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# Potential evaporation trends over land between 1983–2008: driven by radiative or turbulent fluxes?

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## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

We model the Penman potential evaporation (PE) over all land areas of the globe for the 25-year period 1983–2008, relying on radiation transfer models (RTMs) for the shortwave and longwave fluxes. Penman's PE is determined by two factors: available energy for evaporation and ground to atmosphere vapour transfer. Input to the PE model and RTMs comprises satellite cloud and aerosol data, as well as data from reanalyses. PE is closely linked to pan evaporation, whose trends have sparked controversy in the community, since the factors responsible for the observed pan evaporation trends are not determined with consensus. Our particular interest is the temporal evolution of PE, and the provided insight to the observed trends of pan evaporation. We examine the interannual trends of PE and various related physical quantities, such as net solar flux, net longwave flux, water vapour saturation deficit and wind speed. Our findings are the following: Global warming has led to a larger water vapour saturation deficit. Global dimming/brightening cycles in the last 25 years slightly increased the available energy for evaporation. PE trends seem to follow closely the trends of energy availability and not the trends of the atmospheric capability for vapour transfer, almost everywhere on the globe, with trends in the Northern hemisphere significantly larger than in the Southern. These results support the hypothesis that secular changes in the radiation fluxes, and not vapour transfer considerations, are responsible for potential evaporation trends.

## 1 Introduction

There have been many reports on significant changes in pan evaporation for widespread locations across the globe, e.g. European Russia, Siberia, and the USA (Peterson et al., 1995; Golubev et al., 2001), India (Chattopadhyay and Hulme, 1997), the USA (Lawrimore and Peterson, 2000), Israel (Cohen et al., 2002), China (Liu et al., 2004), Australia (Roderick and Farquhar, 2004), the Tibetan plateau (Zhang et al.,

## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2007), and many others (references in Roderick et al. (2007) and Fu et al. (2009)). However, a study for Australia (Jovanovic et al., 2008) cast some doubt on the veracity of the Australian trends. It reported that unaccounted discontinuities (e.g. the installation of bird meshes) produced a spurious declining trend, which disappears if the time series are homogenised. There is a need for similar studies in other regions, but until they are carried out, the emerging general picture is one of worldwide decreasing pan evaporation, with some exceptions, e.g. east USA, a single pan in Israel, central Australia, etc. However, Global Circulation Model (GCM) runs on the one hand (Wetherald and Manabe, 2002), and reanalyses (Trenberth et al., 2005) and empirical hydrological evidence (Huntington, 2006) on the other, dictate that in a warming world the hydrological cycle should be enhanced and evaporation should increase.

This disagreement between the trends of actual evaporation and pan evaporation was termed the “evaporation paradox” and was initially addressed when Brutsaert and Parlange (1998) brought forward the complementary hypothesis, already proposed by Bouchet (1963) and applied by Morton (1975). It consists of the following reasoning: in humid environments, with ample supply of moisture to the surface, the actual evaporation takes values close to the potential evaporation. Also, the pan evaporation corresponds directly to the potential evaporation, after multiplication with the pan coefficient. However, in arid environments actual evaporation cannot reach the values of potential evaporation, and therefore a larger portion of the available energy takes the form of sensible heat flux, thus warming the atmosphere. The warmer atmosphere now is characterized by the apparent potential evaporation, which is larger than the potential evaporation at the same water-limited location. The pan evaporation is related to the apparent potential evaporation. In these lines, if the available energy for evaporation is constant, an increase in actual evaporation decreases the sensible heat flux, decreases the apparent potential evaporation, and finally decreases the pan evaporation. Lawrimore and Peterson (2000) after examining precipitation and pan evaporation trends in the USA, and assuming that precipitation and actual evaporation have to be related over large areas, lend support to the complementary hypothesis. Golubev et al.

**Potential evaporation trends**

C. Matsoukas et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

(2001) after deriving actual evaporation rates over the former Soviet Union and the USA, also find the complementary hypothesis reasonable. Zhang et al. (2007) calculated potential and actual evaporation from 16 watersheds in the Tibetan plateau and analysed them for the validity of the complementary hypothesis. They found indications for the existence of a complementary relationship, although weaker than the one originally proposed by Bouchet (1963).

However, during the same period an alternate theory appeared. Stanhill and Cohen (2001) showed that the solar irradiance had been declining the past decades (global dimming), with potential influences on the evaporation. Cohen et al. (2002) in an Israel case study, argued that the known sensitivity of pan evaporation to net radiation at the surface is enough to explain its decrease in a globally dimming world. They proposed that aerosol and cloud-induced global dimming is the main reason for the general downward trend of the pan evaporation, because the vapour pressure deficit (VPD) was displaying increasing trends, contrary to the expectations of the complementary hypothesis. Roderick and Farquhar (2002) supported the global dimming solution to the paradox, showing that the recent solar flux decrease is enough to account for the pan evaporation trend in a former Soviet Union area. Linacre (2004) in a study with simplified global average changes of temperature, dew point temperature, solar radiation, agrees that global dimming is the major factor in the decreases of pan evaporation. Wild et al. (2004) showed Global Energy Balance Archive (GEBA) data, indicating that the net shortwave and longwave radiation available for evaporation has been declining. In order to reconcile the decreasing radiative energy with the increasing temperature observations, they conclude that the hydrological cycle (and thus the evaporative cooling) has to weaken. Therefore, they disagree with the complementary hypothesis, which requires enhanced evaporation. The global dimming has reversed to brightening in the 1990s, and according to Wild et al. (2008), Wild (2009) and references therein, the hydrological cycle shows signs of transition from weakening to strengthening at the same time.

## Potential evaporation trends

C. Matsoukas et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Potential evaporation trends**

C. Matsoukas et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

To further complicate the picture, case studies in Australia (Roderick et al., 2007) and the Tibetan plateau (Zhang et al., 2007) showed that neither radiation trends, nor humidity issues were the major factor in pan evaporation trends. Instead the authors attribute the change to wind speed decreases. Johnson and Sharma (2010) calculated the pan evaporation trend in Australia from station, reanalysis and GCM data. Although the station data identified the wind change as the factor with the strongest contribution to the trend, the reanalysis data attributed the trend mostly to water vapour deficit change. However, it still remains to be seen if the effect of the wind has a regional or even global character.

Brutsaert (2006) has proposed that the reported decreases in pan evaporation can be attributed partly to solar dimming and partly to actual evaporation increases via the complementary relationship. In other words the two hypotheses do not have to be mutually exclusive. Teuling et al. (2009) have found that evaporation depends on different drivers, in regions of Europe and North America. In drier water-limited regions, such as South Europe and the US Southwest, evaporation follows the interannual fluctuations of precipitation, while in wetter energy-limited regions, such as central and North Europe and the American Northeast, evaporation follows in suite with global dimming and brightening. Therefore, evaporation can be increasing or decreasing with decreasing pan evaporation, depending on the location. For example, global dimming in energy-limited areas, will cause both pan evaporation and actual evaporation to decrease. On the other hand, a positive precipitation trend in water-limited regions, will increase actual evaporation, but decrease pan evaporation. Teuling et al. (2009) agree that the two hypotheses do not have to be mutually exclusive.

A recent review by Fu et al. (2009) on the subject lists the significant problems associated with each of the two explanations of the paradox, i.e. solar dimming and complementary hypothesis. In order to address these problems, they propose five priorities. First, homogenization of the data sets or quantification of the errors. Second, investigation on which of the three major factors (net radiation, vapour pressure deficit, and wind) is most significant in a regional context. Third, extension of the analysis to post

1990 years, when a reversal from global dimming to global brightening is noted. Fourth, the relationship between pan evaporation and reference potential evaporation needs to be further clarified. Fifth, the separate study of land and ocean evaporation trends. Sixth, they highlight that the crux of the problem is the trend of the actual evaporation and we need to find ways to advance our knowledge there.

