5.x Ensemble Design

5.x.1 State of the Science

Ensemble predictions are increasingly being used for providing situational awareness of high-impact weather forecast events, informing the forecaster of the range of possible weather scenarios. Ensembles are now also commonly used to provide estimates of forecast-error covariances in data assimilation methods.

There are two sources of forecast uncertainty in ensemble prediction systems. The first is initial-condition uncertainty. An ensemble should be initialized with samples from the distribution of plausible analysis states. The second is model uncertainty, which can bias the mean forecast and limit the spread of simulations, resulting in an overconfident ensemble, especially for surface-related variables (e.g., surface temperature and precipitation) and tropical forecasts such as hurricane tracks. These contributions to forecast error can be attributed to model deficiencies as well as from deterministic assumptions built into the forecast models' components, such as parameterizations.   As NOAA moves to more fully utilize coupled forecast models (atmosphere/ocean/land/ice, and perhaps more), the challenges of estimating forecast uncertainty will extend to estimating the coupled initial-state uncertainty and sources of model uncertainty in coupled system.

Addressing the atmospheric initial-condition uncertainty, has progressed in recent years more than the latter, model uncertainty. With ensemble Kalman filters and hybrid methods, there is now a direct method for sampling analysis uncertainty. The accuracy of such methods, however, depends critically on ensemble size, the treatment of model uncertainty in the data assimilation cycle, the extent of non-linearity/non-Gaussianity of error statistics, and the chosen methods for dealing with position errors of coherent features.

Model uncertainty treatments are less advanced. Researchers are seeking ways of ameliorating forecast bias and increasing forecast spread that are physically realistic. Lacking these, they also seek appropriate methods of post-processing the forecast guidance to ensure that it is as bias-free, skillful, and reliable as possible. As we anticipate the use of coupled models in the future, imperfections in the interactions of the coupled state components will also need to be simulated properly.

5.x.2 Objectives

The overall objectives of the ensemble design component of NGGPS are to: (1) develop and implement improved methods for initializing ensemble predictions (see also the data assimilation component of the NGGPS implementation plan), including the initialization of the coupled environmental state (ocean, atmosphere, land, sea ice, and so forth); (2) to develop methods to accurately quantify model uncertainty in ensemble prediction systems, including coupled systems; and (3) to develop ensemble prediction system improvements that will facilitate the generation of reliable and maximally skillful guidance to lead times of + 30 days and beyond. Together, these should dramatically improve the probabilistic forecast guidance of high-impact weather elements that can be provided directly from raw ensembles, making the forecast guidance much more skillful, reliable, and detailed.

5.x.3 Milestones, Resource Requirements, and Outcomes Objectives

Many of the physically based methods of treating model uncertainty can be improved and initial objectives include:

1. Improve the numerical methods used for treating model uncertainty in global ensemble prediction systems in collaboration with Federal agencies and universities.

a)

- **Lead Organization:** EMC
- **Activities:** Develop and implement physically based methods to quantify the contribution to uncertainty from the dynamical forecasts.
- **Milestones and deliverables:** + 1 year past project start: deliver comparison of past and possible future methods for quantifying dry dynamical forecast uncertainty. +2 years past start: deliver code for pre-operational testing. + 3 years past start: implement method operationally.
- **Anticipated collaborating organizations:** ESRL/PSD, possibly ESRL/GSD, universities
- **Priority:** Medium. Judging from the comparisons of dynamical cores in HIWPP project, there are differences in the simulations of common phenomena like mid-latitude cyclones between various candidate dycores. This suggests that there is some moderate potential for improvement in ensembles through quantifying this and developing methods to estimate it in ensemble prediction systems. However, the impact is not expected to be as large as with stochastic parameterizations of, for example, deep convection.
- **Duration:** 3 years.
- **Points of contact:** Yuejian Zhu, EMC

b)

- **Lead Organization:** EMC
- **Activities:** Develop, test, and implement physically based stochastic schemes to quantify model uncertainty for GEFS extended (35 day) forecasts. Model uncertainty is a necessary component to produce reliable estimates of the forecast uncertainty at that range.

