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# Potential evaporation estimation through an unstressed surface energy balance and its sensitivity to climate change

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## Abstract

Potential evaporation ($ET_P$) is a basic input for hydrological and agronomic models, as well as a key variable in most actual evaporation estimations. It has been approached through several diffusive and energy balance methods, out of which the Penman–Monteith equation is recommended as the standard one. In order to deal with the diffusive approach, $ET_P$ must be estimated at a sub-diurnal frequency, as currently done in land surface models (LSM). This study presents an improved method, developed in the ORCHIDEE LSM, which consists in estimating $ET_P$ through an unstressed surface energy balance (USEB method). The results confirm the quality of the estimation which is currently implemented in the model (Milly, 1992). $ET_P$ has also been estimated using a reference equation (computed at a daily time step) provided by the Food and Agriculture Organization (FAO).

First, a comparison for a reference period under current climate conditions, shows that both formulations differ, specially in arid areas. However, they supply similar values when FAO's assumption of neutral stability conditions is relaxed, by replacing FAO's aerodynamic resistance by the model's one. Furthermore, if the vapour pressure deficit (VPD) estimated for FAO's equation, is substituted by ORCHIDEE's VPD or its humidity gradient, the daily mean estimate is further improved.

In a second step, $ET_P$'s sensitivity to climate change is assessed comparing trends in both formulations for the 21st Century. It is found that the USEB method shows a higher sensitivity. Both VPD and the model's humidity gradient, as well as the aerodynamic resistance have been identified as key parameters in governing $ET_P$ trends. Finally, the sensitivity study is extended to three empirical approximations based on temperature, net radiation and mass transfer (Hargreaves, Priestley–Taylor and Rohwer, respectively). The sensitivity of these methods is compared to the USEB method's one to test if simplified equations are able to reproduce the impact of climate change.





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## 1 Introduction

Potential evaporation ($ET_P$) is a basic input for hydrological and agronomic models, which summarizes their interactions with the atmosphere. In addition, $ET_P$ is the basis of most evaporation estimations (Milly, 1992; Wang and Dickinson, 2012). Consequently, changes in $ET_P$ due to a warmer climate will likely produce an effect on actual evaporation and more generally on the primary production of plants.

The UNFCCC (United Nations Framework Convention on Climate Change) estimated in 2007 the additional annual investment need and financial flow necessary by 2030 to be able to assume the adaptation costs to climate change. It was predicted to be up to 171 billion dollars at a global scale, out of which 8 and 6.5 % correspond to the agricultural and water sectors respectively (Parry et al., 2009). As $ET_P$ determines agronomic and water resources estimates, the uncertainties in predicted trends for $ET_P$ should be taken into account.

$ET_P$ is defined as the amount of evaporation that would occur if enough water was available at the surface. In other words, it is the atmospheric water demand (Hobbins et al., 2008). Several methods have been developed to approach its estimation. They can be grouped in two different families. One of them is dominated by the turbulent diffusion equation and mostly used in land surface models (LSM's). The other one is centred on a surface energy balance equation (Monteith, 1981). The Penman–Monteith equation, which is recommended as the standard method to estimate $ET_P$ belongs to the second group. Even though both families consider the two equations (turbulent diffusion and surface energy balance), each one focuses the estimation of $ET_P$ on one of them. This paper will refer to them as the diffusive and the surface energy balance approaches. It must be remarked that $ET_P$ is a conceptual flux, since it can not be observed. Furthermore, as each method uses different hypothesis and approximations they can only provide an estimate of $ET_P$.

In Budyko's scheme (Budyko, 1956) a diffusive equation is used to estimate potential evaporation. It is obtained as the result of the quotient between a humidity gradient







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and an aerodynamic resistance, times the air density. The gradient is the difference between the saturated humidity at the surface and the air's humidity. The virtual surface temperature ($T_w$), which differs from the actual one in the fact that it is related to a hypothetically wet surface, is used to compute the saturated humidity. However, the most common way to implement this method in a general circulation model (GCM) is by using the actual surface temperature instead of the virtual one (Manabe, 1969). Since this leads to an overestimation of $ET_P$, Milly (1992) proposed a corrective term which takes into account the soil moisture stress' effect on the actual surface temperature. This paper presents a further step in the $ET_P$ computation by estimating virtual surface temperature through an unstressed surface energy balance (USEB method). Thereby, the diffusive equation used to estimate $ET_P$ is closer to the original Budyko hypothesis and the Penman–Monteith method. It has been implemented in the ORCHIDEE (ORganising Carbon and Hydrology In Dynamic EcosystEms) LSM, developed by the Institut Pierre–Simon Laplace.

The second approach focuses on the energy partition between sensible and latent heat fluxes to obtain $ET_P$. An example is Penman–Monteith's equation, which is the basis for further simplifications, like the reference equation proposed by the FAO (Food and Agriculture Organization) and detailed in (Allen et al., 1998). In this case, $ET_P$ is given using standard meteorological data over a reference surface. This is an advantage for agronomic and hydrological models which do not have an explicit representation of the surface energy balance and thus need an $ET_P$ estimation. Approximations have been derived for FAO's equation concerning various time discretizations, from which the daily time step has been used for this study, as it is the most widely used.

The lack of data availability, the will to simplify the estimation of $ET_P$ or the need to perform local estimates have led to a number of approximations. Such is the case of temperature, radiation and mass transfer based methods. For example, the Hargreaves or Priestley–Taylor equations, approximate $ET_P$ through the air temperature and net radiation respectively (Xu and Singh, 2002). Further examples of potential evaporation estimation are by means of remote sensing (de Bruin et al., 2010) or




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through pan evaporation (Campbell and Phene, 1976). In the first case, $ET_P$ is estimated using geo-stationary satellite observations, daily downward solar flux at the surface, through a radiation-temperature based approximated formula given by Makkink (Makkink, 1957). In the latter case, it is estimated using the method of Kohler (Kohler et al., 1955).

All of these approximations have in common that they have been adapted to provide comparable estimates of $ET_P$ in the current climate. However, it is known that variables determining $ET_P$ are affected by climate change. (Kingston et al., 2009) analyses the climate change signal provided by six different $ET_P$ estimates. To perform this study, a 2 °C rise in global mean temperature scenario and five global climate models are used. Apart from showing that the simulated trend differed between them, it was identified as an important factor in global freshwater availability projections. Therefore, the assumptions made in different methods when approximating $ET_P$ may not provide a correct sensitivity to a warming climate. This would result in a misleading estimation of $ET_P$ and eventually lead to poor projections which affect decisions regarding water resource management or crop yields.

The aim of this paper is to study $ET_P$'s sensitivity to changes in atmospheric parameters which are expected to occur with climate change. To do so, $ET_P$ will be estimated through different methodologies. On the one hand, three LSM based methods will be used. In this way, advantage will be taken of the LSM's sub-diurnal time step, the fact that it solves the energy balance and provides access to all atmospheric parameters needed. On the other hand, $ET_P$ will be computed using FAO's reference equation and by means of three empirical approximations. These are a temperature based (Hargreaves), a radiation based (Priestley–Taylor) and a mass transfer based (Rohwer) methods. Special attention will be paid to the aerodynamic resistance ($r_a$), as well as the vapour pressure deficit (VPD) and the humidity gradient, since they are approached in different ways in the methods and are found to be critical in the estimation of $ET_P$.

The methodology defined to carry out this study is given in the next section. $ET_P$'s computation and implementation in ORCHIDEE are described, as well as FAO's refer-





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ence equation. The three empirical approximations are also explained. A result section will follow, showing a comparison between the LSM and FAO's methodologies and how under the current climate, the difference between them is reduced when the atmosphere's stability is taken into account in FAO's equation. Afterwards, the impact of climate change on $ET_P$ will be studied. In addition, variables used for $ET_P$'s estimation will also be analysed in order to identify the key parameters which are sensitive to the expected changes. Finally the paper will conclude with a recommendation for estimating $ET_P$ in a changing climate.

## 2 Methodology

The different methodologies used to estimate $ET_P$ in this study will be explained and summarized in Table 1. Next, the forcing data used will be presented. Lastly, a comparison between FAO's VPD and ORCHIDEE's humidity gradient and VPD, as well as their $r_a$ definitions, will be exposed. This will lead to the definition of six different options to compute $ET_P$ regarding FAO's equation, which will be detailed in Table 2.