In this work, we focus on the potential (open-water) evaporation rate over all land areas of the planet. In order to estimate it, we assume the existence of a small shallow water body in each land location. The hypothetical water body has to be small, so that the regional climate can be considered undisturbed, and shallow, so that heat storage considerations can be ignored. The open water evaporation from this small, shallow water body can be assumed to be the (apparent) potential evaporation at the same location. Our objectives here are the accurate calculation of potential evaporation over land areas, derivation of its regional trends, and quantification of the contribution of solar decadal fluctuations and water vapour transfer changes to the potential evaporation trends. The link of potential evaporation to the pan evaporation will provide some insight to the pan evaporation decadal changes.

In more detail, we will analyse the monthly potential evaporation for years 1983–2008, in a spatial  $2.5^{\circ} \times 2.5^{\circ}$  resolution, over all land areas of the globe. We use our radiation transfer models for solar and thermal longwave radiation, already employed in a variety of climatic studies (Hatzianastassiou and Vardavas, 1999, 2001a,b; Hatzianastassiou et al., 1999, 2004a,b, 2005, 2007a,b; Pavlakis et al., 2004, 2007, 2008; Vardavas and Taylor, 2007; Matsoukas et al., 2010) for the calculation of the necessary radiation fluxes. We also employ reanalysis humidity, wind and temperature data, in order to calculate the evaporation component due to mass transfer processes. We are thus in a position to include both parameters in our analysis: net radiation fluxes and water vapour transfer factors. Moreover, out of the six priorities proposed by Fu et al. (2009), our approach addresses priorities one, two, and three. Priority one, because we partly homogenise the data, using the same global data sources and same methodologies. Priority two, because all proposed quantities are included in our trend

## Potential evaporation trends

C. Matsoukas et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

analysis. Priority three, because our period of study extends well beyond 1990. In Matsoukas et al. (2005, 2007), we touched upon priority five, but due to lack of inter-annual, spatially distributed heat storage data in the oceans, the trend of general ocean evaporation is beyond our reach.

## 2 Methodology and data

Our objective is to estimate the monthly potential evaporation globally over all land areas in  $2.5^\circ \times 2.5^\circ$  resolution. In each  $2.5^\circ \times 2.5^\circ$  cell the aerodynamic evaporation rate  $E_a$  is estimated from

$$E_a = UC_w(e_s - e) \quad (1)$$

where  $U$  is the scalar wind,  $e_s$  the saturation water vapour pressure at the 2 m temperature, and  $e$  the observed water vapour pressure at 2 m. The difference  $e_s - e$  is the vapour pressure deficit (VPD).  $C_w$  is a turbulent exchange coefficient, estimated by a variety of methods, e.g. Brutsaert (1982, chap. 4), Winter et al. (1995). The derivation of  $C_w$  is relatively simple for neutral atmospheric stability conditions, but once atmospheric instability is included in the analysis, it becomes considerably more complex. Neglecting air stability issues in the estimation of potential evaporation can lead to serious errors when the time resolution is finer than 24 h. However, for resolutions coarser than daily, the errors tend to cancel out and the assumption of neutral stability works well (Mahrt and Ek, 1993; Brutsaert, 1982, p. 217). Since our approach uses monthly values, we assume that using the neutral form of  $C_w$  is sufficient. We have verified the validity of the above assumption for the evaporation of the Mediterranean Sea in Matsoukas et al. (2005). For its calculation we use the following method from Brutsaert (1982)

$$C_w = \frac{0.622a_v k^2}{R_d T_a \ln \frac{z_2}{z_{0v}} \ln \frac{z_1}{z_{0m}}} \quad (2)$$

## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



with  $k = 0.41$  the von Kármán constant,  $a_v = 1.13$  the ratio of von Kármán constants for water and wind,  $R_d$  the specific gas constant for dry air,  $T_a$  the air temperature,  $z_1$  and  $z_2$  the measurement heights for wind speed and humidity, and  $z_{0v}$  and  $z_{0m}$  the roughness lengths for water vapour and momentum.

5 The aerodynamically derived evaporation  $E_a$  is one model of the evaporative process, taking into account only the drying power of air. It has the advantage of requiring as input few and easily available physical quantities, i.e. air temperature, humidity, wind speed, air pressure. All these data were taken in a monthly,  $0.5^\circ \times 0.5^\circ$  resolution from the European Centre for Medium Range Forecast (ECMWF) Re-Analyses, namely ERA-40 (Uppala et al., 2005) up to August 2002 and the latest ERA Interim for the period January 1989–June 2008. The main objectives of ERA Interim were “to improve on certain key aspects of ERA-40, such as the representation of the hydrological cycle, the quality of the stratospheric circulation, and the handling of biases and changes in the observing system” (Berrisford et al., 2009), including wind measurements, which is of specific interest in this study. ERA data were regridded to  $2.5^\circ \times 2.5^\circ$  resolution, in order to match the radiation transfer model resolution.

Another way to model evaporation is through the energy balance method, which estimates the available energy  $R_n$  for the turbulent fluxes (evaporation and sensible heat) using the principle of energy conservation:

$$20 \quad R_n = Q_s - Q_l - \Delta H - G \quad (3)$$

where  $Q_s$  is the net solar energy flux,  $Q_l$  the net terrestrial flux corresponding to radiative cooling,  $G$  is the energy flux advected away from the surface, and  $\Delta H$  is the stored heat assumed. Since our model is applied to a shallow water body,  $\Delta H$  can be neglected (Brutsaert, 1982, p. 153). Also, for monthly resolutions  $G$  is relatively small and can be considered negligible (Shuttleworth, 1993).

The energy balance evaporation rate  $E_r$ , which corresponds to  $R_n$  is

$$E_r = \frac{R_n}{\rho L} \quad (4)$$

## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



where  $\rho$  is the density of water and  $L$  its latent heat of evaporation, estimated by

$$L = 2.501 \times 10^6 - 2350T_a (\text{J kg}^{-1}) \quad (5)$$

with the air temperature  $T_a$  in  $^{\circ}\text{C}$ .

Chow et al. (1988, pp. 86–87) state that “the evaporation may be computed by the aerodynamic method when energy supply is not limiting and by the energy balance method when vapour transport is not limiting. But, normally, both of these factors are limiting so a combination of the two methods is needed”. Doing just that, the method developed by Penman (1948) gives the evaporation rate  $E_p$  as a weighted average of  $E_r$  and  $E_a$ , using the formula

$$E_p = \frac{\Delta}{\Delta + \gamma} E_r + \frac{\gamma}{\Delta + \gamma} E_a \quad (6)$$

where  $\Delta$  is the slope of the saturation water vapour pressure curve at the air temperature  $T_a$ , and  $\gamma$  is the psychrometric constant

$$\gamma = \frac{c_p \rho}{0.622L} \quad (7)$$

with  $c_p$  the moist air heat capacity and  $\rho$  the atmospheric pressure.

Penman’s method has consistently ranked among the best methods for the calculation of potential evaporation over water bodies. Chow et al. (1988, pp. 86–89) classified it as the best evaporation method when all relevant data are available and the necessary assumptions are justified. Winter et al. (1995), Rosenberry et al. (2004, 2007) found it one of three best out of at least eleven methods in the cases of Lake Williams in Minnesota, a prairie wetland in North Dakota, and a small mountain lake in the north-eastern USA, respectively. Their comparison baseline was the energy balance method. Tanny et al. (2008) in a case study of a small reservoir in northern Israel ranked the Penman method between the two best out of five evaporation models. Their comparison was performed against eddy covariance evaporation measurements. However, its application requires many physical quantities, some of them not readily available. The

## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



ones that are not measured at every meteorological station are the radiation fluxes  $Q_s$  and  $Q_l$ . Therefore, using radiation transfer models to calculate them everywhere on the globe, is our only recourse.