- **Milestones and deliverables:** +1 year past project start: deliver comparison of past and possible future methods for quantifying increasing forecast uncertainty for extended forecasts. +2 years past start: deliver code for pre-operational testing. +3 years past start: implement method operationally.
- **Anticipated collaborating organizations:** ESRL/PSD.
- **Priority:** High. Extending predictions to the sub-seasonal range is a NWS priority. This activity will be in coordination with other activities focusing on the development of near-surface uncertainty assimilation and ocean uncertainty assimilation.
- **Duration:** 3 years.
- **Points of contact:** Yuejian Zhu and Walter Kolczynski, EMC

c)

- **Lead Organization:** ESRL/PSD
- **Activities:** Develop, test, and implement physically based stochastic parameterization methods for deep convection. This will increase spread in precipitation-related variables and also, via upscale propagation, affect spread of other fields (temperature, wind). This is envisioned as likely two funded or more projects, one that is a shorter-term development and implementation of mature technologies developed elsewhere (e.g., Shutt's convective backscatter) and another that addresses some more fundamental issues in stochastic parameterization of deep convection.
- **Milestones and deliverables:** <u>First project</u>: end of first year: code and provide preliminary tests of improved method; calibrate parameters of the scheme in the cycled En-Var data assimilation system. End of second year. Deliver report on extensive tests of new method with GEFS forecasts to +16 days, as well as code suitable for adaptation to the operational GEFS. End of third year. A successful operational implementation after completion of parallel tests and evaluations. Documentation of the project in the form of a peer-reviewed journal article. <u>Second project</u>: Milestones should be more flexible. This project is likely a collaboration between university or NOAA cooperative institute scientists and partners at ESRL and/or EMC. The first part of the project (roughly year 1) would involve testing a particular hypothesis for how to generate physically meaningful perturbations to deep convective parameterizations. A second part would involve the development and testing of the proposed method in the GEFS system (roughly years 2-3). A third part would be the pre-implementation testing and operational implementation (year 4).
- **Anticipated collaborating organizations:** EMC, possibly universities, possibly ESRL/GSD.
- **Priority:** High
- **Duration:** 4 years past start.
- **Points of contact:** Jeff Whitaker, Tom Hamill, and Jian-Wen Bao, ESRL/PSD.

d)

- **Lead Organization:** ESRL/PSD
- **Activities:** Develop, test, and implement physically based stochastic parameterization methods for microphysics. This is expected to increase spread in ensembles for cloud- and precipitation-related variables.

- **Milestones and deliverables:** This project starts from less of a foundation of existing basic research than stochastic parameterizations for deep convection. The existing microphysics parameterization is the very simple diagnostic Zhao-Carr method, which needs to be upgrades (see parameterization plan). Once a new microphysics parameterization has been developed and is ready for implementation, so a reasonable milestone for the first two years will be articles which provide some increased understanding of the magnitude of predictive uncertainty that can be attributed to appropriate perturbations to aspects of microphysical parameterizations. Deliverables in years 3-5 are more conventional; development of a new physically based method (year 3), documentation and testing in GEFS system (year 4), pre-implementation testing and operational implementation in GEFS system (year 5).
- **Anticipated collaborating organizations:** EMC, universities.
- **Priority:** Moderate-high. Given the relative lack activity in this area of research, his makes it higher in risk, but also potentially higher in reward.
- **Duration:** ~ 5 years, full length of NGGPS.
- **Points of contact:** Robert Pincus, CIRES and ESRL/PSD, Jian-Wen Bao and Tom Hamill, ESRL/PSD

2. Develop and implement improved methods of modeling the forecast uncertainty that can be attributed to the interactions with the land, ocean, and ice.

a)

- **Lead Organization:** ESRL/PSD
- **Activities:** Continue with the implementation of methods for stimulating realistic variability of near-surface variables over land, in collaboration with the NGGPS land project. Notes: this project was begun with NWS Sandy Supplemental funds, but those funds were not sufficient to carry the project through to a full operational implementation. The expected benefits are increased spread of ensembles in near-surface variables such as temperatures, surface winds, and precipitation amount and type.
- **Milestones and deliverables:** An operational implementation of a procedure for improving spread in GEFS system of near-surface variables over the land, and precipitation, in the 2016-2017 timeframe
- **Anticipated collaborating organizations:** EMC
- **Priority:** High. This is low-hanging fruit, with some moderate expected benefit for a modest investment.
- **Duration:** early 2016 – mid 2017
- **Points of contact:** Tom Hamill, ESRL/PSD.

b)

- **Lead Organization:** EMC
- **Activities:** Further develop and implement methods for stimulating realistic variability of near-surface variables over water and ice. Some preliminary explorations have been performed both at EMC (Malaquias Pena) and at ESRL/PSD (Gary Bates). With the intent of using a coupled system out to and beyond the monthly time scale, methods are needed for initializing ocean initial states (see next

task) as well as modeling the uncertainty due to interactions of the atmosphere with the ocean and ice surface (this task). The expected impact will be a greater spread in near-surface temperatures and winds over the ocean and ice pack, which may result in greater spread of phenomena like MJOs, which then can mean a greater spread in mid-latitude features that are teleconnected with MJO.

