How is Climate Change Likely to Change Transpiration Rates From Plant Canopies?

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Climate Change

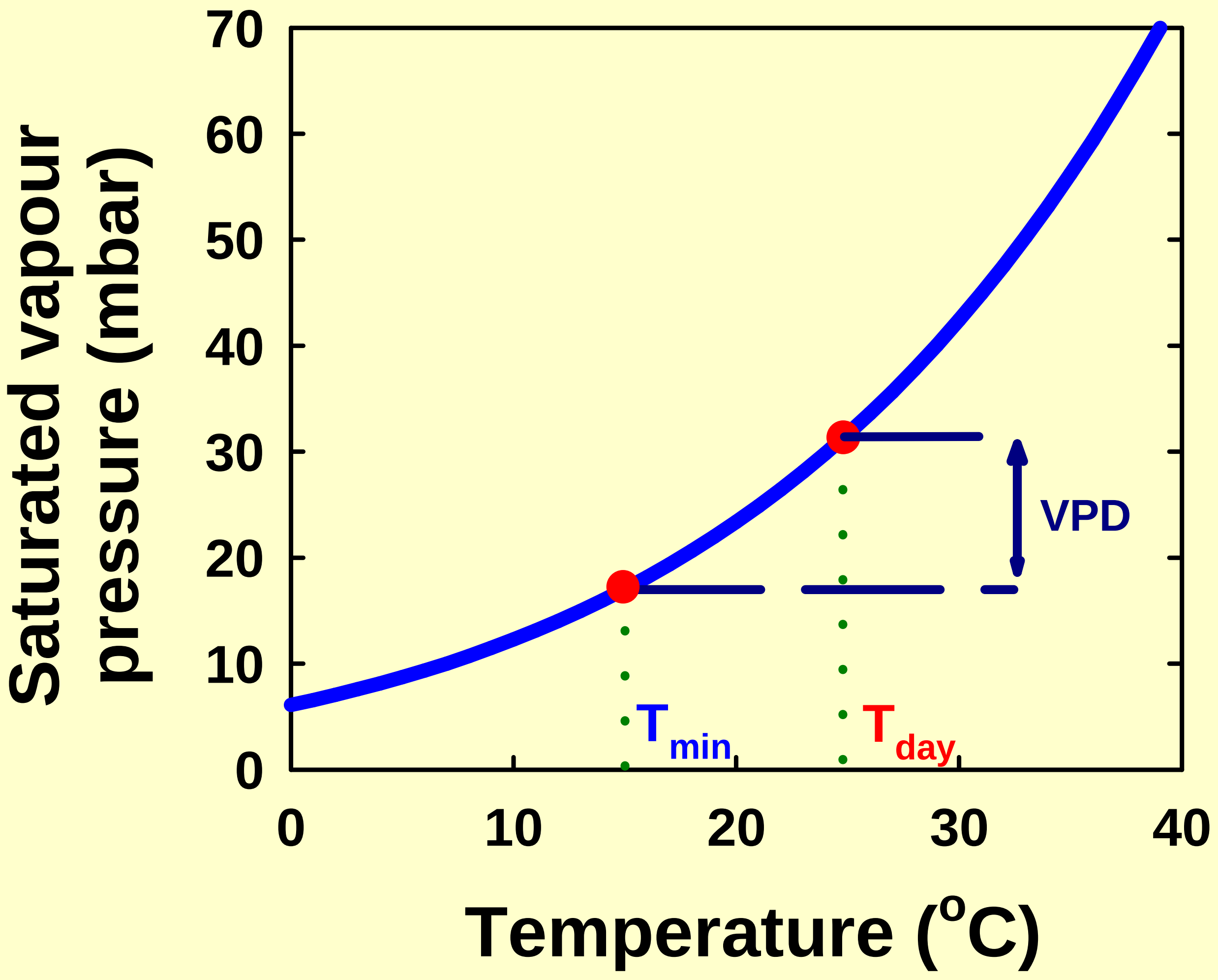
Temperature response of potential evapotranspiration rates (ET_0)

