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A remote sensing observatory for hydrologic sciences: A genesis for scaling to continental hydrology

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[1] Uncertainties in assessing the effects of global-scale perturbations on the climate system arise primarily from an inadequate understanding of the hydrological cycle: on land, in oceans, and in the atmosphere and biosphere. Because of this uncertainty, almost all science-based initiatives have expressed the need for continued advances in global observations and modeling of the Earth system. It is in this spirit that we advocate establishing a hydrologic remote sensing observatory (RSO) to advance sensing technologies and their use in scientific inquiry into hydrologic processes. There are two fundamental reasons why establishing such a RSO is timely. The first is operational: Developing assimilation techniques to estimate unobserved fluxes and uncertainties in hydrologic forecasts has sufficiently matured to take advantage of computing facilities and detailed hydrologic observations shaped by the RSO. The second is scientific: This RSO will permit us to refine knowledge from physical and hydrologic models that can then be converted to local and global strategies for water resources management and ecosystem health evaluation. The authors outline the conceptual design, scope, and functionality of a RSO and present four examples to illustrate how the hydrologic community can take advantage of such facility.

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1. Introduction and Problem Statement

[2] The complexity and heterogeneity of hydrologic interactions exists over a wide range of scales in space and time. It is also widely accepted that remote sensing, broadly defined as a collection of noncontact observational methods, offers the potential to capture some of the intricacies of these spatial and temporal processes. Yet, hydrology today finds itself in a paradigm lock with respect to understanding the controls on hydrologic fluxes and states and how these controls vary spatially and temporally with scale and how the land surface and subsurface couples with the overlying atmospheric boundary layer. The current paradigm is that a given hydrological scale, whether it be a "Darcian," catchment, or the atmospheric boundary layer, the nonlinear dynamics describing water transport is presented as a function of the state at that resolved scale, and all finer scale (or faster) processes are treated as subgrid. Much coarser scale processes are generally assumed to be either sufficiently slow, or their effects are prescribed as forcing. It is clear then that the high dimensionality of hydrologic processes prohibits us from tracking cross-scale interactions across space and time. This knowledge gap invites the use of multiscale data offered by remote sensing platforms; however, the remote sensing algorithms are insufficiently developed for these complex processes to provide the spatial observations necessary for exploring cross-scale information flow.

[3] To break this lock we propose establishing an integrated remote sensing observatory (RSO) where research across the spectrum of hydrologic remote sensing can be integrated with hydrologic processes occurring at scales of less than a meter to thousands of kilometers. Historically, remote sensing products have been evaluated through short-term activities focusing on a single geophysical variable. We question this approach, and instead offer a vision of a community observatory where fundamental research on the estimation of water-energy-ecosystem variables can be carried out in an integrated manner across complex landscapes. The observatory offers the potential of improved predictions from remote sensing measurements for other

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regions, thus offering the hope that remote sensing can be used to address fundamental hydrologic research questions at local to global scales. These are the issues of critical importance to international activities such as the World Climate Research Programme's Global Energy and Water Cycle Experiment (GEWEX), the Prediction in Ungauged Basins (PUB) [*Sivapalan et al.*, 2003], and the United States Global Change Research Program's Water Cycle Initiative.

[4] This opinion paper is developed around our belief that understanding terrestrial hydrologic processes across scales must include remote sensing measurements at multiple scales, and that the proper use of the data requires, as a logical first step, research into the statistical and physical relationships among remote sensing measurements, in situ measurements, and hydrologic modeling. Existence of a long-term observatory would allow effective pursuit of these goals and efficient use of collective resources and efforts. We envision a "prototype" of such an observatory to be a piece of land that is well instrumented with in situ and ground-based high-resolution remote sensing instruments that allow detailed observations of the hydrologic processes occurring at the site. In that respect the embryonic form of the RSO would be similar to an extended field experiment such as those conducted in the past, with the main difference being the duration and comprehensiveness of instrumentation and variables measured. Careful definition of control volumes and nested sampling schemes would facilitate resolving the terms of the energy and water balances with known errors and providing observations for investigations of scaling relationships.

[5] Recurrence of major field experiments, such as the recent Soil Moisture–Atmosphere Coupling Experiment (SMACEX [*Kustas et al.*, 2005]) and NASA's Ground Validation programs for precipitation, are all indications that the concept of a RSO is sound. Below, we offer a sample set of examples appropriate for such an observatory, and sketch out how the observatory would foster the research. We also show that the proposed observatory is consistent with the scope of the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) HydroView research infrastructure.

[6] While it is clear that over the last decade, satellites have proven the capability to monitor many aspects of the total Earth system on a global scale, it is also clear that aircraft- and ground-based systems play a vital role in improving our understanding of hydrologic processes and their interactions. Thus the first step in constructing the skeleton of such a RSO is to use well-established methods that have a proven success record such as weather radar, lidar, as well as radiometers and spectrometers. The main hydrologic variables of interest include precipitation (especially liquid), snow water equivalent, evapotranspiration, surface water reservoirs and river discharge, soil moisture, precipitation interception, groundwater storage, soil freezing and thawing, and ecosystem variables like vegetation biomass and carbon content.

2. Science and Research Questions and Issues

[7] We argue that the hydrologic research community needs a remote sensing observatory to address numerous science questions that range from the spatial-temporal dynamics of hydrologic processes across complex landscapes to the statistical properties of hydrologic variables retrieved via remote sensing and their assimilation into hydrologic models. Below we offer four examples that in our opinion are representative of important hydrologic research problems to which remote sensing can contribute and for which an observatory is the appropriate mechanism for answering the questions.

2.1. Question 1: A Changing Landscape

[8] Globally, landscapes are changing in a dramatic fashion through such processes as deforestation-reforestation, anthropogenic water management in agriculture such as irrigation or tile drainage, and urbanization. Implications of these changes in both the terrestrial hydrologic budget and alterations in weather and climate have been documented. Since these changes occur spatially across the landscape, remote sensing is needed to monitor the land surface characteristics, to observe changes in hydrologic states and fluxes, and to compare these with predictions from hydrologic models. Remote sensors have the ability to make spatially resolved measurements over large areas. Remote sensing also often allows us to visualize complex processes because the spatial data can be captured regularly over time.

