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Anthropogenic influence on multidecadal changes in reconstructed global evapotranspiration

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Global warming is expected to intensify the global hydrological cycle[1], with an increase of both evapotranspiration (EVT) and precipitation. Yet, the magnitude and spatial distribution of this global and annual mean response remains highly uncertain[2]. Better constraining land EVT in twenty-first-century climate scenarios is critical for predicting changes in surface climate, including heatwaves[3] and droughts[4], evaluating impacts on ecosystems and water resources[5], and designing adaptation policies. Continental scale EVT changes may already be underway[6,7], but have never been attributed to anthropogenic emissions of greenhouse gases and sulphate aerosols. Here we provide global gridded estimates of annual EVT and demonstrate that the latitudinal and decadal differentiation of recent EVT variations cannot be understood without invoking the anthropogenic radiative forcings. In the mid-latitudes, the emerging picture of enhanced EVT confirms the end of the dimming decades[8] and highlights the possible threat posed by increasing drought frequency to managing water resources and achieving food security in a changing climate.

Detection is the process of demonstrating that an observed change cannot be explained by internal climate variability. Attribution of a change to anthropogenic influence requires the additional demonstration that the detected change is consistent with the change simulated in response to a combination of external forcings, including anthropogenic changes in the composition of the atmosphere, and not consistent with alternative explanations. This implies that all important forcing mechanisms (anthropogenic greenhouse gases and aerosols, but also solar radiation and volcanism) must be considered. With the increasing confidence that recent global warming is very likely caused by human activities, detection and attribution (D&A) studies have gradually moved to climate variables more relevant for understanding climate change impacts, such as on the water cycle. Some success has been obtained at detecting human-caused changes in zonal mean precipitation[9]. D&A of continental scale changes in the other components of the land-surface water budget, however, remains a challenge given the limited instrumental record and the strong spatiotemporal variability of hydrological variables[10].

As far as EVT is concerned, only relatively few monitoring sites operate around the world and the period of record is quite short[11]. Two recent studies[6,7] have used such *in situ* measurements for tuning global empirical EVT schemes based on remote sensing and standard meteorological data. They agreed on a global increase in annual mean EVT by about 7 mm per year per decade from 1982 to the late 1990s. These results were compared with EVT outputs of process-oriented land-surface models and were found to be relatively robust[6]. The 1982–2008 period is, however, too short for a formal D&A. Moreover, one study[6] suggested that the increase in global EVT could have ceased after 1998, thereby highlighting the need to account for multidecadal variability rather than only linear trends in D&A algorithms.

Here we use two offline global hydrological simulations, respectively from the Interaction Soil–Biosphere–Atmosphere (ISBA; ref. 12) and Variable Infiltration Capacity (VIC; ref. 13) models, as pseudo-observations to detect and attribute changes in land EVT over the 1951–2005 period. The offline mode consists of driving the models with a hybrid atmospheric forcing that merges subdaily meteorological reanalyses and monthly means of both *in situ* and satellite observations[14]. Our offline simulations are based on two different land-surface schemes (see Supplementary Informations S1 and S2) and two different precipitation forcings (see Supplementary Information S3). As a consequence, they provide four parallel EVT estimates. Not surprisingly, they show some discrepancies on interannual to decadal timescales, which are mainly owing to the different physics and parameters between ISBA and VIC, but share common features on longer timescales.