## 2.1 Radiative transfer model description

The deterministic 1-D spectral radiative transfer model used here was developed from a radiative-convective model (Vardavas and Carver, 1984; Vardavas and Taylor, 2007). The sky is divided into clear and cloudy fractions. The cloudy fraction includes three non-overlapping layers of low, mid and high-level clouds. The model input data include cloud amounts (for low, mid, high-level clouds), cloud scattering and absorption optical depths, cloud-top pressure and temperature (for each cloud type), cloud geometrical thickness and vertical temperature and specific humidity profiles. For the total amount of ozone, carbon dioxide, methane, and nitrous oxide in the atmosphere, we used the same values as in Hatzianastassiou and Vardavas (2001a).

All of the cloud climatological data for our radiation transfer model were taken from the International Satellite Cloud Climatology Project (ISCCP-D2) data set (Rossow and Schiffer, 1999), which provides monthly means for 72 climatological variables in  $2.5^\circ \times 2.5^\circ$ , monthly resolution, for 15 cloud types and for the 25-year period July 1983–June 2008. ISCCP converts  $30 \text{ km} \times 30 \text{ km}$  cloud data every 3 h to an equal-area map grid with 280 km resolution. The Stage D2 data product is produced by further averaging over each month, first at each of the eight 3 h time slots and then over all time slots. The cloud-top temperature is derived from the infrared radiances, while the cloud-top pressure from the vertical temperature profile of the atmosphere.

The water vapour and temperature vertical atmospheric profiles, used in the radiative transfer model, come from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) global reanalysis project (Kistler et al., 2001), corrected for topography as in Hatzianastassiou and Vardavas (2001a). These data are also on a  $2.5^\circ$  resolution, monthly averaged and cover the same 25-year period as the ISCCP-D2 data.

## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Our radiation transfer model is accordingly customised and applied in two different radiation domains, the shortwave (SW, solar) and the longwave (LW, terrestrial). Below, we present briefly the two separate models.

### 2.1.1 Shortwave radiation transfer model

5 The incoming solar irradiance conforms to the spectral profile of Thekaekara and Drummond (1971) and corresponds to a solar constant  $S_0$  of  $1367 \text{ W m}^{-2}$  (Willson, 1997; Hartmann, 1994, p. 23). The model makes adjustments for the elliptical Earth orbit and apportions 69.48% of the incoming spectral irradiance to the ultra violet–visible–near infrared (UV-Vis-NIR) part (0.20–1  $\mu\text{m}$ ) and 30.52% to the near infrared–infrared (NIR-IR) part (1–10  $\mu\text{m}$ ). Then, the radiative transfer equations are solved for 118 separate wavelengths for the UV-Vis-NIR part and for 10 bands for the NIR-IR part, using the Delta-Eddington method of Joseph et al. (1976). For a more detailed model description the reader is referred to Hatzianastassiou et al. (2004b,a, 2007a,b).

15 The model takes into account Rayleigh scattering due to atmospheric gas molecules, as well as absorption from  $\text{O}_3$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , and  $\text{CH}_4$ . The  $\text{O}_3$  column amount is taken from the Television Infrared Observational Satellite (TIROS) Operational Vertical Sounder (TOVS). Complete aerosol data are provided by the Global Aerosol Data Set (GADS) (Köpke et al., 1997).

20 The model output can include downwelling and upwelling fluxes at the top of atmosphere, at the surface and at any atmospheric height. The focus of this study is the solar energy absorbed at the surface, or net (downwelling minus reflected) flux at the surface. As mentioned above, in this study we use the fluxes absorbed by a hypothetical shallow water body on the ground. Therefore, in the estimation of the net shortwave flux we use the water surface albedo, modelled using Fresnel reflection as a function  
25 of the solar zenith angle and corrected for a non-smooth surface.

## Potential evaporation trends

C. Matsoukas et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## 2.1.2 Longwave radiation transfer model

The detailed radiative-convective model developed for climate change studies of Var-  
davas and Carver (1984) is modified for the radiation transfer of terrestrial infrared  
radiation, in order to compute the downwelling longwave radiation (DLR) and upwelling  
fluxes at the surface of the Earth. The model has monthly,  $2.5^\circ \times 2.5^\circ$  resolution (dic-  
tated from the resolution of ISCCP-D2) and a vertical resolution of 5 mb, from the sur-  
face up to 50 mb, to ensure that the atmospheric layers are optically thin with respect to  
the Planck mean longwave opacity. The atmospheric molecules considered are  $\text{H}_2\text{O}$ ,  
 $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{O}_3$ , and  $\text{N}_2\text{O}$ . The sky is divided into clear and cloudy fractions. The cloudy  
fraction includes three non-overlapping layers of low, mid and high-level clouds. The  
model input data include cloud amounts (for low, mid, high-level clouds), cloud scatter-  
ing and absorption optical depths, cloud-top pressure and temperature (for each cloud  
type), cloud geometrical thickness and vertical temperature and specific humidity pro-  
files.

A full presentation and discussion of an earlier version of the model can be found in  
Pavlakis et al. (2004). There, a series of sensitivity tests were performed to investigate  
how much uncertainty is introduced in the model DLR by uncertainties in the input pa-  
rameters, such as air temperature, skin temperature, low, middle or high cloud amount  
as well as the cloud physical thickness, cloud overlap schemes, and the use of daily-  
mean instead of monthly-mean input data. The model DLR was also validated against  
BSRN station measurements for the entire globe (Pavlakis et al., 2004; Matsoukas  
et al., 2005). Here, we use a newer version with an improved spectral resolution of 28  
bands for the longwave spectrum.

### Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



### 3 Results

#### 3.1 Long-term average

We start by using Eq. (1) to compute the bulk aerodynamic evaporation  $E_a$  for the globe, with input data (air temperature, humidity, wind speed, air pressure) originating from ERA-40 and ERA Interim. This quantity corresponds only to mass transfer procedures and assumes unlimited energy availability. A long-term average (July 1983–June 2002) of the annual  $E_a$ , calculated from ERA-40 data is presented in Fig. 1 (top left), showing maxima over generally dry areas, such as deserts and minima over wetter and colder areas. A direct comparison with the long-term annual average of the VPD in Fig. 1 (top right), shows the qualitative resemblance with  $E_a$  and highlights the dominance of the VPD in the geographical distribution of aerodynamic evaporation. The long-term annual average of wind speed is shown in Fig. 1 (bottom). The regional patterns of  $U$  and  $E_a$  do not correlate very well, indicating that the wind speed  $U$  plays only a secondary role in the bulk aerodynamic evaporation regional distribution. This is also true for the the exchange coefficient  $C_w$ .

We proceed by calculating the available energy  $R_n$  for turbulent processes, i.e. evaporation and sensible heat flux. As mentioned before, this energy is derived from our radiative models, run over fictitious small and shallow water bodies at each location. If we assume that all this energy flux is used up in evaporation, we obtain the evaporation rate  $E_r$ , whose global distribution is shown in Fig. 2 (top left). A comparison of  $E_a$  in Fig. 1 (top left) with  $E_r$  in Fig. 2 (top left) shows that there are two very distinct processes that govern potential evaporation. In some dry locations  $E_a$  is larger than  $E_r$ , meaning that the available energy does not suffice to maintain the potential evaporation rate dictated by mass transfer and potential evaporation is energy limited there. This is highlighted in Fig. 2 (top right), where we present the ratio  $E_a/E_r$ . In areas where this ratio increases above one, e.g. the Sahara and Australian deserts, potential evaporation is limited by energy. In other locations, e.g. North Eurasia and America, South America,  $E_r$  is larger than  $E_a$  and the ratio drops below one, meaning that the

potential evaporation there is vapour transfer limited.