[9] What are the observational requirements of remote sensing measurements to help us better understand the effects of a changing landscape and changes in water management on hydrologic processes and their subsequent feedback to weather and climate at the regional to continental scales? Modern forecasting methods have sufficiently matured to include the basic processes that govern climate so that large-scale weather prediction is fairly reliable on some timescales. More importantly, the predictability timescale has been well quantified in such systems. At smaller scales, the problem is considerably more complex. Historically, researchers have made convenient mathematical assumptions such as homogeneity because the capacity to resolve the flow domain attributes was severely restricted. It is for this reason that serious issues exist in our understanding of small-scale flows, particularly in complex environments [see *Tenhunen and Kabat*, 1999, and references therein].

[10] Traditional techniques of measuring hydrologic variables rely on point sensors to collect information, which is then assumed to be representative of large areas. In some cases, the point measurement does represent a "hydrologically integrated" catchment area (e.g., streamflow at a point). However, this approach is not particularly helpful in complex or heterogeneous environments where the data cannot be assumed to represent a much larger area. Part of the problem is that the bulk of the Earth's surface is not horizontally homogeneous with respect to topography, geology, soil moisture availability, soil type, or canopy. More highly resolved information is necessary to separate the contributions of each of these variables. The surface-atmosphere interface is an example of a system that is highly variable in both space and time [e.g., *Cooper et al.*, 1992, 2000; *Eichinger et al.*, 2000]. Details of the soil surface affect soil moisture availability, which in turn affects both canopy development and local evapotranspiration rates. Detailed measurements at scales approaching a meter are needed to separate the effects of canopy, topography, and soil moisture on the evapotranspiration rate. In fact, the

problem of biosphere-atmosphere exchange from canopies on complex terrain serves as an illustration of how nonlinear dynamics can "break" symmetries and produce high spatial variability even when the canopy is uniform and the terrain is a gentle cosine hill [*Katul et al.*, 2006].

[11] In many regions, landscapes are changing spectacularly, particularly with respect to land use and water management in agriculture. There is evidence that these changes affect regional climates. For example, there is evidence that irrigation in Nebraska has changed the amount of precipitation in Iowa, that irrigation in Texas has led to an increase in tornado activity, and that mesoscale changes in land use can significantly affect storm events [e.g., *Doran and Zhong*, 2000; *Weaver and Avissar*, 2001]. El Nino events in the Pacific Ocean result in different climate signals in different parts of North America, halfway around the world. While researchers can show correlations between suspected causes and effects, we do not have sufficient measurements to conclusively and quantitatively document processes such as these that occur on near-continental to global scales; nor do we have appropriate and complete mathematical models for these processes. There is little ability to connect local measurements to intermediate, large, and global scales. A quantitative description of events and processes is needed so we can properly understand and propagate them across scales, thereby leading eventually to a capability for predictive modeling.

[12] The recent development of land data assimilation systems (LDAS) [*Mitchell et al.*, 2004; *Rodell et al.*, 2004] is an important step toward using remote sensing observations to merge the effects of a changing landscape with incomplete models of hydrologic processes. The primary goal of these systems is to produce optimal output fields of land surface water and energy states and fluxes by using data from advanced observing systems. These systems include one or more land surface models (LSMs) that are typically run retrospectively "offline," or uncoupled, using a blend of modeled and observed precipitation and radiation forcing to overcome the inherent weaknesses of the representations of cloud and precipitation processes by atmospheric models. In addition to numerous other applications, these output fields, e.g., soil moisture and temperature profiles, may be used to initialize coupled land-atmosphere models to explore the subsequent feedback of landscape changes to weather and climate at the regional to continental scales. Further, by employing these land data assimilation systems in coupled or uncoupled observing system simulation experiments (OSSEs) [*Atlas*, 1997], one can estimate the impact of planned future observing systems and determine requirements or gaps to help guide priorities for unplanned future observing systems.

[13] Current LDAS include the Global LDAS (GLDAS) [*Rodell et al.*, 2004], the North American LDAS (NLDAS) [*Mitchell et al.*, 2004], and the new NASA's Land Information System (LIS) [*Peters-Lidard et al.*, 2001] that unifies the capabilities of GLDAS and NLDAS and provides community Grid Analysis and Display System (GRADS) Data Server (GDS). The LIS is capable of running an ensemble of land surface models (currently Noah, CLM, VIC, Mosaic) on points, regions, or the globe at spatial resolutions from 2.5° × 2.5° down to 1 km or finer.

[14] The substantial intermodel differences and errors relative to the observations in the NLDAS project were highlighted by *Mitchell et al.* [2004] and more fully discussed by *Robock et al.* [2003]. Their findings imply that any LDAS' ability to explore the impacts of changing landscapes or of additional observing systems depends heavily on the accuracy of the required input data sets and the physics of the models. Even more challenging is the attribution of these differences to input parameters, forcings, or physics, and being able to discriminate statistically significant differences. For example, most LSM physics has been developed and evaluated at a few sites selected for their data richness (e.g., the Department of Energy Atmospheric Radiation Measurement program's Southern Great Plains region), while the remote sensing inputs to these models have been evaluated at typically separate "validation sites." The LDAS experience suggests that the interactions between input parameters, forcings, and model physics is complex and requires careful forethought and metrics to distinguish between uncertainties in the inputs, models, and responses due to changes in landscapes. A remote sensing observatory could fill a critical role toward addressing this signal/noise problem.

[15] Recent work [e.g., *Bosilovich*, 2002] has suggested that the joint spatial distribution of parameters and forcings yields nonlinear effects that can propagate to larger scales, again, highlighting the need for quantifying cross-scale information flow in hydrology. A critical need to help us evaluate the effects of local landscape change (e.g., urbanization, irrigation, deforestation) at regional and continental scales is one or more test beds where such impacts on the hydrologic cycle can be studied at multiple spatial scales to inform the required complexity of coupled modeling systems. It is clear that remote sensing provides the only reasonable means to quantify heterogeneity and change at regional and continental scales, and a hydrologic RSO that can support multiscale studies of land-atmosphere interaction could serve a central role in addressing this problem.

