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Recent decline in the global land evapotranspiration trend due to limited moisture supply

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More than half of the solar energy absorbed by land surfaces is currently used to evaporate water¹. Climate change is expected to intensify the hydrological cycle² and to alter evapotranspiration, with implications for ecosystem services and feedback to regional and global climate. Evapotranspiration changes may already be under way, but direct observational constraints are lacking at the global scale. Until such evidence is available, changes in the water cycle on land—a key diagnostic criterion of the effects of climate change and variability—remain uncertain. Here we provide a data-driven estimate of global land evapotranspiration from 1982 to 2008, compiled using a global monitoring network³, meteorological and remote-sensing observations, and a machine-learning algorithm⁴. In addition, we have assessed evapotranspiration variations over the same time period using an ensemble of process-based land-surface models. Our results suggest that global annual evapotranspiration increased on average by 7.1 ± 1.0 millimetres per year per decade from 1982 to 1997. After that, coincident with the last major El Niño event in 1998, the global evapotranspiration increase seems to have ceased until 2008. This change was driven primarily by moisture limitation in the Southern Hemisphere, particularly Africa and Australia. In these regions, microwave satellite observations indicate that soil moisture decreased from 1998 to 2008. Hence, increasing soil-moisture limitations on evapotranspiration largely explain the recent decline of the global land-evapotranspiration trend. Whether the changing behaviour of evapotranspiration is representative of natural climate variability or reflects a more permanent reorganization of the land water cycle is a key question for earth system science.

Land evapotranspiration (ET) is a central process in the climate system and a nexus of the water, energy and carbon cycles. Global land ET returns about 60% of annual land precipitation to the atmosphere⁵. Terrestrial ET can affect precipitation⁶, and the associated latent heat flux helps to control surface temperatures, with important implications for regional climate characteristics such as the intensity and duration of heat waves^{7,8}.

Acceleration or intensification of the hydrological cycle with global warming is a long-standing paradigm in climate research², but direct observational evidence of a positive trend in global ET is still lacking. A global network (FLUXNET) of continuous *in situ* measurements of

land-atmosphere exchanges, including of water vapour, has been established over the last decade³, and these data can be used to estimate global ET dynamics. We have designed an approach to assessing the temporal behaviour and global spatial distribution of ET over the past 27 years. It integrates point-wise ET measurements at the FLUXNET observing sites with geospatial information from satellite remote sensing and surface meteorological data in a machine-learning algorithm (the model tree ensemble or MTE; ref 4). The approach is data-driven and thus largely independent of theoretical-model assumptions.

We estimate a mean annual global land-surface ET value from 1982 to 2008 of $65 \pm 3 \times 10^3 \text{ km}^3$ per year, with the spatial distribution shown in Fig. 1a. This estimate is consistent with the value reported in ref. 5 ($65.5 \times 10^3 \text{ km}^3$ per year), and falls within the model range (58×10^3 – $85 \times 10^3 \text{ km}^3$ per year) estimated by the Global Soil Wetness Project 2 (GSWP-2; ref. 9). The validity of our data-driven ET product is supported by internal cross-validation at FLUXNET sites (Fig. 1b), corroboration against independent ET estimates from 112 catchment water balances (Fig. 1c), and the simulations of 16 land-surface models participating in GSWP-2 (Fig. 1d and Supplementary Methods Section 6; ref. 9).

Our global land-ET estimate, derived from FLUXNET, remote sensing and meteorological observations, suggests that the rate of land ET increased from the early 1980s to the late 1990s with a linear trend of $7.1 \pm 1 \text{ mm}$ per year per decade for 1982–1997 ($P < 0.01$ according to the Mann–Kendall test). The positive ET trend shown in Fig. 2 is consistent with the expected ‘acceleration’ of the hydrological cycle caused by an increased evaporative demand associated with rising radiative forcing¹⁰ and temperatures. Indeed, interannual variability in temperature correlates well with ET variability from 1982 to 1997 (Pearson’s correlation coefficient 0.84, $P < 0.01$). This trend of rising land ET disappears after the last big El Niño event in 1998, and the subsequent decline of the global terrestrial ET trend is consistent with estimates from nine process-oriented ET land-surface models (see Supplementary Table 5) driven by meteorological fields and vegetation states (Fig. 2 and Supplementary Discussion Section 2). The trend of the median global land-ET anomalies derived from these models becomes negative during 1998–2008 (-7.9 mm per year per decade, $P < 0.05$). We are cautious regarding the robustness of this recent ET

