Year 3 Progress and Final Report: GC11a-578 - Development of a Prototype High Resolution Prediction System for Precipitation, Soil Moisture and Stream Flow over North America

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1. Results and Accomplishments

The goal of this proposal was to improve hydrologic prediction skill on subseasonal to seasonal time scales by developing and evaluating a prototype high-resolution drought prediction system. Substantial progress was made during the third and final year of this proposal, to improve our understanding of land-atmosphere feedback involving planetary wave structures in the development of short tern drought (section 1a), to assess hydrologic prediction skill over the U.S. using the National Multi model ensemble (section 1b), and to assess via a case study the impacts of downscaling by demonstrating that the hydrologic forecasts are able to enhance the SM and RO forecasts (section 1c). The year 3 highlights are presented in section 2. The final summary (years 1-3) report is given in section 4.

1a. A Mechanism for Land-Atmosphere Feedback Involving Planetary Wave Structures

While the ability of land surface conditions to influence the atmosphere has been demonstrated in various modeling and observational studies, the precise mechanisms by which land-atmosphere feedback occurs are still largely unknown – particularly the mechanisms that allow land moisture state in one region to affect atmospheric conditions in another. We examined such remote impacts in the context of atmospheric general circulation model (AGCM) simulations, leading to the identification of one potential mechanism: the phase-locking and amplification of a planetary wave through the imposition of a spatial pattern of soil moisture at the land surface. A brief description is provided here; for full details, see Koster et al. (2014).

The modeling system utilized in the study is the NASA/GSFC GEOS-5 system. Our simulations used only the coupled atmospheric and land model components of the system, prescribing sea surface temperatures (SSTs) from observations using AMIP-style protocols. To examine how land conditions may affect dynamical patterns in the atmosphere, we compared two ensembles of GEOS-5 simulations. The control ensemble consists of 192 AMIP-style simulations covering April-July of 2012, a period for which the real world experienced warm conditions in the Great Plains. The experiment ensemble is identical to the control except for the imposition of a soil moisture dipole pattern, obtained through the use of extremes in forcing: during April in these simulations, any precipitation simulated over a northwestern region of the U.S. (the blue box in Figure 1a) was artificially increased five-fold before being applied to the land surface (with the increase deposited as liquid), and precipitation simulated over the Great Plains (the red box in Figure 1a) was zeroed. Precipitation in the simulations was not modified during the May-July period.

Shown in Figure 1bcd are the resulting differences in key July fields (experiment minus control). Prior to plotting, all fields in both ensembles were standardized (turned into Z-scores) using the means and standard deviations established in the control ensemble. The April precipitation modifications led to soil moisture anomalies that extended into July, which in turn induced strong July temperature anomalies, including a heating in the Great Plains and a cooling in the Northwest U.S. (Figure1b). Precipitation in July was also affected (Figure 1c), with strong deficits generated in the Great Plains and a surfeit of precipitation produced in the Northwest U.S.. As with the temperature changes, many of the precipitation changes in these regions are significantly different from zero at the 99% level.

The imposed soil moisture dipole had an impact on the atmosphere's general circulation as well, as manifested in the meridional winds at 250 mb (V250) – Figure 1d shows a wavelike pattern in the Z_{V250} field. The source of the V250 pattern can only be the imposed dipole, as all other aspects of the two ensembles are identical. The wavelike pattern does not appear until June (not shown) and July, which is consistent with the idea that soil moisture fields influence the atmosphere the most during the months of strongest insolation, when evaporation is highest.

Simply stated, our analysis indicates that the imposition of the soil moisture dipole led to the production of a planetary wave pattern that in turn amplified warming in the Great Plains. Additional experimentation (not shown in this summary but described in the paper) shows that a wet anomaly in the Northwest U.S. produces, all by itself, the planetary wave pattern that encourages Great Plains warming – that is, there is direct evidence in the model of soil moisture impacts on remote climate variables.

