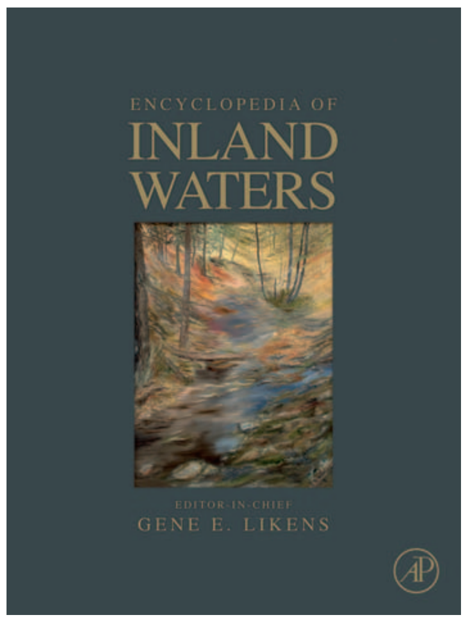

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Evapotranspiration

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Introduction

Earth's water is highly dynamic and continuously in motion, and the terms 'water cycle' or 'hydrologic cycle' describe the continuous movement of water molecules on, above, and below the surface of the Earth. The water cycle concept may be traced back to the Greeks, evidenced for example in the Iliad (written around 800 BC), when Homer described the "oceans from whose deeps every river and sea, every spring and well flows..." suggesting interconnectedness of all of the Earth's water. Leonardo's Codex Leicester, written between 1506 and 1510, was a seminal document mostly focused on water, and also advanced the concept of a large-scale water cycle by offering keen observations on the dynamics and transport of water (and suspended particles) by streams and rivers originating in the mountains and continuing through the plains to the sea. More importantly, the Codex Leicester is one of the first 'Albums of Fluid Motion' or flow visualization studies, discussing many aspects of the hydrologic cycle and its connection to fossils, geology, and climate.

Because of its intrinsic role in the hydrologic cycle, the study of evapotranspiration (ET), the sum of evaporation (E) and plant transpiration (T), has a rich research history, and to discuss every nuance of the topic is beyond the scope of a single chapter. The focus here is on ET, the engine of the hydrologic cycle, crucial for determining usable water for humans and ecosystems. We explore how the projected climatic and land cover changes might alter ET over a hierarchy of scales ranging from global to continental to local. Throughout, E here refers to the movement of water to the atmosphere from sources such as the soil matrix, rainfall intercepted by plant canopies, and water bodies, while T refers to the loss of water in the form of vapor molecules passing through leaf stomata.

The first attempt to quantify the role of ET in the hydrologic budget is often attributed to John Dalton, who carried out the necessary calculations to construct hydrological balances of major rivers (including the Thames), and published them in 1802 in the manuscript titled "Experiments and observations to determine whether the quantity of rain and dew is equal to the quantity of water carried off by the rivers and raised by evaporation; with an inquiry into the origin of springs." Dalton is also known for his work on partial pressures, which lead to the first physically based quantitative model of evaporation (see Box 1).

In the next section, it is demonstrated that Dalton's seminal work, along with others in the nineteenth century, lead to developments of quantitative laws for E that find wide use today in constraining estimates of the acceleration of the hydrologic cycle because of projected increases in global air temperature. The term 'acceleration of the hydrologic cycle' refers to the fact that higher temperatures provide more kinetic energy to water molecules, leading to more evaporation and thus more precipitation.