[16] A case has been made that measurements of hydrologic variables are needed with high spatial and temporal resolution at continental to global scales. The sheer volume of data that this represents will likely preclude achievement of this goal. However, if we can understand small-scale processes (e.g., $\sim$1 m) and develop methods to obtain representative values for hydrologic variables at somewhat larger scales (e.g., $\sim$1 km) to bridge the gap between the smallest scales at which variability occurs and scales at which modeling is possible and appropriate, the problem becomes far more tractable. This then is an important first requirement for a remote sensing facility to address how to make truly representative measurements at a given scale from a limited number of measurements.

[17] There are not currently remote sensors capable of making all of the measurements that may be required by all of the various branches of hydrology. The identification of specific requirements and the development of techniques to address current and evolving issues would also be a task for a remote sensing facility.

2.2. Question 2: Scaling of Hydrologic Variables

[18] For over 25 years, theories on spatial hydrologic processes have been developed and tested through modeling or exhaustive point measurements [e.g., *Wood et al.*, 1988;

Famiglietti and Wood, 1995; *Blöschl and Sivapalan*, 1995; *Rodriguez-Iturbe and Rinaldo*, 1997; *Crow et al.*, 2000; *Brown et al.*, 2002; *Milne et al.*, 2002; *Rietkerk et al.*, 2004]. Much of these developments have been related to the space-time organization of soil moisture fields and their influence on runoff production, and more recently their influence on vegetation and its organization. Rainfall, surface and subsurface flow, and soil moisture also have received much attention through scaling studies [e.g., *Gupta and Waymire*, 1990; *Gupta et al.*, 1996].

[19] It is critical that we understand the observational requirements for remote sensing if we are to assess whether remote sensing offers the potential to provide a multiscale view of the landscape so that such theories can be further developed and tested. We need to move measurements from scale to scale, and it appears that remote sensing is the only approach that has the potential. This means that we need to understand at each scale the uncertainty in the retrievals and in model prediction, so that theories on how hydrologic variability may change with scale can be adequately tested. For this, we also need to understand the effects of landscape heterogeneity on coarse-scale remote sensing measurements, and to develop methods to combine these with small-scale representations of hydrologic processes and their physics. Thus an important question is, Can remote sensing be used to test theory on spatial and temporal ecohydrologic processes, and can it provide us with multiscale measurements, so that these processes are transferred correctly across scales?

[20] Although many components of the hydrologic cycle exhibit considerable variation in space and time that changes with scale, to focus our discussion we use soil moisture as an example. Soil moisture is the amount of water stored in the unsaturated zone above the water table. Although small relative to the other terrestrial reservoirs in the hydrologic cycle (groundwater, glaciers and snow, permafrost, lakes), soil moisture is an important and active reservoir since it is directly linked to several hydrologic fluxes, namely precipitation, runoff, evapotranspiration, and drainage. Remote sensing appears to be the only technique that can provide measurements of near-surface soil moisture over the range of spatial scales required to understand its variability.

[21] Spatial and temporal variations of soil moisture can be observed with microwave remote sensing using both passive (radiometry) and active (radar) techniques. Soil dielectric properties at microwave frequencies are strongly dependent upon water content [*Wang and Schmugge*, 1980; *Dobson et al.*, 1985]. The relationship between soil moisture and both microwave brightness [*Schmugge*, 1978] and microwave backscatter [*Ulaby et al.*, 1978] has been well documented. In contrast to high-frequency optical and infrared radiation, microwaves penetrate vegetation and soil because of their longer wavelength. At 1.4 GHz, soil emissivity/reflectivity is determined by the first several centimeters of the soil moisture profile. Radiometric sensitivity to soil moisture through vegetation as dense as a full corn canopy has been demonstrated [*Hornbuckle and England*, 2004]. At higher frequencies there is sensitivity to only the first centimeter of the soil, and the temperature, architecture, and moisture content of the vegetation canopy begin to dominate the signal. At frequencies lower than a gigahertz, there is the potential for measurements of rooting depth soil moisture through vegetation as dense as forests [*Moghaddam et al.*, 2000].

[22] Soil moisture is the product of several hydrologic processes that operate on different spatial and temporal scales. Soil moisture is primarily a function of topography, soil type, vegetation, and precipitation. Variables such as topography and soil type do not change rapidly in time but can have high spatial variability. Other variables, such as precipitation and vegetation through evapotranspiration driven by energy balance, influence soil moisture on much shorter timescales. Consequently, soil moisture variability and its spatial pattern can be both scale- and time-dependent [e.g., *Hills and Reynolds*, 1969; *Kachanoski and de Jong*, 1988; *Wilson et al.*, 2004]. Can observed soil moisture variability be predicted from hydrologic theory using knowledge regarding hydrologic processes and observed spatial data on vegetation, soils, and topography? Some theoretical efforts to employ Reynolds-averaged equations to predict the temporal dynamics of the spatial variability in soil moisture appear promising, at least on small scales [e.g., *Katul et al.*, 1997]. Remote sensing will play the key role in answering this question by providing soil moisture data at a variety of spatial scales with the relevant temporal frequency.

[23] *Nykanen and Foufoula-Georgiou* [2001] observed a break (transition) in the scaling of the variance of relative soil moisture content (the ratio of volumetric soil moisture to porosity) with spatial scale for areas of Oklahoma and Kansas. The break was between the smallest scale soil moisture data that were obtained by aggregating point samples and data from an aircraft radiometer that were used at the other scales. At the smaller scales, a linear log-log relationship between soil moisture variance and scale was observed. At the larger scales, a different scaling relationship that also changed with time was found. Similar transitions in soil moisture variability between scales have been observed in other experiments [*Crow and Wood*, 1999].

[24] Is this transition due simply to different data sets, or is the transition real and are these observations a correct characterization of the physical processes involved? Would this transition appear if only one data set were used? Furthermore, can present land surface models reproduce this transition? Remote sensing is the only viable method that can be used to determine whether there indeed exists a transition between the variability at small spatial scales and variability at large scales, and what hydrologic processes control this transition.

