Development of a Prototype High Resolution Prediction System for Precipitation, Soil Moisture and Stream Flow over North America

S. Schubert, H. Wang, R. Koster, M. Suarez, and K. Mo

Abstract

Despite considerable advances in our understanding of drought mechanisms (role of SST, land atmosphere feedbacks, etc.), there has been little improvement in drought predictions on seasonal time scales. In fact, seasonal forecast information appears to provide little additional skill to hydrologic forecasts, beyond that obtained from the initial land conditions, though some improvement can be achieved by conditioning the forecasts on ENSO.

In this proposal we seek to improve hydrologic (precipitation, soil moisture, stream flow) prediction skill on subseasonal to seasonal time scales by developing and evaluating a prototype drought prediction system that takes advantage of a number of recent advances in our modeling and understanding of precipitation variability, as well as improvements in the soil moisture initial conditions. These advances consist of:

1) New understanding of the nature and role of stationary Rossby waves in controlling summertime middle latitude precipitation and surface temperature extremes on subseasonal time scales.
2) The development of ultra-high resolution (3.5 to 14km) versions of the NASA GEOS-5 non-hydrostatic global atmospheric model capable of resolving meso-scale and other high impact weather systems.
3) The availability of multiple land models to better span the uncertainties in the predictions tied to land model uncertainty.
4) Improved soil moisture initial conditions from the assimilation of AMSR-E and SMOS data.
5) A new set of forecasts/hindcasts using the latest versions of both the NOAA/CFS and NASA/GEOS-5 coupled models that have been initialized by the latest reanalysis products (CFSR and MERRA, respectively).

In order to leverage current capabilities, we divide the prediction approach into three tiers. Tier 1 consists of the new set of medium resolution (order 100km in the atmosphere) re-forecasts being produced by the atmosphere/ocean coupled NCEP/EMC and NASA/GMAO models. We will use the Tier 1 SST to drive our high-resolution (order 10km) Tier 2 AGCM predictions, with the atmosphere and land initialized from the MERRA reanalysis. We will also statistically downscale the Tier 1 atmosphere to 10km to provide a benchmark for the high-resolution AGCM predictions. The third tier consists of an ensemble of land model predictions, using atmospheric forcing (from the ensemble of tier 2 high resolution AGCM forecasts or the statistically downscaled Tier 1 predictions) and using multiple land models spun up with NLDAS forcing data. A subset of the Tier 3 ensemble members will be initialized with new soil moisture estimates obtained by the assimilation of AMSR-E and SMOS observations as they become available from the GMAO. Our deliverable is a prototype prediction system with a preliminary assessment of forecast skill. We will also work to extend the forecasts into near real time so that they could become a contribution to the NOAA/CPC drought

briefings, providing additional guidance to drought outlook forecasters, as well as, contribute to the NIDIS goal of creating an "early warning system" for drought that provides accurate, timely, and integrated information.

Assimilating Soil Moisture and Snow Products for Improved Drought Monitoring with the North American Land Data Assimilation System (NLDAS)

PI: Christa D. Peters-Lidard
Co-PI: David Mocko (SAIC at NASA/GSFC)
Co-Investigators: Sujay Kumar (SAIC at NASA/GSFC),
Michael Ek (NOAA/NCEP/EMC), and
Youlong Xia and Jiarui Dong (IMSG at NOAA/NCEP/EMC)

Abstract

Background and Objectives
The North American Land Data Assimilation System (NLDAS) has a long successful history of producing surface meteorology and precipitation datasets used as forcing for land-surface models (LSMs) to produce soil moisture, snow cover, and runoff/streamflow products. These products have been used in numerous applications for researchers both within GAPP & CPPA as well as in other communities. Real-time NLDAS products are used for drought monitoring and as initial conditions for a drought forecast system. Currently, remotely-sensed estimates of land-surface states such as soil moisture and snowpack are not assimilated into NLDAS. Therefore, the primary objective of this proposal is to support the routine assimilation of remotely-sensed soil moisture, snow-covered area (SCA) and snow water-equivalent (SWE) in NLDAS. We believe that assimilating satellite products into NLDAS will not only produce improved soil moisture profiles and snowpack states to better represent evolving conditions, but will directly improve the monitoring of drought. To accomplish our objective, we propose to implement the current NLDAS system within the Land Information System (LIS) architecture, which will allow multiple LSMs to assimilate soil moisture, SCA and SWE. Additionally, we will implement the Catchment LSM (a successor to Mosaic) as well as the latest versions of Noah, SAC, and VIC.

Brief Summary of Work to be Completed
The proposed work will include the following Tasks: 1) Benchmark and extend NLDAS data production within the latest LIS architecture, including implementation of Catchment and the latest version of Noah, in addition to (re-)producing NLDAS outputs for the 1979-present retrospective period; 2) Assimilating AMSR-E soil moisture and SWE products and MODIS SCA products into the NLDAS system for better diagnosis of drought and improvement of initial land conditions in the NLDAS drought forecast system at NOAA/EMC; and 3) Evaluate NLDAS output products and drought monitoring skill both with and without assimilation.

Relevance to Program Announcement Research Area
The proposed work will be primarily relevant to the MAPP theme #2 – Develop an Integrated Drought Prediction Capability. The improvements to the NLDAS drought monitoring and data products for the drought forecast system will be made using multiple data sources and models to objectively evaluate model and data upgrades to soil moisture, hydrology, and vegetation. The capability to simultaneously execute multi-model ensembles and assimilate soil moisture and snow products using the existing capabilities

of LIS at NCEP will represent a significant advance over the current state-of-the-art in drought assessment and prediction.

