ON THE THEORY RELATING LONG-TERM CHANGE IN ACTUAL AND PAN EVAPORATION

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Question:

“Is the global hydrological cycle changing?”

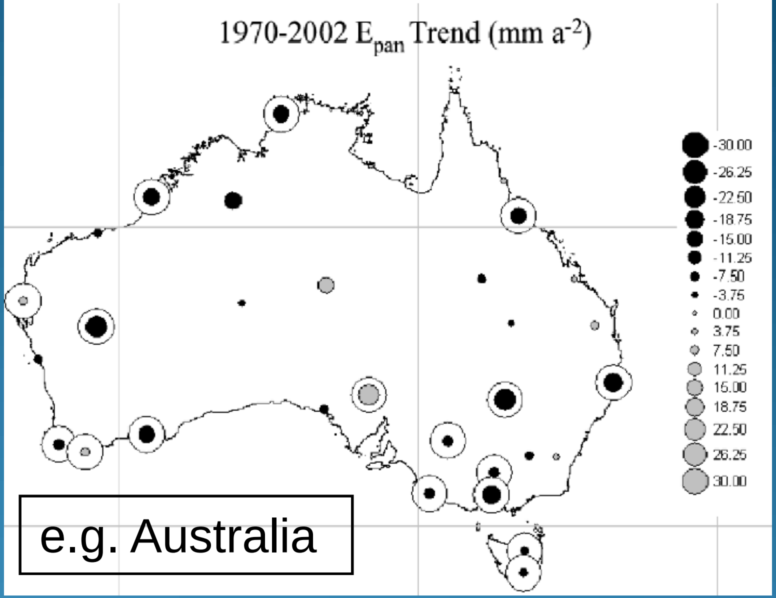
in particular

“Is there observational evidence of a gradual change in area-average evaporation?

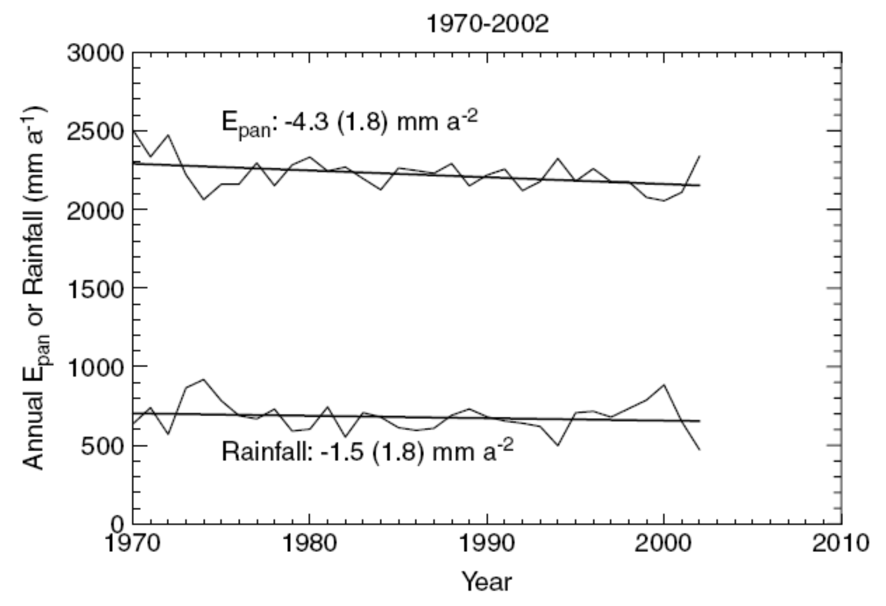
- There are no long-term, reliable measurements of actual evaporation (e.g. FLUXNET too recent and too inaccurate.)
- Some attempts using water balance; difficult because average precipitation poorly measured and changes in runoff may have other origin (e.g. land cover, etc)

Changes in Pan Evaporation

- There are long-term measurements from evaporation pans. Have these changed?



e.g. Australia



- YES. There is worldwide well-documented, evidence of a systematic reduction in pan evaporation of around 4 mm per year on avergae.

Does observed reduction in pan evaporation mean there has been a change in area-average evaporation?

Hypothesis 1:

Both pan-evaporation and area-average evaporation have reduced because surface radiation has been reduced by higher aerosol absorption of greater cloud cover.

Hypothesis 2:

Area-average evaporation has increased giving higher atmospheric humidity and this is what has reduced pan evaporation

HUGE CONTROVERSY: WHICH IS CORRECT?

Cause of this Controversy

Confusion caused by using the old fashioned "potential evaporation" theoretical approach when describing actual evaporation

Hypothesis 1: $E_{act} = (\mathit{factor}) \times E_{pot}$

If both pan and actual evaporation are assumed related to a potential rate, when one reduces so must the other

Hypothesis 2: $E_{act} = E_{pot}\,(\mathit{rad.\ est.}) - E_{pot}\,(\mathit{def.\ est.})$

If Bouchet's "Complementary Evaporation" hypothesis assumed, increased actual reduces deficit *Epot* estimate

[E_{pot} (*rad. est.*) = "Priestley-Taylor": E_{pot} (def. est.) = "Penman"]

