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Scaling in Surface Hydrology: Progress and Challenges

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Abstract: This paper presents a review of the challenges in spatial and temporal scales in surface hydrology. Fundamental issues and gaps in our understanding of hydrologic scaling are highlighted and shown to limit predictive skill, with heterogeneities, nonlinearities, and non-local transport processes among the most significant difficulties faced in scaling. The discrepancy between the physical process scale and the measurement scale has played a major role in restricting the development of theories, for example, relating observational scales to scales of climate and weather models. Progress in our knowledge of scaling in hydrology requires systematic determination of critical scales and scale invariance of physical processes. In addition, viewing the surface hydrologic system as composed of interacting dynamical subsystems should facilitate the definition of scales observed in nature. Such an approach would inform the development of careful, resolution-dependent, physical law formulation based on mathematical techniques and physical laws.

Keywords: *Scale, heterogeneity, nonlinearities*

Surface hydrology has experienced tremendous progress in the last few decades thanks to observational campaigns and platforms, the development of new theories and models, and the increase in computational power. Still, the spatial scales resolved in weather (~10 km) and climate (~100 km) models remain too coarse for accurate water resource management, prediction of floods, ecosystem services, and water quality, as well as accurate stream flow determination.

Surface hydrologic processes are often viewed or analyzed at the scale of watersheds, which is also the scale at which water resources management occurs. Larger watersheds may be subdivided into a set of smaller watersheds. The area of a watershed ranges from a few hectares (100 m^2) to thousands of square kilometers. The smaller watersheds are interconnected and constrain the surface water budget. Even over small watersheds, heterogeneities in the soil, topography, and vegetation can profoundly affect the surface water cycle (Maxwell et al. 2007; Weigel et al. 2007). Consequently, the current generation of numerical weather and climate prediction models fall short of reasonably forecasting the local surface hydrologic state (e.g., soil moisture, evapotranspiration, and surface runoff). Higher-resolution modeling is thus required (Wood et al. 2011) for accurate surface hydrologic prediction.

The large range of temporal scales in hydrology, from sub-hourly to decadal and beyond, also creates challenges. Even while our ability to numerically model the range of time scales has greatly improved with increased computational power, the datasets necessary to validate models across the entire range of scales are absent. Thus, it is quite possible that a model that works well on a particular time scale may be insufficient on other time scales.

A further challenge to accurate representation of the surface hydrologic state involves the scaling of physical surface hydrologic processes themselves (Entekhabi et al. 1999). At present, our understanding of the scaling (both up and down) of such processes remains relatively unsophisticated. Land-surface and numerical weather prediction models are often used across a wide range of spatial scales (1-100 km) without modifications to the physical representations, even though component physical schemes may have been developed and tested at much smaller scales. Natural heterogeneity profoundly affects the response of surface hydrology through myriad non-linear processes that cannot easily be scaled up or down to the scale of interest. In addition, most hydrologic laws have been developed at scales of order ~1-100 m and may not accurately represent these processes on a coarser scale (Bloschl and Sivapalan 1995; McDonnell et al. 2007). At the hillslope scale, for instance, preferential flow is observed, which cannot be explained by directly scaling up local hydrologic flow (Weiler and McDonnell 2007). A new paradigm is thus needed to systematically develop scaling laws in surface hydrology.

Systemic Issues

Our objective here is to describe some of the major challenges associated with the scaling and resolution in both modeling and measurements of surface hydrologic processes. Rather than an exhaustive survey, we view three systemic issues as key: nonlinearities and heterogeneities; non-local transport processes; and scale discrepancies between observations and models. These issues must be overcome to build a stronger foundation in hydrologic scaling.

Nonlinearities and Heterogeneities

Nonlinearities are common features of natural physical systems, and surface hydrology is no exception (Schertzer et al. 2010). However, many of the laws in physical models are based on linear approximations. Here, we review several examples of nonlinearities pertaining to surface hydrology.

