and initialization shock problems, improving stratosphere-troposphere coupling and ozone, assimilating satellite data, higher resolution for intra-seasonal forecasts etc.

2.5 Need to better coordinate and prioritize the planning between atmospheric physics and aerosols.

2.6 The data assimilation people and MAPP Reanalysis Task Force should provide feedback to EMC’s Reanalysis plan.

3. User interface and O2R support to the community

3.1 User requirements from the external community include: NCEP’s CFSv3 development plan, timelines and metrics; model documentation; a script to run the model, post-processing, and diagnostics for CFS development; model (and possibly data assimilation) codes (the latest GFS; coupled models, single column model); experimental model outputs.

3.2 Collaborative model development efforts between EMC and external users, such as Climate Process Teams (CPTs) need to get functional version of codes and scripts used as a ‘test harness’ to develop and evaluate CFSv2 as soon as possible, so that they can optimize their activities toward useful skill improvements for CFSv3. This can and should be done before a full NEMS interface and support for a new candidate ocean model are available.

3.3 The CFSv3 plan needs to describe the user interface and the mechanisms to meet the above user requirements from the community, e.g., how to make the model codes available to users. NOAA Climate Test Bed (CTB) can be a mechanism to provide infrastructure and Operation-to-Research (O2R) support to the external community in CFS development

Appendix D: Acronyms

3DVar	Three-Dimensional Variational Analysis (Data Assimilation)
ACRE	Atmospheric Circulation Reconstructions over the Earth
AM3	Atmospheric Model, version 3 (GFDL)
AMIP	Atmospheric Model Intercomparison Project
BCL	Buoyant Condensation Level
CESM	Community Earth System Model
CFS	Climate Forecast System
CFSR	CFS Reanalysis
CIN	Convective Inhibition
CIRES	Cooperative Institute for Research in Environmental Sciences
CMDTF	Climate Model Development Task Force
CMIP	Coupled Model Inter-comparison Project
COLA	Center for Ocean-Land-Atmosphere Studies
CPO	Climate Program Office
CPT	Climate Process Teams
CTB	Climate Test Bed
CTRL	Control
CU	University of Colorado
CWF	Cloud Work Function
ECMWF	European Centre for Medium-range Weather Forecasts
EMC	Environmental Modeling Center
ENSO	El Niño and the Southern Oscillation
ERA	ECMWF Re-Analysis
ESGF	Earth System Grid Federation
ESMF	Earth System Modeling Framework
ESRL	Earth System Research Laboratory
FLake	Freshwater Lake
FV3	Finite Volume Cubed-Sphere Dynamical Core
GEFS	Global Ensemble Forecast System
GFDL	Geophysical Fluid Dynamics Laboratory
GFS	Global Forecast System
GODAS	Global Ocean Data Assimilation System
GPRA	Government Performance and Results Act
GSFC	Goddard Space Flight Center
GSI	Gridpoint Statistical Interpolation
GSM	Global Spectral Model
GTB	Global Test Bed
GVF	Green Vegetation Fraction
HCF	Heated Condensation Framework