Modifications by other factors

Comparison of equations

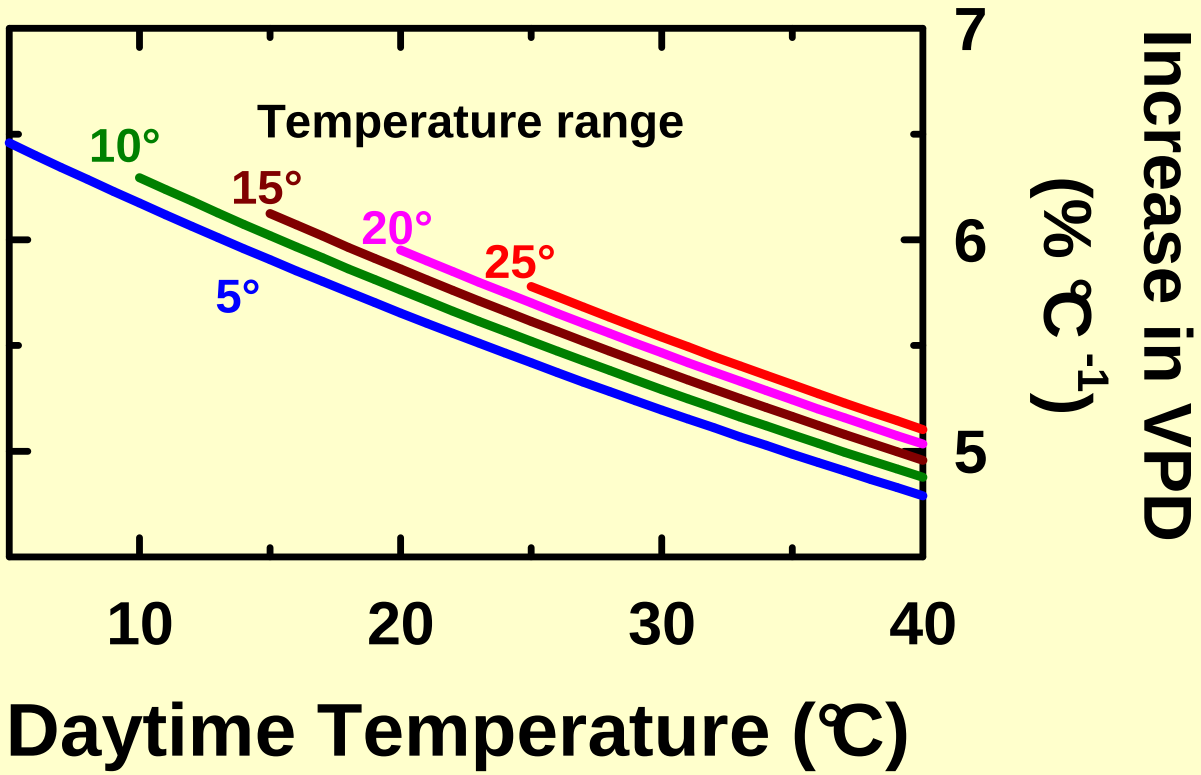
Thornthwaite and Penman-Monteith

The vapour pressure curve drives the response to temperature



Key points: Vapour pressure deficit is given by the difference between saturated water vapour at daytime temperatures and the saturated vapour pressure at the overnight minimum temperature, or at a low temperature where the air was last cooled to its condensation point. If the diurnal temperature range remains the same (but see later), then VPD increases with warming because the saturated vapour pressure curve is steeper at higher than lower temperatures.

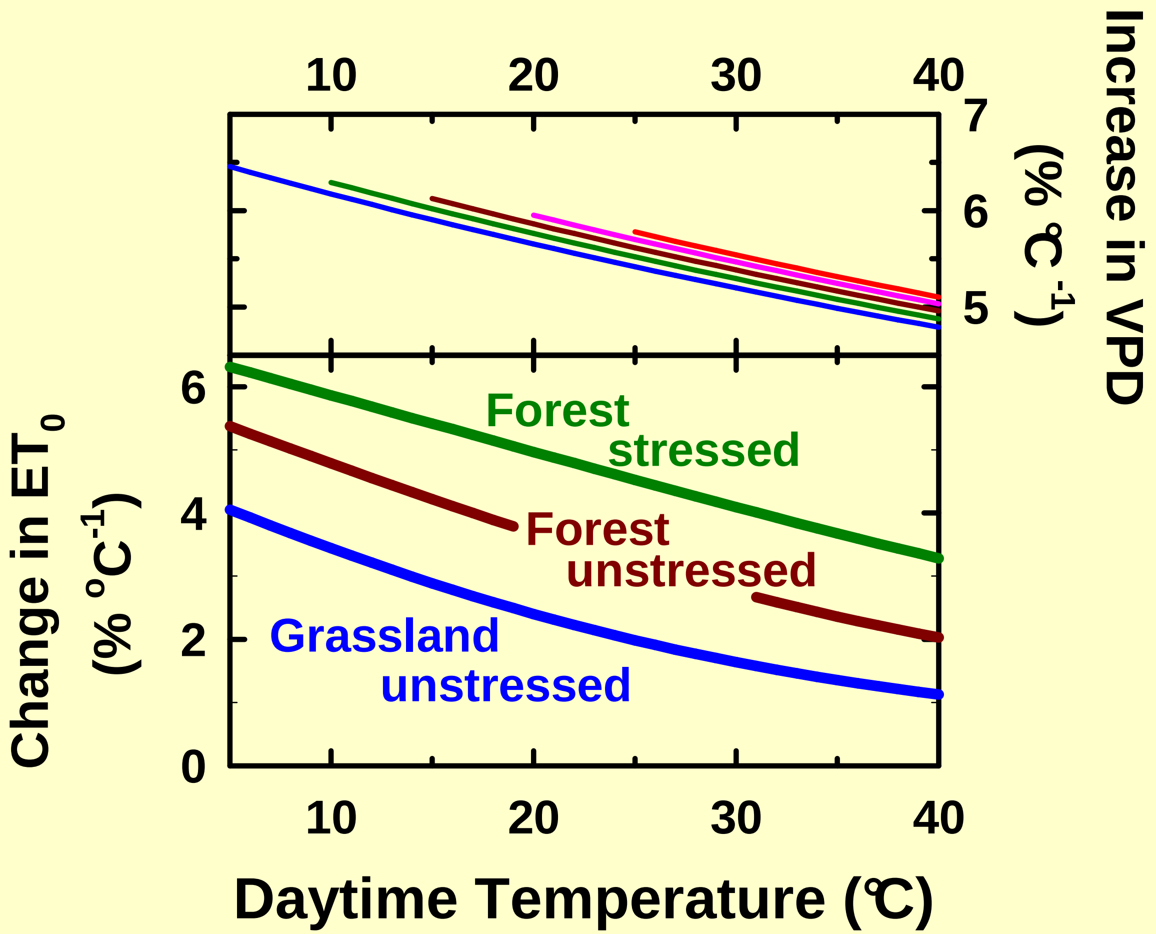
Changes in VPD with temperature



Key points: For an unchanged diurnal temperature range, it is easy to calculate the change in VPD with warming. While different numeric values result for different daytime temperatures and diurnal temperature ranges, the differences are only slight, and VPD increases by 5-6% $^{o}C^{-1}$ over the range of relevant temperature combinations.