Soil Moisture

The famous Richards equation, which represents the movement of water in unsaturated soils (Richards 1931), is a nonlinear partial differential equation that describes the flow of water in surface hydrologic models. Richards' equation is based on the conservation of moisture and Darcy's law (Darcy 1856), which was originally derived at a scale of order 10-100 m and can be theoretically derived based on averaging the Navier-Stokes equation in a homogenous porous medium via homogenization. In most land-surface and weather/climate models, the Richards equation applies directly to horizontal scales ranging from 10 to 100 km (see Figure 1). However, it remains unclear whether this equation should hold at these scales; assuming that it does, one still faces the task of determining precisely how subgrid-scale heterogeneity should be accounted for in the large-scale version. Indeed, even the very meaning of soil moisture at the larger scale is unclear: is it a weighted version of local values, or can we directly compare the coarse-scale estimate from a model or remote sensing to the locally observed value? Recent studies have demonstrated that topography, subsurface flow, and land-atmosphere interactions have a fundamental impact on soil moisture organization and require high-resolution modeling (500 m) to meaningfully describe the soil moisture field (see Figure 3, adopted from Maxwell et al. 2007).

Evapotranspiration

Our understanding of turbulent heat (i.e., sensible and latent) fluxes at the land surface is based on observations performed on a local scale, on local scaling considerations, and the use of the Richardson or Monin-Obukhov theories (Monin and Obukhov 1954; Paulson 1970; Businger et al. 1971; Dyer 1974; Louis 1979; Mahrt 1987; Holtslag and Beljaars 1989). Even though considerable effort has been devoted to account for sub-grid scale heterogeneity in the land surface (Entekhabi and Eagleson 1989; Koster and Suarez 1992; Liang et al. 1994; Mahrt 1996; Best et al. 2004), there remain fundamental gaps in our understanding of the scaling up of surface turbulent fluxes, namely how to scale up relationships that were developed on a relatively local scale (10-100m) to the grid size of the land surface model or NWP and climate models (1-100km). The turbulent heat flux scaling laws are fundamentally non-linear and their representativeness is not clear at larger scales. The surface can exhibit heterogeneity over a large range of spatial scales induced by the landscape, topography, and vegetation. In addition, atmospheric turbulence leads to horizontal variations in the properties of the boundary layer (depth, temperature, humidity) at scales of about 1 km, which can profoundly impact the surface heat fluxes in return. Considerable effort is thus required to represent turbulent heat fluxes with fidelity in land-surface and climate models.

Snow

In many parts of the world, snow plays an important role in regional hydrology, and snow suffers from many of the same issues as soil moisture. The development of the seasonal snowpack is a time-integrative, spatially-varying process, with periods of accumulation and melt that are spatially varying. Within the scale of a land surface model or remote sensing pixel (~10-100 km), topography and land cover exert considerable controls on snow processes. Some models account for sub-grid heterogeneity (Cherkauer and Lettenmaier 2003), but this is done in a statistical framework that requires additional parameterization. There can also be considerable redistribution of snow within the grid cell scale due to high winds, which is dependent on topography and wind fetch and rarely accounted for in models (Bowling et al. 2004). Along with blowing snow, sublimation can occur, which suffers from the same problems of heterogeneity as discussed in the evapotranspiration section above.

Non-Local Transport Processes

As described in the previous section, most fundamental laws used in the representation of surface hydrologic processes were derived at scales of 1-100 m. There is, however, compelling evidence that many hydrological transport