HiRAM	High-resolution Atmospheric Model (GFDL)
HPC	High-Performance Computing
HYCOM	Hybrid Coordinate Ocean Model
IGBP	International Geosphere-Biosphere Programme
ISI	Intra-Seasonal to Interannual
JMA	Japan Meteorological Agency
LAI	Leaf Area Index
LETKF	Local Ensemble Transform Kalman Filter
LFC	Level of Free Convection
LSM	Land Surface Model
MAPP	Modeling, Analysis, Predictions and Projections
McICA	Monte Carlo Independent Column Approximation
MERRA	Modern Era Retrospective-analysis for Research and Applications
MODIS	Moderate Resolution Imaging Spectroradiometer
MOM	(GFDL) Modular Ocean Model
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCR	NOAA Climate Reanalysis
NEMS	NOAA Environmental Modeling System
NGGPS	Next-Generation Global Prediction System
NMME	North American Multi-Model Ensemble
NOAA	National Oceanic and Atmospheric Administration
NOAH	NCEP – OAR – Air Force –Hydrologic Research Laboratory LSM
NOAH-MP	Noah with Multiple-Parameterizations
NSF	National Science Foundation
NUOPC	National Unified Operational Prediction Capability
NWS	National Weather Service
O2R	Operations-to-Research
OAR	Office of Oceanic and Atmospheric Research
PI	Principal Investigator
PBL	Planetary Boundary Layer
PDF	Probability Density Function
QBO	Quasi-Biennial Oscillation
R2O	Research-to-Operations
RTOFS	RealTime Ocean Forecast System
S2S	Sub-seasonal to Seasonal
SAS	Simplified Arakawa-Schubert
SGS	Sub-Grid-Scale
SHOC	Simplified Higher-Order Closure
SIP	Strategic and Implementation Plan
STATSGO	State Soil Geographic

STI	NWS Office of Science and Technology Integration
UCACN	UCAR Community Advisory Committee for NCEP
UCAR	University Corporation for Atmospheric Research
UGCS	Unified Global Coupled System
UKMO	United Kingdom Meteorological Office
UMAC	UCACN Modeling Advisory Committee
UP	Unified Parameterization
USGCRP	United States Global Change Research Program
WCRP	World Climate Research Programme

