THE DISTRIBUTED HYDROLOGIC MODEL INTERCOMPARISON PROJECT (DMIP): AN OVERVIEW OF PHASE 2

Michael Smith[1], michael.smith@noaa.gov; Victor Koren[1], Victor.Koren@noaa.gov; Seann Reed[1], Seann.Reed@noaa.gov; Ziya Zhang[1], ziya zhang@noaa.gov; and Fekadu Moreda[1], Fekadu.Moreda@noaa.gov, Zhengtao Cui, zhengtoa.cui@noaa.gov; Fan Lei, fan.lei@noaa.gov; Shuzheng Cong, shuzheng.cong@noaa.gov; Dong-Jun Seo, dongjun.seo@noaa.gov.

[1]Research Hydrologist, Hydrology Laboratory, Office of Hydrologic Development
NOAA National Weather Service
1325 East West Highway, Silver Spring, MD 20910

<u>Abstract:</u> The Hydrology Laboratory (HL) of the NOAA National Weather Service (NOAA/NWS) proposes the second phase of the Distributed Model Intercomparison Project (DMIP). The NOAA/NWS realizes the need for a continued series of science experiments to guide its research into advanced hydrologic models for river and water resources forecasting. This need is accentuated by NOAA/NWS' recent progression into a broader spectrum of water resources forecasting to complement its more traditional river and flash flood forecasting mission. To this end, the NOAA/NWS welcomes the input and contributions from the hydrologic research community in order to better fulfill its mandate to provide the Nation with valuable products and services.

DMIP 2 is designed around two themes: 1) continued investigation of science questions pertinent to the DMIP 1 test sites, and 2) distributed and lumped model tests in hydrologically complex basins in the mountainous Western US. DMIP 2 will be supported by linkages to the Oklahoma Mesonet, and the Hydrometeorological Testbed (HMT) program of the NOAA Environmental Technology Laboratory. As such, DMIP 2 will contribute to the goals of these partner institutions in a way that will garner greater results than if these programs were executed in an isolated manner.

NOAA 'Weather and Water Mission Goals' (NOAA, 2004) are directly addressed through DMIP 2 by conducting experiments to guide the development, application, and transition of advanced science and technology to operations and new services and products. DMIP 2 also contributes to the NOAA 'Cross-Cutting Priority' of ensuring sound, state-of-the-science research as a vigorous, forward-looking effort that invites contributions from academia, other federal agencies, and international institutions.

We expect that DMIP 2 will provide multiple opportunities to develop data requirements for modeling and forecasting in hydrologically complex areas. These requirements fall into the general categories of needed spatial and temporal resolution and quality. From these, new sensor platforms could be designed or appropriate densities of existing gauges could be specified to meet specific project goals. From the river forecasting viewpoint, we think these data needs are particularly acute in the mountainous west.

INTRODUCTION

The first phase of DMIP (hereafter called DMIP 1) proved to be a landmark venue for the comparison of lumped and distributed models in the southern Great Plains (Smith et al., 2004; Reed et al., 2004). Twelve groups participated in DMIP 1, including representatives from China, Denmark, Canada, New Zealand, and universities and institutions in the US. Models ranged from conceptual representations of the soil column applied to various computational elements, to more comprehensive physically-formulated models based on highly detailed triangulated representations of the terrain. DMIP 1 resulted in the publication of a DMIP Special Issue of the Journal of Hydrology in October, 2004. In addition, DMIP 1 provided valuable guidance to the NWS HL research program for improved hydrologic models for river and water resources forecasting.

DMIP 1 formally concluded in August, 2002 with a meeting of all participants at NWS headquarters in Silver Spring, Maryland. The purpose of this meeting was to present and discuss the formal analyses of participants' results. At this meeting, the participants eagerly discussed the need for a second phase of DMIP. Ideas from this meeting were compiled and are presented herein along with other science questions.

