Recent Trends in Land Surface Evapotranspiration across the Contiguous United States

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Abstract: Terrestrial evapotranspiration (ET) for water years of 1980-2014 has been estimated by three independent methods [North American Regional Reanalysis (NARR) latent heat data, Advection-Aridity (AA), and a water balance model] for 18 regions with two-digit Hydrologic Unit Code (HUC2) values, covering the conterminous United States. The common feature of the watersheds (with three exceptions) is that ET, together with vapor pressure (VP), followed an overall, but not monotonic, declining trend with a peak around 2000 in most cases. The largest drop after the turn of the century took place in the Central-US catchments draining to the Gulf of Mexico. In the New England, North Atlantic and Great Lakes regions the models gave conflicting results but VP has increased significantly, so it is suspected that ET rates did so as well. In water-limited regions (17 of the 18) annual ET displayed the strongest association with precipitation (P) having an estimation method averaged linear correlation (r) value of $\langle r \rangle = 0.64$, followed by vapor pressure ($\langle r \rangle = 0.6$), and its deficit ($\langle r \rangle = -0.59$). In the only energy-limited region of New England, the highest ET correlations were found with net surface radiation but are weaker than the previous ones.

Keywords: *Complementary relationship, Advection-Aridity model, reanalysis*

1. Introduction

In the second half of the 20th century terrestrial pan evaporation rates displayed an overall decreasing trend globally (Peterson et al. 1995). With the help of the complementary relationship (CR) of evaporation (Bouchet 1963), Brutsaert and Parlange (1998) explained that the observed decreasing evaporative demand trends were indicators of actual increasing land ET rates in water-limited environments. A surge of studies afterwards reported increasing ET rates (Walter et al 2004; Huntington 2006; Qian et al 2007; Wild et al. 2008; Wang et al 2010; Liu et al 2013a,b; Huntington and Billmire 2014; Sharma and Walter 2014; Kramer et al 2015) in accordance with observed increases of global precipitation rates (Gu et al 2015). However, as Teuling et al (2009) point out, regional variations of terrestrial ET and their drivers are significant, having strong influence on the resulting ET trends. For example, Szilagyi (2001), with the help of data from 210 Solar and Meteorological Surface Observation Network (SAMSON) stations across the contiguous US, found a statistically significant ET increase only in the Eastern US for 1960-1990. Recently, ET increases (as well as decreases in fewer numbers) were reported by Jung et al (2013) for 255 minimally disturbed small watersheds across the contiguous US for the 1951-2010 period, using a simplified water balance approach and a linear trend function.

Quite surprisingly though, Jung et al (2010) discovered a global reversing trend in land ET rates starting in 1998 and conjectured that limited moisture supply may be putting the break on actual ET rates. Their findings about a reversing global land ET trend were corroborated by Zeng et al (2014) who also found depleted soil moisture as the most likely cause of the decline. On the other hand McVicar et al (2012) and Vautard

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et al (2010) report an ongoing atmospheric stilling phenomenon which manifests itself in decreased surface wind velocities over land. They attribute it, at least partly, to increased surface roughness, thus possibly reducing land ET rates especially in the 1980-1990 period which coincides with radiation dimming, followed by re-brightening after the 1990s (Wild 2009). The effect of wind stilling may, in theory, be further enhanced by decreasing leaf conductance (Field et al 1995) of the more abundant vegetation due to elevated CO_2 levels. However, potentially depressed vapor pressure deficits (VPD), as a result of increased ET rates, could lead to an opposite effect in leaf conductance (Wang et al 2009), further boosting transpiration rates, thus counteracting the effect of dimming and stilling. Although some decrease in VPD has indeed been reported for 1960-1990 over the conterminous US by Szilagyi et al (2001) but not a statistically significant one. Fyfe et al (2013), on the other hand, argued that the cause of the observed global land ET decline is more likely the increasing levels of stratospheric aerosols after the Mount Pinatubo eruption in 1992. These alternative explanations are important because then soil moisture may not present a 'permanent "braking effect" on the terrestrial hydrological cycle' (Zeng et al 2014).