Evaporation and the Projected Acceleration in the Global Hydrologic Cycle

It is now accepted that increases in greenhouse gas emissions lead to increases in air temperature. However, the effects on the hydrologic cycle are far more difficult to predict. It is appropriate to start with a first-order estimate of how much the global hydrologic cycle is expected to accelerate following an increase in global air temperature (δT_a) using only the nineteenth century equations presented by John Dalton, Rudolf Clausius, and Benoit Paul Emile Clapeyron (see Box 1). From Box 1, it can be shown that the combination of these nineteenth century laws lead to

$$\frac{\delta P}{P} = \frac{\delta E}{E} = 0.0675\delta T_a$$

where δP and δE are projected changes in global rainfall and global evaporation in response to δT_a, respectively. On the basis of the nineteenth century laws, a 1 °C warming (roughly commensurate with the warming trend experienced over the past century, which is estimated at 0.15 °C per decade) leads to a 6.8% increase in global rainfall (or E). Furthermore, a 4 °C projected warming trend, predicted to result from a doubling in atmospheric CO_2 concentration, can produce up to a 27% increase in rainfall (or E). These calculations may be compared with contemporary estimates obtained using the state-of-the-art high-resolution climate models that couple oceanic and atmospheric circulation (and stretch the best currently available supercomputing facilities) that predict

$$\frac{\delta P}{P} = 0.035(\delta T_a - 1.4)$$

This modern estimate suggests that a 4 °C projected warming will result in about 9% increase in rainfall.

Box 1 Acceleration of the Global Hydrologic Cycle with Increased Temperature

A Scaling Analysis Using Nineteenth Century Formulations

A first-order estimate of the acceleration in the hydrologic cycle in response to a global increase in air temperature (δT_a) is carried out using physical laws (in boxed quantities) derived by the nineteenth century scientists John Dalton, Rudolf Clausius, and Benoit Paul Emile Clapeyron. At the global scale, once sufficiently long periods of time have elapsed (e.g., decades or longer) it is safe to state that the global hydrologic balance can be reduced to $P \approx E$, where P is the global rainfall. Hence, any change in the global hydrological cycle due to an increase in air temperature must affect both rainfall and evaporation expressed as

$$\frac{\delta P}{P} = \frac{\delta E}{E}$$

where δP and δE are changes in global rainfall and global evaporation due to a δT_a. Using Dalton's law,

$$E \approx g_w D$$

where g_w is referred to as the conductance of the surface to water vapor, and D is the vapor pressure deficit defined as $e^*(T_a)(1 - \mathrm{RH})$, where e^* is the saturation vapor pressure at T_a and RH is the global air relative humidity. The Clausius–Clapeyron equation can now be used to relate e^* to T_a using,

$$e^*(T_a) = a \exp\left(\frac{bT_a}{T_a + c}\right)$$

where T_a is the temperature (°C), $a = 0.611$ kPa, $b = 17.5$ °C^{-1}, and $c = 249.93$ °C for typical atmospheric pressures. In existing climate simulations, the effects of increased greenhouse gases on δT_a do not lead to appreciable changes in RH, even across a wide range of climate scenarios. Hence, in a first-order analysis, assuming that RH maintains its present global value, we find that

$$\frac{\delta P}{P} = \frac{\delta E}{E} = \frac{\delta D}{D} = \frac{\delta e^*(T_a)}{e^*(T_a)} = \left(\frac{-bT_a}{(c + T_a)^2} + \frac{b}{c + T_a}\right)\delta T_a$$

An order of magnitude analysis demonstrates that $\frac{-bT_a}{(c+T_a)^2} \ll \left(\frac{b}{c+T_a}\right)$ resulting in

$$\frac{\delta P}{P} = \frac{b}{c + T_a}\delta T_a$$

Using the current global air temperature $T_a = 15$ °C, and substituting $b = 17.5$ °C^{-1}, and $c = 249.93$ °C results in

$$\frac{\delta P}{P} = \frac{\delta E}{E} = 0.0675\delta T_a$$

Note that this δP differs from the estimate in Box 1 in slope (by about a factor of 2), and by the offset of 1.4 K that can be attributed to thermal inertia in the Earth system (i.e., some finite warming is necessary before the hydrologic cycle begins to be impacted). The differences in the slopes between these two estimates can be traced back to inefficiencies in the hydrologic cycle that are accounted for in climate models, as well as the many feedbacks not accounted for in the calculations shown in Box 1. Examples of such feedbacks include the formation of clouds in advance of rainfall, which block direct sunlight from arriving at the surface and reduce bulk conductance, thereby decreasing ET. Hence, according to Box 1, the projected acceleration in the global hydrologic cycle is primarily due to a global increase in ET, and nineteenth century laws provide a reasonable *upper limit* to constrain its value.