It is natural to ask if such remote impacts also appear in nature. Because nature does not allow the type of experiments just described, demonstrating this conclusively is essentially impossible. Supporting evidence for the feedback is nevertheless found in the best reconstructions of historical weather available to us. The maps in Figure 2 are derived from a 35-yr observations-based record (1979-2013). Composites are based on the strength of the soil moisture dipole in April, with a positive dipole defined as anomalously wet conditions in the Northwest U.S. and dry conditions in the Great Plains. Observations-based root-zone soil moistures are taken here from the North American Land Data Assimilation (NLDAS) product as produced by the VIC land surface model. The NLDAS product is, in essence, a set of soil moistures obtained by driving a state-of-the-art land surface model with gridded observations-based meteorological forcing over the 35-year period. Analysis of the 35-year NLDAS dataset identifies 8 years as having a soil moisture dipole in April along the lines of that shown in Figure 1a: 1982, 1986, 1996, 2000, 2003, 2006, 2011, and 2012. The composite of April soil moisture conditions over all eight years is shown in Figure 2a. Results are expressed in terms of average Z-score, with means and standard deviations taken from the 35-years of NLDAS data. The dipole is, by construct, apparent in the plot.

The observations-based T2M and V250 fields examined here are taken from the ERA-Interim reanalysis produced by the European Centre for Medium-Range Weather Forecasts. The precipitation data are taken from the GPCP dataset, Version 2.2, a well-regarded dataset constructed from extensive in situ gauge and satellite-based precipitation measurements. We convert the observations-based T2M, P, and V250 data into Z-scores, using means and standard deviations from the corresponding raw data fields. We then composite the data for July over the 8 years used for the composite in Figure 2a. Figure 2b shows the July Z_{T2M} composite. Warm July conditions, with an average anomaly of up to 1K or more (in terms of absolute anomaly), are found in the Great Plains for the subsetted years – the historical temperature anomalies were arguably predictable from the presence of the April soil moisture dipole. The composited years also show a deficit of precipitation in the Great Plains (Figure 2c), with some local deficits approaching 1 mm/day. Furthermore, the composite July Z_{V250} anomaly field for these years (Figure 2d) shows a pattern similar to that seen in Figure 1d, supporting the idea that the soil moisture dipole had an impact on the planetary wave structure.

These results cannot be considered conclusive; given the small size of the composite, the values plotted in Figure 2b,c are generally not statistically significant. Nevertheless, the patterns in the data are fully consistent with the feedback mechanism established for the AGCM. The agreement between the patterns shown in Figure 2 with those of Figure 1 either constitutes support for the feedback mechanism or must be deemed a strong coincidence.

The dipole examined in our experiments is, of course, only one of potentially many soil moisture patterns of relevance to land-atmosphere feedback in the climate system. The approaches examined in this study could prove useful in identifying and analyzing additional patterns.