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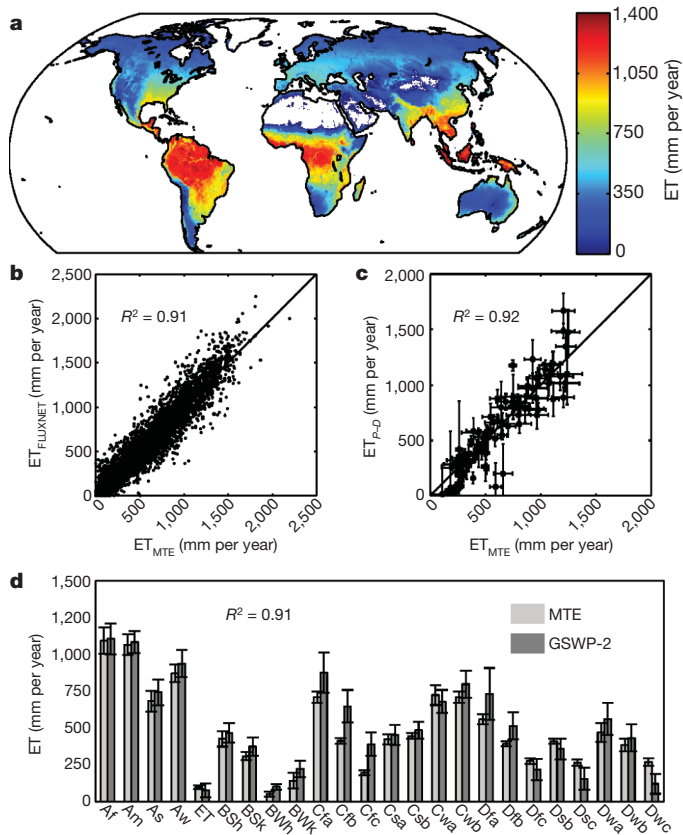


Figure 1 | Validation of global land ET product from MTE. **a**, Map of mean annual ET (1982–2008) in mm per year from MTE. **b**, Performance of MTE in predicting monthly ET at FLUXNET sites ($n = 4,678$), based on internal ten-fold cross-validation (units converted to millimetres per year for consistency). R^2 , coefficient of determination. **c**, Comparison of mean annual MTE ET against mean annual ET from catchment water balance calculated as precipitation (P) minus discharge (D) ($n = 112$). **d**, Comparison of annual MTE ET (1986–1995) stratified by bioclimatic zones ($n = 24$) against the median GSWP-2 model ensemble. All error bars are one s.d. See Supplementary Methods Section 6 for details. Af, equatorial, fully humid; Am, equatorial, monsoonal; As, equatorial, summer dry; Aw, equatorial, winter dry; BWk, cold arid desert; BWh, hot arid desert; BSk, cold arid steppe; BSh, hot arid steppe; Cfa, humid, warm temperate, hot summer; Cfb, humid, warm temperate, warm summer; Cfc, humid, warm temperate, cool summer; Csa, summer dry, warm temperate, warm summer; Csb, summer dry, warm temperate, warm summer; Cwa, winter dry, warm temperate, hot summer; Cwb, winter dry, warm temperate, warm summer; Dfa, snow, humid, hot summer; Dfb, snow, humid, warm summer; Dfc, snow, humid, cool summer; Dsb, snow, summer dry, warm summer; Dsc, snow, summer dry, cool summer; Dwa, snow, winter dry, hot summer; Dwab, snow, winter dry, warm summer; Dwb, snow, winter dry, cool summer; Dwc, snow, winter dry, cool summer; ET, polar tundra.

slowdown, given that the ensemble median is based on only relatively few models towards the end of the period.

