WSTB

A newsletter from the Water Science and Technology Board — *National Research Council*

In This Issue

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Land Data Assimilation Systems

BY PAUL HOUSER

Accurate assessment of the spatial and temporal variation of surface hydrology is essential for addressing a wide variety of highly socially-relevant science, education, application, and management issues. Rainfall-runoff prediction, meteorologic processes studies, climate system and ecosystem modeling, and soil system science all greatly benefit from improved knowledge of land surface conditions. Improved land surface water and energy storage estimates also find direct application in agriculture, forest ecology, civil engineering, water resources management, and crop system modeling. As people increasingly modify the land surface, concern grows about the ensuing consequences for weather, climate, water supplies, crop production, biochemical cycles, and ecological balances of the biosphere at various time scales (Wetzel and Woodward, 1987).

Accurate initialization of land surface moisture and energy stores in weather and climate system models is critical for extended atmospheric and hydrologic prediction because of their regulation of surface water and energy fluxes between the surface and atmosphere over a variety of time scales (Shukla and Mintz, 1982). Soil moisture, temperature, and snow exhibit persistence on seasonal-to-interannual time scales; together with external forcing and internal land surface dynamics, this persistence has important implications for the extended prediction of climatic and hydrologic extremes (Koster and Suarez, 1995). Because soil moisture, temperature, and snow are integrated states, errors in land surface forcing and parameterization accumulate in these stores, which leads to incorrect surface water and energy partitioning.

However, new high-resolution land surface observations are becoming available that will provide the additional information necessary to constrain land surface predictions at mul-

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NEW REPORT

Inland Navigation System Planning: The Upper Mississippi River-Illinois Waterway

BY JEFFREY JACOBS

The Upper Mississippi River-Illinois Waterway (UMR-IWW) system is an important component of the nation's inland navigation systems. The 29 locks and dams on the Upper Mississippi River were constructed and are operated by the U.S. Army Corps of Engineers. In addition to commercial navigation, sport fishing, recreational boating, and tourism are popular activities on the Upper Mississippi River and generate billions of dollars per year for the regional economy.

Waterway traffic congestion presents a problem to towboat operators. Although congestion on the waterway's locks is spotty, towboat operators occasionally must wait several hours before passing through some locks, especially those on the lower portion of the Upper Mississippi.

In the late 1980s, the Corps began a feasibility study to gauge the economic viability of extending several locks on the UMR-IWW. Most of the waterway's locks, constructed in the 1930s and 1940s, are 600 feet long. But tows on the waterway today are frequently 1,200 feet long, which requires that they be split in order for them to pass through the locks. The additional time required for these multiple lockages increases shipping costs. The U.S. com-

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Paul R. Houser is the head of the Hydrological Sciences Branch at NASA's Goddard Space Flight Center, Greenbelt, MD.

CURRENT PROJECTS

Assessing the Scientific Basis of the Total Maximum Daily Load Approach to Water Pollution Reduction

At the request of Congress, the WSTB has initiated a superfast-track study to review of the quality of science used to develop and implement Total Maximum Daily Loads (TMDLs). The TMDL program, part of the Clean Water Act, requires states to (1) identify sources of pollution to "impaired" water bodies, (2) quantify the relative contributions to different pollutant loadings and their origins, and (3) implement management practices would reduce pollutant loadings and thus achieve water quality standards. New rules for the program were written by EPA in 2000, but will not be implemented until October 2001, during which time Congress is seeking input on the program from the WSTB. The study will investigate the scientific basis underlying the development and implementation of Total Maximum Daily Loads (TMDLs) for water pollution reduction, focusing on (1) what information is needed to determine TMDLs for impaired waters, (2) the sufficiency of knowledge about point and nonpoint sources of pollution, (3) the state of monitoring and modeling to assess and predict pollutant loads, and (4) the effectiveness of management approaches in controlling nonpoint source pollution.

