Research towards the next generation of NOAA Climate Reanalyses
Abstract to the NOAA MAPP Program, NOAA-OAR-CPO-2013-2003445

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Abstract

The fidelity of new reanalysis datasets (MERRA, 20CR, CFSR, ERA-Interim) at representing climate variability of the 20th century has enabled significant advances in climate research. In this research proposal, we will investigate 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: Boundary-forced, 1850-present "AMIP" simulation with large ensemble
Stream 1: Historical, 1850-present using only surface data
Stream 2: Modern, 1946-present using only surface and conventional upper air data
Stream 3: Satellite, 1973-present using quality-controlled satellites, Global Positioning System Radio Occultation, and surface and conventional upper air data.

One of the foci of this research will be to use observing system experiments. In these, the 2000-2010 observing system is reduced to that of selected historical periods to investigate the impact to the time-varying quality and density of the observing system and determine ways to reduce this impact. We will use 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 will leverage 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 will 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 will be crucial in achieving the project's goals on a limited budget.

This project is directly related to foci 1 of Priority 1 of the MAPP call for proposals. It is directly relevant to NOAA's Next-Generation Strategic Plan goals for climate adaptation and mitigation. As noted by the WMO Global Framework on Climate Services, reanalyses are a key component of the climate information needed for informed decision making for climate change mitigation and adaption. The NGSP recognizes that a strong scientific basis is needed for developing "climate adaptation and mitigation" strategies, which will require "improved scientific understanding of the changing climate system and its impacts" and "assessments of current and future states of the climate system." For NOAA to achieve these objectives, we must develop climate reanalysis products that are free of artificial trends and that provide reliable information about the frequency of weather and climate extremes. This proposal directly addresses the MAPP call to pursue research on "Outstanding issues in atmospheric reanalysis", in particular by attempting to "overcome the impact of data inhomogeneities due to changes in the observing system and data biases", "overcome the impact of model bias", "better quantify uncertainties in reanalysis data including the impacts of data and model error", and "exploit new data".

Strategies to Improve Stratospheric Processes in Climate Reanalysis

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1) Abstract

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.

We propose to address 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.

Exploration of advanced ocean data assimilation schemes at NCEP

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(2) Abstract

The first task will be to upgrade 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 atmosphere-ocean analysis system, in turn providing the initial conditions for NCEP's atmosphere/ocean Climate Forecast System, version 2, (CFSv2). The second task will be to combine the 3DVar and LETKF systems to form a hybrid version of GODAS. We will explore the effectiveness of this hybrid system to represent timeevolving local correlations due, for example to fronts or currents, while at the same time maintaining large-scale correlations. An additional task will be to examine the computational efficiency of the hybrid filter relative to its 3DVar and LETKF alternatives.

The proposal will bring together researchers from the University of Maryland experienced in the development and use of LETKF with NCEP researchers who have overseen development of 3DVar-GODAS and the first two versions of the CFS. The rationale for proposed work is: 1) It will result in 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 atmosphere-ocean-land analysis system in which both ocean and atmosphere components use coupled ensemble-based estimates of flux error at the interface. 2) The implementation of LETKF in GODAS will provide 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 eddy-resolving Real-Time Ocean Forecast System (RTOFS) (using a HYCOM-based ocean model). The new development work proposed here will be carried out in NCEP's computing environment thus facilitating the integration of the resulting system into operations.

This proposal addresses the NOAA Next Generation Strategic Plan's call to 'create accurate and reliable estimates of the state of the ocean, including its temperature, salinity, and motion fields for accurate forecasts and assessments'. Likewise it addresses the Climate Program Office Strategic Climate Objective: I *Improve Scientific Understanding*, specifically the goals of improved monitoring and improving initial conditions to explore '*useful predictions of climate variability and change for the next one to three decades*'. Within the Modeling, Analysis, Predictions, and Projections (MAPP) program 2013 Call the developments described in this

proposal address Priority Area 1: Research to Advance Climate Reanalysis and Research Focus 2: Integration among Earth System reanalysis components by improving the integration of the atmospheric and ocean analysis systems.

Evaluating CFSR Air-Sea Heat, Freshwater, and Momentum Fluxes in the context of the Global Energy and Freshwater Budgets

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2. Abstract-Priority Area 1, Research to Advance Climate Reanalysis Type II

This proposed research aims at providing a comprehensive assessment of the partially coupled Climate Forecast System Reanalysis (CFSR) by NOAA NCEP in representing air-sea heat, freshwater, and momentum fluxes in the context of the global energy and water budgets. The proposed research addresses the MAPP call on improving our ability to "better quantify uncertainties in reanalysis data including the impacts of data and model error", and addresses the climate objectives of NOAA's Next Generation Strategic Plan (NGSP) with particular focus on providing quantitative assessments of current state of the climate system.