While DMIP 1 served as a successful comparison of lumped and distributed models, it also highlighted problems, knowledge gaps, and topics that need to be investigated. First, DMIP 1 was limited by a relatively short data period containing only a few major rainfall-runoff events in the verification period from which statistics could be computed and inferences made. Thus, the need remains for further DMIP 1-like testing in order to properly evaluate the hypotheses related to lumped and distributed modeling. At this time, almost five years of additional data are available to support such additional comparisons. Also, DMIP 1 was somewhat hampered by the quality of the radar estimates of observed precipitation. The quality of these data has been oft-studied (e.g., Stellman et al., 2001; Young et al., 2000; Johnson et al., 1999; Wang et al., 2000; Smith et al., 1999) and includes problems such as underestimation and non-stationarity resulting from changes in the processing algorithms. Recently, the raw data from the NEXRAD series of platforms has been reprocessed with consistent algorithms for some regions of the US. We anticipate that use of this re-analysis data set is necessary to evaluate the conclusions of the DMIP 1 testing.

Moreover, additional model comparisons must be performed in more hydrologically complex regions. Most notably, experiments are needed in the western US where the hydrology of most of the areas is dominated by complexities such as snow accumulation and melt, orographic precipitation, steep and other complex terrain features, and data sparcity. The need for advanced models in mountainous regions is coupled with the basic requirement for more data in these areas. Experts at NWS River Forecast Centers (RFCs) point to the need for explicit and intense instrumentation programs to determine the required sensor network density to improve forecast operations. Advanced models cannot be implemented for RFC forecast operations without commensurate analyses of the data requirements in mountainous regimes.

Another unresolved question from DMIP 1 is: 'Can distributed models reproduce processes at basin interior locations?' Included here is the computation of spatial patterns of observed soil moisture. DMIP 1 attempted to address this question through blind simulations of nested and basin interior observed discharges at a limited number of sites. Investigations into this question have typically been hampered by a lack of soil moisture observations organized in a high spatial resolution. While much work has been done to estimate soil moisture from satellites, these methods are currently limited to observing only the top few centimeters of the soil surface. The test basins in DMIP 1 are mostly contained in Oklahoma, offering an opportunity for the soil moisture observations from the Oklahoma Mesonet to be used. Despite the limitations of the Oklahoma Mesonet, (e.g., one sensor per county) it is prudent to perform experiments to understand the real value of the currently available data and work towards developing requirements for future sensor deployment.

Yet another major need highlighted by DMIP 1 experiments is the testing of models in a 'pseudo-forecast environment' with forecast-quality forcing data. Such tests are a logical complement to the process simulation experiments in DMIP 1. The well-documented model intercomparsion experiment of the WMO (WMO, 1992) highlighted the testing of models in a forecasting environment. Now, we propose that DMIP 2 include a forecast test component as a natural complement to the process experiments in DMIP 1.

Finally, as with DMIP 1, the NOAA/NWS realizes the need for an accelerated venue of science experiments to guide its research into advanced hydrologic models for river and water resources forecasting. This need is accentuated by NOAA/NWS' recent progression into a broader spectrum of water resources forecasting to complement its more traditional river and flash flood forecasting mission (NWS, 2004a,b). Moreover, the NOAA/NWS heeds the recommendations of the National Research Council (NRC) that point to hydrologic forecasting as one of the ten 'grand challenges' in environmental sciences in the next generation. (NRC, 2000). To this end, the NOAA/NWS welcomes the input and contributions from the hydrologic research community in order to better fulfill its mandate to provide the Nation with meaningful products.

SCIENCE QUESTIONS

We present the following science questions to be addressed in DMIP 2. Some of these are repeated from DMIP 1 in order to evaluate them given longer archives of higher quality data than were available in DMIP 1. We frame the science questions for the interest of the broad scientific community and in most cases provide a corollary for the NOAA/NWS.

Can distributed hydrologic models provide increased simulation accuracy compared to lumped models? If so, under what conditions? Reed et al. (2004) showed that only one of the DMIP 1 basins showed improvements from deterministic distributed modeling. Furthermore, work by Carpenter and Georgakakos (2004) indicates that even when considering operational parametric and radar-rainfall uncertainty, flow ensembles from lumped and distributed models are statistically distinguishable in the same basin where the deterministic model showed improvement. The specific question for the NOAA/NWS mission is: under what circumstances should NOAA/NWS use distributed hydrologic models rather than lumped models to provide hydrologic services? What role does calibration play in realizing improvements?