### 2.1 Definition of potential evaporation in ORCHIDEE: bulk, Milly and USEB's methods

Before this study was initiated and the USEB method implemented in ORCHIDEE, there were already two methods for computing potential evaporation implemented in the LSM: the bulk method and Milly's one (de Rosnay et al., 2002).

#### 2.1.1 Bulk method

Potential evaporation is computed following Manabe's scheme, 1969. It is based on Budyko's approach, where $ET_P$ is the product between the air density $\rho$ and the humidity gradient, divided by the aerodynamic resistance $r_a$. In its definition, the gradient's saturated humidity is computed using a virtual temperature, $T_w$. However the way in



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which this method is usually implemented in LSM's is using the actual surface temperature, $T_s$:

$$\mathrm{ET_P}(T_s) = \frac{\rho}{r_a}\left[q_s(T_s) - q_a\right] \tag{1}$$

Where $q_s$ is the specific humidity of saturated air and $q_a$ the specific air humidity. The actual surface temperature, verifies the following simplified energy balance equation:

$$R_n - G = \beta_s \frac{L\rho}{r_a}\left[q_s(T_s) - q_a\right] + \frac{\rho c_p}{r_a}\left[T_s - T_a\right] \tag{2}$$

$R_n$ being the net radiation and $G$ the soil heat flux. $T_a$ is the air temperature, $L$ the latent heat of vaporization of water and the specific heat of the air is denoted by $c_p$. $\beta_s$ is a parameter named moisture availability function, which reduces $\mathrm{ET_P}$ to actual evaporation (ET) when water supply is limited:

$$\mathrm{ET} = \beta_s \mathrm{ET_P}(T_s) \tag{3}$$

From now on, the $\mathrm{ET_P}$ computed by means of Eq. (1) will be referred to as $\mathrm{ET_{P\ BULK}}$.

Models computing potential evaporation as indicated in Eq. (1) will overestimate it, since $T_s$ is higher or equal (if the surface is unstressed) to $T_w$. As the surface gets drier, the difference between $T_w$ and $T_s$ will increase, amplifying the overestimation of $\mathrm{ET_P}$. In order to obtain a better estimate, the humidity gradient must be reduced. There are two possibilities to do so. The first one is to develop a correcting factor for the bulk formula (Milly, 1992). The second one is to compute a virtual temperature and calculate the humidity gradient with it (USEB method).

Since it has been proven that the bulk method overestimates $\mathrm{ET_P}$ (Milly, 1992), its estimation will not be analysed in this paper. Nevertheless, its response to climate change will be analysed and compared to the other methodologies.




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### 2.1.2 Milly's method

In order to reconcile $ET_P$'s estimation using $T_s$ instead of $T_w$, Milly proposed to apply a correction to the bulk formula in 1992. He did so by computing the relative error ($\xi$) given by the use of the actual surface temperature:

$$\xi = \frac{ET_P(T_s) - ET_P(T_w)}{ET_P(T_w)} = \frac{\frac{L\rho}{r_a} q_s'(T_a)\left[1-\beta_s\right]}{4\varepsilon T_a^3 + \frac{\rho c_p}{r_a} + \frac{L\rho}{r_a} q_s'(T_a)\beta_s} \quad (4)$$

Where $\varepsilon$ is the emissivity. From now on, the $ET_P$ computed by means of Eq. (1) with Milly's correction applied to it (see Table 1) will be referred to as $ET_{PMILLY}$.

### 2.1.3 USEB method

The aim of the USEB (Unstressed Surface Energy Balance) method is to estimate $ET_P$ in a LSM considering a non stressed surface. It is a new means of computing $ET_P$ which has been developed in ORCHIDEE. Just as the other two methods, it has been implemented in the SECHIBA module, Schématisation des EChanges Hydriques à l'Interface Biosphère-Atmosphère, (de Rosnay and Polcher, 1998) which simulates physical processes between the ground, vegetation and atmosphere, as well as the ground's hydrological cycle. The LSM can be run coupled with the General Circulation Model LMDZ, which was developed by the Laboratoire de Météorologie Dynamique (LMD) or on a stand-alone mode. For this study, off-line simulations have been carried out. The computation time step is typically 30 min, leading to a full representation of the diurnal cycle.

The first step is to compute a new energy balance in ORCHIDEE, differing from the existent one by the fact that the surface is considered to be saturated, as proposed by (Milly, 1992). This is achieved by neglecting the surface resistance in the energy balance calculation. It must be remarked that the soil heat flux is the one used in the normal energy balance. The effect of $G$ on the unstressed surface energy balance has



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been assumed to be negligible. Next, the virtual temperature is used to calculate the saturated humidity. Finally $ET_P$ is obtained following (Budyko, 1956). The relation used is Eq. (1), but the virtual temperature, $T_w$, is used instead of $T_s$ (see Table 1). From now on the $ET_P$ computed using the USEB method, will be referred to as $ET_{P\ USEB}$.

Actual evaporation may be computed through an unstressed surface energy balance. In order to do this, it is computed using Eq. (3), but $ET_P(T_w)$ and $\beta_w$ have to be used instead of $ET_P(T_s)$ and $\beta_s$. It can not be expected that $\beta_w$ and $\beta_s$ are equal, because the different assumptions on the temperature used in $ET_P$ will lead to a very different atmospheric demand. Therefore, it is very likely that the different assumptions made in LSM's regarding $ET_P$ lead to a different adaptation of the parameters used in the formulation of the moisture availability function.

### 2.2 FAO reference evapotranspiration equation

The Food and Agriculture Organization Irrigation and Drainage Paper n°56, provides a methodology to estimate daily mean $ET_P$ using meteorological data (referred to 2 m high) considering a reference surface. This surface is defined as a "hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m$^{-1}$ and an albedo of 0.23". It is described as an extensive surface of green grass of equal height, actively growing, not short of water and where the ground can not be seen. From the various options provided according to the time scale calculation, we limit ourselves to the daily mean estimate as it is the most widely used.

The Penman–Monteith combination method, which combines the surface energy balance and the diffusive approach, is adopted as the standard for reference evaporation:

$$\text{LET} = \frac{\Delta (R_n - G) + \rho c_p \frac{\text{VPD}}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \quad (5)$$

Where $\Delta$ is the slope of the vapour pressure curve, $\gamma$ is the psychrometric constant and $r_s$ the surface resistance. The VPD represents the vapour pressure deficit of the





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air. It is the difference between the saturation vapour pressure $P_s(T_a)$ and the actual one $P_a$. In order to obtain FAO's reference equation, the $\rho$ and the $c_p$ are replaced by the following expressions:

$$c_p = \frac{\gamma e L}{P} \tag{6}$$

$$\rho = \frac{P}{\delta_v (T_a + 273) R} \tag{7}$$

$\delta_v = 1.01$ and is used to approximate the virtual temperature throughout $T_a$. $R$ is the specific gas constant ($\mathrm{kJ\,kg^{-1}\,K^{-1}}$), $e$ the ratio of molecular weight of water vapour/dry air and $P$ the atmospheric pressure.

Neutral stability conditions, together with the fact that a fixed reference surface is taken into account, approximate the surface resistance to $70\,\mathrm{s\,m^{-1}}$ and the aerodynamic one to:

$$r_{\mathrm{a\ FAO}} = (C_{\mathrm{D\ FAO}} U_2)^{-1} \tag{8}$$

Where $C_{\mathrm{D\ FAO}} = 208^{-1}$ is referred to in this paper as FAO's drag coefficient and $U_2$ is the wind speed.

Finally if these approximations are replaced in Eq. (5) together with Eq. (6) to Eq. (8), the $\mathrm{ET_P}$ given in $\mathrm{mm\,d^{-1}}$ is:

$$\mathrm{ET_{P\ FAO}} = \frac{\frac{1}{L}\Delta(R_n - G) + \left[\frac{N_d e}{R} C_{\mathrm{D\ FAO}} \frac{1}{\delta_v}\right] \frac{\gamma}{T_a + 273} U_2 \mathrm{VPD}}{\Delta + \gamma\left(1 + \left[r_s C_{\mathrm{D\ FAO}}\right] U_2\right)} \tag{9}$$

Where $N_d$ is the number of seconds per day. The numerator's term in square brackets is approximated to 900 and the denominator's one to 0.34. As it has been explained in the previous section, no surface resistance has been considered in the USEB's method implementation. Since our aim is to estimate $\mathrm{ET_P}$ as in USEB, $r_s = 0$ in FAO's equation.