[25] Another significant problem in hydrology is that the spatial scale of a measurement or a model is often different than the scale at which hydrologic predictions are needed. Consequently, upscaling and downscaling of measurements must occur. Can remote sensing provide multiscale measurements to transfer hydrologic processes correctly across scales? Ground-based radars and radiometers have meter-scale spatial resolutions [*O'Neill et al.*, 1996; *Laymon et al.*, 2001]. Microwave remote sensing instruments mounted on airplanes [*Jackson*, 2001; *Njoku et al.*, 2002] can observe soil moisture at spatial scales on the order of a kilometer. Satellite radiometers can produce global observations with a temporal frequency of a few days at spatial resolutions of

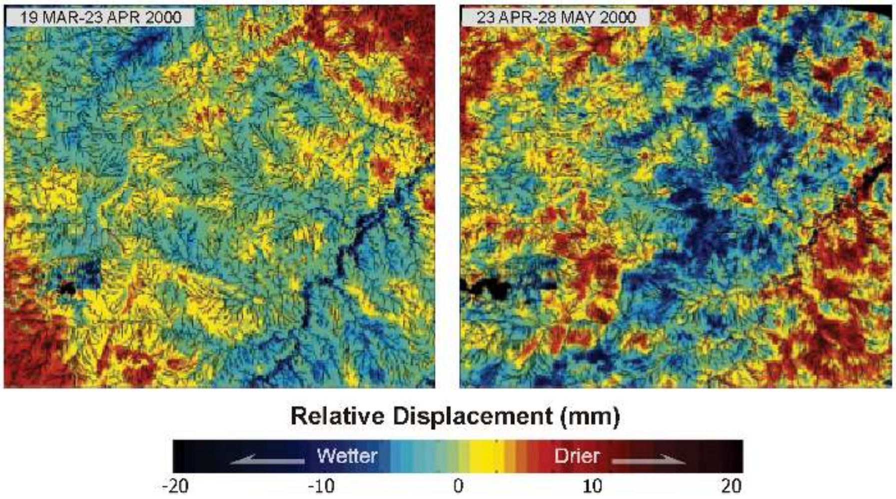

Figure 1. Differential interferogram (DIG) of an area of the Colorado High Plains produced with DINSAR at 5.3 GHz. Areas of positive relative displacement correspond to areas which are drier, while a negative relative displacement indicates wetter conditions for the second date of data acquisition as compared to the first date. Dates of data acquisition appear in the upper left-hand corner of the image. The black lines are stream channels. After *Nolan et al.* [2003].

tens of kilometers [*Kerr et al.*, 2001; *Entekhabi et al.*, 2004]. Satellite radars typically have better spatial resolutions but lower temporal measurement frequencies. Various areal coverage up to global is possible with remote sensing. The support of remote sensing observations spans six orders of magnitude, from meters to hundreds of kilometers.

[26] An example of the fine spatial detail possible with microwave remote sensing, and the hydrologic processes that can be revealed, is shown in Figure 1. This is a differential interferometric synthetic aperture radar (DINSAR) image of an area of the Colorado High Plains at 5.3 GHz using data from the ERS-2 satellite [*Nolan et al.*, 2003]. The image maps the relative change in phase of the SAR signal between two acquisitions of data. Wetting the soil decreases the penetration depth of the propagating wave and can increase the surface elevation (clay swelling). Both effects result in a decreased path length and a change in phase of the SAR signal. Hence a change in relative displacement indicates areas where soil moisture has increased (negative displacement) or decreased (positive displacement). The spatial resolution of the image is 50 m. Are the differences in Figure 1 due to rainfall, snowmelt, soils, vegetation, or topography, or a combination of these processes? Can the differences be apportioned quantitatively among these hydrologic processes? If so, how? Furthermore, can these processes be transferred across scales? Some variables that directly affect soil moisture, such as porosity, appear to be scaling, while others, such as residual soil moisture, appear to be multiscaling [*Peters-Lidard et al.*, 2001]. What is the effect of averaging nonlinear hydrologic processes so that large-scale aggregations may be interpreted correctly? Such questions can only be answered with multiscale measurements available via remote sensing.

[27] A dedicated RSO would be able to address several key issues that currently hinder our ability to use remote sensing in the context of spatial hydrologic processes and scaling. The first key issue is infrastructure. It can take several years for a single research group to plan and prepare for a ground-based microwave remote sensing experiment. Airborne and satellite instruments require enormously more planning, preparation, and resources. In each case, the net result may be only one or two weeks of data. Microwave radiometers and radars are not readily available and normally are custom-made by members of the research group themselves. In addition, such custom instruments normally require significant maintenance to keep them in operating condition. Besides the engineering expertise required to fabricate complex instruments, the research group must also be adequately adept in traditional hydrologic measurement techniques. In the past, only groups with significant expertise and focus in hardware design have been able to undertake these endeavors, and as a result, the science return has been reduced. An observatory could have remote sensing instruments and a procedure for maintaining these instruments already in place so that the time, resources, and effort required to undertake experiments could be greatly reduced.

[28] There is also a need for further integration of remote sensing and hydrologic data. Such integration would be encouraged by a remote sensing observatory. For example, integration of remote sensing and hydrologic measurements at many spatial scales will further our understanding of landscape heterogeneity and its contribution to within-pixel variability [*Famiglietti et al.*, 1999; *Mohanty and Skaggs*, 2001; *Bindlish and Barros*, 2002]. Additionally, models of microwave brightness, and particularly backscatter, do not match observations in some situations. Further development of these microwave models will likely require the complete consideration of competing processes besides soil moisture, such as changes in important soil properties (roughness, macropores) and the effective constitutive properties of vegetation (canopy structure, water content). Furthermore, remote sensing measurements must be combined with models of land surface processes in order to make the hydrologic predictions that our society needs. When micro-

wave remote sensing measurements are assimilated into land surface process models, better estimates of the spatial patterns of hydrologic properties, hydrologic reservoirs, and hydrologic fluxes are produced [*Houser et al.*, 1998; *Reichle et al.*, 2001]. Assimilation is the only way quantities such as soil hydraulic conductivity [*Burke et al.*, 1998], the full soil moisture reservoir [*Wigneron et al.*, 1999], evapotranspiration, runoff, and groundwater recharge can be determined [*Liou et al.*, 1999]. Integration of remote sensing measurements with land surface process models will also provide the framework through which hydrologic measurements at different scales and remote sensing measurements will be related.

