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COMMENTARY

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Key Points:

- ET science and applications have significantly advanced across a wide array of fields over the past several decades
- Critical outstanding ET-based research and applied science questions from local to global scales remain due to deficiencies in our observational capabilities
- National and international research priorities should include ET-focused satellite observational investments and programs

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The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources

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Abstract The fate of the terrestrial biosphere is highly uncertain given recent and projected changes in climate. This is especially acute for impacts associated with changes in drought frequency and intensity on the distribution and timing of water availability. The development of effective adaptation strategies for these emerging threats to food and water security are compromised by limitations in our understanding of how natural and managed ecosystems are responding to changing hydrological and climatological regimes. This information gap is exacerbated by insufficient monitoring capabilities from local to global scales. Here, we describe how evapotranspiration (ET) represents the key variable in linking ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources, and highlight both the outstanding science and applications questions and the actions, especially from a space-based perspective, necessary to advance them.

1. Introduction

The response of the terrestrial biosphere to changes in climate remains one of the largest sources of uncertainty in climate projections [*Friedlingstein et al.*, 2014]. Tightly coupled to the water cycle, ecosystems can act as either carbon sinks (photosynthesis, primary production) or carbon sources (respiration, decomposition, mortality, combustion), and provide climate feedbacks through latent heat fluxes, albedo, and water cycling. However, the water cycle is rapidly changing, resulting in greater variance and more extremes [*Ziegler et al.*, 2003; *Syed et al.*, 2010]. For example, the worst drought in its recorded history struck the Amazon basin in 2005, reversing this long-term carbon sink into a carbon source [*Phillips et al.*, 2009]. In 2010, an even stronger drought hit the Amazon basin, which had not fully recovered from the impacts of the earlier event, and 2015 saw yet another recurrence [*Lewis et al.*, 2011; *Saatchi et al.*, 2013; *Jiménez-Muñoz et al.*, 2016]. The United States Midwest also experienced its worst drought in decades in 2011, followed by an even stronger one in 2012, which impacted 80% of US agriculture; in parallel, a multiyear drought from 2012 to 2015 along the West coast significantly impacted food production for the entire country [*Long et al.*, 2013; *Mallya et al.*, 2013; *AghaKouchak et al.*, 2014; *Wolf et al.*, 2016]. Overall these patterns of extreme drought have been mirrored throughout nearly all major terrestrial vegetated biomes of the world, as well as in the key food production regions of every inhabited continent [*Ciais et al.*, 2005; *Soja et al.*, 2007; *Cook et al.*, 2010; *Schwalm et al.*, 2012; *Fisher et al.*, 2013b; *van Dijk et al.*, 2013; *Famiglietti*, 2014].