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To estimate $ET_P$ by means of FAO's reference equation, the daily mean forcing variables which are required are: the wind speed ($m\,s^{-1}$), for the $r_a$, and the net short-wave and long-wave radiation ($MJ\,m^{-2}\,d^{-1}$), to compute $R_n$ and $G$. Moreover, the maximum and minimum relative humidity (%) and temperature (°C) are also needed to obtain the daily average of VPD and $\Delta$, which is a function of temperature. Section 2.4 details how they have been obtained.

### 2.3 Temperature, radiation and mass transfer based-methods

Potential evaporation has also been computed in this study for three different empirical approximations. These are: Hargreaves (temperature based method), Priestley–Taylor (radiation based method) and Rohwer (mass transfer based method), all detailed in Xu and Singh (2002). The selection criteria has been the data availability and selecting methods where $ET_P$ was approximated through different variables. The equations are presented in Table 1.

(Hargreaves and Samani, 1982, 1985), approximate $ET_P$ by the air temperature. The difference between its maximum and minimum daily value TD, as well as the extraterrestrial radiation $R_a$ and a parameter $a = 0.0023$ are used to estimate it.

(Priestley and Taylor, 1972) simplifies the combination equation (Penman, 1948), basing $ET_P$'s estimation on the net radiation. Apart from the $R_n$, the $\Delta$ and $\gamma$ from FAO's equation and a coefficient $\alpha = 1.26$ are also used.

Finally, Rohwer's method (Rohwer, 1931) is a version of the Dalton equation and approximates $ET_P$ through the VPD and $U_2$. The VPD has been computed as it is proposed in FAO's reference equation.

Since these formulations include site specific parameters which need to be calibrated for each location, their $ET_P$'s representation over the globe will not be examined in this paper. Nevertheless, their sensitivity to the impact of climate change on the atmospheric forcing can be considered to a first order as independent of the site specific parameters. Therefore, this paper will examine the general global shape of the response





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of these empirical $ET_P$ formulations, assuming that they will be mostly independent of site specific adaptation, which would have to be undertaken before their application in impact models.

### 2.4 Forcing data

The study has been carried out for two different periods: a reference one (from 1990 to 2000) and a future scenario period (from 2000 to 2100). The ORCHIDEE simulation for the reference period allows to perform a validation of the model and FAO's output. The future scenario simulation is performed in order to examine the sensitivity of the $ET_P$ estimations to climate change.

The Water and Global Change (WATCH, www.eu-watch.org) Forcing Data (WFD) used for the reference period simulation, corresponds to sub-daily, regularly gridded meteorological forcing data, with a resolution of half a degree, from 1958 to 2001 (Weedon et al., 2011). Regarding the future period, the forcing data employed, corresponds to the IPSL A2 scenario (Piani et al., 2010) which comprehends data from the year 2000 till 2100. It is considered to be a greenhouse gas increase scenario, which is based on the IPCC fourth Special Report on Emissions Scenarios.

FAO and the empirical approximation's estimates will use daily averages of WFD except for variables which are affected by land surface properties. For these variables, daily averages diagnosed within ORCHIDEE are used. Therefore, atmospheric variables, namely maximum and minimum relative humidity and air temperature as well as the wind speed correspond to that given by WFD. On the other hand, surface related parameters, like the net radiation, contain information from both: the WFD and ORCHIDEE. The same simulations have been used to estimate $ET_P$ using all of the methodologies listed in Table 1. As a result, the climate conditions are equal for all estimations of $ET_P$.





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### 2.5 Comparison of methodologies

FAO's approximation of the $r_a$ and VPD differs from their computation in ORCHIDEE. So, apart from the original $ET_P$ estimation proposed by the FAO, five alternative estimations were performed replacing the original $r_a$ by ORCHIDEE's one and its VPD by the VPD computed in ORCHIDEE and the model's humidity gradient. These as well as ORCHIDEE's estimations are explained in Table 2.

#### 2.5.1 Aerodynamic resistance

When a reference surface is considered to compute $ET_P$, the area of validity is limited. For instance, the Environmental and Water Resources Institute (EWRI) provides a standardized reference evapotranspiration equation, which distinguishes between tall and short crops regarding the reference surface (Walter et al., 2005). This implies a difference in the aerodynamic resistance between the two types of crops. Since $r_a$ will be lower for tall ones than for short ones, $ET_P$ will increase for the first kind.

FAO's $r_a$ considers neutral stability conditions and a reference surface with specific characteristics. This results in a constant drag coefficient ($C_{D\ FAO}$) and the wind speed being the only time evolving variable in the calculation of $r_a$. On the contrary, the drag coefficient in ORCHIDEE's computation ($C_{D\ ORC}$) varies as a function of the surface roughness and atmospheric stability following the Louis scheme (Louis, 1979). This $r_a$ is used in the bulk formula, the USEB and Milly's method, and is obtained with:

$$r_{a\ ORC} = (C_{D\ ORC} U_2)^{-1} \quad (10)$$

Unlike FAO's proposal, ORCHIDEE is not limited to a unique reference surface, meaning that roughness is variable in space and time. It provides a representation of the vegetation variability considering 13 different PFT (Plant Functional Types), detailed in (Krinner et al., 2005). So, if ORCHIDEE's $r_a$ replaces FAO's one, we will not only take into account the different surface types, but as well, the time evolving atmospheric stability.





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To replace FAO's $r_a$ by ORCHIDEE's one, the drag coefficient computed in the LSM ($C_{D\,ORC}$), has been saved for usage in FAO's equation. For the cases where the $r_a$ is replaced, $ET_{P\,FAO}$ will be computed as follows:

$$ET_{P\,FAO} = \frac{\frac{1}{L}\Delta\left(R_n - G\right) + \left[\frac{N_d e}{R} C_{D\,FAO} \frac{1}{\delta_v}\right] \frac{\gamma}{T_a + 273} U_2 \frac{C_{D\,ORC}}{C_{D\,FAO}} \mathrm{VPD}}{\Delta + \gamma} \quad (11)$$

### 2.5.2 VPD and humidity gradient

(Allen et al., 1998) states that the difference between the water vapour pressure from the evaporating surface and the surrounding atmosphere, is the driving force that removes water vapour from the surface. It is approached in a different way depending on the methodology used to calculate $ET_P$. For example, estimations based on observations only will use a VPD, because $T_w$ can not be measured. The Penman–Monteith combination method, which is the basis of FAO's equation, computes a VPD. However, $ET_P$ estimates in models generally use the gradient, as surface information is available. In the first case, the calculation is limited to the air at 2 m, while in the second one both the air and the surface are considered.

FAO's equation proposes several approximations of the VPD, and the user chooses basing on the availability of atmospheric data. For this study the approximation using maximum and minimum 2 m temperature and relative humidity, RH, has been employed. In order to compute it, daily averages of these variables have been obtained from the WFD data sets.

On the other hand, $ET_{P\,BULK}$, $ET_{P\,USEB}$ and $ET_{P\,Milly}$ are computed using a humidity gradient. Taking advantage of ORCHIDEE, it uses the Clausius–Clapeyron equation at a 30 min time step, resulting in a precise representation of the diurnal cycle. It must be remarked that two different gradients are computed in ORCHIDEE. In the first place, there is one used in the bulk formula and Milly's method, where $q_s$ is computed with $T_s$. Secondly, regarding the USEB method implementation, $q_s$ is computed by means of the virtual temperature, $T_w$.





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In order to test the differences between the two representations of the water vapour removal, $ET_{P\ FAO}$ has been computed replacing its VPD by ORCHIDEE's humidity gradient, converted to a vapour pressure gradient. Since FAO's equation considers an actual temperature instead of a virtual one, the LSM's gradient from the bulk formula, which is calculated using $T_s$ is more appropriate to be used in FAO's formulation. To compute it, ORCHIDEE's daily estimates of the saturated surface and the air's humidity have been used. Apart from this computation, the difference between the saturated vapour pressure and the air vapour pressure at 2 m ($VPD_{ORC}$) has also been saved from the WFD, in order to calculate $ET_{P\ FAO}$. This will allow for the validation of the results obtained using the humidity gradient and test the quality of FAO's estimation of the daily mean VPD.