[29] Finally, a RSO would provide longer periods of time over which to test microwave and land surface process models. As we discussed earlier, spatial statistics are time-dependent. Much of the previous research in remote sensing has suffered from the lack of long time series data. There are important diurnal [*Hornbuckle and England*, 2005] as well as seasonal changes [*Hornbuckle et al.*, 2003] that must be considered. For example, plot-scale microwave brightness (tens of meters) and satellite-scale microwave brightness (hundreds of kilometers) match well in homogeneous areas [*Kim and England*, 2003]. In heterogeneous areas, seasonal hydrologic phenomena (such as winter snow cover) can make the landscape much more uniform [*Judge et al.*, 2001]. The representation and effects of diurnal and seasonal hydrologic changes in microwave models must be improved.

2.3. Question 3: Data Assimilation

[30] Substantial amounts of research suggest that hydrologic forecasts can be improved if hydrologic variables, like precipitation, soil moisture, snow cover, and freeze-thaw state, along with ground observations, could be fused correctly into hydrologic models [e.g., *Houser et al.*, 1998; *Reichle et al.*, 2002; *Crow and Wood*, 2003; *Margulis and Entekhabi*, 2003; *Drusch et al.*, 2005; *Dunne and Entekhabi*, 2005; *Walker and Houser*, 2005]. To correctly combine different sources of data requires knowledge of the uncertainty in all three components of the prediction system: the retrieved remotely sensed variables, the ground-based observation system, and the predictive hydrologic model. Therefore a general question for the hydrologic community involved in using predictive models is, In what ways can remote sensing data be combined with other data and hydrologic models to improve hydrologic predictive skill, and can this increased skill be quantified?

[31] To illustrate how addressing this question could benefit from carefully constructed experiments within a remote sensing observatory we use an example of predicting evapotranspiration. Reliable measurement of evapotranspiration at the watershed scale is a major challenge in hydrology. Evapotranspiration is the second largest component of the surface water balance and remains a major source of uncertainty in estimates of groundwater recharge. Because of the spatial variability of evapotranspiration and its influence on soil water storage and antecedent moisture, it also can strongly influence runoff estimation. Remote sensing is ideally suited to assist with estimating evapotranspiration because it is able to map spatial distributions of vegetative cover and surface temperature; two quantities closely related to evapotranspiration. Here we describe a method that combines remote sensing observations with ancillary ground measurements to map evapotranspiration from scales of tens of meters to thousands of kilometers. The methodology described below is in the early stages of development. The potential for routine implementation of this technique would be greatly enhanced by having a remote sensing observatory.

[32] Regional-scale land surface models are typically prognostic; that is, they use operational inputs such as weather, and detailed soil and vegetation information to predict fluxes and states of the surface. Because of constraints on input data availability, prognostic land surface models operating over regional or continental scales evaluate the water and energy balance at resolutions on the order of 1–10 km or larger. Not only is this resolution typically too coarse to demarcate actual variations in land use/land cover on the hydrologic cycle, but comparison to ground-based observations of the surface energy balance results in a significant mismatch in scale. Tower-based measurements represent a source area of ~100 m (micrometeorological scale), an order of magnitude smaller than the output from such models. Airborne flux instruments can sample larger scales, although such measurements are not routinely available. A means of comparing model output directly with ground reference data at matching scales is critical to establishing the credibility of land surface models.

[33] While prognostic models predict land surface states (e.g., surface temperature and moisture), diagnostic models infer these conditions from remote-sensing observations and therefore can operate at the spatial resolution of the remotely sensed images, which can range from a few meters to several kilometers. In the following, we describe two very different kinds of diagnostic models that predict fluxes at micrometeorological scales: a surface temperature-based system called the Atmosphere-Land Exchange Inverse (ALEXI) model and associated disaggregation technique (DISALEXI), and a system using Raman lidar data, which analyzes fluxes from an atmospheric perspective. Agreement between these two approaches will lend credibility to both.

[34] The ALEXI/DISALEXI multiscale modeling system has been developed to disaggregate regional fluxes based on 5 km resolution thermal data from GOES (Geosynchronous Operational Environmental Satellite) to finer pixel resolutions associated with Landsat/MODIS/ASTER or aircraft-based remote sensing instruments. The ALEXI model component [*Anderson et al.*, 1997; *Mecikalski et al.*, 1999] uses 5 km GOES-based remotely sensed surface temperature and AVHRR/MODIS-based vegetation cover coupled with an atmospheric boundary layer growth model to compute fluxes at 5–10 km resolution. These regional-scale flux predictions from ALEXI can be disaggregated to finer scales (1–1000 m resolution) more commensurate with micrometeorological observations by using high-resolution surface temperature and vegetation cover information collected by Landsat/MODIS/ASTER or an aircraft-based system. The disaggregation procedure [DISALEXI) [*Norman et al.*, 2003; *Anderson et al.*, 2004] uses ALEXI predictions of air temperature at 50 m above ground level as an upper boundary field for local scale flux evaluations, and enforces conservation in aggregated sensible heating.