Penman's method (Eq. 6) takes into account the two processes and derives a more accurate estimate  $E_p$  of the potential evaporation. The long-term average  $E_p$  is shown in Fig. 2 (bottom), with its expected latitudinal gradient, its maximum values close to the Equator, its poleward decrease and its minimal values in Antarctica and Greenland.  $E_p$  follows closely  $E_r$ , because  $\Delta$  is usually larger than  $\gamma$  in Eq. (6) and therefore the  $E_r$  contribution to  $E_p$  dominates the  $E_a$  contribution in all but the coldest regions. The global average of the potential evaporation of small shallow water bodies over land areas for July 1983 to June 2002 is  $2.6 \text{ mm day}^{-1}$ .

### 3.2 Global trends

We now focus on the interannual behaviour of global potential evaporation, as well as the quantities that affect it, namely wind speed, VPD, net solar flux and net terrestrial flux. In this study “global” means the area-weighted average of land-only values. We first present in Fig. 3a the evolution of global mean bulk aerodynamic evaporation  $E_a$ , calculated by Eq. (1), using data from ERA-40 (blue line) and ERA Interim (red line). There is a consistent difference between the two time series during the temporal overlap between January 1989 and August 2002, when data were available from both ERA-40 and Interim. The reason for the larger Interim values is the consistently increased wind speeds compared to ERA-40, as can be seen in Fig. 3b). Except from the wind speed, the global means of the other relevant quantities (2 m air temperature, dew point temperature, VPD) do not show significant differences between ERA-40 and Interim. For example, in Fig. 3c we show the time series of the VPD global mean, where the two lines are very close.

Fitting linear trends to raw time series, such as the ones in Fig. 3, is not a good practice, because the large seasonal fluctuations hide possible trends and keep them from attaining statistical significance. Moreover, the switch from ERA-40 to ERA Interim after 2002 would introduce a spurious trend, especially if the same quantity has different long-term mean in the two data bases, as for example wind speed. In order to perform

## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



a more robust trend analysis, we take the deseasonalised time series, normalised by the standard deviation of the interannual variability for each specific month. For example, the normalised anomaly of June 2001 is the difference between the June 2001 value and the mean of all June values, divided by the standard deviation of all June values. In this fashion we have derived normalised plots for wind speed  $U$ , VPD, and bulk aerodynamic evaporation  $E_a$  (Fig. 4), net solar flux  $Q_s$ , net terrestrial flux  $Q_l$ , and energy balance evaporation  $E_r$  (Fig. 5), and Penman potential evaporation (Fig. 6).

As expected, the seasonality of the quantities is not apparent in these plots and we can proceed to check if interannual trends are present globally over land. Also, the differences between normalised anomalies of ERA-40 and Interim for quantities  $U$ , VPD,  $E_a$ , and  $E_p$  (Figs. 4 and 6), seem small and non-systematic. Therefore, for each one of the aforementioned quantities, we generated a “blended” time series with only ERA-40 normalised anomalies for July 1983–December 1988, the average of ERA-40 and Interim normalised anomalies for the overlapping period of January 1989–August 2002, and ERA Interim only for September 2002–June 2008. These “blended” time series will be used for the rest of the paper in order to calculate linear trends for the relevant variables  $U$ ,  $e_s - e$ ,  $E_a$ , and  $E_p$ .

There seems to be a wind speed decrease in the 90’s, which has stopped (if not reversed) around 2000. The VPD seems to be increasing since the 90’s, as does  $E_a$  (but less steeply). Trends in  $Q_s$ ,  $Q_l$ ,  $E_r$ , and  $E_p$  are not very obvious and dependent on the choice of the period of interest and its start and end points.  $Q_l$  in particular displays an increasing trend in the last two decades.

Fitting linear trends to the generated normalised anomaly time series produces the trend values shown in Table 1. The numbers in italics mean that the 95% confidence interval of the slope does not contain zero. The normalised anomalies have also been averaged over North and South Hemispheres and their trends are presented separately.

Restricting ourselves to the statistically significant trends at the 95% confidence level, we can draw some conclusions. The VPD has the steepest increasing trend, already

apparent in Fig. 4b), driving the bulk aerodynamic evaporation  $E_a$  trend to positive statistically significant values. Although  $Q_s$  shows a positive trend in the late eighties and throughout the nineties (solar brightening), after 2000 this trend has levelled off (Wild et al., 2009). In the full period (July 1983–June 2008) there remains a weak but statistically significant increase in the net solar heating of the surface. The radiative cooling of the surface  $Q_l$  is increasing more steeply than  $Q_s$ . The same sign of trends in solar heating and thermal radiation cooling cause a statistically non significant change in the net energy flux at the surface, therefore  $E_r$  has a weak, non significant trend. However, our result for the apparent potential evaporation  $E_p$  over land areas, estimated by Penman's method, is a statistically significant increase over the last decades. The ratio  $E_a/E_r$  is also increasing with statistical significance, indicating a potential evaporation that is less limited by vapour transfer, but more limited by energy fluxes. In other words, the VPD has increased, resulting in a more vapour-hungry atmosphere, but the net energy at the surface has not increased as much as to satisfy this demand. All above trends are stronger in the North Hemisphere than either globally or in the South Hemisphere. In SH the only statistically significant trends are found for VPD and  $E_a$ . On the other hand, in NH all examined quantities seem to be significantly changing, with the wind speed decreasing and everything else increasing.

There is a general reluctance to derive trends from reanalysis data. The main reason is that the observational data assimilated by the reanalysis scheme may at some times be less dense than other times, or that the assimilation scheme may be revised. These changes could produce spurious, statistically significant trends. However, we decided to use reanalysis data for the calculation of  $E_p$  trends for two reasons. First, ERA Interim starts in 1989, when satellite data were mature, global and abundant, leading us to expect small changes in data coverage and density. Second, reanalysis data trends affect mainly  $E_a$  and not  $E_r$ . As we note above,  $E_p$  depends weakly on  $E_a$ , except in the very cold regions. Therefore, spurious reanalysis trends, will affect  $E_p$  only slightly. With this caveat in mind, we continue our analysis.

**Potential evaporation trends**

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



### 3.3 Geographically resolved trends

We compile monthly timeseries at every  $2.5^\circ \times 2.5^\circ$  cell of the globe for the period July 1983–June 2008. Each individual timeseries is transformed to a normalised anomaly timeseries and fitted with a least-squares line. For quantities originating from both ERA-40 and Interim, a blended normalised anomaly time series has been calculated and all plots and results reported here are derived from it. Each slope is tested for difference from zero with statistical significance at 95% confidence level. Below, we present the regional distribution of these trends for potential evaporation and all other relevant physical quantities. Only statistically significant slopes are presented. The normalised anomalies are unitless. An interpretation of the values of quantities in the following trend plots (Figs. 7 and 8) is the change per decade of the difference of the quantity from its interannual monthly mean over its interannual monthly standard deviation.