Daily potential evaporation has been computed for the different methodologies and cases. Afterwards, the monthly and yearly means have been calculated. Negative monthly $ET_P$ occurring under inconsistent atmospheric forcings has been set to zero in the averaging processes.

In order to approach the climate change sensitivity study, trends for the different $ET_P$ methods, as well as the VPD, gradient, $r_a$ and $R_n$ have been computed. The significance level chosen in this analysis is 95 %, being computed by means of the Cox–Stuart test.

## 3 Results and discussion

The various estimations of $ET_P$ will be compared in this section. To begin with, the reference period will be assessed, showing ORCHIDEE's computation (USEB and Milly's methods) as well as FAO's equation results computed as explained in Tables 1 and 2. Afterwards, $ET_P$ trends for ORCHIDEE's computations, FAO's reference equation (considering the six cases) and the three simplified approximations will be analysed regarding climate change.





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In order to ease the comparison, four regions have been selected to analyse the different methodologies with the aim to sample different climates, surface characteristics and vegetation types. The dry areas chosen are situated in northern Australia (110° E to 140° E, 10° S to 30° S) and at the Sahel (20° W to 15° E, 10° N to 20° N), representing semi-arid and arid regions. On the other hand, the two humid areas have been selected in a temperate region, Central Europe (0 to 14° E, 44° N to 54° N), and in a tropical one, the Amazon basin (70° W to 50° W, 2° N to 14° S).

### 3.1 Validation of $ET_P$ estimates

Table 3 shows mean annual $ET_P$ values for the selected regions computed using the USEB and Milly's method, as well as the six cases defined for FAO's equation. This comparison between methodologies is also analysed at a global scale in Fig. 1. It must be stressed that the results from Table 3 are general over the globe as it can be observed in Fig. 1, which shows mean annual $ET_P$ values for the USEB method in Fig. 1a and its percentage difference with Milly's method in Fig. 1b and FAO's $ET_P$ estimation Fig. 1c to f. Cases 5 and 6 for FAO's computation have not been included, due to their similarity with cases 2 and 4.

In the first place, USEB and Milly's methods provide equivalent results in humid and arid regions. This result shows that using the actual surface temperature overestimates $ET_P$, and that both methodologies achieve their purpose of lowering it (Milly, 1992).

In the second place, values estimated by FAO's equation (case 1) are lower than those provided by the USEB method, specially in arid areas, as shown in Fig. 1c. For example, in the Australian region FAO's $ET_P$ is 60 % lower than USEB's one, whereas in the Central European region, it is 24 % lower. Smaller differences are expected between the formulations in humid regions, since FAO's equation is conceived for continuously wet areas. In order to explain the differences between these two methodologies, the cases defined for FAO's equation, and thus the role of the approximations made for the VPD and $r_a$, have been analysed. The differences between cases 1, 2 and 5 will inform about the effect of FAO's VPD approximation compared to ORCHIDEE's gradient and to the $VPD_{ORC}$ (computed at a higher frequency). Case 1 compared to case 3 will serve to test the impact of the aerodynamic resistance effect when the assumption of neutral stability conditions defined in FAO's estimation is lifted. Finally, cases 4 and 6 will show the combined effect of the LSM's gradient, or $VPD_{ORC}$, with its $r_a$.

Table 3 and Fig. 1e identify case 3 as the one that provides the largest increase of $ET_P$ in FAO's equation. According to its definition (see Table 1), $ET_P$ increases if the $r_a$ decreases. Taking into account that higher $ET_P$ values are yielded when ORCHIDEE's $r_a$ is used in FAO's equation (cases 3, 4 and 6), we conclude that the assumption of a neutral atmosphere made by FAO's formulation and the fact that it does not consider the surface roughness, tend to overestimate $r_a$. Comparing case 1 to cases 3, 4 and 6, it can be concluded that the assumption on the surface layer turbulence plays an important role. If it is relaxed by using the LSM's $r_a$, the difference with the USEB method is strongly reduced, as shown in Fig. 1e and f.

The gradient obtained from the bulk formula and the $VPD_{ORC}$ are smaller than FAO's VPD, leading to higher estimates of FAO's case 1 compared to cases 2 and 5. As expected, $VPD_{ORC}$ and FAO's VPD are very close to each other and the humidity gradient differs slightly more. Actually, FAO's proposal of the VPD estimation is expected to overestimate $ET_P$ in non reference (arid) areas. The reason is that there is a higher $T_a$ and a lower $P_a$, which implies a higher VPD than what would occur under reference conditions (Allen et al., 1998). As a result, FAO's VPD approximation with the maximum and minimum 2 m temperature and relative humidity overestimates the atmospheric demand. On the other hand, deriving $VPD_{ORC}$ or using ORCHIDEE's humidity gradient implies a sub-diurnal frequency computation, the availability of all the variables needed and a better representation of the diurnal cycle. So we recommend the use of a LSM to compute the VPD instead of the approximation of FAO. Apart from $VPD_{ORC}$, FAO's equation has also been computed with the bulk formula's gradient and the results match each other. If Fig. 1c and d are compared, the effect of using FAO's approximation or the humidity gradient from the bulk formula can be observed.





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Figure 1f shows that the combined effect of ORCHIDEE's $r_a$ with the bulk formula's gradient (case 4) provides an $ET_P$, which is in good agreement with the USEB method. Results are similar if $VPD_{ORC}$ and ORCHIDEE's $r_a$ (case 6) are used. In both cases, the difference with ORCHIDEE's computation is below 20 % in most parts of the world. These are the configurations of FAO's equation that best match globally the USEB method. It must be remarked that case 3 provides estimates which are closer to the USEB method concerning certain arid regions. However, this is due to the overestimation of FAO's VPD.

To sum up, both $ET_{P\ USEB}$ and $ET_{P\ Milly}$ provide similar results, confirming the fact that using $T_s$ in $ET_P$'s estimation overestimates it. $ET_{P\ USEB}$ and $ET_{P\ FAO}$ are different due to certain assumptions made for the derivation of FAO's equation, like the atmospheric stability for instance. ORCHIDEE's $r_a$ provides a more detailed characterization of the surface and a better description of the atmospheric stability. When used in FAO's equation, the differences with the USEB method are reduced by more than 50 % in some regions. The gradient used in the bulk formula, as well as the $VPD_{ORC}$ are lower than FAO's approximation of the VPD, which is known to be overestimated in arid regions. Globally, the combined effect of the $VPD_{ORC}$ and the LSM's $r_a$ in the first place, and the gradient and the LSM's $r_a$ in the second one, provide the closest match to the $ET_P$ estimates of the USEB method.

### 3.2 Sensitivity of physically based $ET_P$ estimates

This section analyses the sensitivity of estimated $ET_P$ to climate change, as simulated by the IPSL model for the A2 scenario. Special attention is paid to the USEB method and FAO's reference equation because they are based on robust equations and represent the two families in which $ET_P$'s estimations are approached. This study is performed after analysing the causes of the different behaviours shown by both formulations (see Sect. 3.1). The Hargreaves, Priestley–Taylor and Rohwer approximations have also been studied, in the next section, to analyse their sensitivity to the evolution of atmospheric conditions expected in a warmer climate.





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Climate change is driven by an increase in greenhouse gases which leads to higher incoming long-wave radiation resulting in warmer surface and air temperatures. This, added to a lower diurnal amplitude of surface temperature will affect both, the VPD and the gradient between the surface and the atmosphere. Although rainfall and actual evaporation will experience changes too, they are only expected to affect $ET_P$ in an indirect way.

$ET_P$'s linear dependence of VPD/humidity gradient and its inverse relation with the $r_a$ are two common characteristics shared by ORCHIDEE's $ET_P$ methodologies and FAO's equation. However, while the $R_n$ is considered through the gradient computation in the first ones, it is an additive factor to the VPD in FAO's formulation. Since climate change modifies variables used to estimate potential evaporation the sensitivities of (i) ORCHIDEE's and FAO's $r_a$, (ii) both VPD's and the bulk formula's gradient, as well as (iii) the $R_n$, have been analysed in order to study their impact on $ET_P$. Figure 2 shows the trends which are statistically significant in percentage per decade.

