A regional perspective on trends in continental evaporation

A. J. Teuling,[1] M. Hirschi,[1] A. Ohmura,[1] M. Wild,[1] M. Reichstein,[2] P. Ciais,[3] N. Buchmann,[4] C. Ammann,[5] L. Montagnani,[6] A. D. Richardson,[7] G. Wohlfahrt,[8] and S. I. Seneviratne[1]

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[1] Climate models suggest that enhanced greenhouse gas concentrations and aerosols have major impacts on the land energy and water cycles, and in particular on evapotranspiration (ET). Here we analyze how the main external drivers of ET (incident solar radiation and precipitation) vary regionally, using recent data from a eddy-covariance flux tower network (FLUXNET) and a multi-model re-analysis (GSWP-2). Trends in radiation (global "dimming" and "brightening") are expected to impact ET only in regions where ET correlates with radiation. In central Europe this correlation is particularly strong, and trends derived from weighing lysimeters and river-basin water budgets follow trends in radiation. In central North America the correlation is weak, and trends in precipitation rather than radiation explain trends in ET. Our results reconcile previous hypotheses by demonstrating the strongly regional and temporal differentiation of trends in evaporation. **Citation:** Teuling, A. J., et al. (2009), A regional perspective on trends in continental evaporation, *Geophys. Res. Lett.*, *36*, L02404, doi:10.1029/2008GL036584.

1. Introduction

[2] Evaporation over land (evapotranspiration, hereafter ET) is a key component of the climate system as it links the hydrological, energy and carbon cycles. It amounts to as much as 60% of the total precipitation falling on land. The energy associated with latent heat flux (ET multiplied by the latent heat of vaporization) can play a central role in impeding or fostering the occurrence of heatwaves [*Seneviratne et al.*, 2006]. Furthermore, transpiration (the main contributor to total land evapotranspiration) is directly linked with CO_2 assimilation. Potential changes in ET have been studied intensively since the mid 1990s. However these studies relied on indirect evidence such as observations of pan evaporation [e.g., *Roderick and Farquhar*, 2002], runoff [e.g., *Gedney et al.*, 2006], soil moisture [e.g., *Robock and Li*, 2006], or precipitation [e.g., *Lawrimore and Peterson*, 2000].

[1] Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland.
[2] Max-Planck Institute for Biogeochemistry, Jena, Germany.
[3] Laboratoire des Sciences du Climat et de l'Environnement, LSCE, Gif-sur-Yvette, France.
[4] Institute of Plant Sciences, ETH Zurich, Zurich, Switzerland.
[5] Agroscope ART, Zurich, Switzerland.
[6] Forest Services and Agency for the Environment, Bolzano, Italy.
[7] Complex Systems Research Center, University of New Hampshire, Durham, New Hampshire, USA.
[8] Institute of Ecology, University of Innsbruck, Innsbruck, Austria.

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[3] The lack of direct observations has led to several conflicting hypotheses concerning the drivers and even the sign of the trends. The main issues concerned the interpretation of trends in pan evaporation in terms of their relation to actual evapotranspiration [e.g., *Brutsaert and Parlange*, 1998; *Roderick and Farquhar*, 2002; *Brutsaert*, 2006], the interpretation of scattered runoff observations in terms of global (runoff and) evapotranspiration trends [*Gedney et al.*, 2006; *Piao et al.*, 2007], and model-dependent aspects [*Gedney et al.*, 2006; *Hobbins et al.*, 2008]. In particular, it has been recently argued that current hydrological data are insufficient to derive global trends in evapotranspiration [e.g., *Peel and McMahon*, 2006].

[4] Here, instead, we identify drivers of actual evapotranspiration rates on the regional scale from a multi-model re-analysis of land surface conditions and an extensive flux tower network, and hypothesize that regional trends in ET are most likely induced by trends in the limiting driver. This approach relaxes the need for long-term records of ET. We focus on global radiation (hereafter Rg, the sum of diffuse and direct solar radiation incident at the Earth surface) and moisture availability as main external drivers of ET [see *Teuling et al.*, 2006; *Wei et al.*, 2008; *Hobbins et al.*, 2008], and in particular on the possible impact of tropospheric air pollution-induced "dimming" and "brightening" trends [e.g., *Wild et al.*, 2005].