What simulation improvements can be realized through the use of re-analysis forcing data?
One of the issues faced in DMIP 1 was the time-varying biases of the NEXRAD precipitation

data (Reed et al., 2004) which affected the simulations in the model calibration and verification periods. For DMIP 2, we propose to use re-analysis precipitation forcing derived using the Multi-sensor Precipitation Estimation (MPE) algorithm. Note that while the MPE reanalysis focuses on the use of a consistent algorithm to process the raw NEXRAD data, it does not include the human quality control present in the NEXRAD data available in DMIP 1. For the NOAA/NWS, the question is whether the MPE data lead to improved simulations as well as serve as consistent data for model calibration and real-time operational forecasting.

What is the performance of (distributed) models if they are calibrated with observed precipitation data but use forecasts of precipitation? While much work has been done to evaluate the improvements realized by distributed models in simulation mode, the NOAA/NWS also needs to investigate the potential gains when used for forecasting. For example, the following questions are relevant: is there a forecast lead time at which the distributed and lumped model forecasts converge? How far out into the future can distributed models provide better forecasts than currently used lumped models? Reed et al. (2004) stated that because forecast precipitation data have a lower resolution and are much more uncertain than their observed counterparts, the benefits of distributed models may diminish for longer lead times.

Can distributed models reasonably predict processes such as runoff generation and soil moisture re-distribution at interior locations? At what scale can we validate soil moisture models given current models and sensor networks? The soil moisture observations derived through the Oklahoma Mesonet provide a good opportunity to address the latter question over a large spatial domain. Koren et al. (2005) present a comparison of computed and observed soil moisture using the Mesonet data. For the NOAA/NWS, the corollary question is: can distributed models provide meaningful, spatially-varied estimates of soil moisture to meet the US needs for an enlarging suite of water resources forecast products?

In what ways do routing schemes contribute to the simulation success of distributed models? In other words, can the differences in the rainfall-runoff transformation process be better understood by running computed runoff volumes from a variety of distributed models through a common routing scheme? Such experiments are necessary complements to validating distributed models with interior-point flow and soil moisture observations in that we are attempting to generate 'the right results for the right reasons.'

What are the effects of the spatial variability of rainfall and basin physiograpic features on runoff generation processes? What physical characteristics (basin shape, feature variability) and/or rainfall variability warrant the use of distributed hydrologic models for improved basin outlet simulations? The corollary question for the NOAA/NWS is: at what river forecast points can we expect distributed models to effectively capture essential spatial variability so as to provide better simulations and forecasts?

What is the potential for distributed models set up for basin outlet simulations to generate meaningful hydrographs at interior locations for flash flood forecasting? Inherent in this question is the hypothesis that better outlet simulations are the result of accurate hydrologic simulations at points upstream of the gauged outlet. For the NOAA/NWS, we restate this question as: can distributed runoff and flow predictions for small, ungauged locations be used to improve upon the existing NOAA/NWS flash flood forecasting procedure?

What are the advantages and disadvantages associated with distributed modeling (versus lumped) in hydrologically complex areas using existing model forcings? DMIP 1 was limited to experiments in test basins in the southern Great Plains. These basins contain few complications such as snow accumulation and melt, forcing data scarcity, and orographic precipitation patterns. Many distributed hydrologic models have been developed to account for such complexities through accounting for slope, aspect, governing albedo, etc. (e.g., Wigmosta et al., 1994). The NOAA/NWS corollary is: what can be improved over the current lumped model (Snow-17) used in the NWSRFS?

Is there a dominant constraint that limits the performance of hydrologic simulation and forecasting in mountainous areas? If so, is the major constraint the quality and/or amount of forcing data, or is the constraint related to a knowledge gap in our understanding of the hydrologic processes in these areas? In other words, given the current level of new and emerging data sets to drive advanced distributed models, can improvements be realized? Or, do we still not have data of sufficient quality in mountainous areas? As a corollary to the latter question, what data requirements can be specified for the NOAA/NWS to realize simulation and forecasting improvements in mountainous areas? Simpson et al. (2004) state that the primary limiting factors in the application of snow accumulation/melt models continue to be the 1) lack of spatially-resolved meteorological inputs corresponding to the model computational units, and 2) lack of spatially relevant observations of hydrologic and snowpack conditions. The NOAA ETL HMT instrumentation efforts in the American River hold great promise to explore this critical concern.