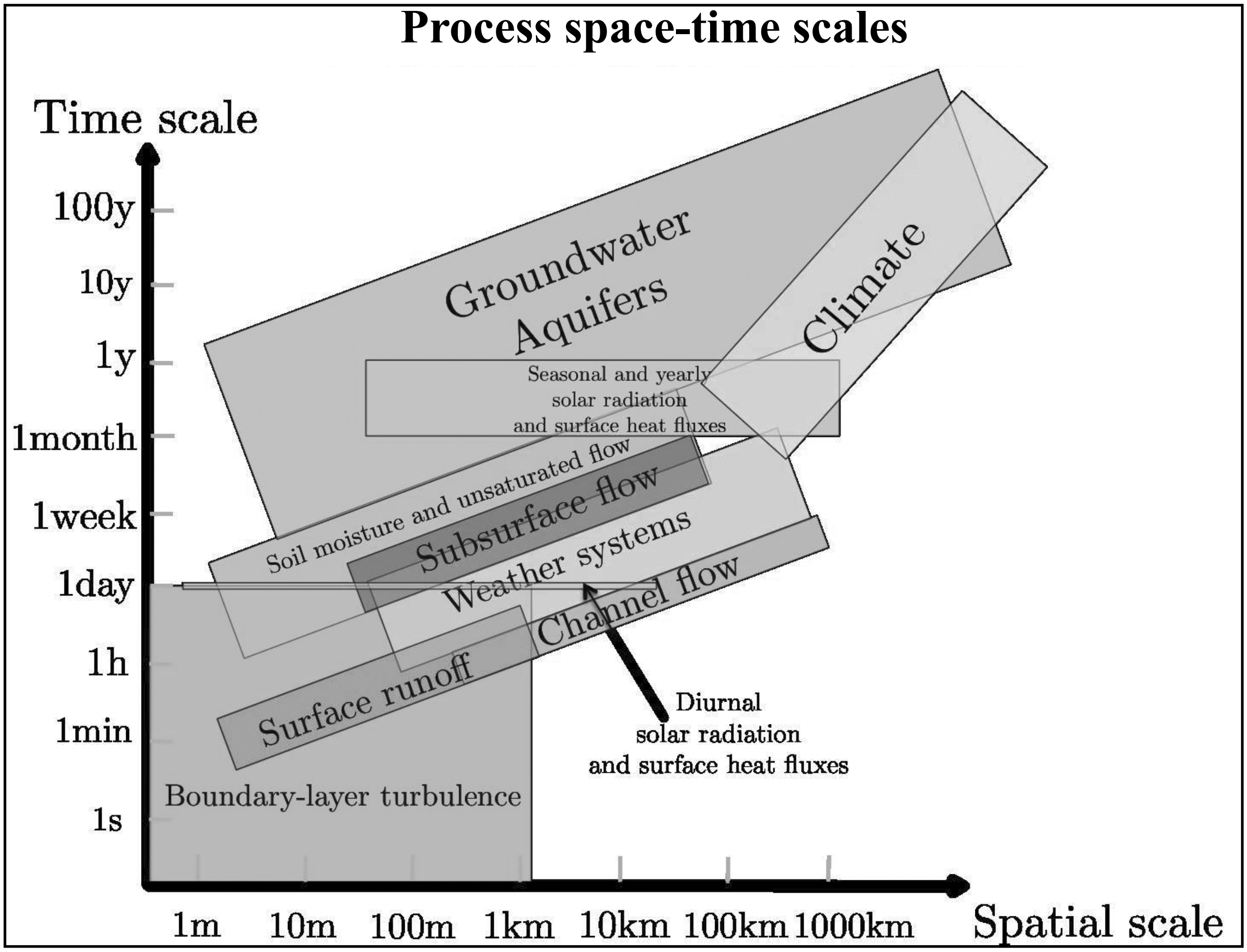

Figure 1. Spatial and temporal scales of hydrological physical processes.

processes are non-local in nature. Thus, site-level, "point" measurements may provide an incomplete picture of the actual processes. For instance, it has been recently demonstrated that sediment transport on a hillslope and bedrock channel evolution are non-local (Starj 2009; Foufoula-Georgiou 2010) and exhibit a wide range of scales with a fractal structure (modeled with a fractional Fickian process) and cannot be modeled using a typical Fick's law, in which flux is proportional to some potential gradient.

Similarly, careful analytical derivation of Darcy's law in both saturated and unsaturated media (Hu and Cushman 1994) has proven that the typical representation of Darcy's law as a local Fick's law is incomplete. The general form of Darcy's law implies non-local transport over a wide range of scales (Paradisi et al. 2001). At the hillslope scale the larger-scale moisture transport process might be the dominant transport and cannot be explained by local observations and the calibration of local processes. This might partly explain why physically-based, spatially distributed hydrologic models outputs are still at odds with field observations (Kirchner 2003, 2006), especially in ungaged basins (Sivapalan 2003). Simple hydrological models are still able to perform better than detailed distributed hydrologic models (Kirchner 2009) and have many less parameters to tune.

The atmospheric boundary layer is the lower part of the atmosphere directly influenced by the diurnal cycle of turbulent heat fluxes. Historically, heat, moisture, and momentum transports in the atmospheric boundary layer were first modeled using diffusive formulations (Fick's law). Those formulations were however unable to explain observations within the boundary layer (non-zero heat flux transport along with zero gradients, which contradict a diffusive transport). In fact it was well known that atmospheric turbulence exhibit a wide range of scales from characteristic dissipation scales (~cm) to the depth of the boundary layer (~km) (Kolmogorov 1941). Of course, the explicit representation of boundary layer turbulence remains a challenge since computational power is insufficient to capture all the scales observed in turbulence. The inclusion of a non-local, convective term in the boundary layer led to fundamental advancements in our capacity to accurately predict the state of the boundary layer as well as cloud development (Deardorff 1966; Troen and Mahrt 1986; Holtslag and Moeng 1991; Siebesma et al. 2007; Neggers et al. 2009).