2. Methods

[5] Simulations of land surface conditions originate from the Global Soil Wetness Project (GSWP-2). The multi-model product (resolution 1°) represents the average of more than a dozen land surface models, and is generally superior to any of the individual models [*Dirmeyer et al.*, 2006]. All models were driven by the same atmospheric conditions and had standardized soil and vegetation distributions. Concomitant observations of ET and Rg come from the new FLUXNET synthesis dataset (www.fluxdata.org). It provides direct and continuous eddy covariance flux measurements of ET and Rg for over 170 sites across different climate and vegetation zones [*Baldocchi et al.*, 2001]. Most observations started after the year 2000. The analysis was limited to rain-free days in the months May–September with less than 20% gapfilling.

[6] Long-term observations of Rg were taken from a new version of the Global Energy Balance Archive (GEBA) [Gilgen et al. 1998]. Runoff data were either taken from the Global Runoff Data Centre, from the U.S. Geological Survey (USGS), or from local sources. Gridded precipitation comes from the Full Data Product of the Global Precipitation Climatology Centre and catchment masks are derived from the USGS HYDRO1k topography. To account

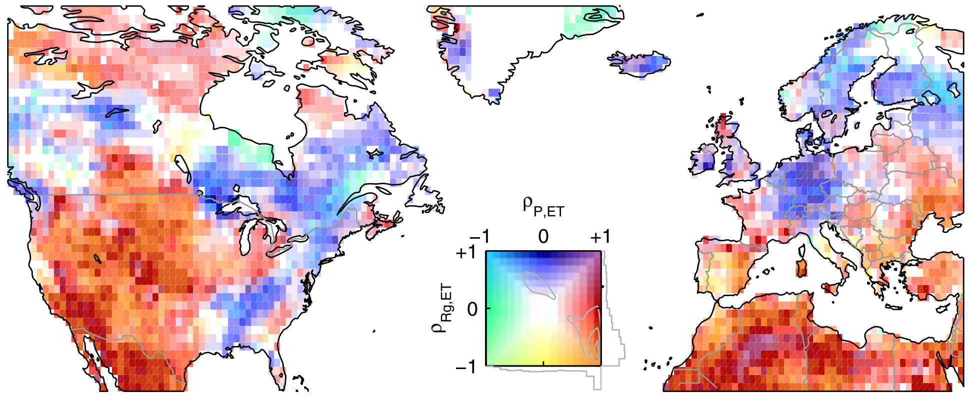

Figure 1. Multi-model analysis of controls on yearly evapotranspiration. Correlation between yearly evapotranspiration and global radiation ($\rho_{Rg,ET}$), respectively precipitation ($\rho_{P,ET}$), for the period 1986–1995. Each color corresponds to a unique combination of $\rho_{Rg,ET}$ and $\rho_{P,ET}$. The grey lines (legend) show the global frequency distribution.

for the effect of interannual storage changes, a 5-year moving average window was applied. Trends were only calculated for 10 or more years of data. Lysimeter observations come from Rietholzbach in Switzerland (www.iac.ethz.ch/groups/seneviratne/research/rietholzbach, in operation since 1976), and Rheindahlen in Germany (www.niederrheinwasser.de, since 1982).

[7] We limit our analysis to Europe and North America, where most datasets show the highest station density. Linear correlation (evaluated at different timescales) is used to express the strength of the relation between ET and its drivers. While correlation does not imply causality, radiation and soil moisture availability have been consistently put forth as two main drivers of ET at the scales considered here.

3. Results

[8] In Figure 1 we display the correlation of ET with incident solar (global) radiation (Rg), respectively precipitation (P), on the yearly timescale in the GSWP-2 reanalysis. Annual P is used as a surrogate for soil moisture availability. Most of the correlations in Figure 1 are high, and the resulting spatial pattern is distinct. The bimodal spatial frequency distribution (legend) reveals the existence of two dominant regimes: a humid regime characterized by high correlation with radiation ($\rho_{Rg,ET}$) but low correlation with precipitation ($\rho_{P,ET}$) (dark blue tones), and a more arid regime characterized by high $\rho_{P,ET}$ but low $\rho_{Rg,ET}$ (red tones). Since Rg and P tend to be negatively correlated (Figure S1), yearly variations in ET either reflect variations in Rg or P, but not in both.[1] Central Europe is among the regions with the highest $\rho_{Rg,ET}$, while in more arid regions such as the U.S. Midwest and the Sahara, ET is correlates only with precipitation.