Can better identification of the rain/snow line improve simulations? Partitioning between rainfall and snow fall plays a major role in determining both the timing and amount of runoff generation in high altitude basins (Kim et al., 1998). Advanced instrumentation such as vertically pointing wind profilers and S-Band radars have been used to detect freezing levels by locating the bright-band height (BBH) (White et al., 2002). For the NOAA/NWS, such information is critical. Advanced sensors from the NOAA ETL HMT (e.g. Ralph et al., 2003) will provide new data products to explore this critical question.

What are the dominant scales (if any) in mountainous area hydrology? Mismatches exist between the spatial and temporal scales of observations and the scales over which snowpacks and runoff vary (Simpson et al. (2004). For the NOAA/NWS, the question can be restated as: is there an appropriate modeling scale in the mountainous areas that captures the essential rain/snow processes?

DESCRIPTION OF PROPOSED SITES

Figure 1 shows the two major geographic regions for the experiments to be conducted in DMIP 2. As seen in Figure 1, the Oklahoma region and watersheds in DMIP 1 will be used. Second, we propose two neighboring basins in the Sierra Nevada mountains as good candidates for hydrologically complex areas. These two western basins have been studied by numerous researchers, thus possibly reducing project ‘spin-up’ costs for prospective participants.

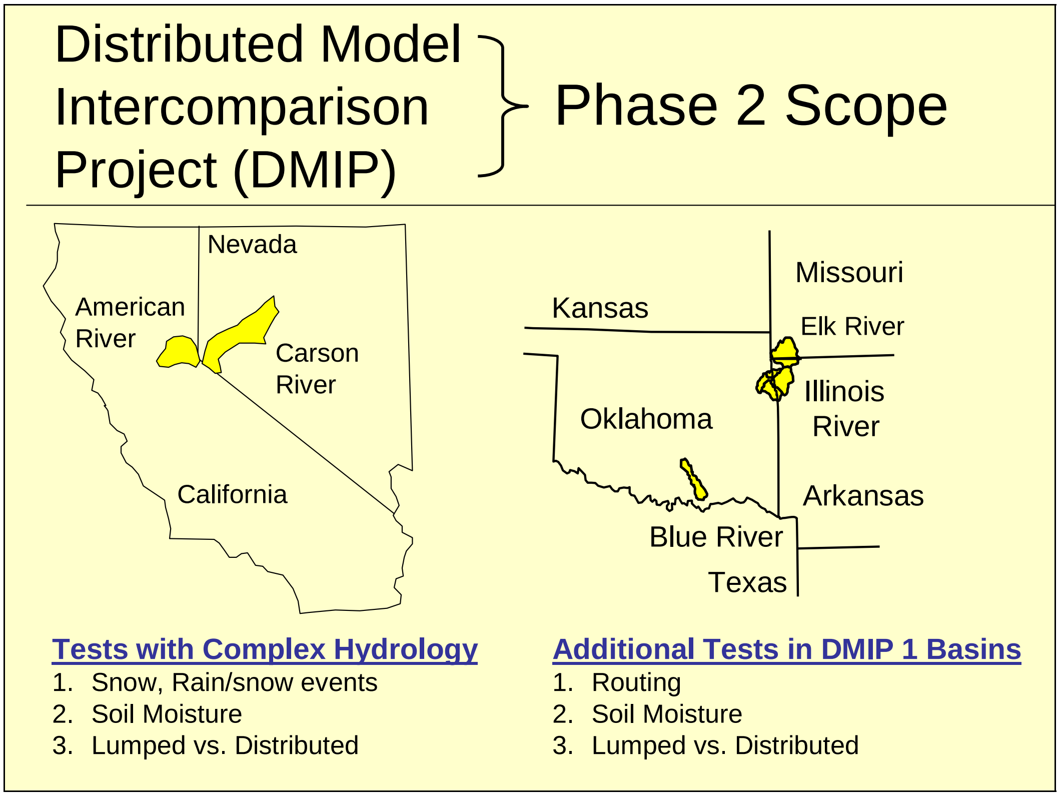

Figure 1. The geographic scope of DMIP 2 experiments

OVERVIEW OF EXPERIMENTS

For both areas, calibrated and un-calibrated simulations from participants' distributed models will be tested against observed streamflow and corresponding calibrated and uncalibrated lumped-model simulations. These will essentially follow the DMIP 1 Project Design and Modeling Instructions (Smith et al., 2004).

