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A Remote Sensing Observatory for Hydrologic Sciences: A Genesis for Scaling to Continental Hydrology

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Abstract

The authors propose establishing a hydrologic remote sensing observatory to further advance sensing technologies and their use in scientific inquiry of hydrologic processes. They pose four fundamental questions the answering of which would benefit from a specialized observatory. The questions address issues that range from global needs to monitor changing landscapes and the associate hydrologic effects, to understanding scale effects on hydrologic variability, to improving our predictive skills, to the need for quantification of uncertainty of remote sensing based estimates of hydrologic variables. The authors elaborate four examples illustrating how each question could be addressed if the hydrologic community had a remote sensing observatory. They outline the conceptual design, scope and functionality of such a facility in the context of the CUAHSI HydroView research infrastructure.

1. Introduction and Problem Statement

The energy and water cycle is driven by a multiplicity of complex processes and interactions, many of which are inadequately understood and poorly represented in hydrologic models. Its terrestrial characterization requires an understanding of moisture and energy reservoirs and exchanges between and within the Earth's atmosphere, land, and biological systems over a wide range of space and time scales. A central element for understanding the role of the terrestrial hydrosphere-biosphere in Earth's climate system and a central focus of many research programs (e.g. NASA's Earth Sciences Enterprise's Science Strategy; World Climate Research Programme's Global Energy and Water Experiment, or GEWEX, Science Strategy; United States Global Change Research Programe's Water Cycle Initiative), is satellite measurement of variables such as radiation, precipitation, snow properties, vegetation state, surface temperature, amongst others. Such measurements are required to further our understanding of the terrestrial hydrology and its variability, both spatially and temporally. Additionally, such observations further our understanding of coupling between the terrestrial and atmospheric branches of the hydrologic cycle, and how this coupling may influence hydrologic variability and its predictability.

Over the last decade, satellites have proven the capability to monitor many aspects of the total Earth system on a global scale. This is a capability unmatched by surface based systems which are generally limited to land areas which cover only about 30% of the planetary surface and are concentrated in the northern hemisphere. Currently, satellite systems are used to monitor the evolution and impacts of El Nino, weather phenomena (particularly clouds and precipitation), natural hazards and extreme events such as floods and droughts, vegetation cycles, including crop development, changes in snow cover, deforestation and other land cover change, forest fires, urban development and other terrestrial variables. These observations are used in decision-making and for strategic planning and management of industrial, economic, and natural resources. Examples include weather and climate forecasting, crop monitoring, energy and water resources management, urban planning, forestry, fisheries, and early warning systems for natural disasters and human health impacts.

On June 2, 2003, a Group of 8 (G8) Action Plan on Science and Technology for Sustainable Development included a commitment to strengthen international cooperation on global observations that included the development of global observation strategies for the next ten years, and to produce reliable data products on atmosphere, land, fresh water, oceans and ecosystems. The action plan has resulted in two Earth Observation Summits (EOS), July 2003 and April 2004, and the formation of the *ad hoc* Group on Earth Observations (GEO). GEO is charged to develop a 10-Year Implementation Plan that provides a broad framework for earth observations that includes comprehensive *in-situ* measurements, satellite observations and modeling systems for "achieving comprehensive, coordinated, and sustained Earth Observations for the benefit of humankind", and will be presented to the Third Earth Observation Summit in early 2005.

The assumption that remote sensing will provide measurements suitable for subsequent derived hydrologic products, with sufficient accuracy to be useful for scientific studies in hydrology and for the monitoring and decision-making called for under the sustained Earth Observations of EOS/GEO is open to question. Remote sensing sensors measure the emission and/or reflectance of radiative energy ranging from visible light to microwave frequencies. (An exception is the recently launched Gravity Recovery and Climate Experiment, GRACE, which measures micro-gravity anomalies). These measurements are then used to estimate hydrologic, energetic and biological variables, such as precipitation, soil moisture or vegetation canopy density through what is often referred to as 'retrieval algorithms' or models. Among the most significant outstanding gaps in obtaining accurate retrievals are for precipitation, especially solid precipitation, snow water equivalent, and evapotranspiration. For hydrologic variables like surface water reservoirs and river discharge, ground water storage, soil freezing and thawing, and ecosystem variables like vegetation biomass, space-borne remote sensing observation systems are not yet in place.

A casual look from an airplane window reveals a landscape that is highly heterogeneous with respect to soils, topography and vegetation. Whether from irrigation or rainfall, patterns of soil moisture are often seen, as is the pattern of partial snow coverage as the snow cover melts. Ground-based, point observations are incapable of capturing the complexity of this landscape or the variability of the processes like precipitation that produce it. Remote sensing offers the only observational tools that have the potential to capture these spatial patterns, yet there are limitations due to sensor resolution or observation frequency.

Hydrology today finds itself in a paradigm lock with respect to understanding hydrological processes across heterogeneous landscapes, especially 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 couples with the overlying atmospheric boundary layer. Insufficient knowledge exists to develop terrestrial hydrologic models that capture this complexity properly, and remote sensing retrieval algorithms are insufficiently developed for these complex landscapes to provide the spatial observations necessary for improved hydrologic models. Breaking this lock should be one of the very highest research priorities for CUASHI.

One reason for the current situation is the lack of an integrated remote sensing observatory where research across the spectrum of hydrologic remote sensing can be integrated with hydrologic processes occurring at scales from meters to 1000's of kilometers. Historically remote sensing 'products', like precipitation, have been 'validated' through short-term activities focusing on a single geophysical variable. We reject this approach, and instead offer a vision of a CUASHI observatory where fundamental research on the retrieval of water-energy-ecosystem variables can be carried out in an integrated manner, across complex landscapes, and where the effects of this complexity can be assessed by estimating the uncertainty in the retrievals and compared to the uncertainty in both ground-observations and model predictions. The observatory offers the potential of improved predictions from remote sensing measurements for other regions, thus offering the hope that remote sensing can be used to address fundamental climate research questions at regional to global scales; issues of critical importance to CUASHI or to international activities such as GEWEX or the Group on Earth Observations.

This vision paper is developed around our belief that understanding hydrologic processes across scales must include remote sensing measurements, and the proper utilization of the data requires research into the statistical relationship amongst remote sensing measurements, ground-based measurements and hydrologic modeling. CUASHI can take the lead in developing a new scientific approach to remote sensing through the establishment of a remote sensing observatory. We offer an example set of science questions appropriate for such an observatory, and sketch out how the observatory would foster the research. We also offer a suggested set of design criteria that would be appropriate for such an observatory, and show that the proposed observatory is consistent within the scope of other CUASHI hydrologic observatories.

2. Science and Research Questions

A remote sensing observatory can be used to address numerous science questions that range from the spatial-temporal dynamics of hydrologic processes across complex landscapes to the statistical properties of remote sensing based, retrieved hydrologic variables and their assimilation into hydrologic models. Below we offer four examples that we feel 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 research question.

2.1. Example Question #1

> *Can remote sensing observations be used to better understand the effects of changing landscape and water use on hydrologic processes and the subsequent feedback to weather and climate at the regional to continental scales, and if so what are the observational requirements of the remote sensing measurements?*

Globally, landscapes are changing in a dramatic fashion through deforestation-reforestation, anthropogenic water management in agriculture like irrigation or tile drainage, urbanization, and so forth. Additionally, changes in the landscape often manifest themselves as a fragmentation of the landscape. Understanding the hydrologic implications of these changes in the terrestrial hydrologic budget, and to related changes in weather and climate, is of critical importance. Since these changes occur spatially across the landscape, remote sensing is needed to monitor the land surface characteristics (like vegetation), to observe (through retrieved variables) changes in hydrologic states and fluxes like soil moisture or evapotranspiration, and to compare with hydrologic predictive models.

2.2. Example Question #2

> *Can remote sensing be used to test hydrologic theory on spatial hydrologic processes, and can it provide us with multi-scale measurements, so hydrologic processes are transferred correctly across scales?*

For over twenty-five years, theories on spatial hydrologic processes have been developed and tested through modeling or exhaustive point measurements. Much of this theory has 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, especially in semi-arid or savanna environments. Understanding the remote sensing observational requirements is critical in assessing whether it offers the potential to provide a multi-scale view of the landscape so such theories can be tested. We need to move measurements from scale to scale, and it appears that remote sensing is the only measurement method 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 (for example) theories on how soil moisture 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 develop methods to combine these with small-scale representations of hydrologic processes and their physics.