Project Title: DUAL ASSIMILATION OF MICROWAVE AND THERMAL-INFRARED SATELLITE OBSERVATIONS OF SOILMOISTURE INTO NLDAS FOR IMPROVED DROUGHTMONITORING

X. Zhan (*PI: NESDIS*), M.C. Anderson (*Co-PI: USDA-ARS*), C Hain (*NESDIS; IMSG*), M. Ek (*NCEP*),
M. Svoboda (*NDMC*), B. Wardlow (*NDMC*), W. Crow (*USDA-ARS*), J.R. Mecikalski (*U Alabama*), W.P.
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ABSTRACT

We propose to produce an operational data assimilation (DA) system for optimal integration of thermal infrared (TIR) and microwave (MV) soil moisture (SM) information and near real-time green vegetation fraction (GVF) into the Noah land-surface model component of the National Land Data Assimilation System (NLDAS). NLDAS produces hydrologic products (e.g. soil moisture, evapotranspiration, and runoff) used by NCEP for operational drought monitoring, but these products are sensitive to model input errors in soil texture (affecting infiltration rates) and prescribed precipitation rates. These types of model errors can be compensated for by periodically updating SM state variables in LSMs through assimilation of remotely sensed SM information. The work proposed here will build on a project currently funded under the Climate Test Bed Program entitled "A GOES Thermal-Based Drought Early Warning Index for NIDIS", which is developing an operational TIR SM index (Evaporative Stress Index; ESI) based on maps of the ratio of actual-to-potential ET (*fPET*) generated with the Atmosphere-Land Exchange Inverse (ALEXI) surface energy balance algorithm.

The assembled research team has demonstrated that diagnostic information about SM and evapotranspiration (ET) from MW and TIR remote sensing can significantly reduce SM drifts in LSMs such as Noah. The two retrievals have been shown to be quite complementary: TIR provides relatively high spatial resolution (down to 100 m) and low temporal resolution (due to cloud cover) retrievals over a wide range of GVF, while MW provides relatively low spatial (25 to 60 km) and high temporal resolution (can retrieve through cloud cover), but only over areas with low GVF. Furthermore, MW retrievals are sensitive to SM only in the first few centimeters of the soil profile, while in vegetated areas TIR provides information about SM conditions integrated over the full rootzone, reflected in the observed canopy temperature. The added value of TIR over MW alone is most significant in areas of moderate to dense vegetation cover where MW retrievals have very little sensitivity to SM at any depth.

Building on this work, the proposed study will develop an optimal strategy for assimilating TIR and MW SM signals into the Noah model over the NLDAS domain using the Land Information System (LIS) developed by NASA. Additionally, near real-time green vegetation fraction (GVF) data products generated in NESDIS will be ingested, replacing climatological fields currently used in NLDAS, which are not always representative of actual conditions on the ground, especially in areas suffering from drought. We propose to use relative TIR / MW skill maps developed by Co-I Hain to spatiotemporally modify error characteristics needed by the EnKF as a function of GVF.

Assimilation results will be validated in comparison with in-situ SM observations and using a data denial validation methodology. Outputs from the operational DA system will include near real-time (updated each night) maps of surface and root-zone SM, ET and runoff. Anomalies computed from these improved hydrologic products will be compared to ALEXI ESI and standard drought metrics, including the operational NLDAS output. Output will be distributed in real-time to NCEP-CPC for use in the North America Drought Briefing and to the National Drought Mitigation Center in support of the U.S. Drought Monitor.

Title: Improving seasonal drought predictions in the western USA: Developing and evaluating an ensemble snow modeling framework in the Community Hydrologic Prediction System (CHPS).

Institutions: National Center for Atmospheric Research, University of Colorado, Colorado Basin River Forecast Center, OHD
Investigators: Martyn Clark, Andrew Slater, Andrew Wood, Thomas Hopson, Ethan Guttmann, Pedro Restrepo

The predictability of hydrologic drought depends in large part on land surface memory; in particular, the capability to simulate the seasonal evolution of snow and soil moisture. The skill of seasonal drought predictions in the western USA is therefore intimately linked to the validity of hydrologic and land-surface models that are used to produce the predictions. The goal of this proposal is to improve predictions of hydrologic drought in the western USA; specifically to both improve model representations of snow processes and quantify uncertainty in snow simulations. We focus on snow because a large amount of predictability in seasonal streamflow in the western USA is derived from knowledge of the accumulated snowpack.

Our proposed research has four elements:

1) Develop and test a framework for improving model selection/specification in hydrologic modeling. This involves summarizing the different decisions regarding process selection and representation, and integrating multiple representations of all important snow processes into a common modeling framework.
2) Apply this framework to assess appropriateness of current modeling approaches, and provide recommendations on methods to improve existing snow models. Testing model hypotheses requires data that is not routinely collected in standard observing networks, and, as such, we propose to collate data from existing experimental studies. Using these data we will identify appropriate quantitative metrics to evaluate model decisions and identify a range (ensemble) of scientifically defensible model representations.
3) Quantify uncertainty in model simulations by allowing for ambiguity in the representation of different processes. Explicitly formulating the multiple working hypotheses at the level of model sub-components (rather than entire models) can mean that inter-model differences in our system provide a superior estimate of structural uncertainty than in multi-model systems that include a small number of individual models of varying complexity.
4) Incorporate these modeling approaches in the CHPS system to evaluate the value of physically realistic snow models for seasonal drought predictions. Use of flexible modeling approaches and multi-model approaches provide a thorough test of CHPS as an integrative modeling system.

This proposed project directly addresses the desired elements of the FY2011 call, specifically by (i) providing a capability to link multiple model components; and (ii) evaluating uncertainties based on model formulation.

