Land-Hydrology Modeling at NCEP

Michael Ek[1]*, Jesse Meng[1], Rongqian Yang[1], Helin Wei[1], Vince Wong[1], Youlong Xia[1], Yihua Wu[1], Weizhong Zheng[1], Jiarui Dong[1], and Sid Katz[2]

NOAA (National Oceanic and Atmospheric Administration) Science Center
National Weather Service (NWS)
National Centers for Environmental Prediction (NCEP)
5200 Auth Road, Room 207, Suitland, MD 20746 USA

[1]Environmental Modeling Center (NCEP/EMC)
[2]Climate Prediction Center (NCEP/CPC)
**michael.ek@noaa.gov*

Abstract

We describe the land-hydrology modeling program and associated use of the Noah land-surface model and its development at the National Centers for Environmental Prediction.

1. Introduction

The land-hydrology program at NCEP is focused on use of the Noah land-surface model which provides bottom boundary conditions for NCEP weather and climate models, for short-term regional (North American Mesoscale, NAM), to medium-range global (Global Forecast System, GFS) and seasonal climate (Climate Forecast System, CFS) forecasting. Additionally, the Noah land model is used in an uncoupled mode driven by atmospheric forcing (from observations and/or model output), in the regional setting of the North American Land Data Assimilation System (NLDAS, which also includes other partner land models), and in the global setting of Global LDAS (GLDAS). Related activities involve development of ancillary files and model code, i.e. initial land states, land parameter files and data sets, and surface-layer turbulent exchange; data assimilation systems and techniques; and participation in relevant Global Energy and Water Cycle Experiment (GEWEX) and other programs. Some research is also sponsored by external sources with the goal of transition to NCEP operations, i.e. the NOAA Climate Program Office/Climate Prediction Program for the Americas (CPO/CPPA) for N/GLDAS-related and seasonal climate studies, and the Joint Center for Satellite Data Assimilation (JCSDA; www.jcsda.noaa.gov) for land data sets and land data assimilation.

The Noah land-surface model is computationally efficient and of intermediate complexity. Taken from the original Oregon State University (OSU) land model (Pan and Mahrt, 1987), the Noah model uses a Jarvis-Stewart canopy conductance approach, and a linearized (non-iterative) solution to the surface energy balance; it carries multiple soil layers with predicted states of soil moisture and temperature (using soil moisture diffusion and heat conduction equations, respectively) along with intercepted canopy water (see Chen et al 1996, Ek et al 2003). The Noah model is formulated with a single-layer snowpack (with snow density) and frozen soil physics (Koren et al 1999), and includes the effect of snow cover patchiness on surface fluxes. The infiltration scheme includes subgrid variability of precipitation runoff and soil moisture (Schaake et al 1996). Surface exchange coefficients (and thus surface fluxes) are determined via the surface layer parameterization described Chen et al (1997). (See: www.emc.ncep.noaa.gov/mmb/gcip.html)

Noah model physics upgrades generally (but not always) start with site-specific offline (1-D) model testing (e.g. at flux measurement sites), followed by testing in the uncoupled NLDAS (regional) and sometimes GLDAS (global) settings, with transition into the coupled model systems at NCEP, often first in the NAM (regional) model, then transition to the medium-range (GFS), and finally to the global climate setting (CFS). Throughout these stages of testing, various metrics are used in model evaluation in order to deem the Noah model upgrades as positive, and allow implementation in NCEP operational models.

Noah land model development is ongoing with a number of research partners within the unified-Noah-model, NLDAS, and JCSDA-land working groups, e.g. at the National Center for Atmospheric Research (NCAR, F. Chen et al) with upgrades to the NCEP-NCAR unified Noah model coupled to the mesoscale Weather Research and Forecasting (WRF) model (www.ral.ucar.edu/research/land/technology/lsm.php), University of Arizona (X. Zeng et al) on surface-layer formulations, snowpack physics and related data sets, University of Washington (D. Lettenmaier et al) on snowpack physics, National Aeronautics and Space Administration (NASA Goddard/Hydrological Sciences Branch, C. Peters-Lidard et al) on use of the NASA/Land Information System (LIS) for parallelized code, re-scaling, land data assimilation, etc, and University of Texas (Z.-L. Yang et al) for the Noah-MP (Noah model with multi-physics options) which includes major new components such as a multi-layer snowpack, dynamic vegetation, carbon fluxes, and groundwater.

