

A TEN-YEAR VISION FOR RESEARCH ON TERRESTRIAL-ATMOSPHERIC INTERACTIONS: ADVANCING COUPLED LAND-ATMOSPHERE PREDICTION

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1. Abstract

This document presents a vision for progress in land-atmosphere interaction research, as it relates to improving weather and climate prediction systems. Rather than providing a comprehensive review of the issues in land-atmosphere research, as has been done in numerous, recent high-level documents, this report aims to isolate a handful of critical challenges and opportunities which will be prominent over the next ten years. In particular, issues related to the complex linkages between terrestrial hydrological and atmospheric processes and the challenge of working across numerous spatial and temporal scales is focused upon. As part of the core vision, issues related to emerging observation platforms and their impact on coupled land-atmosphere research are detailed. Critical areas of improvement in the current formulation of land-surface model parameterizations are presented as are their role in improving coupled weather and climate model prediction systems. Specific discussion is also given to defining the role of land data assimilation in land-atmosphere research. As a synthesis to the Vision elements, a coherent strategy is proposed for developing an integrated research program. The principal component of the implementation strategy includes the development of a land-surface parameterization (LSP) test-bed facility, whose mission will be to link the operational and research communities, provide conduits for emerging data streams into operational models and to integrate community research expertise into the next generation of models and land data assimilation systems. The document concludes with a logistical discussion on how the concepts proposed in the vision statement compliment proposed activities and infrastructure of the Consortium of Universities for the Advancement of Hydrological Sciences, Incorporated (CUAHSI).

2. Introduction: Problem statement and context

As of the writing of this document the world's population exceeds 6.2 billion with nearly two people being added every second (U.S. Census Bureau, 2002). Given that every single person requires a consistent fresh water supply to meet basic living requirements a significant burden is being placed on global freshwater resources. This burden is only expected to increase in the coming century as population continues to expand. In the U.S., as in other countries, land and water resources are forced to be utilized with ever increasing degrees of efficiency while resources of historically marginal quality are being counted on as mainstay supplies. Increased human demand for freshwater also implies decreasing supplies for the maintenance of existing ecosystems. The critical demand on efficient use of natural resources necessitates the development and implementation of reliable and robust operational environmental prediction systems. Predictions of environmental conditions such as weather, climate and hydrological conditions, must be applicable across a broad spectrum of projects as well as across a broad range of space and time scales. Simultaneously, these systems must be fed with high quality observations of surface and atmospheric conditions in order to sustain a high fidelity in prediction capability.

The recognition of land surface processes as critical components of the global water cycle cannot be overstated. The exchanges of energy and water at the Earth's surface, regulated by ecological and anthropological controls, constitute primary forcing and feedback mechanisms to the atmospheric system affecting weather and climate across a range of spatial and temporal scales. These processes modulate both fast and slow response fluctuations in the coupled land-atmosphere system. As noted in USGCRP (2001), "a scientific challenge is to understand the scales at which interactions and feedbacks of these processes occur, isolating the slower modes of variability from the faster for enhanced predictive ability at a wide range of scales." Accepting this viewpoint acknowledges that the coupled land-atmosphere system must be thoroughly understood and accurately represented in today's hydrometeorological and hydroclimatological prediction systems in order to have acceptable levels of confidence in their predictions. Advancing the strategies and opportunities for improving our observation, understanding and modeling of land-atmosphere interactions is the focus of this 10-Year Vision Statement.

To put this vision statement in the proper context, it is useful to review some of the progress that has been made over the past 10 years. In 1995, the United States Weather Research Program, with funding from NOAA and the NSF, formed a Prospectus Development Team charged with "recommending scientific directions...from a fundamental and theoretical perspective" (Emmanuel, 1995). What emerged from this effort was a prospectus outlining some 17 emerging basic research opportunities in weather and forecasting related research of which a significant fraction were focused on the land-atmosphere interactions. One of the principal points from this report was, "The main stumbling block to realizing significant progress in basic research and operational meteorology is the need for better measurements of the atmosphere, oceans and land surface..." This call has been followed up by numerous high-level reports, many of

which were sponsored by the National Research Council (NRC), which have consistently reiterated the need for improvements in understanding and representation of coupled land-atmosphere behavior, and for developing an improved capacity to observe the land surface states and fluxes and the planetary boundary layer. For example, Entekhabi et al. (1999) put forth a broad set of priority science questions and research strategies aimed at achieving progress in land surface hydrological research. Comprehensive in scope, Entekhabi et al. made a structured proposal for organizing an international effort to address key land surface hydrology research questions in basic process understanding, observational capacity development, data assimilation and modeling. Through summaries of the recent state of land-surface hydrological research, USGCRP (2001), Emmanuel et al. (1995), Entekhabi et al. (1999), NRC (1998), Rasmussen et al. (2001) and NRC (2002) have each forwarded broad agendas for continuing research over the next several years. While these “grand challenge” documents are not reviewed here in detail, their contents serve as the foundation for the social and scientific justification and theoretical premises for the present Vision Statement. From this point forth this statement seeks to articulate key elements from these broad research agendas through which additional research focus stands to yield a high probability of producing tangible results over the next 10 years. As such, the present work is limited in scope and expectations compared to the “grand challenge” documents and, instead, focus on very practical achievable objectives aimed at improving our understanding and simulation of land-atmosphere interactions.

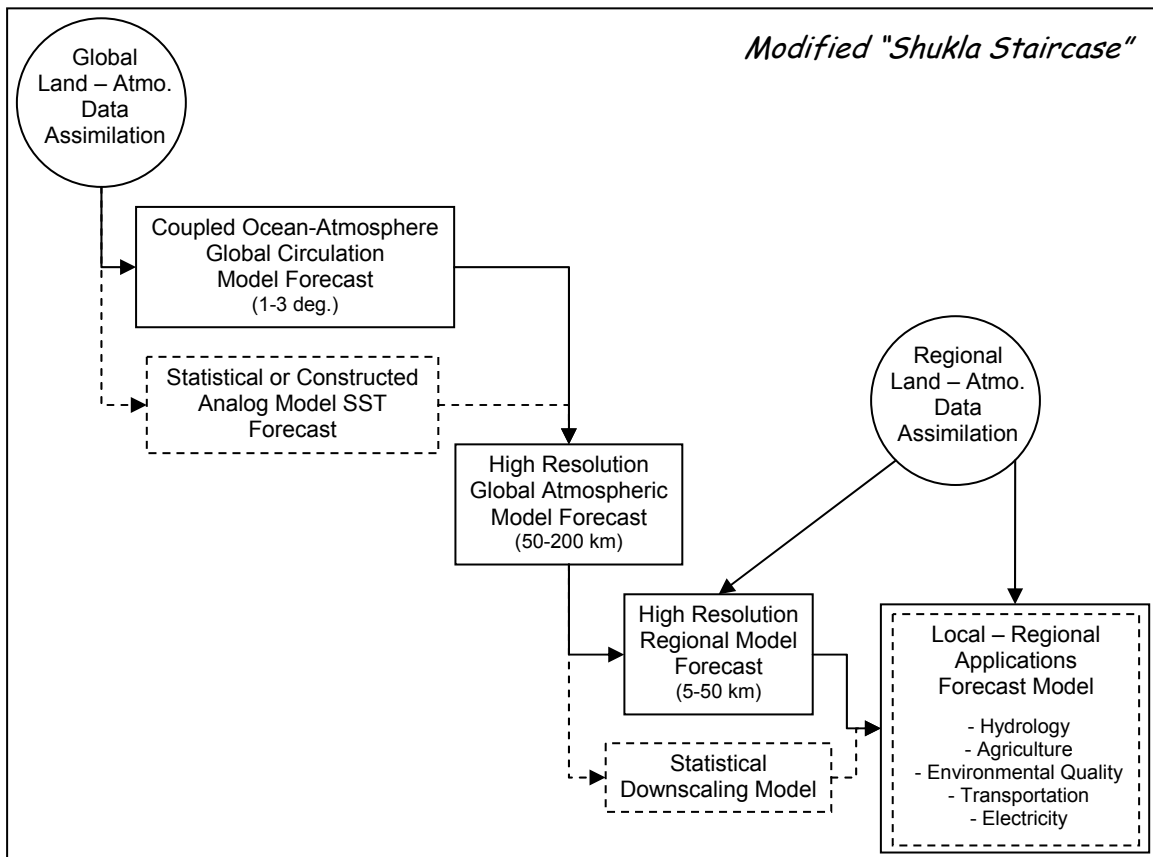


Figure 1.

Flowchart detailing the broad chain of activities involved in dynamical forecast generation; often referred to as the “Shukla staircase” after J. Shukla; a pioneer in climate prediction. Dashed lines represent optional components of the system that are based on statistical as opposed to dynamical techniques.

The Current Forecast Paradigm

A broadly accepted agenda for improving water cycle predictions across scales has been put forward in several of the strategic documents reference above. This agenda is centered on the premise of nesting numerical prediction tools, initialized with comprehensive data assimilation systems, across a range of spatial and temporal scales. As shown in Figure 1 (adapted from USGCRP (2001) and Rasmussen et al. (2001)) this forecast process usually begins with a global data assimilation system responsible for ingesting observations of surface and atmospheric states during a period leading up to the forecast initiation. Being global in scale, the density of observations and the detailed accuracy of the analyzed fields are expected to be relatively low. Nevertheless, such analyses should generally be sufficient for the initialization of a coarse scale O(100km, or 1 deg.) global circulation model (GCM). The GCM then executes a forecast cycle, of varying durations depending on the forecast problem. Presently, the coarse resolution of today’s GCM’s lend them most applicable to simulating and predicting broad synoptic scale weather and climate patterns. Although the quality of operational GCM forecasts has greatly improved over the past several years, their low spatial resolution often precludes their application to detailed weather and climate forecasts of key water cycle variables such as precipitation, evaporation, runoff and recharge.