The impact of climate change on wind speed affects directly the $r_a$ as used in FAO. It is shown in Fig. 2a, where $r_a$'s trends are driven by the wind speed. On the other hand, Fig. 2b provides the trends in ORCHIDEE's $r_a$, which is impacted by climate change through the wind speed and the atmospheric stability. Thus it provides a stronger and more diverse response to climate change, since it yields trends which range from −20 % to 20 % per decade. Contrary to FAO's equation, the fact that ORCHIDEE's $r_a$ displays stronger negative trends, can induce increases of $ET_P$. Therefore, it has to be noted that even in regions where the trend in $r_a$ is not statistically significant, it can still impact $ET_P$.

Of the three sets of variables considered, the VPD and the bulk formula's gradient have a systematic increase over the world, as seen in Fig. 2c and d, just as the $ET_P$. A similar behaviour is shown by USEB's gradient in Fig. 2e, which provides a generalized positive trend for most continental surfaces, but shows negative ones in some mountainous regions. The trend coherence shown between the $ET_P$ and the VPD/humidity gradient, is reassured by the spatial correlation between them,





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which is 0.54 for FAO's case and 0.61 for USEB's one. It has to be noted that spatial correlation was also computed between the $ET_P$ and $r_a$, obtaining weaker relations. These reasons, as well as the fact that there is a linear dependence between $ET_P$ and VPD/humidity gradient, prove that these are the dominant term in $ET_P$'s trend for the climate change scenario we are considering.

Finally, the net radiation's sensitivity has also been studied, because it determines the energy available at the surface for evaporation. ORCHIDEE's computation of $ET_P$, FAO's reference equation and Priestley–Taylor's equation, use the same radiation dependence. The trends in $R_n$, shown in Fig. 2f, are positive in most cases as a direct consequence of an increase in greenhouse gases (Philipona and Dürr, 2004).

Figure 3a shows a significant increase of $ET_P$ over the entire globe (from 0 to 8 % per decade), computed with the USEB method. Based on the discussion above regarding the parameters it depends on, we conclude that it is essentially driven by the humidity gradient.

In order to compare the trends obtained for the various estimates of $ET_P$, the difference in trends as % of the value obtained for USEB's one has been diagnosed. Therefore, Fig. 3b to e display differences in % of % per decade. This information is also detailed for the selected regions and the methodologies chosen to compute $ET_P$ in Table 4. It has to be remarked that the $ET_P$ computed using the bulk formula has also been considered in the sensitivity study, and thus included in Table 4.

Apart from the fact that $ET_{P\ Milly}$ provides estimates which are in good agreement with the USEB method (see Sect. 3.1), the similarity in trends between both methods indicates that their sensitivities are also comparable. However, the bulk formula overestimates $ET_P$'s sensitivities, because it uses $T_s$ in its computation, without applying a correcting factor.

Compared with FAO's reference equation (case 1), the USEB method provides higher trends and thus higher sensitivity to climate change, as shown in Fig. 3b. For example, a difference of 54 % is found over part of the region defined for Australia. This means that if the USEB method has an increase of 2.45 % per decade, FAO's trend is




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only of 1.13 % per decade. Since the $ET_P$ values provided by the two formulations differ (see Table 3), these percentages correspond to increases of 0.33 and 0.06 mm $d^{-1}$ per decade for the USEB method and FAO's equation respectively. Therefore, it must be emphasized that a difference of an order of magnitude can be yielded between the two methodologies.

Table 4 shows that the differences are reduced when ORCHIDEE's $r_a$ is used in FAO's equation (cases 3, 4 and 6) in all regions except the Amazon basin. This implies that considering atmospheric stability generally amplifies $ET_P$'s trends. Therefore, even though $r_a$ may not drive a global $ET_P$ trend, it does amplify or decay it. For instance, Fig. 3b shows that the difference in trends between $ET_{P\,USEB}$ and $ET_{P\,FAO}$ is higher in the north than in the south of Australia. Cases 1 and 3 were compared and FAO case 1 has a difference in trends of 1 % between the northern and southern Australian regions, while if the atmospheric stability simulated by ORCHIDEE is taken into account (case 3), this difference rises to 38 %. Therefore, the VPD/humidity gradient drives $ET_P$'s trend and the spatial variation of $r_a$ produces the contrast seen in the USEB method and not in FAO's one.

Comparing case 1 with cases 2 and 5 in Table 4, $ET_P$'s sensitivity increases when $VPD_{ORC}$ or ORCHIDEE's gradient are used in FAO's equation. This implies that FAO's estimation of the VPD is less sensitive to climate change than $VPD_{ORC}$ and ORCHIDEE's gradient.

As found for the reference period, the combined effect of ORCHIDEE's humidity gradient or the $VPD_{ORC}$ with $r_a$ (FAO's cases 4 and 6), provides trends which are in good agreement with USEB's ones. For the Amazon region, where no strong trends were found regarding the VPD and $r_a$, no significant difference is expected between the two methodologies, as shown in Table 4.

Another issue to be taken into account is the fact that GCMs may have significant errors and thus estimates of $ET_P$ can have a strong bias. However, even though they might be affected by systematic biases, the estimate of the trend will include aspects of climate change in the wind speed and turbulence that can not be integrated into the





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more classical estimates of $ET_P$'s daily equation. So it might be more suitable to unbias $ET_P$ estimates originating in GCMs, than the variables needed to compute it by means of FAO's equation.

### 3.3 Sensitivity of empirical $ET_P$ estimates

The three empirical approximations show different behaviors regarding their sensitivity to climate change. None of them consider changes in atmospheric stability, which is a key aspect in the FAO formulation as it has shown to amplify $ET_P$'s trends for a changing climate. Rohwer's equation shows higher trends than the USEB method, which in some cases are increased by more than 400 %, as shown in Fig. 3e. The cause is that $ET_P$ is approximated by only keeping the dependence on the wind speed and the VPD, which provides positive trends from 0 to 30 % per decade, shown in Fig. 2c, and has been identified as the driving variable of $ET_P$'s trends. On the other hand, the Hargreaves and Priestley–Taylor methods show a positive difference in trends in Fig. 3c and d respectively, which implies that they provide lower sensitivity to climate change than the USEB method. Hargreaves' trend is driven by $T_a$ and from a global point of view, it has higher sensitivity to climate change than FAO's method. However, Priestley–Taylor's trend is driven by the $R_n$ and provides lower/higher trends than FAO's equation in arid/humid regions. This result is in good agreement with (Weedon et al., 2011) as well as (Kingston et al., 2009), who found that the lack of dependence of VPD in this formulation affects more arid regions than humid ones.

Because the empirical methods do not include the complex interaction in changes of the driving variables ($R_n$, $r_a$, VPD/gradient) they are not able to reproduce the trends found with the more physically based estimates. Furthermore, they are also regionally constrained. For instance, Fig. 2f shows that the $R_n$ has a high impact in the Amazonian region and the approximation that provides the closest sensitivity to USEB's one is Priestley–Taylor, which is radiation based. The other two methods do not consider the net radiation. As a result, Rohwer's trend differs by 106 %, while Hargreaves equation does not even provide any significant trend in that region.





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As occurred in Sect. 3.1, the values analysed from Table 4 show results which are representative of the general behaviour of the trends provided by the different methodologies.

Summing up the sensitivity study performed for $ET_P$ estimates, the VPD/humidity gradient has been identified as the key parameter that drives the increase of $ET_P$ for the IPSL A2 climate change scenario. The stability assumption made by FAO is probably an oversimplification which leads to a lower sensitivity than the USEB method's one. The three empirical estimations of $ET_P$ show different sensitivity to climate change, depending on the region selected and the parameters used to compute $ET_P$ and none of them seem compatible with the physically estimates.