2.3. Example Question #3

> *In what ways can remote sensing data be fused with ground-based data (including ground-based remote sensing data) and hydrologic model outputs to improve hydrologic predictive skill, and can this increased skill be quantified?*

Substantial amounts of research suggest that hydrologic forecasts can be improved if hydrologic variables, like precipitation, soil moisture, snow cover and properties and freeze-thaw state, along with ground observations could be fused correctly into hydrologic models. The improved predictions range from flood discharge forecasting on the order of days to seasonal climate forecasts on the order of months. 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. Carefully constructed experiments within a remote sensing observatory can help evaluate the impact on hydrologic predictions. Historically the focus has been on assessing one retrieved variable at a time, but the observatory offers a multi-variable perspective that allows researchers to consider whether the remote sensing retrieval algorithms are sufficiently accurate and whether the scale of remote sensing observations is sufficient to understand the hydrologic processes. It can also assess the sufficiency of the observation scale as well as current (or planned) remote sensing capabilities under a general theme of an integrated measurement system, which can better estimate, collectively, the hydrologic variables.

2.4. Example Question #4

> *What is the best way to validate remote sensing data, and can we quantify uncertainty in hydrologic variables with remote sensing products, given that ground-based observation are sparse, incomplete, and uncertain?*

Historically the validation of remote sensing products consisted of comparisons to ground-based measurements with the goal of having the former match the latter. Too often the comparisons were based on short field campaigns, and the retrievals algorithms applied to areas of questionable validity without any statement of their uncertainty. This approach to validation needs to be revised. Too often the ground-based observations are taken at different spatial and temporal scales than the remote sensing measurements rendering them inappropriate for direct comparison. The ground-based observations contain measurement errors, especially for variables like soil moisture or evapotranspiration that are often not considered. Thus, the observatory offers the opportunity to develop new approaches for validating remote sensing products.

3. Objectives and Scope of this Vision Paper

The main objective of this paper is to argue that remote sensing should be an essential component of the CUAHSI research agenda for the future. We presented several science questions the answering of which requires involves remote sensing. We introduced the concept of remote sensing observatory as a central piece of CUAHSI research infrastructure.

In the following sections of the paper we demonstrate how a remote sensing observatory could advance hydrologic science and its relevance to addressing societal problems. We discuss how our vision of such an observatory could lead to specific solutions to the example questions we introduced earlier. We have limited our discussion to just a few examples but it is clear to us that the list could easily be much longer.

We also discuss general principles of the observatory design and functioning. We demonstrate its feasibility and estimate the resources needed for its development. We argue that for CUASHI to fulfill its vision of new research into hydrologic processes, as well as related regional to continental hydrologic processes, CUASHI needs to take the lead in developing a new scientific approach to relating remotely sensed information to address relevant questions.

4. Examples of Addressing the Research Questions

4.1. Questions #1

There are two major issues in hydrology that must be addressed in order for predictive models to advance and become more reliable. The first issue deals with the effects of surface heterogeneity and the second is the study of hydrologic processes at very large scales. Advances in these areas are required to better understand the effects of changes in landscape on hydrologic processes and of feedback mechanisms involving weather and climate at regional to continental scales.

Modern science has come a long way towards understanding the interaction between the surface and the atmosphere. Much is known about the basic processes that govern climate so that large scale weather prediction is fairly reliable. At smaller scales, the problem is considerably more complex. Historically, researchers have assumed homogeneity over large areas, only recently realizing the true degree of heterogeneity that exists. Serious issues also exist in our understanding of small scale flows, particularly in complex environments. Traditional techniques of measuring hydrologic variables rely on point sensors to collect information which are then assumed to be representative of large areas. However, this approach is not particularly helpful in complex or heterogeneous environments where the data cannot be assumed to represent a much larger area. In these kinds of environments, traditional sensors have limited usefulness. This is because they often have relatively small footprints, there are a necessarily limited number of sensors which can be used to make the measurements, and because of our current inability to extend the values measured at a point (or series of points) to understanding the details of processes that occur on much larger scales. 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. It is in this situation that remote sensing can be particularly helpful.

Remote sensors that can make spatially resolved measurements over large areas can be particularly valuable, not just in providing spatial data, but often allowing visualization of complex processes. The surface - atmosphere interface is an example of system that is highly variable in both space and time (Cooper et al. 1992; 2000; Brutsaert 1998; Eichinger et al. 2000). Details of the soil surface affect soil moisture availability which in turn affects both canopy development and local evapotranspiration rates. It is possible to obtain spatially resolved evapotranspiration estimates from surface temperature measurements made by aircraft (Neale et al. 2000) or satellite (Moran et al. 1989; Anderson et al. 1997; 2004) and from three dimensional water vapor measurements from lidar (Eichinger et al. 2000; 2004). Supporting these studies are remote sensing methods to estimate canopy cover at scales as small as a meter and developing methods to obtain spatially resolved soil moisture estimates. Detailed measurements at scales approaching a meter are needed to separate the effects of canopy, topology, and soil moisture on the evapotranspiration rate. Current hydrologic methods are based upon algorithms and methods rooted in the concepts of stationarity and homogeneity. As a result, we have only a limited understanding of hydrologic processes across heterogeneous landscapes. This is particularly true with respect to understanding feedback mechanisms which control hydrologic fluxes and how these mechanisms vary spatially and temporally. Recognizing the integrating power of the atmosphere, at least at small scales, it is necessary to know the extent to which spatial variability at the surface is important.

From both a modeling and a remote sensing perspective, a critical unsolved issue is spatial/temporal aggregation and disaggregation from the point/instant to the satellite footprint/sub-diurnal scale and vice-versa. Current (e.g., AMSR-E, MODIS, GRACE, TRMM) and future (e.g., HYDROS, GPM) sensors/missions are/will be very limited in their spatial and temporal sampling rates. As discussed by Cosgrove et al (2003) and Rodell et al, 2004, modeling studies attempting to use remote sensing data must implement spatial and temporal interpolation techniques to provide information at the typically finer temporal and spatial scales of the modeling system. However, without an integrated observatory to systematically study and evaluate these approaches, this may never be possible. An integrated remote sensing observatory capable of studying these issues could make a major contribution supporting the usefulness of both models and the available data.

The issue of spatial variability at small scales is also important in estimating areal averages of hydrologic variables. For many modeling purposes, what is needed is a value for a given variable that is representative of some region. Traditional measurement methods of all of the hydrologic variables represent volumes of space that may be as much as 8 orders of magnitude smaller than the size of the region for which a value is desired. Methods to reconcile measurements made at various scales are needed as are techniques to obtain regional estimates of hydrologic variables with a limited number of measurements. There is evidence that soil moisture measurements made at one scale may not be appropriate to use in models needing soil moisture information at different scales (Nykanen and Foufoula–Georgiou 2001).

Globally, landscapes are changing dramatically, 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 and that irrigation in Texas has led to an increase in tornado activity and that mesoscale changes in land use can significantly affect storm events (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, much less 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. This is needed to properly understand and model the events in a quantitative way, leading eventually to a capability for predictive modeling.

Changes to the landscape are often manifested as fragmentation of the landscape. Understanding the hydrologic implications of these changes in the terrestrial hydrologic budget, and to related changes in weather and climate, is of critical importance. Since these changes occur randomly across the landscape, over large areas, remote sensing is needed to monitor the land surface characteristics (like vegetation), to observe (through retrieved variables) changes in hydrologic states and fluxes like soil moisture or evapotranspiration, and to compare with hydrologic predictive models. Insufficient knowledge exists to develop terrestrial hydrologic models that capture this complexity properly. Compounding the problem is that remote sensing retrieval algorithms are insufficiently developed for these complex landscapes to provide the spatial observations necessary to improve hydrologic models. Many of the remote sensing retrieval algorithms assume a spatial homogeneity that does not exist.

The recent development of Land Data Assimilation Systems (LDAS; Mitchell et al. 2004; Rodell et al. 2004) is an important step towards using remote sensing observations to better understand the effects of a changing landscape on 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 atmospheric models’ representations of cloud and precipitation processes. 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 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, while simultaneously developing improved methodologies to assimilate remotely-sensed observations.

Current LDAS include the Global LDAS (GLDAS; Rodell et al. 2004), the North American LDAS (NLDAS; Mitchell et al. 2004), and the new NASA/GSFC Land Information System (LIS; Peters-Lidard et al. 2001) infrastructure that unifies the capabilities of GLDAS and NLDAS, in addition to providing high performance computing and communications infrastructure and community GrADS/DODS data servers. The Land Information System includes all the functionality of the NLDAS and GLDAS systems, and 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 degrees down to 1 km or finer.

The substantial inter-model differences and errors relative to the observations in the NLDAS project highlighted by Mitchell et al. (2004) and more fully discussed in Robock et al. (2003), 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 datasets and the physics of the models. For example, as shown in Figure 1, inter-model differences and errors relative to SGP-area observations in predicted energy fluxes can be comparable in magnitude to the fluxes themselves. Even more challenging is the attribution of these differences to input parameters or 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 SGP 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 uncertainty in the inputs, models and responses due to changes in landscapes. A remote sensing observatory could fill a critical role towards addressing this signal/noise problem.

Recent work (e.g., Bosilovich et al. 2002; Dickinson et al. 2004) has suggested that the joint spatial distribution of parameters and forcings yields nonlinear effects that affect hydrologic processes at larger scales. 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 testbeds 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 remote sensing observatory that can support multiscale studies of land-atmosphere interaction could serve a central role in addressing this problem.