In the Oklahoma area, we propose a 'pseudo' forecast experiment similar to that undertaken by the WMO (1992). Participants will use their calibrated (with NEXRAD re-analysis data) distributed models. Forecast-quality data from numerical weather models will be made available.

We also propose that participants set up their model to run over an area encompassing the Oklahoma Mesonet shown in Figure 1. Models can be set up at any resolution, but must convert the soil moisture estimates to the 4km grid scale. We propose to compare computed and observed soil moisture contents at the 0-25mm and 25-75mm depth ranges. Models will not perform routing, only water balance computations. No model calibration will be performed. We propose to evaluate state variables: soil moisture and runoff volumes.

In another series of experiments, we propose to rout participants' runoff time series through a common channel routing scheme. This will help discern differences amongst the participants' rainfall-runoff mechanisms. We propose that participants generate runoff volumes (aggregated to one hour time step) at the 4km grid scale. Here, participants provide the runoff that they use in their models before hillslope and channel routing. We will ingest the runoff volumes and route them through the HL distributed model using kinematic hillslope and channel routing. We will then compute goodness-of-fit statistics. We propose to run such simulations for a 2-3 year period on the Blue and Tahlequah River basins.

In the American and Carson sites, we propose a general multi-model inter-comparison of lumped and distributed models similar to DMIP 1. Models will be parameterized and set up to generate calibrated and uncalibrated simulations of streamflow, snow cover, and soil moisture, depending on the basin. These experiments are designed to take advantage of the instrumentation efforts of the HMT in the North Fork of the American River. In the HMT, a dense network of surface gauging sites is planned as well as advanced radar platforms, providing observations in the cold seasons through 2008. These data sets will facilitate a multi-institutional examination of the required level of network density for complex regions. We propose simulations with and without the data from the HMT to demonstrate the expected benefits from advanced sensors and higher density networks.

EXPECTED RESULTS

We envision that DMIP 2 will provide a wealth of results that can help fill the identified knowledge gaps. First, based on updated and revised radar precipitation data sets, we expect to confirm the primary results of DMIP 1 (Reed et al., 2004) regarding lumped and distributed models in hydrologically simple terrain. Large-scale comparison of simulated and observed soil moisture will undoubtedly add to our understanding of distributed modeling to correctly model interior processes. The forecast component of DMIP 2 should underscore the issues surrounding operational river and flash flood forecasting. As occurred in DMIP 1, DMIP 2 will provide a positive opportunity for developers to evaluate their models in yet another arena, potentially uncovering needed algorithmic and/or science corrections or enhancements.

We also expect that DMIP 2 will provide multiple opportunities to develop data requirements for modeling and forecasting in hydrologically complex areas via the NOAA ETL HMT. We expect DMIP 2 to positively impact forecasting operations at the relevant RFCs through successful technology transfer. Potentially, candidate models could be transferred to the RFCs and run in parallel with their existing models. Research into the questions posed by this plan could be applied to either existing RFC tools and data sources or to new tools and data sources developed for DMIP 2.

REFERENCES

Carpenter, T.M., and Georgakakos, K.P., 2004. Intercomparison of lumped versus distributed hydrologic model ensemble simulations. Journal of Hydrology, submitted.

Johnson, D., Smith, M., Koren, V., and Finnerty, B., 1999. Comparing mean areal precipitation estimates from NEXRAD and rain gauge networks. Journal of Hydrologic Engineering, Vol. 4, No. 2, April, 117-124.

Kim, J., Miller, N.L., Guetter, A.K., and Georgakakos, K.P., 1998. River flow response to precipitation and snow budget in California during the 1994/1995 winter. Journal of Climate, Vol. 11, 2376-2386.