The CFSR is the first and only reanalysis that incorporates a coupled atmosphere-oceanland climate system with an interactive sea-ice component, and the one that has the finest spatial resolution (~0.5°) ever produced by any reanalysis. Evidence has clearly pointed to the advantages and strengths of the finer-resolution coupled CFSR reanalysis in characterizing airsea fluxes at regional and global scales, but biases/errors in the CFSR flux components at various temporal scales have also been reported. 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 Wm-2, which is about 10 Wm-2 higher than the estimates from the earlier NCEP reanalyses. We recognize that balancing the global energy/water budgets has long been a challenging issue, with global energy budgets differing considerably, from 2 to 30 Wm-2, when computed using reanalyzed, ship-, and satellite-based 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 next-generation Earth System reanalysis. Therefore, this proposed assessment study will analyze the biases/errors in the CFSR surface fluxes in the context of the global energy/water budget and will also compare the CFSR with the earlier and the latest reanalyses as value-added evaluation.

The proposed approaches include: (i) in situ validation, in which a database consisting of more than 130 flux buoys is used as ground truth for identifying and quantifying biases/errors in flux products; (ii) spectral analysis, in which ship- and satellite-based global flux analyses are 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) are used to test the physical consistency of flux products with ocean state variables (temperature and salinity).

The primary objectives of the proposed research are to (i) identify the strength and weakness of the CFSR surface flux components by comparison with in situ flux measurement, satellite-based analyses and other reanalyses products and understand 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, (iii) investigate the use of physical constraints together with ocean state variables to diagnose and understand the uncertainties in CFSR air-sea fluxes.

The significance of the proposed research is in the potential to (i) establish a baseline that can be used to help determine the scope and extent of the CFSR surface fluxes to be applied; (ii) improve our understanding of the state-of-estimation of air-sea fluxes in latest reanalyses; (iii) obtain new insights on the cause of the discrepancies in global energy/freshwater budget estimates based on air-sea fluxes; and (iv) obtain practical recommendations for future improvement of air-sea flux estimation in reanalyses.

ABSTRACT

Title: Improving the land-surface components of Climate Forecast System Reanalysis (CFSR)

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Global reanalyses, starting with the NCEP/NCAR reanalysis in the mid-1990s, are widely used as surrogates for space time observations in both the atmosphere and the land surface (and, to a lesser extent, the oceans). Early (e.g. NCEP/NCAR) reanalysis land surface products had many problems, including discontinuities near the beginning of the satellite era in the 1970s, and unrealistic land surface variables (such as soil moisture) resulting from updates to some land surface variables intended to resolve deficiencies in atmospheric moisture and moisture transport profiles. These issues have been mitigated to some extent in more recent reanalyses (e.g., Climate Forecast System Reanalysis (CFSR), ERA-40 and ERA-Interim and the North American Regional Reanalysis, NARR). Nonetheless, the fidelity of land variables from land atmosphere reanalyses remains questionable. We believe that the land data assimilation system used in upcoming reanalyses can be enhanced via improved (1) land characterization data sets (e.g. vegetation type and soil texture class, and the characterization of urban areas, etc.), (2) atmospheric forcing data sets (e.g. precipitation, downward solar and longwave radiation), (3) assimilation of near-real time land states (e.g. surface skin temperature, albedo, soil moisture, snow extent, vegetation greenness and density), (4) land-model spin-up procedures, and (5) downscaling techniques for forcing data and land states. We intend to investigate options for making these improvements, in the context of an enhanced CFSR framework. Additionally, currently missing in reanalyses is the inclusion of some key variables in the land surface water budget, such as groundwater, streamflow (routed to the mouths of major rivers), and lakes, reservoirs (managed), and wetlands. All of these are needed to complete the water cycle for a fully-coupled system, and to account for feedbacks to the atmosphere and coupling between the terrestrial and atmospheric budgets (e.g. over long periods river discharge from a region equals net atmospheric convergence into the region, so errors in river flow predictions must manifest themselves in the atmospheric moisture fields). We intend to investigate inclusion of such representations in the context of the new Noah-MP land surface modeling framework, which will be the land surface scheme for NCEP's next generation reanalyses. Co-PIs Lettenmaier and Wood have extensive experience in representation of the above variables in the context of the VIC land model, and some of the VIC parameterizations may be transferred to Noah-MP as needed. Furthermore, all co-Is have extensive experience in development of model evaluation data sets, through programs like NLDAS and GLDAS, which we will draw from.

Diagnosing and quantifying uncertainties of the reanalyzed clouds, precipitation and radiation budgets over the Arctic and SGP using combined surface-satellite observations

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2. Abstract: This proposal is in response to the FY13 call of NOAA-OAR-CPO-2013-2003445, **MAPP-Research to Advance Climate Reanalysis**, with particular focus on addressing some outstanding issues in atmospheric reanalysis. We will use an innovative diagnostic method to quantify the uncertainties of reanalyzed cloud-precipitation-radiation over the Arctic and US SGP regions. The five reanalyses being evaluated in this study are (i) CFSR, (ii) 20CR, (iii) MERRA, (iv) ERA-I, and (V) JRA-25. We will compare the reanalyzed results with observations, find their similarities and differences, and finally investigate how these differences relate to large-scale dynamic patterns and variables using the Self Organizing Maps (SOM) method. **The goal of this study is to guide improvement for the cloud/radiation/precipitation parameterizations in these five reanalyses, modify current ones, and/or develop new ones. Therefore, we propose the following two objectives.**