Some problems must be studied on a large scale. Water use practices along the Rio Grande are an example of this. In the region along the Rio Grande, there is an increasing demand for water for urban areas, increased amounts of irrigated agriculture as well as the creation of riparian zones and wetlands. Each of the changes in and of itself is small, but the large scale effects of these small changes along the entire river has led to the river drying up in mid-summer, a situation unacceptable both ecologically and agriculturally. Because of the tremendous variability of the region in elevation, geology and canopy, individual point measurements of hydrologic variables have little meaning beyond the immediate area in which they were measured. Evaporation, the most important water loss pathway in the region, is difficult to measure even locally because of the small size of the homogeneous patches. Models are needed that can effectively deal with the heterogeneity of the terrain, canopy, and water availability.

A case has been made that measurements are needed of hydrologic variables 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 and develop methods to obtain representative values for hydrologic variables at somewhat larger scales, so as 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.

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.

4.2. Questions #2

Many components of the hydrologic cycle exhibit considerable variation in space and time, and this variation often changes with scale. One such component is soil moisture, 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 (ground water, 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. Because of these interactions, the state of the soil moisture reservoir is constantly changing.

The spatial and temporal variations of soil moisture can be measured 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 for many years.

In contrast to high–frequency optical and infrared radiation, microwaves penetrate vegetation and soil because of their longer wavelength. As a result, moderate vegetation is semi–transparent and a shallow layer of the soil beneath the canopy is “visible” at microwave wavelengths. The fraction of the soil moisture reservoir that can be measured with microwave remote sensing varies with wavelength. At 1.4 GHz, soil emissivity/reflectivity is determined by the first few centimeters of the soil moisture profile. At 19 GHz, there is sensitivity to only to the first few millimeters of the soil since scattering within the vegetation canopy and changes in vegetation temperature and moisture dominate the signal. Hence the lower microwave frequencies are most useful for monitoring changes in near–surface soil moisture, while the higher microwave frequencies are most sensitive to the state of the vegetation canopy. Both of these quantities affect the spatial and temporal variability of several important components of the hydrologic cycle.

The sensitivity of 1.4 GHz brightness temperature to near–surface soil moisture as a function of vegetation water content is shown in Figure 2. The points represent experimentally measured soil moisture sensitivities for bare soil and through a corn (maize) canopy at different levels of above–ground vegetation biomass (Hornbuckle and England 2004). The solid and dashed lines plot the predictions of a commonly used model for non-scattering and weakly scattering vegetation using parameters appropriate for a canopy mass of 6.3 kg m^{-2}. This last point corresponds to the sensitivity through a corn canopy at the highest biomass observed during a growing season. Given a typical microwave radiometer precision of < 1 K, near–surface soil moisture changes of < 0.02 m^3 m^{-3} can potentially be detected throughout the growing season. One disadvantage of microwave radiometry is its poor resolution from satellite platforms, which is on the order of 10's of km.

Radiometers and radars mounted on airplanes (Jackson 2001; Njoku et al. 2002) can measure the near–surface soil moisture of large areas. Satellite systems can produce global measurements with a temporal frequency of a few days (Entekhabi et al. 2004). An example of the kind of spatial data that can be acquired with microwave remote sensing is shown in Figure 3. 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 of 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 this image is 50 m, three orders of magnitude better than a satellite radiometer. However, significant soil moisture sensitivity is only expected in areas of sparse vegetation where the biomass is less than 0.25 kg m^{-2}.

Regarding the hydrologic context of soil moisture variability, an important question arises: "Can remote sensing provide multi–scale measurements to transfer hydrologic processes correctly across scales?" Soil moisture is the product of several hydrologic processes that operate on different spatial and temporal scales. Consequently, soil moisture variability and its spatial pattern can be both scale and time dependent (Hills and Reynolds 1969; Kachanoski and de Jong 1988). In the simplest case of a scaling process, no characteristic length scale exists and the statistical characteristics of spatial data do not change with scale. In a multiscaling process, the relationship between spatial statistical properties and scale is more complicated (Dubayah et al. 1997). An example of scaling and multiscaling behavior is shown in Figure 4. Here the variance of near–surface relative soil moisture content (the ratio of volumetric soil moisture to porosity) is plotted as a function of scale for areas of Oklahoma and Kansas (Nykanen and Foufoula–Georgiou 2001). The smallest scale soil moisture data were obtained by aggregating point samples. Data from an aircraft radiometer were used at the other scales. The set of straight lines at the smaller scales show a linear log–log relationship between soil moisture variance and scale indicating a simple scaling process that had been found in a previous analysis of the data (Rodriguez–Iturbe et al. 1995). Further analysis at larger scales produced the set of curved lines that are characteristic of a multiscaling process. Note also that the set of curved lines do not lie as close together as the set of straight lines, indicating that the relationship between soil moisture variance and scale changes with mean soil moisture and is therefore time–dependent.

Landscape heterogeneity must also be considered when examining how soil moisture variability changes with scale. A comparison of plot–scale microwave brightness, as measured by ground–based radiometers, with SSM/I satellite brightness is shown in Figure 5 (Judge et al. 2001). The measurements were made in an agricultural area near Sioux Falls, South Dakota. Although the data are at very different scales (10 m^2 for the ground–based radiometers and 625 km^2 for the satellite), plot–scale and satellite–scale observations match well in the winter when the scene within the satellite pixel was fairly homogeneous due to widespread snow cover. In the late fall and early spring, however, satellite brightness fell between the brightness of the grass canopy observed by the ground–based radiometers and bare soil brightness measured at an adjacent site.

The importance of the role of an observatory in improving our ability to use remote sensing to further understanding of spatial hydrologic processes and scaling cannot be overstated. An optimal soil moisture remote sensing strategy will combine both passive and active techniques to take advantage of the sensitivity of radiometry and the higher spatial resolutions of radar. On its own, however, microwave remote sensing will produce a limited amount of information: only a shallow layer of the soil moisture reservoir can be sensed and these measurements will be constrained to specific resolutions and time intervals. Great progress will be made when these measurements are *combined with models of land surface processes*. When microwave 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 (Reichle et al. 2001; Crow and Wood 2003). 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 (Liou et al. 1999) can be determined.

A dedicated remote sensing observatory would advance our ability to use microwave remote sensing to study the scaling of spatial of hydrologic processes by facilitating such a model approach where measurements of other variables besides those directly measured with remote sensing techniques would also be used. For example, although significant soil moisture sensitivities have been measured experimentally, models of microwave brightness, and particularly backscatter, do not match observations in many situations as shown in Figure 5. Further development of these microwave models will only come when other competing processes besides soil moisture, such as changes in the effective constitutive properties of soil (roughness, macropores) and vegetation (canopy structure, water content), are considered with as much attention. Furthermore, the long–standing problem of validating remote sensing measurements of soil moisture may best be accomplished by using a landscape model to produce estimates of soil moisture conditions. This landscape model would provide a framework through which both traditional point measurements of soil moisture and remote sensing measurements could be related. For example, it would simply be impossible to validate an image such as that shown in Figure 3 with point measurements. Such a landscape model could also provide a way to account for the heterogeneity in the land surface, as well for how this heterogeneity affects the scaling of soil moisture variability. Finally, a remote sensing observatory would provide longer periods of time over which to test microwave and land surface process models. As shown in Figures above, many hydrologic processes change over both short and long time scales. Much of the previous research in this area has suffered from the lack of long time–series data.

4.3. Questions #3

A major challenge in hydrology is the reliable measurement of evapotranspiration at the watershed scale. 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 for Hydrologic Sciences.

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. Due to 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 to 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 ~100 m in size (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.

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.

The ALEXI/DisALEXI multi-scale 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 to an atmospheric boundary layer growth model to compute fluxes at 5 to 10 km resolution. These regional-scale flux predictions from ALEXI can be disaggregated to finer scales (1 to 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.

In Figure 6, spatially distributed output of evapotranspiration (ET) from the multi-scale 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 ET fields is the tower location for both sites and the approximate extent of the upwind source-area contributing to the flux measurements. Due to local heterogeneity in surface conditions, Fig. 6 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.

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 ET over a ~1×1 km area with relatively fine (~25 meter) spatial resolution (Eichinger et al. 1999). The utility of the technique to determine ET fluxes over complex terrain and canopies with non-ideal micrometeorological fetch conditions has been demonstrated (Eichinger et al. 2000). An example application of this technique is illustrated in Figure 7 showing a 30 m resolution ET 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 ET patterns at this resolution highlight the degree of non-uniformity present even in agricultural fields. DisALEXI output created with Landsat data over the same area provides a unique opportunity to access consistency in the spatial pattern of the ET field.