Examining the regional wind trends, it is apparent that in the last 25 years wind speeds are generally decreasing everywhere except Antarctica, scattered parts of North America and East Asia, extended parts of South America and North Africa, central Europe, the Kalahari, Indochina and Indonesia. These trends are in agreement (at least qualitatively) with Roderick et al. (2007), Zhang et al. (2007), and McVicar et al. (2008). McVicar et al. (2008) point out that Australian stations and ERA-40 reanalysis data agree well in wind climatologies, but the reanalysis trends are weaker than the station ones. Our ERA analysis is also in agreement with Pryor et al. (2009), who however find differences in reanalysis and station trends for the contiguous US and show scepticism in using reanalysis data for trend detection. We understand the difficulties in substituting local wind measurements with reanalysed data, but we should also note that there is no consensus on the magnitude of wind trends in Australia, even between station-only analyses (Jovanovic et al., 2008).

The bulk aerodynamic evaporation  $E_a$  and the VPD (i.e.  $e_s - e$ ) are globally on the rise except (not necessarily with statistical significance) in India, West Australia, South

## Potential evaporation trends

C. Matsoukas et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Africa and various scattered small regions throughout the globe. Only statistically significant trends are shown in Figs. 7 and 8. The VPD trend is caused by the fact that in ERA both air temperature  $T$  and dew point temperature  $T_d$  are rising, but  $T$  is doing so faster than  $T_d$  (results not shown). The positive trend of  $T_d$  shows that the water cycle is intensifying, but not enough to decrease the VPD in a warming world. This increase in the “drying capacity” of air runs contrary to the complementary hypothesis.

The globe seems to be divided in half with respect to the prevalence of global dimming or global brightening in the period July 1983–June 2008. Decadal changes in net solar heating  $Q_s$  led to less radiation (dimming) in parts of Canada, Greenland, North Eurasia, East Asia, most of Australia, and Antarctica (not shown, but very similar to Fig. 8a). All other areas witnessed brightening. The surface seems to be radiating increasingly net longwave flux  $Q_l$  during the examined period, contributing to less available energy for evaporation. Exceptions are West South America, West Africa, West Australia, Central Eurasia, Indonesia and scattered spots in various locations (not shown). The combined trends of  $Q_s$  and  $Q_l$  produced the trend of  $E_r$ , shown in Fig. 8a. The general image is similar to the trends in  $Q_s$ , indicating that the major player in radiative flux changes is the solar energy and not the terrestrial longwave. Also, Penman potential evaporation  $E_p$  regional trends in Fig. 8b agree quite well with  $E_r$  in Fig. 8a. In some regions, opposite signs of trends in  $E_r$  and  $E_a$  have removed statistical significance in  $E_p$  changes, e.g. parts of Greenland and North-east Asia, but the differences between the two figures are small.

#### 4 Discussion: is potential evaporation driven by energy or mass transfer issues?

Let us revisit the two competing hypotheses on the decreasing pan evaporation trends. On the one hand the complementary hypothesis proposes that changes in the water vapour mass transfer are responsible for the observed pan evaporation trends. On the other hand, the secular global dimming/brightening is supposedly enough to account

for the pan evaporation trends. In order to provide some insight into this problem, it is important to elucidate the relationships between the deseasonalised, normalised trends of  $U$ ,  $e_s - e$ ,  $E_a$ ,  $Q_s$ ,  $Q_l$ ,  $E_r$  and  $E_p$ . To this end, we compile Table 2 with the cross-correlation coefficients  $R^2$  between all possible pairs of the above quantities.

We will examine the values greater than 0.5, namely the ones corresponding to the pairs  $E_a$ -VPD,  $Q_s$ - $Q_l$ ,  $E_r$ - $Q_s$ ,  $E_p$ -VPD,  $E_p$ - $Q_s$  and  $E_p$ - $E_r$ . The large correlation of  $E_a$  and VPD has been inferred previously in this study, by the similarities in both their regional distributions and their global normalised anomalies.  $Q_s$  and  $Q_l$  are correlated because of their common relationship to cloud cover. For example, when clouds are present, they obstruct both net solar heating and terrestrial cooling, leading to smaller values of  $Q_l$  and  $Q_s$ . The long-term global average values of  $Q_s$  and  $Q_l$  are respectively  $150 \text{ W m}^{-2}$  and  $48 \text{ W m}^{-2}$ , so  $Q_s$  dominates  $Q_l$ . If we also take into account Eqs. 3 and 4, the close relationship of  $E_r$  with  $Q_s$  is not surprising. Finally, we have already pointed out the stronger relationship of  $E_p$  with  $E_r$ , rather than with  $E_a$ , due to the usually larger coefficient of  $E_r$  in Eq. (6). Notably, with a 0.97 correlation coefficient, we can see that Penman's potential evaporation  $E_p$  trend is almost exclusively dictated by the trend of the available energy  $E_r$ . The  $E_p$ - $E_a$  correlation is not negligible, but rather weak compared to the pair  $E_p$ - $E_r$ .

This result is examined further, by presenting the geographically distributed cross-correlation between deseasonalised and normalised trends of  $E_p$  on the one hand and  $E_r$  or  $E_a$  on the other, in Fig. 9. The very strong cross-correlation found for the global normalised, deseasonalised trends of  $E_p$  and  $E_r$  (top of Fig. 9) in the previous paragraph seems very robust. In most areas this correlation coefficient is above 0.9, with some exceptions in the Sahara, Greenland (where it is still larger than 0.8) and parts of Antarctica.  $E_p$  trends are dominated by  $E_a$  trends only in parts of the latter region (bottom of Fig. 9), while everywhere else in the globe  $E_r$  is more important. This result can be extended to pan evaporation, since potential and pan evaporations are generally considered proportional, with "pan coefficient" being the coefficient of proportionality for a specific pan.

## Potential evaporation trends

C. Matsoukas et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

This finding comes to the support of the hypothesis that global dimming/brightening controls the trends in potential and pan evaporation. The bulk aerodynamic evaporation  $E_a$  is also positively correlated with the potential evaporation  $E_p$ , but this effect is of principal importance only in parts of Antarctica. The energy balance evaporation  $E_r$  is not totally independent of  $E_a$ , so all three quantities are linked. However, the degree of  $E_r$  and  $E_p$  trend correlation is very prominent and provides a clear answer. In this study, the available energy (mainly solar) is the driver for potential (and consecutively pan) evaporation trends in our dataset and not water vapour transfer.

## 5 Conclusions

Pan and potential evaporation are directly proportional and therefore a study on potential evaporation can shed some light on the factors that affect the much discussed observed trends of pan evaporation. We use Penman's method to calculate the potential evaporation for all land areas of the globe in a monthly  $2.5^\circ \times 2.5^\circ$  resolution. Penman's method is widely recognised as one of the most accurate calculations of potential evaporation. It takes into account two relevant processes: the drying power of the air (the water vapour transfer potential) and the energy available to the evaporation process. Penman's method then compromises the two sometimes conflicting processes and produces an estimate for potential evaporation. Since it requires modelling of both radiative and turbulent fluxes, it is data intensive and needs quantities (e.g. net radiation fluxes), which are not readily measured in all world regions. We employ radiation transfer models as a way to circumvent the problem of radiative flux availability. In order to run the radiative transfer models we need data for clouds (ISCCP-D2), aerosol (GADS), and atmospheric temperature and humidity profiles (NCEP/NCAR reanalysis). ECMWF reanalysis data (ERA-40 and ERA Interim) are used for the turbulent flux model.