The objective of this study is to examine ET trends across the contiguous United States over the past 35 years, i.e. 1980-2014; check if a reversing trend in ET rates is indeed discernible after 1998, and; test which possible atmospheric or hydrologic driver displays the strongest association with the annual ET estimates.

2. ET estimation methods

ET trends for water years of the 1980-2014 period were investigated across the lower 48 states of the US with data from the NARR (Mesinger et al 2006) and the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) (Daly et al 1994) in combination with United States Geological Survey (USGS) hydrologic unit averaged runoff values (source: waterwatch.usgs.gov). ET rates are estimated in three independent ways: a) on a monthly basis by the NARR-published latent heat fluxes (E_{NARR}); b) by the CR-based AA model (E_{AA}) (Brutsaert and Stricker 1979); and c) on a water-year basis (E_{wb}) by a simplified water balance approach of taking the difference in precipitation (P) and two-digit hydrologic unit code (HUC2) runoff rates (Q). Description of the NARR-model ET calculations can be found in NCEP (2005). The AA-model estimates ET as

$$E_{AA} = (2\alpha - 1)\frac{\Delta(T_a)}{\Delta(T_a) + \gamma} R_n - \frac{\gamma}{\Delta(T_a) + \gamma} f_u VPD \tag{1}$$

Here α is the dimensionless Priestley-Taylor parameter, R_n is net radiation at the surface, specified in water depth per unit time (i.e., mm d^{-1}), Δ is the slope of the saturation vapor pressure curve at the air temperature (T_a), γ [= $c_p p$ / $(0.622L)$] is the psychrometric constant, where c_p is the specific heat of air at constant pressure (p) and L is latent heat of vaporization for water. VPD is the vapor pressure (VP) deficit (i.e., saturated minus actual) in hPa, and f_u is the so-called Rome wind function, traditionally expressed (Brutsaert 1982) as $f_u = 0.26(1 + 0.54u_2)$, where u_2 is the wind speed (in meters per second) at 2 m above the ground.

The coefficient α (> 1) in equation 1 is generally accepted to express the evaporation-enhancing effect of large-scale entrainment of drier free-tropospheric air resulting from the growing daytime convective boundary layer (Brutsaert 1982; deBruin 1983; Culf 1994; Lhomme 1997; Heerwaarden et al 2009). In this study an α value of 1.06 was calibrated with the help of 0.25-degree resampled (in order to get a regular grid) NARR data via the following objectives: the number of cells with a) $\overline{ET} = 0$ be zero; b) $\overline{ET} > \bar{P}$ be minimal. The overbar denotes the mean annual value for the study period. The third objective to be met was to keep the spatial average of the resulting $\overline{ET}$ values close to the spatial average of $\bar{P} - \bar{Q}$, i.e., within 540 ± 20 mm yr^{-1}. Precipitation was obtained from the PRISM values, considered to be the most accurate such data set (Daly et al 2008), yielding a US-averaged mean annual precipitation rate of 791 mm, which is 75 mm larger than that of NARR.

The monthly values of the ET estimates (together with the associative variables: R_n, P, Q, T_a, VP, VPD, u_2) were temporally aggregated for water years and spatially averaged over the 18 HUC2 regions (Figure 1). Finally, third-order polynomials rather than typical first order ones were fit over the annual values due to the expected change in trends around 1998-2000. Overall monotonic trends for the whole period were also tested by a nonparametric approach (Hamed and Rao 1998).