Again, these two flux-mapping approaches are complementary yet completely independent; one being surface based and the other being atmospheric 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. Further validation of spatial patterns and flux distributions at local scales can be obtained with airborne measurement systems, using for example the 250 m resolution transect segmentation technique of Mahrt et al. (2001). Figure 8 compares tower flux measurements over soybean and corn during the SMACEX study period, indicating significantly different ET rates for these two crops. ALEXI predicts an area-averaged ET midway between these tower-based fluxes, consistent with the observed cropping fractions (roughly 50% corn and 50% soybean). ET at the watershed scale is further confirmed by aircraft-based eddy covariance measurements averaged over 6-12 km transects across the study area (Figure 7).

This example demonstrates the power of combining tower and aircraft micrometerological 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.

4.4. Questions #4

To demonstrate how remote sensing observatory could help address the validation issue, we use an example of radar-rainfall estimation. There seems to be a consensus within the hydrologic community that precipitation, and rainfall in particular, is the most important driver of many other hydrologic processes. Prior to advent of remote sensing, hydrologists relied on rain gauge networks and suffered from their inability to account for the high spatial and temporal variability of rainfall. With arrival of radar networks, e.g. NEXRAD system in the United States, our ability to detect storms has improved dramatically and we gained a wealth of information on spatial and temporal structure of rainfall systems, but uncertainty of the quantitative estimates of rainfall radar provides is largely unknown (e.g. Krajewski and Smith 2003). Anecdotal information support contention that errors in rainfall products based on data provided by the WSR-88D radars are often significant. The few existing studies on the product evaluation are consistent in reporting difficulties with obtaining independent information of resolution and quality appropriate for the task. Also, there seem to be no plan or commitment on the part of the NEXRAD mother agencies to address this shortcoming. Yet, it is clear from the science credibility point of view that that unless uncertainty of NEXRAD precipitation products is quantified, the research benefits of the data will be limited.

It is our vision that a remote sensing observatory could fulfill this need by designing, deploying, and maintaining a network of sensors that could provided complementary and independent information sufficient for quantifying uncertainty in radar-rainfall estimates. The main challenge in designing such a network adequate for 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.

In our vision the rainfall validation network will comprise several types of sensors: (1) standard rain gauges to facilitate transfer standard; (2) disdrometers i.e. devices for measuring drop size distribution 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 with cutting edge technology tools. We discuss their required characteristics and principles of arrangement below. Krajewski (2004) gives more details in a similar context.

4.4.1 Dense Rain Gauge Network

We begin with rain gauge networks and the characteristics they should have to serve as useful reference. First, we address the issue of random error of tipping bucket rain gauge. Habib et al. (2001) and Ciach (2003) conducted experimental studies that provide mathematical models of rain gauge rainfall accumulation errors. The main conclusion from these studies is that tipping bucket rain gauges, when well maintained and deployed as a pair (see Figure 9), provide accurate observation of rainfall accumulations at scales from 10 minutes up. The standard errors decrease with increasing rain amount and time integration scale.

Deploying the tipping bucket rain gauges in pairs, advocated by Ciach and Krajewski (1999) and Steiner et al. (1999), has many advantages. The most important one is data quality control. Since rainfall displays significant variability in space and time, analysis of “reasonableness” of single gauge record often fails detecting cases of gauge malfunctioning. The main assumptions of the concept of using two gauges at a single location are: (1) it is highly unlikely that two gauges would fail in exactly the same way; and (2) that rainfall variability at the scale of gauge separation distance (~1 m) is negligible. Thus, when the gauges function well the data show good agreement with each other. A disagreement is a sign of at least one of them malfunctioning and the site should be checked.

The second issue is designing networks of gauges for validation studies. Consider two objectives for design of validation networks: (1) characterizing statistical behavior of rainfall in space and time; and (2) estimating rainfall over an area as accurately as possible. It turns out that these two objectives lead to quite different network configurations. To illustrate this, let us pose a question relevant to direct validation (Krajewski and Smith 2002): "How many gauges are required in a 2×2 km^2 area (equivalent to a typical radar-rainfall product) to obtain areal estimates with high accuracy (say, better than 5%)?" If the accuracy is specified in terms of mean square error, answering this question requires knowledge of the spatial covariance function of the relevant rainfall regime (Moore et al. 2000). To estimate the shape of covariance (or correlation) function of rainfall intensity or accumulation over short time scales the network has to sample several separation distances. In particular, accuracy of gauge-based estimated rainfall over an area comparable is size (linear) with the decorrelation distance of rainfall is sensitive to the shape of the covariance function near the zero separation distance (see Habib and Krajewski 2002 for an illustration). Thus the network must include gauges that are close to each other as well as far from each other.

The first design problem has been well studied (e.g. Bras and Rodriguez-Iturbe 1985) while the second has not. In general, for a network to estimate well mean area rainfall, the gauges should be organized on a uniform grid covering the area of interest. Such design maximizes rain cell detection. Estimation of network sampling errors associated with simple averaging of rain gauge values can be accomplished numerically using the methodology proposed by Morrissey et al. (1995). Thus, questions on network density required for achieving certain level of accuracy, or questions of network expansion to improve accuracy can be easily studied if the rainfall spatial covariance function is known.

With such information at hand (Krajewski et al. 2003), we can attempt answering such question as "What is the number of gauges needed to estimate rainfall over a 2 km by 2 km pixel with accuracy better than 5%?" Consider two cases: exponential decay with the correlation distance of 5 km and 15 km. In the first case we need about 20 gauges uniformly covering the pixel to reach the 5% error level (Krajewski 2004). In the second case only 5-8 gauges will achieve the same objective (Moore et al. 2000). The pixel size is more appropriate to the validation of radar-rainfall problem. For the scale of a satellite rainfall product pixel (about 5 km by 5 km), 5% error level can be achieved with about 35 gauges for highly variable rainfall and with only about 10-12 for the less variable regime typical of mid latitudes.

We present these cases to show that solving the validation problem is both feasible and not terribly expensive (i.e. compared to the cost of building and maintaining a radar network or a satellite). Rain gauge networks of the size we mentioned above can be easily deployed and operated at a remote sensing observatory. As a matter of fact, the smaller the area the easier and cheaper it is to maintain a network. For example, clusters of the 2 km by 2 km size can be placed at the airport where many other meteorological instruments are often placed. Cell phone based data communication provides a simple way of near real time operation and dual-gauge design provides means for demand-only maintenance visits (Kruger and Kanukurthy 2004).

Another rain gauge network design objective results from considerations of ground networks that include scanning radar. It is well known that radar-rainfall uncertainty depends on radar range (e.g. Smith et al. 1996; Vignal and Krajewski 2001). Thus, if we are to benefit from radar estimated rainfall for the validation of satellite rainfall products, we need to organize observational networks that can address the radar-range effects (Krajewski and Ciach 2003). A simple solution is placing dense clusters along a radar beam. The question is “How many?” and “How should they be spaced?” Principles of answering these questions are discussed by Krajewski (2004) and we do not repeat those inhere for the sake of brevity.

4.4.2 Disdrometers

Disdrometers provide more general information about rainfall processes than rain gauges by measuring rain drop size distribution (DSD). From DSD data, not only point rainfall can be calculated but also many other quantities relevant to remote sensing of rainfall and its hydrologic applications. For example, one can calculate variables such as radar reflectivity, optical extinction, kinetic energy, etc. Knowing DSD would allow studies of the spatial and temporal radar reflectivity and its relationship with rainfall rate, i.e. defining the Z-R determination problem in the radar expert lingo. Thus, why not simply replace the rain gauges in the experimental (i.e. validation) networks with disdrometers?

Remote sensing observatory could certainly consider this alternative but first several issues would have to be addressed. The relatively high cost, power consumption requirements, little know error characteristics, and other deployment considerations would have to be explored. Since disdrometers measure DSD indirectly and the cumulative experience with their operation is much less than in the case of rain gauges, they require thorough testing. Several intercomparison experiments point to sensitivity of the obtained 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.) These experiments used different types of instruments collocated or in a close proximity of each other. To distinguish the measurement error effects associated with a particular instrument from the cross-instrument differences it is necessary to compare several collocated disdrometers of the same kind.

Other DSD measurement issues include drop shape. This is important for the interpretation of polarimetric radar observations of rainfall (Bringi and Chandrasekar 2001). Two-dimensional video disdrometer (e.g. Kruger and Krajewski 2002) is capable of providing information on drop shape but suffers from wind effect. Nešpor et al. (2000) demonstrated that the large size and the shape of the two-dimensional video disdrometer made by Johannum Research in Austria, under certain conditions may cause significant distortion of the observed DSD. Other optical instruments with smaller structures are less susceptible to this effect but may suffer from strong directional dependence on wind directions. With the current day computational fluid dynamics technologies undertaking relevant studies is relatively straightforward although significant practical and theoretical issues remain (Habib and Krajewski 2001).