The temporal evolution of potential evaporation for our examined period (July 1983–June 2008) is of particular interest because it provides insight to the observed trends

## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Potential evaporation trends**

C. Matsoukas et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

of pan evaporation. We examine the interannual trends of potential evaporation and various related physical quantities, such as net solar flux, net longwave flux, vapour pressure deficit (VPD) and wind speed. Trends of reanalysis quantities, which are related to turbulent fluxes, such as the VPD, wind, and bulk aerodynamic evaporation  $E_a$ , should be reported carefully because of possible changes in data coverage and assimilation techniques during the reanalysis period and the consequent generation of spurious trends. In our case, we think spurious effects are minimal because data coverage changes are small after 1989, with satellites routinely providing uninterrupted global coverage. Moreover, Penman potential evaporation depends weakly on turbulent fluxes but more strongly on radiative fluxes, which are less sensitive to reanalyses.

Atmospheric temperature, dew point temperature, and vapour pressure deficit (VPD) appear to be globally increasing. The increase of dew point temperature is an indication of an enhanced water cycle, in line with the complementary hypothesis. However, the agreement stops here, because the temperature is increasing even faster than the dew point temperature, resulting in decreasing relative humidity and increasing VPD and  $E_a$ .

Global dimming/brightening cycles in these 25 years increased the available solar energy, driving the total energy available for evaporation to larger values. Radiative longwave cooling also increased, having the opposite to solar (but smaller) effect on total available energy. The energy balance evaporation  $E_r$  is proportional to this available energy for evaporation and therefore it has a positive trend. The ratio  $E_a/E_r$  is also increasing with statistical significance, indicating a potential evaporation that is less limited by vapour transfer, but more limited by energy fluxes. All above trends are stronger in the North Hemisphere than either globally or in the South Hemisphere. In SH the only statistically significant trends are found for VPD and  $E_a$ . On the other hand, in NH all examined quantities seem to be significantly changing, with the wind speed decreasing and everything else increasing.

Potential evaporation trends seem to follow closely the trends of energy availability and not the trends of the atmospheric capability for vapour transfer. This finding is

geographically robust, with the exception of Antarctica, where there is a mixed picture. The results above tend to support the hypothesis that secular changes in the radiation fluxes are responsible for potential evaporation trends, and not vapour transfer issues, such as the ones proposed by the complementary hypothesis.

5 *Acknowledgements.* The ISCCP D2 data were obtained from the International Satellite Cloud Climatology Project web site <http://isccp.giss.nasa.gov> maintained by the ISCCP research group at the NASA Goddard Institute for Space Studies, New York, NY. The GADS aerosol data were obtained from the Meteorological Institute of the University of Munich. NCEP/NCAR Reanalysis Derived data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at <http://www.cdc.noaa.gov/>. ERA-40 and Interim reanalysis data were provided by the European Centre for Medium-Range Weather Forecast (ECMWF) and downloaded from <http://www.ecmwf.int/>. Part of this work has been performed in the frame of the European Union Integrated Project CIRCE (contract no. 036961).

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## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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**Potential evaporation trends**

C. Matsoukas et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Potential evaporation trends

C. Matsoukas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



L., Bidlot J., Bormann N., Caires S., Chevallier F., Dethof A., Dragosavac M., Fisher M., Fuentes M., Hagemann S., Holm E., Hoskins B. J., Isaksen L., Janssen P. A. E. M., Jenne R., Mcnally A. P., Mahfouf J.-F., Morcrette J.-J., Rayner N. A., Saunders R. W., Simon P., Sterl A., Trenberth K. E., Untch A., Vasiljevic D., Viterbo P., and Woollen J. The ERA-40 re-analysis, *Quart. J. Roy. Meteorol. Soc.*, 131, 2961–3012, doi:10.1256/qj.04.176, 2005. 10942

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## Potential evaporation trends

C. Matsoukas et al.

**Table 1.** Global, North Hemisphere (NH) and South Hemisphere (SH) normalised anomaly trends for potential evaporation over land areas and other relevant physical quantities, for the period July 1983–June 2008. The numbers are the slopes of Figs. 4–6 (except the  $E_a/E_r$  slope) in units of decade<sup>-1</sup>. Numbers in italics correspond to trend slopes significantly different from zero at the 95% confidence level.

Time Series	Global Trend	NH Trend	SH Trend
$U$	-0.010	-0.021	0.012
$e_s - e$	<i>0.048</i>	<i>0.050</i>	<i>0.026</i>
$E_a$	<i>0.036</i>	<i>0.040</i>	<i>0.016</i>
$Q_s$	<i>0.014</i>	<i>0.026</i>	-0.009
$Q_l$	<i>0.029</i>	<i>0.035</i>	-0.006
$E_r$	0.012	<i>0.021</i>	-0.010
$E_p$	<i>0.023</i>	<i>0.031</i>	0.002
$E_a/E_r$	<i>0.015</i>	<i>0.017</i>	0.010

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


## Potential evaporation trends

C. Matsoukas et al.

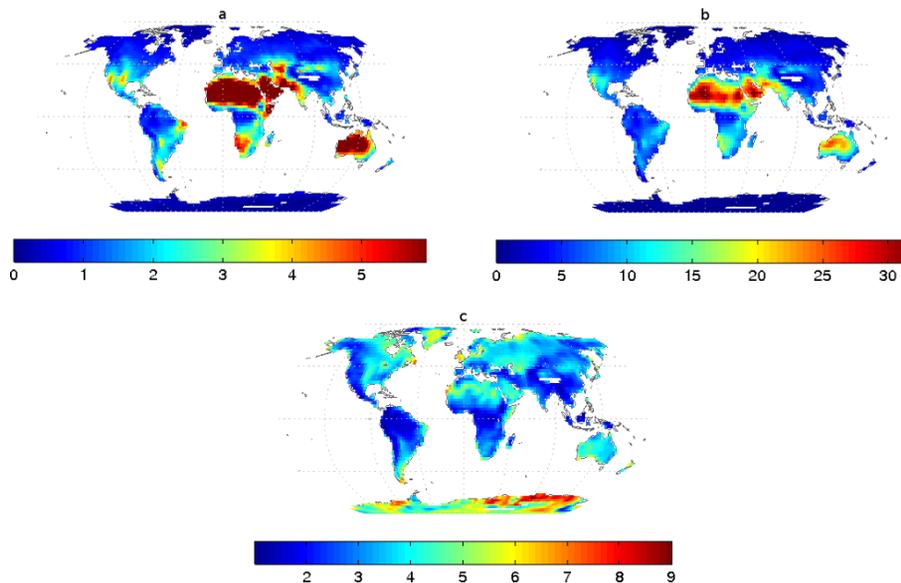
**Table 2.** Cross-correlation coefficients between potential evaporation  $E_p$  and relevant quantities. The analysed timeseries are the normalised anomalies for the period July 1983–June 2008.

	$U$	$e_s - e$	$E_a$	$Q_s$	$Q_l$	$E_r$	$E_p$
$U$	1.00						
$e_s - e$	-0.11	1.00					
$E_a$	0.12	0.92	1.00				
$Q_s$	-0.24	0.45	0.39	1.00			
$Q_l$	-0.01	0.36	0.39	0.51	1.00		
$E_r$	-0.27	0.41	0.33	0.96	0.26	1.00	
$E_p$	-0.28	0.55	0.46	0.91	0.25	0.97	1.00

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[I◀](#)
[▶I](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


**Potential evaporation trends**

C. Matsoukas et al.



**Fig. 1.** Long-term averages (July 1983–June 2002). Top left: the bulk aerodynamic evaporation rate  $E_a$  ( $\text{mm day}^{-1}$ ) computed from wind speed, air temperature and humidity data from ERA-40. The  $E_a$  values reach as high as  $14\text{mm day}^{-1}$  over the Sahara. Top right: the VPD (mb) computed from air temperature and humidity data from ERA-40. Bottom: the wind speed  $U$  ( $\text{m s}^{-1}$ ) from ERA-40.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