- **Milestones and deliverables:** By end of 2016: Evaluate a range of methods for increasing spread over the ocean and ice state in GEFS system offline. End of 2017: Advanced testing of modified GEFS, with documentation of the expected impact from ocean- and ice-state treatments relative to baseline GEFS without treatment of this source of uncertainty. End of 2018: operational implementation of these methods in GEFS system.
- **Anticipated collaborating organizations:** ESRL/PSD.
- **Priority:** Medium. Initial tests have shown that candidate methods like NSST over the oceans introduce only a small amount of spread.
- **Duration:** 3 years.
- **Points of contact:** Xiaqiong (Kate) Zhou, and Yuejian Zhu, EMC

3. Develop and implement adjustments to the GEFS system to make its forecasts suitable for the full 0-30 day prediction period.

a)

- **Lead Organization:** EMC
- **Activities:** Develop and implement a methodology for the *initialization* of the ocean state that preserves realistic consistency with the atmospheric state (e.g., for a windy ensemble member, associated greater vertical mixing in the ocean for that member). Notes: there have been some experiments, largely in the university setting, of coupled “breeding” methods between the ocean and atmosphere. Recently, the GEFS switched from an enhanced breeding method known as ETR to initialization with EnKF perturbations. While in the long run it would be desirable to have a fully coupled ocean-atmosphere ensemble-based data assimilation system, this is an activity that is complicated and would involve basic research extending over a ~ 5-year period prior to implementation. Hence this activity can be seen as an interim step to carry us over till a coupled data assimilation method is ready for operations. The expected methodology is anticipated to be akin to a coupled breeding method, but where the atmospheric perturbations are supplied by the EnKF rather than bred/ETR perturbations.
- **Milestones and deliverables:** By end of year 1, development of code for a coupled breeding /EnKF-type methodology for initializing the ocean to be roughly consistent with atmospheric EnKF perturbations. By end of year 2, demonstration in GEFS system of the impact of these methods relative to baselines such as an ocean with no initial-condition variability.
- **Anticipated collaborating organizations:** Universities such as UMD with faculty experienced in breeding and data assimilation would be natural partners. Possibly CPC.

- **Priority:** Medium. The main time scale where this would have some effect are the longest time scales anticipated for the GEFS, ~ 1 month, where predictable signals are very small. This may improve those signals very slightly.
- **Duration:** Anticipated 3 years till an operational implementation
- **Points of contact:** Malaquias Pena and Yuejian Zhu, EMC.

b)

- **Lead Organization:** EMC
- **Activities:** Develop, test, and evaluate methods for modeling ocean-atmosphere *forecast* interactivity at the intra-seasonal time scale. As opposed to the previous task (initialization), this task is intended to develop methods for correctly modeling the ocean-atmosphere interactions during the forecast. Evaluate several candidate methods (mixed layer ocean, fully prognostic ocean, others TBD). Determine which candidate approach is to be recommended for 30-day ocean modeling in the GEFS. Produce a report outlining the costs/benefits and impacts of each approach. Implement the most appropriate methodology as determined by testing
- **Milestones and deliverables:** by the end of year 1, develop a software infrastructure for the testing of various candidate methods (mixed layer ocean, fully prognostic ocean). By end of year 2, a report describing the approaches and the results from their comparative evaluation. By the end of year 3, an operational implementation of the most promising methodology.
- **Anticipated collaborating organizations:** Possibly CPC.
- **Priority:** High. This is the most critical task related to extending the GEFS to 30 days, or beyond.
- **Duration:** 3 years.
- **Points of contact:** Wei Li and Yuejian Zhu, EMC

4. Associated Proposal: Development and testing of a multi-model ensemble prediction system for sub-monthly forecasts.

- **Lead Organization**: Dr. Andrew W. Robertson – Lead PI, Columbia University.
- **Activities**: Develop and test a multi-model ensemble (MME) prediction system for sub-monthly forecasts, based on established methodologies used in probabilistic seasonal climate forecasting. A prototype MME of weekly-averaged gridded precipitation and near-surface temperature (Weeks 2-4) will be constructed from available hindcasts, specifically the NCEP CFSv2, ECMWF and the Environment Canada model, and other models that become available. The project will utilize hindcasts archived in the WWRP/WCRP Sub-seasonal to Seasonal Prediction Project (S2S) database at ECMWF that will come on line in January 2015.
- **Milestones and deliverables**:
    - Quantify the sub-monthly hindcast skill of the CFSv2 and selected other individual models over the U.S. in terms of: gridded fields of precipitation and temperature, as well as atmospheric indices such as the NAO and PNA; lead time and averaging range, including weekly averages in weeks 2-4;

deterministic and probabilistic forecast skill metrics; and diagnostics of predictability.