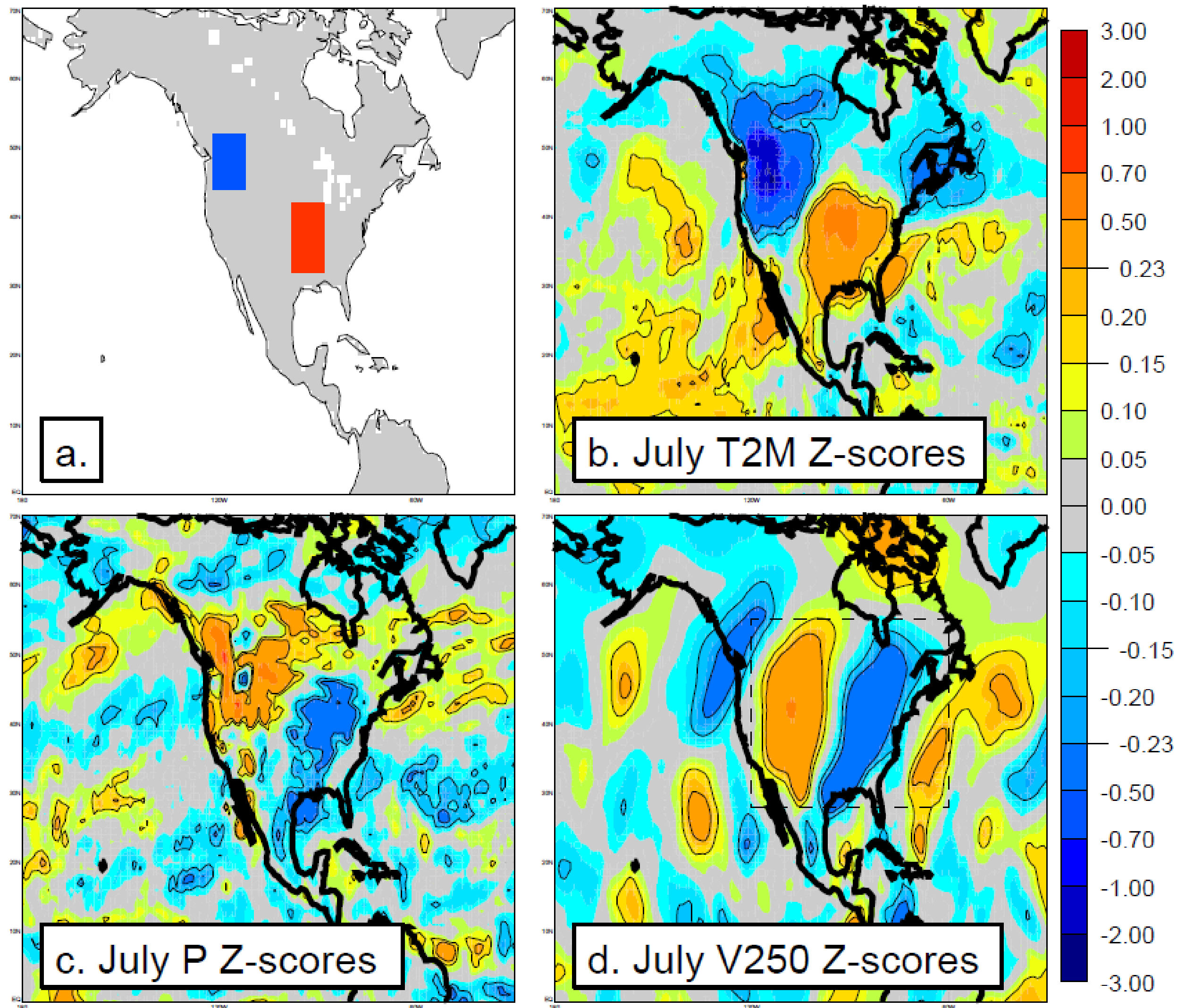

Figure 1. a. Locations where April precipitation is modified in a specialized experiment. April precipitation water applied to the land surface is increased five-fold in the blue area, and it is set to zero in the red area. b. Resulting July surface air temperature anomalies, in terms of Z-score (defined using moments of the control simulation). c. Resulting July precipitation anomalies, in terms of Z-score. d. Resulting July 250 mb meridional wind anomalies, in terms of Z-score. The contours at 0.15 and 0.23 represent values that are significantly different from zero at the 90% and 99% confidence levels, respectively.