Once the instrumental effects are well understood, we should undertake efforts to improve our knowledge of the spatial variability of variables relevant to remote sensing rainfall. The most prominent variable is radar reflectivity. Its variability at the scale of radar-rainfall pixel directly affects quantitative interpretation of the estimates rainfall maps and products. The issues of observational network design, i.e. the number and distribution in space of the disdrometers are similar to those we discussed in the section above. As radar reflectivity is a higher order moment of the DSD than rainfall rate, and there is now unique relationship between the two, it is likely that its characteristics scale (e.g. correlation distance) is significantly different from that of rainfall. Thus, we may need to organize experiments that will be able to capture a wide range of distances so that we can model the shape of the covariance function and other measures of association adequately.

Only when we understand the error characteristics of the instruments we use will our interpretation of the results be meaningful. Thus we need to continue supporting development of new, less expensive disdrometers, conducting their intercomparisons, and designing and carrying out small scale studies of spatial and temporal variability of various rain drop characteristics. Remote sensing observatory is a right facility for such studies. These studies should be conducted in a continuous deployment mode as opposed to the more traditional campaign style typical for atmospheric experiments. This is necessary to enable conditional analysis of the collected data.

4.4.3 Vertically Pointing Radars

Vertically pointing Doppler radars provide crucial information for radar remote sensing. They are capable of observing vertical profile of precipitating clouds and identify features affecting radar observables (Figure 10). These features include thickness and height of the melting ice at cloud based (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 drop size distribution. These estimates are more reliable if the profiler operates at multiple frequencies so that air and raindrop motion can be distinguished. However, for such radars the sampling volumes are not well matched. For high variability conditions such as convective core this is a cause of concern as volume mismatch results in increased uncertainty of the measurements. Profiler based studies of precipitation systems and the related instrumental and estimation issues have been well documented in a number of publications, for example Wakasugi et al. 1986; Gage et al. 1999, Gage et al. 2000, Gage et al. 2002; Williams 2002; Williams et al. 2000; Kollias et al. 2002.

We propose to use these proven technologies to explore the spatial variability of the vertical profile of precipitating clouds. Although the time resolutions of the VPRs is also very high, essentially providing continuous observations, our understanding of the space-time relation for rainfall processes is still limited (e.g. Fabry 1996). Thus, having several, say five, such instruments evenly distributed over a small area (Figure 9), would provide additional insight into this relationship and the special variability of the processes affecting radar as well as space-based sensors. This is particularly important for rainfall estimation over land where varied emissivity of the land surface introduces difficulties into interpretation of the satellite data.

4.4.4 Networks of Small Polarimetric Radars

Recently, another attractive technology is emerging that may offer many advantages to address the problem of validation of space-based remote sensing of precipitation: special purpose *networks* of inexpensive radars. Several groups have demonstrated advantages of using X-band polarimetric radars for rainfall estimation (Matrosov et al. 2002; Anagnostou et al. 2004).

Because X-band radars are widely used for navigation, many manufacturers compete in this market. This drives down the cost of waveguides, microwave sources, and test equipment. Relatively small antennas can give high azimuthal resolution at X-band, compared to C-band and S-band radars. For example, to achieve 1.5º resolution requires an antenna with a diameter of 2 meters, which translates to a tremendous cost advantage compared to C- and S-band. It is easy to install this size antenna on a small building or mount on a trailer. The polarimetric measurements at X-band also offer certain advantages, such as increased sensitivity to rainfall, as compared to longer wavelengths (e.g. Matrosov et al. 1999; Matrosov et al. 2002; Zrnic and Ryzhkov 1999).

X-band (3 cm) waves are subject to more attenuation than the longer C-band or S-band waves in heavy rainfall. This is an issue if one needs a long operating range, but our focus is on short range and high resolution. If the network radars' use is limited to 20 km, and there are multiple radars looking at the same area from different directions, the resultant multi-radar estimates of rainfall will not suffer much from attenuation. The radars are polarimetric, and some polarimetric observations, such as K_{DP}, are insensitive to partial attenuation.

The physical concept behind polarization diversity is that, under aerodynamical forces, falling hydrometeors take oblate shapes, which depend on their size, and as a result, impact differently the propagation and backscattering of incoming horizontal (H) and vertical (V) electromagnetic waves. The most common polarimetric radar measurements are (1) the reflectivity factors at H and V polarization (Z_H, Z_V); (2) the differential reflectivity factor (Z_{DR}); and (3) the propagation differential phase (Φ_{DP}). Over a certain radial distance Δr, one can calculate the specific differential phase shift (K_{DP}). All of these parameters, in various combinations, have been shown to contribute to improve rainfall estimation and enable retrieval of drop size distribution (Bringi and Chandrasekar 2001; Anagnostou et al. 2004).

Development and operation of a network of radars offers numerous advantages. For example, consider a network of four radars overlooking a regular dense network of rain gauges. Its operation leads to:

1. Improved accuracy of rainfall algorithms. Sound algorithms can only be developed from large samples of data, since rainfall is highly variable in both space and time, and is highly intermittent (long periods of no rain between short duration events). This is contrary to past practice where a great deal of research and conclusions were based on case studies. As we emphasized in other sections of this paper, evidence is mounting that proper evaluation of remote sensing of rainfall can be established only from large sets of data. This need for large samples is increasing, as there is a trend to develop different algorithms for different atmospheric situations. To perform such conditioning for a sufficiently large sample, the data set from which the sample is drawn should be as large as possible.

2. Increased resolution. While single polarimetric X-band radar may have useful resolution limited to about 200 m, with proper design and deployment of the networks, resolution on the order of 100 m is possible.
3. Increased reliability. It rains only about 5% of the time, so if the radar happens to be down we lose data. With four radars, it is unlikely that we will miss any rainfall events. We will be able to reduce the measurement error variance, and thus the uncertainty of the estimates of rainfall.
4. Reduced development and operating costs: as network radars share spare parts and technical support. A network of four X-band radars may cost as little as $1M.
5. Repeatability. Credibility of the system, and therefore the confidence of users of the data will be greatly increased if the individual radars in the system demonstrate consistent performance when considered individually. On the other hand, viewing the same storm from different aspect angles will mitigate the adverse effects of signal attenuation and data noise.

The main context for considering such networks is the need for closing the spatial gap between operational radar (providing the bulk of rainfall information for numerous hydrologic studies) and rain gauges (providing accurate point observations of rainfall quantities on the ground.) With 100 m resolution of these radars, single rain gauge data are relevant to evaluation of their rainfall estimates. Once their error characteristics are know, their can provide useful information for the scale of operational radars and satellites. Another context relevant to remote sensing observatory is providing high-resolution rainfall information for remote sensing soil moisture studies and validation.

Still, much research remains to be done to fully realize the above benefits. These include technological advancements of radar hardware, software to operate the radar as a true network and not simply a collection of four individual radars, and, of course, rainfall estimation algorithms. Addressing these tasks is appropriate for CUAHSI and its infrastructure.

4.4.5 Summary and Discussion

It should be clear from our discussion above that there are no other facilities in the United States, or the rest of the world for that matter that allow this kind of focused, systematic, long-term studies of radar rainfall estimation and validation problems. Similar capabilities are needed for other remote sensors.

5. Design of a Remote Sensing Observatory

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 RSO is that it 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 RSO is quite similar to a hydrologic observatory with the main difference being the size. We contend that an area of a RSO does not need to be larger than about 10 km by 10 km. Such size is greater than the resolution of most remote sensing platforms yet not to be too large to be unmanageable. The questions: “Where? and “How many?” immediately follow. We will not address these questions as they are not critical to establish the soundness of the concept.

Issues relevant to site selection include variability of the hydrometeorological processes, access to land, and representativeness to other areas. The variability requirement is important as we would like to sample a range of conditions for generalization purposes. A place where it rarely rains would not be a good choice for remote sensing of rainfall studies. 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, to the merits of the RSO concept.

After site selection the next critical question is what instruments should be deployed, how many of them and in what configuration? As our examples above illustrate, the answer depends on the variable of interest. Our knowledge is sufficient to address the specific design issues now (e.g. rainfall); while for other variables we have major gaps in our understanding (e.g. soil moisture). 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 adopt the sensor network as our knowledge of the relevant processes increases. For many variables, the scale of the variability may be such that they 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 locations representative for elements present in the observatory to allow integration to the entire domain or the scale relevant for a particular remote sensing sensor of interest. For example, rather than deploying a uniform network of flux towers, we may deploy them within 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 (simulation) of the local hydrologic processes based on our current state of knowledge for the design of our observational network.

So, what variables are of primary interest? It seems that the priority should be the variables that control or determine 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 characteristics of the surface, as well as boundary layer processes including wind profiles.

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 intercomparison short-term experiments while 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 give location should be guided by frequent assessment of the need to help our understanding. Thus, if we as community feels that a particular aspect of RS is well-understood and dealt with, we can move on to study another one moving the appropriate infrastructure. For example, if we understand measurements and estimation of evapotranspiration over uniform vegetation on flat terrain, there is little sense to maintain an array of instrumentation for long time doing just that.