A limited area model is then executed using the large-scale synoptic patterns forecasted by the GCM as lateral boundary forcing. The goal of the limited area prediction system is to greatly improve the spatial resolution of surface and atmospheric variables to a scale necessary to resolve key weather and climate forcing mechanisms and to be useful for applications prediction problems. In state of the art limited area models (LAMs), the prediction process is infused with a regional scale data assimilation system of which a land data assimilation system (or LDAS) is a key component. The LDAS is responsible for generating a relatively detailed representation of land surface state variables (e.g. soil moisture and temperature, land cover/land use, vegetation characteristics, snow cover and snow water equivalent) at the time of forecast initialization. A core element of the LDAS is the land-surface hydrology model used to create thermodynamically adjusted analyses. The regional atmospheric model coupled to a land surface parameterization (LSP), then executes its forecast cycle over a specified forecast duration.

Depending on the specific forecast objective, the limited area model forecast can be taken as is or used as input to higher resolution applications models such as a rainfall-runoff model, an air pollution transport model, an agricultural growth model, etc. (For the sake of the present work the discussion is restricted to hydrology models.) These applications models then form the basis of operational management decisions and planning activities. Lacking more promising or more practical alternatives we continue to endorse this dynamical-downscaling approach as a premise for the Vision presented below.

Scope

The 10-Year Vision presented herein is intended to be limited to key issues relating to terrestrial-atmospheric exchanges. Hence, this document is a practical interpretation of existing and proposed research agendas related to land-atmosphere interactions and is not intended to be a fully-encompassing assessment of hydrometeorological and hydroclimatological research as has been done in the aforementioned “grand challenge” documents. Specifically, this Vision statement seeks to put forth key issues, opportunities and recommendations for:

- 1) Identifying critical yet tractable problems related to land-atmosphere interactions
- 2) Presenting a few emerging research areas and observing systems that will be critical to addressing those problems
- 3) Proposing some strategic avenues for integrating research between the hydrologic and atmospheric science communities

Following the forecast paradigm shown in Fig. 1, this statement will concentrate on issues related to the observation and assimilation of land-surface data and lower atmospheric data and on issues related to the modeling of land-surface processes in each the GCM and the LAM.

A Brief Evolution of Land Surface Parameterizations

One area of research that has witnessed remarkable growth over the past 10-20 years has been in the development of land-surface physics parameterizations. These parameterizations have the primary responsibility of accounting for the energy and mass exchanges (including water) between the land surface and the lower atmosphere. In fact, much of our knowledge of the effects of vegetation and hydrology on weather and climate comes from models and their depiction of land-atmosphere interactions. Land-surface models coupled with atmospheric models simulate the absorption of radiation at the land surface, the exchanges of sensible and latent heat between land and atmosphere, storage of heat in soil, and the frictional drag of vegetation and other surface elements on wind. Hydrological processes in the models typically include: interception, throughfall, stemflow, infiltration, runoff, and basic snowpack dynamics. From simplistic beginnings in so-called “bucket” formulations, land-surface parameterizations (LSPs) have evolved to a sophisticated level (Figure 2). The evolution of LSPs can be broken into several generations based on key developments in their formulation.¹

¹ (Note: While no clear dividing line between generations is present in reality, this generational mapping serves to illustrate how LSPs have evolved to their current state and what evolutionary pathways might be expected over the next decade. Also, the generational mapping between land surface parameterizations between weather and climate models differs somewhat due to differences in the requirements of the various modeling systems. For the sake of discussion here we have focused more on the generational mapping of LSPs designed for climate models as they generally have lead the integration of new ecohydrological processes.)

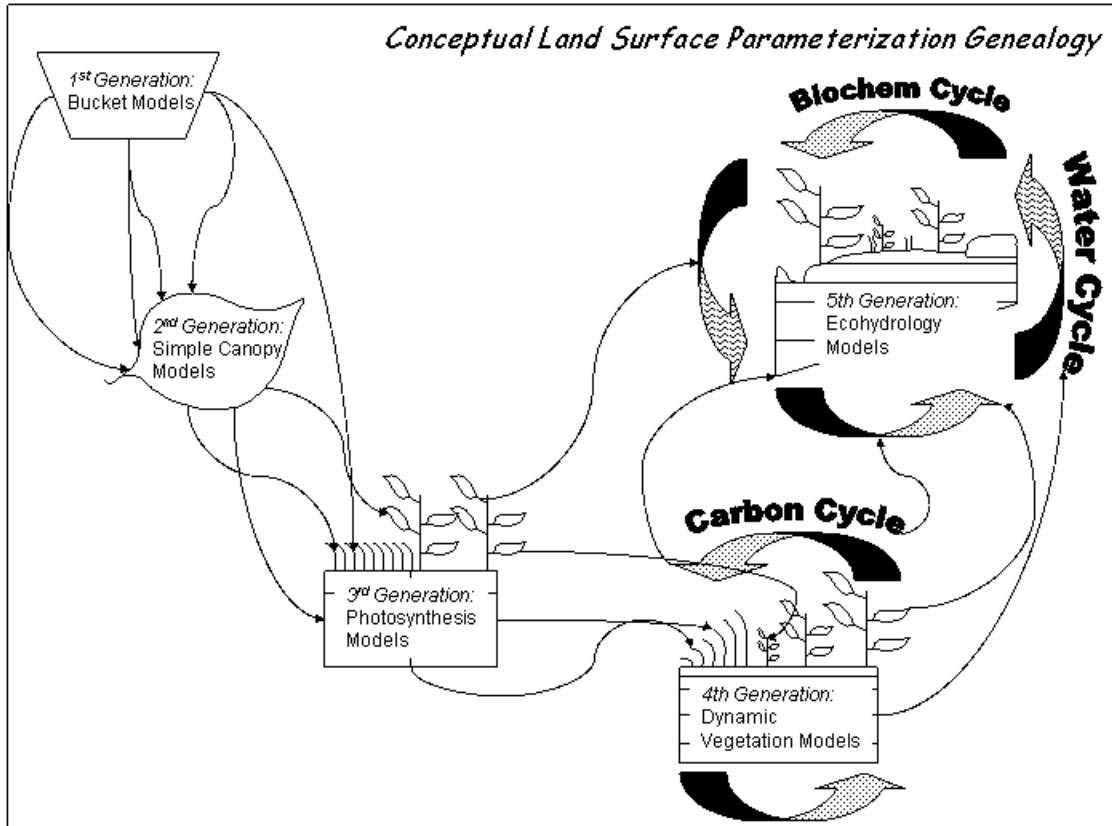


Figure 2.

Conceptual evolution of land surface parameterizations used in climate simulation models. The thin lines between the generations are meant to illustrate that there are many paths upon which various modeling systems have evolved, some of which could have “skipped” a generation in the process. As emphasized in the text this “genealogy” is meant to be illustrative more than a rigorous classification system.

- 1) First generation models parameterized land-atmosphere exchanges of heat and moisture using simple bulk aerodynamic transfer equations and simple prescriptions of albedo, surface roughness, and soil water (Sellers et al., 1997).
- 2) The first generation models evolved into a second generation of models such as the Biosphere-Atmosphere Transfer Scheme (BATS, Dickinson et al., 1993) or Simple Biosphere Model (SiB, Sellers et al., 1996a,b) that included simple formulations for more explicitly quantifying the effects of soil hydrology and vegetation on energy and water fluxes.
- 3) A third generation of models related photosynthesis to transpiration, and stomatal conductance to provide a more physically-consistent parameterization of energy, water, and carbon exchanges (Sellers et al., 1997). Third generation models, such as the Community Land Model (CLM) simulate energy, moisture, and momentum fluxes between land and atmosphere, the hydrologic cycle, and soil temperature (Bonan et al., 2002). Improved methodologies for representing snow cover and

soil hydrology over those present in second generation models is also a common feature of third generation models.

- 4) A fourth generation of models currently under development simulates the terrestrial carbon cycle and allows vegetation to change as climate changes (e.g. Berthelot et al., 2002)².

What lies ahead over the next decade or so is the evolution of the so-called ‘fifth-generation’ land-surface models. As the entire field of land-surface research diversifies so do the models themselves and thus the fifth-generation models are expected to represent an ever widening range of biogeophysical processes. These fifth-generation improvements are expected to include:

- a) More complete terrestrial hydrological formulations including improved vadose zone processes along with aquifer and stream/lake/wetland interactions
- b) Comprehensive aqueous phase biogeochemistry, which represents the principal components of key nutrient cycles such as nitrogen and phosphorous along with critical water quality parameters of interest to human applications (e.g. toxicity and salinity)
- c) Human management and alteration of the terrestrial water cycle to account for local to regional scale hydrologic exchanges such as groundwater pumping, inter-basin transfers, large-scale irrigation projects and the diminution of freshwater inputs to the world’s oceans.

However, because each of the various components (e.g. terrestrial and atmospheric hydrologic cycles, biogeochemical cycles, vegetation community evolution, human alteration) are intrinsically dependent upon one another, progress along any one pathway is likely to be dependent on progress in each of the other pathways. Much of the progress towards developing fifth-generation models will be dependent upon improving the collaboration between hydrologists, ecologists, chemists, engineers and water managers and those in the atmospheric modeling community. (The need for this integration is elaborated on in Section 3.3 below, which discusses the vision for specific improvements in fifth-generation LSPs.)