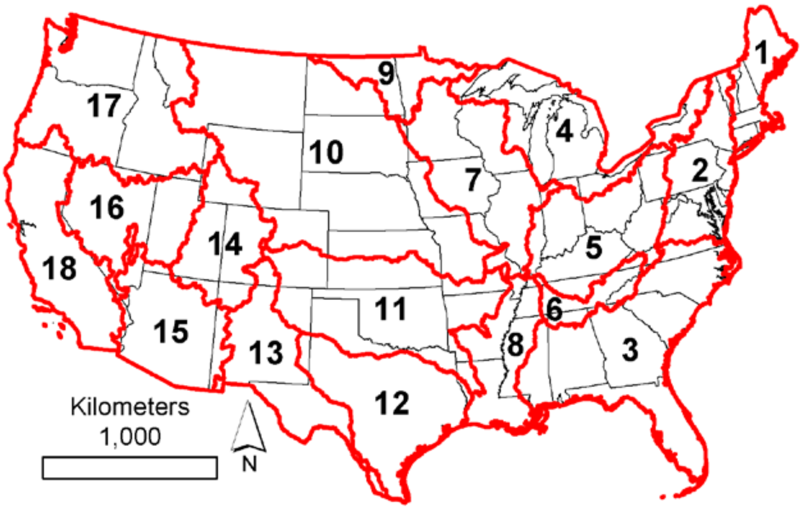


Figure 1 Distribution of the HUC2 regions (separated by red lines) across the contiguous US.

3. Results and discussion

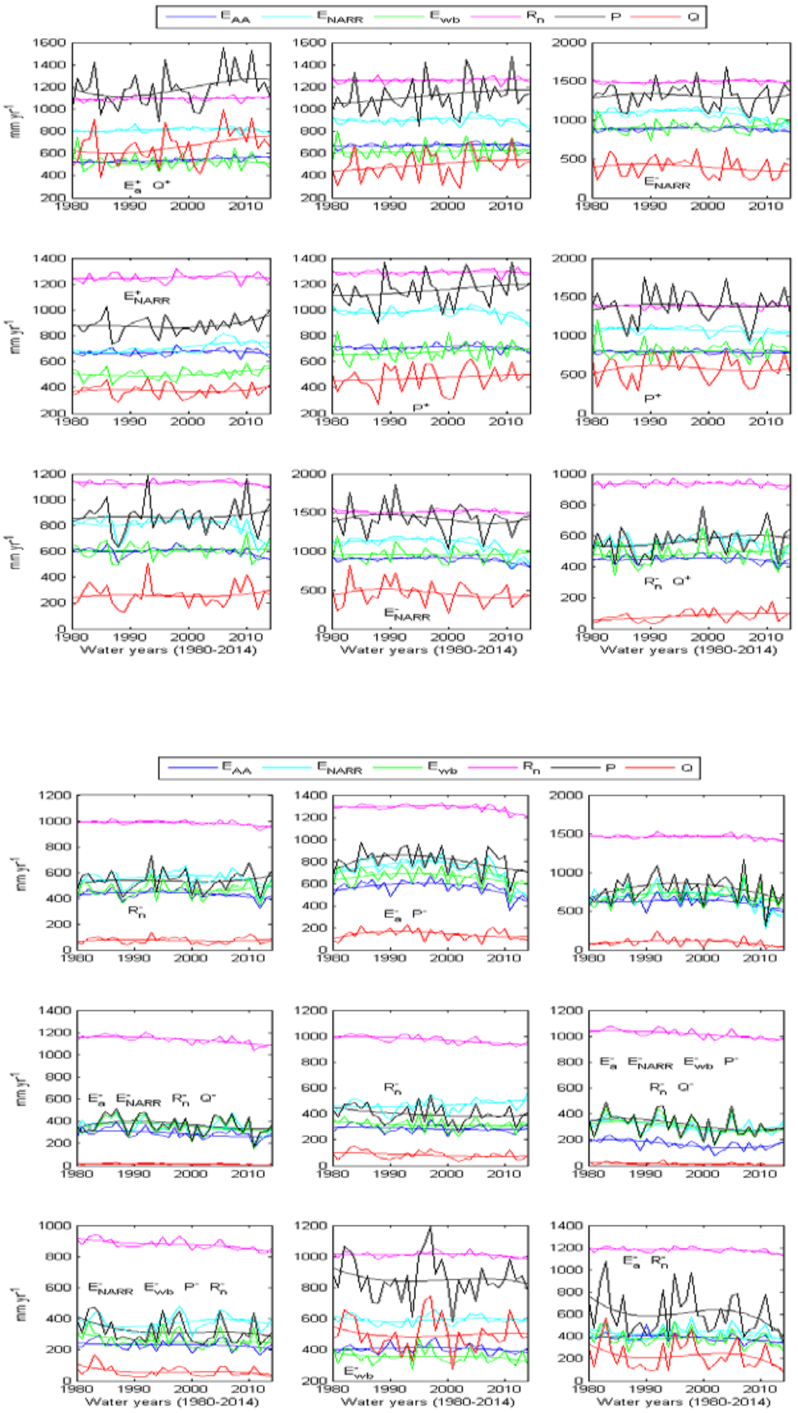
In 15 regions out of the 18, covering the conterminous US, ET rates have declined, although not always monotonically, over the 1980-2014 study period (Figure 2). ET has increased only in the north-eastern corner (HUC2 codes of 1, 2, and 4) of the US. In cases where trends of the three ET estimates were in conflict (in altogether 8 regions, with the largest discrepancy of a 220 mm decline by NARR vs a 130 mm water-balance derived increase over the 35-year study period), the trend in VP was decisive (Figure 3), since changes in VP (as effect) must reflect changes in ET rates (as cause). In these three north-eastern regions annual ET generally expressed the strongest, but still a relatively weak, association with R_n (HUC2- and estimation-method-averaged r, $<r> = 0.36$) beside VP ($<r> = 0.47$) (Figure 4). From the seven associative variables probably only R_n can be considered as a true driver of ET, and even that only in HUC2# 1. This is so because this region is being closest to an energy-limited environment by having precipitation rates in excess of R_n (expressed in water depth equivalent). The remaining six variables are all influenced, although in varying degree, by the resulting ET rate, thus mixing possible cause and effect and so driver and drivee. For example, Ozdogan et al (2006) found that increases in regional ET rates influence even the wind patterns.