In order to meet a June 1, 2001, deadline imposed by Congress, the first phase of the study is being carried out by a committee of seven experts: chairman Kenneth Reckhow, Duke University; Anthony Donigian, AquaTerra; James Karr, University of Washington; Jan Mandrup-Poulsen, Florida DEP; Vladmir Novotny, Marquette University; Richard Smith, USGS; and Christopher Yoder, Ohio EPA. Len Shabman, WSTB's visiting scholar from Virginia Tech, is providing additional expertise. The first of two committee meetings was held January 24–26, 2001 in Washington, DC. Multiple presentations from a wide variety of stakeholder groups addressed the committee during the two-day open session. The second meeting, to be held in closed session, is scheduled for March 8–10, 2001. The first phase of the study is being funded by EPA.

The second phase of the study draws heavily from the WSTB's proposed study of nonpoint source pollution. It will be conducted by an expanded committee of 15 members who will meet approximately six times. Funding for Phase 2 is being solicited from multiple federal agencies in addition to EPA. For further information or to make nominations for the Phase 2 committee, contact Laura Ehlers at 202-334-3422 or *lehlers@nas.edu*.

Agenda for Water Resources Research in the 21st Century

The WSTB has sent its report about water management challenges of the 21st century and the adequacy of the water research arrangements to meet those challenges to external review. The

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tiple scales. These constraints can be imposed in two ways (Figure 1). Firstly, by forcing the land surface primarily by observations (such as precipitation and radiation), the often severe atmospheric numerical weather prediction land surface forcing biases can be avoided. Secondly, by employing innovative land surface data assimilation techniques, observations of land surface storages such as soil temperature and moisture can be used to constrain unrealistic simulated storages. These land data assimilation systems also have the ability to maximize the utility of limited land surface observations by propagating their information throughout the land system to unmeasured times and locations. Data assimilation is a scientific tool that can not only lead to better predictions, but also helps to diagnose model weaknesses and suggests where better parameterization is needed. The fusion of modeling and observations via data assimilation requires access to large volumes of surface atmospheric and hydrologic variables, usually in near-real time.

Significant progress has been made in land-surface observation and modeling at a wide range of scales. Projects such as the International Satellite Land Surface Climatology Project (ISLSCP), the Global Soil Wetness Project (GSWP), and the GEWEX Continental-Scale International Project (GCIP), among others have paved the way for the development of operational Land Data Assimilation Systems (LDAS). The development of LDAS serves as an integrating linkage between a variety of Earth science disciplines and geographical locations. But most importantly, LDAS integrates state-of-the-art modeling and observation on a operational basis to provide consistent high quality land states in a timely enough manner to be used in real-time applications.

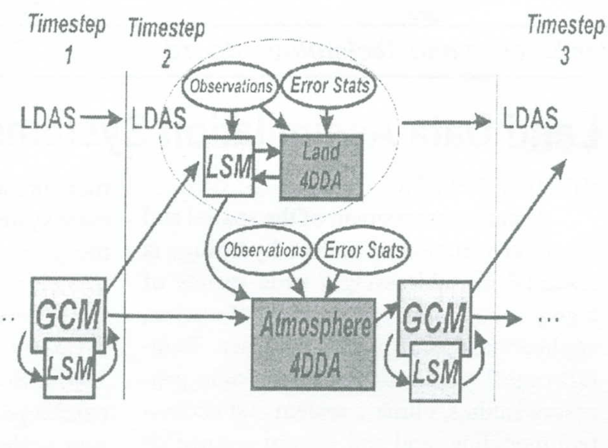

Figure 1: Interaction of the *Land Data Assimilation Scheme* (LDAS) with an operational *Numerical Weather Prediction* (NWP) system. The atmospheric *General Circulation Model* (GCM) is coupled with the *Land Surface Model* (LSM), and both use a *4-Dimensional Data Assimilation* (4DDA) process to integrate past forecasts with observations to improve performance.