A practical example helps to illustrate the need for forwarding such an integrated modeling agenda. One of the key constituents to global warming is the production of methane from natural (and human-constructed) wetlands. The rate of methane production from wetlands is dependent on many biogeophysical parameters such as temperature, water availability and nutrient availability. The hydrology of a wetland is

² (Some third and fourth-generation models, such as the CLM, also include a separate module for vegetation dynamics and biogeography so that the plant functional types present in a grid cell change over time in response to disturbance and climate change (Bonan et al., 2003). Vegetation is updated in response to resource competition, allocation, mortality, biomass turnover, litterfall, establishment, and fire. The model simulates global biogeography, net primary production, and dynamics of tundra, boreal forest, northern hardwood forest, tropical rainforest, and savanna ecosystems that are consistent with observations.)

intricately linked to its geological setting and its relation to watershed characteristics such as contributing source areas, soil structures and stream/drainage network characteristics. The detailed hydrology controlling the horizontal redistribution of surface and subsurface water is currently not a working functionality in today's state-of-the-art, fully-coupled land-surface models. Without detailed hydrological representation on the catchment scale, today's models have no chance of tracing the biogeochemical pathways or aqueous phase chemistry cycles which control the growth and decay of plant communities that in turn control the release of methane. Only through the development of sophisticated, scale-appropriate models will we be able to address this kind of issue and further our understanding of how such surface processes influence our global climate.

3. Research vision

3.1 Where do we need to be in terms of understanding?

A basic goal of Earth systems research over the next ten years is to make measured improvements in advancing our weather and climate forecast systems closer to the theoretical limits of predictability. These limits themselves have yet to be clearly defined for a broad range of problems, and could potentially expand with increased understanding. Nevertheless, critical advances in process understanding, data acquisition and assimilation and numerical modeling will need to progress in tandem to achieve this goal. The "grand challenge" documents consistently place the improved integration of land-surface hydrology and atmospheric science as a leading research priority. The nature of the feedback between the land surface and atmosphere, and, perhaps equally as important, the human influence on this feedback, persist as unresolved issues. While much progress in improving our understanding of these feedbacks has been obtained over the past several decades, future advances will require the sustained commitment of resources and intellect.

A principal constraint of land-atmosphere interaction research is the cross-scale dependence of atmospheric forcing and land surface states and fluxes. Inherently, this feature results in a multi-scale problem precluding the application of many assumptions, which could potentially simplify the closure of water and energy budgets. Various processes and forcing mechanisms scale up and down in the coupled land-atmosphere system. Ideally, closure of spatially-distributed water and energy budgets from the small patch, to the watershed, to the continental, to the global scale all need be achieved simultaneously. Superimposed on issues of water and energy balance closure is the presence of climate change and variability. Hypothesized acceleration of the global water cycle under climate change scenarios could potentially complicate the long-term application of diagnostic research using historical data sets to future situations. Similarly, as computational resources improve, the gap between weather and climate prediction continues to erode. This erosion highlights the importance of being able to diagnose and adequately represent the various fast and slow response mechanisms of the coupled land-atmosphere system.

In order to link the water cycle across scales there must be improved understanding and representation of the energetics of water and in understanding its distribution in space and time. Further clarification of the roles of local versus remote sources of heat and moisture on weather and climate processes remains a key cross-cutting theme. Explicit physical treatment of complex processes such as atmospheric convection in the emerging generation of cloud resolving models should greatly assist in this capacity. However, a simultaneous increase in understanding in how surface processes modulate boundary layer structure and enhance or suppress precipitation initiation is needed to fully realize these gains. Over the next ten years research into land-atmosphere interactions needs to move beyond the simple statistical treatment of the effects of land-surface heterogeneity and further elucidate the effects of complex organizational states of land-surface features such as topography, vegetation and soil moisture. Focused field programs in boundary layer processes (e.g. CASES-97 (LeMone et al., 2000), IHOP-02 (Weckwerth et al., 2004)) have shown that this underlying complexity is intricately linked to the sustained generation of boundary layer circulations which often organize upscale to initiate mesoscale circulations. Linking the influences of organized surface features on the development organized atmospheric circulations remains as an unresolved yet tractable issue in hydrometeorological research given the expected progress in coupled land-atmosphere research over the next ten years.

Accepting the goal stated at the beginning of this subsection and the attendant complications, this Vision Statement aims to present practical challenges and opportunities in land-atmosphere interaction research. The requirements to address the current challenges and opportunities include; 1) high-impact advances in observation systems and data acquisition and interpretation, 2) advances in land-surface and boundary layer formulations, 3) advances in coupled data assimilation and prediction systems, and, with less emphasis here, specific advances in theoretical understanding. In the subsections below, each of these themes is presented from a hydrometeorological/hydroclimatological forecasting perspective. For the sake of brevity, physical processes are emphasized more than biochemical processes. It is the intent of this document that readers should come away with a clearer understanding of what is needed and, moreover, what they are most likely to expect in terms of meeting the above requirements. It is also the intent of this document to actively engage the various scientific communities in the collaborative address of the research issues presented.

3.2 Emerging observation platforms

As articulated in Emmanuel et al. (1995), sound improvements in weather and climate forecasts and, presumably, the understanding of the water cycle, are constrained by the capacity to effectively observe its various components and their exchanges. Hence, to realize the improvements proposed in this Vision Statement and to meet the “grand challenges” of earlier reports, a sustained effort in maintaining and improving observation systems must be undertaken. What follows in this subsection is a presentation of a few selected observation technologies that are expected to witness marked evolution over the next ten years. The discussion is centered on very practical

and definable advances in observing system capabilities that are expected to significantly impact land-atmosphere interactions research. Water cycle observation capacity building is clearly a need without borders as improvements in national observation networks are often tempered by the stagnation or decay of networks abroad. While the present discussion is centered on infrastructure within the U.S. it is wholly acknowledged that international capacity building is a critical element to improving the understanding and prediction of the global water cycle. Improvements in the global observing system are being coordinated through a variety of international programs (c.f. CEOP, 2004).

Weather Radar

The reliable generation of distributed, quantitative precipitation estimates (QPE) remains a principle challenge despite decades of research in instrumentation, network design and analytical methods. Currently, the operational weather radar network (Weather Surveillance Radars-1988 Doppler; WSR-88D) or the ‘NEXRAD’ network combined with a modestly dense surface raingauge network provides the core of near real-time and diagnostic QPEs in the continental United States. However, the algorithms used to generate QPEs are based on single polarity reflectivity returns that are over a decade old and suffer significant biases, particularly in regions of complex terrain and in regions of mixed phase (liquid and ice) precipitation. The empirical methods used to estimate rain rates from reflectivity returns have effectively reached a plateau of maturity and newer, more sophisticated methods are now available for implementation.

Over the next 3-5 years the U.S. National Weather Service will be upgrading the operational weather radar network (WSR-88DP; “Doppler Polarimetric”) with a suite of enhancements, which will greatly improve both the quality and quantity of information derived from radar scans. The principle upgrade to the radar network will be to enable dual polarimetric retrieval of radar echoes. Along with other upgrades to the radar processors, dual polarimetric retrieval will enable the generation of an unprecedented variety of information including:

1. Cloud rain drop size distribution
2. Improved microphysical characterization
3. Improved mixed phase and ice phase precipitation detection

These improvements will permit better depiction of storm microphysical characteristics, critical to many aspects of research and operational applications. First, and perhaps most important for hydrologists, is the ability to differentiate and characterize microphysical constituents that can lead to up to a 30-40% reduction in storm to storm biases in rain rate estimates. Improved estimates of cloud microphysics are critical to improving our understanding of microphysical processes and eventually their parameterization within numerical weather prediction models. It also means that we will be able to generate more reliable detection of critical meteorological features such as the cloud freezing level and the occurrence of snow and hail. The ability to differentiate between liquid and ice phase precipitation will allow improved estimates of rain rates in mixed phase regions, which previously suffered severe biases.

Upgrades in radar processors and computer hardware will permit the more rapid acquisition of radar echoes which translates into both finer resolutions of precipitation products and faster scanning strategies. Currently the radial resolution, or “gate-length”, of an operational WSR-88D is approximately 1 km. Gate lengths in the enhanced radar network will be reduced to approximately 250 m. Faster processors will also enable more scanning angles, which will improve the vertical resolution of the radar scans. Enhanced vertical resolution will improve the vertical characterization of cloud microphysical parameters and, when operating in Doppler mode, the depiction of cloud-scale circulations. It will also improve the precision of the estimate of the atmospheric freezing level.

The impacts of these enhancements are not at all trivial and will play a significant influence on how operational hydrology and hydrological research is conducted over the next 10-15 years. Firstly the improvement in rain rate estimates at higher spatial and temporal resolutions promises to significantly reduce well-known errors in hydrological models. Unreliable QPEs are typically considered to be one of the leading sources of error in the current generation of rainfall-runoff models. Basic improvements in QPE are critical to resolving fine-scale temporal and spatial intensity structure of precipitation, which is the principal driver of interception, infiltration and runoff partitioning. Rainfall estimates in complex terrain and regions of anomalous propagation will see improvements through the application of specific differential phase measurements. Improved freezing level and microphysical characterization (e.g. differentiating between rain, snow and mixed-phase precipitation) will also significantly impact hydrometeorological research and forecasting in complex terrain regions. Being able to differentiate where precipitation is falling as rain versus snow, combined with a priori knowledge of soil conditions such as degree of saturation or degree of frozen soil, could greatly improve the ability to estimate storm runoff in cool and transitional season storms, such as rain-on-snow events. Improved characterization of the cloud drop size distribution also promises to provide quantitative information on raindrop energy; critical to the study of erosion processes. From a meteorological standpoint an improved drop-size distribution will help provide better estimates on how much rainfall is likely to reach the ground or be evaporated below the cloud. Not only does such information effect rain rate estimates but it can also provide key information on storm scale thermodynamics such as cold pool formation, microburst potential and various other mesoscale phenomena.

