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Current Challenges in Evapotranspiration Determination

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The following reflection on ET was initiated at an informal meeting in Canmore, Canada, during the 8th GEWEX Open Science Conference in May 2018. A subsequent e-mail discussion took place among a wider grouping, with inputs from Z. Su (University of Twente), A. Teuling (Wageningen University and Research), J. Vila (Wageningen University and Research), C. van Heerwaarden (Wageningen University & Research), V. Vionnet (University of Saskatchewan), H. de Bruin (Wageningen University & Research), P. Gentile (Columbia University), F. Bosveld (Royal Netherlands Meteorological Institute), A. Beljaars (European Centre for Medium-Range Weather Forecasts), F. Beyrich (German Meteorological Office), S. Seneviratne (Swiss Federal Institute of Technology in Zurich), J. Polcher (Laboratoire de Météorologie Dynamique), A. Boone (Centre National de Recherches Météorologiques), J. Edwards (UK Met Office), E. Blyth (Centre for Ecology and Hydrology), A. Martínez de la Torre (Centre for Ecology & Hydrology), S. Boussetta (European Centre for Medium-Range Weather Forecasts), B. van den Hurk (Royal Netherlands Meteorological Institute), P. Greve (International Institute for Applied Systems Analysis), Li Jia (Chinese Academy of Sciences), Q. Duan (Beijing Normal University), S. Kumar (National Aeronautics and Space Administration), T. Holmes (National Aeronautics and Space Administration), J. Wang (Georgia Institute of Technology), R. Padron (Swiss Federal Institute of Technology in Zurich), L. Gudmundsson (Swiss Federal Institute of Technology in Zurich), J. Grob (Leibniz Centre for Agricultural Landscape Research & Jülich Research Centre), A. Graf (Jülich Research Centre), H. Cleugh (Commonwealth Scientific and Industrial Research Organisation) and P. van Oevelen (GEWEX).

Evapotranspiration (ET) from soil and vegetation is a key part of the energy and water budgets and, with condensation, a process that links both explicitly. Accurate experimental determination of ET is a requirement, but it is challenging both in situ and remotely, introducing uncertainties for model parameterization development and validation. Furthermore its representation often ignores important processes for specific conditions. We list a number of issues that we consider to deserve further reflection, grouped under four main challenges. It is addressed to members of the main scientific communities concerned, namely meteorologists, hydrologists, soil physicists, plant physiologists, agronomists, land-surface modelers and remote-sensing researchers.

First Challenge: Defining and Understanding ET

While *actual evapotranspiration* (ET_a or simply ET) refers to the amount of water vapor coming from any surface, not

necessarily vegetated or well-watered, *potential evapotranspiration* (ET_p) is the theoretical value if water limitation at the surface is removed, and *reference ET* (ET₀) is the theoretical value without water limitation and replacing the existing vegetation with a standard grass crop. A closely related concept is the *atmospheric water demand*, which, according to the American Meteorological Society (AMS) glossary, is "the evapotranspiration that would be achieved from a well-aerated soil/plant surface at a field water-holding capacity."

Even though ET_p can be a useful reference tool, there is a vast array of situations and related processes contributing to ET that are not taking place under such idealized conditions and yet are very relevant over the Earth's surface. For example:

- *Sublimation*: this transition takes place from areas covered (totally or partially) by snow and ice, including the intercepted snow by vegetation canopy. It is also relevant for wind-blown snow. Important factors to consider are the physical properties of surface snow, in particular hardness and roughness. Evaporation and sublimation may happen simultaneously when liquid water is present in the top layer of the snowpack.
- *Evaporation from free water surfaces*: this depends on an equilibrium term (dominated by radiation) and an advective term, controlled by the atmospheric vapor pressure deficit with respect to the surface, and the wind speed. In sunny and windstill conditions the first term may dominate. Ponds with shallow waters may be treated differently from larger and deeper water bodies. The importance of the energy storage term has yet to be analyzed.
- *Rainfall interception*: for canopies, the determination of the amount of intercepted water is a significant challenge, both to measure it experimentally and to parameterize it in models. Canopy structure and within-canopy resistances, which are usually calculated as a function of the leaf area index, play an important role for ET from intercepted water.
- *Nocturnal phase changes*: even though some applications neglect them, nocturnal ET values can be on the order of 10% of the total daytime values, both from soil evaporation induced by wind and from nocturnal plant transpiration sustaining the integrity of the vascular system. On calm, clear nights, condensation is common and may be a very significant contributor to the water budget of ecosystems in arid to humid regions. Moisture adsorption by bare soil taking place mostly during late afternoon and evening is another important process.
- *Plant transpiration*: water absorbed by roots is transported to the leaves by the vascular system. Water lost through the stomata generates the tension that maintains the filling of the xylem and cools the leaves to prevent overheat-