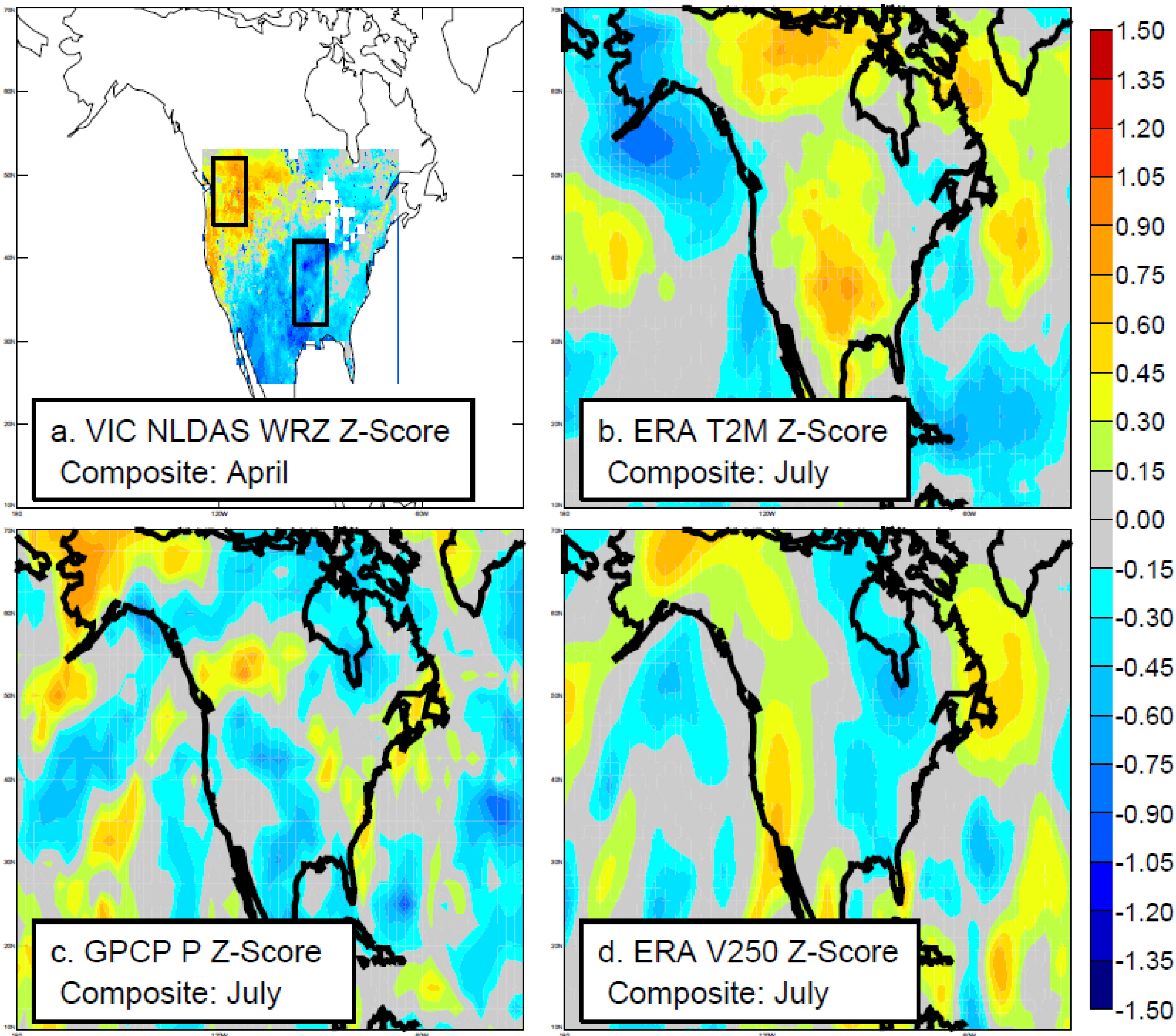

Figure 2. a. Composite of NLDAS-based April soil moisture, composited over the eight years for which a positive April soil moisture dipole appears in the outlined areas (see text for details). b. Corresponding composite (i.e., for the same eight years) of July surface air temperature anomalies from the ERA-Interim dataset. c. Corresponding composite of July precipitation anomalies from the GPCP dataset. d. Corresponding composite of July 250 mb meridional wind anomalies from the ERA-interim dataset. All data are expressed in terms of Z-score.

1b. Hydrologic prediction over the U.S. using the National Multi model ensemble

We analyzed the skill of monthly and seasonal soil moisture (SM) and runoff (RO) forecasts over the United States performed by driving the Variable Infiltration Capacity (VIC) hydrologic model with forcings derived from the National Multi-Model Ensemble hindcasts (NMME_VIC). We compared the grand ensemble mean NMME_VIC forecasts to Ensemble Streamflow Prediction (ESP) forecasts derived from the VIC model forced by resampling of historical observations during the forecast period (ESP_VIC), using the same initial conditions as NMME_VIC. The forecast period is from 1982 to 2010 with forecast initialized on 1 January, 1 April, 5 July and 3 October. An example is given by Fig. 3, which shows the skill measured by the Pearson correlation for soil moisture forecasts. Overall, forecast skill is seasonally and regionally dependent. We find that: 1) The skill of the grand ensemble mean NMME_VIC forecasts is comparable with that of the individual model that has the highest skill; 2) For all forecast initiation dates, the initial conditions play a dominant role in forecast skill at 1-month lead. At longer lead times, forcings derived from NMME forecasts start to contribute to forecast skill. For higher lead times, the forecasts are still skillful over the western interior regions; 3) The initial conditions dominant contributions to skill for a dry climate regime that covers the western interior states for all seasons and the North Central part of the country for January. In this regime, the forecast skill for both methods is high even at 3 -month lead. This regime has low mean precipitation and precipitation variations, and the influence of precipitation on SM and RO is weak. In contrast, a wet regime covers the region from the Gulf States to the Tennessee and Ohio Valleys for forecasts initialized in January and April, the Southwest monsoon region, the Southeast and the East Coast in summer. In these dynamically active regions, where rainfall depends on the path of the moisture transport and atmospheric forcing, forecast skill is low. For this regime, the climate forecasts contribute to skill. Skillful precipitation forecasts after lead-1 have the potential to improve SM and RO forecast skill, but we find that this mostly is not the case for the NMME models.