Integrating Data Assimilation and Multi-modeling Within CHPS for Improved Seasonal Drought Prediction

(PI) Hamid Moradkhani, Portland State University
Co-PI Pedro Restrepo, OHD
(Collaborator) Andrew Wood, Development and Operations Hydrologist, CBRFC
(Collaborator) Donald Laurine, Development and Operations Hydrologist, NWRFC

Abstract

MAPP supports developing an Integrated Drought Prediction Capability that incorporates research advances into operational intraseasonal to interannual climate and hydrologic prediction by means of multiple data sources and models, land-surface and hydrologic modeling, and data assimilation. Improved long-range hydrologic drought forecasts can help to mitigate drought impacts-they provide guidance to agencies responsible for water allocation, water conservation, and the mitigation of other adverse impacts such as wild land fires. With respect to drought characterization and prediction, the U.S. Drought Monitor (DM) and the NOAA Climate Prediction Center's (CPC) US Drought Outlook (DO), are the primary operational tools available to water managers charged with dealing with drought contingencies. However, both the DM and DO depend on a range of tools from simple statistical indices to water balance models driven by statistical forecasts.

Remote sensing-based real-time snow extent fields can, in some regions, help characterize one of the key components used to define drought, which is critically important for identifying conditions that could flicker seasonal droughts. In operational forecasting, however, consideration has been given to methodologies that include coupling both multiple climate and multiple hydrological models, increasing the pool of streamflow forecast ensemble members and accounting for cumulative sources of uncertainty. Here, we propose a three-year collaborative research project that will quantify and reduce the major uncertainties involved in drought forecasting by implementing state of the art of land data assimilation methods and Bayesian multi-model combination in the context of seasonal hydrologic forecast system. We will focus in particular on those observed variables that have been shown to have the greatest potential for improving hydrological forecasts in the western U.S., specifically in situ observations of Snow Water Equivalent (SWE); remotely sensed observations of Snow Cover Extent (SCE) from MODIS and streamflow from USGS gauges. We will also investigate, on a more local basis, the potential for assimilation of in situ soil moisture from the USDA SCAN network given the difficulty and inaccuracy in using remotely sensed soil moisture fields for the western US.

The system we propose will use Community Hydrologic Prediction System (CHPS) as the framework to incorporate hydrologic and land surface models developed over the last three decades with methods of improving hydrologic initial conditions (i.e., land data assimilation) and its integration with Ensemble Streamflow Prediction (ESP) which are the key aspects of the proposed research. This proposal, which is a

collaboration of Hamid Moradkhani at Portland State University (PSU) with Andy Wood at CBRFC and Donald Laurine at NWRFC responds to the second area solicited on the MAPP Information Sheet "*Develop an Integrated Drought Prediction Capability by incorporating research advances in climate prediction, land-surface and hydrologic modeling, and data assimilation*". It will integrate past CPPA-funded research by the PI and others in the development and application of drought forecasting. In particular, project benefits from the participation of development and operation hydrologists at two RFCs to ensure the transition of research to operation in the western US with the transformable potential to other regions. Summary of work to be completed include the following tasks: **1)** Establish domains for retrospective analysis. To limit the data volumes involved in proposed analyses, sub-basins or sub-regions of the domains will be identified. Criteria to be considered will include the availability of the observed verification datasets and the presence of drought; **2)** Gather and pre-process in situ and historical remote sensing datasets. For the domains identified in Task 1, the necessary remote sensing products will be processed into convenient form for analysis and archived for further analysis; **3)** Set up each hydrologic model for the study domains and implement the advanced model calibration to ensure the suitability and effectiveness of each model for further analysis; **4)** Implement ensemble data assimilation to quantify the uncertainties associated with the land surface initial condition required for 1-12 months ensemble streamflow prediction; **5)** Develop the multi-model ensemble combination of hydrologic forecasting for both soil moisture and streamflow; **6)** Conduct retrospective assessment on the hydrologic/drought prediction skills using single and multi-modeling as developed in Tasks 4 and 5; **7)** Incorporate the framework within the newly developed operational Community Hydrologic Prediction system (CHPS).

Title: Implementation of the Noah land surface model upgrades in the NCEP Climate Forecast System
Institution: EMC/NCEP/NOAA
Co-Principal Investigators: Michael Ek and Jesse Meng
EMC/NCEP/NOAA
Co-Investigator: Rongqian Yang, EMC/NCEP/NOAA

The objective of this proposal is to transition and infuse the recent developments of the Noah land surface model into NCEP operation to improve the skill and reliability of NCEP seasonal climate predictions of precipitation, temperature and land-surface hydrological variables, such as soil moisture, runoff and snowpack. The improvement in prediction skill is to be accomplished by means of improved representation of land surface processes and land-atmosphere interactions in the NCEP operational global and regional climate prediction systems, including their companion land data assimilation systems.

The scientific basis for this objective is that climate predictability on intraseasonal to interannual time scales is largely determined by slow variations of the ocean and land surface states. This proposal aims to improve the understanding and modeling of land surface processes through a focus on better understanding of land-atmosphere interactions and related hydrometeorological physics. Upgrades in the Noah land surface model, coupled to the NCEP Climate Forecast System, will be the parameterizations for cold season snow processes, surface thermal roughness, groundwater and runoff, vegetation canopy layer, and dynamic vegetation.

To achieve the above objective, this proposal will establish explicit interfaces between internal NCEP operational climate prediction model developers and external academic researchers, in particular those who received funding from the NOAA Climate Program Office, to facilitate the transition from research to operation. Specifically, to transition those tested, proven, CPO funded research projects to NOAA operations.

