Pathways to Substantial Improvement of the Climate Forecast System (CFS)

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Executive Summary

The main actions required to ensure substantial improvement in the Climate Forecast System (CFS) of the National Centers for Environmental Prediction (NCEP) are:

- Develop the vision, scope, strategy and resource requirements for the next generation of CFS, with full support of the management of the National Oceanic and Atmospheric Administration (NOAA), including considerations for adequate infrastructure support, high-performance computing, effective engagement of the research and user communities, and a set of measures of success that will drive innovation and improvement.
- Initiate and execute a fully unified weather-climate model strategy.
- Establish an NCEP Climate Modeling Team.
- Increase the scope and effectiveness of collaborations with the research community inside and outside NOAA.
- Develop a strategy to feed research advances back into the CFS development cycle
- Develop more effective mechanisms for including user input to the model development process.
- Improve NCEP infrastructure, modeling framework and reward system.
- Accelerate the CFS development cycle and implementation cycle.

1. NOAA Requirements for a Climate Forecast System

One of NOAA's long-term goals is a Weather-Ready Nation in which "*Society prepares for and responds to weather and climate-related events*". The National Weather Service (NWS) Mission in support of NOAA goals is "*To provide weather, water and climate forecasts and warnings for the protection of life and property and enhancement of the national economy, based on data that forms a backbone of global environmental information.*" A key societal outcome of the NWS Mission includes necessary actions to prepare for and respond to climate variability and change.

A long-term goal for climate in the NWS Strategic Plan is to *"Enhance climate prediction and services as part of a global framework to help communities, businesses, and governments understand climate risks and respond to changing conditions"*. NWS has requirements to achieve this goal, including:

- Real-time operational delivery of seamless weather and climate products and services
- Information for preparedness, response and recovery at regional and local scales
- Analysis, advancing understanding, and preparation for weather and climate extremes

In order to meet NWS requirements and accomplish this long-term goal, NOAA must make progress on several high-priority scientific challenges for intra-seasonal to interannual (ISI) prediction (National Research Council, 2010). Key among these challenges are steady improvements in coupled climate models, observational networks, and data assimilation systems leading to improved understanding and more reliable prediction over time.

NCEP is committed to using coupled climate models to advance predictions of climate variables. The NCEP CFS (Saha et al. 2006) is the global coupled climate model that is used to deliver U.S. operational climate forecasts. This commitment to CFS is intended to support NOAA in attaining and sustaining world leadership in ISI modeling and prediction-based services. Improvements in CFS are required to achieve the NOAA goal of a Weather Ready Nation, in particular to improve our ability to anticipate climate and weather related events, especially extremes, and increase confidence in our ability to predict them on ISI timescales. There are many research results (National Research Council, 2010) available to suggest that there remains untapped predictability at ISI time scales such that improved models could produce superior predictions. The improvement in CFS will also benefit from model improvements in other US modeling centers through the collaborations within the emerging National Multi-Model Ensemble (NMME) prediction system and other collaborations between NCEP, other NOAA labs and centers, and a broad external community of academic and private organizations that are interested in CFS or utilize its forecasts.

The current CFS (CFSv2) was implemented in NCEP operations in March 2011. The assessment of CFSv2 demonstrated many improvements over the previous version (CFSv1), for example, improved MJO prediction capability. The assessment of CFSv2, however, uncovered some problems with CFSv2 including discontinuities in the CFS Reanalysis, very little improvement in seasonal precipitation forecasts, lack of closure in expected balances of physical variables and processes, improper representation of long-term climate processes, problems in data archiving and access, and model documentation. These problems suggest that further development and improvement will enhance the ability of CFS to provide climate information to meet user requirements beyond the current level of accuracy, resolution, and usability.

This document discusses the key strategic issues for the development and implementation of the next generation of the CFS (CFSv3). It provides recommendations for collaborative research and development processes and a practical strategy to guide the advance and improvement of CFS over the next several years or more. The strategy document has drawn on recommendations from both NCEP and the external community and has benefited from discussions in the CFSv3 Planning Meeting in August 2011 and the CFSv2 Evaluation Workshop in April 2012.