ing. This process depends mostly on atmospheric conditions and soil moisture availability. In models, it is often parameterized by assuming that leaves present a "resistance" to evaporation in addition to a resistance posed by the air. Many models assume the validity of the Monin-Obukhov similarity theory over the leaf surface, and use a "big-leaf" approach to calculate the transpiration of the canopy. Multi-source or multi-layer (generally two: vegetation and bare soil) approaches are available in some models as well. Different formulations exist to express the relation between stomatal conductance and soil moisture availability, which may depend on soil water potential, the root distribution and the hydraulic properties of the roots.

- *Evaporation from the soil:* evaporation of moisture from the soil is determined by the distribution of soil pore sizes and the humidity of the soil air within these pores, from the soil layer between the "evaporation front" and the soil surface. The pore size distribution depends on the soil texture, dry bulk density and organic matter contents as well as on biological activity. Hydraulic properties and soil water flow dynamics determine the amount of water reaching the evaporation front, where water vapor can be transported, via diffusion or convection, to the surface. Hydraulic models employ pedotransfer functions (PTFs) derived from soil databases, and these PTFs and the consequent hydraulic properties vary largely between models.
- *Vertical and lateral transport of air moisture:* ET is measured at specific locations, but its value also depends on the state of the surrounding areas. Entrainment of air from the free atmosphere may significantly modify the near-surface atmospheric humidity (drying/moistening for wet/arid surfaces). Land surface heterogeneity may result in lateral advection processes that would humidify or dry the air above a location and consequently change ET compared to a homogeneous area. Moisture transport by terrain-induced slope flows should also be considered.
- *ET across scales:* depending on the application, ET is generally considered at a specific temporal and spatial scale. Available formulae do not explicitly take into account the scale, although these equations have often been derived under specific restrictions, usually locally and for the daily or monthly scales. As the spatial scale increases, there is a concomitant increase of the heterogeneity of the concerned area, and improved ways of accounting for this are an active area of current investigation.

Second Challenge: Measuring ET In Situ

ET can be estimated experimentally by a variety of methods, like those based on aerodynamic or atmospheric methods, which include the eddy-covariance and the flux-gradient methods plus scintillometry; those using the soil and plant water balance, like lysimeters, soil moisture monitoring or sap flow at the leaf level; or those based on the surface energy balance residual.

At local and short time-scales, water vapor fluxes are generally estimated using the *eddy-covariance method* (EC), by sampling the three components of the wind vector and water vapor concentrations at high frequency to compute water vapor fluxes at typical averaging periods between 10 minutes and one hour. This expensive, high-maintenance setup is normally found in the research context and rarely in operational settings. EC implicitly assumes local surface homogeneity and stationarity of the regime during the averaging period. The surface energy budget (SEB) shows a lack of closure in the range of 10-25% when turbulent heat fluxes are determined using the EC method. For some applications, closure is achieved by increasing both the sensible heat flux (H) and latent heat flux (LE) while maintaining the Bowen ratio.

ET can be estimated through the *flux gradient method*, where the flux is taken proportional to the vertical gradient of humidity. The proportionality coefficient depends on the wind and the atmospheric stability, and is determined using a similarity theory, usually restricted to homogeneous and stationary conditions. When one atmospheric measurement and one surface estimate are used to compute the flux, we refer to that as the "bulk aerodynamic method." If we assume that the proportionality coefficients are the same for heat and moisture, we can obtain the so-called Bowen ratio (H/LE) from the gradients of air temperature and water vapor pressure at two levels. With knowledge of net radiation (R_n) and ground heat flux (G) (see *the residual method* below), we can then obtain the values of H and LE.

Scintillometers estimate an area-averaged value of ET by analyzing the intensity fluctuations induced by turbulence on electromagnetic waves propagating over a path of 100 m to 10 km length. Optical scintillometers at visible or near infrared (NIR) wavelengths allow for the determination of H and then LE assuming the SEB closure. A combination of an optical and a microwave scintillometer allows for the direct estimation of LE. Monin-Obukhov similarity theory is used to derive H and LE from the temperature and humidity structure parameters, which are the primary turbulence parameters determined from the scintillation measurements.

The *residual method* estimates ET (or its equivalent, the latent heat flux, LE) using the values of the other three main terms of the SEB: R_n , G and H while assuming closure of the energy balance. R_n and G can be determined by direct measurements, while H may be measured with a sonic anemometer through EC, by the gradient method using air and surface temperatures (see below), or with the sigma-T method using fast thermocouples. The resulting ET error depends on the quality of the values of the other terms and it attributes all possible deficits of the SEB components to LE.