Scale Discrepancy between Obersvations and Modeling

One of the major challenges facing surface hydrology is the discrepancy between the models and observations against which validation occurs. A schematic comparison of these is depicted in Figures 1 and 2. Overlapping colors represent overlapping space-time scales of the different processes and/or measurements.

Hydrologic processes operate across a wide range of scales and are interacting with other processes across this range. The observational scales do not generally match the scales of the process modeling (Figure 2). For instance, soil moisture values from coupled (land-surface and atmospheric) numerical weather prediction and climate models are usually obtained at scales of 20-30 km and 100 km, respectively. By contrast, observations of soil moisture are usually obtained at a point using a gravimetric method or a probe, and multiple measurements must be performed to sample a larger area. Even with multiple sampling the total areal extent covered by a set of measurements is usually very small (1 ha or less). Further, it often reflects a very shallow layer of the soil (first few centimeters). Serious doubts can be cast on the representativeness of such measurements compared to the much larger scales from models. By default, soil moisture model outputs are still often compared to local observations, even though basic central limit theorem implies that a coarser soil moisture resolution may lose some physical behavior, since some of the dynamics will be averaged out.

A promising path toward systematic observations of soil moisture at a scale compatible with weather forecast models is currently underway with new or upcoming, satellite-borne L-band microwave observing systems (Soil Moisture Ocean Salinity, launched Nov. 2009: Kerr et al. 2010 and Soil Moisture Active Passive missions, launch date Nov. 1 2014: Entekhabi et al. 2010). There are still important challenges toward the operational use of satellite measurements in comparison with model outputs, or to constrain the model outputs' data assimilation (Reichle et al. 2002; Crow and Wood 2003; Margulis et al. 2006; Reichle et al. 2007; Pan et al. 2009). Indeed these platforms do not directly measure soil moisture but measure the microwave brightness temperature, which can be related in a non-trivial way to soil moisture. The algorithms relating those measurements to soil moisture are still in their infancy (Entekhabi et al. 2010). In addition, the coarse-scale representation of surface hydrological processes, landscape heterogeneities, nonlinearities in the transport processes, and reduced details of the topography in land-surface models can introduce systematic biases in the representation of the area-averaged soil moisture state (Maxwell et al. 2007; Weigel et al. 2007). Hence, even with perfect measurements, a coarse-grid representation of the processes will usually be insufficient to accurately describe the dynamics of the area-averaged soil moisture.

Similarly turbulent heat fluxes are usually measured at a relatively small scale (about 10-100 m with eddy-correlation or Bowen ratio measurements of 1-2 km with scintillometers, Chehbouni 2000). The development of a global network of flux observation stations (Baldocchi et al. 2001) has led to fundamental improvement of our understanding of the exchange of momentum, heat and moisture across the surface, vegetation and the atmosphere interface. However, the scale at which flux site measurements are obtained cannot directly be compared to the outputs of land-surface models within current generation weather or climate models. Heterogeneities in vegetation cover, for example, can drastically influence the turbulent heat fluxes at the land surface, especially at the meso-scale (5 to 100 km) and even the precipitation process (Avissar and Pielke 1989; Chen and Avissar 1994; Li and Avissar 1994;