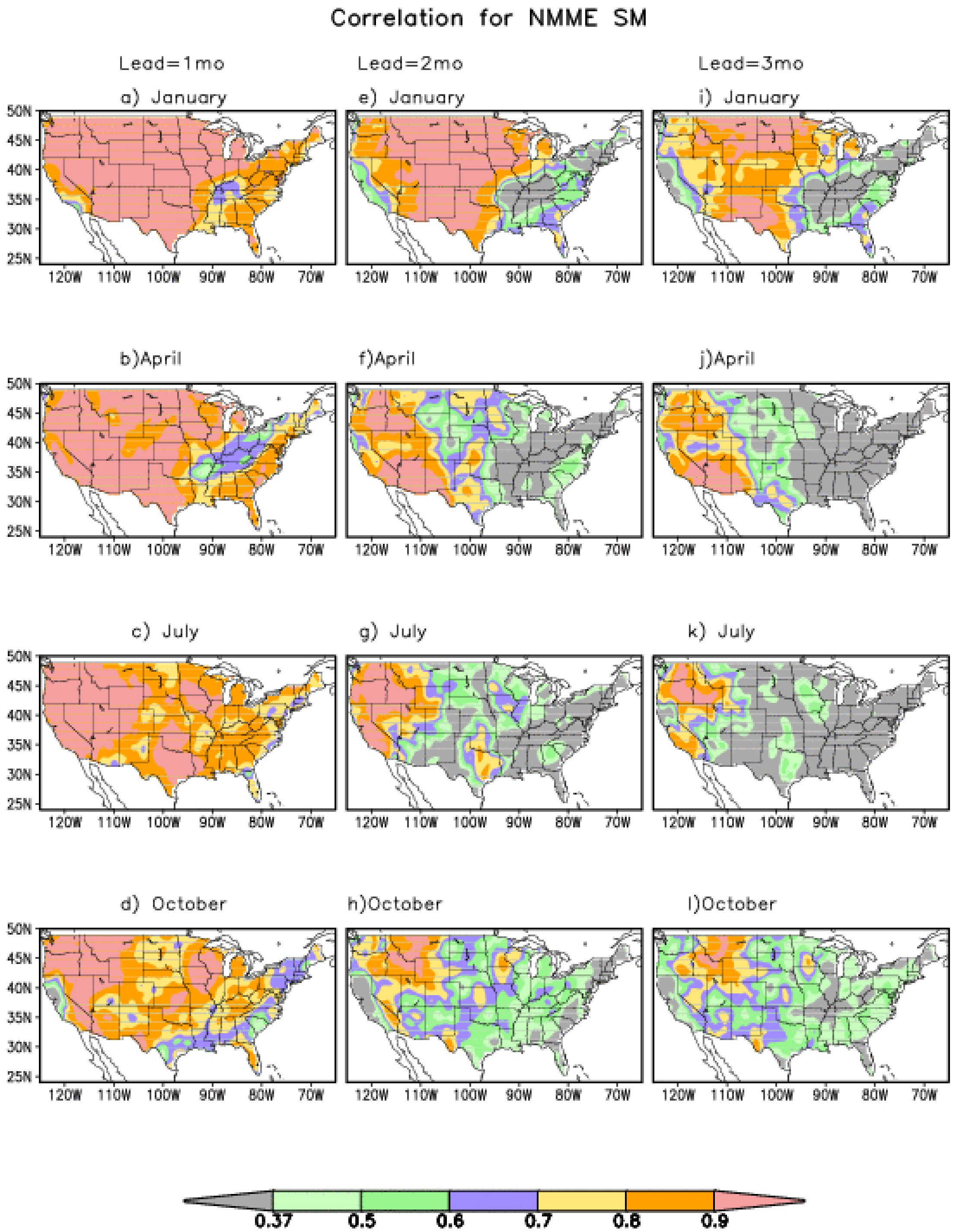

Fig. 3: Forecast skill measured by the Pearson correlation between the NMME soil moisture (SM) forecasts and the corresponding (SM) simulation from the VIC model for forecasts initialized in (a) January, (b) April, (c) July and (d) October at lead 1 month. Contours are indicated by the color bar, (e)- (h) same as (a)-(d), but for forecasts at lead 2 months, (i)-(l) same as (a)- (d) but for lead 3 months.