Title: Enhancement of high resolution hydrological modeling on the CONUS HRAP grid using operational NOAA NCEP and NOAA OHD models
Institutions: OHD/NWS/NOAA, EMC/NCEP/NOAA, and CPC/NCEP/NOAA
Principal Investigators: Brian A. Cosgrove (OHD) and Jiarui Dong (EMC)
Co-Investigators: Michael Ek (EMC) and Kingtse Mo (CPC)

This proposal centers on supporting NOAA/NCEP's, NOAA/OHD's, and NOAA/CPC's operational hydrological and land surface modeling missions, as well as furthering their support of the NOAA Hydrology Test Bed, the NOAA Climate Test Bed, and the National Integrated Drought Information System (NIDIS). New capabilities resulting from this joint NOAA NCEP/OHD/CPC effort will allow for the execution of *enhanced* Noah and Sacramento Heat Transfer (SAC-HT) models on the 4km HRAP grid over the Continental United States (CONUS). Enhancements will impact all stages of modeling operations and will include improved downscaled forcing data, spin-up strategies, data assimilator modules, model physics, and model validation procedures, and will enable national runoff routing of both Noah and SAC-HT output. Additionally, for the National Integrated Drought Information System, this research will yield 31-year high-resolution model climatologies in support of the monitoring and prediction of drought and other hydrologic variables.

The proposed work will leverage forcing data from the North American Land Data Assimilation System which features a 1/8th degree spatial resolution, and topography that differs significantly from that which will be used in the proposed 4km modeling effort. As such, we will apply a novel lapse-rate-based elevation adjustment scheme to downscale the NLDAS forcing to the 4km HRAP grid. As the lapse rate has been found to vary significantly in space and time, we further propose to find a proxy to quantitatively predict the variations of the lapse rate.

Accurate initialization of land surface and hydrological models is critical for correct hydrological predictions, because the process of a model adjusting to its forcing can severely bias land surface simulations. We propose to make a thorough investigation and develop a technique to generate optimal initial conditions for the 31-year (1979-2009) 4km Noah and SAC-HT retrospective simulations and to provide guidance for realtime simulations.

Complementing the forcing and spin-up work described above will be improvements to the models' data assimilation modules. We will design and test several innovative data assimilation techniques for ingesting the MODIS snow cover area observations into the SAC-HT/Snow17 and Noah models. The proposed algorithm is superior to existing methods in that it (i) uses the traditional bisection method to study the inverse of the usual problem by finding the SWE which optimally matches the MODIS-derived SCF observations, (ii) incorporates improved error estimates for snow observations, and (iii) dynamically propagates estimated model error for snow states within a Kalman filtering framework. Results will be compared with existing analysis products and validated using ground based measurements.

The final aspect of this research centers on the CONUS-wide testing in NASA's Land Information System (LIS) of SAC-HT, Snow17, and Noah model physics and parameter improvements. Two recent improvements in SAC-HT will be extensively evaluated: 1) Incorporation of Noah's evapotranspiration physics, and 2) Improvement of sub-surface runoff modeling. OHD's Snow 17 model will benefit through imtegratopm of a new dynamic parameterization scheme which will negate the need to manually derive many of the model's parameters. Similarly, a suite of Noah LSM improvements will be integrated and assessed including a new snow albedo scheme, a canopy conductance formulation, a surface flux formulation. Both models will benefit from incorporation into LIS of OHD's streamflow routing module. Together, the proposed improvements will greatly enhance the operational and research modeling capabilities of NOAA/NCEP and NOAA/OHD, as well as the numerous research groups who make use of these publically available models.

Title: Improving land evaporative processes and land-atmosphere interactions in the NCEP Global Forecast System (GFS) and Climate Forecast System (CFS).
PI and institution: Eric Wood, Princeton University.
Co-PI and institution: Michael Ek, NCEP EMC.
Co-I and institution: Justin Sheffield, Princeton University.

Introduction to the Problem: Surface evapotranspiration is often considered *the* climate linchpin variable because it forms the bridge across the water, energy and carbon cycles. Evaporation plays a central role in coupling the land and atmosphere, and operates over fast (diurnal) and slow (seasonal) time scales. Evaporation from water bodies, vegetation intercepted precipitation or soil surfaces, and transpiration from plants combine to return available water at the surface layer back to the bulk atmosphere in a process referred to as evapotranspiration (ET). Controls on terrestrial ET are particularly complicated and are constrained by the surface radiation, the state of the vegetation-soil system, or the atmospheric boundary layer and its surface meteorology. Accurately modeling terrestrial evapotranspiration processes, including land-atmospheric coupling and recycling, is fundamental to climate predictions and projections. Errors in ET directly cascade through the water, energy and carbon cycles at all time scales. The goal of the proposed project is to analyze, evaluate and improve land evaporative processes in the Noah land surface component of the NOAA National Centers for
Environmental Prediction (NCEP) Global Forecast System (GFS) and Climate Forecast System (CFS) that will directly lead to improved climate predictions in these and other NCEP models. The focus of the project is on warm season terrestrial evaporative processes that include free evaporation from water bodies and canopy intercepted precipitation, evaporation of soil water, and transpiration by vegetation.
All of the above processes are parameterized separately in the GFS/CFS but collectively considered as ET or, in its energy form, latent heat flux.
Rationale: Over the last ten years a significant body of research has shown that little agreement exists among climate models in their simulations of land evaporative fluxes, even for current 20th C climate.
Analyses of land-atmospheric coupling, as measured by metrics like the inferred lifting condensation level (LCL), show wide disparity from weak to extremely tight coupling. Careful assessments of the parameterizations that control vegetation response to soil drying show that values being used are inconsistent with vegetation characteristics and provide unrealistic responses. Collectively, analyses to date show that climate models do a poor job in representing land evaporative processes. Given the central role of evaporative processes in the climate system, resolving these inadequacies is extremely relevant to improvements in climate models. Recent years have seen advancements in the analysis of evaporative processes (especially in the understanding of how surface heat fluxes couple to the boundary layer), in measuring land evaporative fluxes through eddy correlation techniques from towers under the AmeriFlux (and globally the FluxNet) initiatives, and in measuring atmospheric and surface properties from spaceborne sensors. These and other advances will be used to analyze and evaluate the land evaporative processes in the NCEP climate models and to develop improved parameterizations.