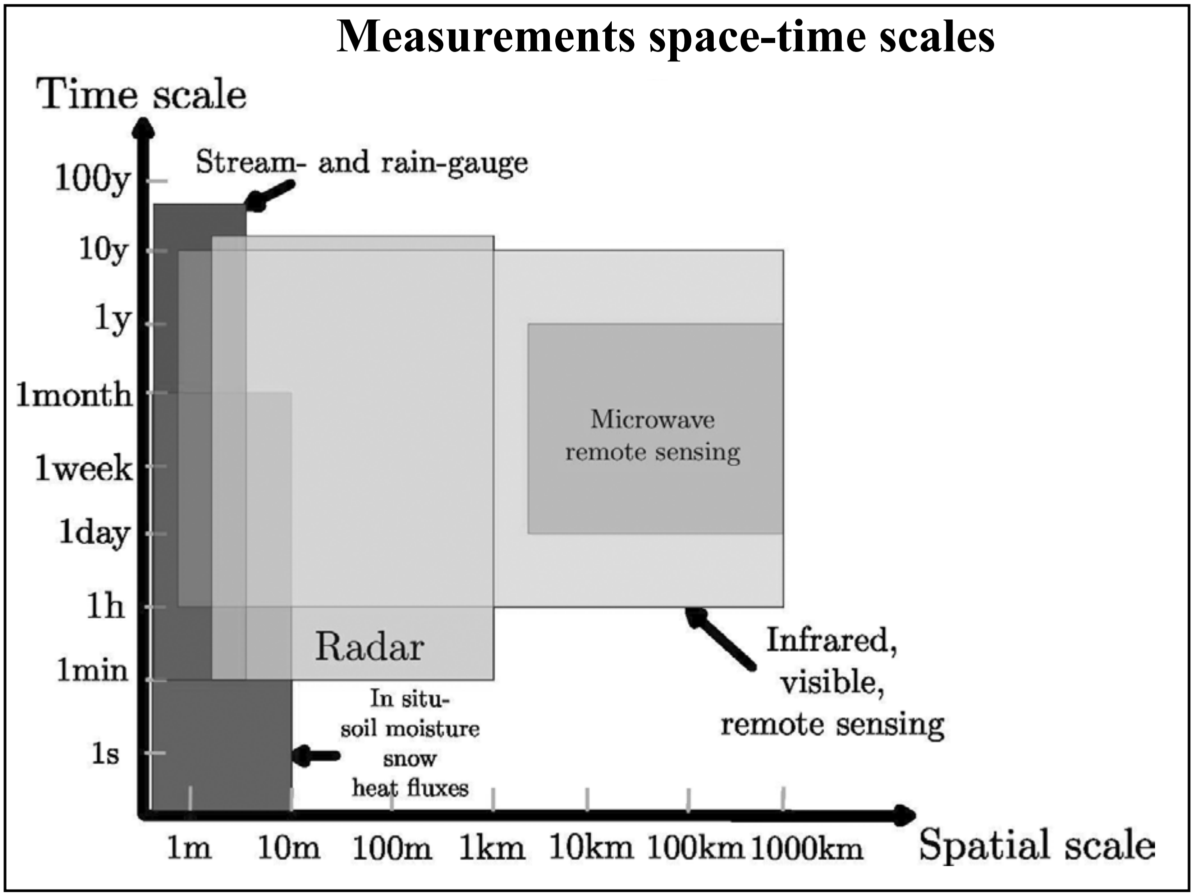

Figure 2. Spatial and temporal scales of hydrological measurements.

Lynn et al. 1995; Avissar 1995; Avissar and Schmidt 1998; Roy et al. 2003; Taylor et al. 2011). Development of new theories specifically geared toward systematic description of turbulent heat fluxes as a function of scale are needed (Jacobson 1999; Pielke 2002; Nappo 2002).

One of the major challenges restricting the development of new theories for soil moisture and turbulent heat fluxes at a weather or climate model scale (10-100 km) is the need for the creation of large-scale surface hydrology field campaigns. In such field campaigns all components of the surface