Kirschbaum (2000)

Changes in ET_0 with temperature

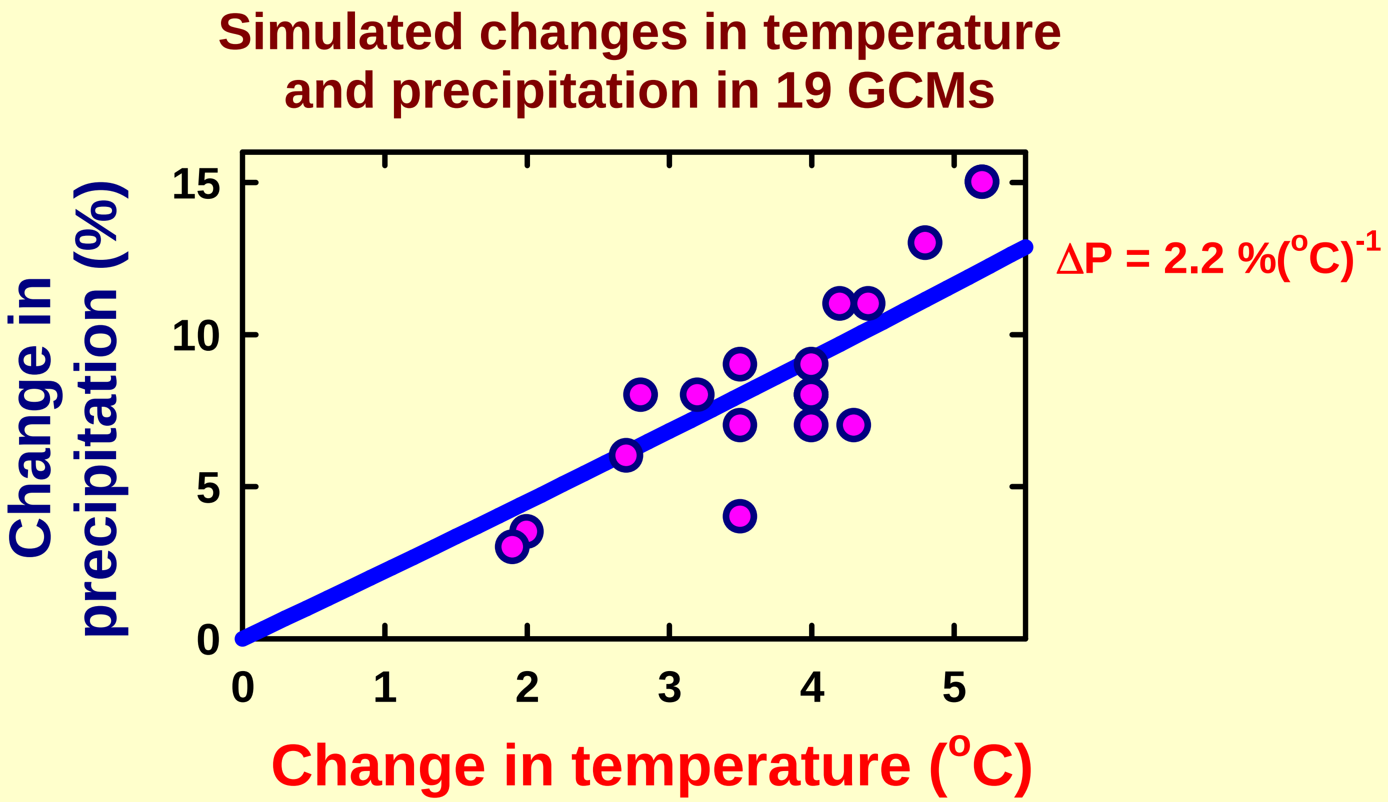


Key points: Using the calculated change in VPD, it becomes possible to calculate the change in potential evapotranspiration with warming. ET_0 varies with temperature and is less for grasslands than forests, and becomes even more for forests under stress. Grasslands respond less because ET_0 from grasslands is more closely linked to radiation receipt whereas VPD has stronger control of ET_0 of forests.

Kirschbaum (2000)