Summary of work to be completed: *1. Data set selection and compilation* of the in-situ flux tower and remote sensing data sets for long-term flux tower sites that represent a range of climates and vegetation types for the modeling and diagnostic analyses. *2: Generation of off-line and coupled climate model runs* using the Noah off-line version of the NCEP land surface scheme using forcing data for the tower sites and extending existing GLACE-2 hindcasts to nearer realtime. *3. Diagnostic analyses of off-line and coupled runs* of evaporative processes using metrics of land contribution to climate prediction skill and land-atmosphere coupling. *4. Model experiments for assessing process deficiencies*. *5. Developing and testing new ET parameterizations* including calibration of existing parameterizations, inclusion of canopy physiology models, sub-grid scale soil moisture variations, prognostic canopy airspace parameterizations, and improved canopy interception.

Proposal Title: Seasonal Prediction for Ecosystems and Carbon Cycle Using NCEP/CFS and a Dynamic Vegetation Model
Institution: University of Maryland, College Park
Principal Investigator: Ning Zeng**; Co-PI:** Eugenia Kalnay
NOAA Collaborator: Arun Kumar (NCEP/CPC)

Abstract

In recent years, many advances have been made in the science and practice of seasonal climate predictions. For example, seasonal climate predictions have attained operational status and have come to rely increasingly more on dynamical prediction models. Such advances notwithstanding, application of seasonal climate outlooks to applications of societal importance has been slow to materialize. The aim of this proposal is to develop one such application, i.e., *a capability to forecast terrestrial ecosystem productivity and carbon sources and sinks on seasonal-interannual time-scale*. The modeling system is global, but the focus of validation and application will be for North America.

The development of an outlook capability for the ecosystem will rely on several components that have evolved following independent pathways and have reached a state of maturity in their respective domains of interest. The key effort of this proposal will be bringing together these modeling and prediction component systems.

The modeling components of the proposed predictive capability include:

1. A dynamic Vegetation-Global-Atmosphere-Soil (VEGAS) model with full terrestrial carbon cycle
2. Operational climate forecasts at the Climate Prediction Center and dynamical seasonal forecasts based on the Climate Forecast System (CFS) (both at NCEP)

Specific tasks under the proposal will include (and will build upon a prototype carbon cycle prediction already in place):

- Developing a procedure to specify vegetation and soil initial conditions derived from some form of data assimilation system
- Developing procedures to forecast ecosystem and carbon variables using ensemble climate prediction information from CFS
- Validation of prediction system based on hindcast skill by comparing model predictions against a suite of observed variables such as satellite vegetation index, CO2 flux measurements, and assimilated carbon fluxes
- Comparison of the CFS based skill with other baseline estimates of skill for predicting eco-carbon variables, e.g., prediction based on operational CPC forecasts
- Testing the prediction system in a real-time operational setting, getting feedbacks from a wider community, improving the system.

Deliverable of this project will be a seasonal forecasting system for terrestrial ecosystem productivity and carbon fluxes that later will be transitioned to operations using the Climate Test-Bed (CTB) infrastructure.

Title: Collaborative Research: Enhancing operational drought monitoring and prediction products through synthesis of N-LDAS and CPPA research results

PIs and Institutions: Eric F Wood (efwood@princeton.edu), Princeton University
Dennis P. Lettenmaier (dennisl@u.washington,edu), Univ. of Washington

Budget Period: May 1, 2010 – April 30, 2013 (3 years)

Drought has had tremendous societal and economic impacts on the United States. In April 2003 the Western Governors in partnership with NOAA initiated planning for a *National Integrated Drought Information System (NIDIS*), which was implemented by Congress with NOAA as the lead agency. The NIDIS concept is that drought management should be risk-based, and aimed at better quantitative monitoring, early warning and prediction. The NOAA Climate Test Bed (CTB) was established "*To accelerate the transition of scientific advances from the climate research community to improved NOAA climate forecast products and services"*. Studies over the last two decades have demonstrated the feasibility of making useful seasonal climate predictions, with the expectation that associated outlooks and forecasts can contribute to seasonal hydrologic and drought prediction capabilities. Developing a seasonal hydrological and drought forecasting capability has been the goal of the NOAA Climate Program Office's (CPO) Climate Prediction Program for the Americas (CPPA) through its research support to external investigators, including the PIs, and CPPA's Core Project funding to NCEP's Environmental Modeling Center (EMC) and the NWS Office of Hydrologic Development (OHD) in support of the North American Land Data Assimilation System (NLDAS). We propose herein to transition, in cooperation with EMC and the NOAA Climate Prediction Center (CPC), advances in seasonal hydrological and drought forecasting made at Princeton University and the University of Washington to the CTB. This constitutes a critical next step in enhancing CPC's operational drought prediction capabilities. This proposal responds to priority area 3 of the FY 2010 CTB Information Sheet: *Enhancing Operational Drought Forecast Products and Applications*. Operationally, CPC provides leadership in drought assessments within NOAA by providing drought outlooks and monitoring through its contributions to the National Drought Monitor (DM) and its Seasonal Drought Outlook (DO).

Current procedures underlying the DM and DO rely on a suite of information that includes primarily qualitative evaluations of current hydrologic and agricultural conditions, combined with (in the case of the DO) seasonal climate forecasts. CPC would like to transition to *objective* drought monitoring and prediction approaches. EMC, through funding from CPPA. has executed pilot demonstrations of a multi-model hydrological drought monitoring system based in substantial part on approaches developed by the PIs and implemented in experimental systems at the PIs' institutions, e.g. the University of Washington National Surface Water Monitor. Both PIs have participated extensively in adaptation of CPPA-funded research to these EMC pilot demonstrations.