As with any significant technological enhancement, the upgrade of the national radar network will require an enormous research effort to realize these expected benefits. Critical work on integrating the volumes of new information into meaningful content will be necessary. Basic research will still need to be performed in differing regions in order to validate the new QPE's. Both basic and applied research will be required on using the new microphysical characterizations in the development of improved model parameterizations in numerical weather prediction models and climate models. There will be significant opportunities for research into methodologies for assimilating the real-time radar information into operational weather prediction models. Each of these

endeavors will require the innovative participation of teams of meteorologists and hydrologists from a variety of institutions and backgrounds in order to forward each evolution as rapidly as possible.

Space-borne Observation Platforms

Over the next 5-10 years a series of new space-borne observation platforms will be launched into orbit by the National Aeronautics and Space Administration (NASA) and other national and international research institutions. These platforms will provide an unprecedented capacity to observe various states of the global water cycle on the Earth's surface and throughout the atmosphere. Three of these new missions are discussed here as they are expected to play major roles in the nature and evolution of land-atmosphere interaction research.

a. Precipitation Estimation (GPM)

As of the preparation of this statement The Global Precipitation Measurement (GPM) mission was scheduled to be launched in 2010. The GPM system builds upon the knowledge and experience acquired from the Tropical Rainfall Measurement Mission (TRMM), which was the first space-borne platform to carry a precipitation radar along with a passive microwave imager and visible and infra-red scanners. Combined these instruments have yielded a detailed depiction of cloud and precipitation structures across the tropical and sub-tropical regions of the globe. Operating in an historically data-sparse region, TRMM has provided critical information on tropical precipitation occurrence and intensity, storm evolution, and cloud structures. GPM will expand this capacity by employing a dual-polarized precipitation radar (DPR) upon a single core satellite and launching a constellation of satellites with passive microwave sensors. This core-constellation satellite strategy will permit the near-global estimation of precipitation on a three-hourly basis. The GPM DPR will provide constant calibration to the microwave estimated rain rates and will provide a host of information on hydrometeor characteristics such as those discussed above in the weather radar section. Upon implementation, GPM will provide the atmospheric and hydrological communities with timely, globally-distributed information on precipitation rain rates which will serve as critical inputs into weather, climate, streamflow and data assimilation models alike.

b. Soil Moisture (HYDROS)

Despite its critical influence on surface-atmosphere exchanges, spatially distributed observations of soil moisture have, until recently, been nearly non-existent. Like precipitation, soil moisture exhibits pronounced spatial and temporal variability across a very wide range of scales. This heterogeneity has restricted the applicability of in-situ measurement platforms to a limited scope of activities. For operational weather, climate and hydrological prediction, however, it is now regarded as essential to have as accurate an estimate of the spatially-distributed soil moisture state as possible. With this impetus NASA is designing a new space-borne platform to remotely estimate soil moisture from both passive and active microwave emission measurements. The Hydrosphere State Mission (HYDROS), expected to be launched in 2010, will involve the deployment of an orbiting satellite with an L-band (cm-scale) radar and radiometer. Combined these

instruments will permit the near-global estimation of soil water content and soil freeze/thaw state on a regular, near real-time basis. The spatially-distributed estimates of soil moisture and soil freeze/thaw state will simultaneously serve as critical model initialization and model validation data and will help to constrain a critical yet previously highly uncertain component of the global water cycle.

c. Land Surface and Atmosphere Characteristics (NPOESS)

Polar orbiting satellites, and their attendant visible infra-red and microwave imagers, have a long history of providing valuable information to the terrestrial and atmospheric sciences. Possessing a high degree of value across wide variety of scientific, government and economic sectors, there is strong motivation for maintaining and improving the character and accessibility of data stemming from these platforms. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) represents the convergence of decades of satellite research and applications into a coherent program. Some 15 new instruments will be launched aboard several new satellite platforms over the next few years to provide a significantly upgraded Earth observing capacity. Many of these instruments will provide images of surface and atmospheric features and conditions at the sub-kilometer length scale. Others will yield estimates of atmospheric profiles of temperature and humidity. Measurements will also be taken across an unprecedented range of spectral channels. The NPOESS generation of satellites will build upon the various legacies of existing programs such as the National Oceanic and Atmospheric Administration (NOAA) POES system, the NASA TERRA and AQUA satellites and the Department of Defense (DoD) Defense Meteorological Satellite Program (DMSP). Additionally, several new sensors will provide information on surface and atmospheric microwave emissions, visible and longwave radiation emissions, land-surface terrain and ocean surface height among other parameters. A key challenge moving into a this new data rich era will be concerted research on the validation, calibration and assimilation of multiple new data streams into operational forecasting systems.

Boundary Layer Observations

Despite its critical importance in coupling the land surface to the free atmosphere, the planetary boundary layer (PBL) has historically been a poorly sampled region of the atmosphere. Large changes in vertical extent and stability characteristics, and substantial horizontal variability complicate the design of an effective operational observation system. The key features of the PBL that need to be studied have been documented in earlier reports (e.g. Emmanuel (1995), NRC (1998)). To address these research issues marked improvements in PBL observation capacity must be implemented. Several emerging concepts and technologies are now being developed and tested which may contribute to this end.

Fast-response, in-situ surface flux stations (e.g. eddy-covariance) continue to improve and be implemented in a wider range of environmental settings. Although eddy-covariance theory and technology is relatively mature, new instruments for sensing water vapor content, temperature and trace gas concentrations continue to emerge. The new generation of instruments possesses markedly faster response times than do previous

sensors making it possible to improve the resolution of turbulent fluxes between the surface and PBL. This improved resolution is critical for characterizing small-scale turbulent fluxes such as those that occur within stably-stratified nocturnal boundary layers. The implementation of flux measurement systems across a wider variety of settings is helping to characterize and constrain patch scale fluxes. However, as has been well documented, there are inherent limitations to making *in-situ* flux measurements with regards to site representativeness and analytical assumptions about atmospheric stability profiles. While it is expected that sustained flux measurements will continue to expand into the foreseeable future, a key challenge is to merge the point scale information from *in-situ* stations with spatially distributed observations of PBL properties, such as wind, temperature and humidity. Additionally, the emerging national network of flux stations (e.g. AMERIFLUX and FLUXNET programs) need to be further coordinated with existing surface observing networks that feed operational data assimilation models.

As discussed above, weather surveillance radar is poised to undergo rapid evolution over the next several years. A product of this evolution will be an enhanced capacity to map lower tropospheric and PBL humidity, temperature and wind fields using enhanced Doppler and beam refraction methodologies. Techniques, which effectively mine radar signal information have been and will continue to be developed to improve the quality and reduce the uncertainty of measurements (NRC, 2002). Combined with the aforementioned improvements in radar resolution and scanning frequency, improvements in radar signal processing will yield a new generation of spatially-distributed environmental conditions which should be directly applicable to weather and hydrological modeling and diagnostic activities. Recent field research has documented the capability of such systems to diagnose key boundary layer stability, convergence and circulation features, which are all thermodynamic precursors to precipitation initiation and significantly influence land-surface fluxes. A key challenge to the atmospheric and hydrological science communities will be to find effective ways of integrating and assimilating these new data streams into diagnostic and forecasting activities.

A still newer technology in PBL observation is the use of Unmanned Aerial Vehicles (UAVs) mounted with environmental monitoring equipment. Manned research aircraft have been a mainstay of atmospheric research for several decades. Such vessels though are often restricted in their capability to acquire repetitive, very low altitude measurements as are required to conduct integrated PBL research. Small UAVs hold the promise of being ideally suited to conduct such research. For example, while it may be impractical for a large manned aircraft to perform repeated flight tracks over a riparian corridor of a few hundred meters in scale, a small UAV should be able to make repeated measurement tracks over such a feature at a fraction of the cost and risk. While not particularly well suited for very large-scale applications, small UAVs should yield valuable information on near-surface fluxes in a spatially distributed manner that has heretofore been impossible. Such attributes may be particularly beneficial in conducting research in regions of complex terrain.

One emerging technology that appears to hold some promise for improving the characterization of humidity in the lower atmosphere is that of Differential Absorption

LIDAR, or water vapor ‘DIAL’. Building on the principles of basic LIDAR the DIAL system uses a multi-spectrum methodology to resolve the detailed structure of boundary layer humidity. Currently the technology is not cost or labor-effective for operational use in a national network. However, research from recent field programs (e.g. IHOP) has provided significant promise into the applicability of this technology for PBL analysis, data assimilation and NWP initialization. Effectively, a properly designed and operated water vapor DIAL system should provide profiles of atmospheric humidity between approximately 100 and 3000 m above ground level with around a 100 m resolution. When the water vapor DIAL is deployed in tandem with a Doppler LIDAR it is also possible to retrieve flow velocity of water vapor. Hence, a hybrid system incorporating both a water vapor DIAL and a Doppler LIDAR shows significant promise in being able to estimate vertical fluxes of water vapor throughout the lower atmosphere, a key feature of convective initiation. Being an emerging technology it is not yet clear how rapidly such a system could move into an operational capacity. However, given the significant impact that vertical flux and state profiles of lower atmospheric moisture would make on mesoscale analysis and NWP, research into water vapor DIAL technology should remain a high priority for the foreseeable future.