## 4 Summary and conclusions

The study detailed in this paper has consisted of three stages. In the first one, a new method to compute Penman–Monteith's potential evaporation ($ET_P$) through an unstressed surface energy balance (USEB) has been implemented in the ORCHIDEE land surface model. During the second stage, a comparison between several methodologies has been performed for the current climate. These are the USEB method, the previous estimation implemented in ORCHIDEE (Milly, 1992) and FAO's reference evapotranspiration equation. In the third stage, $ET_P$'s sensitivity to climate change has been studied for the same methodologies, as well as for three empirical approximations (Hargreaves, Priestley–Taylor and Rohwer). The study has been extended to $ET_P$'s parameters in order to identify the key ones for a changing climate.

The USEB method is based on Budyko's hypothesis and thus is a more robust equation than FAO's recommendation of the Penman–Monteith method (Allen et al., 1998). FAO's equation has been developed for a reference surface and considers a neutral atmosphere. In order to adapt it, the aerodynamic resistance ($r_a$) as proposed by ORCHIDEE has been introduced in FAO's equation. Furthermore, the humidity gradient



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(used in ORCHIDEE's estimations) and the VPD, also computed in the land surface model, have been used in FAO's equation too.

The results have shown that USEB and Milly's estimations are in good agreement regarding $ET_P$'s global average as well as its sensitivity to climate change. However, USEB differs from FAO, since it provides higher estimates and contrast in annual spatial variance as well as a higher climate change signal. Significant differences have also been found with the amplitude of the trends provided by the empirical approximations and with their spatial structures. The sensitivity study of $ET_P$'s parameters has shown a similar behaviour between FAO's VPD approximation and ORCHIDEE's VPD and humidity gradient, being the last two more sensitive to climate change. FAO's proposal of the aerodynamic resistance has been found to reduce the spatial structures and the global average of $ET_P$'s trends when compared to ORCHIDEE's methods. Correlation studies between the $ET_P$ and the evolution of these parameters have shown strong spatial relations between the VPD/humidity gradient and the atmospheric water demand. Such relations were not found for the aerodynamic resistance.

It can be concluded from the study that the consistency of the USEB and Milly methods shows that they are reasonable estimates of Penman–Monteith's $ET_P$ estimation. Both of them agree that the $ET_P$ obtained through the bulk formula is overestimated because of a humidity gradient which is exaggerated through the usage of the actual surface temperature. It has to be remarked that although the USEB method implies more computational time, it has fewer assumptions than Milly's correction and thus should be more robust. It can also be concluded that the USEB method presents a higher sensitivity to climate change than FAO's one. As for the empirical approximations, the simplifications made in the $ET_P$ estimation, neglect processes that play an important role when the climate warms. Concerning $ET_P$'s key parameters, on the one hand, the assumption of neutral stability conditions is one of the weakest ones made in FAO's formulation. On the other hand, the humidity gradient and the VPD have been identified as the driving variable for the estimate of $ET_P$ carried out with the USEB and FAO's methodologies respectively.





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This study has been performed focusing on annual mean $ET_P$. However the analysis has also been carried out in the Sahelian region for the humid and arid seasons. No fundamental difference has been found at the seasonal scale and thus have not been shown above. The VPD and humidity gradient are confirmed to be the key parameters that drive the positive trend of $ET_P$, noticing that their sensitivities increased during the humid season.

Agronomic and hydrological models which need to estimate evaporation take as basic estimates of $ET_P$ those derived from Penman–Monteith equation. If these models are to be used in climate change studies, attention has to be paid to its sensitivity. This paper has shown that various methods developed to estimate $ET_P$ do not provide equivalent estimates neither comparable sensitivities to climate change. The estimation of $ET_P$ in the LSM is the method that contains most of the physical processes that we believe are important in the climate change impact on $ET_P$. These processes have been identified and in some cases, found to be missing in other $ET_P$ estimations.

For all these reasons, we determine that the USEB and Milly's methods not only provide a good estimate for current climate, but also produce a realistic sensitivity of $ET_P$ to climate change. Therefore, we suggest that they should be regarded as an essential variable of climate models and propose to keep it as a standard output of any IPCC simulation.

Potential evaporation is a key variable in the climate system, because it represents the interactions between the surface and the atmosphere. It should provide a good summary of the impact of climate change on surface processes, since it depends on variables like temperature, net radiation and humidity.

Different methods have been developed to estimate its value and we believe that they should not only be tested for accurate representation of current climate, but its sensitivity to climate change should be considered too. In addition, regarding climate change studies, we recommend to unbias $ET_P$ modelled estimates, instead of reestimating them from basic atmospheric variables.





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## References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements, FAO Irrigation and Drainage Paper No. 56, Rome, 1998.

Budyko, M. I.: Heat Balance of the Earth's Surface, Gidrometeoizdat, Leningrad, 1956.

Campbell, R. B. and Phene, C. J.: Estimating potential evapotranspiration from screened pan evaporation, Agr. Meteorol., 16, 343–352, 1976.

de Bruin, H. A. R., Trigo, I. F., Jitan, M. A., Temesgen Enku, N., van der Tol, C., and Gieske, A. S. M.: Reference crop evapotranspiration derived from geo-stationary satellite imagery: a case study for the Fogera flood plain, NW-Ethiopia and the Jordan Valley, Jordan, Hydrol. Earth Syst. Sci., 14, 2219–2228, doi:10.5194/hess-14-2219-2010, 2010.

de Rosnay, P. and Polcher, J.: Modelling root water uptake in a complex land surface scheme coupled to a GCM, Hydrol. Earth Syst. Sci., 2, 239–255, doi:10.5194/hess-2-239-1998, 1998.

de Rosnay, P., Polcher, J., Bruen, M., and Laval, K.: Impact of a physically based soil water flow and soil-plant interaction representation for modeling large-scale land surface processes, J. Geophys. Res., 107, 4118, doi:10.1029/2001JD000634, 2002.

Hargreaves, G. H. and Samani, Z. A.: Estimation of potential evapotranspiration, Journal of Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, 108, 223–230, 1982.





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Hargreaves, G. H. and Samani, Z. A.: Reference Crop Evapotranspiration from Temperature, Appl. Eng. Agr., 1, 96–99, 1985.
Hobbins, M. T., Dai, A., Roderick, M. L., and Farquhar, G. D.: Revisiting the parameterization of potential evaporation as a driver of long-term water balance trends, Geophys. Res. Lett., 35, L12403, doi:10.1029/2008GL033840, 2008.
Kingston, D. G., Todd, M. C., Taylor, R. G., Thompson, J. R., and Arnell, N. W.: Uncertainty in the estimation of potential evapotranspiration under climate change, Geophy. Res. Lett., 36, L20403, doi:10.1029/2009GL040267, 2009.
Kohler, M. A., Nordenson, T. J., and Fox, W. E.: Evaporation from pans and lakes, Weather Bureau Research Paper 38, US Department of Commerce, Washington, 1955.
Krinner, G., Viovy, N., de Noblet-Ducoudré, N., Ogée, J., Polcher, J., Friedlingstein, P., Ciais, P., Sitch, S., and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochem. Cy., 19, GB1015, doi:10.1029/2003GB002199, 2005.
Louis, J.-F.: A parametric model of vertical eddy fluxes in the atmosphere, Bound.-Lay. Meteorol., 17, 187–202, 1979.
Makkink, G. F.: Testing the Penman Formula by means of lysimeters, Journal of the Institute of Water Engineers, 11, 277–288, 1957.
Manabe, S.: Climate and the ocean circulation, 1. the atmospheric circulation and the hydrology of the earth's surface, Mon. Weather Rev., 97, 739–774, 1969.
Milly, P. C. D.: Potential evaporation and soil moisture in general circulation models, J. Climate, 5, 209–226, 1992.
Monteith, J. L.: Evaporation and surface temperature, Q. J. Roy. Meteor. Soc., 107, 1–27, 1981.
Parry, M., Arnell, N., Berry, P., Dodman, D., Frankhauser, S., Hope, C., Kovats, S., Nicholls, R., Satterthwaite, D., Tiffin, R., and Wheeler, T.: Assessing the Costs of Adaptation to Climate Change, A Review of the UNFCCC and Other Recent Estimates, Grantham Institute for Climate Change, Imperial College London (UK), 2009.
Penman, H. L.: Natural evaporation from open water, bare soil and grass, P. R. Soc. London, 193, 120–145, 1948.
Philipona, R. and Dürr, B.: Greenhouse forcing outweighs decreasing solar radiation driving rapid temperature rise over land, Geophys. Res. Lett., 31, L22208, doi:10.1029/2004GL020937, 2004.