Remote Sensing of the Land Surface: The observational emphasis of LDAS is to assimilate spatially-distributed observations (i.e., remotely sensed observations) of the land surface that will provide memory to land-atmosphere interaction. Remote observations of interest include temperature, soil moisture (surface moisture content, surface saturation, total water storage), other surface water bodies (lakes, wetlands, large rivers) and snow (areal extent, snow water equivalent).

Remote sensing of surface temperature is a relatively mature technology. The land surface emits thermal infrared radiation at an intensity directly related to its emissivity and temperature. The absorption of this radiation by atmospheric constituents is smallest in the 3 to 5 and 8 to 14 μm wavelength ranges, making them the best windows for sensing land surface temperature. Some errors due to atmospheric absorption and improperly specified surface emissivity are possible, and the presence of clouds can obscure the signal. Generally, surface temperature remote sensing can be considered an operational technology, with many spaceborne sensors making regular observations (i.e., Landsat TM, AVHRR, MODIS, and ASTER) (Lillesand and Kiefer, 1994). The evolution of land surface temperature is linked to all other land surface processes through physical relationships, which makes its assimilation possible.

Remote-sensing of soil moisture content is a developing technology, although the theory and methods are well established (Eley, 1992). Long-wave passive microwave remote-sensing is ideal for soil moisture observation, but there are technical challenges in correcting for the effects of vegetation and roughness. Soil moisture remote sensing has previously been limited to aircraft campaigns (e.g. Jackson, 1997a), or analysis of the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) (Jackson, 1997b). SSM/I has also been successfully employed to monitor surface saturation/inundation (Basist and Grody, 1997). The EOS-Advanced Microwave Sounding Unit (AMSR) instrument will provide additional C-band microwave observations that may be useful for soil moisture determination . The Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), which is very similar to AMSR, is much better suited to soil moisture measurement (because of its 10 Mhz channels) than SSM/I, and is also currently available. All of these sensors have adequate spatial resolution for land surface applications, but have a very limited quantitative measurement capacity, especially over dense vegetation. However, Sipple *et al.* (1994) demonstrated that it is possible to determine saturated areas through dense vegetation using SMMR, which can greatly aid land surface predictions. Because of the large error in remotely-sensed microwave observations of soil moisture, there is a real need to maximize its information by us-

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ing algorithms (such as data assimilation) that can account for its error and that extend its information in time and space.

There is a potential to monitor variations in total water storage (ground water, soil water, surface waters (lakes, wetlands, rivers), water stored in vegetation, snow and ice) using satellite observations of the time variable gravity field. The Gravity Recovery and Climate Experiment (GRACE), an Earth System Science Pathfinder mission, will provide highly accurate estimates of changes in terrestrial water storage in large watersheds when it is launched this year. Wahr *et al.* (1998) note that GRACE will provide estimates of variations in water storage to within 5 mm on a monthly basis. Rodell and Famiglietti (1998) have demonstrated the potential utility of these data for hydrologic applications, including their application in large (>150,000 km^2) watersheds; and they further discuss the potential power of GRACE for constraining modeled water storage in land surface models when combined with surface soil moisture and altimetery observations. Birkett (1998) demonstrated the potential of satellite radar altimeters to monitor height variations over inland waters, including climatically-sensitive lakes and large rivers and wetlands. Such altimeters are currently operational on the ERS-2 and TOPEX/POSEIDON satellites, and are planned for the ENVISAT and JASON-1 satellites.

Key snow variables of interest to LDAS include areal coverage and snow water equivalent. While the estimation of snow water equivalent by satellite is currently in research mode, snow areal extent can be routinely monitored by many operational platforms, including AVHRR, GOES and SSM/I. Recent algorithm developments even permit the determination of the fraction of snow cover within Landsat-TM pixels (Rosenthal and Dozier, 1996). Cline *et al.* (1998), describe an approach to retrieve SWE from the joint use of remote sensing and energy balance modeling.