2. Developing a vision for the NCEP Climate Forecast System

There are many issues related to the vision for the development and implementation of the next generation of the NCEP CFS. This section discusses the key strategic issues based on the current CFS status and based on the discussions within NOAA and NCEP and with the external community.

a) <u>How bold and far-reaching should the vision be?</u>

A fundamental question to be resolved is whether the next upgrade of CFS should be incremental or a significant redesign aimed at substantial improvement. The general consensus from the CFSv2 Evaluation workshop was that a bold and far-reaching approach is preferred. There are many potential ways forward. Below are some raised in both the CFSv2 Evaluation Meeting and the CFSv3 Planning Workshop.

- Alternative fully coupled models (e.g., NASA GEOS5; NCAR CESM)
- Alternative system components, such as, land models, ocean models, sea ice models from other modeling centers or labs (e.g., ESRL, GFDL). Also see discussion in 2b below about unified weather and climate modeling
- Alternative sub-component models
    - AGCM dynamic core (e.g., isentropic coordinates; enhanced vertical resolution; non-hydrostatic equations of motion)
    - AGCM sub-grid-scale physical parameterizations (e.g., perturbed physics, super-parameterization, stochastic physics, optimized physics ensemble)
    - OGCM dynamic core (e.g., isopycnal coordinates)
    - OGCM physics (e.g., eddy-resolving vs. parameterized eddies)
    - LSM choices (e.g., mosaic, catchment; VIC)
- Alternative data assimilation methods (e.g., methods developed outside of NCEP)
- Alternative Reanalysis strategy and initialization strategy: see discussions in 2d) and 3e)
- Alternative ensemble strategy (e.g., perturbed vs. lagged ensemble)

The workshops did not produce conclusions on the specific options for the CFS vision, but recognized that different options would require different implementation strategies and metrics for success and would have different implications on NCEP operations and resource requirements. For example, if an optimized physics ensemble (OPE) approach is chosen, the CFS model will need to incorporate multiple alternative schemes for each of the key physical processes. The performance of these schemes as individuals depends on climate regimes and application scales, but combining the schemes with optimized weights can maximize the overall system predictive skill.

b) <u>Should NCEP embrace a fully unified weather-climate modeling strategy?</u>

The National Weather Service (NWS) mission is to provide reliable and skillful forecast products and services from weather to short-term climate time scales. The models used to produce weather and climate predictions solve different subsets of the same governing equations that encapsulate the conservation laws of the fluids (atmosphere and oceans) and matter (land and ice). No theory suggests that weather forecast skill is insensitive to variations in the ocean or land surface, or that ISI climate predictions are insensitive to atmospheric variations on weather time scales. Despite the divergence of numerical weather prediction and climate simulation and prediction practices, these commonalities support argument for the unification of the models used for weather and climate (Palmer et al. 2008; Hurrell et al. 2009; Shapiro et al. 2010; Shukla et al. 2010). Furthermore, this seamless prediction concept emphasizes the fundamental importance of scale interactions across time and space. Also, the unified weather-climate modeling strategy promotes shared knowledge, infrastructure, and technical capabilities on modeling of common processes and mechanisms to benefit both weather forecast and climate prediction.

The current NCEP model development is guided by a GFS-centric one-way strategy, in which the CFS benefits from development of the Global Forecast System (GFS, similar to that used at the European Centre for Medium-range Weather Forecasts (ECMWF). The current CFS development process involves:

- Developing a coupled ocean-sea ice-land-atmosphere model using the latest operational or near operational global atmosphere/land model – GFS – and a version of the GFDL modular ocean model (MOM) and updating it with potential future upgrades under consideration for GFS.
- Performing sensitivity experiments to optimize the coupled system
- Using the analysis system from GFS and adapting it to work for both past and present observing systems.
- Using this coupled model and analysis system (CFS) to compute a coupled reanalysis and reforecasts.
- Coordinating with NCEP Central Operations (NCO) and implementing the forecast system operationally.

