From High Overhead:
ET Measurement via Remote Sensing

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The wide variability in evapotranspiration (ET) in both space and time poses a huge challenge to quantify total volumes of evaporation over large areas and time periods. To address this, satellite-based ET maps are being integrated with land-surface modeling or point measurements of ET to provide accurate estimates for large areas. The 1999 launch of Landsat 7 lowered the cost of medium-resolution satellite imagery by a factor of ten to about $400 per image. Numerous surface energy balance algorithms were subsequently developed or refined. Most utilize thermal (infrared) imagery collected by a satellite system to estimate actual ET, which may be less than potential ET due to shortage of soil water.

Deriving regional ET solely by ground-based "flux" measurements using eddy covariance (EC) and Bowen ratio (BR) or other systems can result in large uncertainty at substantial expense. Even with the best of equipment and exercise of care, ground-based flux measurements can sample only a single representation of spatial features that are rich in variations in soil type, soil moisture, vegetation type, vegetation cover, water table depth, slope, and aspect. Extrapolating these ground-based flux measurements over large areas becomes difficult and speculative, even with the help of numerical models.

Potential ET is approximated using maps of vegetation cover, which can be generated with reasonable accuracy using short-wave imagery available from many remote-sensing satellites. Actual ET, however, also depends on ecosystem health, which is affected by water shortages, as well as on weather conditions such as wind, radiation as affected by cloud cover, air temperature, and humidity. The thermal images from satellites function as a sort of "thermometer" of ecosystem health by integrating all the factors that influence actual ET. Given the same vegetation cover, the higher the temperature is, the greater the water shortage exhibited, and thus the lower the actual ET rate is relative to the potential rate.

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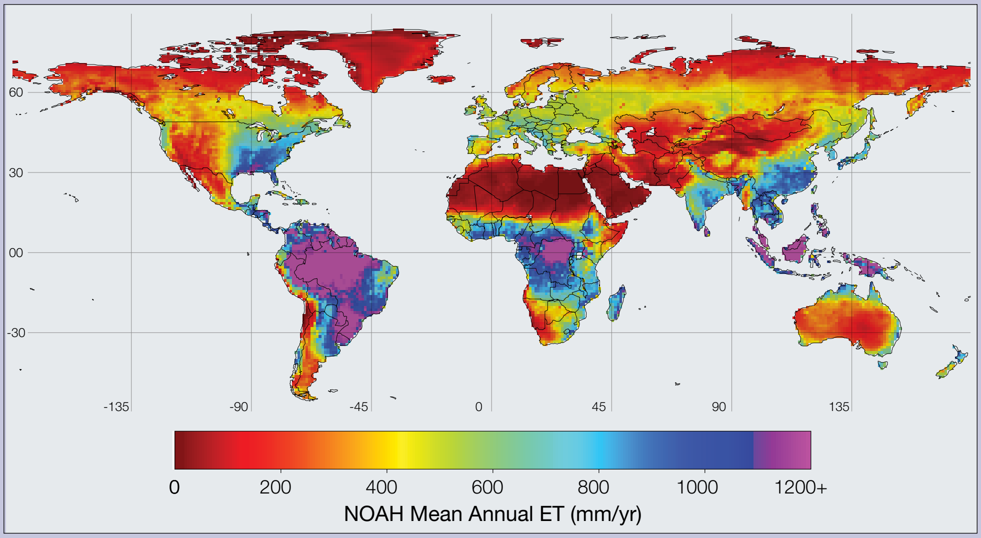
Combining spatial ET data from satellites with point measurements or modeling data of ET and soil moisture provides a cost-effective means to improve accuracy in ET mapping. For example, data assimilation methods have been used by NASA's Land Information System to integrate satellite and surface observations into model runs to construct local to global hydrologic forecasts with resolutions beginning at about one-half mile and ranging to 15 miles, with time steps of less than one hour (Cosgrove and others, 2003).



Annual ET, mm/year, for the terrestrial regions of the globe, modeled using the Global Land Data Assimilation System NOAH model (Rodell and others, 2004b).