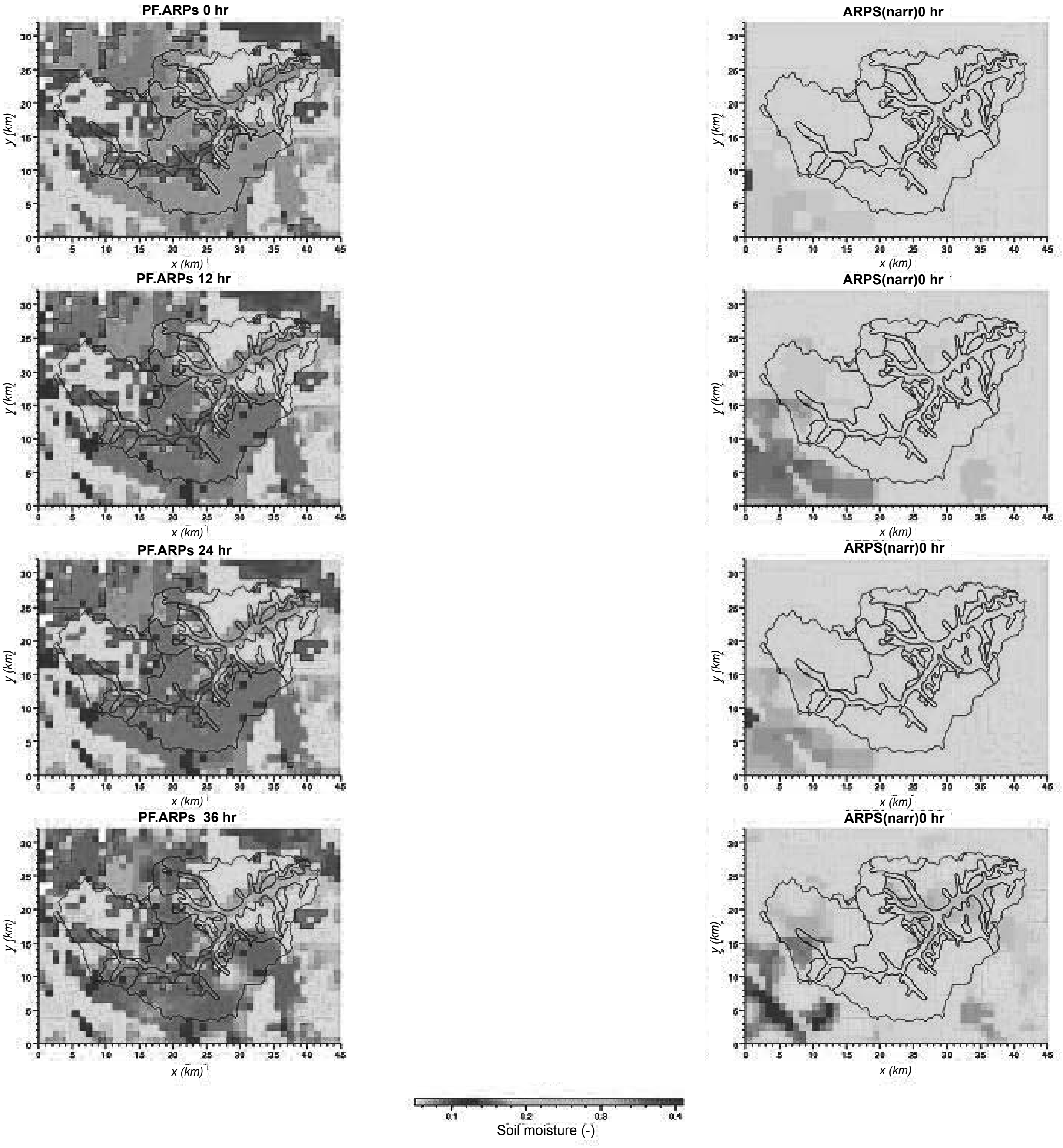

Figure 3. From Maxwell et al. 2007, Advances in Water Resources Copyright. Modeled time series of soil mositure field sampled every 12 hours using a fully coupled model (subsurface hydrology (ParFlow)-land surface atmosphere (ARPS). Left panels were initialized with a fully coupled spin-up procedure. Right panels were initialized using soil moisture interpolated from the North America Regional Reanalysis dataset.

hydrologic cycle would be evaluated at several scales, from local (10-100 m) to the largest one (10-100 km). Such an experiment would allow for the determination of scaling properties as the size of the experiment is increased. This would potentially help develop our understating of the non-local transport laws (see previous section) and thus reduce the gap in our understanding of the physical processes taking place at the hillslope and watershed level. Substantial scientific and financial resources are required to achieve the goal of reconciling the observed and modeled hydrologic scales, as initiated by several hydrologic-related programs (e.g., International Hydrological Programme, Global Energy and Water Cycle, Terrestrial Regional North American Hydroclimate Experiment workshop).

Another major problem is related to the discrepancy between the temporal scales of the physical processes, the temporal resolution of the numerical models, and the observed scales (see Figure 1 and 2). Compared to the spatial scales, the capacity to represent the smallest time scales (hours to minutes) has advanced significantly in recent years with the increase in computing power. Still, a common problem is that models are calibrated for one purpose at one time scale, but then used for a variety of purposes across multiple scales. For instance, a model can be calibrated to match monthly streamflow and then used for flood forecasting, which happens at the daily scale. The opposite can be true as well, where the model will be calibrated for short time periods and then directly used as such in climate models. Slow drift might occur on seasonal and yearly time scales, which might be loosely constrained by the short-term observations. The lack of long-term data to estimate slow land-surface processes remains a major problem of the field. At this stage, stream flow and pan evaporation are the only data available on scales of decades.

Toward a Systematic Scaling Framework

We identify four methodologies required to achieve robust, objective scaling of surface hydrologic laws.