We 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. Considering the cost of a single satellite mission this seems like a bargain. The new capability afforded the research community would quickly result in value added products and would pave roadways for future advances.

6. Closing Remarks

The concept of 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. There are a number of questions and issues that remain to be resolved and we 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 RS products and ground measurements. We need to improve our understanding of sub-grid heterogeneity and its effects on hydrologic processes. We need to develop approaches assimilation of RS data and products in the context of new models and theories.

At remote sensing observatories many variables would be monitored at comparable scales. This multicomponent approach to remote sensing validation seems a necessity and those involved in validation efforts realize it more and more. 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-dimentional wind structure, humidity of the pre- and post-storm environment are critical for proper interpretation of the results.

How should we go about establishing a network of RSOs? It seems that CUAHSI’s developing structure is well-suited for the task; our objective in this paper was proposing a concept not a design. The CUAHSI Synthesis Center would be in a good position to bring experts together and consider trade-offs between augmenting existing sites vs. establishing new ones, selecting sites in “easy” vs. complex terrain, and deciding the size and number of such sites. Perhaps sub-areas of the HO could serve as RSOs. This seems like a good idea adding purpose to the HOs and potentially saving initial and operating costs. This should not preclude thou other options as the range of scope of RS is wide and developing smaller focused prototypes may be a good path to follow as well. In designing them we should capitalize on lessons learned from previous community experiments such as FIFE, BOREAS, Hapex-Mobhily-Sahel, LBA, etc. and coordinate with efforts of agencies involved in hydrologic remote sensing. The CUAHSI Information Technology System would handle the data distribution, arriving and mining.

A remote sensing observatory would allow us to be more quantitative about assessing the state-of-the-art on remote sensing and hydrologic prediction and thus provide a credible path towards future progress. Without being able to determine uncertainty of many RS 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. RSO will greatly improve our capability for credible scientific bases of resources investments, including those directly affecting the research enterprise.

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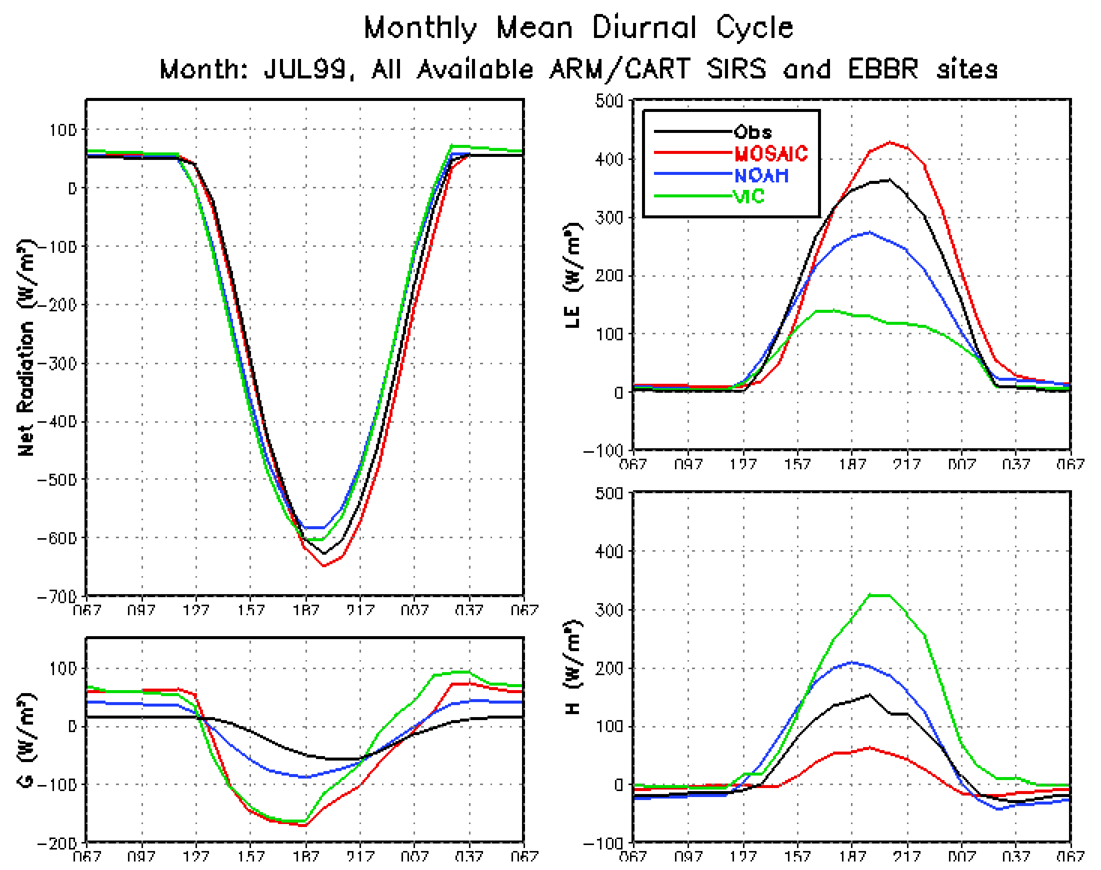
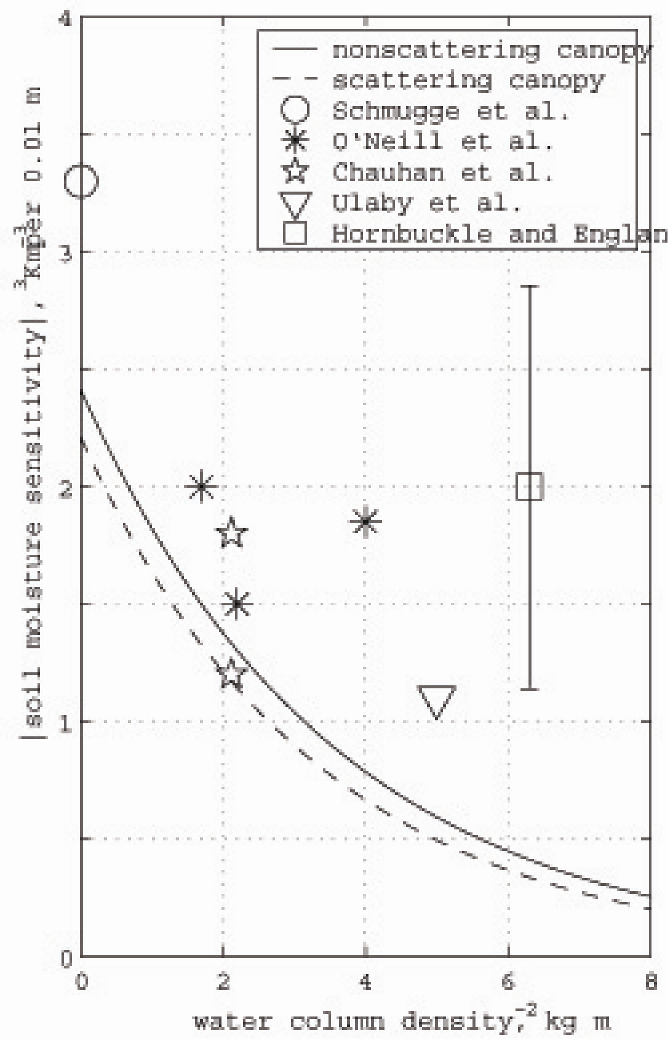


Figure 1. Monthly mean diurnal cycles of observed and NLDAS modeled energy fluxes for July 1999, from Robock et al. 2003. Terms include net radiation, ground heat flux (G), latent heat flux (LE) and sensible heat flux (H). Notice that in many cases, the inter-model differences and errors relative to the observations are comparable in magnitude to the flux itself.