3.3 Core physical model development: Evolution towards 5th generation LSPs in NWP and climate models

Over the next ten years Earth systems modeling is poised to witness marked advances in complexity, detail and precision. Integration across Earth science disciplines will be absolutely essential to achieving these gains as will basic research within individual disciplines. One certainty is that increases in computing capacity will continue to permit the development and implementation of Earth system models of finer and finer spatial scales. However, many of the crude formulations that have served in the past will become increasingly inadequate as basic scaling assumptions used in their development will be violated. This fact will become particularly true in the realm of numerical weather prediction (NWP) at length scales of order 1 km and below but will also be true for climate models as they will have their own requisite set of improvements to implement as their spatial resolution is reduced to 10’s of kilometers. We now discuss a host of improvements to operational LSPs which are expected to be implemented over the next decade.

Improving Soil Hydrology

Most of today’s operational LSPs view the soil as a single 1-d column, of a fixed depth and single type or classification discretized into various layers. Designated within the various soil layers is also some specification of plant root density. Soil scientists have long documented, at local and regional scales, the variability in soil structures and types and the influence these characteristics have on the movement of water and nutrients. In order to improve the ability to accurately simulate and predict the movement of water and nutrients through the soil profile methods must be adopted to represent soil columns of varying depth as well as changes in soil type (i.e. soil ‘horizons’) with depth. The depth

of the soil column has a direct effect on the capacity of the soil to store water. The fact that a shallow soil column can not store as much water as can a deeper soil column has been well known by watershed hydrologists for some time. Variations in soil depth and, hence, total water holding capacity can have a pronounced impact on the development of contributing source areas for surface runoff. Shallow soils also can not store as much heat as can deeper soil profiles. Having a diminished capacity to store heat and water, shallow soils exhibit faster response times to atmospheric forcing, which, in turn, affects the surface energy balance. These effects become particularly pronounced in regions of complex terrain; regions in which there are still marked difficulties in weather and climate prediction.

A similar, yet, slightly different issue is posed for improving the representation of soil structure. In nature, many soils exhibit marked stratigraphy where soil types such as sands, clays, loams and organics and their infinite combinations may overly each other in infinite combinations. The configuration of this stratigraphy can have a significant influence on movement of water through the soil profile. Hydraulic barriers (conduits) can be formed which may restrict (enhance) the drainage of water from the profile. Restrictions in transmittance may also affect the lateral redistribution water from uplands to lowlands. Depending on the soil type, soil structure can also enhance or diminish the capacity of plants to extract water from the soil profile. Different soil types also possess different thermal characteristics. For instance, sandy soils, with large airspaces tend to have a much lower thermal conductivity than do soils with higher clay contents.

Plant roots exert a very important influence on soil hydrology serving as the sole conduits for moisture from the soil matrix to the plant. In most operational NWP models, plant rooting depth and density is specified in look-up tables by a broad plant classification. Recent research, however, has shown that rooting structure of individual species within plant communities can vary appreciably with some plants (e.g. mesquite trees) having very deep tap root systems. This variability allows some plants to actively transpire during dry periods while others may be forced to close stomata. Improvements in the documentation and designation of rooting structures in plant communities will go a long way in improving the representation of biospheric influences on local and regional water balances. On climate timescales from the interannual to interdecadal, it may also be advantageous to implement dynamic rooting capabilities within LSPs. This functionality could potentially allow for a more realistic adjustment of the root zone structure to environmental forcing, most notably, the access to water. However, basic field and laboratory research should precede the development of such methodologies.

Each of these soil hydrology processes provides potential constraints on the amount of moisture available for evapotranspiration back to the atmosphere, which in turn, affects the surface energy budget. Soil hydrology also constrains the partitioning of water between runoff and infiltration and governs how water is laterally redistributed across the landscape. As NWP models approach the spatial resolution of 1 km and finer, the detailed movement of water both horizontally and vertically through the soil profile plays an increasing role in local and regional water and energy budgets. Given the wide range of timescales at which many of these processes operate, some become more important

than others. For example, on the diurnal cycle the heating of a thin, upland soil profile as compared to a deep riparian soil profile may be important in the local surface energy budget. On longer timescales, the slow movement of water down through the soil profile and downslope to a riparian area can provide deep soil moisture reservoirs near riparian corridors thereby sustaining the vigor of transpiring riparian vegetation. Each of these processes contributes to improving the organizational structure of land surface heterogeneity, which can induce mesoscale circulations in the atmosphere. Thus in order to improve our ability to simulate many of the detailed structures of the lower atmosphere there must be an improvement in basic process modeling related to soil hydrology. Such improvements will only come about with the entrainment of soil scientists and hydrologists into the development of state of the art LSPs.

Improving Snow Processes

The effects of snow cover on weather and climate are profound. While wintertime weather features tend to be dominated by synoptic scale forcing mechanisms, local variability in snow cover can have a significant influence on air temperature. More importantly, winter snowpack serves as a principal water resource reservoir feeding streams, lakes and the soil with water during the melt season. On larger scales, regional anomalies in snow cover have been shown to have a significant effect on inter-seasonal climate variability by exerting large scale changes in surface albedo and land surface heat and moisture fluxes. Given these critical influences it is expected that much work needs to be focused over the next ten years on improving the representation of snow in LSPs and in defining the role of snow in the global water cycle. Interaction between atmospheric modelers and snow hydrologists will be essential in meeting these demands.

Nearly all operational weather and climate models possess methodologies to deal with snow covering the land surface. However, there is a very large range in the complexity with which these formulations are implemented. Most snow components of current LSPs account for changes in surface albedo (often as a function of sun angle), thermal fluxes, a multi-layered structure (which typically don't account for real snow stratigraphy but does attempt to account for the differences in heat exchange in near-ground and near-atmosphere layers), snow water equivalent (SWE), sublimation, evaporation and melt. Many LSPs also implement basic methods to implicitly account for incomplete or "patchy" snow cover.

Snow, especially in regions of complex terrain, exhibits marked spatial heterogeneity in terms of depth of snowpack and in snowpack structure. Snow cover patchiness can have a pronounced influence on the local surface radiation budget, which in turn affects snowpack melt rates, infiltration and runoff, as well as heat and moisture fluxes to the atmosphere. Patchiness in snow cover is present across a very wide range of spatial scales from the sub-meter to hundreds of kilometers. Hence as atmospheric models increase their spatial resolution, the need for methods to improve the representation of patchy snow cover will persist if not increase. In addition to accounting for patchy effects on surface albedo and surface emissivity, new LSPs will need to be able to account for spatial heterogeneity in soil heat flux in areas of exposed soil, the effects of

patchy frozen soils (both underlying the snowpack and exposed to the atmosphere), the heterogeneity in SWE in various patches, and perhaps most importantly the effects of tree and plant canopies on snow. While many current formulations do account for combined snowpack-plant canopy effects on the albedo, most do not consider these effects as a function of sun angle and terrain slope and aspect. It is well known that insolation varies greatly in regions of sloping terrain. Changes in insolation can dramatically affect snowpack evolution and melt rates throughout the cold and melt seasons. Plant canopies can also serve to shade and, thus, radiatively “decouple” the snow pack from the atmosphere at low sun or high slope and aspect angles, which inhibit the penetration of insolation to the snow surface. Regions of persistent shading (whether by terrain or vegetation) can result in the preferential development and persistence of snowpacks. These regions can become critical long-term stores of moisture, which may not runoff and/or infiltrate into the soil until late in the melt season if at all. They can also contribute to spatial heterogeneity in land surface fluxes of heat and moisture to the atmosphere. Computationally-efficient, yet physically accurate methods to account for these fine-scale effects need to be developed over the next several years to improve land surface flux estimation.

In addition, to varying spatially throughout the cold and melt seasons, snowpacks vary internally in response to atmospheric forcing. These changes involve the metamorphosis of snow crystals into a coherent matrix, which can have pronounced stratigraphy. As with soils discussed above, this stratigraphy can affect vertical fluxes of heat and moisture through the snowpack between the land surface below and the overlying atmosphere. From a hydrological standpoint, this stratigraphy can be critical to how the snow pack melts during the spring. In regions of complex terrain snowpack stratigraphy is also critical to the formation of unstable layers that can result in avalanches, which in turn serve as episodic horizontal redistributions of moisture from slopes to valleys. While not all of the details of snowpack stratigraphy are going to be of first-order importance to closing the surface energy budget in an atmospheric modeling framework, basic research needs to be undertaken to assess the importance of key snowpack structural features on seasonal snowpack evolution and, most importantly, how they affect the release of meltwater. Improvement in the understanding and simulation of rain on snow events may provide a key focal point from which such enhancements could be based.