based on
Penman-Monteith

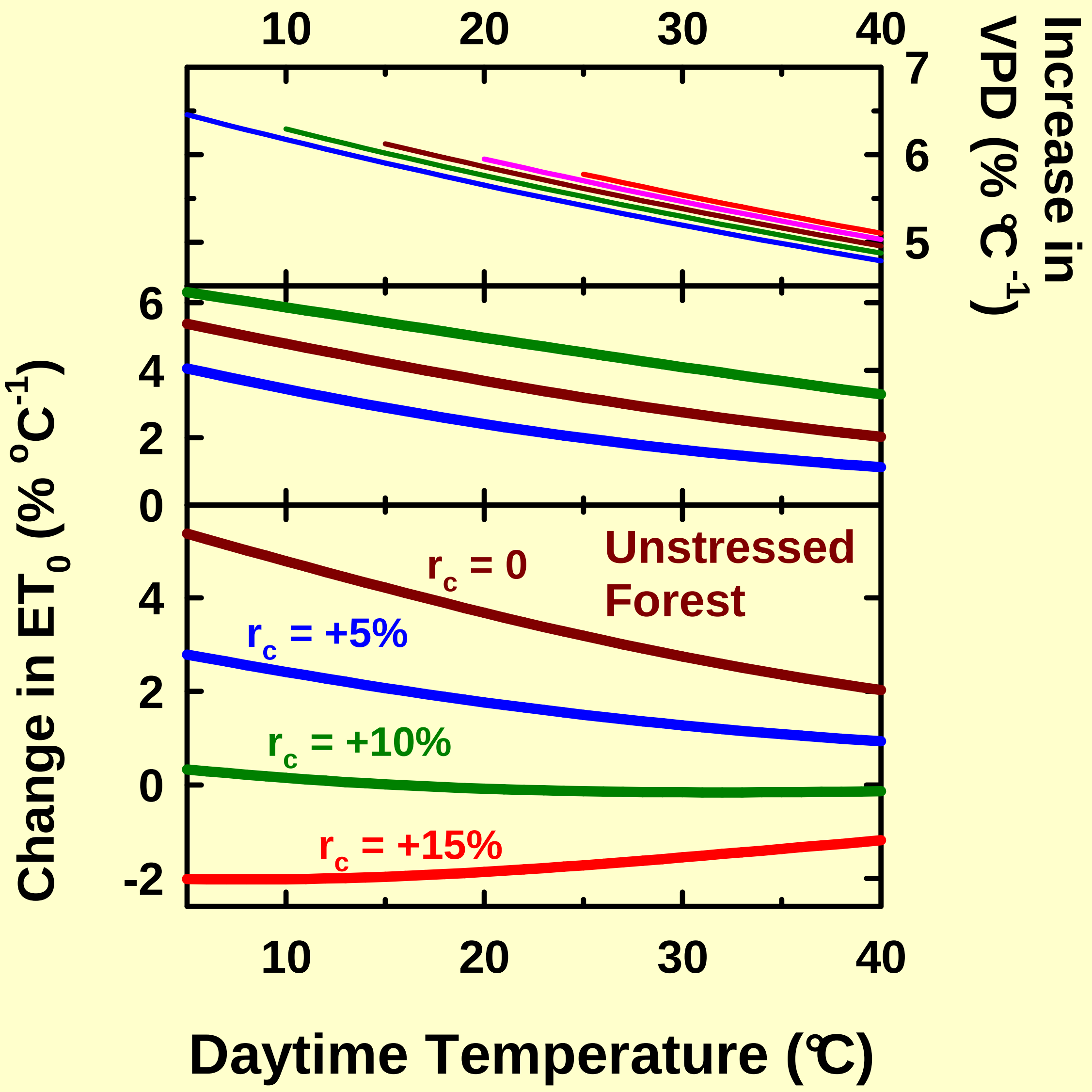
Changes in rainfall and temperature



Key points: The numeric differences shown in the previous graph can be compared against GCM-derived changes in precipitation. It suggests, that, for the globe as a whole, grasslands may have their future water requirements met by increased precipitation whereas for forests, there could be shortfalls. There are also likely to be large regional differences, but the analysis shown here suggests that for grasslands, there will be as many winners as losers, whereas for forests, there could be more losers than winners. However, additional factors need to be considered (see below).

Data from Cubash and Cess (1990); summarised in Kirschbaum (2000)

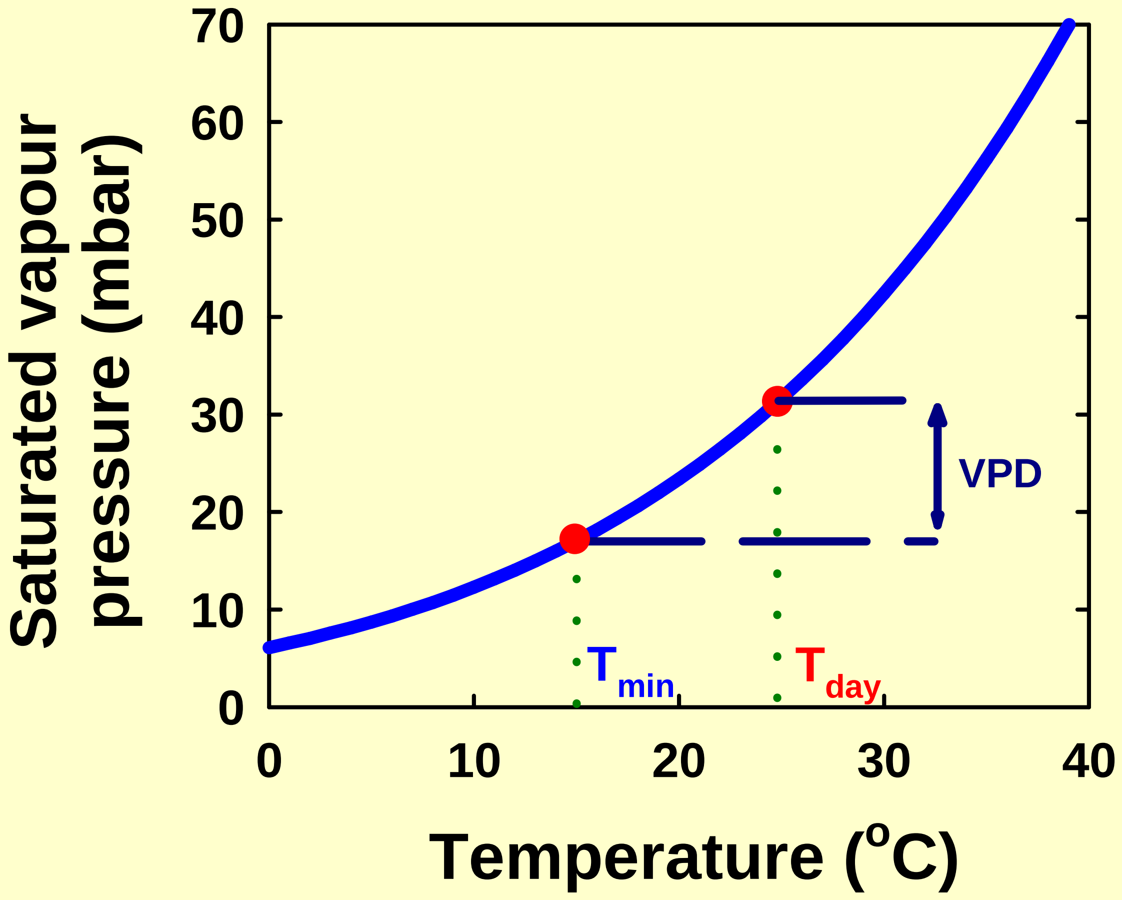
Changes in ET_0 with stomatal closure



Key points: If stomata close in response to factors such as increasing CO_2, it will reduce ET_0 as shown in the bottom panel (for unstressed forests). ET_0 increases by 2-5% °C^{-1} without stomatal adjustment (brown line marked r_c=0), but that reduces to virtually no change in ET_0 if stomata close by 10% with a temperature increases by 1°C.