Errors and Uncertainty

Loescher and others (2005) and Hendrickx and others (2007) have examined, respectively, land-based EC and scintillometer flux measurement uncertainties. Linear regressions for sensible heat fluxes of eight EC instruments in neutral and unstable conditions revealed differences of up to 30 percent, with typical uncertainties of 7 to 11 percent. Two studies with five large-aperture scintillometers in New Mexico showed typical differences among paired instruments of 5 to 10 percent.

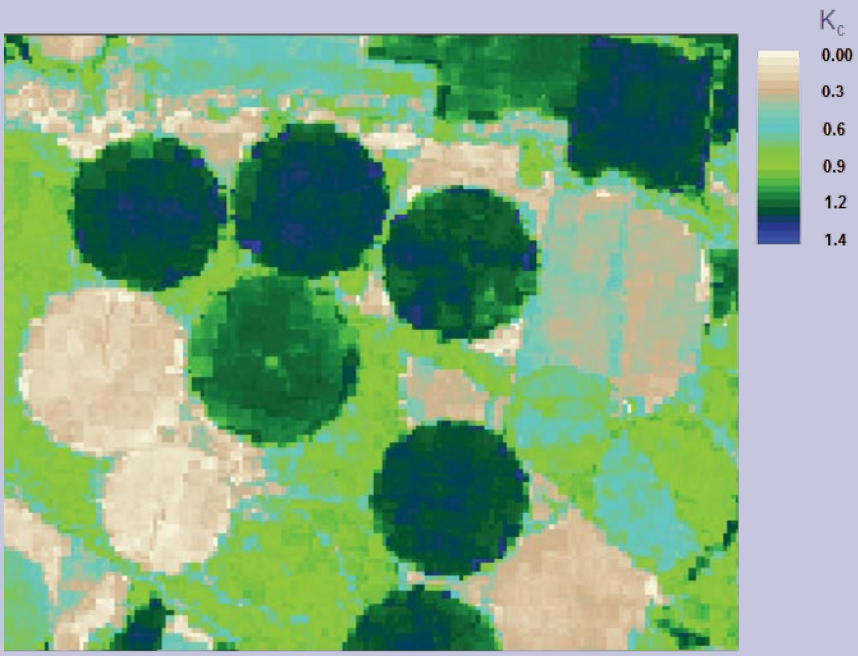
Uncertainties associated with ET derived from remotely based energy balance systems under ideal conditions may be no greater than those common to ground-based systems. Uncertainties in satellite-based estimates result from random error and systematic biases in: estimation of surface reflectance and albedo, net radiation, surface temperature, air temperature gradients used in sensible heat flux calculations, aerodynamic resistance estimation, atmospheric corrections of reflectance, soil heat flux estimation, and estimation of wind speed fields. Most polar-orbiting satellites travel 440 miles above the earth's surface, yet the transport of vapor and sensible heat from land surfaces is strongly impacted by aerodynamic processes including wind speed, turbulence, and buoyancy, all of which are invisible to satellites.

Most of the common satellite-based energy balance systems have automatic techniques to calibrate around many of these errors (Allen and others, 2007a). Quality-controlled ground-based measurements or routinely produced indices such as reference ET are frequently used to calibrate remotely sensed ET estimates to improve accuracy. Flux towers can provide time-continuous validation at discrete points within the remote-sensing and modeling domain, while high-spatial resolution remote-sensing data can inform models calibrated or forced using flux measurements.

Scaling Up and Down

Remote-sensing algorithms can infer long-term carbon, water, and energy budgets across areas ranging from watershed to global scales. One approach to "upscaling" fluxes is to use land-atmosphere transfer schemes and computer models linked to remotely sensed boundary conditions (Anderson and others, 2007a). The gridded model output can be validated at the positions of available ground measurements; if the agreement is reasonable and the observation sites are representative, the remote sensing-derived flux maps can be used to represent conditions beyond the ground measurements. This upscaling bridges the gap between flux tower footprint scales (around 200 to 1,000 feet) and the target scales of interest (hundreds to thousands of miles for the continental United States).