How reliable are these global annual mean EVT reconstructions? ISBA and VIC belong to a generation of land-surface models in which subgrid variability of hydrological processes has been accounted for and carefully evaluated on the basin scale against observed river discharges (see Supplementary Informations S1 and S2). This explains why ISBA and VIC global annual mean EVT (1.18 and 1.08 mm d^{-1} respectively over the 1989–1995 period) is on the low side of the multimodel distribution found in the Global Soil Wetness Project 2 (GSWP2; ref. 15). Indeed, it has been shown that many land-surface models, including ISBA at the time of GSWP2, had a too low annual mean runoff/precipitation ratio, especially at low resolution, when driven by observed precipitation. Since GSWP2, ISBA has been strongly improved in this respect (see Supplementary Information S1). Beyond annual mean runoff, recent global evaluation studies have shown that it compares favourably to seasonal and interannual total water storage variations inferred from the twin satellites of the Gravity Recovery And Climate Experiment over recent years, as well as with discharge observations over large river basins on interannual to multidecadal timescales[16,17]. This gives us confidence in our gridded EVT estimate, which is then the only component of the land-surface water budget that is not directly constrained with observations.

Our study is not a strict D&A analysis on EVT as global gridded measurements of EVT do not exist. Although the ground truth is unknown and will always remain uncertain given the limited instrumental record, our EVT reconstructions can, however, be regarded as a physically based merging of all observed EVT-driving variables into a single diagnostic. The use of offline simulations

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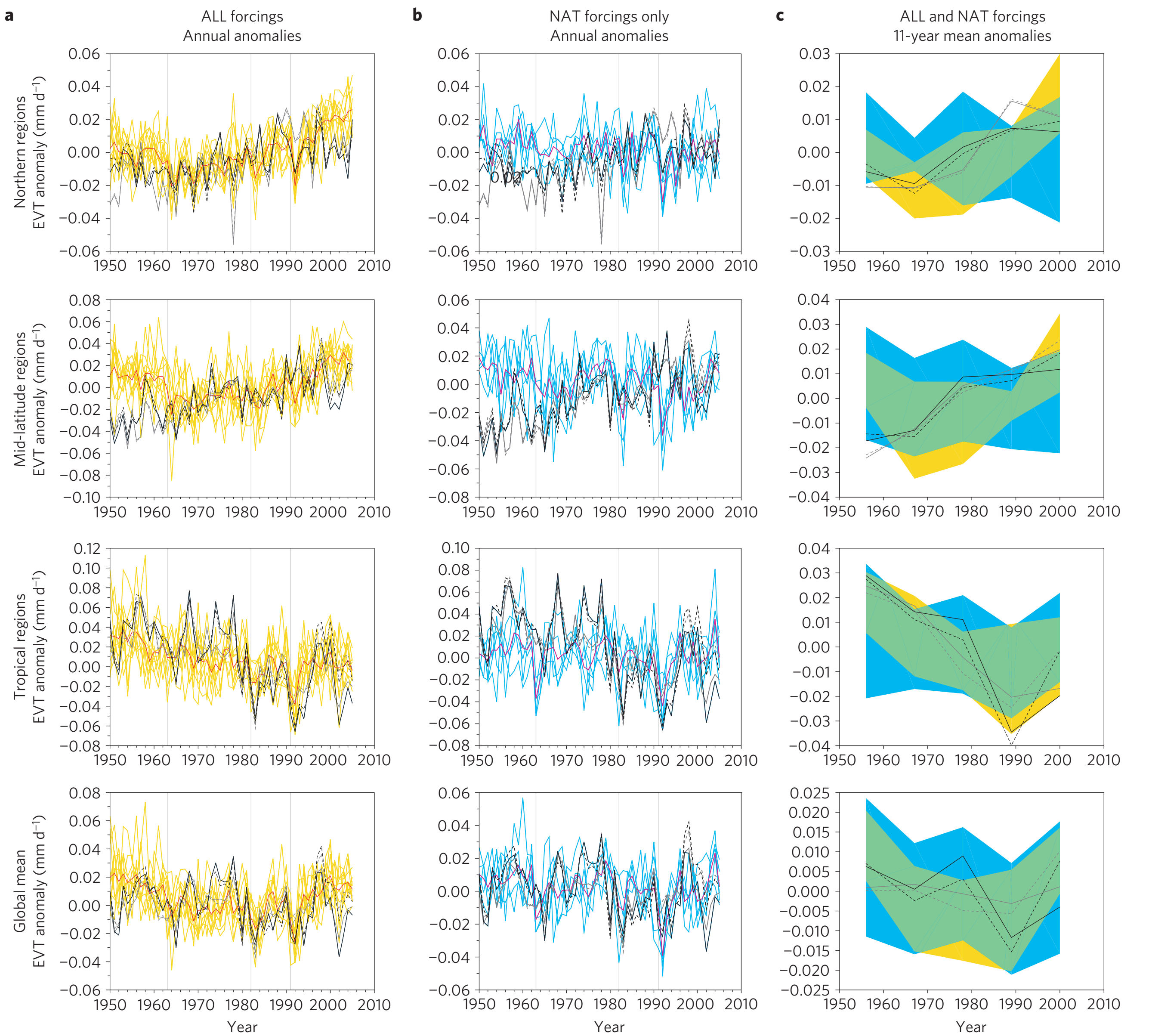