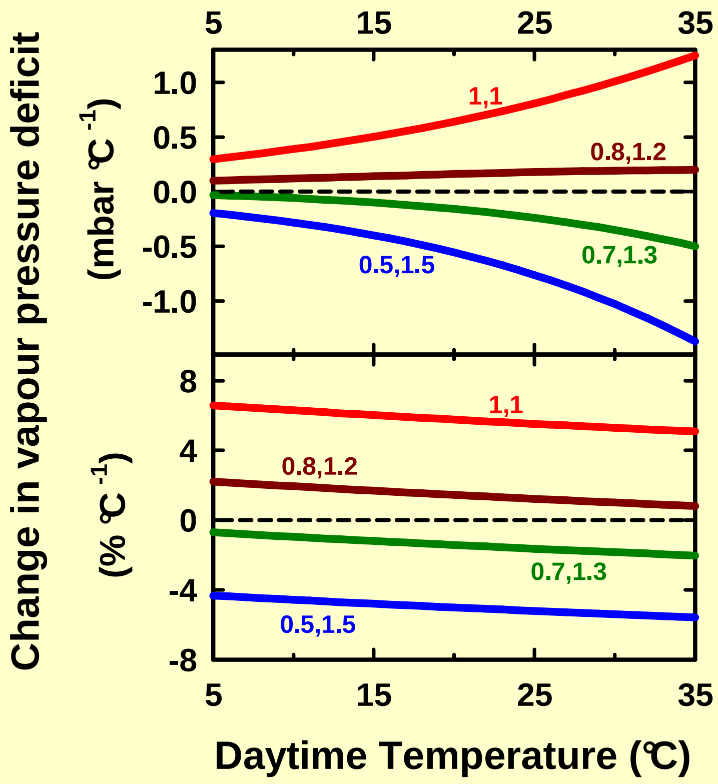
Kirschbaum (2000)

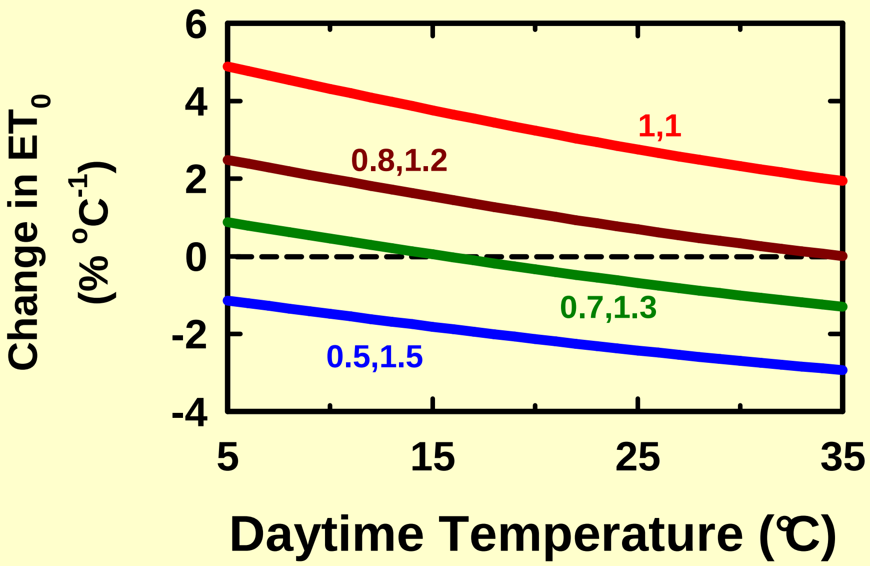
VPD with min and max temperatures



Key points: If the diurnal temperature range diminishes, as it did for the latter part of the 20th century, then VPD decreases. While increasing temperature drives an increase in VPD, a reducing temperature range drives a decrease in VPD. That is further quantified in the next Figure.

Changes in VPD and ET_0 with more night-time warming





Numbers give daytime and night-time temperature increases

Kirschbaum (2004)

Key points: If the diurnal temperature range stays the same, VPD increases strongly with warming (red line on the left graph). That change in VPD diminishes greatly if night-time temperature increases are greater than increases during the day. This has corresponding effects on ET_0 (right graph). With the combination of daytime and night-time temperature increases observed during the latter part of the 20th century, ET_0 would have been close to 0. More recent temperature records suggest that daytime and night-time temperatures now increase at similar rates.

Thornthwaite or Penman-Monteith?

Key points: There are some studies that indicate significant increases in evapotranspiration over recent decades and an expectation that evapotranspiration may increase strongly into the future (Trenberth et al. 2007). Much of that expectation has been based on studies using the Thornthwaite Method or the Palmer Drought Severity Index, which is also based on the Thornthwaite Method. How do values calculated with the Thornthwaite Method compare with measurements based on the more physically-based Penman Monteith equation?

The Thornthwaite and Penman-Monteith equations

$$\mathrm{ET}_0(\mathrm{T}) = \mathrm{k}_1\left[\frac{T}{f_1(T_a)}\right]^{f_2(T_a)}$$

Thornthwaite

T = Monthly mean temperature
T_a = Annual mean temperature

$$\mathrm{ET}_0(\mathrm{P\text{-}M}) = \mathrm{k}_2\,\frac{f_3(R_n) + f_4(VPD)/r_a}{f_5[(r_a + r_c)/r_a]}$$