Daily fluxes have been mapped using the ALEXI process of Anderson and others (2007b) across regional and continental scales at 3- to 6-mile resolution using the Geostationary Operational Environmental Satellite (GOES). These coarse-scale flux estimates can also be downscaled to a finer resolution at sites of particular interest (such as around a flux tower, aircraft flightpath, or experimental site) using higher-resolution imagery from the thermally equipped Landsat, ASTER, or MODIS satellites. Maps of actual-to-potential ET ratio from ALEXI correspond well with patterns of antecedent precipitation and are being evaluated for use in operational monitoring of drought conditions at local to continental scales.



A close-up of ET within center-pivot irrigated fields in central Spain during 2003, where the actual ET rate is expressed as a fraction (Kc) of ET from well-watered grass, derived by Allen and others (2007b) using Landsat 5, including the thermal band, with 30-meter (about 100 feet) resolution.

Applications at All Scales

Use of actual ET derived by surface energy balance models using high- to medium-resolution thermal-based satellite imagery has been adopted by a number of western states for their routine water operations and planning programs. The Idaho Department of Water Resources and University of Idaho have partnered to use Landsat-based maps of actual ET to: 1) estimate water budgets for hydrologic modeling of river basins, 2) monitor compliance of irrigated farms having stipulated caps on water use, 3) support water resources planning where quantification of total ET from water sources is otherwise unavailable, 4) estimate net depletions of water from aquifers by thousands of unmetered irrigation pumps, 5) support groundwater model calibration/operation, 6) estimate water use by irrigated agriculture, 7) estimate historical water use for valuating agricultural water use for transfer of water rights, 8) develop new ET curves for agricultural crops, and 9) evaluate relative performance of large irrigation projects by comparing ET with diversions (Allen and others, 2007b). In the Rio Grande Valley of New Mexico, Landsat-

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scale ET maps helped estimate water consumption by invasive species along riparian corridors. In the Imperial Valley of California, ET maps have been used to assess irrigation and salinity management.

NASA has partnered with the University of Montana to explore the development of a global product for actual ET using data from the MODIS satellite. The process uses land cover-based parameterization of resistance parameters in the Penman-Monteith method coupled with regionally gridded weather data. (*www.ntsg.umt.edu/modis/*).

The USGS EROS center has developed a relatively simple technology that uses thermal and short-wave imagery from MODIS to estimate relative ET for major portions of the world, most commonly in underdeveloped countries where ET data can be used to assess food security or drought conditions. Bastiaanssen and others (2005) routinely estimate crop yields and ET from satellite data in developed and developing countries for the World Bank and other clients.

Rodell and others (2004a) have experimented with deriving ET for large areas using the GRACE gravimetric satellite using a regional water balance where ET = precipitation - stream outflow + change in soil water storage. The "change in soil water storage" component is derived from the change in local gravity detected by GRACE, primarily due to variations in the water table. These observations have very low resolution, on the order of hundreds of kilometers.

The Future Looks… Bleak?

Over the past thirty years, engineers and scientists have advanced the development of energy balance principles and relationships between vegetation amounts and ET to produce valuable maps of ET. Remote sensing surface energy balance estimates require the measurement of surface temperature via satellite or airplane, and thermal sensors are expensive and rare, especially at resolutions needed to estimate ET at scales of thin ribbons of riparian vegetation and irrigated fields. Unfortunately, the U.S. government has expressed reluctance to fund a thermal sensor on the next Landsat satellite, scheduled for launch in 2011. This effectively discontinues a 25-year archive of extremely valuable, high-resolution (200-400 feet) thermal imaging at the global scale. No other satellite platform routinely provides affordable, readily applied thermal imagery at this critical resolution, allowing discrimination between moisture conditions in adjacent agricultural fields. This occurs just when Landsat thermal data are beginning to be put to hard use in managing water resources and supporting hydrologic studies including impacts of climate change.

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