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Piani, C., Weedon, G. P., Best, M., Gomes, S. M., Viterbo, P., Hagemann, S., and Haerter, J. O.: Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models, J. Hydrol., 395, 199–215, 2010.

Priestley, C. H. B. and Taylor, R. J.: On the assessment of surface heat flux and evaporation using large-scale parameters, Mon. Weather Rev., 100, 81–92, 1972.

Rohwer, C.: Evaporation from free water surface, USDA Technical Bulletin, 271, 127, 1–96, 1931.

Walter, I. A., Allen, R. G., Elliot, R., Itenfisu, D., Brown, P., Jensen, M. E., Mecham, B., Howell, T. A., Snyder, R., Eching, S., Spofford, T., Hattendorf, M., Martin, D., Cuenca, R. H., and Wright, L.: The ASCE standardized reference evapotranspiration equation, Task Committee on Standardization of Reference Evapotranspiration Final Report, ASCE Environmental and Water Resources Institute, Reston, VA, 2005.

Wang, K. and Dickinson, R. E.: A review of global terrestrial evapotranspiration: observation, modeling, climatology, and climatic variability, Rev. Geophys., 50, RG2005, doi:10.1029/2011RG000373, 2012.

Weedon, G. P., Gomes, S., Viterbo, P., Shuttleworth, W. J., Blyth, E., Österle, H., Adam, J. C., Bellouin, N., Boucher, O., and Best, M.: Creation of the WATCH forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century, J. Hydrometeorol., 12, 823–848, 2011.

Xu, C.-Y. and Singh, V. P.: Cross comparison of empirical equations for calculating potential evapotranspiration with data from Switzerland, Int. Ser. Prog. Wat. Res., 16, 197–219, 2002.

**Table 1.** The different methodologies used in this study to compute $ET_P$.

| $ET_P$'s Methodologies | | |
|---|---|---|
| Method | Equation | Comments |
| Bulk | $ET_{P\ Bulk} = \frac{\rho}{r_a}\left[q_s(T_s) - q_a\right]$ | Since $T_s$ is higher than $T_w$, $ET_P$ is overestimated. |
| Milly | $ET_{P\ Milly} = \frac{\rho}{r_a}\left[q_s(T_s) - q_a\right]\left(\frac{1}{1+\xi}\right)$ | $T_s$ and $q_s(T_s)$ are computed through the normal surface energy balance. Milly's correction for soil moisture stress is applied. |
| USEB | $ET_{P\ USEB} = \frac{\rho}{r_a}\left[q_s(T_w) - q_a\right]$ | $T_w$ and $q_s(T_w)$ are computed through an unstressed surface energy balance. |
| FAO (saturated surface) | $ET_{P\ FAO} = \frac{\frac{1}{L}\Delta(R_n - G) + \left[\frac{N_d e}{R} C_{D\ FAO} \frac{1}{\delta_v}\right]\frac{\gamma}{T_a+273}U_2 \mathrm{VPD}}{\Delta+\gamma}$ | The surface is considered to be unstressed and no surface resistance has been considered. |
| Hargreaves | $ET_{P\ HAR} = aR_a\, TD^{1/2}(T_a + 17.8)$ | Temperature based method |
| Priestley–Taylor | $ET_{P\ PT} = \alpha\frac{\Delta}{(\Delta+\gamma)}\frac{R_n}{\lambda}$ | Radiation based method |
| Rohwer | $ET_{P\ ROH} = 0.44(1 + 0.27U_2)\mathrm{VPD}$ | Mass transfer based method |



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**Table 2.** Description of $ET_{P\ USEB}$, $ET_{P\ BULK}$, $ET_{P\ Milly}$ and the cases defined to compute $ET_{P\ FAO}$, according to the variables they depend on and the assumptions made for their calculation. The computation has been carried out at a daily time step, except:
[a] The time step computation of $ET_P$ has been the LSM's one, 30 min. A daily mean has been computed afterwards.
[b] The parameter's time step computation has been the LSM's one, 30 min. Next a daily mean has been saved to use it in FAO's equation.

| | $ET_P$'s Methodologies and Assumptions | | |
|---|---|---|---|
| Method | Temperature | Deficit/Gradient | Aerodynamic Resistance |
| [a] USEB | $T_w$ | $q_s(T_w) - q_a$ | $r_{a\ ORC} = (C_{D\ ORC} U_2)^{-1}$ |
| [a] Bulk and Milly | $T_s$ | $q_s(T_s) - q_a$ | As USEB |
| FAO case 1 | $\frac{T_{a\ max}+T_{a\ min}}{2}$ | FAO's proposal | FAO's proposal |
| | | $VPD = P_s(T_a) - P_a$ | $r_{a\ FAO} = (C_{D\ FAO} U_2)^{-1}$ |
| FAO case 2 | As FAO Case 1 | ORCHIDEE's computation | As FAO Case 1 |
| | | $Gradient = P_s(T_s) - P_a$ | |
| FAO case 3 | As FAO Case 1 | As FAO Case 1 | As USEB |
| FAO case 4 | As FAO Case 1 | As FAO Case 2 | As USEB |
| FAO case 5 | As FAO Case 1 | [b] ORCHIDEE's computation | As FAO Case 1 |
| | | $VPD_{ORC} = P_s(T_a) - P_a$ | |
| FAO case 6 | As FAO Case 1 | As FAO Case 5 | As USEB |





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**Table 3.** Mean $ET_P$ for the reference period regarding USEB and Milly's methods, as well as FAO's six cases.

| $ET_P$ (mm d$^{-1}$) – Reference Period – | | | | | |
|---|---|---|---|---|---|
| Method | | Australia | Sahel | Central Europe | Amazon Basin |
| ORCHIDEE | USEB | 14.5 | 9.5 | 2.1 | 3.8 |
| | Milly | 13.8 | 9.5 | 2.2 | 4 |
| FAO | Case 1 | 5.8 | 5.4 | 1.6 | 2.5 |
| | Case 2 | 5.7 | 4.9 | 1.2 | 2.4 |
| | Case 3 | 14.2 | 9.3 | 2.5 | 4.2 |
| | Case 4 | 13.5 | 7.9 | 1.8 | 3.5 |
| | Case 5 | 5.6 | 5.2 | 1.5 | 2.4 |
| | Case 6 | 13.3 | 8.9 | 2.3 | 3.6 |

**Table 4.** Significant increases of $ET_P$ are given in % per decade. Their relative changes compared to the USEB method are expressed as a %: $\left(\frac{\text{USEB}-\text{Method}}{\text{USEB}}\right)100$. The N/A appears when no significant trend has been found.

| $ET_P$ Sensitivity Study – Future Scenario – | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Method | | $ET_P$ change (% per decade) | | | | Trend difference to USEB (%) | | | |
| | | Australia | Sahel | Central Europe | Amazon Basin | Australia | Sahel | Central Europe | Amazon Basin |
| ORCHIDEE | USEB | 2.45 | 1.85 | 2.05 | 1.24 | | | | |
| | Milly | 2.1 | 1.62 | 2.26 | 1.4 | 14 | 12 | −10 | −13 |
| | Bulk | 4.9 | 4.36 | 5 | 3.61 | −100 | −136 | −144 | −191 |
| FAO | Case 1 | 1.1 | 0.57 | 1.31 | 1.05 | 55 | 69 | 36 | 15 |
| | Case 2 | 1.45 | 0.8 | 1.63 | 1.1 | 41 | 57 | 20 | 11 |
| | Case 3 | 2.04 | 1.36 | 2.01 | 1.01 | 17 | 26 | 2 | 19 |
| | Case 4 | 2.51 | 1.69 | 2.39 | 1.46 | −2 | 9 | −17 | −18 |
| | Case 5 | 1.11 | 0.64 | 1.32 | 1.05 | 55 | 65 | 36 | 15 |
| | Case 6 | 2.06 | 1.46 | 2.04 | 1.04 | 16 | 21 | 0 | 16 |
| Simplif. Approx. | Hargreaves | 1.47 | 0.86 | 1.67 | N/A | 40 | 54 | 19 | N/A |
| | Priestley–Taylor | 0.43 | 0.44 | 1.59 | 1.1 | 82 | 76 | 22 | 11 |
| | Rohwer | 4.05 | 3.61 | 4.01 | 2.56 | −65 | −95 | −96 | −106 |