[9] We validate the model-based results in Figure 1 with observations from FLUXNET. Due to the limited length of the records, we calculate $\rho_{Rg,ET}$ on a daily rather than yearly timescale. To minimize the impact of seasonality on $\rho_{Rg,ET}$, only the warm season (May–September) is considered. In spite of the different timescale and local variations in land conditions at the scale of the flux footprint, a pattern similar to that in Figure 1 emerges in Figure 2. In Europe, a clear north–south gradient exists, with a near-perfect linear correlation $\rho_{Rg,ET}$ in central Europe and Scandinavia (indicating fully energy-limited ET) which decreases toward the Mediterranean. A similar gradient can be seen across North America, with high $\rho_{Rg,ET}$ in the more humid north(east)ern regions, and very low $\rho_{Rg,ET}$ in the U.S. Southwest. Regions of lower observed $\rho_{Rg,ET}$ in Figure 2 also correspond to regions where the models predict higher $\rho_{P,ET}$ (Figure 1).

[10] Next, we focus on long-term changes in global radiation during the dimming and brightening phases (Figures 3a and 3b and Tables S1 and S2). Most GEBA stations show a strong negative trend in Rg during the period 1958–1982 (Figure 3a). Although the exact transition from dimming to brightening is uncertain and differs regionally, upward trends were already present in the early 1990s [*Wild et al.*, 2005]. The positive Rg trend during the period 1983–2006 (Figure 3b) is most pronounced in industrialized regions such as central Europe and less in regions with considerable inflow of maritime air (e.g., Scandinavia, Iceland). By overlaying Figures 1 and 2 with Figures 3a and 3b, central Europe can be identified as a hot spot for radiation impacts on ET. Not only is ET extremely sensitive to changes in radiation, but changes in radiation are also among the highest.

[11] One alternative to direct observations of ET is to derive estimates at the river-basin scale. By assuming that long-term trends in storage are negligible, trends in ET can be derived from the difference in precipitation (P) and runoff (Q). Both have been measured accurately over continental midlatitude regions considered here. The trends in ET_{P-Q} (Figures 3c and 3d) match well the results inferred from Figures 1 and 2. Over central Europe, most basins show a negative trend in ET_{P-Q} during the global dimming phase. During that period, the positive trend in Q is induced by reduced ET rather than increased P. After 1983, ET_{P-Q} increased in all central European basins (brightening phase), even though trends in P and Q may have differed in sign for individual basins. Thus these results suggest that ET trends follow radiation trends in central Europe. In contrast, in the U.S. Midwest upward trends in ET_{P-Q} before 1983 are

[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL036584.

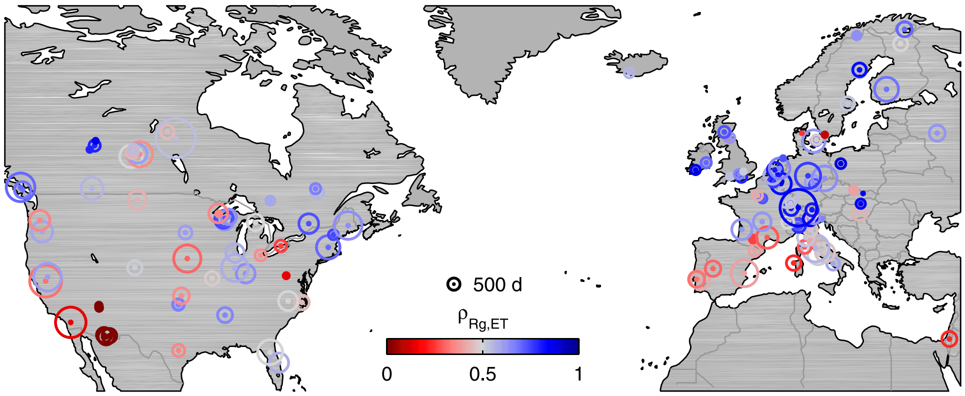

Figure 2. Observed radiative control on daily evapotranspiration. Colors indicate the magnitude of the correlation $\rho_{Rg,ET}$ between evaporation and global radiation (May–September) at eddy-covariance flux stations and the Rietholzbach lysimeter. Clusters of stations are grouped and the circle area is proportional to the number of days used. Since the impact of water availability on ET is a slow process (*Teuling et al.*, 2006), the removal of rain days has little impact on $\rho_{Rg,ET}$.

followed by decreasing trends. These may be explained by trends in P (Figures 3e and 3f) combined with high $\rho_{P,ET}$ and low $\rho_{Rg,ET}$ values as inferred from Figures 1 and 2. Here, trends in P are reflected in $ET_{P\text{-}Q}$ rather than Q. Contrastingly, changes in P impact Q rather than $ET_{P\text{-}Q}$ in the high-latitude Mackenzie basin. In the Lower Mississippi basin, a continuous increase in P has caused $ET_{P\text{-}Q}$ to increase from the late 1950s [see also *Milly and Dunne*, 2001].