For many decades, ETp was estimated using an *evaporation pan*, measuring the water lost by a shallow circular basin with a free surface of water. Its use is decreasing as it ignores the contribution of the soil-vegetation system and it is not consid-

ered representative of its surroundings.

Agronomists and soil physicists use a variety of methods: i) a *lysimeter* determining the loss of water mass of a volume of soil and vegetation by weighting it, ii) *sap flow sensors* estimating the transpiration flux by measuring the speed of sap as the passage of a warm pulse heated somewhere below is detected, iii) *closed flux chambers* instantaneously measuring ET from leaves or the soil and iv) trying to establish correlations between soil moisture or water potential and ET. These techniques represent very diverse spatial and temporal scales.

Sometimes there is a need to *distinguish between evaporation and transpiration*, which may be determined by analyzing the isotopic composition of Deuterium and ^{18}O in the condensed atmospheric water vapor, and for water at different depths of the soil. With relatively novel measurement techniques, profiles of isotopic composition can now be monitored continuously, providing information with much higher temporal resolution. Methods using microlysimeters below the plant canopy are under development.

EC and lysimeters are usually taken as the best ET estimates and the other methods are calibrated using them. Comparisons between the two have been made with inconclusive results, probably related to the different scales relevant to each method, although modern lysimeters with high-frequency weight measurements allow ET estimates at an hourly time resolution. Using the Bowen Ratio method to close the SEB equation for both EC and lysimeter measurements provides similar values for both systems.

New global observation networks are needed for Earth system monitoring and modeling. FLUXNET provides ET estimates basically using the EC method, and it still has large spatial gaps at the global scale. There are also time lags due to inappropriate weather conditions. Lysimeters are progressively becoming part of networks like the Integrated Carbon Observation System (ICOS) or the Terrestrial Environmental Observatories (TERENO).

Third Challenge: Parameterizing ET

Estimated values for ET_p have been generated for more than half a century using simple empirical approaches relating air temperature and usually some insolation-related parameter. A number of them have been widely used since the proposal of Thornthwaite in 1948, initially for monthly values. Currently the Food and Agriculture Organization (FAO)-modified Hargreaves formula is recommended for ET_p at the daily scale if only temperature and radiation are available.

The Penman-Monteith (PM) equation is the most widely used today, following Penman's initial formula in 1948, which was later expanded by Penman and Monteith to plant canopies. Based on the SEB equation, it makes a number of assumptions: i) the SEB is represented by only four terms (H , LE , G , R_n) that close the budget; ii) H and LE are proportional to the

temperature and humidity gradients between the surface and the air above; iii) the conductances (or resistances) depend on surface layer theory and the vegetation and soil state; and iv) the saturating water vapor pressure is assumed to vary linearly with the temperature. Additionally, the net radiation at the surface is often expressed in terms of air temperature with subsequent modification of conductances. It is common to further simplify the equation by parameterizing G as a function of R_n .

The PM formulation implicitly assumes surface homogeneity and steady conditions. The extension to a vegetated surface was made by including a physiological conductance, essentially determined by the stomatal aperture in the conceptual framework of the "big leaf" model, where each canopy component has its own conductance and they are added in parallel.

The first of two very popular expressions for ET_p conceptually evolving from PM is the Priestley-Taylor equation, which depends solely on net radiation and a coefficient 1.26 for well watered surfaces; that is, a limit of PM when aerodynamic resistance is large and surface resistance is small. The second is the PM FAO-modified in 1998 by Allen et al. for daily crop ET values, imposing specified values for the canopy surface resistance (70 sm^{-1}) and assuming neutrally stratified conditions and $G=0$.

An alternative approach, proposed originally by De Bruin in 1987, follows Makkink in considering that ET for a well-watered surface is well-represented by the shortwave radiation at the surface. He expanded the concept in 2016 with his co-authors, adding a correction factor that takes into account the dry air entrainment at the top of the atmospheric boundary layer.

Other estimates of ET are obtained by varying the coefficient of the Priestley-Taylor equation to represent the water stress of the surface, or by the use of two-source/two-layer models. These include the model introduced by Shuttleworth and Wallace based on PM in 1985, which considers separate equations for the canopy and the soil in the case of sparse canopies. These models have recently evolved to multi-layer models as developed by Verhoef and colleagues.