1c. A case study of the hydrologic prediction of the 2012 drought

GCMs usually have coarse spatial resolution relative to the heterogeneities of the land surface. In part for this reason, the soil moisture (SM) and runoff (RO) forecasts directly taken from the GCMs are not useful. We performed a downscaling experiment to demonstrate that the hydrologic forecasts are able to enhance the SM and RO forecasts by using the 2012 drought over the Great Plains as a case study.

The GCM forecast were performed using the GMAO model with 1-degree resolution. The forecasts for 2000 to 2011, which have 4 members, are used to determine the models climatology. The forecasts for 2012 have 20 members. All GCM runs were initialized at 21May of that year. The daily precipitation, maximum temperature, minimum temperature and wind speed from the GCM outputs were linearly interpreted to 1/8 degrees and the mean errors were corrected by subtracting the differences between the model mean and the observed mean. The corrected forcings then force a VIC model with 1/8 degrees resolution to obtain the SM and runoff (RO). The VIC experiments started from 1 June each year with initial conditions taken from the VIC simulation driven by the observed P and Tsurf.

The model climatology for a given variable for summer (June and July) was the mean of that variable averaged over all members from 2000 to 2011. The forecast anomaly for 2012 is defined as the departure from the models climatology. The GCM run is compared with the VIC simulation (Fig. 4). The GCM run is able to capture the intense heat in the 2012 summer and drought with negative P anomalies over the Great Plains. The VIC experiments also capture the SM and RO deficit.

This experiment indicates that the hydroclimate forecasts using a land surface model are able to capture SM and RO anomalies if the GCM forecasts are skillful.

