Land-Atmosphere Interactions: Evapotranspiration

Synonyms

Evaporation; Water flux

Definition

Evapotranspiration (ET): the transfer of liquid water from open water and through plant transpiration to the atmosphere as water vapor.
Transpiration: the loss of water vapor through plant pores called stomata on leaves/needles or stems.

Basics of evapotranspiration

Evapotranspiration (ET) is the movement and transfer (i.e., flux) of water as a liquid at the Earth's surface to the atmosphere as a gas. ET is a combination of open water evaporation and plant transpiration (Sublimation, which is the transition of solid water (i.e., ice, snow) to vapor due to low atmospheric pressure (i.e., high altitude), dry air and high sunlight, is generally considered separate from ET.). Sources of open water evaporation could include oceans, seas, lakes, rivers, ponds, puddles, and water on objects such as plants, buildings, rocks, the soil surface (including movement of water vertically through the soil to the surface), or in the context of measuring devices such as a pan. Plants take up water from the soil through their roots, transferring that water through their stems via conduits called xylem to their leaves, where it is used in the process of photosynthesis. The photosynthetic machinery in leaves (e.g., chlorophyll) takes in CO_2 from the atmosphere through stomatal pores, and combines it with water and energy (i.e., light) to create sugars used to maintain and grow plant tissue and functions. While stomata are open, plants may lose water from their leaves to the atmosphere – this water loss is called transpiration. Plants regulate the opening and closing of their stomata to minimize water loss (closed), yet maximize CO_2 absorption (open).

Energy is required to break the strong bonds that hold water molecules together as a liquid – when those bonds break, the individual water molecules may enter the surrounding atmosphere as vapor. Energy may be in the form of heat, radiation, or pressure. Regardless of the availability of energy, water molecules may not be able to enter the atmosphere if the atmosphere is already saturated with moisture (humidity) or if there is no wind to facilitate the transfer of the molecules from the water source to the atmosphere. The wind itself may be differentially influenced by friction as it passes over smooth versus rough surfaces. Therefore, solar radiation (or, indirectly, air temperature), air humidity, and wind speed are the main climate influences on ET. The main vegetative controls include leaf and canopy structures, regulation of stomata, and rooting dynamics. Finally, soil characteristics control soil moisture retention of precipitation inputs. All of these potential controls vary in influence depending on the system in question, as well as the associated spatial and temporal scales of analysis (Fisher et al. 2011).

Remote sensing of ET

ET can be measured "remotely" with instruments attached to towers extending over vegetation using the eddy covariance technique (e.g., FLUXNET: Baldocchi et al. 2001). These same instruments may be attached to airplanes for regional measurements. However, ET cannot be measured directly from satellite remote sensing, so it must be inferred from a model or the residual of other measurements. There are three orders of complexity in space-based estimation of ET:

- Simple: Empirical, semiempirical
- Intermediate: Water balance, energy balance
- Complex: Land surface/Earth system models

Empirical, semiempirical approaches

One of the simplest approaches to estimating ET is to take another closely related variable that is measureable, and convert that to ET using a statistical relationship. The statistical relationship (e.g., linear regression) may be developed from studies where both the other variable and ET were measured, then used to extrapolate beyond the site. One commonly used variable is the Normalized Difference Vegetation Index (NDVI), as well as related “greenness” indices, constructed from measurements primarily in the Red and Near-Infrared (NIR) wavelengths, and which is indicative of plant productivity. Where there is plenty of water and energy, there will be both high NDVI and ET; where there is no water and energy one would not expect much NDVI and ET. However, this relationship may fall apart, for example, under deforestation or nutrient limitation (high ET, low NDVI), or diurnal/seasonal water stress (low ET, high NDVI). NDVI may be obtained from satellite instruments such as the Advanced Very High Resolution Radiometer (AVHRR), the MOderate resolution Imaging Spectroradiometer (MODIS), or the Visible Infrared Imager Radiometer Suite (VIIRS), for example.
Another commonly used variable is Land Surface Temperature (LST), constructed from thermal infrared (TIR) measurements. A given surface may be cooled (lower LST) when evaporating, and hotter when there is less ET. However, other forces may change the temperature of the surface, including advecting warm/cool/dry/moist air. LST may be obtained from satellite instruments such as MODIS, the Atmospheric Infrared Sounder (AIRS), or Landsat, for example. LST may be combined with NDVI for a somewhat more complex empirical approach. One of the leading empirical approaches comes from the MPI-BGC product, which is constructed from a machine learning technique and model tree ensemble that developed statistical relationships between measured ET and globally available ancillary data at over 250 FLUXNET sites (Jung et al. 2009). Finally, many agriculturalists use semiempirical algorithms to estimate ET, using physics-based equations for potential ET (PET), then converting or downscaling PET to actual ET (AET) using an empirical scalar multiplier, called a crop coefficient, developed for their specific crop and location.