Objective 1: Quantifying the uncertainties of reanalyzed Arctic cloud-radiation properties

Reanalyzed cloud properties, such as cloud macrophysical (total/low/middle/high cloud fractions and vertical distribution) and microphysical properties (particle size, LWP/IWP, optical depth) will be evaluated with NASA CERES Ed4 and CloudSat/CALIPSO results over entire Arctic region and locally at the ARM NSA ground-based observations. The reanalyzed surface and TOA radiation fluxes will be evaluated with NASA CERES EBAF results and ARM/BSRN observations. The reanalyzed cloud properties will be compared with CERES-MODIS retrievals for the period 2000-2011. Then we will identify key discrepancies in the comparison for different regions and seasons. To discriminate between these potential problems, Self Organizing Maps (SOM) will be used to classify the atmospheric state from the reanalyses. Intercomparisons of classified atmospheric states between different reanalyses will allow us to determine how the reanalyzed cloud-radiation biases vary with model dynamics.

Objective 2: Investigating the reanalyzed hydrological cycle at SGP

There are two sub-objectives in Objective 2. In the first sub-objective, we will compare the monthly mean cloud fractions and accumulated precipitations from five selected reanalyses

with different observational platforms, such as ARM, Oklahoma mesonet system, GPCP, NEXRAD Q2, TRMM, and UND hybrid radar/GOES product over the SGP region during the period 1997-2011 (as we did in Figs 3 and 4). Through this comparison, we will statistically evaluate the strength and weakness in cloud fractions, precipitation strength, frequency occurrence, and areal coverage for each reanalysis. In the second sub-objective, we will perform the case studies during the MC3E over the ARM SGP site during April-June 2011. The aircraft in-situ measured cloud properties, various radar observations and retrievals, and UND hybrid dataset during the MC3E field experiment provide a "cloud/precipitation-truth" dataset and are an invaluable data source for us to evaluate the reanalyzed clouds and precipitation over the SGP region. It is a great addition to the statistical comparison in the first sub-objective.

The two proposed objectives build on our experience in evaluating both GCM/SCM simulations and reanalyses using both surface-satellite observations, and are a natural extension of our current research. They are strongly relevant to one of the NOAA NGSP goals: *Assessments of current and future states of the climate system that identify potential impacts and inform science, service, and stewardship decisions*. In particular, the two proposed objectives fit in the following MAPP targeted areas: *1) the hydrological cycle, 2) the quality and uncertainties of reanalyses over the Arctic regions, 3) Representation of surface fluxes.*

Improving the Prognostic Ozone Parameterization in the NCEP GFS and CFS for Climate Reanalysis and Operational Forecasts

Abstract to the NOAA MAPP Program, NOAA-OAR-CPO-2013-2003445

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The objective of this proposal is to improve the representation of stratospheric ozone (O3) and water vapor in NOAA's climate reanalyses. This work will also 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 Global Forecast System (GFS) atmosphere/land model used in the 20th Century Reanalysis and operational forecasts, and also used in the coupled Climate Forecast System (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 (CHEM2D-OPP). It includes terms representing net production and loss and a dependency on the ozone mixing ratio itself. It is based on gas-phase chemistry of the late-20th 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 is needed to represent pre-CFC stratospheric O3 chemistry. To understand, analyze, and predict atmospheric variability in the 21st century, the parameterization should utilize additional interactions included in CHEM2D-OPP that affect stratospheric O3. Stratospheric water vapor is also an important radiative constituent. Its representation in the GFS will also be improved, paving the way for improved assimilation of satellite radiances and for interactive chemistry.

In this proposal, a more advanced O3 parameterization using the full CHEM2D-OPP and an improved treatment of stratospheric water vapor will be implemented for use in new versions of the GFS, CFS, and next generation NOAA climate reanalysis systems. The O3 parameterization will include the effect of changes in temperature, changes in the vertical distribution of O3, and the time-variation of CFCs. As a first step, the parameterization will be

tested with two modes, one for times before CFCs and one for times after CFCs began to be released in large quantities. The team will also implement a new stratospheric H2O climatology as a necessary first step toward future implementation of parameterized H2O photochemistry. The upgraded parameterization and new climatology will be 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 will be evaluated using comparisons with both historical and modern O3 and temperature observations throughout the troposphere and stratosphere as well as with UV radiation observations.

This project is directly related to both foci of Priority 1 of the MAPP call for proposals. It is also directly relevant to NOAA's Next-Generation Strategic Plan goals for climate adaption and mitigation. As noted by the WMO Global Framework on Climate Services, reanalyses are a key component of the climate information needed for informed decision making for climate change mitigation and adaption. This proposal directly addresses the MAPP call to pursue research on “Outstanding issues in atmospheric reanalysis”, in particular by attempting to “overcome the impact of model bias” and “exploit new data”. Improved stratospheric ozone and water vapor representations will both reduce model error in the first guess fields and permit more effective assimilation of satellite radiances affected by these constituents. The improved stratospheric O3 and water vapor will also be an important contribution to foci 2 as explicit chemistry begins to be included in Earth System analyses.