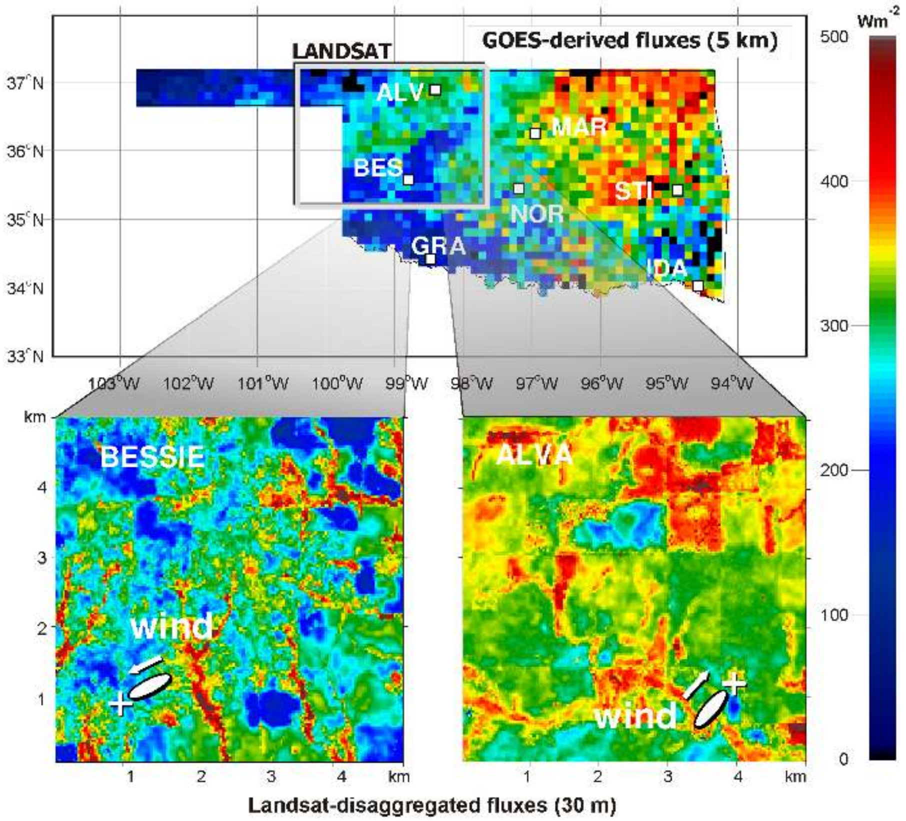

Figure 2. Latent heat flux, 29 May 2000 at the Oklahoma Mesonet.

[35] In Figure 2, spatially distributed output of evapotranspiration from the multiscale modeling system is illustrated for the state of Oklahoma at the 5 km ALEXI resolution. Sites having micrometeorological flux towers are indicated with two of these sites having exploded views where DISALEXI is run using Landsat imagery with a sharpened surface temperature field derived from a procedure described by *Kustas et al.* [2003a]. Also illustrated in the DISALEXI evapotranspiration fields is the tower location for both sites and the approximate extent of the upwind source area contributing to the flux measurements. Because of local heterogeneity in surface conditions, Figure 2 shows that changes in wind direction (and therefore the source area influencing the tower measurements) can significantly affect the flux measured at a given tower site. Model predictions at 5–10 km resolution cannot capture such local effects, and thus direct comparison with tower measurements is degraded.

[36] An independent evaluation of the DISALEXI high-resolution flux fields can be obtained with a Raman lidar technique for making three-dimensional measurements of water vapor concentration in the atmosphere. These water vapor profiles can be combined with local wind measurements to map evapotranspiration over a $\sim 1 \times 1$ km^2 area with relatively fine ($\sim$25 m) spatial resolution [*Eichinger et al.*, 1999]. The utility of the technique to determine evapotranspiration fluxes over complex terrain and canopies with nonideal micrometeorological fetch conditions has been demonstrated [*Eichinger et al.*, 2000]. An example application of this technique is illustrated in Figure 3 showing a 30 m resolution evapotranspiration map over adjacent corn and soybean fields from lidar data collected during the Soil Moisture Atmosphere Coupling Experiment (SMACEX) in Iowa [*Kustas et al.*, 2003b]. The evapotranspiration patterns at this resolution highlight the degree of nonuniformity present even in agricultural fields. DISALEXI output created with Landsat data over the same area provides a unique opportunity to assess consistency in the spatial pattern of the evapotranspiration field.

[37] Again, these two flux-mapping approaches are complementary yet completely independent, one being surface-based and the other being atmosphere-based. In combination, and in comparison with ground-based tower measurements, a strong argument can be made for the validity of flux predictions at meter-scale resolution over regions the size of a watershed basin.

[38] This example demonstrates the power of combining tower and aircraft micrometeorological measurements with diagnostic modeling techniques for robust validation of evapotranspiration estimates at watershed and regional scales. Prognostic models at coarser spatial resolutions are more difficult to validate directly. Furthermore, the range in resolution afforded by multiscale diagnostic modeling allows for the investigation of the impact of land cover/land use variability on hydrologic fluxes, both of which have length scales on the order of 10^1–10^2 m.

2.4. Question 4: Validation

[39] Historically, the validation of remote sensing products consisted of comparisons to ground-based measure-

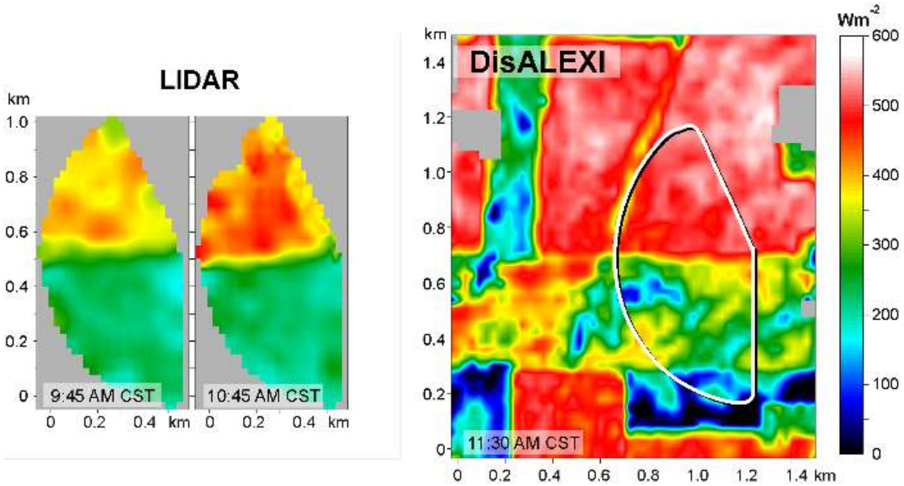

Figure 3. Output of latent heat flux from lidar-based technique over corn and soybean fields in central Iowa in comparison to DISALEXI output using aircraft imagery during SMACEX.

ments with the goal of having the former match the latter. Too often the comparisons were based on short field campaigns, and the retrieval algorithms applied to areas of questionable validity without any statement of their uncertainty. This approach to validation needs to be revised. We define validation as quantitative determination of uncertainty of remote sensing products. Thus the problem of validation becomes equivalent to answering the question: What is the statistical structure of uncertainties associated with remote sensing products at different space-time scales?

[40] Implicit in this questions are issues of error definition (additive or multiplicative), and determination of bias, probability distribution of the errors with their moment characterization, and spatial and temporal dependence. Adequate ground-based observations either are too sparse or do not exist. Their measurement errors are often not well recognized. Thus the observatory offers the opportunity to develop new rigorous approaches for validating, i.e., evaluating, remote sensing products.