Figure 1 | Simulated and reconstructed 1950–2005 time series of land EVT anomalies. Annual anomalies averaged over northern latitudes (>60° N), middle latitudes (60° S–30° S and 30° N–60° N) and tropics (30° S–30° N), as estimated from ISBA (black) and VIC (grey) pseudo-observations, forced with Global Precipitation Climatology Centre (GPCC; solid line) or Climate Research Unit (CRU; dotted line) and simulated by CNRM-CM5 in two ensembles of coupled simulations that include **a**, all, or **b**, only natural forcings. Individual members of the ALL (respectively NAT) ensemble are represented as thin yellow (respectively blue) lines, whereas the ensemble mean appears as the red (respectively violet) thick line. In both cases, the comparison is done at the annual time step and the three main volcanic eruptions observed over the period (Agung in 1963, El Chichon in 1982 and Pinatubo in 1991) are indicated with vertical grey lines. **c**, The same data sets averaged over five non-overlapping 11-year periods as done in the optimal fingerprint analysis. Yellow (respectively blue) shading indicates the 95% (2.5–97.5%) confidence interval of each 11-year mean as computed from the ALL (respectively NAT) ensemble. Please note that the green shading is simply an overlap of blue and yellow shading.

allows us to carry out a single-step study, as defined by the Intergovernmental Panel on Climate Change (ref. 18), which provides the most direct demonstration of the influence of external forcings. Moreover, and despite the limitations of the forcing data, the reconstruction covers the whole 1951–2005 period, which is critical for a formal D&A study and a possible interpretation of the observed changes. Finally, note that the use of reconstructions instead of direct observations has no reason to bias the results towards, for example, a too-frequent detection.

ISBA is also coupled to the Centre National de Recherches Météorologiques—Coupled Model version 5.1 (CNRM-CM5) global climate model participating in phase five of the Coupled Model Intercomparison Project (CMIP5; see Supplementary Information S4) to evaluate the twentieth-century response of land EVT to changes in either/both natural or/and anthropogenic radiative forcings. Here we use three ensembles, NAT (natural forcings only), ANT (anthropogenic forcings only) and ALL (all historical forcings), of 1850–2005 climate simulations to detect and attribute changes in EVT over the late twentieth century. A long control experiment with external forcings fixed to their pre-industrial values (CTL) is also used to evaluate internal climate variability. Figure 1a (b) compares the 1950–2005 time series of zonal mean annual EVT anomalies averaged over four latitudinal continental domains (northern high latitudes, mid-latitudes, tropics and global land sur-