Identification of Critical Scales

A first step toward accurately defining the surface hydrologic laws at a given scale is the definition of critical scales. By critical scales we mean scales that are relatively well defined in the surface hydrologic processes and their equations and that should be used as reference values in their equations when up or down scaling. For instance, meso-scale landscape heterogeneities introduce a breeze effect between dry, hot patches and cool, humid patches (Avissar and Pielke 1989; Chen and Avissar 1994; Li and Avissar 1994; Lynn et al. 1995; Avissar 1995; Avissar and Schmidt 1998; Roy et al. 2003) at scales imposed by the landscape (5-100 km). Currently, most so-called mosaic approaches trying to aggregate surface heterogeneity into larger-scale climate models only use a statistical approach. The entire area is divided into fractional cover (i.e., a number between 0 and 1) without spatial information. However, the shape of the landscape fundamentally determines the meso-scale circulation and heat fluxes. This circulation depends on the geometry of the heterogeneities (Wang et al. 1998) and has, for example, important implications for deforestation studies.

Within the boundary layer, theoretical concepts, such as the blending height, defined as the level inside the planetary boundary layer above which the flow becomes horizontally homogeneous in the absence of other influences (Wieringa 1986), could be used to define a critical scale for the averaging of surface heterogeneities in a more rigorous way (Raupach and Finngan 1995; Mahrt 2000; Molod et al. 2003; Bou-Zeid et al. 2004). Rigorous definitions of the critical scales, which play a major role in the heat and moisture transport, in the soil, and in the boundary at the land surface, are a requirement for the development of accurate scaling of surface hydrologic variables and meaningful representation of those variables across scales.

Identification of Scale Invariances

In some cases it may not be possible to define critical scales. Instead, the processes take place over a large, continuous range of scales, as is the case for turbulence depicted in Figure 4.

Substantial progress in the comprehension of the origins of scale invariance and power-law structure has been realized in hydrologic problems in the last few decades pertaining to a large class of problems: cloud structure; landscape, vegetation and river network organizations; atmospheric turbulence; and sediment transport. (Kolmogorov 1941; Lovejoy and Schertzer 1985; Schertzer and Lovejoy 1987; Lovejoy et al. 1987; Tarboton et al. 1988; Lovejoy and Schertzer 1990; Rodríguez-Iturbe et al. 1992; Tessier et al. 1993; Rodríguez-Iturbe and Rinaldo 1997; Schertzer et al. 1997; Cieplak et al. 1998; Sposito 1998; Rodríguez-Iturbe et al a, b 1998; D'Odorico and Rodríguez-Iturbe 2000; D'Odorico and Rodríguez-Iturbe 2000; Lovejoy and Schertzer 2006; Paola et al. 2006; Scanlon et al. 2007; Stark et al. 2009; Foufoula-Georgiou et al. 2010; Schertzer et al. 2010). At present, few of these conceptual developments have been integrated in hydrologic models, yet they are required for sound hydrologic prediction across scales from the smallest (at a point) to the largest (hillslope and watersheds). In many instances, models are overparameterized and calibrated for the local scale but are used at a larger scale. However, local scale models cannot fundamentally work at a larger scale since many processes operating at these larger scales are not correctly represented (e.g., non-local transport, large scale organization).

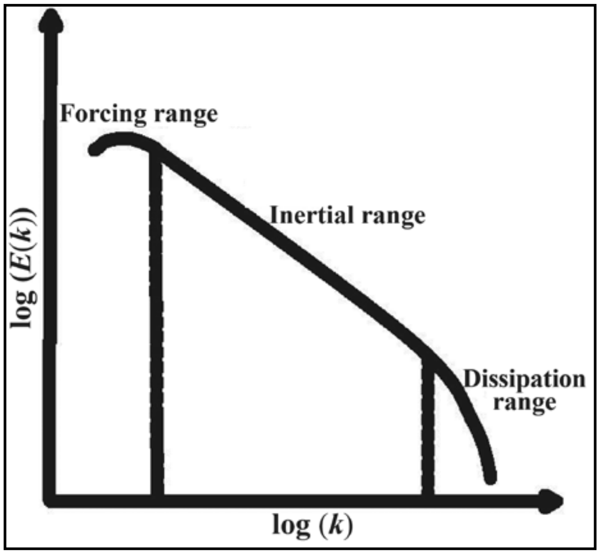

Figure 4. Kolmogorov turbulent cascade. The energy spectrum *E(K)* is plotted as a function of the wavelength *k*. In the inertial range the energy spectrum follows a power law with 5/3 exponent.