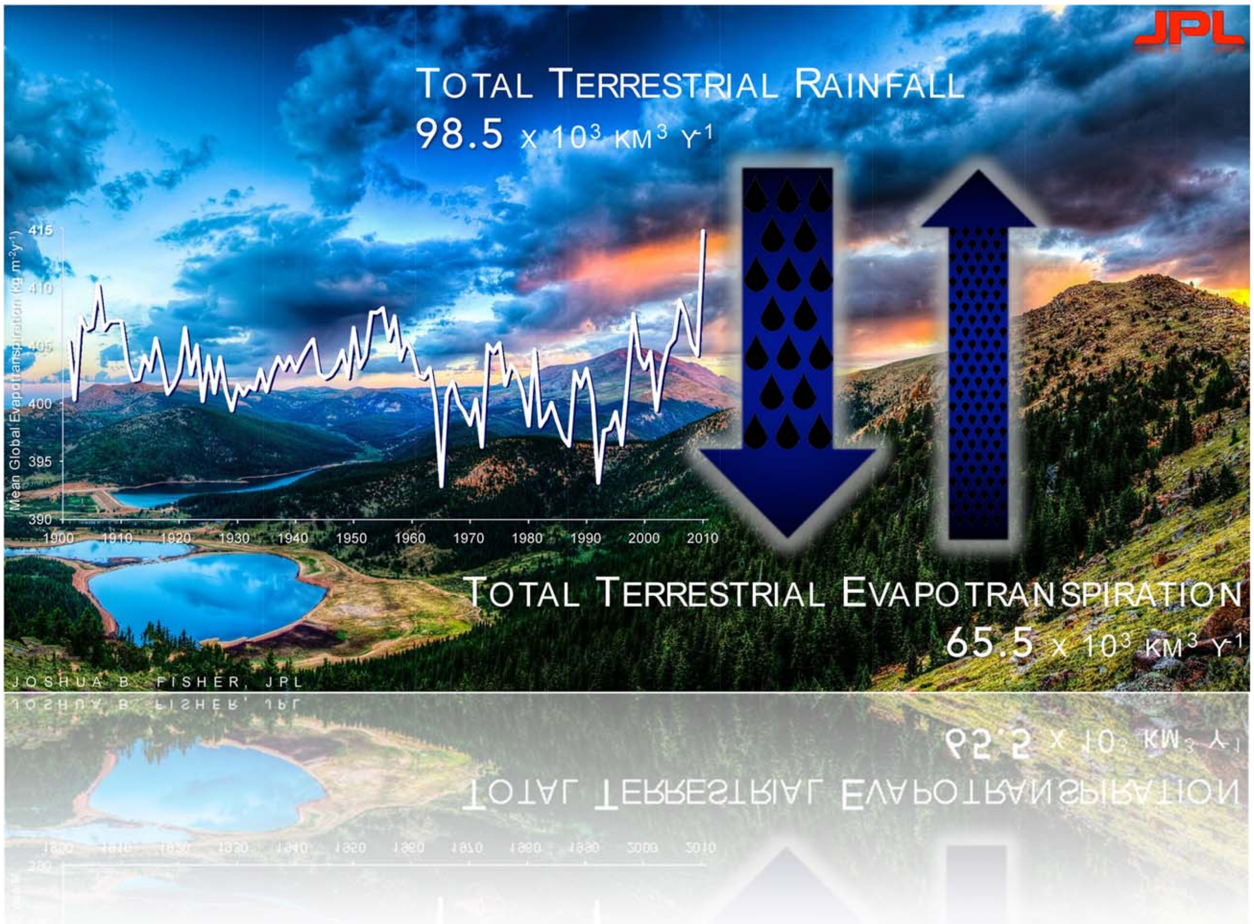

Figure 1. Terrestrial evapotranspiration (ET) consumes two-thirds of total global terrestrial precipitation [*Oki and Kanae*, 2006], and the trajectory of ET is highly uncertain [*Mao et al*., 2015]. *Background image from hdwallpapers.cat*.

While many ecosystems may be unable to adapt to such changes in drought frequency, duration, or severity, human society has the potential to adapt given the right information at the right time. As it currently stands, however, our collective infrastructure is insufficiently equipped to buffer these changes in water availability, with storage and supply now increasingly outpaced by demand [*Vörösmarty et al*., 2000; *Famiglietti*, 2015]. Moreover, drought predictive capabilities are in need of significant improvements. For example, United States drought monitors failed to predict the 2012 U.S. Midwest megadrought in terms of its magnitude and intensity [*Freedman*, 2012]. This was in large part due to missing information on land-atmosphere coupling, i.e., evapotranspiration (ET), and an underemphasis on the response of vegetation to drought [*Meng et al*., 2014]. One of the few drought metrics to capture the magnitude, intensity, and timing (i.e., early-warning indicator) of the drought at resolutions applicable for management was based on ET: the Evaporative Stress Index (ESI) [*Anderson et al*., 2010; *Otkin et al*., 2016]. Accurate and timely drought forecasting can be a vital tool to water managers who need to know how to allocate dwindling water resources in water-limited regions to benefit society and optimize productivity, while mitigating economic, societal, legal, and ecological damage. Such resource allocation problems are expected to become even more pressing, with projections that a global population of 9B people by 2050 will necessitate a 60% increase in food production, with a commensurate increase in water supplied from already stressed hydrologic systems [*IPCC*, 2014].