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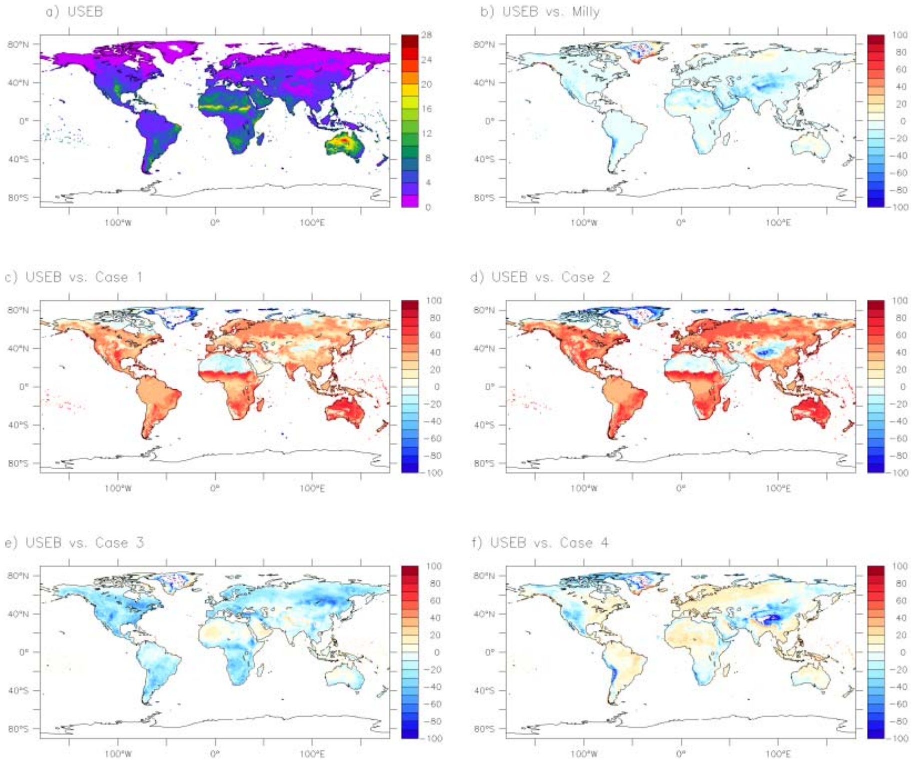


**Fig. 1.** The USEB method's $ET_P$ mean annual values ($mm\,d^{-1}$) for the reference period **(a)**. Differences given in %, between USEB and Milly's methods **(b)** as well as between the USEB method and the first four cases defined for FAO's equation (**c** to **f**). Whereas red colours provide higher values dealing the USEB method, blue ones imply that FAO's reference equation or Milly's method provide higher $ET_P$ values.





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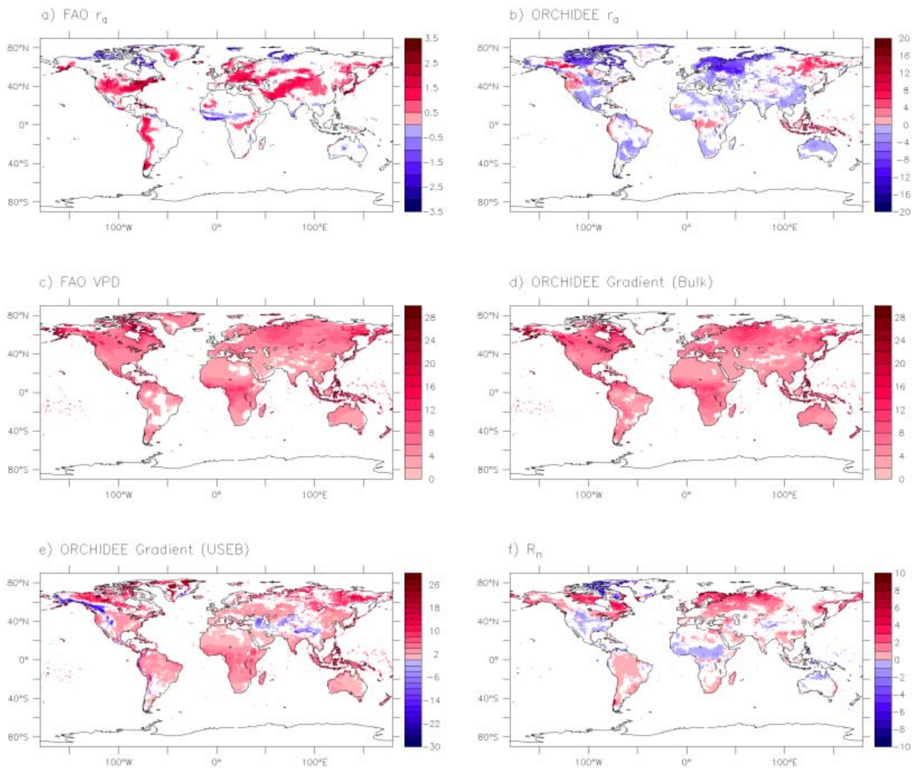


**Fig. 2.** Significant trends showing the increasing or decreasing % per decade for the aerodynamic resistance ($r_a$), the VPD, the humidity gradient, and the net radiation ($R_n$), regarding the future period and the different formulations. The blank areas correspond to regions where no significant trends have been found.





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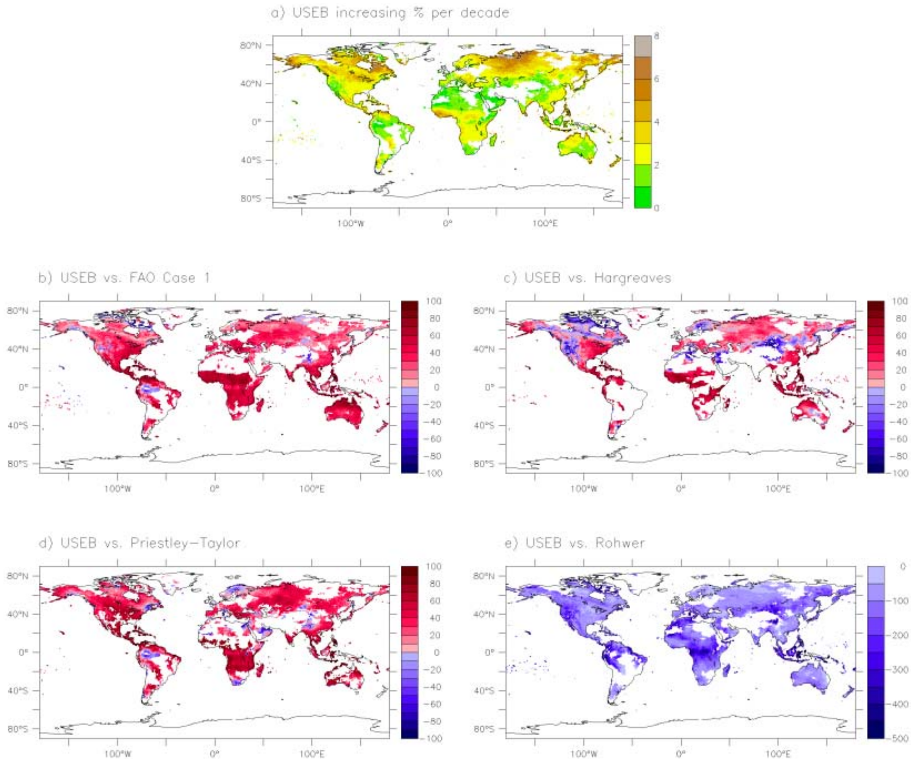


**Fig. 3.** The USEB method's $ET_P$ significant trend showing the increasing % per decade **(a)**. Differences, given in % of % change per decade, between the USEB method and FAO's case 1 **(b)** and between the USEB method and Hargreaves', Priestley–Taylor's and Rohwer's approximations (**c** to **e**). The blank areas correspond to regions where no significant trends have been found.





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