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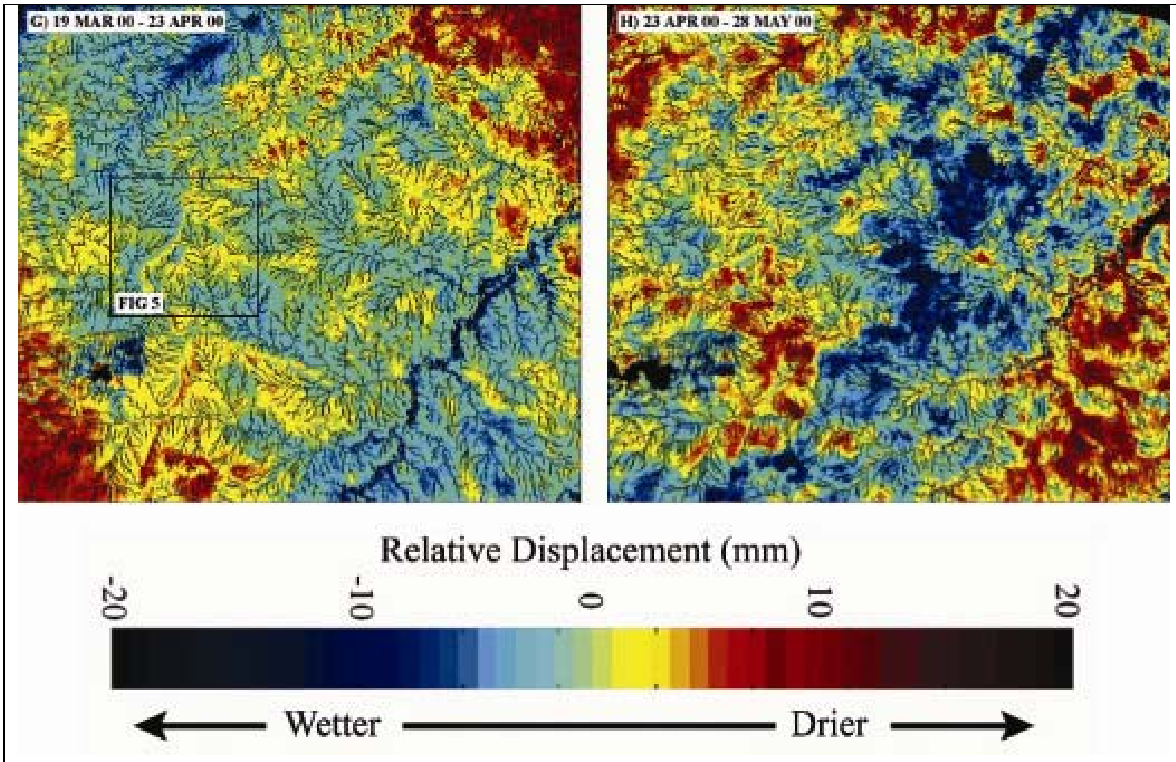

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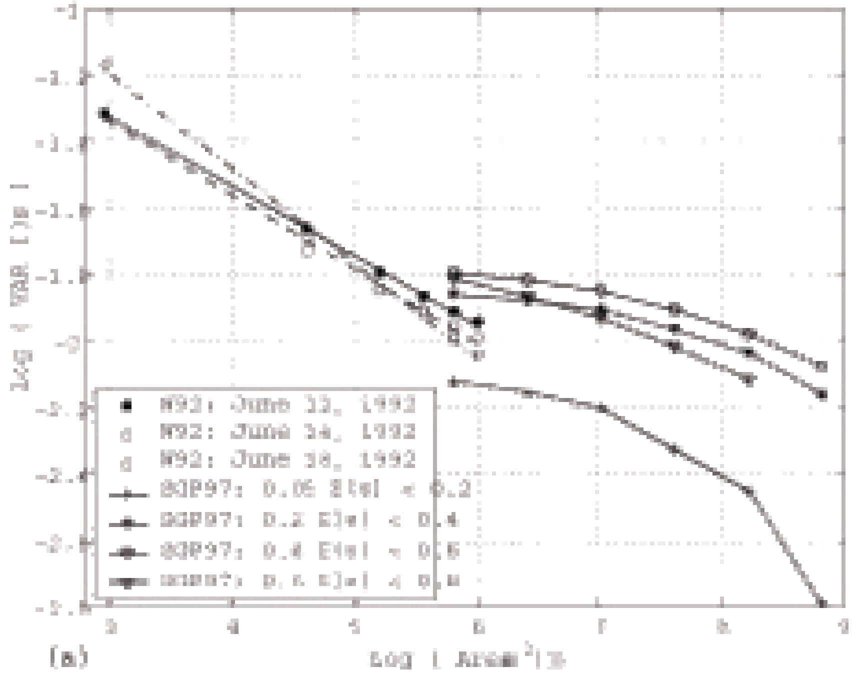

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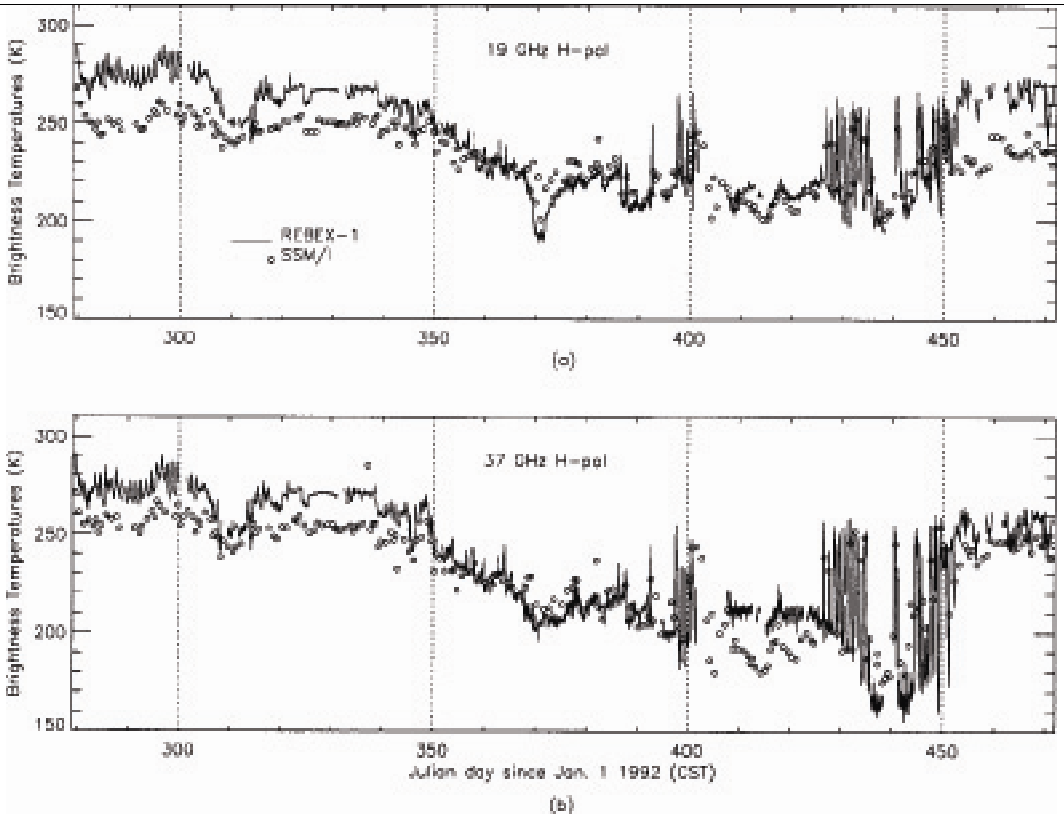

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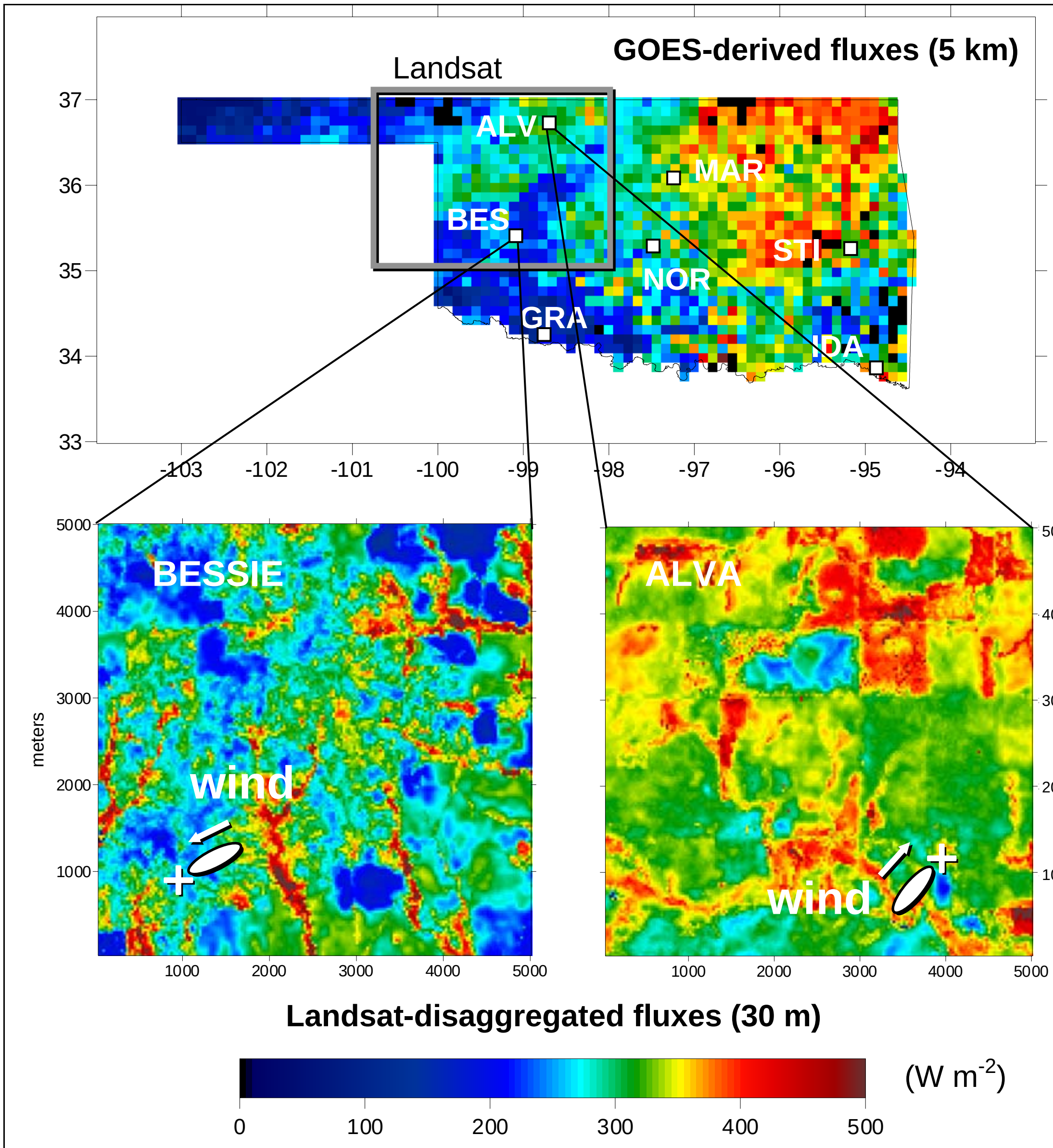