[12] Weighing lysimeters accurately measure actual evapotranspiration, but only few stations have been in operation long enough to derive meaningful trends. In central Europe, two such stations are Rietholzbach and Mönchengladbach. Measurements from these two stations together with long-term $ET_{P\text{-}Q}$ of four river basins in the same region (Rhine, Weser, Elbe, and Danube upstream of Linz) are displayed in Figure 4. The long-term global radiation observations at Potsdam/Lindenberg and Zurich illustrate the strong dimming and subsequent brightening in the region. The minimum in yearly radiation is slightly different for the two sites but occurs during the early 1980s.

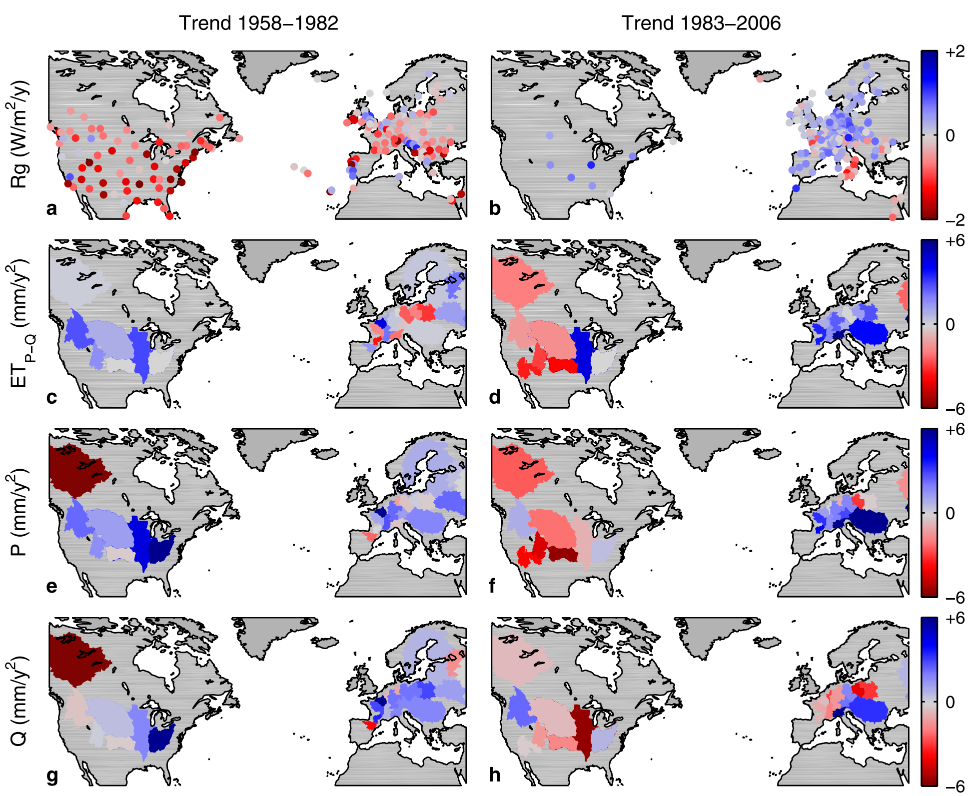

Figure 3. Trends during the global dimming (1958–1982, left) and brightening (1983–2006, right) phases. (a and b) Global radiation Rg, (c and d) evapotranspiration $ET_{P\text{-}Q}$, (e and f) precipitation P, and (g and h) runoff Q. Note the number of U.S. stations with long records strongly decreased during the 1980s (Figure 3b).