Modeling of the Land Surface: Recent advances in understanding soil-water dynamics, plant physiology, micrometeorology, and the hydrology that control biosphere-atmosphere interactions have spurred the development of Land Surface Models (LSMs), whose aim is to represent simply yet realistically the transfer of mass, energy, and momentum between a vegetated surface and the atmosphere (Dickinson *et al.*, 1993; Sellers *et al.*, 1986). LSM predictions are regular in time and space, but these predictions are influenced by model structure, errors in input variables and model parameters, and inadequate treatment of sub-grid scale spatial variability. Consequently, LSM predictions of land surface hydrology and land surface states will likely be much improved by the assimilation strategies.

There are many different approaches to land surface prediction, which has lead to great diversity in LSMs. Three recent LSMs that are currently used in LDAS are presented here. These are the Mosaic LSM of Koster and Suarez (1992) and Koster *et al.* (1998), the National Centers for Environmental Prediction (NCEP), Oregon State University (OSU), United States Air Force (USAF), and Office of Hydrology (OH) LSM, called NOAH, and the recently emerging Common Land Model (CLM).

The Mosaic LSM addresses the problem of subgrid heterogeneity by subdividing each GCM grid cell into a user-specified mosaic of tiles (after Avissar and Pielke, 1989), each tile having its own vegetation type and hence water and energy balance. Surface flux calculations for each tile are similar to those described by Sellers *et al.* (1986). Tiles do not directly interact with each other, but influence each other indirectly, by their collective influence on the overlying atmosphere. Like the plethora of LSMs that have been developed over the past decade (e.g. the PILPS participants, Henderson-Sellers *et al.* [1993]), Mosaic is well suited to modeling the vertical exchange of mass, energy and momentum with the overlying atmosphere, but includes a poor representation of lateral moisture movement, which significantly controls variations in soil water, surface energy fluxes and runoff. Recognizing this weakness, Koster *et al.* (1998) developed a new, catchment-based LSM that includes a more realistic representation of hydrological processes, including the lateral transport of soil water through the subsurface. The catchment-based model, which relies heavily on the concepts originally put forth by Famiglietti and Wood (1994) (i.e. the TOPLATS model), will represent a major advance in LSMs for the following two reasons. First, the TOPMODEL [Beven and Kirkby, 1979], topographically-based framework will result in improved runoff prediction, and consequently, more realistic catchment-scale water balance. Second, the downslope movement of moisture within the watershed will yield sub-catchment-scale variations of surface and unsaturated-zone moisture content, which will result in more realistic prediction of within-catchment variations in surface fluxes. Improved simulation of runoff will ultimately result in a more realistic flux of continental streamflow from the land to the oceans, and similarly, the within-catchment variations in surface fluxes result in more representative catchment-average exchanges with the atmosphere.

The NOAA-NOAH LSM simulates soil moisture (both liquid and frozen), soil temperature, skin temperature, snowpack water equivalent, snowpack density, canopy water content, and the traditional energy flux and water flux terms of the surface energy balance and surface water balance. This model has been used in a) the NCEP-OH submission to the PILPS-2d tests for the Valdai, Russia site, b) the emerging, realtime, U.S.-domain Land Data Assimilation System (LDAS), c) the coupled NCEP mesoscale Eta model [Chen *et al*, 1997] and the Eta model's companion 4-D Data Assimilation System (EDAS), as well as in d) the coupled NCEP global Medium-Range Forecast model (MRF) and its companion 4-D Global Data Assimilation System (GDAS).

The Common Land Model (CLM) is being developed by a *grassroots* collaboration of scientists who have an interest in making a general land model available for public use. By *grassroots*, we mean that the project is not being