To date, most hydrologic studies have tended to focus on the supply side of the water problem (e.g., precipitation, snow, soil moisture, groundwater), but have largely ignored the demand side (i.e., ET; the loss of water to the atmosphere). However, increasing water demands (both climate-driven and management-driven) and droughts have now made it critical to understand both sides of the supply-demand equation,

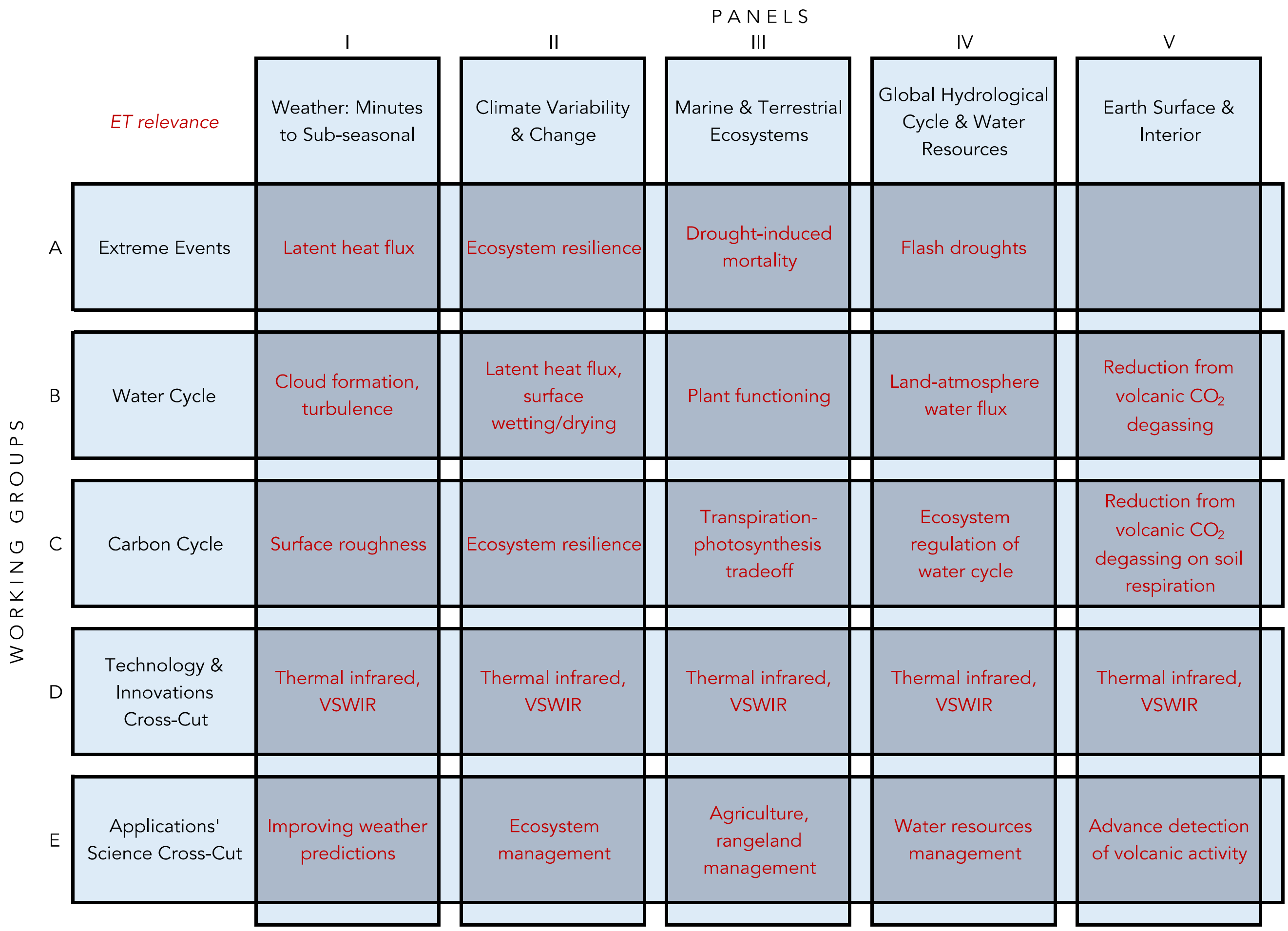

Figure 2. Evapotranspiration (ET)-based science cross-cuts across all the five U.S. National Research Council Decadal Survey panels and all five of the working groups. The specific science and application targets enabled by ET measurements are highlighted in red within each panel and working group: (IA) The latent heat flux, functionally equivalent to ET, is a driver of fine-scale weather and is impacted by extreme events, particularly heat waves and droughts; (IB) ET provides the primary terrestrial water input for cloud formation as well as turbulence; (IC) ET defines, in part, the type of vegetation that can grow in any given area, and the type of vegetation defines the surface roughness, which affects wind; (ID) Thermal infrared and VSWIR technology and innovations, in particular, will help provide the data to inform understanding of weather; (IE) ET influences weather and subsequent weather predictions; (IIA) Ecosystem water use requirements determine the resilience to extreme events such as droughts, which also impact their ability to feedback to climate through water release and carbon uptake; (IIB) ET is a key component to net surface wetting or drying, and is also the latent heat flux that contributes to the total surface energy balance; (IIC) Like IIA for longer-term mean conditions; (IID) Like ID for reducing uncertainty in climate variability and change; (IIE) Ecosystems can be managed based on water requirements, which can impact climate; (IIIA) Ecosystem water use and requirements are critical for understanding vulnerability to droughts; (IIIB) Plant functioning controls water use; (IIIC) Water loss through