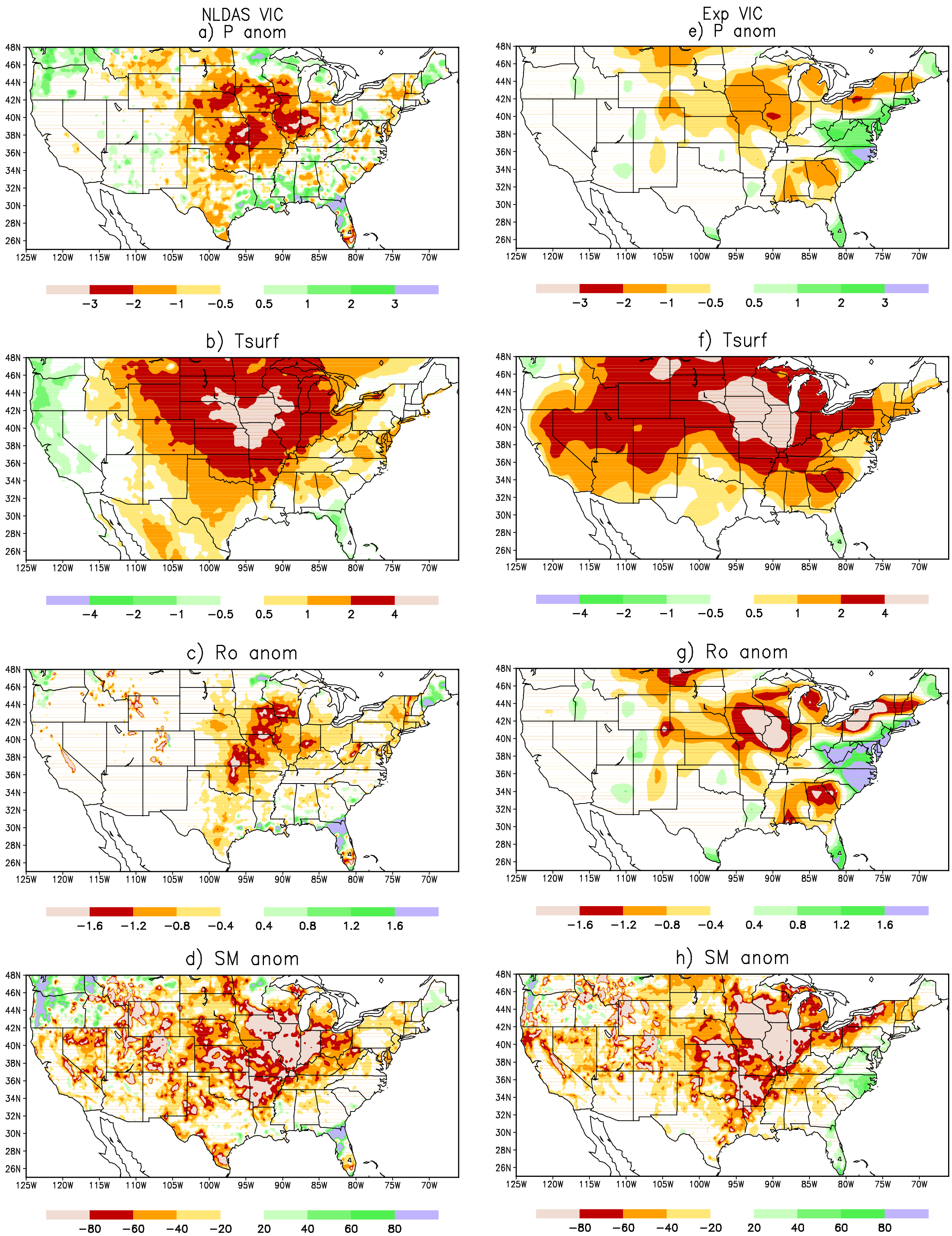

Figure 4: (a) Precipitation anomalies for June and July 2012 mean defined as the departure from the 2000-2011 observed P analysis. The unit is mm day^{-1}. Contours are given by the color bar, (b) same as (a) but for the Tsurf. The unit is C, (c) same as (a) but

for runoff anomalies from the VIC simulation. The unit is mm day^{-1} and (d) same as (a) but for SM anomalies. The unit is mm. , (e) -(f) same as (a)-(b) but for the mean GCM forecast anomalies for June and July 2012 and (g)-(h) same as (c) and (d), but for the VIC experiment.

2. Highlights of year 3 accomplishments

Key findings from year 3 are:

- The skill of the grand ensemble mean NMME_VIC forecasts is comparable with that of the individual model that has the highest skill;

- For all forecast initiation dates, the initial conditions play a dominant role in forecast skill at 1-month lead. At longer lead times, forcings derived from NMME forecasts start to contribute to forecast skill. For higher lead times, the forecasts are still skillful over the western interior regions;

- The initial conditions dominant contributions to skill for a dry climate regime that covers the western interior states for all seasons and the North Central part of the country for January.

- Downscaling experiments indicate that the hydroclimate forecasts using a land surface model are able to capture SM and RO anomalies if the GCM forecasts are skillful.

- An important mechanism by which the land surface can have remote impacts was identified, involving the phase-locking and amplification of a planetary wave through the imposition of a spatial pattern of soil moisture at the land surface. In particular, idealized AGCM experiments show that the imposition of a soil moisture dipole produces a planetary wave pattern that in turn amplified warming in the US Great Plains.

3. Publications (year 3):

Koster, R. D., Y. Chang, and S. D. Schubert, 2014: A mechanism for land-atmosphere feedback involving planetary wave structures. J. Climate, 27, 9290-9301.

Mo, K. C. and D. P. Lettenmaier 2014: Hydrologic prediction over the Conterminous U.S. using the national multi model ensemble. J. Hydromet. In press.

4. Summary report

The results of this study provide important groundwork for the development of a high resolution prediction system for precipitation, soil moisture and stream flow over North

America. This includes improved understanding of the causes of drought, and the ability of climate models forced with observed SST to reproduce recent high profile events, the establishment of a baseline for assessing any improvements in the skill of hydrologic models forced with coupled model forecasts, an assessment of downscaling and multi-model forecasts, and a better understanding of why parts of the continental United States would not benefit from the added information contained in high-resolution precipitation forecasts.

In particular, we identified the important role of the tropical Pacific, tropical Atlantic, and Indian Ocean SST, the key role of soil moisture feedbacks, and the importance of unforced internal atmospheric variability, in the development of drought over North America. A comparison the 2011 and 2012 droughts showed that the early 2011 temperature and precipitation anomalies over the U.S. reflected what is now a generally well-understood response to cold tropical Pacific (La Nina) SSTs, while the intensification of the drought and heat over Texas during the summer of 2011 appears to be unforced by SST.   In contrast, the 2012 anomalies were rather atypical, with unusual warmth spanning the entire continent during the winter and early spring, followed by a rapid development (during May and June) of record-breaking precipitation deficits and extreme temperatures over the central Plains – a spring/summer development that appears to be largely the result of internal atmospheric variability tied to the development of a stationary Rossby wave and an associated anomalous upper tropospheric high maintained by weather transients. The pronounced winter and early spring temperature differences over the U.S. between 2011 and 2012 primarily reflect differences in the contributions from the Atlantic and Indian Oceans during those two years (Wang et al. 2014).