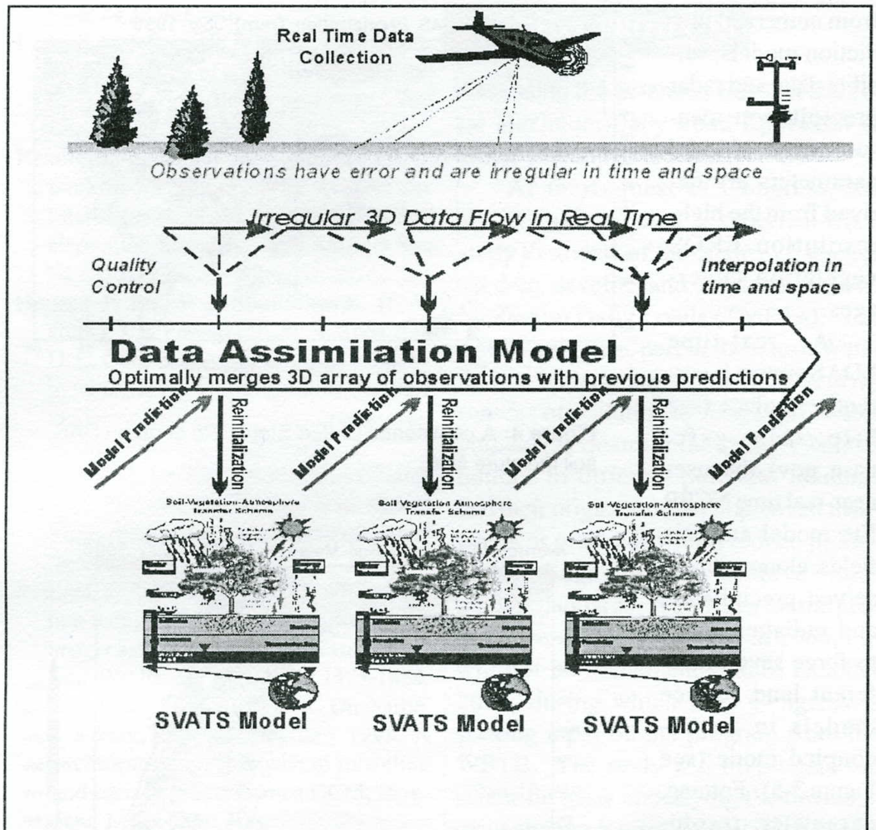

Figure 2: The land-surface data assimilation process.

controlled by any single organization or scientist, but rather, the scientific steering is judged by the community. However, the project began at a subgroup meeting at the 1998 NCAR CSM meeting, and there is a plan to implement the CLM into the NCAR CSM this year. The CLM development philosophy is that only proven and well-tested physical parameterizations and numerical schemes shall be used. The current version of the CLM includes superior components from each of three contributing models: LSM (G. Bonan, NCAR), BATS (R. Dickinson) and IAP (Y.-J. Dai). The CLM code management is similar to *open source*, in that, use of the model implies that any scientific gain will be included in future versions of the model. Also, the land model has been run for a suite of test cases including many of the PILPS (Project for the Intercomparison of Land Parameterization Schemes) case studies. These include FIFE (Kansas, USA), Cabauw (Netherlands), Valdai (Russia), HAPEX (France), and the Amazon (ARME and ABRACOS).

Justification for Using an Uncoupled LSM: There are strong justifications for studying an LSM uncoupled from atmospheric and ocean models. Coupling the LSM to an atmospheric model allows for the study of the interaction and feedbacks between the atmosphere and land surface. However, coupled modeling also imposes strong land surface forcing biases predicted by the atmospheric model on the LSM. These biases in precipitation and radiation can overwhelm the behavior of LSM physics. In fact, several NWP centers must 'correctively nudge' their LSM soil moisture toward climatological values to eliminate its drift. By using an uncoupled LSM, one can better specify land surface forcing using observations, use less computational resources, and address virtually all of the relevant scientific questions. The physical understanding and modeling insights gained from implementing distributed, uncoupled land-surface schemes with observation-based forcing has been vividly demonstrated in recent GEWEX retrospective off-line land surface modeling projects known as PILPS-2c and the Global Soil Wetness Project (Koster and Milly, 1997).