Evapotranspiration and the Continental-Scale Hydrologic Cycle

The problem of assessing how climatic changes propagate through various terms in the continental-scale hydrologic balance is complicated, than in the global case, by the addition of a new term – continental-scale runoff (R_o). Over long periods of time, the continental-scale hydrologic balance can be expressed as

$$p = ET + R_0$$

Nearly all studies investigating continental-scale trends in ET over the past 50–100 years suggest some change has occurred, but conflicting conclusions persist about the direction of this change. While continental-scale ET may be an order of magnitude smaller than oceanic E, replenishment of most water resources and ecosystem goods and services, as well as delivery of essential nutrients to marine estuaries, depends on the continental-scale R_0.

The arguments presented in Box 1 suggest an increase in ET in a warmer climate, but a number of studies have documented an increase in continental-scale runoff in recent years. Hence, how ET may have changed over the past 50–100 years appears to be controversial, and reconstructing how continental-scale ET changed over the past 100 years is a logical test of current skills in predicting the future of the hydrologic cycle.

Three hypotheses have been promoted as plausible explanations for a decreasing ET over the past 50–100 years, each with certain limitations. The first is the so-called 'solar dimming' hypothesis. This hypothesis argues that a reduction in solar irradiance occurred because of an increase in cloud cover and aerosols concentration, the latter being consistent with measured increases in air pollution throughout the past 100 years (Table 1). Solar irradiance is a key forcing for the available energy that drives ET and influences bulk conductance through the effect of light on leaf photosynthesis (see Box 2). The decrease in pan evaporation rate measured over the last 50 years over much of the conterminous United States and Russia is used as indirect support for this hypothesis. A pan evaporameter is a simple device consisting of a cylindrical container about 1.2 m in diameter and 0.25 m deep filled with water, a water level measuring device, and a rain gage. Naturally, pan evaporation is influenced by complex micrometeorological

Table 1 Observed global changes in radiation

Dates of measurements	*Observed change in radiation*	*Source*
1958–1992	-0.51 W m^{-2} yr^{-1}	1
1964–1980	-0.41 W m^{-2} yr^{-1} in densely populated areas, -0.16 W m^{-2} yr^{-1} in sparsely populated areas	2
1984–2001	$+0.24$ W m^{-2} yr^{-1}	4, 5
1992–2002	$+0.66$ W m^{-2} yr^{-1}	6

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Box 2 Changes in Continental-Scale ET

Extending Dalton's law to ET (see **Box 1**),

$$\mathrm{ET} \approx g_c D$$

where now g_c is the bulk conductance of the soil–plant system (i.e., it lumps conductances in the soil and plant). Hence,

$$\frac{\delta \mathrm{ET}}{\mathrm{ET}} = \frac{\delta D}{D} + \frac{\delta g_c}{g_c}$$

Any solar dimming, increased atmospheric CO_2 and its concomitant effect on bulk stomatal conductance, and the overall increase in global deforestation all are viewed as factors leading to a negative $\delta g_c/g_c$ that is greater than any expected increases in $\delta D/D$ with warming (see **Box 1**), resulting in a decline in $\delta\mathrm{ET}/\mathrm{ET}$ over continents. The basic challenge confronting the scientific community today in quantifying $\delta g_c/g_c$ over continents is that the relationships between g_c, light levels, atmospheric CO_2, soil moisture, and species composition are nonlinear and vary considerably across biomes, soil type, etc.

When quantifying $\delta g_c/g_c$, it is convenient to explore the individual conductances (i.e., stomatal and soil conductances) separately because they respond differently to environmental drivers, particularly elevated atmospheric CO_2.

processes like local wind flow and is often used as one indicator of 'potential' ET. Pan evaporation records are amongst the longest available hydrologic records, spanning some 100 years in several locations.