Coupled Systems

Historically, meteorologists and hydrologists have attempted to first develop uncoupled models. Such models aim to isolate one process of interest (e.g., unsaturated zone, runoff). However, like other complex systems, the earth system as a whole may exhibit emergent behaviors, which are different from the behavior of its constitutive systems taken alone. These emergent behaviors may introduce new spatial and temporal scales that are otherwise not evident from the study of individual subsystems. Examples of emergent behaviors in nature include fish schooling or avalanche dynamics. Recent examples of the emergence of new spatial and temporal scales have been demonstrated in surface hydrology (e.g., McDonnell et al. 2007; Gentine et al. 2010, 2011). These behaviors are not the result of chance alone, but are based on the interconnectivity between the subsystems of the global Earth system and are governed by fundamental principles which constrain the organization of the smaller-scale subsystems (e.g., energy minimization, minimum or maximum entropy). It is evident that the interconnectivity between the constitutive elements is at least as important as their respective constitutive behavior to external forcing. Their coherent response can lead to specific spatial and temporal scales with possible self-organization across a wide range of scales including phase transition, (i.e., abrupt change from one state to another).

Consequently, the study of the surface hydrologic system as coupled dynamical subsystems should unravel new time scales of interest, which are not apparent with current uncoupled subsystems and should help inform the design of new observing system and new field campaigns.

Derivation of Up/Downscaling Laws: Micro/Macroscale Equations

Based on the previous definition of critical scales and scale invariance, careful development of scaling hydrologic laws should be undertaken with explicit dependence on the scale considered. Only within such a framework would we have surface hydrologic models that are seamless and valid across different scales, interchangeably. Several methodologies have been developed to understand the effect of scaling from the micro- (local 1-10 m) to macro-scale (1 km or more) (Govindaraju et al. 1990; Chen et al. 1994a and 1994b; Sposito 1998; Western and Blöschl 1999; Bierkens et al. 2000; Anderson et al. 2003; Pachepsky and Radcliffe 2003; Kavvas 2003; Kim et al. 2005; Kim and Kavavs 2006; Haltas and Kavvas 2011). Careful definitions of the relationship between micro- and macro-scale laws should allow fundamental progresses in our capacity to predict the surface hydrologic state and flows.

Conclusions

Temporal and spatial scaling remains a fundamental challenge in surface hydrology, so that predictions made with numerical models become sufficiently reliable to be of practical value to end users (e.g., flood/drought forecasters, water resources managers, dam operators, hydropower managers, and ecological monitors). Substantial challenges still exist. Among these, the heterogeneities and nonlinearities of surface hydrological processes have to be better characterized and represented in our mathematical models. Efforts should also be directed toward understanding non-local transport processes, which fundamentally shape the hydrological response observed at the watershed scale.

Of course, one key difficulty in the development and validation of new theories is the discrepancy between the processes and observations. In the short-term new field campaigns should be designed to address and resolve our understanding of some of the missing scales, with further resources devoted to the design of new observing platforms and campaigns over a longer time frame.

In order to systematically address the effect of up- and downscaling on hydrological processes, we believe that four steps are necessary. First, critical scales of the system should be defined whenever possible and constitutive laws should explicitly include those scales (e.g., boundary-layer blending height, heterogeneity scale(s)). Scale invariance should be exploited and invariant scale parameters (e.g., fractal structure) defined. Moreover, surface hydrologic systems should be viewed as systems comprising coupled dynamical subsystems, with the coupling altering the dynamics of the entire system through mutual interactions and emergent behavior. Finally, careful derivation of upscaling and downscaling physical laws based should be considered based on rigorous mathematical methods (e.g., homogenization techniques) and physical constraints (e.g., conservation laws).

In many end use applications, hydrologic models are treated as black boxes; they may, for example, be applied across scales even if they were initially developed to work at a particular scale (e.g., climate model grid size). In addition, some of the model prognostic equations were direct adaptations of observations at other scales because of the lack of data at the scale of interest. The fantastic development of our monitoring capacity (e.g., remote sensing) in the last few decades should be used not only to constrain hydrologic models, but also to verify the assumptions underlying those models. The surface hydrologic community should thus embark on important developments of the theories underlying the models. Systematic redefinition of our hydrologic models with an explicit scale dependence and validation against those observations should help reconcile hydrologic predictions with field observations.

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