Land Surface Data Assimilation: Charney *et al.* (1969) first suggested combining current and past data in an explicit dynamical model, using the model's prognostic equations to provide time continuity and dynamic coupling amongst the fields. This concept has evolved into a family of techniques known as *four-dimensional data assimilation* (4DDA). "Assimilation is the process of finding the model representation which is most consistent with the observations" (Lorenc, 1995). In essence, data assimilation merges a range of diverse data fields with a model prediction to provide that model with the best estimate of the current state of the natural environment so that it can then make more accurate predictions (See Figure 2). The application of data assimilation in hydrology has been limited to a few one-dimensional, largely theoretical studies (i.e., Entekhabi *et al.*, 1994; Milly, 1986) primarily due to the lack of sufficient spatially-distributed hydrologic observations (McLaughlin, 1995). However, the feasibility of synthesizing distributed fields of soil moisture by the novel application of 4DDA applied in a hydrological model was demonstrated by Houser *et al.* (1998). Six Push Broom Microwave Radiometer (PBMR) images gathered over the USDA-ARS Walnut Gulch Experimental Watershed in southeast Arizona were assimilated into the TOPLATS hydrological model using several alternative assimilation procedures. Modification of traditional assimilation methods was required to use these high density PBMR observations. The images were found to contain horizontal correlations with length scales of several tens of kilometers, thus allowing information to be advected beyond the area of the image. Information on surface soil moisture was also assimilated into the subsurface using knowledge of the surface-subsurface correlation. Newtonian nudging assimilation procedures were found to be preferable to other techniques because they nearly preserve the observed patterns within the sam-

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Land Data Assimilation Systems

pled region, but also yield plausible patterns in unmeasured regions, and allow information to be advected in time.

Land Data Assimilation Schemes (LDAS): The characterization of the spatial and temporal variability of water and energy cycles is critical for the improvement of our understanding of land surface-atmosphere interaction and the impact of land surface processes on climate extremes. Because accurate knowledge of these processes and of their variability is important for climate predictions, most NWP centers have incorporated land surface schemes into their models. However, errors in the NWP forcing accumulate in the surface and energy stores, leading to incorrect surface water and energy partitioning and adversely affecting related processes. This has motivated the NWP centers to impose ad hoc corrections to the land surface states to prevent this drift. *Land Data Assimilation Schemes* (LDAS), which are uncoupled land surface schemes that are forced primarily by observations, and are therefore not affected by NWP forcing biases are currently under development. This research is being implemented in near real time using existing LSMs by NCEP, NASA, Princeton University, Rutgers University, the University of Maryland, and the University of Washington at a 1/8th° (about 10 kilometer) resolution across the United States to evaluate these critical science questions. The LDAS are forced with real time output from numerical prediction models, satellite data, and radar precipitation measurements. Model parameters are derived from the high-resolution EROS vegetation coverages.

A real-time LDAS system is currently in place (see http://ldas.gsfc.nasa. gov), that uses near-real time NCEP Eta model analysis fields, along with observed precipitation and radiation fields to force several different land surface models in an uncoupled mode (see Figure 3-5). Forcing, parameter, resolution, and prediction specifications for this North-American LDAS were carefully chosen by the interinstitution LDAS working group.

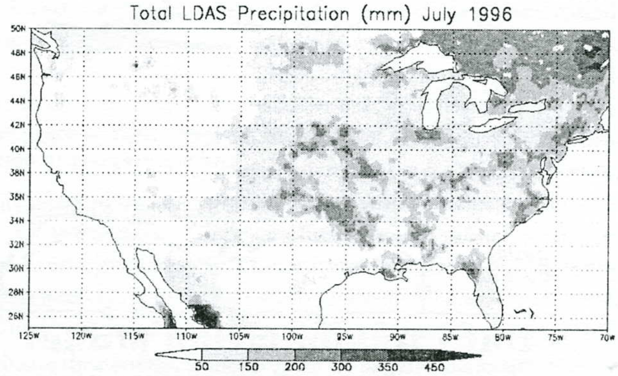

Figure 4: A continental United States 1/8 degree LDAS soil moisture field.