[41] To demonstrate how a RSO could help address the validation issue, we use an example of radar-rainfall estimation. Prior to the advent of remote sensing, hydrologists relied on rain gauge networks and suffered from an inability to account for the high spatial and temporal variability of rainfall. While the arrival of radar networks, e.g., the NEXRAD system in the United States, has dramatically improved our ability to detect storms and offered hydrologists a wealth of information on the spatial and temporal structure of rainfall systems, quantifying the uncertainty of rainfall estimates remains an important challenge [e.g., *Krajewski and Smith*, 2002]. Unless the uncertainty of radar-rainfall products is quantified, the research benefits of the data will be limited.

[42] The main challenge in designing a network adequate for rainfall validation purposes is closing the scale gap. Considering that rain gauge and weather radar have sensor sampling areas differing by some 8 orders of magnitude, it is clear that the challenge is significant and cannot be addressed by a standard operational network.

[43] In our vision the rainfall validation network will comprise several types of sensors [*Krajewski*, 2006]: (1) standard rain gauges to facilitate transferability of results, (2) disdrometers, i.e., devices for measuring drop size distribution (DSD), as these are fundamental to radar (and satellite) remote sensing of rainfall, (3) vertically pointing radars, as the vertical variability of precipitating cloud and rain systems seems to be of fundamental importance for addressing the radar-rainfall estimation problem, and (4) a network of specialized inexpensive radars to provide very high resolution observations.

[44] A strategy based on a colocated collection of the instruments listed above requires characterization of point-scale measurement error. In the case of tipping bucket rain gauge data, *Habib et al.* [2001] and *Ciach* [2003] conducted experimental studies that provide mathematical models of rain gauge rainfall accumulation random errors. The standard errors decrease with increasing rain amount and time integration scale. Another conclusion from these studies is that tipping bucket rain gauges, when well maintained and deployed as a pair [*Ciach and Krajewski*, 1999; *Steiner et al.*, 1999; *Cruse et al.*, 2006] provide accurate observation of rainfall accumulations at scales from 10 min up. Systematic errors in rain gauge measurements can be attributed to wind effect that has been extensively studied experimentally [e.g., *Sevruk and Hamon*, 1984; *Yang et al.*, 1998], and recently numerically [*Nešpor et al.*, 2000; *Habib and Krajewski*, 2001; *Constantinescu et al.*, 2006].

[45] Validation of hydrologic variables, rainfall in particular, using in situ data requires separation of the effects of natural variability from the measurement/estimation uncertainty [*Ciach and Krajewski*, 1999]. This, in turn, implies the need for estimation and characterization of the variability in space and time across spatial and temporal scales. For rainfall this requires specialized networks [e.g., *Moore et al.*, 2000; *Habib and Krajewski*, 2002; *Krajewski et al.*, 2003; *Ciach and Krajewski*, 2006].

[46] Closing the scale gap would be achieved by using high-resolution short range X-band polarimetric radars [e.g., *Matrosov et al.*, 1999; *Zrnic and Ryzhkov*, 1999; *Matrosov et al.*, 2002; *Anagnostou et al.*, 2004] operated as a network [*Krajewski*, 2006]. Attenuation of X-band signal by rainfall would be mitigated by use of multiparameter algorithms,

multiple radars "seeing" the same location, and other corrections [e.g., *Berne and Uijlenhoet*, 2005]. With spatial resolution on the order of 100 m, the effect of spatial variability of rainfall becomes negligible and in situ data can be used to estimate the error structure of these radars, which in turn, "connect" to NEXRAD's network of radar and satellite rainfall estimates. Disdrometers and profilers (i.e., vertically pointing radars) provide additional context and information relevant to rainfall estimation using remote sensing. By measuring raindrop size distribution (DSD) and drop velocity, disdrometers allow us to estimate spatial variability of radar reflectivity, as well as other rainfall characteristics. Since disdrometers measure DSD indirectly and the cumulative experience with their operation is much less than with rain gauges, they require thorough testing. Several disdrometer intercomparison experiments point to the sensitivity of the results to the instrument type [*Sheppard and Joe*, 1994; *Campos and Zawadzki*, 2000; *Williams et al.*, 2000; *Tokay et al.*, 2001; *Miriovsky et al.*, 2004; *Krajewski et al.*, 2006.]

[47] Vertically pointing Doppler radars (VPR) provide crucial information for radar remote sensing. They are capable of observing vertical profiles of precipitating clouds thus identifying features affecting radar observables. These features include thickness and height of the melting ice at cloud base (i.e., bright band problem), precipitation phase, convective cores, updrafts and downdrafts, etc. They are also capable of providing estimates of the vertical profile of DSD. These estimates are more reliable if the profiler operates at multiple frequencies so that air and raindrop motion can be distinguished. Profiler-based studies of precipitation systems and the related instrumental and estimation issues have been well documented in a number of publications [e.g., *Wakasugi et al.*, 1986; *Gage et al.*, 1999, 2000, 2002; *Williams et al.*, 2000; *Williams*, 2002; *Kollias et al.*, 2002].

[48] Development and operation of a network of radars, in concert with other ground-based sensors at a rainfall validation site, offers numerous advantages. For example, consider a network of four radars overlooking a regular dense network of rain gauges. Its operation can lead to (1) improved accuracy of rainfall algorithms, (2) increased resolution, (3) increased reliability, (4) reduced development and operating costs, and (5) repeatability. Still, much research remains before we can fully realize the above benefits. Research needed includes technological advancements of radar hardware, development of software to operate the radar as a true network and not simply a collection of four individual radars, and refinement of rainfall estimation algorithms.

[49] Many of the issues we discussed using validation of rainfall as an example apply to other, but not all, hydrologic variables. For some of the variables, e.g., soil moisture, additional complications immediately come to mind: the validation setup needs to take into account effects of topography, soil type and distribution, and vegetation cover, among others.