Distinguishing land-ET response due to atmospheric demand from that due to terrestrial moisture-supply limitation is a classic ecohydrological problem^{11,12}. ET responds to changing atmospheric demand, for example to changing radiation, or to changing vapour-pressure deficit, which is often associated with temperature, if there is sufficient moisture supply. In contrast, if the soils are too dry, ET becomes restricted by soil moisture. We analysed the spatial pattern of ET-trend changes and found that the largest regional contributions to the declining trend in global ET since 1998 originate from the Southern Hemisphere in Africa and Australia (Fig. 3). The largest trend declines seem to have occurred in regions in which ET is limited by moisture (see Supplementary Methods Section 7). In these regions, lower ET would in turn be expected to feed back to the atmosphere and increase atmospheric dryness. A recent decrease in atmospheric relative humidity detected over Australia¹³ could be caused by declining ET on the Australian continent.

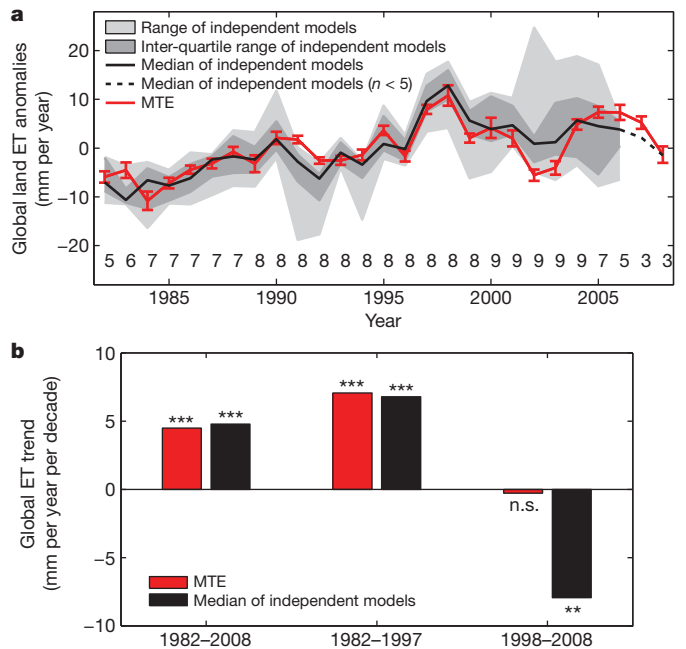


Figure 2 | Global land-ET variability according to MTE and independent models. **a**, Annual global land ET anomalies based on MTE and an ensemble of up to nine independent process-oriented models. Error bars indicate one s.d. within the MTE. Numbers at the bottom show the number of models available each year. **b**, Trends in ET based on MTE estimates and based on the median of the independent models for three different time periods. ***, significance of the trends at the 99% confidence interval; **, significance of the trends at the 95% confidence interval; n.s., not significant.

We wondered whether a soil moisture shortage could be the reason for the decline of the ET trend since 1998. Satellite microwave remote sensing provides consistent large-scale information on soil moisture, although these sensors are only sensitive to the moisture of the upper few centimetres of the soil and the associated uncertainties are large for regions of dense vegetation¹⁴. The Tropical Rainfall Measuring Mission's (TRMM) microwave imager currently yields the longest high-quality record of surface soil moisture since 1998 (ref. 15). The TRMM imaging area is confined to latitudes between 38° S and 38° N, but covers the regions in which the largest ET-trend changes occurred. We found strong coherence between 1998–2008 ET trends derived from FLUXNET data using the MTE approach, and trends in the independent TRMM satellite-observed surface soil moisture in those regions in which moisture supply is expected to control ET (Fig. 4a, b). The Southern Hemisphere pattern of decreasing ET is matched by a soil-moisture decrease over large parts of Australia, East Africa and South America. The coherence between temporal ET and soil-moisture variability remains even when they are averaged over the whole TRMM domain (Fig. 4c). We can rule out the hypothesis that ET changes are caused by changes in atmospheric demand in these regions. Trends in atmospheric demand assessed with potential ET are in the opposite direction to trends in actual ET (Supplementary Figs 5 and 6), except in China and southern India, where potential ET and ET both exhibit positive trends. In these regions ET and soil-moisture trends are opposed, probably because ET remains primarily demand-limited (see Supplementary Fig. 2). Hence, increasing ET due to increasing atmospheric demand (see Supplementary Fig. 5) depletes soil moisture, but not to the extent that it would in turn limit ET.