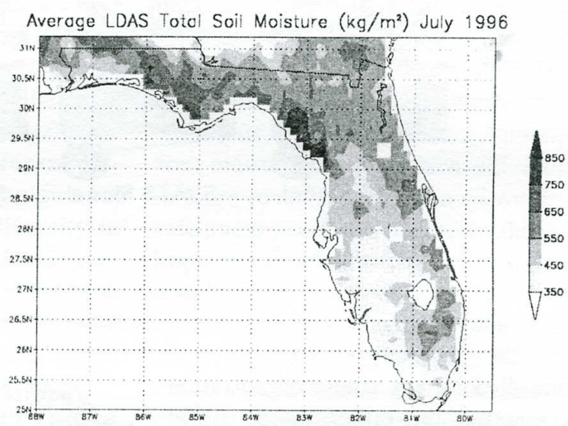

Figure 5: A 1/8 degree LDAS soil moisture field from Florida.

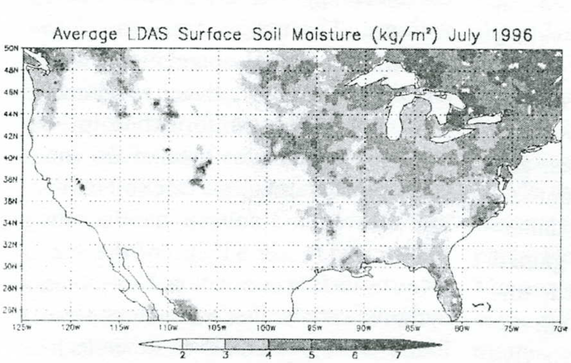

Figure 3: A continental United States 1/8 degree LDAS merged Eta model, NEXRAD Doppler radar, and gage precipitation field.

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CURRENT PROJECTS

Assessing the Scientific Basis of the Total Maximum Daily Load Approach to Water Pollution Reduction

At the request of Congress, the WSTB has initiated a superfast-track study to review of the quality of science used to develop and implement Total Maximum Daily Loads (TMDLs). The TMDL program, part of the Clean Water Act, requires states to (1) identify sources of pollution to "impaired" water bodies, (2) quantify the relative contributions to different pollutant loadings and their origins, and (3) implement management practices would reduce pollutant loadings and thus achieve water quality standards. New rules for the program were written by EPA in 2000, but will not be implemented until October 2001, during which time Congress is seeking input on the program from the WSTB. The study will investigate the scientific basis underlying the development and implementation of Total Maximum Daily Loads (TMDLs) for water pollution reduction, focusing on (1) what information is needed to determine TMDLs for impaired waters, (2) the sufficiency of knowledge about point and nonpoint sources of pollution, (3) the state of monitoring and modeling to assess and predict pollutant loads, and (4) the effectiveness of management approaches in controlling nonpoint source pollution.

In order to meet a June 1, 2001, deadline imposed by Congress, the first phase of the study is being carried out by a committee of seven experts: chairman Kenneth Reckhow, Duke University; Anthony Donigian, AquaTerra; James Karr, University of Washington; Jan Mandrup-Poulsen, Florida DEP; Vladmir Novotny, Marquette University; Richard Smith, USGS; and Christopher Yoder, Ohio EPA. Len Shabman, WSTB's visiting scholar from Virginia Tech, is providing additional expertise. The first of two committee meetings was held January 24–26, 2001 in Washington, DC. Multiple presentations from a wide variety of stakeholder groups addressed the committee during the two-day open session. The second meeting, to be held in closed session, is scheduled for March 8–10, 2001. The first phase of the study is being funded by EPA.

The second phase of the study draws heavily from the WSTB's proposed study of nonpoint source pollution. It will be conducted by an expanded committee of 15 members who will meet approximately six times. Funding for Phase 2 is being solicited from multiple federal agencies in addition to EPA. For further information or to make nominations for the Phase 2 committee, contact Laura Ehlers at 202-334-3422 or *lehlers@nas.edu*.

Agenda for Water Resources Research in the 21st Century

The WSTB has sent its report about water management challenges of the 21st century and the adequacy of the water research arrangements to meet those challenges to external review. The

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