transpiration means carbon uptake for photosynthesis, and vice versa; (IIID) Like ID to characterize terrestrial ecosystems; (IIIE) ET is a top priority for agriculture and rangeland management, as well as other applications (e.g., fire); (IVA) ET is the leading predictor of flash droughts; (IVB) ET is the main water cycle pathway that returns water to the atmosphere; (IVC) Equivalent to IIIC; (IVD) Like ID for capturing a key water cycle component and a critical variable in quantifying water resources; (IVE) ET, as the major water loss pathway, is a key variable for water resources management; (VB) Volcanic CO_2 degassing would lead to stomatal closure; (VC) Reduction in ET from stomatal closure would be available to soil processes; (VD) Like ID for volcanic CO_2 degassing on ecosystems; and (VE) Insight into volcanic activity.

particularly the loss of water through ET (especially agricultural consumptive use—the predominant managed use of water) when mitigating vegetation stress responses (Figure 1). ET is a keystone climate variable that uniquely links the water cycle (evaporation), energy cycle (latent heat flux), and carbon cycle (transpiration-photosynthesis trade-off) [*Monteith*, 1965; *Wong et al*., 1979; *Fisher*, 2013]. It is the leading climatic predictor of biodiversity [*Fisher et al*., 2011], the predominant variable needed for water management in agricultural food production (irrigation so that applied water approximates atmospheric demand for ET) [*Allen et al*., 1998; *Anderson et al*., 2011], and the leading indicator of extreme event flash droughts [*Anderson et al*., 2013; *Otkin et al*., 2016]. ET also plays a critical role in driving weather patterns at the local scale, affecting turbulence, cloud formation, and convection [*Miralles et al*., 2014; *Vergopolan and Fisher*, 2016]. In addition, changes in ET can be used to diagnose climate variability and change, e.g., whether the land surface wets or dries over decadal scales [*Dai et al*., 2004; *Sheffield et al*., 2012; *Greve et al*., 2014; *Prudhomme et al*., 2014; *Mao et al*., 2015].