- Develop the methodology and evaluate the benefit of including an additional 1-3 models in a multi-model ensemble, with focus over the U.S.
- Improve physical understanding of sub-monthly predictability over the U.S.
- Establish the applicability of MME methods developed for seasonal forecasts to the sub-monthly scale.
- Implement a real-time S2S MME at CPC, built using the most skillful and models that are available to NOAA/CPC in real time.

- **Anticipated collaborating organizations**: Co-Investigators: Michael Tippett, Columbia University and Arun Kumar, NOAA/CPC.
- **Priority**: High.
- **Duration**: 05/01/2015-04/30/2017.
- **Points of contact**: Andrew Robertson (awr@iri.columbia.edu).

5. Accelerating Development of NOAA's Next Generation Global Couple System for Week-3 and Week-4 Weather Prediction

- **Lead Organization**: James L. Kinter III, George Mason University. CO-Is: Benjamin Cash, Timothy DelSole, Bohua Huang, Kathleen Pegion, Cristiana Stan
- **Activities**: Conduct a series of model development and rigorous testing exercises designed to (1) correct systematic biases, especially deep convection in the tropics and extratropical fluxes between the ocean and the atmosphere, to improve forecasts for weeks 3 and 4; and (2) quantify the predictability and skill of weather forecasts for weeks 3-4, with special attention to diagnosing their sensitivity to the spatial resolution, predictability factors in the initial condition (e.g., state of the MJO, blocking conditions, etc.), and coupling between atmosphere and ocean. Statistical optimization methods will be used to comprehensively evaluate the predictability and skill at weeks 3-4.
    - Task 1: Ocean-Atmosphere Feedbacks
    - Task 2: Increasing Spatial Resolution
    - Task 3: Evaluation and Analysis
    - Task 4: Sensitivity of Weeks 3 and 4 Predictability to Model Developments & Initial Conditions
- **Milestones and deliverables**:
    - Quantitative, statistically significant answers to the scientific questions regarding forecasting weeks 3 and 4 by extending atmosphere-only runs; the importance of spatial resolution; and the impacts of model errors on forecasts for weeks 3 and 4. These questions are critical to the advancement of week-3 and week-4 weather forecasts. It is anticipated that several papers will be submitted for peer-reviewed publication.

        - Alternative versions of a global four-component (AGCM, OGCM, LSM, SIM) and five component (plus OWM) prediction system under software version control. The alternative versions will have improved representations of clouds and convection, improved representations of land surface-atmosphere interactions, and increased spatial resolution sufficient to provide more accurate representation of mesoscale atmospheric circulations. All versions of the model will be documented and maintained under software version control in the NCEP repository for easy transition to operations as warranted.
        - Rigorous, quantitative estimates of the skill of 3-4 week lead-time forecasts of weather in North America and the statistics of hurricane and typhoon formation for these alternative versions. These assessments will advise NCEP and NOAA on the efficacy of adopting the investigated model developments for operational use.
        - A software test suite for evaluating the skill of new versions of the model.
        - 05/1/2015 – 10/31/2015 Obtain latest version of c-NEMS; Increase AGCM and LSM spatial resolution from T126 (100-km grid spacing) to T382 (35-km grid spacing); create codes for standard metrics of weeks 3-4 skill; run AGCM-only 200-year run and begin perfect-model reforecasts to assess predictability
        - 11/1/2015 – 4/30/2016 Add HCF and SP coupling to c-NEMS; begin reforecasts; begin testing the 35- km (AGCM/LSM) version of c-NEMS; apply standard and information theoretic metrics to available reforecasts; continue reforecasts using initial conditions drawn from 200-year run
        - 5/1/2016 – 10/31/2016 Complete reforecasts with all new versions of c-NEMS; complete reforecasts with 35-km AGCM/LSM configuration; analyze and synthesize results from reforecasts; evaluate predictability based on reforecasts from 200-year run; test difference between all forecasts and forecasts of opportunity
        - 11/1/2016 – 4/30/2017 Prepare papers for peer review documenting results;
    - **Anticipated collaborating organizations**: EMC
    - **Priority**: High.
    - **Duration**: 05/01/2015 – 04/30/2017.
    - **Points of contact**: James Kinter, (jkinter@gmu.edu)