Among the 15 regions of declining ET rates, many display local maxima (supported by the VP trends) around the millennium before a turn downward, while the rest (HUC2# 13-16) express an almost monotonic decrease (Figure 2). Interestingly, the turnaround in ET tendencies takes place during the so-called global brightening period, starting in the 1990s, under a concurrently declining R_n, somewhat contrary to expectations. Note that the simplified water-balance derived ET trend may contradict the other two ET trends (and that of the VP values) for several years due to possible inter-annual changes in soil moisture and groundwater storage.

In water-limited environments (all regions except HUC2# 1) annual ET typically has the strongest association (Figure 3) with P ($<r> = 0.64$), VP ($<r> = 0.6$), VPD ($<r> = -0.59$), and Q ($<r> = 0.49$) in that order. In the only energy-limited region (HUC2# 1), the highest estimation method averaged ET correlations are found with R_n ($r = 0.5$), VP ($r = 0.49$), and T_a ($r = 0.43$).

In spite of the predominantly decreasing ET trends, the Mann-Kendall nonparametric test detects a statistically significant monotonic trend (at a 5% level) in only ten regions among the modeled ET time series (Figure 2). This happens because of the typical non-monotonic nature of the declines.

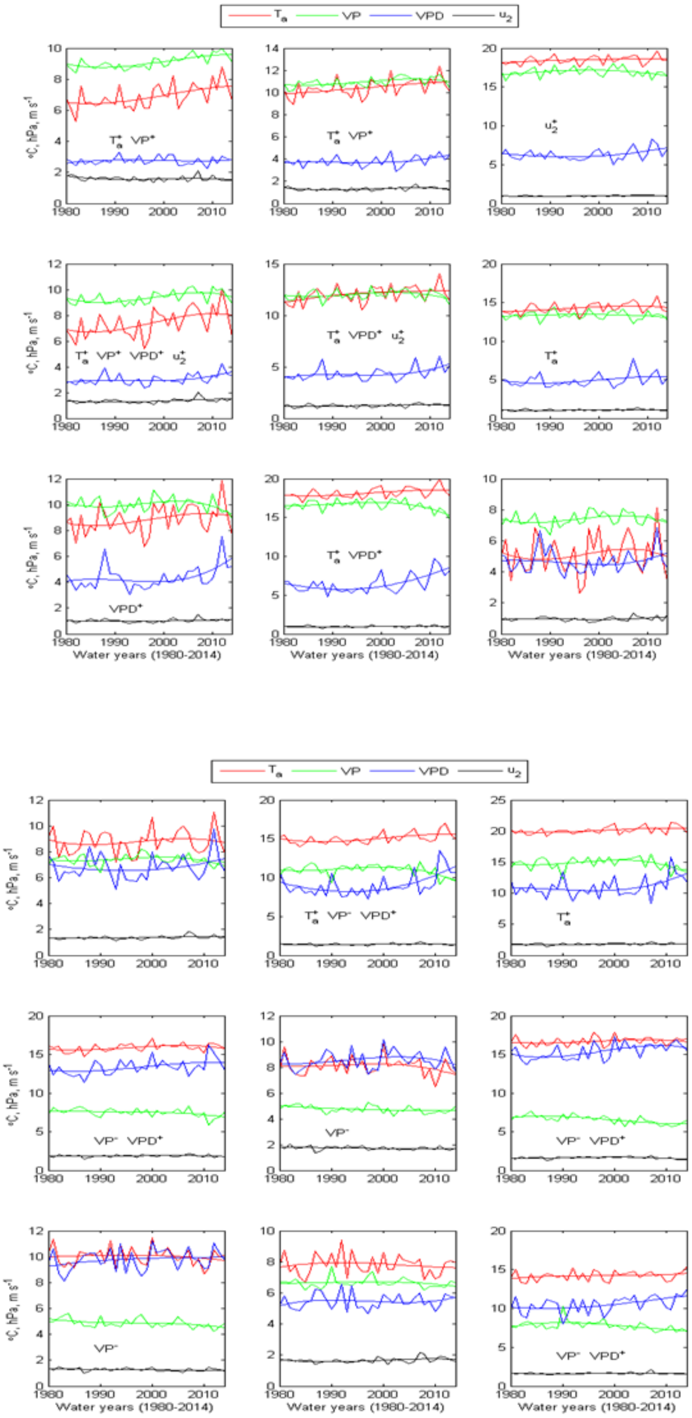
The western part of the US (HUC2# 13-18, i.e., the bottom two rows of Fig 2b) displays the strongest ET declines overall, with statistically significant ET and VP (also in R_n) trends in five of the six regions. In the most arid watersheds (Rio Grande, Colorado and the Great Basin) of the south-west, ET rates declined almost monotonically. The simultaneous precipitation trends are significant only in two regions, mainly due to their higher inter-annual variability. The contrasting observed trends in the moist north-east and the dry south-west seem to follow the coupled land-ocean General Circulation Model predictions of Held and Soden (2006) who concluded that 'wet regions get wetter and dry regions drier' which does not bode well about the future for those tens of millions living in such dry areas of the United States.



(a)

(b)