Complex soil-vegetation-atmosphere transfer models (SVAT) are used to compute ET, especially in numerical models of the atmosphere, with diverse degrees of complexity, relying heavily on the concepts described above. The SEB equation is the basis of their approach, which is equivalent to the PM equation without the surface temperature, since the latter is solved numerically. Soil evaporation and plant transpiration are usually estimated separately, with a multi-source model or a mosaic-tile approach in an attempt to represent surface heterogeneity. Vegetation can go from a simple "big leaf" model to canopy flow models. The modeling of canopy and aerodynamic resistances, the prescription of the soil and vegetation characteristics, the handling of snow and intercepted water,

the coupling to runoff and the improved treatment of terrain heterogeneity are amongst the main challenges that SVAT modeling faces currently.

ET determination in numerical models is now facing the transitioning of weather models into convection permitting models that experience far more fast fluctuations near the land surface than models in which convection is parameterized. A thorough review is needed of whether conventional concepts, such as the Monin-Obukhov Similarity Theory (MOST), need to be improved for the next-generation models. Furthermore, models have to continuously improve their performances related to forecasting, data assimilation, trend analysis and climate projections.

Fourth Challenge: Estimating ET Remotely and at the Catchment Scale

Satellite remote sensing ET estimates normally use the approaches of PM, Priestley-Taylor or the residual method and make a number of further assumptions to obtain H , G or R_n , usually imposing the closure of the SEB. As mentioned above, parameterizing ET essentially as a function of solar radiation is also an option. The resulting values are compared with in situ ET estimates and calibrated accordingly.

To obtain the actual ET, normally a function is derived that varies between wet conditions-corresponding to ET_p -and dry conditions when sensible heat flux prevails. Quantities like albedo, land surface temperature, surface roughness, soil moisture or some vegetation index are used. For heterogeneous vegetated surfaces, two-source energy balance (TSEB) approaches are common. There exist also purely empirical algorithms trained by data, using, for example, neural networks.

Satellite estimates of ET are given at the scale of the pixel, and some applications require information at much higher resolutions, such as the hectometer and subdaily scale. This is leading to the development of downscaling methods for most satellites.

The scale issue has a specific hydrological side, since hydrologists have traditionally analyzed the water budget at the catchment level, looking for closure at relatively large time scales (typically annual) and using the water balance as the basic methodology, with $ET = \text{precipitation} - \text{runoff}$, assuming that storage changes might be neglected at annual time scales. However, hydrological numerical models require estimations of ET at a higher time-space resolution. Annual catchment water budgets may be used as a calibration or validation method for other approaches.

To reflect on these ET-related subjects, a workshop is being organized for 7–9 October 2019 in Sydney, Australia, hosted by the University of New South Wales. It is intended to bring together specialists from different disciplines and provide a space for interaction and scientific progress on the subject. More information will be available at <https://www.gewexevents.org/events/determining-evapotranspiration/>.

Land Surface Interactions with the Atmosphere over the Iberian Semi-Arid Environment (LIAISE)

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Introduction

One of the largest challenges facing environmental science is understanding future changes in the terrestrial water cycle and the subsequent impact on water resources. It has also been recognized by international organizations such as the World Climate Research Programme (WCRP) that human activities are playing a key role in modifying the continental water cycle, and therefore must be accounted for in projections. As highlighted by the WCRP Grand Challenge on “Water for the Food Baskets of the World,” this issue is especially critical in bread basket regions where water resources are already limited, such as the Mediterranean basin. Understanding the processes that drive the hydrological cycle in this region is a key aim of the international Hydrological cycle in the Mediterranean Experiment (HyMeX). Climate projections from the Coupled Model Intercomparison Project phase 5 (CMIP5) predict that the Mediterranean region will be a so-called climate change “hot spot” during the twenty-first century (Diffenbaugh and Giorgi, 2012). However, semi-arid regions are also hot spots for biases in climate model variables, in particular land surface temperature (LST) and components of the surface energy balance. The Mediterranean basin is also characterized by highly heterogeneous land cover in terms of both natural and anthropized surfaces, largely driven by the limited availability of soil moisture and the nature of the precipitation. Since rainfall is essentially limited to winter and mountainous areas, human management of the natural river systems is required to provide water for crops and an ever-increasing population. Dams and extraction for irrigation modify the amount and timing of the water flowing into the ocean. Irrigation is also known to significantly impact local atmospheric boundary layer (ABL) growth and structure, in addition to modifying near surface atmospheric conditions and increasing convective activity and clouds downwind of irrigated areas (e.g., Lawston et al., 2015). It also greatly enhances the aforementioned land surface (flux) heterogeneity.

The current representation of anthropization in land surface models (LSMs) and therefore within global climate models (GCMs) is in a relatively nascent stage and urgently needs attention if we are to make accurate future projections of water resources and modifications to the global water cycle