A final snow-related component of critical importance pertains to deposition of precipitation onto the snowpack. Precipitation may fall onto a snow pack in each solid, liquid and mixed phases and, for the case of the solid phase, may have many different structures (e.g. snow, graupel, hail, etc.). Moisture may also accumulate on a snowpack as dew condensation or frost. In most current weather and climate models hydrometeors are classified in a cloud microphysics parameterization. However, these classifications are often not communicated to the LSP. Instead, precipitation inputs into the LSP are typically considered to be rain or snow water equivalent and are defined on the basis of a temperature criteria. This approach is likely not robust enough to accurately account for variable atmospheric conditions that occur during precipitation events, particularly in complex terrain regions near atmospheric freezing levels. While near-ground air

temperatures may be above freezing, precipitation may be falling as snow and accumulating on the ground or existing snowpack surface. Conversely, near ground air temperatures may be markedly below freezing but if the ground temperature is above freezing then snow will melt upon impact and not accumulate but infiltrate or runoff. It is envisioned that in order to better represent exchange of precipitation from the atmospheric model to the LSP, improvements will need to be made in how hydrometeor information is passed from cloud microphysics schemes to the LSP and how it may change upon descent from the cloud.

Improving land cover heterogeneity & complexity

Improvements in the spatial resolution of atmospheric models will demand improvements in other components of the land-atmosphere system. Until recently, topography has generally been represented rather crudely due to the relatively coarse spatial resolution of the models. As operational NWP models approach cloud resolving scales of 1-3 km in horizontal resolution, topographic attributes such as slope and aspect will exert increasing roles on atmospheric thermodynamics and the simulated land-surface hydrology. Basic adjustments to the various components of the surface radiation budget to account for variations in slope and aspect, while at times computationally cumbersome, are relatively straightforward. Complications do arise however when one attempts to account for the effects of cloud reflected insolation and diffuse radiation from both the sky and surrounding terrain. It is not yet clear how significant the effects of these components on the surface radiation budget and subsequent mesoscale processes will be. Previous research has indicated that such effects can be very important in the melting of snow in complex terrain. Additional difficulties in computational strategies are encountered when trying to assess atmospheric stability in the surface layer over sloping terrain. Moist airflow over complex terrain is a highly non-linear process and the heterogeneity in land surface fluxes that are exhibited in such regions precludes the application of many simplifying assumptions. New strategies, both numerical and analytical, need to be developed and implemented in order to properly represent terrain-atmosphere interactions that will emerge in the next generation of NWP models.

Outside of complex terrain regions, problems still exist as one moves towards progressively finer spatial resolutions. Next generation models and remote sensing platforms will yield unprecedented capabilities in depicting land cover and land use characteristics. On local scales these details can have pronounced impacts on land surface fluxes. As mentioned previously, it is increasingly recognized that the organizational states, or juxtaposition, of certain land surface features can have a very significant influence on fluxes and, at times, can promote upscale organization in mesoscale circulations in the atmosphere. The need for explicit representation of these surface features complicates some of the early attempts to implicitly represent land cover heterogeneity in a statistical or analytical manner. Moving forward, we will be able to classify many land cover types down to the so-called 'patch' (or homogeneous unit) scale, which can often be as fine as 10's to 100's of meters. A key challenge to using this information will lie in developing methods to integrate either fluxes or parameters from the 'patch' scale up to the model grid-scale. Fortunately, this is not an entirely new

problem as land-atmosphere scientists have been working on this problem at coarser scales for some time. Testing and evaluating the significance of sub-grid representation of land cover characteristics is therefore likely to remain a leading research issue for the foreseeable future.

Complexity in vegetation structure has also emerged as a critical area of research over the past several years. Currently, most LSPs used in operational weather and climate models possess a single layer canopy. However, this assumption is typically not valid in many regions of the world. Variations in canopy structure can exert significant influence on the canopy radiation budget as well as dramatically affecting its effective aerodynamic roughness. Detailed information on canopy structure from plot scale studies has emerged from numerous field campaigns and long term observatories, and can be put to use in the formulation of new methodologies. A second area of inquiry has recently focused on the feedbacks to and from the atmosphere on dynamically evolving plant canopies. It is now widely acknowledged that leaf emergence, growth, stress and disturbances can influence weather and climate from local to regional scales. Such feedbacks can have a significant impact on local surface energy budgets and have at times been hypothesized to drive regional climate anomalies, such as drought, on the climate scale. For NWP, defining critical mechanisms controlling leaf emergence in the spring (or, in monsoon regions, rainy seasons) will be a principal task of LSP improvement. For climate models, there needs to be an improved representation of vegetation community response to stress and disturbances. Along a similar vein, since large tracts of the Earth's land surface are covered in agriculture, improvements in accounting for crop phenology need to be made. These changes, broadly classified as "dynamic vegetation" algorithms should yield significant understanding and improvements in process modeling. Through strategic partnerships with ecologists, plant physiologists and micrometeorologists, over the next ten years we should expect a significant evolution in the treatment of in-canopy processes in state of the art LSPs.

Improving the coupling to the Planetary Boundary Layer

Despite many years of research, just exactly how, and under what conditions, the land surface exerts a significant influence on the atmosphere is, often times, unclear. The land surface is coupled to the atmosphere through radiation fluxes and through mass and heat fluxes which must pass through the PBL. Hence, improvements in PBL physics and the coupling of the PBL to the land surface must improve in order to realize improvements in LSPs. Recent research has begun to yield a clearer picture of how this coupling may exist. For the warm season, it is becoming increasingly evident that land surface conditions, such as soil moisture, can affect the atmosphere in various ways that are often regime dependent. Previous studies had indicated that the land surface was important during situations with "light" synoptic forcing. However, more recent research suggests that various combinations of soil moisture state and the static stability and humidity profile of the PBL are also significantly important in PBL growth, the development of clouds and, potentially, the development of precipitation. Under one set of conditions, increased soil moisture may act to promote cloud and rain formation whereas under a second set of conditions, increased soil moisture may diminish the likelihood of cloud

and rain formation. Clarify exactly when and how these relationships work will require additional basic research into PBL processes in a number of different environments. Current research programs are now under development to address these issues and the findings from these programs should be able to contribute significantly improved understanding to land surface PBL interactions in the 10 year time frame if not sooner.

Despite its close proximity to the surface, the PBL remains a difficult region of the atmosphere to study. It exhibits large changes in structure across a wide range of temporal and spatial scales. As discussed above, new tools are emerging which may increase our ability to resolve the detailed structure of the PBL but many of these tools are only in the research phase and are either cost or labor prohibitive for operational deployment. Therefore we currently lack a reliable method to initialize the PBL at the beginning of an NWP or climate forecast cycle. Being a chaotic system these errors can propagate throughout the atmosphere during the forecast cycle and ultimately limit predictability.

Findings from current research programs must be translated into improved parameterizations to overcome some of the current problems in NWP and climate model forecasts. Existing model experiments have shown great sensitivity to use of different PBL parameterizations and to parameter values within a single PBL parameterization. Lacking reliable verification data, this large sensitivity yields a large uncertainty as to what is the correct approach to simulating the PBL. One problem is that most PBL parameterizations use Monin-Obukov similarity theory, which is over 20 years old and often requires assumptions which are not supported by some common real atmospheric conditions, such as stably-stratified nocturnal boundary layers. The breakdown of these assumptions represent significant sources of error in the parameterizations. There is now substantial evidence for a critical need to develop innovative, robust ways to parameterize the PBL in both weather and climate models. A new generation of PBL parameterizations must be able to characterize smaller turbulence structures than those from earlier generations as they will be required to operate at higher spatial scales. They also must be able to adequately account for the increased complexity in land surface representation. In essence, improvements in PBL coupling to the atmosphere must proceed in tandem with improvements in LSPs for such improvements to be realized in superior weather and climate forecasts.

3.4 Analysis and prediction systems

Land Data Assimilation

Transferring increased observational capacity into an improved observational capability will not be a trivial task. Many issues regarding the assimilation of multiple new data streams into physically based prediction models require address before such anticipated progress is realized. This work will require the collaborative efforts of observationalists, applied mathematicians and numerical modelers to insure that information from observations is appropriately and efficiently integrated into state-of-the-art prediction models. Heeding the call of the “grand challenge” documents discussed in the

introductory text above, individuals and institutions, both in the U.S. and internationally, have begun to collaborate on large complex data assimilation efforts. For the sake of brevity, we focus here on the development of *land* data assimilation as opposed to the assimilation of atmospheric data.

One key product of these efforts has been the development of the multi-institution Land Data Assimilation System (LDAS) program. This effort, lead by NASA and NOAA, has, at the time of this writing, implemented an operational regional (North American) and global land data assimilation systems at the $1/8^{\text{th}}$ and $1/4^{\text{th}}$ degree spatial resolutions, respectively. The general framework for assimilating land surface observations is to drive an uncoupled LSP with observed meteorological, and, potentially, hydrological data and adjust or “nudge” model predicted values to match observations within specified error criteria. The data assimilation approach effectively constrains model predicted values of land surface states and fluxes towards observations compared to free-running or non-assimilated predictions. The constraint results in a more accurate depiction of states and fluxes which is beneficial to both the initialization of free-running atmospheric and hydrological prediction models and to diagnostic analyses on multi-scale water and energy budgets. Additionally, the data assimilation framework also permits, theoretically, the utilization of many data sources each of which effectively reduces model degrees of freedom.

Despite the rapid progress that has been witnessed over the past several years, significant challenges and opportunities lie ahead over the next decade with respect to land data assimilation. While numerous methods for data assimilation have been implemented, such as variational and Kalman filter techniques, none of these have yet proved optimum for all situations. (For a current review of general data assimilation methodologies see Dance, 2004). Effectively, different techniques possess either computational or theoretical advantages over other techniques and significant research is still required to both optimize the assimilation of existing data streams and to accommodate emerging and proposed data streams. One key emphasis will be placed on the development of computationally efficient data assimilation methodologies. This is due to the fact that the next generation of high-resolution remotely sensed observations is expected to yield unprecedented volumes of data on land surface conditions. Correspondingly, the data assimilation systems that will emerge over the next ten years need to be built upon scale-appropriate physical models (i.e. LSPs) and do so in a timely manner for operational applications.