Given its importance, ET has provided a key focus for major national and international organizations including, for example, the World Climate Research Programme (WCRP), the United Nations Food and Agriculture Organization (FAO), the US Global Change Research Program (USGCRP), and the US National Research Council (NRC). The current US NRC Decadal Survey 2017, in particular, is evaluating science needs across the spectrum of Earth Sciences to guide policy recommendations for the next decade of space missions; ET-based science and applications are much in consideration. The research and applied sciences communities—represented, in part, as coauthors here—contributed feedback to NRC requests for information, illustrating how ET-based science and applications cross-cut all five Decadal Survey panels and all five of their working groups, and highlighting the importance of this key variable (Figure 2); this Commentary was motivated by those responses. The science communities that can capitalize on improved information on ET are broad and include: (i) Agronomy; (ii) Ecology; (iii) Hydrology; (iv) Atmospheric Science; (v) Climate; (vi) Carbon Cycle; (vii) Coastal Science; (viii) Computer/Data Science; (ix) Statistics; and, (x) Policy/Economics.

ET-based science, from leaf to global scales, has advanced significantly over the past few decades [e.g., *Baldocchi*, 2005; *Gedney et al*., 2006; *Jung et al*., 2009; *Anderson et al*., 2011; *Vinukollu et al*., 2011; *Mueller et al*., 2013; *Polhamus et al*., 2013; *Dolman et al*., 2014; *Badgley et al*., 2015; *McCabe et al*., 2016; *Miralles et al*., 2016; *Zhang et al*., 2016]. We are now able to map ET remotely at multiple scales with relatively high accuracy, and can leverage an extended network of eddy covariance FLUXNET towers throughout the world for in situ assessment [*Baldocchi et al*., 2001]. Information on ET is used in a wide variety of scientific explorations and societal applications, including, but not limited to, biodiversity assessments [*Gaston*, 2000; *Fisher et al*., 2011], regional water balance closures [*Sahoo et al*., 2011; *Marshall et al*., 2012; *Armanios and Fisher*, 2014; *Chen et al*., 2014], climate and cloud formation [*Shukla and Mintz*, 1982; *Rabin et al*., 1990; *Mölders and Raabe*, 1996], agricultural management [*Allen et al*., 1998; *Farahani et al*., 2007; *Allen et al*., 2011], water resources management [*Bastiaanssen et al*., 2005; *Anderson et al*., 2012], detection of drought and heat waves [*Rind et al*., 1990; *Vicente-Serrano et al*., 2010; *Miralles et al*., 2014; *Otkin et al*., 2014], urban heat islands [*Oke*, 1982; *Taha*, 1997], and water rights litigation [*Allen et al*., 2005; *Anderson et al*., 2012].

Despite the sustained and significant advances that have been made, there remain a multitude of critical Earth System Science questions and challenges that require further insight into ET before they will be fully resolved. These largely capitalize on refinements and continuity within our recent advances in ET-based science fostered by increased spatial and temporal resolution, as well as accuracy. As a product of the NRC Decadal Survey process, we identified and synthesized the principal outstanding knowledge gaps into ten research and applied science questions:

1. How are natural and managed ecosystems responding to changes in climate and water availability?
2. How much water do different plant assemblages in ecosystems use and how much do they need?
3. What is the timing of water use among ecosystems, and how does that vary diurnally, seasonally, and annually?
4. How do changes in plant water availability, access, use, and stress regulate photosynthesis and productivity?
5. How is ET partitioned into transpiration, soil evaporation, and interception evaporation, and how are these components differentially impacted by a changing temperature, CO_2, and hydrologic regime?
6. How does ET redistribute water in a strengthening or weakening global hydrological cycle, and what are the underlying causes and consequences?
7. How do changes in ET amplify or dampen climate feedbacks, land-atmosphere coupling, and hydrometeorological extremes at local to regional scales?
8. Can ET observations help constrain and improve short-term weather prediction and future climate projections at seasonal to interannual timescales?
9. Can we unify the water, carbon, and energy cycles globally from space-borne observations, with ET as the linking variable?
10. How can information on ET be applied to optimize sustainable water allocations, agricultural water use, food production, ecosystem management, and hence water and food security in a changing climate to meet the demands of a growing population?

As soon as possible, we need to advance and implement strategies for the collection of critical information gathering on ET to ensure food and water security, and to provide data that will enhance the ability of climate and biospheric models to simulate feedbacks associated with hydrologic and ecosystem responses to a changing climate.

2. Path Forward

To address these science and applications questions, we must be able to map ET with very high fidelity:

1. *High accuracy*: Increased accuracy will allow improved differentiation of water use and water stress among different crops, species, and ecosystems, as well as to enable more efficient water management (Goal: less than 10% relative error);
2. *High spatial resolution*: The length scales required to detect spatially heterogeneous responses to water environments must consider the "field-scale" of agricultural plots, narrow riparian zones, and mixed-species forest/ecosystem assemblages (Goal: 10–100 m);
3. *High temporal resolution*: ET is highly variable both within and among days. Vegetation may regulate transpiration by closing leaf stomata, impacting water management, biomass production, and atmospheric feedbacks. Water management applications of ET require accurate ET information that is provided at timeframes associated with daily irrigation decisions and scheduling, as well as a capacity to detect vegetation responses to water stress in near real-time (Goal: daily to subdaily);
4. *Large spatial coverage*: Global coverage enables detection of large-scale droughts, is necessary to understand climate feedbacks, is required to close the global water and energy budgets, and ensures consistency and dependability in measurements across regions and shared resources (Goal: global terrestrial surface); and
5. *Long-term monitoring*: Because heatwaves, droughts and drought responses evolve over the course of multiple years, and as climate becomes increasingly variable, the need for long-term observations will likewise be increasingly critical (Goal: decadal-scale mission and data science continuity).

ET is a multifaceted variable, supplied by precipitation and subsequent root zone and surface soil moisture, and controlled by a combination of radiative, atmospheric, and vegetation drivers obtainable from remote sensing [*Su*, 2002; *Allen et al*., 2007; *Fisher et al*., 2008; *Anderson et al*., 2011; *Miralles et al*., 2011; *Mu et al*., 2011]. Because ET cannot be measured directly from space at high resolutions as a water variable, it must be physically derived as an energy variable (i.e., the latent heat flux, or the amount of energy used in evaporating water) with multiple types of measurements necessary to ensure that the abiotic and biotic controls are adequately captured. Solar radiation, humidity, air temperature, wind speed, and soil moisture regulate the transfer of water from the land into the air. Information on phenology and vegetation cover is necessary for seasonal dynamics and relative magnitudes of ET fluxes. The evaporative flux in turn modifies the land surface temperature.

In addition to space-based observations, important ground-based observations synergistically complement these data, particularly for water management applications: agricultural practices (irrigation type/management, planting decisions, nutrients, soil composition, tilling practices, seed types), water quality, and plant plasticity/sensitivity/adaptation response—all of which are coupled with computational models (crop, climate, water). Physically based models are critical integrators of these measurements and information, and must continue to be scrutinized, tested, and refined [*Vinukollu et al*., 2011; *Polhamus et al*., 2013; *Chen et al*., 2014; *Ershadi et al*., 2014; *Prudhomme et al*., 2014; *McCabe et al*., 2016; *Michel et al*., 2016; *Miralles et al*., 2016]. In situ measurements of ET from eddy covariance, Bowen ratio systems, flux-gradient approaches, and lysimeters, as well as water balance approaches, are useful tools for such analyses [*Howell et al*., 1991; *Baldocchi et al*., 2001; *Fisher et al*., 2011].