2. Uncoupled Land-Hydrology Modeling

2.1. North American Land Data Assimilation System

The North American Land Data Assimilation System (NLDAS)-phase 2 is an extension of the multi-institution NLDAS-phase 1 pilot project (Mitchell et al 2004), and is a cooperative project with NASA/Goddard/HSB, Princeton University, University of Washington, NOAA/NWS Office of Hydrologic Development (OHD), and other researchers and NOAA CPO/CPPA partners. NLDAS consists of four land models executed in an uncoupled mode using atmospheric forcing to yield surface fluxes and evolving land states. The land models are run at 1/8th-degree resolution over the continental US, and include Noah (from NCEP), VIC (Princeton), Mosaic (NASA), and SAC (NWS OHD). The atmospheric forcing data comes from the real-time extension of the North American Regional Reanalysis based on the mesoscale NAM/Eta model from c. 2003 (Mesinger et al 2006), with GOES-based bias-corrected incoming solar radiation, and observed daily gauge precipitation disaggregated to hourly using radar-based estimates. NLDAS has been run from 1979 to present in a retrospective mode, including a 15-year spin-up, with a 30-year climatology available for each model; output includes surface fluxes and hydrological land-state variables such as soil moisture, snowpack, and runoff (see Figure 1). A companion uncoupled seasonal hydrological prediction system uses the VIC land model driven by seasonal forecasts from three sources for the required surface forcing: Ensemble Streamflow Prediction, NCEP Climate Prediction Center (CPC) Official Seasonal Outlook, and NCEP CFS ensemble dynamical model prediction; 20 ensemble members (via a Bayesian-merging algorithm) are used to generate 1-6 month ensemble seasonal prediction products, e.g. soil moisture, runoff, streamflow, etc (see Figure 1). The motivation for NLDAS-2 is to support drought monitoring and seasonal drought prediction at CPC, and for the National Integrated Drought Information System (NIDIS, drought.gov) by providing NLDAS multi-model analysis, monitoring, and seasonal prediction products. (See www.emc.ncep.noaa.gov/mmb/nldas.) NLDAS datasets include output from the four models and surface forcing data, staged on NCEP public servers: ldas3 for retrospective runs and nomad6 for real-time runs (see: www.emc.ncep.noaa.gov/mmb/nldas/Download_Public_users.txt), and at the NASA Earth Sciences Data and Information Service Center (disc.sci.gsfc.nasa.gov/hydrology/data-holdings).

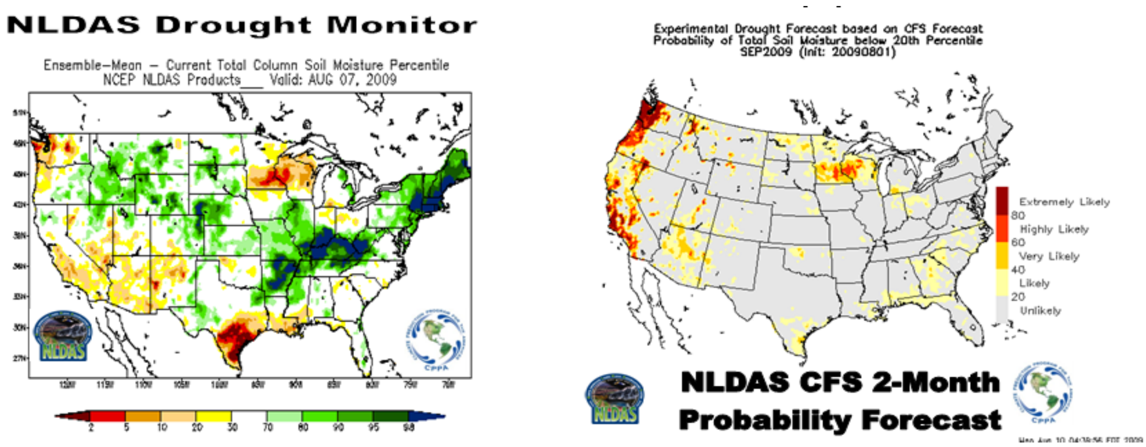

Figure 1. NLDAS drought monitor on 7 August 2009 (left), and NLDAS 2-month probability forecast using the initial condition on 1 August 2009 (right).