Some studies estimate that the measured reduction in pan evaporation is consistent with solar dimming rates of 2–4% per decade. The 2–4% per decade range was independently confirmed from observation for the period between 1960 to late 1980s, using the Baseline Surface Radiation Network (BSRN) of the World Climate Research Program (WCRP). However, solar dimming now appears to be giving way to the so-called solar 'brightening' at a rate of about 1.6% per decade (Table 1). This brightening is partly explained by the recovery from the large aerosol loadings associated with the 1991 Pinatubo eruption, and a decline in Eastern European aerosol emissions due to tighter air-quality regulations in those regions. Other authors question this 'continental' view of dimming and favor local-scale explanations. These studies reported that 'dimming' was four times more frequently observed near population centers (defined as centers with a population size exceeding 0.1 million) than in sparsely populated areas.

Irrespective of whether solar 'dimming,' 'brightening,' or even 'flickering' will be the scenario for the future, the contention that a reduction in pan evaporation can be correlated with actual reductions in ET is not universally accepted. The so-called complementary hypothesis argues that a reduction in pan evaporation actually corresponds to an *increase* in ET, particularly in water-limited ecosystems. This hypothesis is based on the prediction that higher ET increases humidity, cools the air, and reduces the vapor pressure deficit (D), thereby reducing potential (or pan) evaporation. Climatological studies across the conterminous United States suggest that D did not significantly increase over the past 50 years despite a decline in the pan evaporation record, thereby negating one of the assumptions of the complementary hypothesis. However, analysis of published precipitation and stream discharge data for several large basins across the conterminous United States show that ET rates, estimated as the difference between rainfall and runoff, have increased over the past 50 years. It is clear that further studies are necessary to resolve how the pan evaporation record needs to be interpreted and whether it can be used in a complementary formulation for actual ET.

The second hypothesis, promoted by sensitivity studies conducted using climate models, was aimed at exploring why continental-scale runoff increased in the past 50–100 years. This hypothesis argues that a reduction in stomatal conductance should occur following the 100 ppm increase in global atmospheric CO_2 concentration over the past 100 years (see Box 2). The response of plant stomata to elevated atmospheric CO_2 has been studied for over 30 years now and some experiments support a decrease of up to 50% with doubling of atmospheric CO_2. When such stomatal conductance reduction functions are directly incorporated into land-surface models embedded within the larger climate models, ET significantly declined and global runoff increased to levels consistent with runoff observations. These climate models are now routinely used as 'earth simulators' for addressing potential CO_2-induced interactions between terrestrial ecosystems and climate. However, these significant conductance reduction explanation due to elevated atmospheric CO_2 are not entirely supported by recent results from Free Air CO_2 Enrichment (FACE) experiments, which are designed to investigate how elevated atmospheric CO_2 affects both leaf and whole-ecosystem biosphere–atmosphere exchange rates. Several studies have explored how leaf stomatal characteristics are altered by elevated atmospheric CO_2 (Table 2). In particular, these studies examined the phenotypic response of stomatal index (SI), stomatal density (SD), and stomatal aperture (AP) to rising atmospheric CO_2 in 15 species after 4 years exposure to a field CO_2 gradient (200–550 ppm) or within three FACE sites. Along the CO_2 gradient experiments, SI and SD showed no evidence of a decline to increasing CO_2, while AP decreased slightly. It appears that without evolutionary changes, SI and SD may not respond to atmospheric CO_2 in the field and are unlikely to decrease in future climates characterized by high CO_2.