It was shown that the skill of hydrologic models forced with coupled model forecasts varies with lead-time and geographical location. The impacts of the CFSv2 model forcing on skill are limited (with the initial land conditions playing the dominate role). There are however cases where CFSv2 forcing does make a difference, but the contributions are local and seasonally dependent. SM forecast skill is higher over the western interior of CONUS for both ESP_VIC and CFSv2_VIC relative to the eastern part of the domain. For the western interior of CONUS where soil moisture has strong persistence, ESP_VIC has equal or slightly higher skill than CFSv2_VIC forecasts for all lead times. CFSv2_VIC performs better than ESP_VIC over regions where precipitation (P) is modulated by atmospheric circulation at short lead times (Mo et al. 2012).

It was found that the skill of the grand ensemble mean NMME_VIC forecasts is comparable with that of the individual model that has the highest skill (Mo and Lettenmaier 2014b). For all forecast initiation dates, the initial conditions play a dominant role in forecast skill at 1-month lead. At longer lead times, forcings derived from NMME forecasts start to contribute to forecast skill. For higher lead times, the forecasts are still skillful over the western interior regions. The initial conditions dominant contributions to skill for a dry climate regime that covers the western interior states for all seasons and the North Central part of the country for January. Downscaling experiments indicate that the hydroclimate forecasts using a land surface model are able to capture SM and RO anomalies if the GCM forecasts are skillful.

We now have a better understanding of why parts of the continental United States would not benefit from the added information contained in high-resolution precipitation forecasts. In general, in regions and seasons for which evaporation is energy-limited, the added information contained in higher resolution versions of a given precipitation dataset (e.g., from a downscaled precipitation forecast) does not affect the simulation of large-scale streamflow (Koster et al. 2013).

We also explored an objective scheme for drawing boundaries between the D0-D4 classes used by the USDM. The approach is based on multiple SPI, SM and SRI indices, from which we form an ensemble mean index, which we then remap to a uniform distribution by using the climatology of the ensemble (percentile) averages (Mo and Lettenmaier 2014a).

Finally, an important mechanism by which the land surface can have remote impacts was identified, involving the phase-locking and amplification of a planetary wave through the imposition of a spatial pattern of soil moisture at the land surface. In particular, idealized AGCM experiments show that the imposition of a soil moisture dipole produces a planetary wave pattern that in turn amplifies warming in the US Great Plains (Koster et al. 2014).

Two of the investigators (S. Schubert and K. Mo) contributed to the writing of the DTF JHM synthesis paper (Wood et al. 2014).

5. Publications (Years 1-3):

Koster, R. D., G. K. Walker, S. P. P. Mahanama, and R. H. Reichle, 2013: Soil Moisture Initialization Error and Subgrid Variability of Precipitation in Seasonal Streamflow Forecasting. J. Hydromet., under revision.

Koster, R. D., Y. Chang, and S. D. Schubert, 2014: A mechanism for land-atmosphere feedback involving planetary wave structures. J. Climate, 27, 9290-9301.

Mo, K. C., S. Shukla, D. P. Lettenmaier and L. C. Chen 2012 : Do Climate Forecast System (CFSv2) forecasts improve seasonal soil moisture prediction? Geophy. Res. Let 39, L23703 doi:10.1029:/2012GL053598.

Mo, K.C., and D.P. Lettenmaier, 2014a: Objective drought classification using multiple land surface models. *J. Hydrometeor.*, 15, 990�?010. doi: http://dx.doi.org/10.1175/JHM-D-13-071.1.

Mo, K. C. and D. P. Lettenmaier 2014b: Hydrologic prediction over the Conterminous U.S. using the national multi model ensemble. J. Hydromet. In press

Wang, H., S. Schubert, R. Koster, Y.-G. Ham, and M. Suarez, 2014: On the Role of SST Forcing in the 2011 and 2012 Extreme U.S. Heat and Drought: A Study in Contrasts. J. Hydro. Meteor., 15, 1255-1273, 2014.

Wood, E., S. Schubert, A. Wood, C. Lidard-Peters, K. Mo, A. Mariotti, and R. Pulwarty, 2014. Prospects for Advancing Drought Understanding, Monitoring and Prediction. Accepted in the J. Hydro. Meteor., 2014.

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