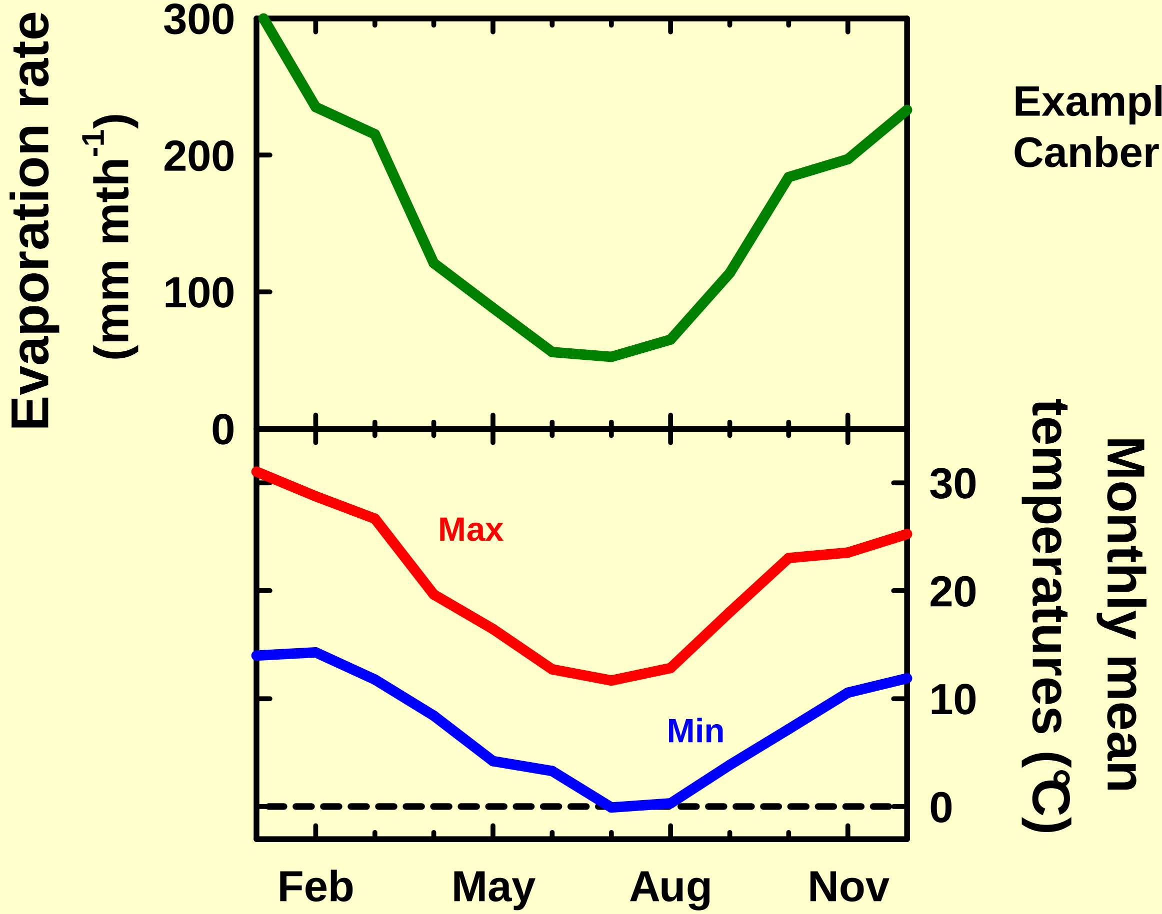
Penman-Monteith

R_n = Net radiation
VPD = Vapour pressure deficit
r_a = aerodynamic resistance
r_c = canopy resistance

Thornthwaite (1948); Monteith (1965);Martin et al. (1989)

Key points: The Thornthwaite equation is empirical and only uses temperature, both monthly and annual, as inputs. The dependence of evapotranspiration rate on radiation is, therefore, implicit.
In the Penman-Monteith equation, the dependence on the two key drivers of evapotranspiration, radiation and VPD, is explicit. Other controlling factors, such as canopy and aerodynamic resistances are also explicitly included, and their effect can be explored (as had been done above).

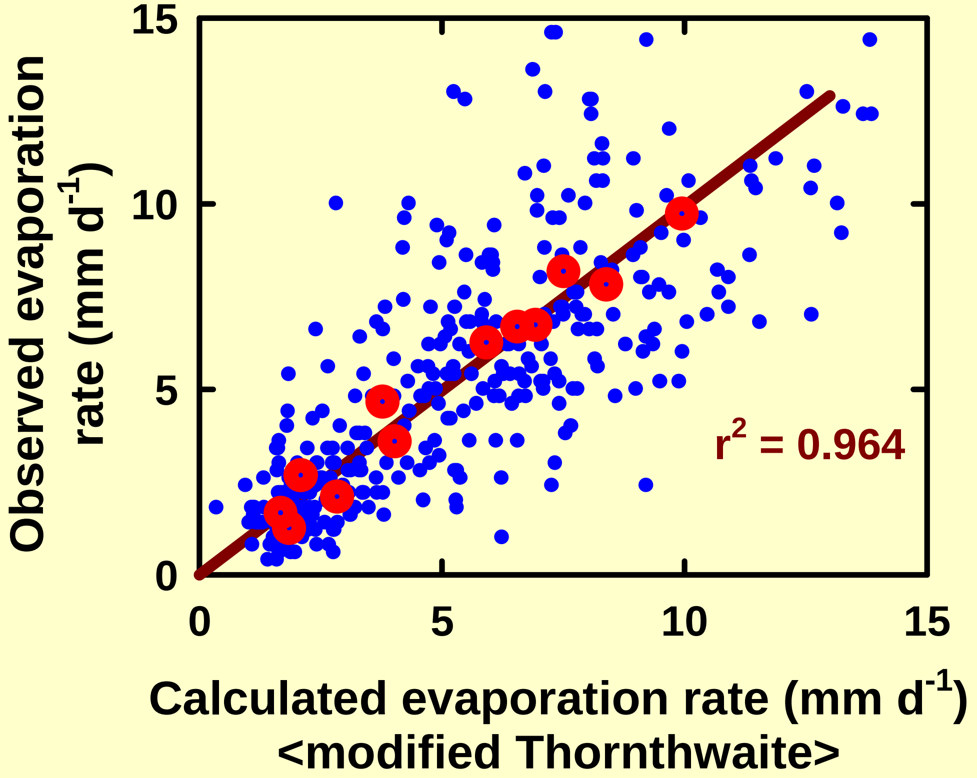
Evaporation rate with modified Thornthwaite



Example from Canberra, Australia

Key points: Testing the Thornthwaite Method on one data set – evaporation rate measured in Canberra, Australia. Shown here are monthly cumulative evaporation rates and mean minumum and maximum temperatures for one particular year.