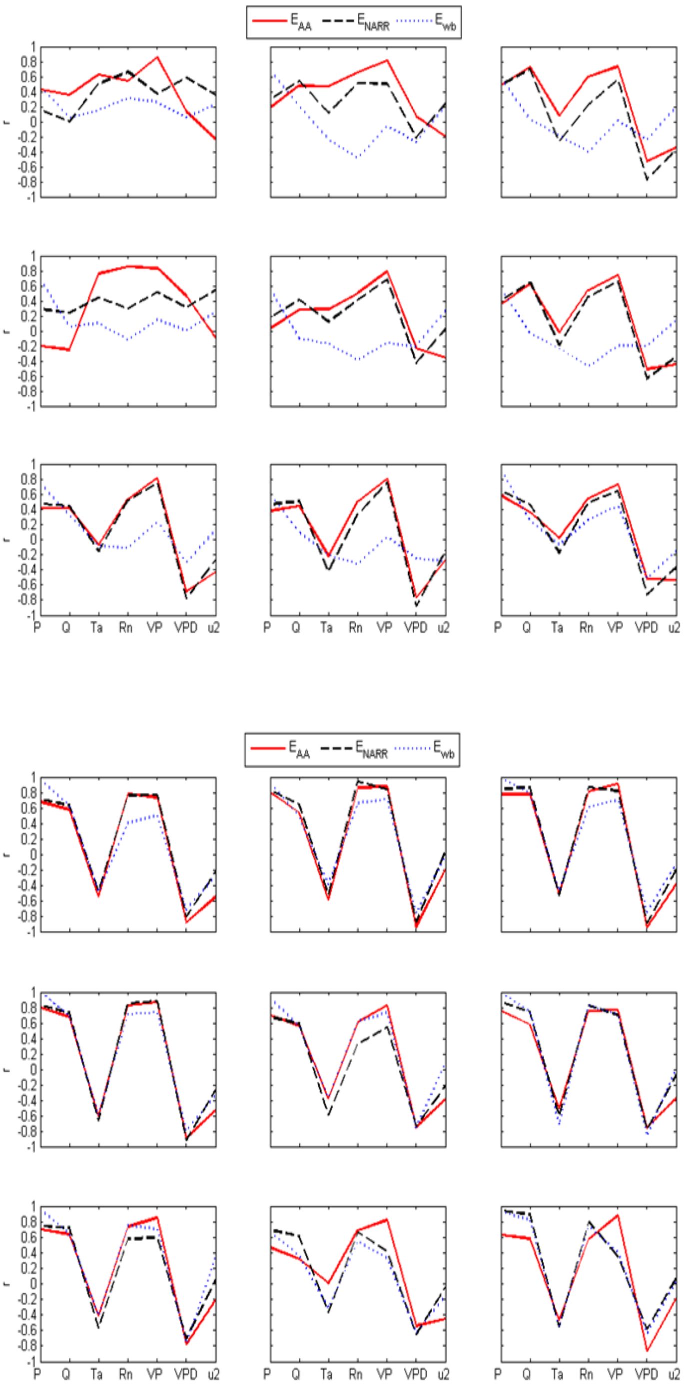
Figure 2 HUC2-averaged annual values of the ET estimates and their third-order best-fit polynomials for the 1980-2014 water years. The variable with a positive/negative superscript denotes a monotonic trend at a 5% significance level of the Mann-Kendall nonparametric test. HUC2 regions are row-continuous, i.e., the first row contains results for HUC2 regions 1 through 3 in Figure 2a and 10 through 12 in Figure 2b.



(a)

(b)

Figure 3 HUC2-averaged annual values of the associative variables and their third-order best-fit polynomials for the 1980-2014 water years. The variable with a positive/negative superscript denotes a monotonic trend at a 5% significance level of the Mann-Kendall nonparametric test. HUC2 regions are row-continuous, i.e., the first row contains results for HUC2 regions 1 through 3 in Figure 3a and 10 through 12 in Figure 3b.



(a)

(b)

Figure 4 Linear correlation coefficient (*r*) values of the HUC2-averaged annual ET estimates and the relevant associative variables. HUC2 regions are row-continuous, i.e., the first row contains results for HUC2 regions 1 through 3 in Figure 4a and 10 through 12 in Figure 4b.

4. Conclusion

It was found that from 1980 to 2014 ET followed a declining trend in 15 of the 18 regions across the contiguous US. Most of these declining trends were not monotonic; ET rates have peaked around the turn of the century followed by a strong downward trend conforming to a globally observed land ET trend reversal. Such a reversal was weak enough in the north-eastern part of the US, containing the only energy-limited region of New England, to produce a trend reversal, so there ET rates continued to increase in the study period. In the majority of the catchments the current findings are in accordance with earlier reported generally increasing land ET trends up until around 2000 when the global trend indeed reversed.

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