FIGURES

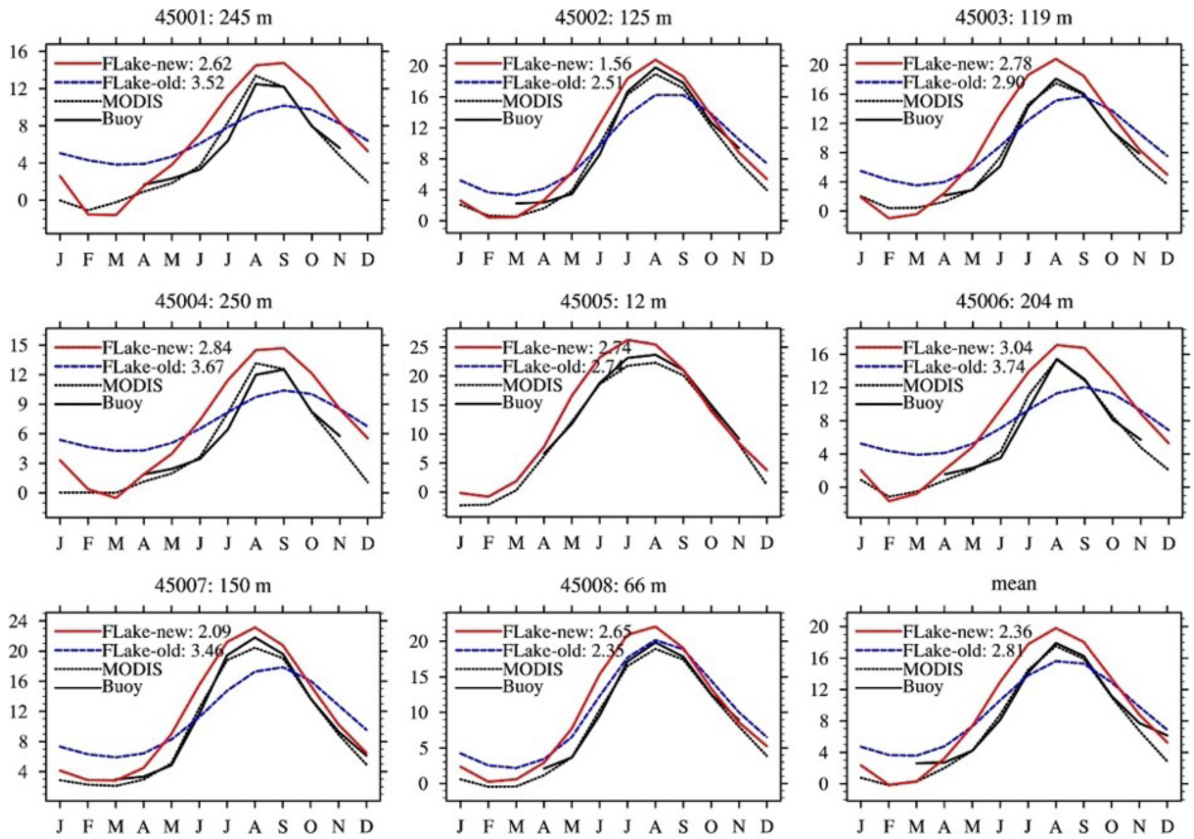

Figure 1: Seasonal lake surface temperature observations and simulations averaged over 2000-2010 for the Great Lakes. Solid dark line is buoy station observations; dashed dark line is MODIS satellite observations; dashed blue line is the original FLake simulations (FLake-old with the RMSE with the MODIS data), and red solid line is modified FLake simulations (FLake-new with the RMSE with the MODIS data). In the title at the top of each figure, the first number is the buoy station ID, and the second number after the colon is the lake depth at the station.