The strong spatial consistency of the patterns in the independently estimated ET and soil-moisture trends suggests that decreasing soil moisture supply in the Southern Hemisphere is the main mechanism contributing to the cessation of the rising ET trend after 1998. Other mechanisms that could be responsible for a stabilization of global land

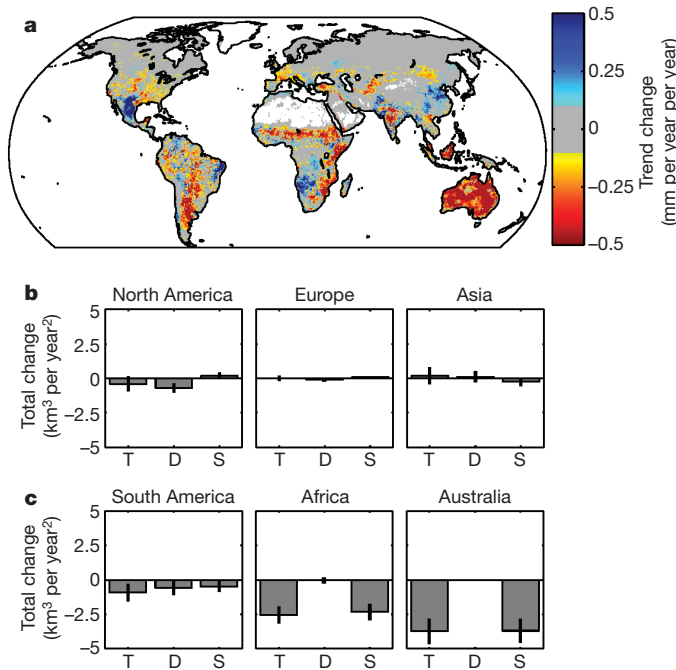


Figure 3 | ET trend changes. a, Map of the change in ET trend between 1982–1997 and 1998–2008 in millimetres per year per year. Small trend changes of ± 0.1 mm per year per year are shown in grey to enhance clarity. Total continental contributions of North America, Europe and Asia (b) and South America, Africa and Australia (c) in cubic kilometres per year per year. T, total area; D, demand-limited area; S, supply-limited area (see Supplementary Fig. 4). Error bars refer to one s.d. and are derived from the individual members of the MTE.

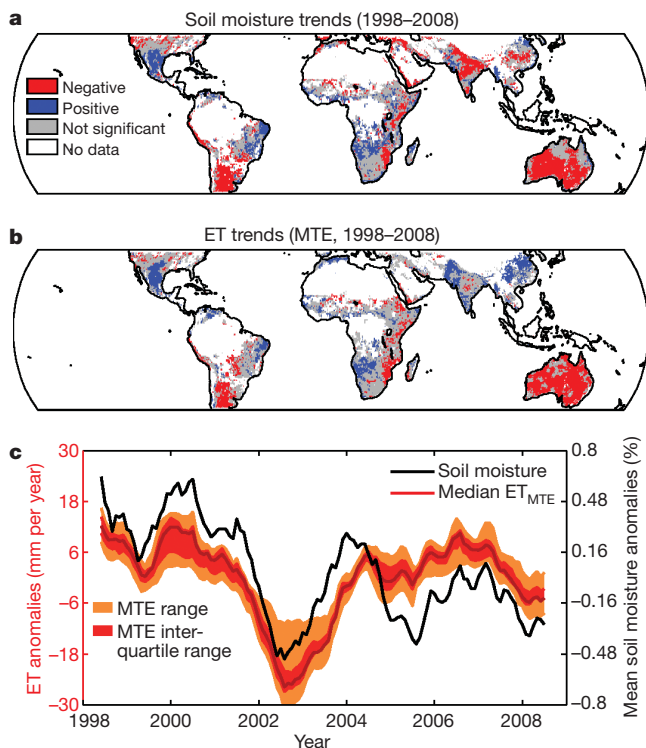


Figure 4 | Soil-moisture and ET trends. Significant ($P < 0.1$) soil-moisture trends derived from TRMM (a), significant ($P < 0.1$) ET trends from MTE (b) and mean ET and soil-moisture anomalies (seasonal cycle subtracted and filtered with an 11-month running mean) of all valid pixels of the TRMM domain (c). For consistency and improved comparability, regions without data in either MTE (non-vegetated areas) or TRMM soil-moisture data (very dense vegetation) are blanked in the trend maps of a and b.