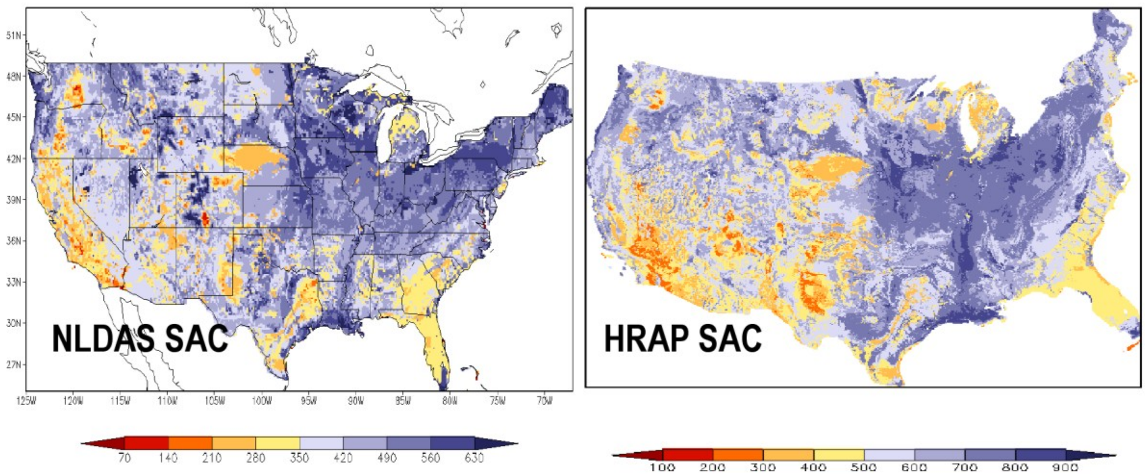

Figure 2. 30-year July climatology of total soil moisture over the continental US for the SAC model on the NLDAS (left) and HRAP (right) grids.

2.2. High-Resolution Hydrologic Modeling

As part of the NOAA/NWS/OHD Hydrology Test Bed, the SAC-HT/SNOW17 land-hydrology model is run uncoupled as a 30-year retrospective (1979-2008), at a high spatial resolution (~5-km) on the HRAP (Hydrologic Rainfall Analysis Project) grid over continental US. The 30-year model climatology is then generated for the hydrological applications, including future real-time runs in support to drought and flood monitoring. To drive the SAC model, the 30-year NLDAS forcing data set is interpolated from 1/8th-degree to the higher-resolution HRAP grid, and includes downscaling the temperature via a lapse-rate adjustment based on elevation. A two-step recursive-1979 then 12-

year spin-up is applied; this approach includes maintaining equilibrium among all the surface fluxes, land-surface states and hydrological variables via spin-up runs, and the climatologic effects through imposing a multiple-year average to the initial conditions. The SAC model is run under NASA/LIS, which offers the advantage of an efficient parallelized code (and data assimilation tools for the future). As an example, a 30-year July climatology of total soil moisture over the continental US from the current NLDAS SAC model is compared with the higher resolution HRAP SAC run (Figure 2). The general patterns are similar for both NLDAS and HRAP, though the SAC HRAP climatology provides more spatial detail. Future work will pursue data assimilation (e.g. snow cover) and the inclusion of streamflow modeling.

3. Regional Modeling

3.1. North American Mesoscale Model

The Weather Forecasting and Research (WRF) model is a next-generation community mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. WRF is suitable for a broad spectrum of applications across scales ranging from local mesoscale to thousands of kilometers. At NCEP, the operational North American Mesoscale (NAM) model uses the WRF with the Non-hydrostatic Mesoscale Model (NMM) dynamic core (www.emc.ncep.noaa.gov/mmb), and includes the unified NCEP-NCAR version of Noah land model. The 12-km NAM model (Figure 3) is run to 84 hours (3.5 days) four times daily (at 00, 06, 12, and 18UTC).