3. Design of a Remote Sensing Observatory

[50] Up to this point we have discussed the remote sensing observatory somewhat in the abstract. In this section we provide more details. A broad definition of the RSO is a piece of land that is well instrumented with in situ and ground-based high-resolution remote sensing instruments that allow detailed observations of the hydrologic processes occurring at the site. In that respect, the RSO is quite similar to a hydrologic observatory with the main difference being the size. We contend that the area of a RSO does not need to be larger than about 10 km by 10 km. Such a size is greater than the resolution of most remote sensing platforms, yet not too large to be unmanageable. The questions "Where?" and "How many?" immediately follow. However, as these questions are not critical to establishing the soundness of the concept, we will not address them at this time.

[51] Issues relevant to site selection include variability of the hydrometeorological processes, access to land, and how well it represents other areas. Obviously, we need to sample a range of conditions; a place where it rarely rains would not be a good choice for remote sensing of rainfall studies. A site having good seasonal variability and representing both cold and warm season processes and their transitions would be preferred. On the other hand, difficult terrain imposes unnecessary obstacles early in our efforts. A mountainous site would make more sense after we convince ourselves, as a community, of the merits of the RSO concept. By the same token, one could argue for a multisite dynamic adaptable facility designed to sample a broad range of heterogeneities focused on variability in vegetation, terrain, and hydroclimatic conditions. This would be possible with participation by a broad international hydrologic community.

[52] After site selection the next critical questions are, "What instruments should be deployed, how many of them do we need, and in what configuration?" As our examples above illustrate, the answer depends on the variable of interest. With some (e.g., rainfall), our knowledge is sufficient to address the specific design issues now; for other variables (e.g., soil moisture) we have major gaps in our understanding. Still, this should not stop us from making the commitment and developing a RSO. The whole point is that the observatory is a "playground" where we can easily modify, enhance, and adapt the sensor network as our knowledge of the relevant processes increases. For many variables, the scale of the variability may be such that it would prevent dense deployment of sensors. In that case, we should consider nested design that would enable gradual bridging of the scale gap and enable upscaling studies. For other variables we need to consider one or more specific locations representative of elements present in the observatory, to later allow integration of the entire domain or the scale relevant for a particular remote sensor. For example, rather than deploying a uniform network of flux towers, we may deploy them at the locations with topography and land use characteristics representative for the particular RSO site. Understanding evaporation over corn or forest at some selected sites would allow upscaling to a larger domain. In some cases we may need to resort to virtual reality modeling of the local hydrologic processes based on our current state of knowledge for the design of our observational network.

[53] What variables are of primary interest? It seems that the priority should be the variables that control or deter-

mine near surface states and fluxes of mass and energy transfer. Precipitation, soil moisture content, and evapotranspiration are the basic variables that constitute a core of observations for a wide variety of hydrologic studies. The measurements would include several components of the radiative energy balance, surface, and near-surface temperatures, other properties of the landscape such as vegetation characteristics, as well as boundary layer processes including wind profiles.

[54] Other principles of the RSO design include high and well-determined quality of the data, redundancy of information, oversampling design, immediate access to data by the entire research community, long-term deployment, automation of data collection, etc. Selection and deployment of specific instruments should be preceded by careful comparisons and short-term experiments, while the double-sensor principle will aid in data quality control and in situ error characterization. The length of deployment of a particular set of instruments at a given location should be guided by frequent assessment of the need to help our understanding. Thus, if we as community feel that a particular aspect of remote sensing is well understood and dealt with, we can move on to study another. For example, if we understand measurements and estimation of evapotranspiration over uniform vegetation on flat terrain, there is little sense in continuing to maintain an array of instrumentation doing just that. The design of the RSO should be inherently flexible to allow for reconfiguration of the site as hypotheses are tested and new hypotheses are formulated.

[55] We have estimated that the cost of establishing a RSO would be about \$10 million, with about \$5 million a year to run the facility. In our calculations we assumed deployment of only ground-based instruments; having an aircraft available to the facility would add additional cost. The staff of the observatory would be about 10–15 highly qualified scientists, engineers, and technicians. The data distribution, archival, and mining would be handled by the Information Technology unit of the RSO. Considering the cost of a single satellite mission, the above price, while only a rough estimate, seems a bargain. The new capability afforded to the research community would quickly result in value added products and would pave the way for future advances.

4. Closing Remarks

[56] The concept of the remote sensing observatory we propose should be viewed as development of new capabilities and not as a large-scale experiment. For remote sensing to be useful in studies at hydrologic observatories as well as in monitoring continental and global-scale water resources, it needs to be investigated through a series of focused studies. A number of questions and issues remain; we have discussed some of them in this paper. We need a statistical approach to test for consistency between remote sensing and ground data. We need to quantify uncertainty in derived remote sensing products and ground measurements. We need to improve our understanding of subgrid heterogeneity and its effects on hydrologic processes. We need to develop approaches to assimilate remote sensing data and products into new models and theories.

[57] At remote sensing observatories many variables would be monitored at comparable scales. The necessity of this multicomponent approach has been recognized by those currently involved in remote sensing validation efforts. For example, the SMEX 2002 experiment in Iowa has demonstrated the value of boundary layer and water vapor monitoring for interpretation of passive microwave remote sensing of soil moisture. Even in validation of precipitation (seemingly an external input) the information on three-dimensional wind structure, atmospheric stability and humidity of the prestorm and poststorm environment are critical for proper interpretation of the results.

[58] How should we go about establishing RSOs? While the developing structure of the CUAHSI seems well suited for the task, it is still somewhat of a moving target. Therefore we resist temptation of putting our RSO concept into the framework of CUAHSI. Our main objective in this paper was proposing a concept, not a design. We hope this paper will stimulate the hydrologic community to initiate more discussion on the issues and needs we raise herein. As the scope of remote sensing is wide, developing smaller focused prototypes of RSOs may be a good first step to consider. In designing such prototypes we should capitalize on lessons learned from previous community experiments such as FIFE, BOREAS, HAPEX-Mobilhy, HAPEX-Sahel, LBA, etc., and coordinate with efforts of agencies involved in hydrologic remote sensing.

[59] A remote sensing observatory would allow us to assess more quantitatively the state-of-the-art on remote sensing and hydrologic prediction, thus providing a credible path toward future progress. Without being able to determine the uncertainty of many remote sensing products, it is hard to argue for resources needed for future progress. Since building observational systems is expensive, societal decisions leading to such investments need to be firmly based in science. The RSO will greatly improve our capability to make credible scientific recommendations of resource investments, including those directly affecting the research enterprise.

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