At the local scale, thermal infrared (TIR) observations of land surface temperature are used to capture fine spatial and temporal dynamics associated with heterogeneous land surface processes controlling energy partitioning and ET [*Bastiaanssen et al*., 1998; *Allen et al*., 2007; *Ershadi et al*., 2013]. TIR measurements across multiple bands ($>$4) ensure that land surface temperature and emissivity are retrieved to within 1 K accuracy (assuming a precision of 0.3 K); this allows ET estimates to be within 10% relative error from land surface temperature uncertainty [*Hook et al*., 2004; *Blonquist et al*., 2009; *Cammalleri et al*., 2012; *Hulley et al*., 2012; *Fisher et al*., 2013a]. Measurements should be acquired at high spatial resolutions (10–100 m) and high temporal resolutions (daily, diurnal), as warranted above [*Allen et al*., 2007; *Chen et al*., 2008; *Allen et al*., 2011; *Anderson et al*., 2012; *Kilic et al*., 2016].

At large spatial and temporal scales, net radiation is among the most important drivers of ET, explaining up to 80% of variability in ET, and must be obtained from a combination of radiative, atmospheric, and surface observations (e.g., VSWIR, TIR) [*Fisher et al*., 2008; *Fisher et al*., 2009; *Jiménez et al*., 2011; *Polhamus et al*., 2013; *Badgley et al*., 2015; *Verma et al*., 2016]. Global-scale ET models are highly reliant on accurate net radiation [*Fisher et al*., 2008; *Miralles et al*., 2011]. As such, errors in net radiation can have proportionally large impacts on errors in ET, and should be obtained to within less than 10% relative error to ensure the goal of less than 10% relative error in ET.

High-quality meteorology, i.e., near surface air temperature and water vapor pressure, is needed for accurate flux retrievals by differentiating microclimates. In general, meteorological variables are well-mixed relative to the much more heterogeneous land surface variables, so meteorological spatial resolution requirements may be less stringent (<5 km), although temporal resolution requirements remain high (daily, diurnal) [*Anderson et al*., 1997; *Allen et al*., 2007; *Fisher et al*., 2008; *Allen et al*., 2011]. Meteorological drivers should be obtained with less than 15% relative error, though there is spatiotemporal dependence on ET error, e.g., when weather patterns are rapidly changing, and in arid/semiarid regions.

Finally, commensurate and collocated visible and near infrared (VNIR) measurements for phenology and vegetation cover are also required at high spatial and temporal resolutions (10–100 m, daily–weekly) [*Anderson et al*., 1997; *Allen et al*., 2007; *Fisher et al*., 2008; *Allen et al*., 2011]. At the global scale, these should be obtained with less than 25% relative error, but are particularly important during phenological events, e.g., spring leaf-out timing, and have considerably more weight at the local scale, during crop planting and harvest, and in arid/semiarid regions [*Polhamus et al*., 2013].

In short, ET requires a combination of accurate information from TIR (especially for local scales), net radiation (especially for large scales), meteorology, and VNIR (for vegetation characteristics). We show, for example, the ET error sensitivity to driving variable error at the global annual average scale for one global-scale ET model (PT-JPL: *Fisher et al*. [2008]) (Figure 3); these sensitivities would vary depending on the model, as well as in space and time. Additionally, soil moisture information can help improve ET estimation, although is not required [*Entekhabi et al*., 2010; *Miralles et al*., 2011; *Purdy et al*., 2016]. Incorporating complementary carbon cycle observations of vegetation response, such as chlorophyll [*Houborg et al*., 2015], carotenoids, and fluorescence [*Frankenberg et al*., 2011] can also aid in better discriminating coupled water and carbon responses.