6. An Investigation of the Skill of Week Two Extreme Temperature and Precipitation Forecasts at the NCEP WPC

    - **Lead Organization**: Dr. Lance F. Bosart, University at Albany, SUNY, Co-I: Dr. Daniel Keyser

- **Activities**: The proposed percentile forecast methods, persistent flow anomalies, and NH climate database are directly applicable to WPC's development of new forecast formats for Days 8-10. These forecast formats and methodologies for identifying EWEs will be tested in the WPC Hydrometeorological Testbed, and then will be implemented into WPC operations. Specifically, WPC developers will introduce the proposed ensemble-based probabilistic forecast procedures to WPC medium-range forecasters with the goal of improving the WPC's ability to anticipate the formation of RWTs, correlate their downstream influence with our daily forecast time periods, and identify the potentially resultant EWE scenarios over the CONUS. We expect the UAlbany research to help inform us of GFS and GEFS biases with respect to EWE scenarios, such that the human forecaster can make science based adjustments to model guidance.
- **Milestones and deliverables**:
  Year one activities:
  - Recruit postdoctoral research associate.
  - Begin UAlbany research effort on EWEs over the CONUS.
  - Spin up collaborative R2O effort with NCEP-WPC.
  - Present preliminary project results at conferences and workshops.

  Year 2 activities:
  - Continue UAlbany research effort on EWEs over the CONUS.
  - Conclude components of UAlbany research effort ready for transfer to operations.
  - Continue collaborative R2O effort with NCEP-WPC.
  - Present project results at applicable conferences and workshops.
- **Anticipated collaborating organizations**:
- **Priority**: High.
- **Duration**: 05/01/2015 – 04/30/2017.
- **Points of contact**: Dr. Lance Bosart, (lbosart@albany.edu)

7. Exploitation of Ensemble Prediction System Information in support of Atlantic Tropical Cyclogenesis Prediction

- **Lead Organization**: Dr. Christopher Thorncroft, University at Albany, SUNY, Co-I: Mr. Jason Dunion, University of Miami
- **Activities**: To ensure that recent and current research concerned with the variability of African easterly waves (AEW) structures and downstream tropical cyclogenesis probability is transferred into operational decision-making at NHC, and to develop and evaluate tools that exploit key information in dynamical ensemble prediction systems in support of tropical cyclogenesis prediction.
  - Task 1: Development and Evaluation of Objective Tropical Cyclogenesis Probabilities associated with AEWs

    - Task 2: Analysis of AEW-Tropical Cyclogenesis statistics in Ensemble Prediction Systems
    - Task 3: Analysis of the Causes of Good and Poor Skill in the Ensemble Prediction Systems
    - Task 4: Development of Tools for Guiding Operational Tropical Cyclogenesis Prediction Probabilities
    - Task 5 Establishing a Website in Support of Operational Forecasting
    - TCGI will be evaluated on the 2014 and 2015 seasons to determine the best utilization of the ensemble information
    - Evaluate the skill of TCGI on storm tracks prior to invest definition, allowing for TCGI probabilities to be verified for up to 5 days where invest locations were not defined.
    - Following outcomes of previous tasks, development a beta ensemble based TCGI product to be run in real-time both on pre-invests and invests.
  - **Milestones and deliverables**:

    Year 1 Milestones
    - Provide quantitative assessment of model skill in prediction of tropical cyclogenesis associated with AEWs, as a function of region and lead time and for both the GFS and ECMWF ensemble prediction systems.
    - Provide quantitative assessment of the key factors influencing predicted tropical cyclogenesis associated with AEWs, as a function of region and lead time and in both the GFS and ECMWF ensemble prediction systems.
    - Finish initial assessment of the physical reasons for good and bad forecasts of tropical cyclogenesis associated with AEWs, as a function of region and lead time and in both the GFS and ECMWF prediction systems.

    Year 2 Milestones
    - Establishment of objective tool for predicting probable forecast skill of tropical cyclogenesis associated with AEWs, as a function of region and lead time and in both the GFS and ECMWF ensemble prediction systems.
    - Establishment of forecast tools and related graphics to provide probabilistic guidance of tropical cyclogenesis probability to NHC forecasters.
    - Establishment of real-time website to communicate forecast tools and related graphics created in previous bullet.
    - Establish a methodology for incorporating ensemble information into the TCGI product.
    - Establish a beta ensemble based TCGI product to be run in real-time both on pre-invests and invests.
  - **Anticipated collaborating organizations**:
  - **Priority**: High.
  - **Duration**: 05/01/2015-04/30/2017.

- **Points of contact**: Dr. Christopher Thorncroft, (cthorncroft@albany.edu)