3.2. Hurricane Model

The hurricane version of WRF (HWRF; www.emc.ncep.noaa.gov/HWRF/index.html) gets its initial and boundary conditions from the NCEP global GFS. The HWRF coupled with the Noah land model then provides a hurricane-related inland flooding forecast via a river-routing scheme (Lohmann et al 2004) using runoff from the Noah model (Figure 3). The HWRF with Noah shows no degradation in hurricane track and intensity forecasts compared to the current slab land model, while the Noah model produces streamflow that is not possible with the slab model since it does not provide runoff. The forecasted streamflow also strongly depends on the initial soil moisture, i.e. HWRF using operational NAM soil moisture initial conditions (ICs; “DRY” in Figure 3) produces similar streamflow as the operational NAM (“NAM”), which is better than with GFS ICs (“WET”), though with uncoupled-Noah ICs (“NLDAS”) providing the best streamflow compared to observations (“BLACK”).

4. Global Medium-Range Modeling

The operational NCEP Global Forecast System (GFS) incorporates a suite of products, including the medium-range global forecast model and a global data assimilation system (see: www.emc.ncep.noaa.gov/gc_wmb), and is fully coupled with the Noah land model. Currently, the 64-level GFS is run out to 384 hours (16 days) four times daily (at 00, 06, 12, and 18UTC); the initial forecast resolution is T382 (about 35-km resolution) out to 7.5 days (180 hours), and T190 (about 80-km) beyond to day 16. All GFS runs get their initial conditions from the Gridpoint Statistical Interpolation (GSI) global data assimilation system (GDAS), which is updated four times during the day, with cycled land states from the Noah model.

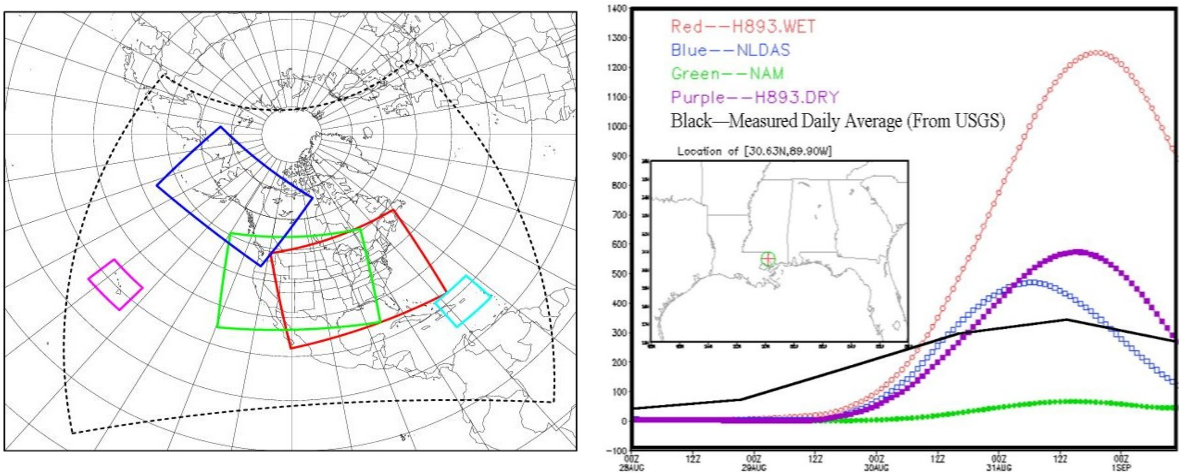

Figure 3. NAM domain (dashed box) with smaller eastern and western US, Alaska, and Hawaii 4-km "nests" (left), and streamflow from a river-routing scheme using runoff from the Noah land model coupled with the HWRF model simulation of Hurricane Katrina in 2005 (right; see text for details).