Water balance

ET may be calculated as the residual of known measurements in the water balance equation:

$$P = dS + Q + ET \tag{1}$$

where P is precipitation (rainfall and snow), dS is the change in stored standing water (e.g., lakes, ponds; or, in/on plants), soil moisture, and groundwater, and Q is runoff. From a remote sensing standpoint, rainfall is measured from a variety of satellites including, for example, the Tropical Rainfall Measuring Mission (TRMM) (The Global Precipitation Mission (GPM) is currently in development as the next major multi-satellite precipitation-measuring mission.); and, snow from MODIS. dS is measureable at large spatial scales from the Gravity Recovery And Climate Experiment (GRACE). Q is not yet measureable from space, (The Surface Water Ocean Topography (SWOT) mission is currently in development to measure river runoff from space.) but is readily obtained from river discharge measurements, though many rivers are sparsely instrumented, for example, in developing nations. Equation 1 may be rearranged to solve for ET given the known measurements of the three other variables in the equation.

Energy balance

ET may also be considered an energy (Water fluxes such as precipitation and ET are usually given in units of depth per time (i.e., $mm \cdot day^{-1}$); the units are consistent when they are in volume per area per time (i.e., $m^3 \cdot ha^{-1} \cdot day^{-1}$). 1 m^3 is equal to 1,000 l. Water can also be expressed in units of mass – 1 kg of water is equal to 1 mm of water spread over 1 m^2. ET, like R_n, can be expressed in units of energy too. Because it requires 2.45 MJ to vaporize 1 kg of water (at 20°C), 1 kg of water is therefore equivalent to 2.45 MJ; 1 mm of water is thus equal to 2.45 $MJ \cdot m^{-2}$.) variable, called the latent heat of evaporation (LE), as it requires a certain amount of energy to convert a given quantity of liquid water to gas. Energy coming from the sun less any radiation that gets reflected back to the atmosphere – or, net radiation (R_n) – is energy available to drive ET. Any R_n that does not drive ET either gets converted to sensible heat (H) or stored in the soil or other objects (G):

$$R_n = ET + H + G \tag{2}$$

A few space-based R_n are available, including those from the Surface Radiation Budget (SRB), the Clouds and Earth's Radiant Energy System (CERES), the International Satellite Cloud Climatology Project (ISCCP), and MODIS. H and, to a lesser extent, G are not remotely measureable, and are the focus of models such as the Surface Energy Balance System (SEBS), the Atmosphere-Land Exchange Inverse (ALEXI), the Surface Energy BAlance for Land (SEBAL), and Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC), all of which rely particularly on remotely sensed LST (Li et al. 2009).

Direct approaches

ET may also be calculated "directly" from the physics that control ET, as outlined earlier in the "Basics of Evapotranspiration" subsection. The most widely used equation for determining ET comes in the form of the Penman-Monteith equation:

$$ET = \frac{\Delta R_n + \frac{c_p \rho VPD}{r_a}}{\Delta + \gamma + \gamma\left(\frac{r_s}{r_a}\right)} \tag{3}$$

where Δ is the slope of the saturation-to-vapor pressure curve, c_p is the specific heat of water, ρ is air density, VPD is vapor pressure deficit, r_a is aerodynamic resistance, γ is the psychrometric constant, and r_s is surface resistance. Equation 3 forms the foundation of the algorithm for the official MODIS ET product (MOD16)(Mu et al. 2011), which relies on MODIS-based leaf area index (LAI), fraction of absorbed photosynthetically active radiation (fAPAR), land cover, and a general biome-specific lookup table to parameterize the resistances. R_n, VPD, and air temperature (T_a; i.e., included in Δ) in MOD16 are derived from the NASA/GMAO Modern Era Retrospective Analysis (MERRA).
The PT-JPL product (Figure 1: Fisher et al. 2008) is based on the PET formulation of the Priestley-Taylor equation, which is a reduced version of the Penman-Monteith equation, eliminating the need to parameterize the stomatal and aerodynamic resistances, leaving only equilibrium evaporation multiplied by a constant (1.26) called the α coefficient:

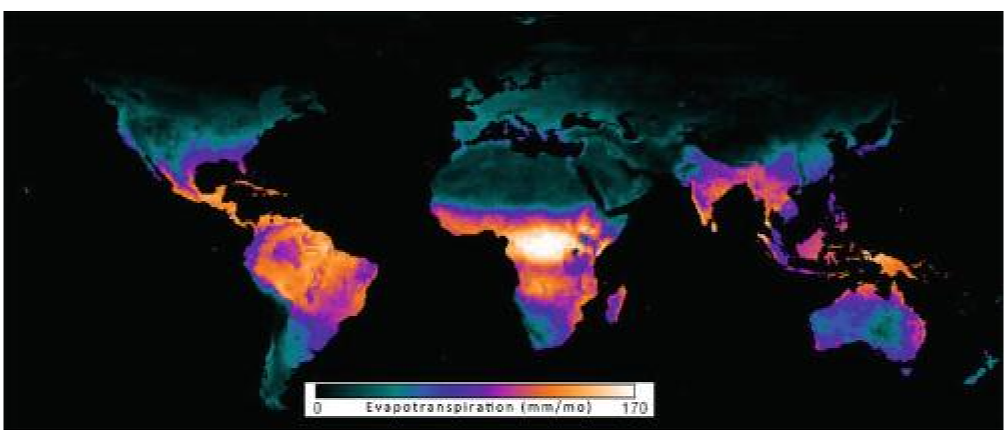

Figure 1 Mean monthly ET for 2004 from the PT-JPL product.

$$PET = \alpha \frac{\Delta}{\Delta + \gamma} R_n \tag{4}$$

PET is reduced to AET using ecophysiological constraint functions (f-functions, unitless multipliers, 0–1) based on atmospheric moisture (VPD and relative humidity, RH) and vegetation indices (NDVI and SAVI):

$$ET = ET_s + ET_c + ET_i \quad (5)$$

$$ET_c = (1 - f_{wet}) f_g f_T f_M \alpha \frac{\Delta}{\Delta + \gamma} R_{nc} \quad (6)$$

$$ET_s = (f_{wet} + f_{SM})(1 - f_{wet}))\,\alpha \frac{\Delta}{\Delta + \gamma}(R_{nc} - G) \quad (7)$$

$$ET_i = f_{wet}\, \alpha \frac{\Delta}{\Delta + \gamma} R_{nc} \quad (8)$$

where ET_s, ET_c, and ET_i are evaporation from the soil, canopy, and intercepted water, respectively, each calculated explicitly. f_{wet} is relative surface wetness (RH^4), f_g is green canopy fraction (f_{APAR}/f_{IPAR}), f_T is a plant temperature constraint ($\exp(-((T_{max} - T_{opt})/T_{opt})^2)$), f_M is a plant moisture constraint ($f_{APAR}/f_{APARmax}$), and f_{SM} is a soil moisture constraint (RH^{VPD}). f_{APAR} is absorbed photosynthetically active radiation (PAR), f_{IPAR} is intercepted PAR, T_{max} is maximum air temperature, T_{opt} is T_{max} at max($R_n T_{max}$SAVI/VPD), and G is the soil heat flux.

Land surface models/Earth system models

The most complex approach to estimating ET is through full Land Surface Models (LSMs) or Earth System Models (ESMs). These models are typically driven by meteorological data, and aim to simulate all of the relevant biogeochemical processes and states governing the exchange of energy, water, and carbon throughout the entire land surface or complete Earth system, including ocean and atmosphere. Some of these models assimilate any relevant observation from both space and in situ to constrain the complexity of linkages and feedbacks. While the estimate of ET from LSMs and ESMs is subject to potentially greater uncertainty relative to the previously described approaches due to increased complexity and degrees of freedom, LSMs and ESMs allow more realistic feedbacks to and from ET given changes in the Earth system or climate (Mueller et al. 2011).

Summary

Remote sensing of ET is currently a high-level research and science priority, especially as ET is central to connecting the water, energy, and carbon cycles, a modulator of regional rainfall, a significant factor in flood and drought processes and models, the primary climatic predictor of biodiversity, and critical for the agricultural industry. In situ measurement of ET requires cost-constraining equipment; as such, major international efforts, such as the Global Energy and Water Cycle Experiment (GEWEX), have focused on determination of ET from existing remote sensing assets (Jiménez et al. 2011; Vinukollu et al. 2011). The techniques described here provide an overview of how the scientific community estimates ET from remote sensing.

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Dr. Joshua B. Fisher	Jet Propulsion Laboratory, Pasadena, USA
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