A second emphasis needs to be placed on integrating new kinds of information that can provide additional constraints on the surface hydrological system. Such new information will be the assimilation of remotely sensed vegetation water content, soil moisture, ground water and aquifer conditions and, potentially, streamflow. Each of these components of the land surface water budget are represented comparatively crudely in the current generation of LSPs. The emergence of the 5th generation LSPs discussed above should afford opportunities in improving the understanding and formulation of the terrestrial hydrological cycle and the new suite of observations will afford the opportunity to validate these models. Over the next ten years, effective assimilation of these key

hydrological variables, which operate across a range of space and time scales, should yield marked improvements in the initialization states of the next generation of weather and climate models.

Coupled Weather and Climate Prediction

Lacking a truly revolutionary paradigm shift, it is expected that the predominant forecasting methodology will broadly resemble that of Fig. 1. It is certainly that the horizontal resolution of the land and atmospheric models will improve over the next ten years. Community integration activities such as the Weather Research and Forecasting (WRF) model development effort have begun to bring together groups of scientists from observational and modeling communities as well as disparate disciplines for the sake of developing a common atmospheric modeling framework. The fact that the WRF model and an attendant suite of physical parameterizations will be used as the national operational mesoscale forecasting model means that research at the individual investigator level can, in theory, be efficiently transferred into improving operational forecasts in a timely manner. A similar movement seems to be occurring in the field of LSP with a few modeling systems emerging as leaders in the community. Open access to source code and data for these modeling systems has been critical in their rapid evolution and acceptance by the research community and it is expected that such a *modus operandi* should persist into the future.

While increases in spatial resolution for some applications of limited area models will obviate some current problems, such as cumulus parameterization, many challenges related to land-atmosphere exchanges will persist. As stated above, much work still remains in order to better define the nature of the soil moisture-precipitation feedback and such issues can only be addressed through coupled modeling systems. Additional research is also needed on better defining the uncertainties in assessing how local and regional land-surface anomalies affect the regional and global climate. Such work is inherently multi-scale in space and time and will demand the development and implementation of more sophisticated LSPs. The initiation and occurrence of continental scale droughts serve as a provocative yet unresolved forecasting problem that requires a sophisticated coupled modeling approach. To move forward significant consideration needs to be given to how the various components of the forecasting system are linked together. For example, ‘Is a simple 1-dimensional “downscale” flow of information, as represented in Fig. 1, adequate or are there places in the forecast chain where a fully-coupled, interactive linkage between modeling systems needs to be implemented for specific forecasting problems (e.g. between the global and regional modeling components)?’

Another key challenge that has persisted has been the accurate simulation and forecasting of weather and climate over regions of complex terrain. Reasons for this deficiency include a lack of spatial resolution necessary to resolve key forcing variables and the lack of quality observations from which simulation models can be initialized and validated. Over the next ten years there lies a significant opportunity to improve forecasting skill in complex terrain regions. As model resolution decreases more of the principal terrain features and the associated heterogeneity in vegetation and hydrological conditions will

become explicitly resolved. This will permit a more dynamic evolution of surface states and fluxes from complex terrain regions in forecast models. Additionally, the next generation of remotely sensed data will have comparatively far richer data coverage in complex terrain regions than did those of the past. Key features such as snow cover extent, snow water equivalent, frozen soil state, vegetation coverage and vigor and soil moisture will potentially be observable and capable of being assimilated over the next ten years. As complex terrain regions serve as a principle source region for terrestrial water resources such an improved capacity stands to yield significant benefits to society in the form of improved forecasts and assessments.

Increasingly, the user community is demanding a higher degree of specification of uncertainty in weather and climate forecasts. Assessment of uncertainty in modeling systems can be difficult to quantify and typically requires the execution of ‘ensemble’ executions of forecast models. Increases in the spatial resolution of the modeling systems will combine with the need for ensemble predictions to yield significant burdens on computational resources. This feature is true for LSPs and hydrological applications models as it is for weather and climate models. In order to minimize such demands, improved, efficient methods for characterizing uncertainty in models and in initialization and forcing data need to be developed. Basic work in uncertainty theory and predictability need to evolve in tandem with improvements in modeling and observational capabilities to ensure efficient pathways to improvement.

4. Strategy for achieving the Vision and the role of CUAHSI

While the Vision components presented above are intended to be tractable goals over the next ten years, achieving these goals will require a significant degree of planning. This is particularly true of objectives which cut across traditional research disciplines. Common languages, milestones and metrics for achievement help foster timely progress in obtaining lofty research goals. Additionally, given the scope of some of the research objectives, institutional frameworks for enabling cross-discipline research and applications need to be constructed. These frameworks include the provision of human, computational and budgetary resources. Properly coordinating large-scale integrative activities, such as those put forth in the strategy below is pivotal for success. CUAHSI, as a community integrator among the hydrological sciences, is well poised to help lead this large-scale effort. With the active participation of other institutions such as Universities, National Center for Atmospheric Research (NCAR), and government agencies, such as NOAA, NASA and the USGS, a coherent research plan can be formulated and will have a high probability of success. Several of these collaborators already possess a significant history in advancing research and development activities in land-surface parameterizations. In the paragraphs below we detail a large multi-institutional strategy aimed at fostering improvement in the development, testing and implementation of LSPs that are used in coupled land-atmosphere modeling systems.

Proposed Strategy Statement: Recognizing the importance of improving the representation of land-surface physics in coupled land-atmosphere modeling systems, we

propose a large, multi-institutional collaborative effort aimed at facilitating; 1) the development, evaluation and implementation of land-surface parameterizations in weather and climate forecast systems, 2) the evaluation of emerging data streams, 3) the design and construction of efficient land data assimilation systems and 4) an education and outreach component to the community for improving the timely adoption of community-based modeling systems. To meet these objectives, this effort will be aimed at addressing the following core elements:

- **Element 1:** Adopt a limited spectrum of common modeling frameworks and data standards for supporting land-atmosphere interaction research. Such selections should be centered on modeling systems with open, communicable software architectures. Based on this Vision statement, the “grand challenge” documents and community input, define a prioritized list of model enhancements for LSP development activities.
- **Element 2:** Develop a land-surface parameterization test-bed facility to provide standardized data and computational support for the evaluation of LSP enhancements. In collaboration with partner institutions, the test-bed facility will leverage on community architectures for processing and evaluating emerging data streams. It will also foster community guidelines for code enhancements and standardized data formats. Principal activities at the facility will be aimed at:
 - Entraining promising research findings into LSPs used in operational weather, climate and hydrological prediction models;
 - Developing and testing the next generation of land data assimilation systems; and
 - Assessing the impact of emerging data streams on diagnostic analyses and model predictions.
- **Element 3:** Create a community education and outreach support program for operational and research personnel to foster the promulgation of these models and research findings to the operational meteorological and hydrological communities.

Breakdown of Core Elements:

Element 1: Currently, there are dozens of land-surface hydrology modeling systems, which have been developed by various government agencies, research institutions and individuals. Each of these modeling systems has a unique heritage and is likely to perform better in specified situations than would others. Data requirements and coding architectures vary widely among these systems. While most of these modeling systems are likely available to the public, if not formally supported in some way, some are proprietary. In order to foster the entrainment of numerous investigators from disparate disciplines it will be beneficial to identify key attributes of existing LSPs that lend them to community-based development. This is not a trivial task and will involve the intense

discussion of various issues related to the design and use of the modeling systems. Hence, it is proposed, that under Element 1 of this implementation strategy, a series of workshops and online discussions be held to define a suite of modeling systems that can be adopted for community-based model development research. To fulfill the objectives stated in this particular Vision Statement, the functional choices would be limited to those modeling systems that are couple-able to weather and climate models. As part of the model selection discussions, a list of priority model-enhancement activities should also be drafted. Such a list will provide focus to both operational and research communities in their efforts to solve specific modeling and data related issues in a methodical manner.

Element 2: A land-surface model test-bed facility is needed as a national, multi-institutional center for the development, testing and implementation of land-surface physics packages. One primary objective of this facility would be to develop and test next-generation models in both coupled-atmosphere and uncoupled simulation and prediction modes. The facility would support and maintain standardized datasets from selected field programs, operational data assimilation systems, re-analysis systems and current operational prediction models. The test-bed would also maintain an archive of diagnostic algorithms, which would provide some standardized metrics for the evaluation of new land-surface model parameterization components. The principal goal of the test-bed facility would be to evaluate new model components that are to be potentially considered for implementation in operational, community weather and climate prediction models. An attendant goal is to also support the enhancement of land-surface models for use within the traditional hydrological community. As such, the test-bed is intended to serve as a significant bridge between the traditionally disconnected community of land-surface modelers from the hydrological and atmospheric science communities.

The products of this facility should be the development of physically-consistent modeling tools which can be used in both coupled and uncoupled modes, in limited area or global prediction systems. Hence, only a selection of models will be applicable for “support” within the test-bed. Standardized versions of the land-surface model codes would then be maintained by the center, available for researchers to obtain, modify and test. Tests would range from the performance in coupled mode in the simulation of land-atmosphere interactions to uncoupled modes in the simulation of runoff, streamflow and groundwater recharge.