This approach allows NCEP to modify the GFS freely as needed to meet various NWS requirements, and to take advantage of the latest global AGCM in the less frequent CFS implementations, but avoids two model development streams (i.e. for weather and climate), and ties improvements in seasonal prediction to model development for weather prediction. Considering that weather and climate have considerable commonality, weather forecasts provide an excellent testbed for developing the "fast physics" of climate models. The skill demonstrated by CFSv2 in ISI prediction illustrates the benefits of employing weather prediction development in the climate modeling strategy.

The critical importance of climate forcing on weather forecasts made using the GFS has not been realized until recently. By analyzing GFS daily forecast errors, studies have revealed that the foremost weather forecast error is not due to random processes, nor to local factors, but rather to large-scale climate biases (Fan and van den Dool, personal communication). Improved understanding of ocean-atmosphere interactions has also highlighted the important role of ocean mesoscale eddies in the skill of weather forecasts (Minobe et al. 2008; Lin et al. 2011). Distinct benefits are also found in coastal weather and hurricane forecasts using a high-resolution model coupled with an ocean model (Bryan et al, 2010; Chelton and Xie, 2010). Because of practical considerations (e.g., weather forecasts are done with a much larger ensemble; for now, weather predictions rely on bias correction schemes that do not require hindcasts, and therefore, initial states are not linked with long reanalysis etc.), at present the implementation of weather and climate forecasts may follow two different streams. In a long run, however, the merger of weather and climate modeling in a truly two-way unified approach is likely to be inevitable, as modeling research continues to show the weather-climate interdependencies.

If a fully unified modeling approach (such as employed by the UK Met Office) is considered, then this would require:

- Coordinated development of the GFS and CFS so that improvements to weather (climate) modeling and prediction feed back to climate (weather) modeling and prediction on a regular basis (e. g. every year or two, or every time there is a major new release of the CFS);
- Coordinated development of data assimilation systems for weather and climate. For example, in the case of climate, continuity is a critical feature of both reanalysis and re-

forecasts, so reducing artifacts associated with changes in the assimilation system is a priority. In the case of weather, the analysis system needs to adapt so that the most recent changes to the observing system are reflected in more accurate initial conditions. Even for climate this may be necessary, e.g. to take advantage of new satellite soil moisture or surface salinity retrievals as they become available.

- Coordinated testing of weather and climate models across time scales and across model components.

Adapting a fully unified weather-climate modeling strategy would benefit weather forecasts by reducing climate biases in weather forecasts and by leveraging modeling efforts from climate modeling communities. Such a unified weather-climate modeling strategy will also simplify the transition to coupled ocean-atmosphere weather forecasts in the future. However, its implementation requires model upgrades that meet both weather and climate requirements, which is very challenging. Furthermore, coupling the weather and climate model development cycles introduces potential stress and tension. The weather forecast cycle needs to be short in order to take advantage of up-to-date model improvements at critical times such as spring tornado season or summer hurricane season. The climate model forecast cycle may take considerably longer if multi-decadal reanalyses and re-forecasts are required as part of each implementation.

c) Should the CFS be a community model?

Many U.S. government agencies have invested considerable resources in climate modeling and ISI predictability and prediction studies over the years. NCEP is an operational service center that has limited resources for model development and basic research. To take full advantage of the CFS and to attain a competitive advantage in the world in providing skillful ISI forecasts, NCEP should join forces with other NOAA labs/centers and the broader external research community. However, the very high cost of maintaining a community model such as the National Center for Atmospheric Research (NCAR) Community Climate (Earth) System Model (CCSM/CESM) and the budget limitations in NOAA make supporting CFS as a full community model that is highly portable and has a worldwide community of users and developers a very challenging task. However, NCEP can still foster and take advantage of external science community. To this end, NCEP could adopt some of the best practices of the CCSM/CESM community activity to support the CFS community. For example, some of the CFS model components could be upgraded based on input from the community. A community interested in fast time-scale processes could be entrained for climate model development – which is a benefit of a unified weather and climate modeling strategy. NCEP should also provide support to external users such as updated model documentation, access to computer resources and run scripts, and occasional short tutorials.

d) Should reanalysis be decoupled from CFS model upgrades?