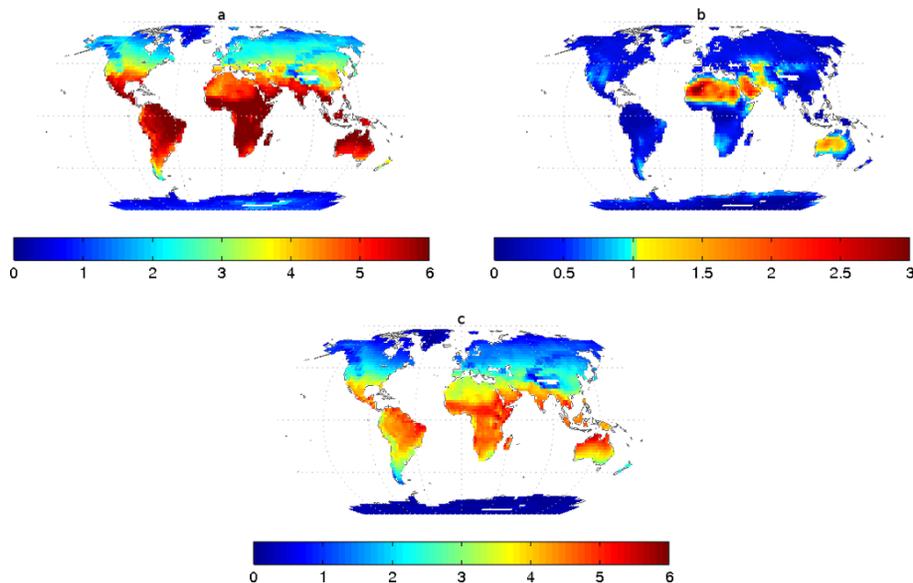
Printer-friendly Version

Interactive Discussion



**Potential evaporation trends**

C. Matsoukas et al.

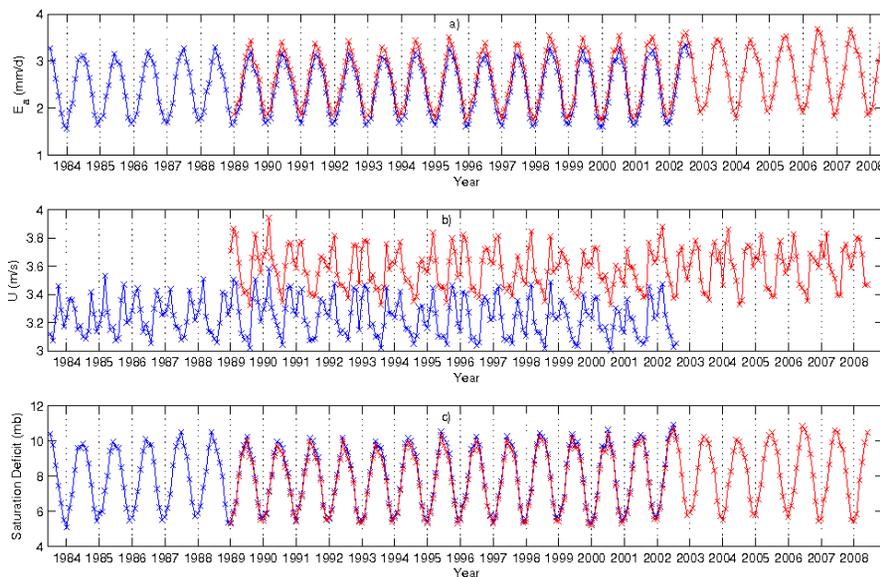


**Fig. 2.** Long-term averages (July 1983–June 2002). Top left: energy balance evaporation rate  $E_r$  ( $\text{mm day}^{-1}$ ) computed by radiation transfer models. The  $E_r$  values reach as high as  $7\text{mm day}^{-1}$ . Top right: ratio  $E_a/E_r$ . Bottom: Penman evaporation rate  $E_p$  ( $\text{mm day}^{-1}$ ), as a weighted average of  $E_r$  and  $E_a$ .

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## Potential evaporation trends

C. Matsoukas et al.

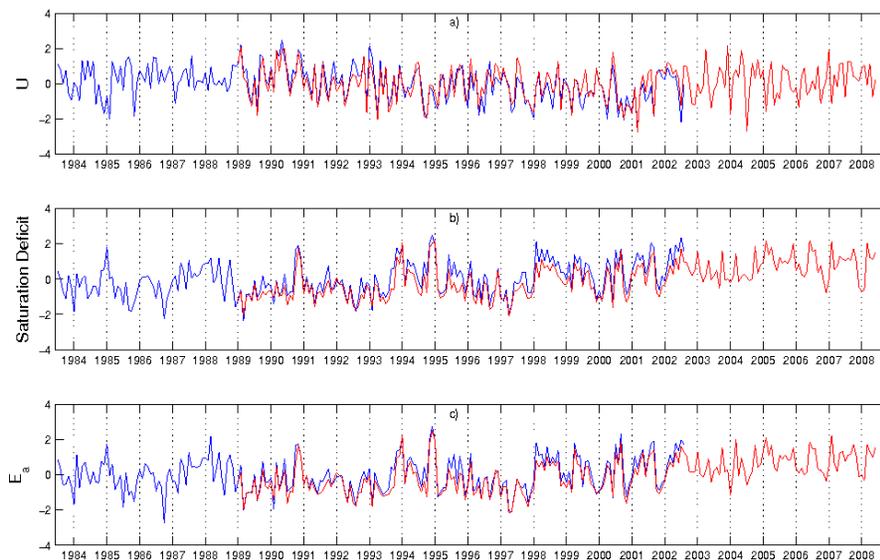


**Fig. 3.** Global means of: **(a)** bulk aerodynamic evaporation  $E_a$  (in  $\text{mm day}^{-1}$ ) calculated from input data by ERA-40 (blue line) and ERA Interim (red line). **(b)** 10 m wind speed  $U$  (in  $\text{m s}^{-1}$ ) by ERA-40 (blue line) and ERA Interim (red line). **(c)** VPD (in mb) by ERA-40 (blue line) and ERA Interim (red line).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## Potential evaporation trends

C. Matsoukas et al.

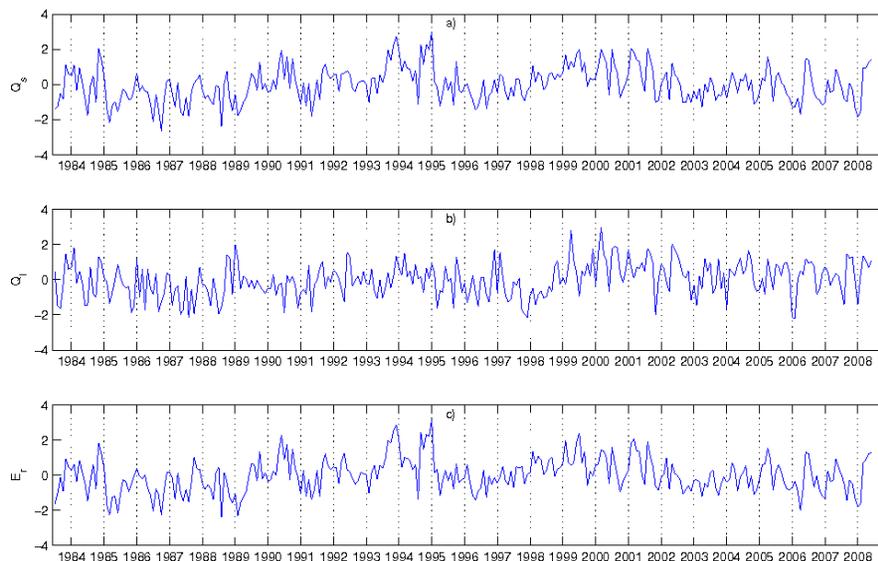


**Fig. 4.** Normalised anomalies of (a) 10 m wind speed  $U$  by ERA-40 (blue line) and ERA Interim (red line) (b) VPD by ERA-40 (blue line) and ERA Interim (red line) and (c) bulk aerodynamic evaporation  $E_a$ , computed by data from ERA-40 (blue line) and ERA Interim (red line).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## Potential evaporation trends