5. Climate Modeling

5.1. Seasonal Forecasting

In support of the NOAA mission to improve global seasonal forecasting, NCEP has developed a fully-coupled land-atmosphere-ocean-ice Climate Forecast System (CFS; cfs.ncep.noaa.gov) that uses the GFS as the atmospheric component, to make seasonal forecasts, e.g. out to 9 months. To examine the impact from CFS land model upgrades and different land-state initializations on summer season forecasts, extensive T126 CFS experiments were carried out for 25 summers with 10 ensemble members each, using the old Oregon State University (OSU) land model and the new Noah land model, with late April through early May initial conditions. The CFS using the Noah model initialized with land states from the Global Reanalysis II (GR2), a companion Global Land Data System (GLDAS), and GLDAS climatology, is compared to the CFS control run using the OSU model initialized with GR2 land states. Using anomaly correlation as a primary measure, CFS summer season prediction skill (out to three months) using different land models and different initial land states are assessed and compared for precipitation over the continental US on an ensemble basis. Results from these CFS experiments indicate that upgrading from the OSU model to Noah land model improves the overall June-July-August (JJA) precipitation prediction, especially during ENSO-neutral years (Figure 4), with the important conclusion that such an enhancement in CFS performance requires the execution of a GLDAS with the identical Noah land model utilized in the land-component of the CFS.

5.2. Global Reanalysis

The Noah land model is implemented as the land-surface component in both the CFS, and its companion CFS Reanalysis where the Noah model is executed within the NCEP GLDAS framework using the NASA/LIS infrastructure to produce the land analysis. Compared to the previous two generations of NCEP global reanalysis, the hallmark of this GLDAS/LIS in the CFS Reanalysis is the use of observed global precipitation analyses as forcing to the Noah model to derive the land analysis, rather than the typical reanalysis approach of using precipitation from the background atmospheric assimilation. Two global precipitation analysis products from the NCEP Climate Prediction Center (CPC), (1) the global daily gauge analysis and (2) the global pentad merged gauge-and-satellite

CMAP analysis, are used to drive GLDAS/Noah/LIS to estimate enhanced global land surface fields of soil moisture, soil temperature, and snowpack for the CFS Reanalysis. The 31-year (1979-2009) NCEP CFS Reanalysis data set has been recently released (nomads.ncdc.noaa.gov); the corresponding CFS reforecasts will be released in 2011.

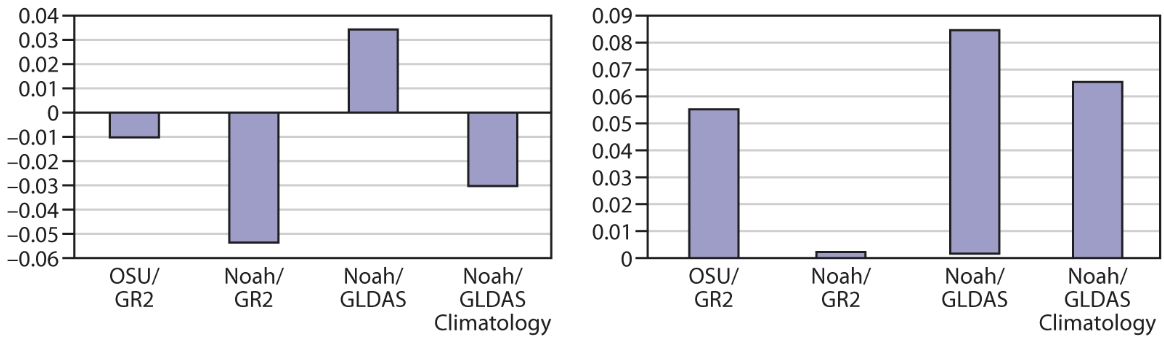

Figure 4. Anomaly correlation for CFS seasonal prediction of JJA precipitation over the continental US using different land model and initial condition configurations for all years (left), and during ENSO-neutral years (right).

6. Land Data Sets and Land Data Assimilation

The calculation of the surface moisture flux in the Noah land model requires land-cover (vegetation type) and green vegetation fraction (GVF). The new MODIS satellite remote sensing provides a high quality, consistent and well-calibrated land-cover data set over the entire globe at 1-km resolution. A MODIS-based 20-class data set has been modified following the International Geosphere-Biosphere Programme (IGBP) classification (with 3 tundra classes added; Figure 5). This IGBP-MODIS data set will replace the older 24-class USGS and 13-class "SiB" land-cover data sets currently used in the Noah land model in the NAM and GFS models, respectively, at NCEP. Additionally, a new weekly 0.144-deg AVHRR/NDVI-based GVF data set using a 24-year climatology (Figure 5) and companion near real-time GVF, will replace the current monthly GVF data set (based on a 5-year climatology). Tests in the mesoscale NAM model with this new IGBP-MODIS land-cover and the new GVF data sets showed a reduction in summertime near-surface temperature and moisture biases over the continental US.