Evaporation rate with modified Thornthwaite

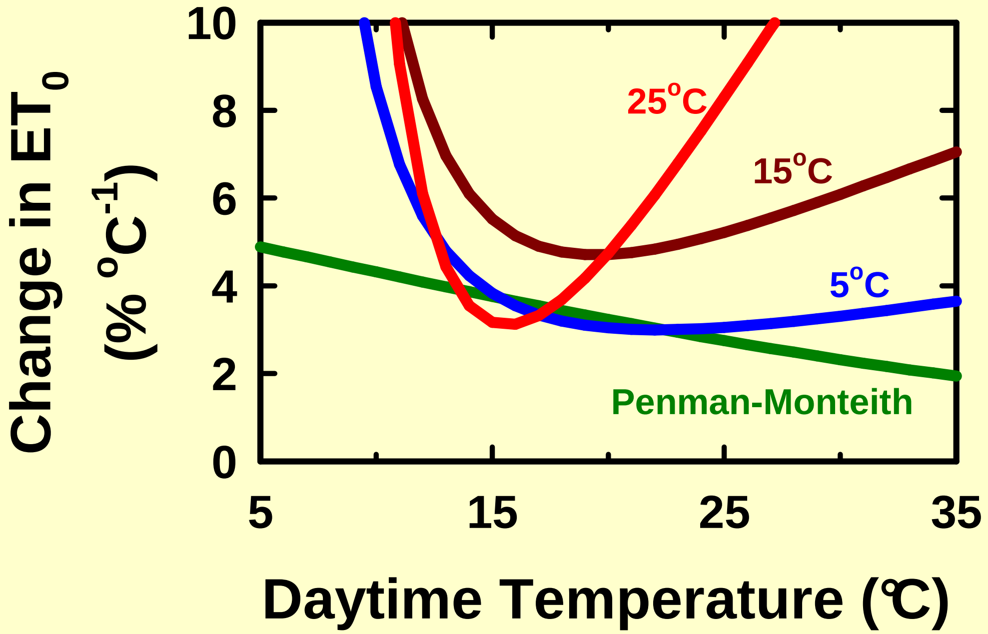


Example from Canberra, Australia

Key points: The Thornthwaite Method with the original parameters did not work well and underestimated evaporation by more than 50%. However, increasing the overall rate constant by 50% and basing calculations on mean maximum rather than mean daily temperatures resulted in model efficiency of over 50% of variation of daily values and 96.4% for mean monthly values. It confirms that the Thornthwaite Method can be used for empirical applications once site specific adjustments are applied.

Kirschbaum (unpublished)

Changes in ET_0 in the seasonal context

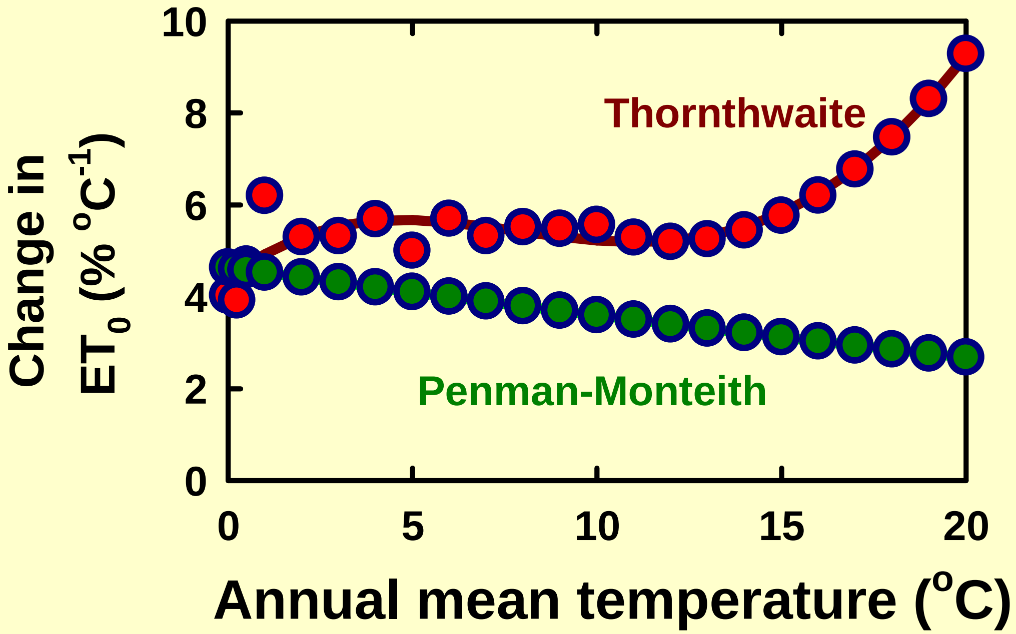


Key points: However, because values calculated with the Thornthwaite Method have little mechanistic basis, it is dangerous to apply it to situations outside its empirical roam. This is illustrated here by comparison with the Penman-Monteith equation (paramterised for forest ET_0). The Thornthwaite Method predicts unrealistically large increases with warming, has a peculiar shape across the range of temperatures and predicts different responses for months with the same temperature, but for which annual heat indices are different. There is no obvious reason why there should be such differences. For the Penman-Monteith equation, the change across the range of temperatures is transparently linked to the effect on VPD as shown earlier.