The proposed project will transition the multi-model seasonal hydrologic and drought monitoring and prediction capabilities developed by the PIs and EMC to the CTB. These existing pilot systems use procedures developed by the PIs that bias correct and downscale seasonal forecasts from CFS dynamical forecasts and CPC official outlook products, as well as simpler methods that resample from climatologies. NLDAS products are used to provide initial conditions for the hydrological and drought predictions as well as real-time monitoring of drought. Overall, these activities have demonstrated that the systems are now sufficiently mature to merit a more rigorous, robust and continuous execution and evaluation via the Climate Test Bed (CTB). We will work closely with our EMC and CPC collaborators to implement a drought monitoring and prediction system in the CTB. Testing and evaluation of the system will utilize the NIDIS Southeast testbed, with special attention to the Savannah and Apalachicola-Chattahoochee-Flint River basins, the latter of which is the water supply source for Atlanta, which has been particularly prone to drought in recent years.

Multi-Model Ensemble Combination and Conditional Stochastic Weather Generation Tool for Improved Streamflow Forecast

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Skillful basin wide streamflow forecasts at short (1-2 weeks) and long (seasonal and longer) time scales are important for efficient water resources management. This is particularly so in the Western US, which is semi-arid and its limited water resources are stressed due to unprecedented socio economic growth. The skillful ensemble hydrologic forecasts require (i) skillful hydrometeorological outlooks, (ii) suite of models – physical and statistical that captures the physical and climate features of the basin and provide ensemble forecasts conditioned on the outlooks and, (iii) an optimal combination tool. The outlooks have to be based on the short term weather forecasting information from NOAA/NWS and the seasonal climate forecast from NOAA. Current forecasts are provided by River Forecasting Centers based on a single physical model with limited ensemble generating capability and recent research suggests that a multimodel ensemble forecasting approach provides enhanced skills in the forecast than any single model. To this end this research proposes to develop two key tools - (i) a conditional stochastic weather generator to provide daily weather ensembles based on the NWS short term and NOAA seasonal outlooks and in-situ data including land surface observations to drive the RFC's physical model to provide ensemble streamflow forecast and, (ii) an optimal multi-model ensemble combination to provide a combined ensemble forecast from physical and statistical models. We will demonstrate the framework by applying it to the Upper Colorado River Basin. The forecasts in this basin are critical for efficient operation and management of major reservoirs and consequently, the impacts on water resources, agriculture, hydropower and aquatic environment in the South Western and Inter mountain region of Western US.

Approach Proposed

The work we propose will involve the following streams:

(1) Development of tools to "translate" short term and seasonal forecasts from NWS and NCEP, respectively, to basin scale ensemble hydrometeorological forecasts.

(2) Drive the physical model with the hydrometeorological ensembles to obtain ensemble streamflow forecasts.

(3) Develop a multi-site statistical ensemble streamflow forecast model

(4) Develop an optimal combination tool to combine these and other available forecasts to provide a multi-model ensemble forecast.

(5) Work with the water managers (USBR) in the basin to implement these forecasts for operations and management.

A framework for improving land-surface hydrologic process representation in CLM over California

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Budget Period: May 1, 2010 to April 30, 2013

PROPOSAL SUMMARY

To address the Climate Prediction Project for the Americas (CPPA), formerly known as the Global Energy and Water Cycle Experiment (GEWEX) American Prediction Project (GAPP) research priority: "**Climate-based hydrologic and water management applications at regional scales**," this proposal has selected California as a data-rich, high population, and scientifically productive study region.

California's wdater supply systems are straining to keep up with economic growth and urban development. The groundwater resource—which accounts for 30-40% of the water California uses -- is diminishing at a rate of millions of acre-feet per year. The state has experienced two major droughts and three major floods since 1980's, and California continues to grow and build. Combined, these regional changes pose an urgent need for accurate models and reliable predictions of key hydrologic processes of regional climate change and guidance for California's water management responses.

The UC Irvine Center for Hydrometeorology and Remote Sensing (CHRS) proposes to respond specifically to the call for "Efforts of development and improvement of integrated (i.e., coupled snow, surface water, soil moisture and groundwater) hydrologic models…data assimilations, model evaluations against high-resolution datasets, and parameterization of water management (e.g. irrigation, reservoir storage, and release, groundwater withdrawal etc.) for use in basin- to continental-scale models." To address this challenge, proposed integrated hydrological models would include: 1) a remote sensing satellite-based snow model, 2) a modified Community Land Model (CLM) Land Surface Model (LSM),
and 3) a two-dimensional MODFLOW (The USGS Modular ground-Water Model—the Ground-Water Flow Process). In addition to simulating the basic hydrologic processes, these coupled models will aim specifically to improve estimations of interactive mechanisms: snow cover and Snow Water Equivalent (SWE) estimation using in-situ and satellite data; the partition of snow water into runoff, soil moisture and groundwater recharge; parameterization of seasonal irrigation and groundwater pumping over the state, and groundwater discharge/recharge to/from river flows.

Among only a few U.S. states that have accumulated decades of ground-based water records, California maintains extensive networks for regular hydrological measurements. Taking advantage of California's wealth of historical and current data, we propose to use long-term data for model parameter calibration and sequential data assimilation techniques to substantially improve model performance.

Calibrating model parameters using information from long-term observations will optimize values for key model parameters, reducing model uncertainty. The sequential data assimilation technique—the Sequential Bayesian Filter with Monte Carlo

implementation (SBF-MC) will integrate near real-time hydrological measurements from satellites (e.g. top layer soil moisture) and/or ground sites (e.g. stream gauge data and groundwater well monitoring) to both improve the predictions of model state variables and quantify prediction uncertainty.