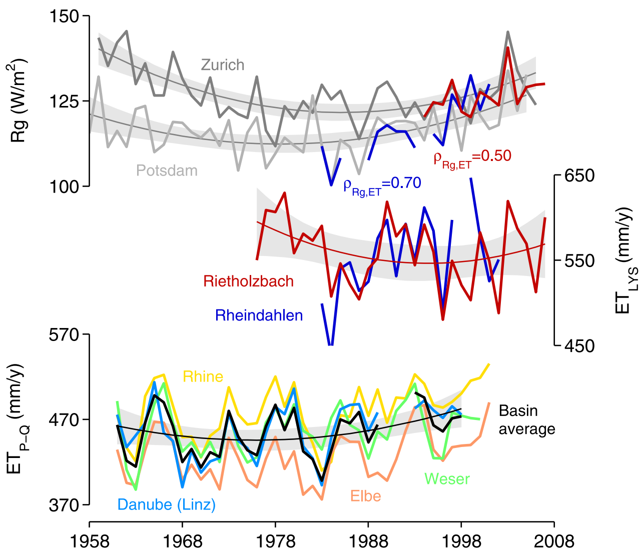

Figure 4. Trends in global radiation and evapotranspiration over central Europe. Solid curves are 2nd order polynomial fits, and the grey areas represent the corresponding 95% confidence intervals. Red lines and $\rho_{Rg,ET}$ are for Rietholzbach, blue for Rheindahlen. Note that values of $\rho_{Rg,ET}$ are lower than their model counterparts in Figure 1 due to measurement error and gap filling.

A net increase due to brightening is to be expected in lysimeter evapotranspiration ET_{LYS}. The observations seem to confirm this, with a strong convex tendency ($p = 0.94$) in ET_{LYS} at Rietholzbach. Although the scatter is large, the correlation $\rho_{Rg,ET}$ for the sites in Figure 4 combined with the strong brightening signal provides extra confidence. The convex tendency in the 2nd order polynomial fit of $ET_{P\text{-}Q}$ mirrors the trends in Rg and is significant at the 95% level, and moreover the relative variations in $ET_{P\text{-}Q}$ and Rg are physically consistent (magnitude 5–10%).

4. Discussion and Conclusions

[13] A consistent picture of trends in evaporation and runoff emerges only when the regional distribution of the sensitivity of evaporation to its main drivers is considered. This also provides additional insight into pan evaporation trends. The inclusion of the regional dimension of evapotranspiration drivers (Figure 1) allows both scenarios of decreasing actual evapotranspiration with decreasing pan evaporation in regions with ample supply of water (e.g., central Europe) [*Roderick and Farquhar*, 2002] and of increasing evapotranspiration with decreasing pan evaporation (e.g., the U.S. Midwest) [*Brutsaert and Parlange*, 1998] to be encompassed. Note that the latter scenario may also occur independently of atmospheric moisture feedbacks and can be induced by precipitation trends only.

[14] In conclusion, we identify that the trends in actual evapotranspiration (and hence runoff) can only be understood regionally (and temporally), by considering regional (and temporal) variations in the main drivers of evapotranspiration [*Roderick and Farquhar*, 2004]. While also other factors are expected to impact evapotranspiration trends (e.g., nutrient availability, CO_2 concentrations, water and land use changes [see, e.g., *Zhang et al.*, 2001]), our results suggest they only play a secondary role. Finally, drivers of evapotranspiration are dynamic, and can change from intra-annual [*Ryu et al.*, 2008] to decadal time scales, for instance due to projected shifts in climate regimes [*Seneviratne et al.*, 2006]. Our findings highlight that many of the previously proposed (and seemingly contradictory) hypotheses on trends may be important in different regions, and are thus complementary to one another. A regional perspective can also lead to an improved representation of evapotranspiration in climate models.

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C. Ammann, Agroscope ART, Reckenholzstrasse 191, Zurich CH-8046, Switzerland.

N. Buchmann, Institute of Plant Sciences, ETH Zurich, Universitätstrasse 2, Zurich CH-8092, Switzerland.

P. Ciais, Laboratoire des Sciences du Climat et de l'Environnement, LSCE CEA-CNRS-UVSQ, Orme des Mersisiers, Gif-sur-Yvette F-91191, France.

M. Hirschi, A. Ohmura, S. I. Seneviratne, A. J. Teuling, and M. Wild, Institute for Atmospheric and Climate Science, ETH Zurich, CHN N 16.2, Universitätstrasse 16, Zürich CH-8092, Switzerland. (sonia.seneviratne@env.ethz.ch; ryan.teuling@env.ethz.ch)

L. Montagnani, Forest Services and Agency for the Environment, Via Brennero 6, Bolzano I-39100, Italy.

M. Reichstein, Biogeochemical Model-Data Integration Group, Max-Planck-Institute for Biogeochemistry, PF 100164, Jena D-07745, Germany.

A. D. Richardson, Complex Systems Research Center, University of New Hampshire, Morse Hall 8 College Road, Durham, NH 03824, USA.

G. Wohlfahrt, Institute of Ecology, University of Innsbruck, Sternwartestrasse 15, Innsbruck A-6020, Austria.