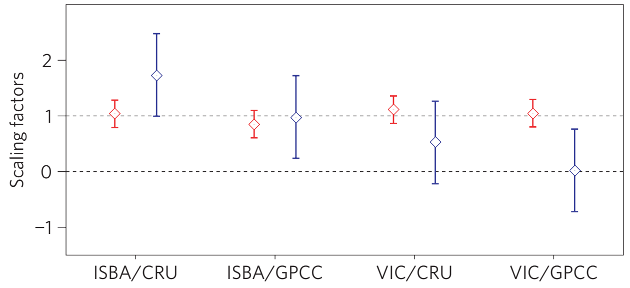

Figure 2 | Scaling-factor best estimates (diamonds) and 95% (2.5–97.5%) confidence intervals as computed from the optimal fingerprint analysis applied to ISBA and VIC pseudo-observed data sets. Two different atmospheric forcings were used (Global Precipitation Climatology Centre and Climate Research Unit), respectively for ANT forcings (red) and NAT forcings (blue). A spatiotemporal optimal fingerprint method is used over the 1951–2005 period (see Methods and Supplementary Information for details).

face except Antarctica) between ALL (NAT) and the offline hydrological simulations. Superimposed on the interannual variability, ALL shows a forced multidecadal evolution that varies from one domain to the other but shares common features with the offline results. In contrast, NAT results are less consistent with the offline reconstructions. It must be noted that the use of three latitudinal belts, although roughly defined, is here very discriminating. In particular, the signal-to-noise ratio corresponding to the long-term trend is improved over each domain compared with the global mean.

To assess the contribution of each external forcing, Fig. 2 shows the results of an optimal fingerprint attribution analysis[19,20] based on ordinary least squares (see Methods and Supplementary Informations S6–S8). The analysis is applied to five consecutive 11-year intervals over three zonally averaged domains (see the three upper panels in Fig. 1c), which allows us to capture some spatiotemporal information while ensuring a tractable dimension for the statistical procedure. This method is based on the estimation of so-called scaling factors, which are the amplitude coefficients that should be applied onto the simulated response to the radiative forcings to best fit the pseudo-observations. According to this linear model, the latitudinal and decadal differentiation of recent EVT variations cannot be understood without invoking the anthropogenic forcing (greenhouse gases and sulphate aerosols). Indeed, the hypothesis that the anthropogenic forcing has no effect on EVT (that is, the hypothesis of a zero scaling factor) is rejected for all EVT reconstructions at the 5% significance level. Moreover, the best estimates of the scaling factors are close to 1, thereby emphasizing that the externally forced variability simulated by CNRM-CM5 is fully consistent with the offline results. In the case of the natural forcing (volcanoes and solar activity), results are sensitive to both model and forcing uncertainties. The hypothesis of a zero scaling factor is rejected (at the 5% significance level) for only two out of four EVT reconstructions. Moreover, the signal-to-noise ratio is lower, which results in larger confidence intervals on the scaling factor. As a consequence, the detection of the natural influence remains unclear.

The main potential confounding factors[18] here are the use of EVT pseudo-observations instead of direct observations on the one hand and the lack of potentially significant forcings (direct CO_2 forcing on plants' EVT and land-use change) on the other hand. The first limitation has already been discussed. The use of constant vegetation distribution and biophysical properties (that is, no CO_2 impact on stomatal conductance and leaf-area index) is here fully consistent between the offline and coupled simulations. Such additional anthropogenic forcings have been considered in former offline studies but have led to contrasted and unreliable conclusions[10,21]. This is another advantage of using EVT reconstructions rather than direct observations that can be influenced by local perturbations (for example, land use or irrigation), which cannot be easily accounted for in global low-resolution climate models. Our results should, at worst, be meant conditionally to the lack of vegetation response to the anthropogenic forcings. Yet, they do show a clear human influence on EVT, irrespective of the use of four different offline reconstructions based on the crossing between two land-surface models and two precipitation forcings.