The third hypothesis argues that the decrease in continental-scale ET over the past 100 years is related to the large-scale land-use change, with deforestation being the 'dominant' trend. It is well known that clearing forests for development or agricultural purposes decreases ET and thus increases surface runoff. Direct experimental evidence of the impact of land cover conversion on ET was explored from long-term eddy-covariance measurements carried out at the Duke Forest, near Durham, North Carolina, at three stands experiencing similar climatic and edaphic conditions (Figure 1, Table 2). These measurements demonstrate that the difference between P (same for all sites) and ET is smallest for a pine plantation (PP), followed by the second-growth mixed hardwood forest (HW), followed by an abandoned agricultural field (OF) that is harvested at least once annually to prevent woody encroachment (Figure 2). Interestingly, the maximum difference in $P - \mathrm{ET}$ for this experiment was 180 mm year^{-1} over this 5-year period here, which is comparable with the reported globally averaged decrease in streamflow following the *afforestation* of grasslands,

Table 2 Reported changes in E, T, and related variables and their attributed causes

Scale of study	*Region of study*	*Variable(s) of interest*	*Change in variable(s)*	*Proposed cause of change*	*Source*
Continental	United States	Pan evaporation	+90–150 mm yr^{-1} from 1960 to 1990	Solar dimming	1
Continental	United States	Pan evaporation/E	110 mm yr^{-1}/No trend from 1960 to 1990	Complementary hypothesis	2
Ecosystem	Eastern TN	$E/T/g_s/g_c$	No Change/−10%/–44%/–14%	Elevated CO_2	3
Ecosystem	Central NC	T/g_c	+4%/No change	Elevated CO_2	4
Global	Global	g_s	−27% to 40% in herbaceous plants	Elevated CO_2	5
Ecosystem	NC, TN, NV	SI, SD, AP	No change/no change/slight decrease	Elevated CO_2	6
Global	Global	R_o	+227 mm yr^{-1} in afforested watersheds	Land-use change	7
Ecosystem	Central NC	E/T	−28%/+58%	Conversion from a grass field to a PP	8

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TN, NC, and NV refer to the states of Tennessee, North Carolina, and Nevada, respectively.

Figure 1 Experimental setup for the afforestation experiment at the Blackwood Division of the Duke Forest, near Durham, North Carolina showing the tower location at the grass site (OF), pine site (PP), and hardwood site (HW).

shrublands, or croplands (227 mm year^{-1} globally, or ~38% on average). Note that this reduction in ET due to land cover conversion from PP to OF is on the order of 20%, which is much larger than the 6.8% increase in $\delta D/D$ resulting from a 1 °C warming (see **Box 1**).

Evapotranspiration at Local Scales: Knowledge Gaps and Why the Problem of its Quantification Persists

Why does ET, studied for over thousands of years, still pose unique challenges to contemporary hydrologists? The answer may lie in the basic laws that describe water movement from the soil to the atmosphere. Movement of water in the soil–plant–atmosphere system begins with water migrating from wetter to drier soil pores adjacent to the root system moving along potential energy gradients. Once water reaches and enters the root system through a patchy and heterogeneous root-membrane, water flows through a tortuous and complex network within the xylem.