Satellite observed brightness temperature (Tb) in various spectral channels is assimilated through the JCSDA Community Radiative Transfer Model (CRTM) on the NCEP Gridpoint Statistical Interpolation (GSI), where land surface skin temperature (LST) is a critical factor to determine Tb simulation for satellite surface sensitive channels. The amount of satellite data assimilated over land in the GSI/CRTM is far less than over ocean because of the large cold bias in GFS predicted LST, primarily over desert and arid regions during daytime in the warm season. The large cold bias in LST results in large errors in CRTM simulated satellite Tb over land, and rejection of satellite data in the GSI, especially for the surface sensitive satellite channels. GFS model testing has revealed a major cause of the cold daytime LST bias is in the treatment of the roughness length for heat (Z0t) in the physics of surface-layer turbulent heat exchange. Alternative formulations for Z0t as well as momentum roughness based on GVF (developed by X. Zeng et al at Univ. Arizona) show significant reductions in the LST cold bias in the western US where the bias is largest. The reduction of LST cold biases results in larger amounts of satellite data being accepted in the data assimilation over land in the GSI/CRTM.

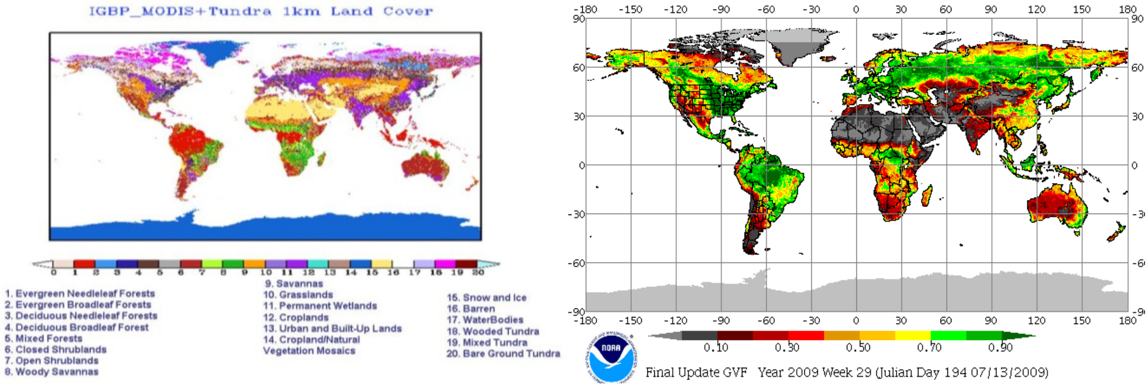

Figure 5. Global 1-km modified IGBP-MODIS land-cover data set (left), and 0.144-deg AVHRR/NDVI-based weekly GVF data set (right).

7. GEWEX Projects

Under the Coordinated Energy and Water Cycle Observations Project (CEOP; www.gewex.org/projects-CEOP.htm), via NOAA CPO/CPPA, NCEP is supplying tailored global forecast model (GFS) output to the CEOP archive for model validation and intercomparison studies. Part of this effort will allow GFS/Noah land model output to be compared with a worldwide network of in-situ observations (known as CEOP "Reference Sites"), in order to systematically evaluate and improve the Noah land model. Additionally, the GEWEX Land-Atmosphere System Study / Local coupled land-atmospheric modeling project (www.gewex.org/glass.html, "LoCo") seeks to understand the role of local land-atmosphere coupling on the evolution of surface fluxes and state variables, including boundary-layer clouds (van den Hurk and Blyth 2008). The theme of land-atmosphere interaction is a research area that is rapidly developing; after the well-known GLACE experiments (Koster et al 2004) and various diagnostic studies, new research has evolved in modeling and observing the degree of land-atmosphere coupling on local scales. Questions of interest are: how much is coupling related to local versus "remote" processes, what is the nature and strength of coupling, and how does this change (e.g. for different temporal/spatial scales, geographic regions, and changing climates)? The GLASS/LoCo working group is investigating diagnostics to quantify land-atmosphere coupling, e.g. the "Omega" coupling parameter (Jarvis and McNaughton 1986). After suitable diagnostics are identified, future activities will involve using weather and climate model output (e.g. reanalysis data sets) to "map" land-atmosphere coupling metrics in regards to the questions above.