Koren, V., Reed, S., Moreda, F., Smith, M., Zhang, Z., Cui, Z., 2005. Evaluation of a grid-based distributed hydrological model over a large area: model uncertainties at different scales. Presented during the VIIth IAHS Scientific Assembly, Foz do Iguaçu – Brazil, April 03 to 09, 2005.

National Research Council (NRC), 2000. Grand Challenges in Environmental Sciences. Committee on Grand Challenges in Environmental Sciences, Oversight Commission onfor the Committee on Grand Challenges in Environmental Sciences, National Academy Press, Washington, D.C., 96pp.

NOAA, 2004. New Priorities for the 21st Century-NOAA's Strategic Plan. Available from http://www.spo.noaa.gov/pdfs/NOAA%20Strategic%20Plan.pdf

NWS, 2004a. National Weather Service Strategic Plan for 2005-2010. Available from http://www.weather.gov/sp/NWS_draft_strategic_plan_10-15-04.pdf

NWS, 2004b. The NWS Integrated Water Science Plan (IWSP), Report of the IWSP team.

Ralph, F.M., Neiman, P.J., Kingsmill, D.E., Persson, P.O.G., White, A.B. Strem, E.T., Andrews, E.D., and Antweiler, R.C., 2003. The impact of a prominent rain shadow on flooding in California's Santa Cruz Mountains: a CALJET case study and sensitivity to the ENSO cycle. J. Hydrometeorology, 4, 1243-1264.

Reed, S., Koren, V., Smith, M., Zhang, Z., Moreda, F., Seo, D.-J., and DMIP Participants, 2004. Overall distributed model Intercomparison project results, Journal of Hydrology, Vol. 298, Nos. 1-4, 27-60.

Simpson, J.J., Dettinger, M.D., Gehrke, F., McIntire, T.J., and Huffurd, G.L., 2004. Hydrologic scales, cloud variability, remote sensing, and models: Implications for forecasting snowmelt and streamflow. Weather and Forecasting, Vol. 19, April, 251-276.

Smith, M.B., Seo, D. -J., Koren, V. I., Reed, S., Zhang, Z., Duan, Q.-Y., Moreda, F., and Cong, S., 2004. The distributed model intercomparison project (DMIP): motivation and experiment design. Journal of Hydrology, Vol. 298, Nos. 1-4, 4-26.

Smith, M.B., Koren, V., Finnerty, B., Johnson, D., 1999. Distributed Modeling: Phase 1 Results, NOAA Technical Report NWS 44, February, 250pp.

Stellman, K.M., Fuelberg, H.E., Garza, R., and Mullusky, M., 2001. An examination of radar and rain gauge-derived mean areal precipitation over Georgia watersheds. Journal of Hydrometeorology, Vol. 16, February, 133-144.

Wang, D., Smith, M.B., Zhang, Z., Reed, S., and Koren, V.I., 2000. Statistical comparison of mean areal precipitation estimates from WSR-88D, operational, and historical gauge networks. 15th Annual Conference on Hydrology, 80th Meeting of the AMS, Long Beach, CA., January 10-14, J2.17

White, A.B., Gottas, D.J., Strem, E.T., Ralph, F.M., and Nieman, P.J., 2002. An automated brightband height detection algorithm for use with Doppler radar spectral moments. Journal of Atmospheric and Oceanic Technology, Vol. 19, May, 687-697.

Wigmosta, M.S., Vail, L.W., and Lettenmaier, D.P., 1994. A distributed hydrology-vegetation model for complex terrain. Water Resources Research, Vol. 30, No. 6, 1665-1679.

World Meteorological Organization, (WMO) 1992. Simulated real-time intercomparison of hydrological models, Operational Hydrology Report No. 38, WMO-No. 779, Secretariate of the World Meteorological Organization, Geneva, Switzerland.

Young, C.B., Bradley, A.A., Krajewski, W.F., Kruger, A., 2000. Evaluating NEXRAD multi-sensor precipitation estimates for operational hydrologic forecasting. Journal of Hydrometeorology, Vol. 1, June, 241-254.