What should be expected for the long-term evolution of EVT? In line with a previous study[6], the major 1997–1998 El Niño event in the tropical Pacific corresponds to a peak of strong global mean EVT followed by a decade of lower annual mean anomalies in all our EVT reconstructions (Fig. 1). Such a peak should, however, not be interpreted as a tipping point in the multidecadal evolution of global EVT. Because our pseudo-observations are consistent with the ALL ensemble twentieth-century simulations, and because global EVT is increasing throughout the twenty-first century in the CNRM-CM5 projections, our results suggest that the assumed stabilization[6] after 1998 is mainly from internal origin. This would be consistent with the conclusions obtained regarding the apparent stabilization of near-surface air temperature over a similar period[22]. Soil-moisture feedback is, however, strongly model dependent[23] so that it remains unclear whether and when soil-moisture limitation will actually dominate the EVT response and lead to a possible EVT decline at least in the tropics and summer mid-latitudes.

Additional results (not shown) suggest that the late-twentieth-century multidecadal variations are only partly owing to changes in precipitation and that changes in EVT are easier to detect and attribute than changes in precipitation or runoff given their stronger signal-to-noise ratio. A simple explanation is that precipitation and runoff are intermittent and nonlinear processes whereas EVT occurs every day and is a much better time integrator of regional climate change. The analysis of the simulated land-surface radiative budget highlights the major impact of both anthropogenic and volcanic aerosols on downward solar radiation, which dominates the enhanced greenhouse effect and the global evolution of net radiation until the early 1990s. Such results are consistent with the stronger efficiency of shortwave versus longwave radiative forcings as far as the global water cycle is concerned[24]. Nevertheless, the decay of global dimming[8] and the emerging picture of enhanced EVT in the mid-latitudes highlights the possible threat posed by increasing drought frequency to managing water resources and achieving food security in an enhanced-greenhouse-affected climate.

Methods

Offline set-up. ISBA and VIC were driven by two different flavours of the Princeton University hybrid atmospheric forcings developed by merging subdaily data reanalyses with monthly observational and remote sensing data sets (see Supplementary Information S3). Essentially, the reanalysis data are used to downscale the observational data in time and the observational data are used to downscale and correct the reanalysis in space. Before the satellite period, trends in humidity and radiation are adjusted to be consistent with observational data. The final data sets have a resolution of three hours and one degree. Anthropogenic and natural forcings are accounted for only through their direct impacts on downward radiation and their indirect impacts on near-surface temperature and other meteorological variables. No vegetation change and no direct CO_2 impact on EVT (ref. 10) is considered here.

Online set-up. The CNRM-CM5.1 global climate model consists of the Action de Recherche Petite Echelle Grande Echelle-Climat v5.2 atmospheric general circulation model, the Nucleus for European Modelling of the Ocean v3.2 oceanic global climate model, the Global Experimental model of Leads and sea ice for Atmosphere and Ocean v5 sea-ice model, the ISBA-Total Runoff Integrating Pathways land-surface hydrology and the Ocean Atmosphere Sea Ice Soil v3 coupler. The external radiative forcings considered in the CMIP5 historical simulations are the concentration of greenhouse gases and chlorine (simplified ozone chemistry), the optical depth of anthropogenic (that is, sulphate, organic, black carbon) and natural (that is, volcanic) aerosols, as well as solar incident radiation at the top of the atmosphere.

D&A method. Attribution is carried out within a regression model where observations y are decomposed as the sum of scaled model-simulated responses to anthropogenic or natural external forcings G plus internal climate variability ε as $y = G\beta + \varepsilon$. Scaling factors β are unknown and estimated from the observations using an optimal ordinary least-square method[19]. Fingerprints of ANT or NAT forcings are evaluated from the ensemble mean of the corresponding set of simulations. Internal climate variability is evaluated from both forced and unforced simulations from the CNRM-CM5 coupled model (see Supplementary Information).

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Author contributions

H.D. designed the research; B.D., R.A. and J.S. produced the global EVT reconstructions; A.R. contributed the D&A tools and the figures, H.D. and A.R. analysed the data and wrote the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to H.D.

Competing financial interests

The authors declare no competing financial interests.