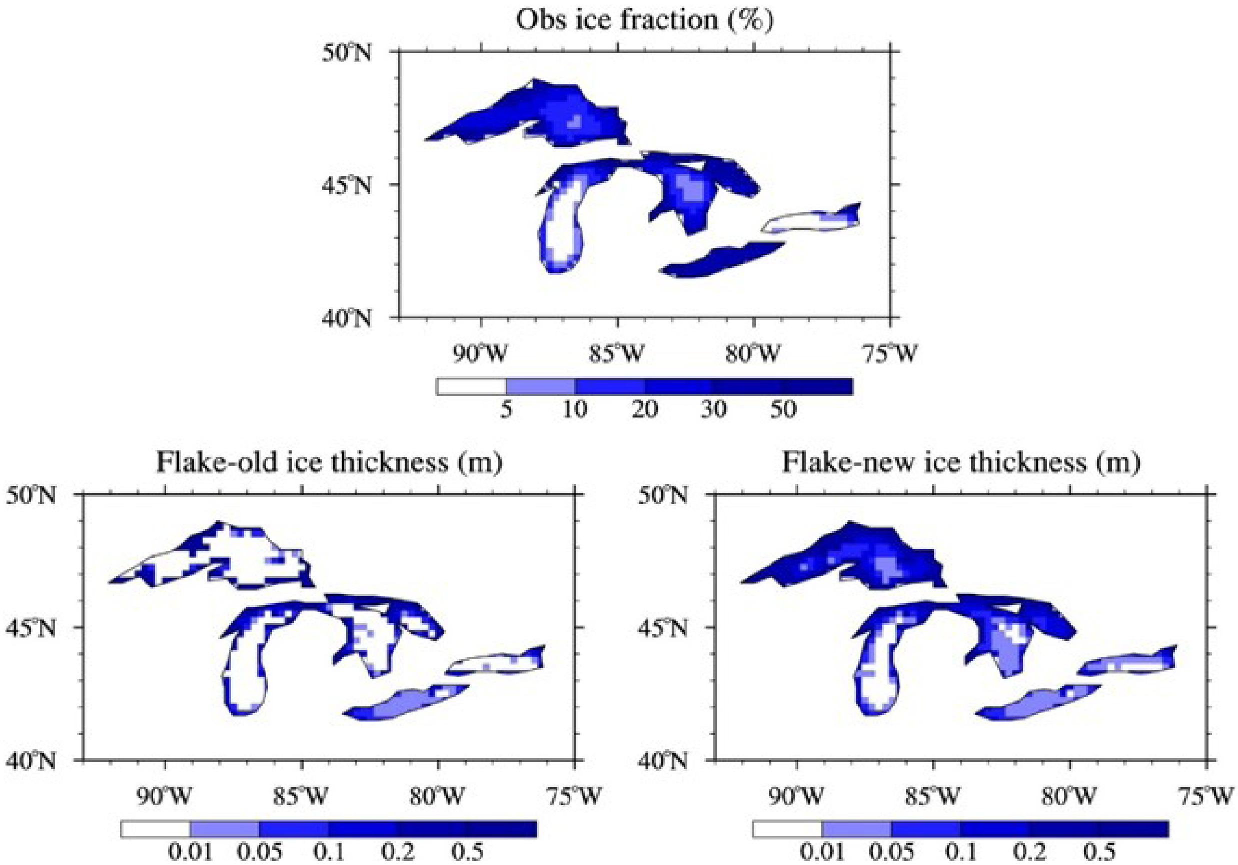

Figure 2: Lake ice observations (ice fraction; top figure) and simulations (ice thickness; two bottom figures) for the Great Lakes averaged over 1984-2002.