Title: Atmosphere-Land Coupling and the Predictability of North American Drought
Institution: University of Miami, Rosenstiel School of Marine and Atmospheric Science
Investigators: Benjamin Kirtman (PI), Robert Burgman (Co-PI), Brian Mapes (Co-PI) and Chidong Zhang (Co-PI).
Budget Period: May 1, 2010 to April 30, 2013

Abstract

The proposed research is based on the hypothesis that the predictability of persistent large-scale drought is due the competition among three processes:
(i) The nature of local coupled atmosphere-land feedbacks (i.e., strength, growth rate, saturation)
(ii) The predictability limiting affects of atmospheric noise or stochastic forcing
(iii) The remote forcing from low frequency global SST variability (e.g., AMO, PDO, NPO…).
We propose to test this hypothesis through a series of modeling experiments that isolate the relative importance of coupled atmosphere-land feedbacks vs. atmospheric stochastic forcing vs. remote SST forcing. These experiments include using the novel interactive ensemble coupling strategy (Kirtman and Shukla 2002) previously used to isolate coupled ocean-atmosphere feedbacks vs. atmospheric stochastic forcing, extended to the problem of atmosphere-land interactions. Part of our modeling strategy builds on the success of the US Clivar drought WG (http://www.usclivar.org/Organization/drought-wg.html) and the international Global Land-Atmosphere Coupling Experiment (GLACE) by explicitly leveraging their experimental protocol. We have chosen to focus on the question of North American drought because of its societal importance to US interests; however, the approach is equally applicable to terrestrial hydro-climate predictability on multiple space and time scales throughout the globe.

Title: Quantification and reduction of uncertainties in projections of climate impacts on drought and agriculture for North America
PI and institution: Justin Sheffield, Princeton University.
Co-PI and institution: David Lobell, Stanford University.

Introduction to the Problem: Agricultural productivity is highly dependent on climate variability and is thus susceptible to future changes including temperature extremes and drought. The latter is expected to increase in frequency regionally over this century. However, the uncertainty in projections of drought and its impacts on agriculture is high due to emission scenarios, climate model differences, uncertainty in initial/boundary conditions, and translation to regional scales.
Climate models are unanimous in projecting future warming but differ in the magnitude and even sign of regional precipitation changes. They also differ in terms of extremes of temperature, precipitation and other meteorology. When projecting future impacts on crop productivity, these uncertainties are compounded because current crop models often use simplified treatments of climate response and do not include comprehensive treatments of water availability. Therefore, projections of regional climate change, variability and its impacts on water availability and agriculture are highly uncertain and reduction of uncertainties requires attention to all levels in the climate-water-agriculture continuum.

Rationale: Given the uncertainties in future agricultural production and the complex relationships between climate, hydrology and crop development, there is pressing need to make improved estimates of future changes in climate change and crop yields. ***We propose to evaluate the uncertainties in estimates of future changes in climate, water availability and agricultural production, and make improved estimates by incorporating state of the art knowledge of the relationships between climate, hydrology and agriculture into modeling and downscaling.***
This has ramifications for disaster preparedness and mitigation, policy making and the political response to climate change, and intersects with fundamental science questions about climate change, extremes and hydrologic cycle intensification. It is central to the mission of the Climate Program Office's MAPP program to "enhance the Nation's capability to predict variability and changes of the Earth's System" and directly addresses its priorities to evaluate and reduce uncertainties in climate projections. This work will leverage from the PIs' experience and ongoing activities in large-scale climate analysis and hydrologic modeling, particularly in changes in drought historically and under future climates, and agricultural modeling and relationships between climate and crop productivity.

Summary of work to be completed: 1. Quantify the relationships between hydroclimate variables and the implications for water, drought and agriculture based on observational data. 2. Evaluate sensitivities of hydrologic and crop models to changes in climate and drought. Differences in climate variability, land-atmosphere coupling and hydrologic persistence will lead to differences in key metrics of water and agriculture which will form the basis for evaluation of the uncertainties in future projections. 3. Evaluate current climate models in how they replicate these observed relationships using the CMIP5 long-term and decadal predictions. 4. Estimate uncertainties in future projections of climate, drought and agriculture using a cascade of climate, downscaling, hydrologic and crop models with strategic sampling to decompose sources of uncertainty. 5. Implement a set of methods to reduce uncertainties in future projections based on observational constraints including merging of climate model predictions, bias correction and scaling of climate model output, and improvements to impact models.

Including the Impacts of Forest Disturbances in Western North America in Climate Models

Fei Chen, NCAR
2009

Abstract: Forest structure plays a major role in forest hydro-climate through its impact on interception, surface radiation budgets, precipitation, soil moisture, evapotranspiration, snow accumulation and ablation, and subsequent runoff. Over the past decade, warming, severe drought periods, and dense forest conditions have resulted in unprecedented levels of forest mortality from bark beetle outbreaks and wildland fires across the western mountain regions of North America. These natural disturbances (insect infestation and wildland fire) significantly alter the physical and physiological properties (e.g., albedo, emissivity, roughness length, canopy resistance) of forests, and therefore affect land-atmospheric exchange, boundary layer structure, snow accumulation and ablation, and cloud characteristics and precipitation. Despite large disturbance areas, however, these physical processes are not represented in current regional and global climate models. The proposed study will combine field observations, remote sensing imagery, and modeling to a) improve the understanding of changes to physical and physiological properties following bark beetle outbreaks and wildland fires, b) include changes in these variables in regional climate models, and c) assess impacts on atmospheric and hydrologic processes. We will first quantify recovery trajectories of biophysical variables following natural disturbance. These findings will be utilized to improve representation of disturbances in the Noah land surface and the coupled Weather Research and Forecasting (WRF)-Noah regional climate models. We will then assess the effects of these disturbances in western forests on intraseasonal to interannual climate variability, focusing on warm season transport of heat and water vapor, and precipitation, and on cold-season snow accumulation, melt, and runoff. Specifically, we will:

1. Collect field observations and remote sensing data for the last ten years over the western mountain regions in North America (primarily focusing on US and Canada).
2. Analyze these data a) for model evaluation and b) to assess the recovery of physical and physiological parameters important for land surface modeling in forested regions following bark beetle outbreak and wildland fire.
3. Use the Moderate Resolution Imaging Spectroradiometer (MODIS) fire products to identify areas impacted by fire, and develop new MODIS-based products to detect tree mortality caused by bark beetle epidemics.
4. Improve the presentation of these disturbances in the Noah land surface model through the use of more accurate land cover data and incorporation of modified model parameters and physical processes.
5. Perform 10-year uncoupled simulations to quantify the impacts of affected forests on surface exchange of heat and water vapor, precipitation, snow accumulation, and runoff, and evaluate simulations with observations.
6. Conduct ensembles of regional climate simulations with the enhanced WRF/Noah coupled model for selected years to investigate the impacts of the improved realism in representing the modified forest structures on intra-seasonal to interannual climate

variability. Our study will be the first to 1) quantify the effects of natural disturbances on biophysical properties over large areas, 2) incorporate these impacts into land surface and regional climate models, and 3) assess impacts on intraseasonal to interannual climate variability.

The Role of Surface, Subsurface, and Vegetation Processes on Droughts

Ruby Leung, Battelle, Pacific Northwest Division; Xu Liang, University of Pittsburgh

2009

Abstract: Drought is a recurrent feature in many parts of the U.S. Multi-year droughts, in particular, are very devastating and costly. Previous studies have suggested that droughts are initiated by seasurface temperatureanomalies that induce changes in the atmospheric circulation, and hence moisture transport and precipitation.

However, some studies have also suggested that once a drought is initiated, it may be prolonged or strengthened by regional scale land-atmosphere feedbacks. Because of the inherent longer time scale, both surface and subsurface processes may be particularly relevant for multi-years and decadal droughts. To realistically represent landatmosphere interactions, and their influence on droughts, we need to consider surface, subsurface and vegetation processes as an integrated system. We propose to focus our investigation on processes that are closely related to evapotranspiration and soil moisture, including: (1) hydraulic redistribution (also called hydraulic lift), (2) plant water storage, (3) dynamical interactions between regular/deep roots with the varying groundwater table and root growth during dry periods, and (4) response of plant phenology to drought. We hypothesize that plants modulate droughts at the initial stage through hydraulic redistribution by roots, root growth, and changes in water storage to tap moisture in the deeper soil layers or groundwater table, and stomatal response to maintain transpiration. However, when the groundwater table falls below a critical level, droughts can be intensified and sustained as plants and surface processes become decoupled to subsurface processes such that reduced surface soil moisture and plants transpiration accelerate the drying through land-atmosphere interactions.

To test this hypothesis, we propose model development to include the effects of hydraulic redistribution and plant storage in the transpiration process, and integrate these effects with a stomatal conductance representation that explicitly considers the dependence of the net rate of photosynthesis and water use. We will also develop a simple plant model of seasonal leaf growth and root growth, and implement these developments in the Variable Infiltration Capacity (VIC) model, which already includes a dynamic representation of groundwater table, and to couple VIC with the Weather Research and Forecasting (WRF) model to simulate land-atmosphere interactions. Offline and coupled simulations will be performed to test our hypothesis, and to investigate the potential impacts of land use change and CO2 on modifying the ability of vegetation to cope with droughts and influence droughts.

This proposal is responsive to the CPPA solicitation to investigate the predictability and mechanisms of droughts, with a particular focus on the role of local land surface interactions on the maintenance and amplification of droughts. The model development efforts proposed here will benefit NOAA as WRF is the primary mesoscale forecast model in operational use at NCEP/EMC, and will likely also be used for operational/experimental seasonal climate forecast at the regional scale.

The Use of Retrospective Hydrologic Forecasts for Forecast System Improvement Using Hydrologic Forecast Verification Concepts

Allen Bradley and Anton Kruger, University of Iowa; Stuart S. Schwartz, University of Maryland Baltimore County

2009

Abstract: Long-range hydrologic forecasts on climate time scales, either from the National Weather Service (NWS) Advanced Hydrologic Prediction Services (AHPS), or as envisioned for nation-wide hydrologic outlooks, have significant potential use in water supply and drought management. But as is evidenced by recent research, advances in translating skillful climate information for hydrologic forecasting can only be achieved with a suitable archive of retrospective climate forecasts; such data sets provide an objective means for evaluating and correcting both the biases that exist in existing climate forecast products, and the inherent mismatch in scales between dominate climate and hydrologic processes. Likewise, for any long-range hydrologic forecasting system to be useful for water resources management, the generation and archival of retrospective hydrologic forecasts must be an integral component of the forecasting system.

The objective of this project is to develop tools and techniques to use archives of retrospective hydrologic forecasts for systematic evaluation and improvement of long-range hydrologic forecasting systems for water resources applications. This will be accomplished by using previously developed capabilities for retrospective forecast generation with the NWS River Forecasting System (NWSRFS), and extending the scope and structure of the AHPS Verification System (AHPS-VS), a prototype system under development at IIHR, to (1) develop a broad suite of summary diagnostic verification measures suitable for evaluating and identifying forecast deficiencies on a regional or national scale, (2) develop optimal ways (based on Bayesian updating) to combine information from archive retrospective forecasts, with ensemble predictions of the operational system, to generate more skillful hydrologic ensemble products, and (3) develop methods to quantify improvements from changes to forecast system components based on rigorous statistical hypothesis testing. This work will build on our collaborations with the RFCs and the NWS Office of Hydrology, and is aimed at their goal of implementing the forecast improvement cycle paradigm within an operational hydrologic forecasting setting.