Implementation of the CFSv2 strived for consistency between the modeling system used for the CFS reanalysis (CFSR, from where the initial conditions are drawn) and the forecast system used for hindcast and real-time prediction. The necessity for this approach was argued based on the experience gained in weather prediction where consistency between the “atmospheric” assimilation and forecast systems is required for skillful short range predictions. For ISI predictions, this approach leads to very large computational overhead whenever the forecast model is changed.

To what extent similar consistency for ISI predictions for different component of the Earth system, e.g., atmosphere, ocean, land, is required remains an open question. It is conceivable that consistency in the analysis of slowly varying components of the ISI prediction system, for example, ocean, is far more important than consistency in the analysis of atmospheric initial states and inconsistencies in the specification of initial conditions for those slowly varying components during hindcasts and real-time forecasts can create serious issues for calibration. The strategy at other operational centers for ISI forecast systems has been to specify atmospheric initial conditions from the latest atmospheric reanalysis (ERA-Interim, for example), and focus their analysis efforts on the ocean and land initial states. A similar strategy could also be followed for the next implementation of the CFS, essentially de-coupling the CFS upgrade from the necessity of generating a new atmospheric reanalysis and making hindcasts for forecast calibration based on the latest reanalysis. It is also interesting to note that in the end the modeling systems used for CFSR and the CFSv2 were not consistent as some changes in the atmospheric component of the CFSR were made prior to settling on the atmospheric component of the CFSv2.

3. Collaborative research and development process

While continuing the discussions with the community on the CFS vision, NCEP should initiate the development cycle for CFSv3 with an improved management process, an improved internal infrastructure, and increased engagement and interaction with the external community. Some of the specifics of the vision for the CFSv3 will be defined and refined through the improved process, improved NCEP infrastructure and increased collaborations with the external community. Some considerations to move forward are discussed below.

a) <u>Initiate a fully unified weather-climate modeling strategy</u>

Recognizing the challenge of implementing a fully unified weather-climate modeling strategy in an operational center such as NCEP as described in section 2a), NCEP may consider some intermediate steps and actions towards that direction:

- Establish a project for parallel weather hindcast testing of CFSv2 and other U.S. climate models (using a quality ‘neutral’ initial condition such as that from ECMWF) to assess strengths and weaknesses as weather forecast models.
- Apply careful analysis of GFS and CFS systematic bias evolution at leads less than one month, including relationship to climatological biases.
- Evaluate changes in the skill of the operational GFS as a seasonal climate forecast model before making major model upgrades primarily to document influence of model changes on the climate of the model, but without use of this information for deciding on the GFS upgrade.

Note: A unified strategy does not imply that the weather and climate models have to be the same all the time, only that they are periodically harmonized to retain important improvements in both models.

<u>b) Establish an NCEP Climate Modeling Team</u>

NCEP should immediately establish an NCEP Climate Modeling Team (NCMT) with a formal partnership between EMC, CPC and NCO as the principal planning and oversight body responsible for the development and implementation of CFS. The advice from the NCMT and broader user community will also help set the requirement for the archive and access of the CFS.