Thornthwaite for three different annual heat indices expressed as mean annual temperature. Penman-Monteith calculated for unstressed forest

Kirschbaum (unpublished)

Changes in ET_0 with annual temperature



Key points: Across different annual mean temperatures, values calculated with the Thornthwaite Method are similar to values calculated with the Penman-Monteith equation at very low temperatures, are about 50% higher across a range of moderate temperatures, and then become extremely large at very high temperatures. Again, there is no obvious reason why there should be such patterns across the temperature range, whereas the gradual decrease in values calculated with the Penman-Monteith equation is explicitly linked to the underlying physics..

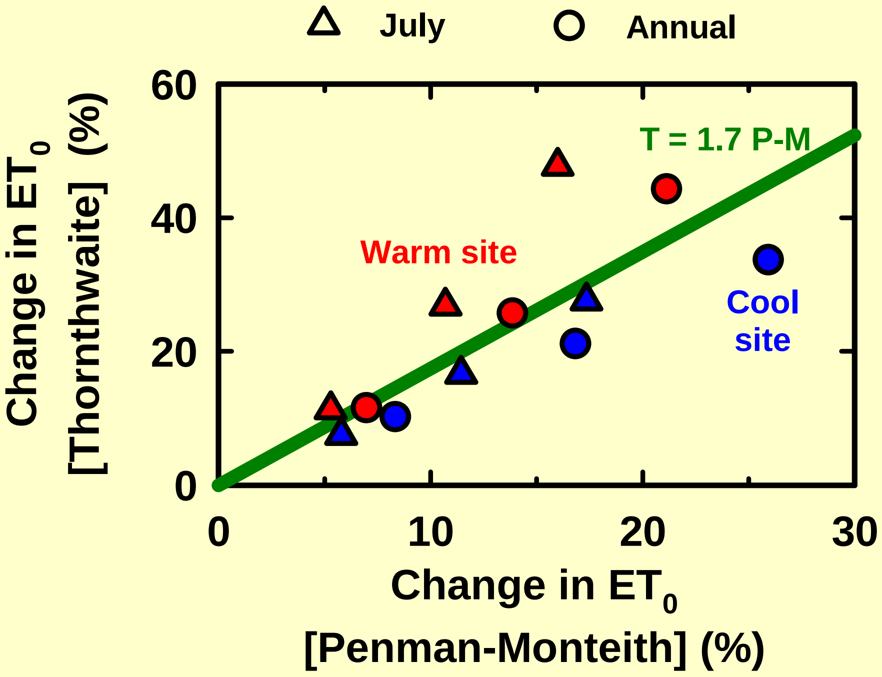
Kirschbaum (unpublished)

Applied either Thornthwaite or Penman-Monteith, seasonal T range = 20ºC, diurnal T range = 10ºC, unstressed forest.

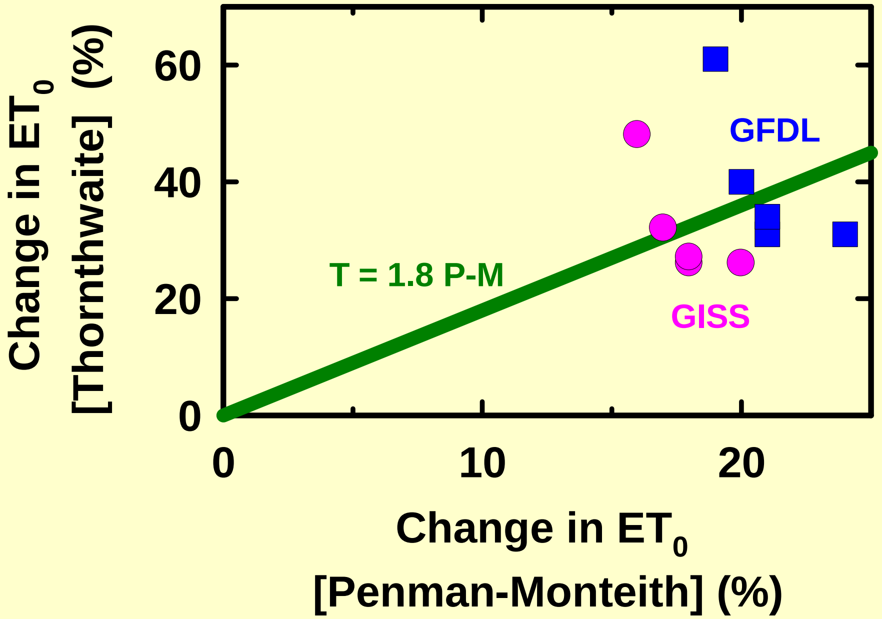
Changes in ET$_0$ with temperature

(McKenney and Rosenberg 1993)

Key points: Criticism of application of the Thornthwaite Method to climate change applications is not new. It was clearly highlighted in a paper written by McKenney and Rosenberg in 1993. Their key findings are reproduced here. The Thornthwaite Method always produced larger increases than Penman-Monteith equation, and the differences become larger the warmer the sites investigated.



2 US locations, T increase by 2, 4, 6℃, applied either Thornthwaite or Penman-Monteith.



5 US locations, 2 GCM scenarios, applied either Thornthwaite or Penman-Monteith – applied temperature changes only

Penman-Monteith

- Is explicitly based on known drivers of evapotranspiration (temp, radn, VPD).
- It allows explicit inclusion of varying and invariant factors.
- It provides the best description of key drivers – could be used for “calibration”
- It can deal explicitly with variations in VPD or stomatal adjustments

Thornthwaite

- Dependence on radiation is implicit. Does not work when implicit correlation between drivers is lost – predicted responses are overestimated! Especially at high temperatures
- It cannot differentiate between canopies
- It cannot represent physiological adjustments (to increasing CO_2)
- It cannot deal with variations in VPD (linked to diurnal temperature range)
- It cannot deal with other changes

Conclusions

- Warming leads to faster water loss – more for forests than grasslands
- Water loss is reduced by stomatal adjustment
- Water loss is reduced if $\Delta T_{min} > \Delta T_{max}$
- Thornthwaite Method is a good empirical method
- But….Thornthwaite Method should not be used for climate-change impact assessments

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