References

Chen, F., Z. Janjic', and K. E. Mitchell, 1997: Impact of atmospheric surface-layer parameterizations in the new land-surface scheme of the NCEP mesoscale Eta model. *Bound.-Layer Meteorol*., **85**, 391-421.

Chen, F., K. E. Mitchell, J. Schaake, Y. Xue, H.-L. Pan, V. Koren, Q.-Y. Duan, M. Ek, and A. Betts, 1996: Modeling of land-surface evaporation by four schemes and comparison with FIFE observations. *J. Geophys. Res*., **101**, 7251-7268.

Ek, M., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley, 2003: Implementation of Noah land-surface model advances in the NCEP operational mesoscale Eta model. *J. Geophys. Res*., **108**(D22), 8851, doi:10.1029/2002JD003296.

Jarvis, P. G., and K. G. McNaughton, 1986: Stomatal control of transpiration: Scaling up from leaf to region. *Adv. Ecol. Res*., **15**, 1-49.

Koren, V., J. Schaake, K. E. Mitchell, Q.-Y. Duan, F. Chen, and J. Baker, 1999: A parameterization of snowpack and frozen ground intended for NCEP weather and climate models. *J. Geophys. Res*., **104**(D16), 19,569-19,585.

Koster, R. D., P. A. Dirmeyer, Z. Guo, G. Bonan, E. Chan, P. Cox, C. T. Gordon, S. Kanae, E. Kowalczyk, D. Lawrence, P. Liu, C.-H. Lu, S. Malyshev, B. McAvaney, K. E. Mitchell, D. Mocko, T. Oki, K. Oleson, A. Pitman, Y. C. Sud, C. M. Taylor, D. Verseghy, R. Vasic, Y. Xue, and T. Yamada (The GLACE Team), 2004: Regions of strong coupling between soil moisture and precipitation. *Science*, **305**(5687), 1138-40, doi:10.1126/science.1100217.

Lohmann, D. and co-authors, 2004: Streamflow and water balance intercomparisons of four land-surface models in the North American Land Data Assimilation System project. *J. Geophys. Res*., **109**, D07S91, doi: 10.1029/2003JD003517.

Mesinger, F. and co-authors, 2006: North American Regional Reanalysis. *Bull. Amer. Meteorol. Soc.*, **87**(3), 343–360, DOI: 10.1175/BAMS-87-3-343

Mitchell K. E., D. Lohmann, P. R. Houser, E. F. Wood, J. C. Schaake, A. Robock, B. A. Cosgrove, J. Sheffield, Q. Y. Duan, L. Luo, R. W. Higgins, R. T. Pinker, J. D. Tarpley, D. P. Lettenmaier, C. H. Marshall, J. K. Entin, M. Pan, W. Shi, V. Koren, J. Meng, B. H. Ramsay, A. A. Bailey, 2004: The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. *J. Geophys. Res.*, **109**, D07S90, doi:10.1029/2003JD003823.

Pan, H.-L., and L. Mahrt, 1987: Interaction between soil hydrology and boundary-layer development. *Bound.-Layer Meteorol*., **38**, 185-202.

Schaake, J., V. Koren, Q.-Y. Duan, K. E. Mitchell, and F. Chen, 1996: Simple water balance model for estimating runoff at different spatial and temporal scales. *J. Geophysical Res*., **101**(D3)7461-7475.

van den Hurk, B., and E. Blyth, 2008: WATCH/LoCo (EU/WATCH - GEWEX-GLASS/LoCo) *Workshop. GEWEX News*, **18**(4), 12-14.