Within the NCMT, EMC brings expertise on model development, testing and evaluation of the GFS, including model dynamics, physics, software engineering and data assimilation. CPC brings resources for maintaining climate simulations and conducting model evaluation and diagnostics. NCO provides the infrastructure support for operational execution of the weather and climate models at NCEP, thus providing the institutional framework between model development, execution, archive and access activities. A formal partnership between EMC, NCO and CPC is required to accelerate a unified weather-climate modeling strategy. The NCMT management structure should have co-leads from each center [e.g., respective branch Chiefs of the EMC's Global Modeling Branch (or alternatively, EMC's Climate Team Lead) and CPC's Development Branch] for internal functioning, with a close interaction with the CTB Director for liaison with the external community.

The NCMT should be a formal activity, with a governance structure that includes a Terms of Reference. The Team will get guidance from an external advisory group on the NCEP climate modeling strategy and priorities for the NCMT activities, and the criteria that indicate when CFS has improved sufficiently to justify an operational upgrade. The Climate Test Bed (CTB) should provide the coordination within NCEP and with the external community, and to enhance the required Operations-to-Research (O2R) and Research-to-Operations (R2O) activities and support.

c) <u>Make NOAA collaboration with the external community more effective</u>

NOAA should improve mechanisms to enhance collaboration with the external research community inside and outside of NOAA. Although it is challenging for NCEP to support a community model like NCAR CESM, the NCEP CFS can benefit from the community through the following recommended mechanisms:

- Establish an advisory group (possibly a sub-committee on modeling under UCACN) to provide guidance on the NCEP modeling activities
- Engage the private sector in the development of products based on user needs for decision making
- Provide sustained funding, to the extent available, to support collaboration with the external community
    - Competitive research projects (via MAPP-CTB Program) , e.g., Climate Process Teams (CPTs), competitive contracts with private sectors
    - Visiting scientists program
- Develop a strategy to feed research advances (such as CPTs) back into the CFS development cycle
- Adopt some model components for the CFS based on input from the community.
- Form working groups around model components and/or physical processes with participants from both internal and external scientists. The external scientists can be the PIs of MAPP-CTB projects or participants in a visiting scientist program, scientists from

national and internal modeling centers (e.g., NCAR, India), and/or scientists from other NOAA labs (e.g., GFDL).

- Provide infrastructural support to the external collaborators, including
  - User documentation for the models and data assimilation methods
  - Data sets for input to other models (such as regional climate models) that produce finer-resolution climate information directly meeting the need of end users.
  - Data sets for output comparison
  - A code that runs on a few of the main HPC platforms and user-friendly scripts
- Hold annual modeling or GFS/CFS workshops

d) Improve NCEP infrastructure, modeling framework and reward system

- Support a common modeling framework for both GFS and CFS models (with version control, documentation, so that changes are transparent). If GFS and CFS are built on the same framework (e.g., NEMS), it would be easier to implement the unified weather-climate modeling strategy which also includes the development of coupled Earth System Model components that are applicable to both weather and climate predictions.
- Be transparent about the model development pathway and the evaluation metrics and decision points, ensuring adequate opportunity for assessment and decision input from the external research community, before the model is frozen;
- Consider ways to ensure proper credit and protection of intellectual property rights, where appropriate, keeping in mind reward structures inside NCEP and for the external community.

e) Accelerate the CFS development cycle and implementation cycle

One possibility to accelerate the CFS development cycle is to consider alternative strategies for reanalysis and model upgrade. As discussed in Section 2d, to what extent similarity consistency for extended-range prediction for different components of the Earth system (e.g., atmosphere, land, ocean, etc.) is an open scientific question. Some considerations are listed below:

- Consider de-coupling the model development cycle from reanalysis (e.g., as done at the ECMWF and other operational centers with extended-range predictions), where only the reanalysis of slowly varying components, such as ocean and land is developed to provide initial conditions for extended-range predictions. As a first step, NCEP should explore the impact of consistent vs. non-consistent initial conditions for different components of Earth systems on prediction skill prior to making decisions. Answers to such questions can be gleaned from the comparison of skill across extended-range predictions at different operational centers, or based on a set of controlled experiments.
- Join forces with other agencies, such as, NASA/GMAO or ESRL on reanalysis efforts
- Conduct reanalysis/reforecast concurrently with forecast computation (U.K. Met Office)
- Note: reforecasts (or retroactive forecasts) should be made prior to each model upgrade for model calibration purpose.