C. Matsoukas et al.

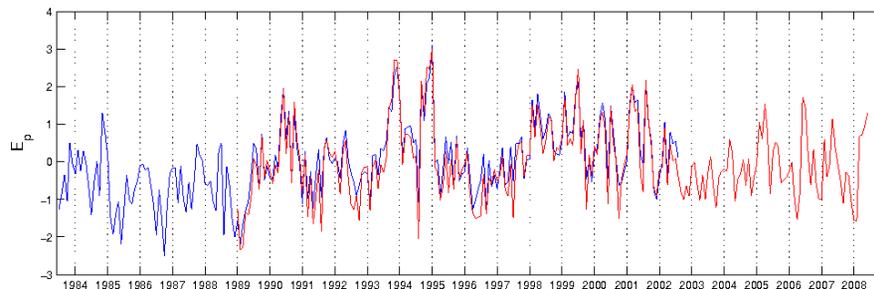


**Fig. 5.** Normalised anomalies of **(a)** net solar flux  $Q_s$ , **(b)** net terrestrial flux  $Q_l$ , and **(c)** energy balance evaporation  $E_r$ , all calculated by our radiation transfer model.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Potential evaporation trends**

C. Matsoukas et al.

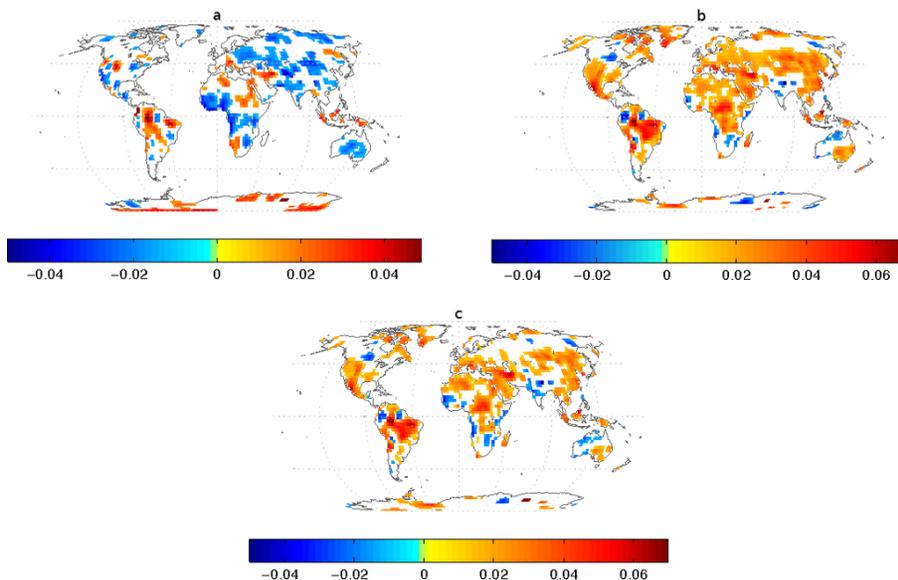


**Fig. 6.** Normalised anomaly of Penman potential evaporation, computed by data from our radiation transfer model, and ERA-40 (blue line) or ERA Interim (red line).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## Potential evaporation trends

C. Matsoukas et al.

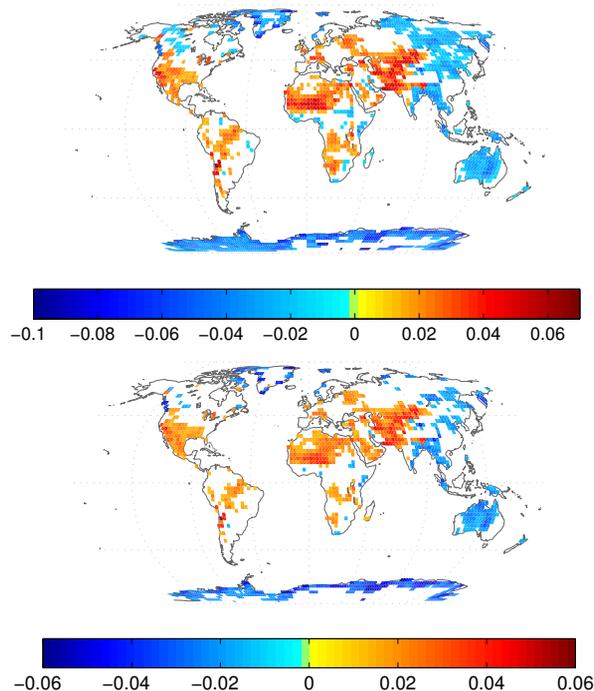


**Fig. 7.** Statistically significant (95% confidence interval) trends of the normalised anomaly of (top left) wind speed  $U$ , (top right) VPD  $e_s - e$ , and (bottom) bulk aerodynamic evaporation  $E_a$ . All three time series are blended from ERA-40 and Interim, at each  $2.5^\circ \times 2.5^\circ$  cell. Units are  $\text{decade}^{-1}$ .

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

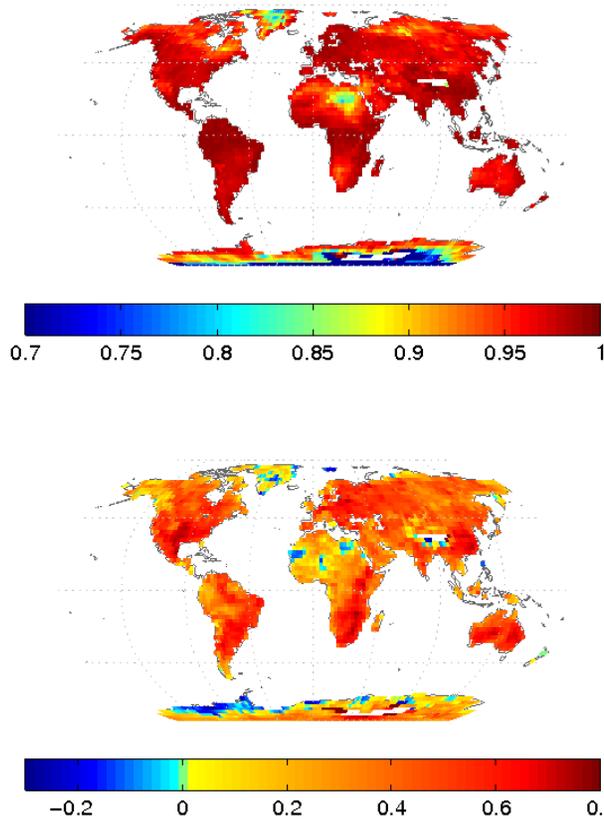
**Potential evaporation trends**

C. Matsoukas et al.



**Fig. 8.** Statistically significant (95% confidence interval) trends of the normalised anomaly of (top) energy balance evaporation  $E_r$  and (bottom) Penman potential evaporation  $E_p$ , at each  $2.5^\circ \times 2.5^\circ$  cell. Units are decade<sup>-1</sup>.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



**Fig. 9.** Geographically distributed correlation coefficient between trends of  $E_p$  and  $E_r$  (top) and between trends of  $E_p$  and  $E_a$  (bottom).

**Potential evaporation trends**

C. Matsoukas et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