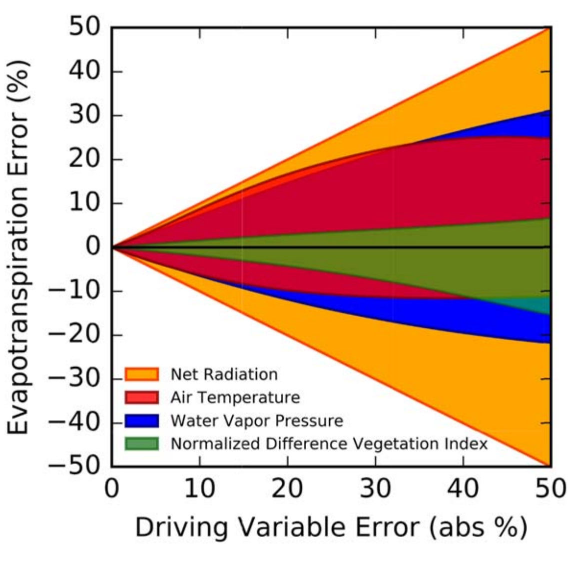

Figure 3. At the global annual-averaged scale, error in evapotranspiration for the PT-JPL model [*Fisher et al*., 2008] is highly sensitive to error in radiative (net radiation) and meteorological (water vapor pressure, air temperature) drivers, and somewhat sensitive to vegetation cover and phenology drivers (normalized difference vegetation index). This sensitivity varies widely in space and time, as well as with model.

A few current and planned space missions/instruments capture some, but not all, of the components necessary to meet the requirements for addressing the key science questions, challenges, and societal benefits described above. For example, Landsat provides excellent spatial resolution (>60 m), but poor temporal resolution (16 days) for TIR and VSWIR. MODIS/VIIRS provide good revisit time (daily), and good spatial resolution for meteorological and net radiation components, but insufficient spatial resolution for TIR and VSWIR (≥375 m). GOES and other geostationary weather satellites capture the diurnal cycle, but at the expense of spatial resolution (>3 km) and cohesive global coverage. ESA's Sentinel-2 provides good spatial (10–60 m) and temporal (5 days) resolutions for VSWIR, but is lacking TIR. ECOSTRESS will provide good spatial (70 m) and spectral resolutions for TIR (5 bands), and good temporal resolution (3–5 days, variable diurnal sampling), but is not an extended mission (1 year) and does not capture the high latitudes. Moreover, TIR retrievals in general are limited to clear-sky conditions, but additional all-sky retrievals can be made from microwave Ka-band sensors, albeit at lower spatial resolution [*Holmes et al*., 2015]. The proposed HyspIRI mission (identified as a Tier 2 mission in the 2007 Decadal Survey) could provide excellent TIR and VSWIR spatial resolution ($\leq$60 m), good temporal resolution (5 days), and global land coverage, but is only in Pre-Phase A (i.e., not yet approved) [*Lee et al*., 2015]. At present, the instrumentation and data algorithms for ET are mature; consequently, an orbital mission or set of missions to support ET capability from space draws upon extensive heritage and demonstrated need. It is only the flight coverage with requisite concurrent measurements that needs to be improved and optimized for ET observation, science, and applications. The timing is urgent to achieve these objectives as soon as possible.

3. Conclusions

ET science and applications have significantly advanced across a wide array of fields over the past few decades; yet, critical outstanding ET-based science and application questions remain from local to global scales due to deficiencies in our observational capabilities. No existing or planned space mission has been specified to fully meet the spatial, temporal, spectral, and accuracy requirements outlined for complete ET-based science and applications. The coauthors, on behalf of the larger science and applications communities that use ET data, strongly support national and international programs and policies, such as the US NRC Decadal Survey, to in prioritization of ET-based investments and programs to advance the critical and urgent science and application questions described within this commentary.

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