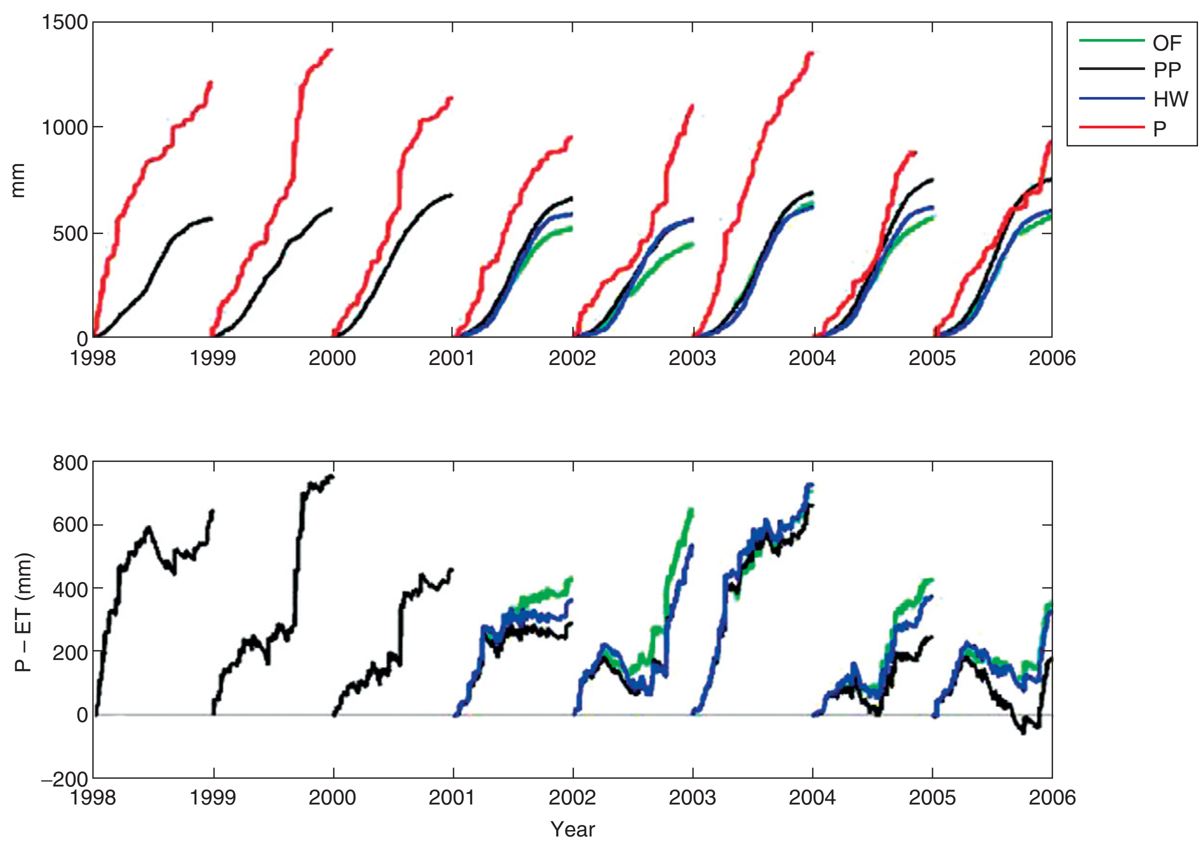

Figure 2 *Top*: Variations in eddy-covariance measured cumulative ET and *P* for the old-field (OF), pine plantation (PP), and hardwood forest (HW). *Bottom*: For reference, *P* – ET, a surrogate for water availability, is also shown.

It experiences phase transition within the leaves, and exits to the atmosphere in the form of water vapor through patchy leaf stomata. The vapor molecules are then transported by turbulent eddies from within the canopy into the free atmosphere. The transporting energy and sizes of these eddies are partially determined by complex interactions among canopy attributes (e.g., leaf area and height), mesoscale forcing (e.g., geostrophic winds and weather patterns), and landscape heterogeneity. Resolving all spatial scales needed to describe the trajectory of water in the soil–plant–atmosphere system necessitates a three-dimensional simulation domain spanning 0.1 μm to tens of kilometers, equivalent to requiring $\sim(10^{10})^3$ computational nodes per time step. This time step must be sufficiently fine to resolve the fastest process, which is the action of viscous dissipation on turbulent fluctuations in the atmosphere ($\sim$0.001 s). This high 'dimensionality' in space and time is well beyond the capacity of any brute-force computation at present and in the foreseeable future. Furthermore, there are numerous insurmountable scale issues in attempting to relate water flow in the soil–plant system with its driving forces. For one, the constitutive laws now used to describe water movement in the soil, root, plant, and atmosphere systems do not share the same representative elementary volume (REV), defined here as the minimal spatial scale of representation for these laws. To elaborate further on these laws, we consider each of them separately for the three compartments of the soil–plant–atmosphere system:

1. *Soil*: Darcy's law, first proposed in 1856 and considered as one of the hallmarks of nineteenth century Earth sciences, describes the water flux, and when combined with the soil moisture conservation of mass equation (referred to as the continuity equation), leads to the so-called Richards equation. This equation describes water movement in unsaturated soils near the rooting-zone at an REV scale containing a sufficiently large number of pore spaces. Richards's equation is a nonlinear partial differential equation that provides a space–time description of water movement, but averages out variability of soil and root matrices at scales smaller than its REV. In soil physics, one of the major theoretical challenges to upscale this equation beyond the REV is how to include the effects of spatial heterogeneities in soil properties, macroporosity, and preferential flows of water and nutrient at discontinuities (e.g., large roots). Even the application of Darcy's law within the REV of a soil–system punctuated by complex rooting remains questionable. It is clear that the laws that describe water movement from the soil pores up to the rooting zone, proposed some 150 years ago, remain approximate.
2. *Plant*: Analogous problems arise at the plant level when describing water movement from the root to the leaf. Laminar flow equations (e.g., Hagen–Poiseulle's law for capillary tubes), based on the continuum assumption in fluid mechanics, are typically used to describe root and xylem water movement (or velocities). These assumptions are now being challenged by recent research in plant hydraulics. For example, prediction of the onset of embolism (cavitation) in the plant xylem requires microscale thermodynamic description of air and water microfluid dynamics not captured by macroscopic flow equations such as Poiseulle's law. The derivation of empirically measured embolism vulnerability curves for various plant organs from first principles has not yet been rigorously tackled and remains a topic of active research. Even the precise hydraulic pathways and connections between stomatal conductance and the plant–xylem system remain a subject of research awaiting novel experiments and theories.
3. *Atmosphere*: For the free atmosphere, being a single medium, the physical laws for mass, momentum, and energy exchanges are well described by the so-called Navier–Stokes equations, yet another hallmark of nineteenth century science. These are a set of nonlinear partial differential equations that are often described as the 'last frontier in classical mechanics.' They require detailed description of boundary conditions at the plant–atmosphere interface. Describing the boundary conditions for these equations remains complicated by stochasticity in the geometry and evolution at multiple scales. Randomness, beginning with patchiness at the stomatal level and progressing to patchiness in stomatal conductance, random leaf distribution, leaf area density, and onwards to the atmosphere must all be accounted for as dynamic boundary conditions. This boundary condition complexity does not diminish the complexity of solving these equations – even for simple static boundary conditions. The Navier–Stokes equations cannot be solved at all the necessary scales except in idealized cases.

Even when these constitutive equations (Richards equation, Poiseuille law, and Navier–Stokes equations) provide reasonable approximations at a particular scale, typically where microscopic heterogeneities can be averaged out within their respective REV, a major challenge remains in the derivation of effective parameters for simplified models at larger scales needed for addressing questions pertinent to the global and regional water cycle.

Conclusions

The importance of ET in sustaining the global and continental hydrologic cycle and the world's freshwater resources is rarely questioned in hydrology, meteorology, ecology, and soil science. Nonetheless, much uncertainty remains regarding the magnitude, and even the direction, of trends in continental-scale ET in the present day and over the course of the next century. Both state-of-the-art climate models and theoretical work indicate that global ET should increase in a warmer climate. Nonetheless, observational studies suggests that continental-scale ET may be increasing or decreasing as a result of a combination of forcings including warmer temperatures, decreased bulk conductance associated with rising CO_2 concentrations, and large-scale land-use change.

Attempts to resolve this uncertainty are challenged by the difficulty in integrating microscale processes, including water transport through soil pores and plant xylem, into a framework that can describe regional- and continental-scale patterns of ET. Constitutive laws such as Richards equation, Poiseulle's law, and the Navier–Stokes equations can describe water movement through soil, plants, and the atmosphere, respectively, under some circumstances. However, even these nineteenth century based hallmark equations, when applied to continental scales, challenge the computational limits. Given that the majority of freshwater available for use by both humans and ecosystems is governed by the difference between *P* and ET on regional to continental scales, it should be clear after this review that novel theoretical 'tactics' are needed to further the development of these constitutive laws and their upscaling for ET applications.

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