ET seem to be less important; they include stomata closure caused by increasing CO_2 concentrations¹⁶, land-use change¹⁷, or decreasing wind speed¹⁸. More-detailed analyses^{17,19,20} did not find a measurable effect on the global land hydrological cycle caused by increased efficiency of water-use in ecosystems under rising atmospheric CO_2 concentrations, as was suggested in ref. 16. Land-use change is likely to have an important role regionally, but is apparently too geographically confined to govern the recent global ET trends. Decreasing surface wind speeds have also been put forward as a possible cause for regional decline of potential evapotranspiration¹⁸, but if lower surface wind speeds were responsible for the recent levelling-off of actual evapotranspiration, we would not see the largest changes in supply-limited regions.

In conclusion, we provide a data-driven, spatially explicit estimate of global terrestrial evapotranspiration over the past 27 years by combining *in situ* measurements, meteorology and remote-sensing information. We infer a rising trend in land-surface ET between 1982 and 1997. This trend seems to have declined since then, probably because of soil-moisture limitation. Owing to the relatively short time period we cannot precisely date a ‘switch’ in behaviour, but our analysis suggests that the late 1990s mark a transition period in which the global land-ET trend decreases. It is hard to evaluate whether this is part of a natural climate oscillation, or a climate-change signal in which land evapotranspiration becomes more and more supply-limited in the long term. The latter would imply that there is a limit to energy- and temperature-driven acceleration of the terrestrial hydrological cycle, and that it may have been reached. The consequences would be decreasing terrestrial productivity and a reduced terrestrial carbon sink, preferential partitioning of energy fluxes at the land surface into sensible, rather than latent, heat flux and thus accelerated land-surface warming, and intensified regional land-atmosphere feedback⁶.

METHODS SUMMARY

We processed half-hourly eddy covariance data from 253 globally distributed flux towers³ using standardized gap-filling and quality-control algorithms^{21,22} and a correction for incomplete energy balance closure²³. This yielded a global data set composed of monthly estimates of local ET and meteorological records from each tower (a total of 4,678 site-months within the period 1997–2006), along with satellite observations of the fraction of photosynthetically active radiation absorbed by the canopy (FAPAR) at 2-km resolution from the sea-viewing wide field-of-view sensor (SeaWiFS; ref. 24), and site-level information on vegetation type and local climate (Supplementary Data Section 1). We used this global data set to train the MTE to create maps of gridded monthly ET at 0.5° resolution covering the whole period 1982–2008. Owing to a lack of measurements in cold and dry deserts, we do not account for non-vegetated areas; this probably results in a small underestimation of the global total ET value. We used an ensemble of 25 model trees to define a median best-estimate and uncertainty based on the spread of the estimates among the individual trees in the ensemble⁴. We used a harmonized FAPAR product from three sensors (AVHRR²⁵, SeaWiFS²⁴, MERIS²⁶), a remote-sensing-based global land-use map²⁷, and observation-based products of climate variables^{28,29} as forcing data. We estimated significance levels of trends on the basis of Mann–Kendall tests. We estimated the slopes of the trends as described in ref. 30.

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Author Contributions M.J. and M.R. designed the study and are responsible for the integrity of the manuscript; M.J. performed the analysis and all calculations. M.J., M.R., P.C., S.J.S. and M.L.G. mainly wrote the manuscript. J.S., G.B., D. Gerten, J.H., J.K., Q.M., K.O., S.R., N.V., E.W., S.Z. and K.Z. contributed independent evapotranspiration model results. N.G. provided remotely sensed FAPAR data; R.d.J. and A.J.D. provided the TRMM soil-moisture data. E.T. and U.W. contributed to data processing. A.C., J.C., D. Giannele, M.L.G., B.E.L., W.E., B.M., L.M., D.P., A.D.R., O.R. and C.W. contributed data provision or data processing. All authors discussed and commented on the manuscript.

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