Figure 6. Latent heat flux, May 29, 2000 at the Oklahoma Mesonet

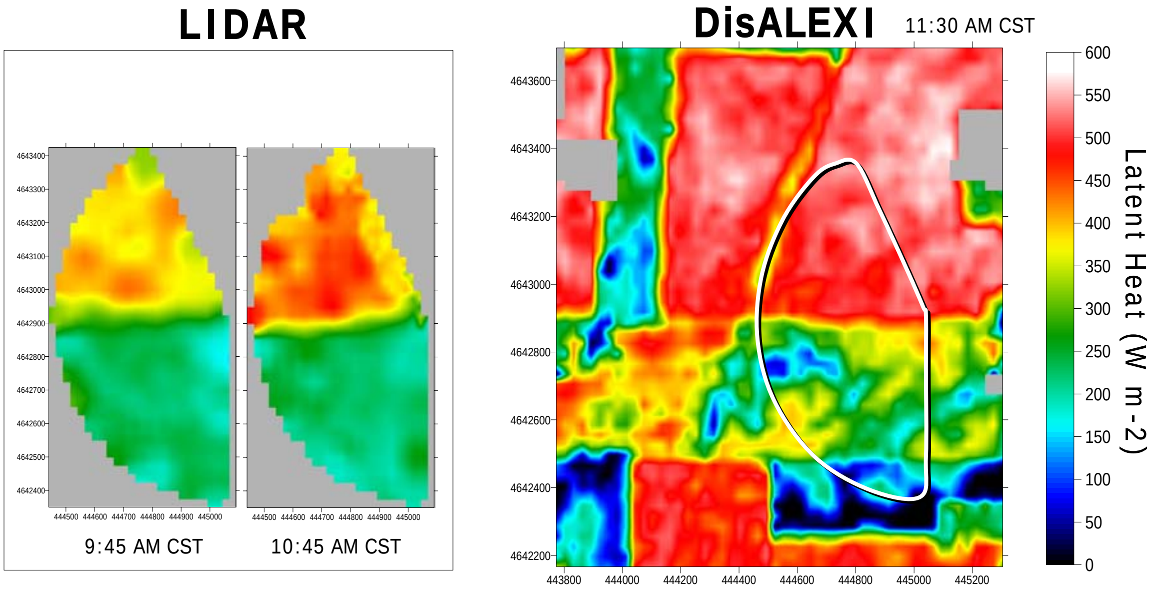

Figure 7. Output of latent heat flux from lidar-based technique over corn and soybean fields in central Iowa in comparison to DisALEXI output using aircraft imagery during SMACEX.

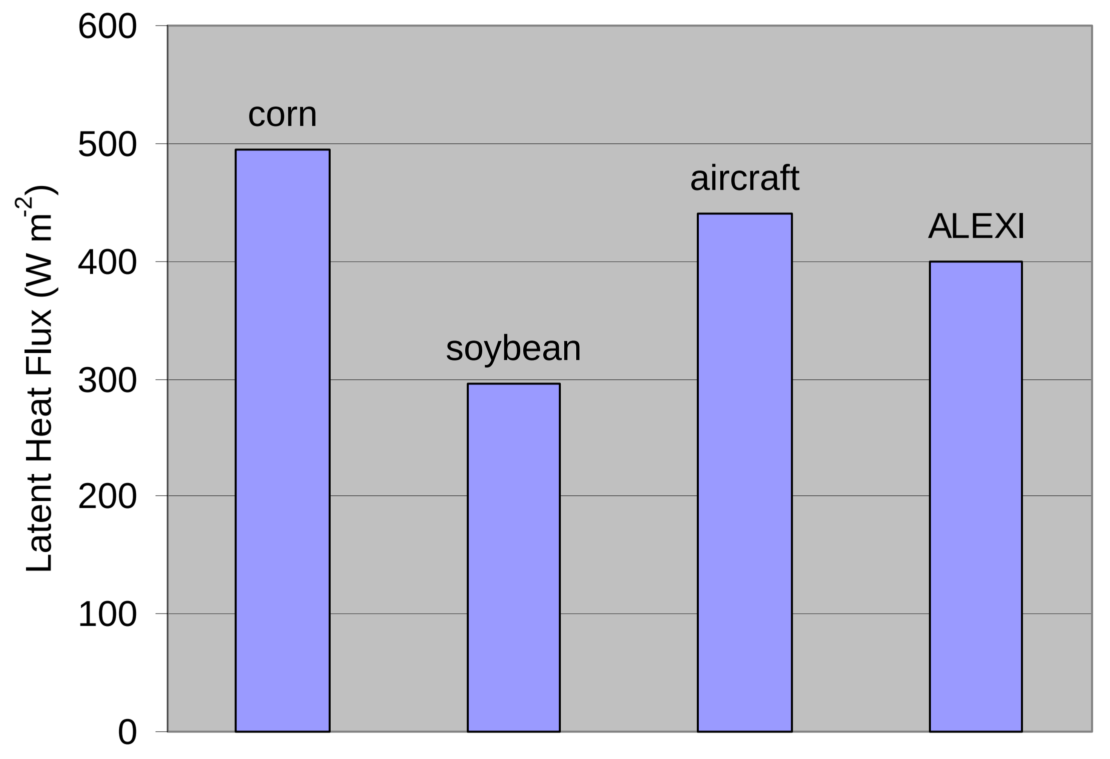

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Figure 9. Schematic of remote sensing observatory for rainfall estimation validation. The NEXRAD basic data grid has resolution of 1 km by 1°. Additional radar grid resolution of 250 in range is shown. The site near Iowa City is only hypothetical to provide realistic landscape elements.

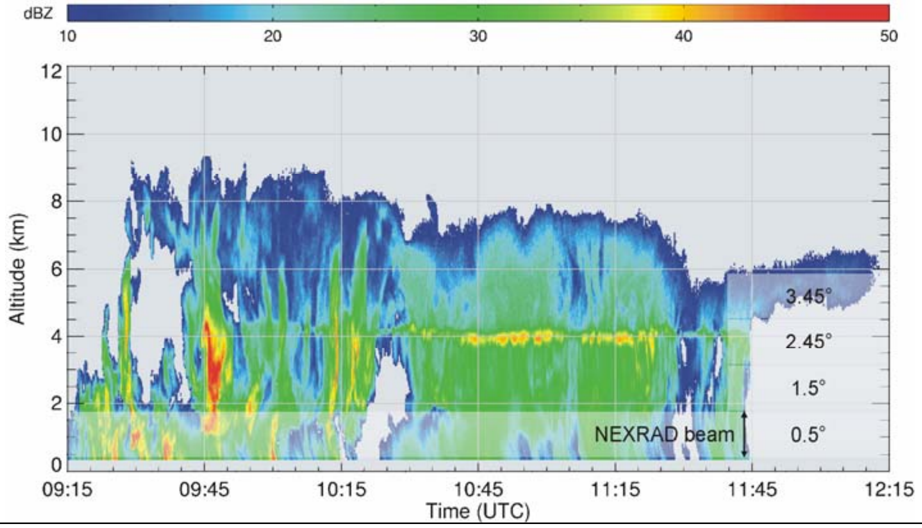

Figure 10. Rainfall observations from vertically pointing radar. The storm shown is from June 19, 2002 in Iowa City, Iowa. The shaded region corresponds to the beam width of the Davenport, Iowa (KDVN) WSR-88D located some 80 km east of the profiler. On the right hand side the beam widths of other antenna elevation angles are indicated.