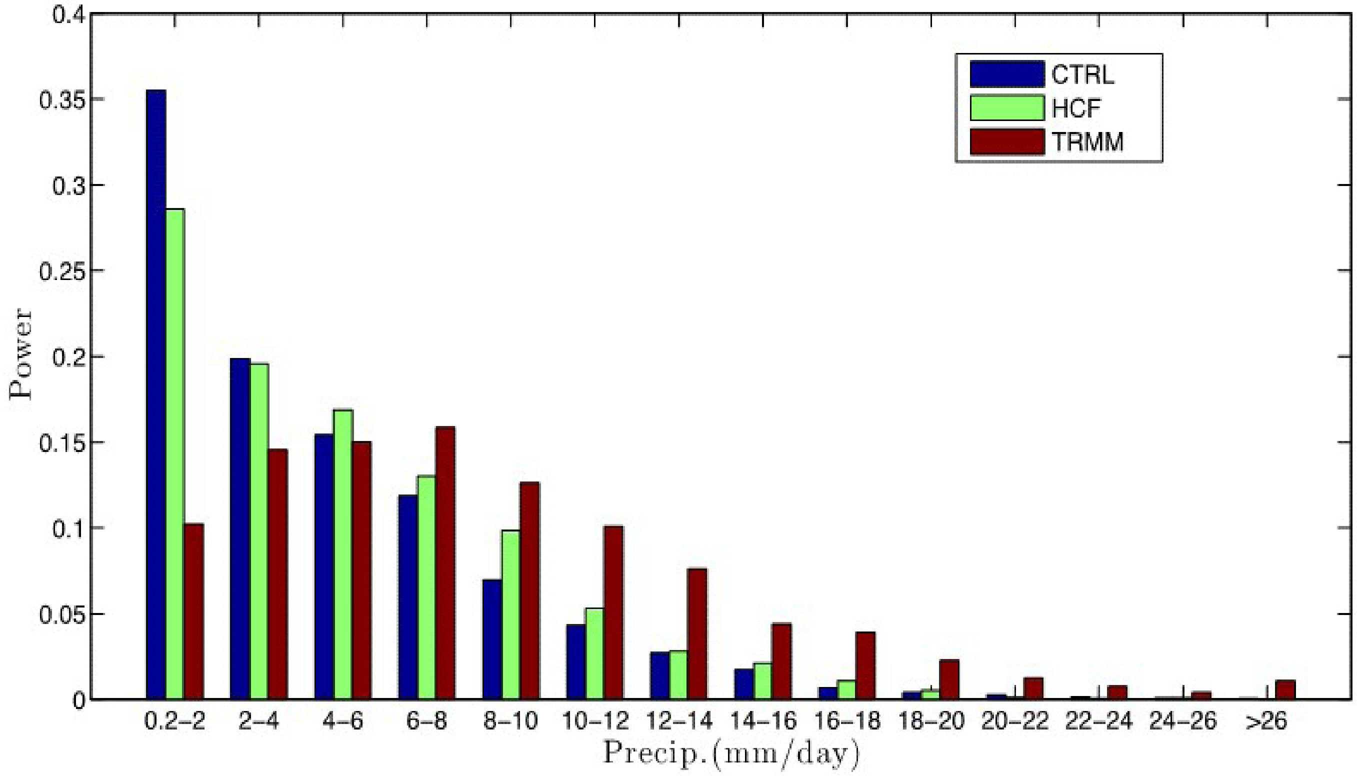

Figure 3: Frequency distribution of daily precipitation (mm/day) for TRMM, HCF, and CTRL over Central India [16.5oN-26.5oN,74.5oE-86.5oE]. The HCF and CTRL distributions are different at 95% confidence level according to a maximum likelihood ratio test.

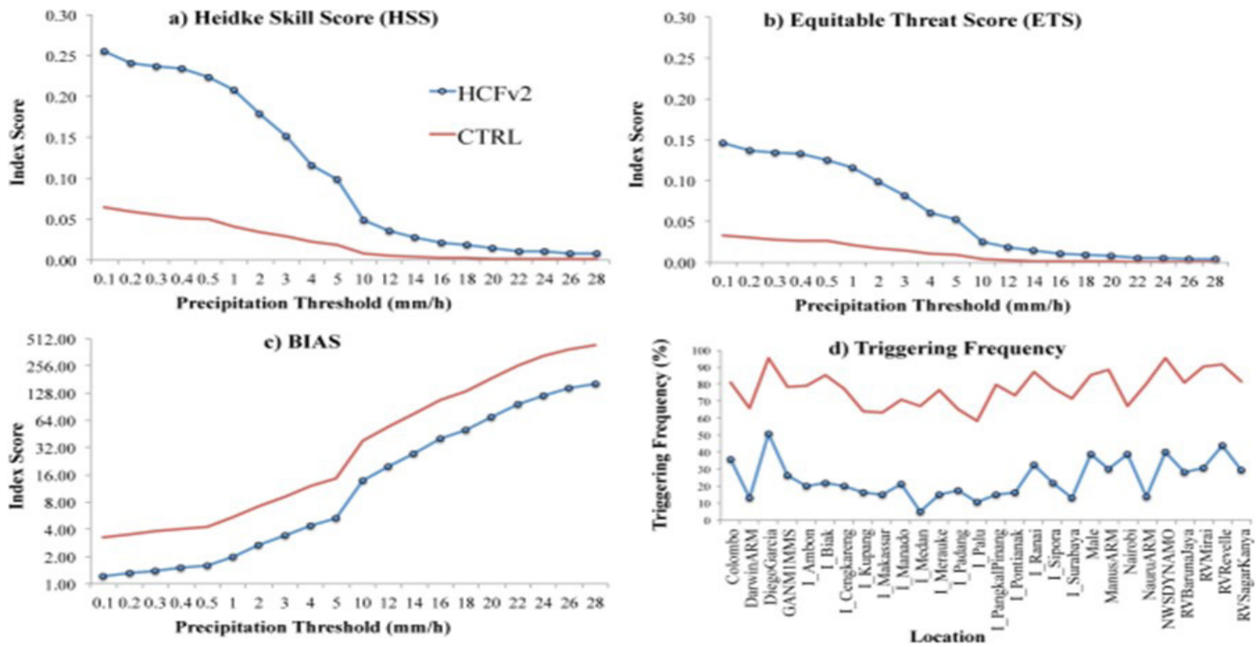

Figure 4: Comparison between the HCFv2 trigger and the original triggering (CTRL) mechanisms shown by (a) the Heidke Skill Score; (b) the Equitable Threat Score; (c) the Bias; and (d) the triggering frequency for each sounding release location.

NOAA Technical Report OAR CPO-X

Climate Model Development Task Force Final Report

https://doi.org/10.7289/V5/TR-OAR-CPO-6