A crucial objective of the test-bed facility would be to foster the development and accessibility of next generation land data assimilation systems to the atmospheric and hydrological communities. Leveraging on existing land data assimilation efforts at collaborating institutions, the test-bed facility would serve as an integrator of land data information and data assimilation technology. Computational architectures, such as that developed under the NASA Land Information System (LIS), could be implemented, tested and refined using a variety of community data sources. Versions of state-of-the-art land data assimilation models would also be made available to the community via the test-bed so that researchers could test the performance of their enhancements within practical, real-world data assimilation scenarios. These scenarios potentially cover a

wide range of forecasting problems in the atmospheric and hydrological sciences. One key feature of the land-surface model test-bed would be the ingest and standardization of key datasets from emerging data platforms, such as the numerous data streams provided by the NASA Earth Observing System. Thus, a primary function of the test-bed facility would be to make available to the community standardized pre-processed datasets for initialization and forcing of the participating land-surface models. Maintenance of these datasets would be a cornerstone of test-bed operations and would serve as a streamlined conduit for testing and evaluating the usefulness of emerging datasets as well as developing land-surface models. Of particular interest to hydrologist would be the ingest and generation of standardized sets of meteorological forcing data, from which detailed hydrological-operations models could be run. Spatially distributed meteorological forcing data is often difficult to obtain and manage given the very large size of the data sets. Being able to efficiently sample from standardized datasets that currently exist, or will emerge in the near future, will greatly facilitate the development of hydrological prediction scenarios required by the water management community.

The LSP test-bed facility will require both a virtual and physical existence. At the time of this writing it is not yet clear where such a facility should be hosted. The decision of where to host such a facility needs to be community-based and could likely emerge from the discussions proposed in Core Element 1. Such a facility could also be a component of the proposed CUAHSI Hydrological Synthesis Center (HSC).

Element 3: It makes little sense to coordinate and create a large, collaborative facility such as the LSP test-bed without explicitly ensuring some mechanism for fostering user support and transferability of data and models to external communities. Hence, as part of the proposed research strategy, a coherent training and outreach component should be developed. This element would focus on developing training materials and courses for instructing operational and research community members on the use of LSPs, data assimilation systems and emerging data streams. Building on the success of the University Corporation for Atmospheric Research (UCAR) COMET program and community atmospheric modeling systems (e.g. MM5 and CCSM), online and classroom tutorials should be developed to foster the usability of the new community modeling tools. This support effort will help entrain community members in the testing and use of the modeling tools and data products. By providing practical training for graduate students, it will also ensure the long-term participation of the research community in the LSP development effort. At the time of this writing, it is foreseen that this user-support element should be designed and hosted in tandem with the test-bed facility detailed in Element 2.

Development of the land-surface model test-bed facility is expected to be a long-term program, with significant ties to both the atmospheric and hydrological modeling communities. A very preliminary timeline for this activity is proposed as follows:

Year 1: Conduct a series of workshops to solicit interest and participation of key sponsors and potential facility hosts. During this year, the scope and mission of

the test-bed would be revised and reviewed by members of the atmospheric science and hydrological communities. A key function of CUAHSI will be to promote the test-bed facility as a resource for integrated modeling.

Years 2-3: Begin the occupation of space, provided by the ‘physical host’ and develop the necessary physical infrastructure for developing the test-bed. Year 2 will initiate a series a pilot projects to demonstrate the function of the test-bed and generate the first generation of standardized testing and evaluation datasets and diagnostic tools (e.g. case studies from various field programs, existing model intercomparison projects, and proposed CUAHSI Hydrological Observatories).

Years 4 and beyond: In coordination with funded projects from various institutions and University investigators, begin full operation of the test-bed facility.

Expected Linkages to Proposed CUAHSI Program Elements:

CUAHSI, as an integrated hydrological research program, is expected to play a significant role in the achievement of the proposed research Vision for land-atmosphere interactions. The CUAHSI implementation plan calls for the establishment of four Infrastructure Elements: Hydrologic Observatories (HOs), Hydrologic Information Systems (HISs), a Hydrologic Measurement Technologies Facility (HMTF), and a Hydrologic Synthesis Center (HSC). The strategy for a proposed LSP test-bed facility neatly compliments each of these infrastructure components. Data generated from the proposed HOs will be critical in the coming decade to solving the modeling and process understanding issues posed in Section 3.3 above. While significant advances in operational observing capabilities are expected to emerge, key data on various hydrological processes (e.g. soil water movement, stream-aquifer interactions, sparse canopy evaporation, riparian area water budgets, etc.) are going to continue to rely on the acquisition of data from focused field campaigns. These processes, and the influences upon them brought by human activities, are expected to be the focus of data acquisition in the HOs. Hence, the LSP test-bed facility provides a conduit for integrating hydrological process understanding into operational weather and climate prediction models.

The proposed LSP test-bed also dovetails into the HIS and HMTF components of CUAHSI. As with Geographical Information Systems, HISs are rapidly gaining popularity in user communities as they provide an efficient method by which one can access and organize volumes of spatially-distributed hydrologic data. Integrating these common data structures with those already present in the atmospheric sciences communities has been a difficult challenge over the past several years. However, the fusion of HIS technology into the LSP test-bed facility provides a focused opportunity for scientific researchers and software engineers to develop complimentary data processing tools that can mutually leverage upon the assets of the other. Similarly, the HMTF is expected to be a progenitor of new kinds of data characterizing hydrological processes. By providing a conduit to robust data assimilation algorithms and infrastructure, the LSP test-bed will serve as a ready user, and evaluator of novel data streams. By designing

integrated data impact studies, feedback from data assimilation and modeling studies can be rapidly fed back to researchers working within the HMTF.

Perhaps the most comprehensive linkage between the proposed LSP test-bed and CUAHSI will be found through the CUAHSI-HSC. As mentioned previously, the LSP test-bed serves a principal role of the HSC, which is to rapidly transfer hydrological research findings into practical applications. With strong links to the weather and climate forecasting communities, the LSP test-bed will ensure that significant research findings are rapidly infused into data assimilation and prediction systems. The LSP test-bed will also serve as a facility to help foster collaborative research efforts between the atmospheric science and hydrological modeling communities. This attribute will manifest itself by allowing investigators from a variety of institutions and backgrounds to design large-scale integrated modeling projects that link weather and climate forecast models with specific applications models, such as those outlined in Figure 1. By leveraging on the computational resources of the LSP test-bed and the HSC, investigators can begin to embark on comprehensive Earth-systems studies including various biogeochemical cycling investigations, on a scale, which has previously not been possible. In essence, the development of a LSP test-bed facility, as proposed under this Vision Statement, goes a very long way in meeting the challenge of integrating cross-discipline research between the atmospheric and hydrological science communities, and readily compliments and promotes the infrastructure elements currently proposed by CUAHSI.

5. Expected impact of the Vision

Successful implementation of the proposed strategy is hypothesized to have number of beneficial consequences. The loftiest of these goals is to definitively contribute to the improved predictive capacity of the weather and climate system. This goal has broadly been applied to justify a number of research activities and is often quite difficult to quantify. The atmospheric system is complex and highly non-linear. As such improvements in model formulations and initialization may be masked by deficiencies in seemingly unrelated components. Despite this difficulty, it is held by the authors of this Vision Statement, as it has been by the authors of the various other “grand challenge” documents, that fundamental improvements in our understanding and representation of land-atmosphere exchanges stands to yield measurable significant improvement in prediction skill across a range of space and time scales.

A series of more practically-attainable goals to be achieved by the proposed research strategy can also be articulated as follows:

- Earth systems modeling, until recently, has proceeded as a fragmented array of activities with each effort deeply rooted in its native discipline. The doors between these disciplines have opened significantly within the past ten years. However, the scale of some of the Earth system modeling problems continue to present computational, logistical and cultural

obstacles to formulating effective research agendas. This proposal focuses on fostering and integrating emerging elements of hydrological research for the benefit of improved weather and climate forecasts. One expected outcome from this endeavor is an improved understanding in the linkage between the terrestrial and atmospheric systems and improved elucidation of biological and chemical pathways between the systems. Understanding the nature of the coupling between the surface and atmosphere is tantamount to quantifying the fluxes of trace constituents.

- As articulated above, the establishment of an LSP test-bed will significantly benefit the evaluation of emerging data streams by providing them a direct conduit into data assimilation, diagnostic and prediction systems. Through such a mechanism, the lag time between data acquisition and assessment of impact on model predictions should be substantially reduced.
- The merging of differing data structures between the atmospheric and hydrological sciences holds promise to revolutionize accessibility among the different disciplines themselves and the broader user community. Significant opportunities exist for merging the highly efficient data structures used in the atmospheric sciences with the content rich data structures and visualization tools widely applied within Geographical Information Systems. The emergence of a common data model between these disciplines, which should be an objective of the LSP test-bed facility, would undoubtedly, have broad applicability beyond participating collaborators.

Most importantly, the proposed strategy forwards a practical methodology for advancing community involvement in the development and support of LSPs. This proposal directly attempts to address the problem of “good science not being put to good use”. By providing community modeling tools and user support, this Vision hopes to broaden the participation of the scientific community in the development of operational prediction tools to a degree far exceeding that of today. While some in the community may find the organization and maintenance of an infrastructure such as that proposed as an over-centralization of resources, we hold that the community at large would benefit from a basic, accessible infrastructure that supports the effective integration of independent creative research results. The observing platforms, model development activities and research programs articulated in this document represent a Vision for promoting and integrating land-atmosphere science in the service of society for the next ten years.

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