NCEP should also consider accelerating the CFS implementation cycle, for example, reducing the overlap time between two versions of CFS implementations. The current overlap time between CFSv1 and CFSv2 is more than one year, while ECMWF gives its customers only about three months to switch to a new seasonal forecast model. Once the new version is advertised well in advance and demonstrates substantial improvement, NCEP should consider shortening this overlap time. This will push users to use NCEP's new and improved models and will also help NCEP free up resources to focus on future model development and implementation.

4. Requirements and measures of success

The full support of NOAA management is required to develop the vision, strategy, resource requirements, and measures of success for the next generation of the CFS.

a) Key requirements for CFS development

- The NOAA grants research programs should play a strategic role in CFS development, by creating opportunities to bring together various NOAA labs/centers and the external research community to work on the best ideas.
- NCEP should provide adequate resources for infrastructure support
  - NCEP internal development: NCEP Climate Modeling Team
  - User support
- NOAA should provide sufficient high-performance computing (HPC) for CFS development and improvement.
- NCEP should have a strategy to effectively feed research advances back into the CFS development cycle.
- NCEP needs to develop more effective mechanisms for including user input to the model development process.

b) Measures of success

- Multivariate, multi-phenomenon probabilistic skill in ISI climate forecast
- Skill in weather forecasts, including at 1-3 week lead times.
- Usefulness of the forecasts, e.g., lead time for warnings
- Improved model usage by the community and users
- Increased use of the forecast, hindcast and reanalysis archives for climate research
- Increased collaboration with other NOAA labs/centers, other modeling centers, and universities, e.g., number of visiting scientists
- Training the next generation of modelers, e.g., numbers of trainees

The CFS Core Team consists of members from NOAA (NCEP and other labs) and members from the external community as follows:

1) Chris Bretherton (U. of Washington)
2) Robert Dickinson (U. of Texas at Austin)
3) John Dutton (Prescient Weather, Ltd)
4) Wayne Higgins (NCEP/CPC)
5) Jin Huang (NCEP/CTB)
6) Jim Kinter (COLA)
7) Arun Kumar (NCEP/CPC)
8) Bill Lapenta (NCEP/EMC)
9) Shrinivas Moorthi (NCEP/EMC)
10) Tony Rosati (NOAA/GFDL)

Glossary:

AGCM: Atmospheric-component of Global Coupled Model
CCSM: Community Climate System Model
CFS: Climate Forecast System
CFSR: Climate Forecast System Reanalysis
CFSv1: Climate Forecast System Version 1
CFSv2: Climate Forecast System Version 2
CFSv3: Climate Forecast System Version 3
CESM: Community Earth System Model
CPC: Climate Prediction Center
CPT: Climate Process Team
CTB: Climate Test Bed
ECMWF: European Centre for Medium-range Weather Forecasts
EMC: Environmental Modeling Center
ESRL: Earth System Research Labotory
GEOS 5: Goddard Earth Observing System Model, Version 5
GFDL: Geophysical Fluid Dynamical Laboratory
GFS: Global Forecast System
ISI: Intra-Seasonal to Interannual
LSM: Land Surface Model
MAPP: Modeling, Analysis, Predictions and Projections
MOM: Modular Ocean Model
NCAR: National Center for Atmospheric Research
NCEP: National Centers for Environmental Prediction
NCMT: NCEP Climate Modeling Team
NCO: NCEP Central Operations
NEMS: NCEP Environmental Modeling System
NOAA: National Oceanic and Atmospheric Administration NOAA
NMME: National Multi-Model Ensemble
NWS: National Weather Service
OGCM: Oceanic-component of Global Coupled Model
UCACN: UCAR Community Advisory Committee for NCEP
VIC: Variable Infiltration Capacity (a macro-scale hydrologic model)

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