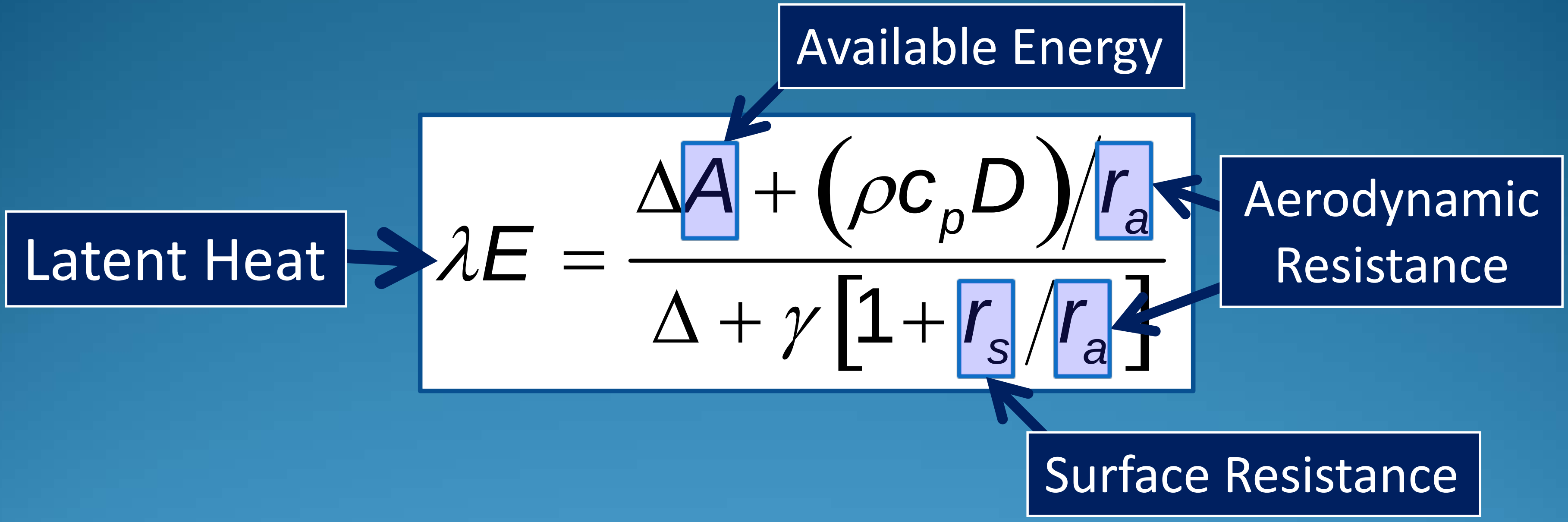
Reanalysis of theory based on “Actual” rather than “Potential” evaporation

Golubev et al (2001) describe potential evaporation as a *“fictitious variable”*

Gash and Shuttleworth (2007) state that “*the term potential evaporation has many subtly and confusingly different meanings and, in our view, is usually best avoided*”

Approach: consider all evaporation rates as actual evaporation rates described by different implementations of the Penman-Monteith Equation

Actual Evaporation: Penman-Monteith Equation with surface specific parameters



Available Energy

Latent Heat

$$\lambda E = \frac{\Delta A + \left(\rho c_p D\right)/r_a}{\Delta + \gamma\left[1 + r_s/r_a\right]}$$

Aerodynamic Resistance

Surface Resistance

Δ	Rate of Change of Saturated Vapor Pressure with Temperature
ρ	Density of Air
c_p	Specific Heat of Air at Constant Pressure
D	Vapor Pressure Deficit
γ	Psychrometric Constant

Actual Evaporation: Forms of the Penman-Monteith Equation

Actual Evaporation Rate	**Equation**	**Aerodynamic Resistance (s m^{-1})**	**Surface Resistance (s m^{-1})**	**Available Energy (W m^{-2})**
Reference Crop	$\lambda E_{rc} = \dfrac{\Delta A_{veg} + \dfrac{\rho c_p D u_2}{208}}{\Delta + \gamma\left[1 + \dfrac{70 u_2}{208}\right]}$	$(h_{crop} = 0.12\text{m})$ $(r_a)_{rc} = \dfrac{208}{u_2}$	**70** (s m^{-1})	**A_{veg}** (W m^{-2})
Area-average	$\lambda E_{aa} = \dfrac{\Delta A_{veg} + \dfrac{\rho c_p D u_2}{110}}{\Delta + \gamma\left[1 + \dfrac{(r_s)_{aa} u_2}{110}\right]}$	$(h_{crop} = 0.5\text{m})$ $(r_a)_{aa} = \dfrac{110}{u_2}$	**Variable** (s m^{-1})	**A_{veg}** (W m^{-2})
Open-water	$\lambda E_{ow} = \dfrac{\Delta A_{ow} + \dfrac{\rho c_p D_2 (1 + 0.536 u_2)}{250}}{\Delta + \gamma}$	$(r_a)_{ow} = \dfrac{250}{(1 + 0.536 u_2)}$	**Zero** (s m^{-1})	**A_{ow}** (W m^{-2})

$$A_{veg} = (1 - 0.23)S + L_n \qquad A_{ow} = (1 - 0.08)S + L_n$$

Penman-Monteith Equation: *Climatological Resistance*

Climatological Resistance

$$\lambda E = \frac{\Delta A + \left(\rho c_p D\right)/r_a}{\Delta + \gamma\left[1 + r_s/r_a\right]} = \Delta A\left(\frac{1 + r_{c\lim}/r_a}{\Delta + \gamma\left[1 + r_s/r_a\right]}\right)$$

where:

$$r_{c\lim} = \frac{\left(\rho c_p D\right)}{\left(\Delta A\right)}$$

Provides a convenient measure of (possible changes in) the relative importance of radiation versus other meteorological controls on actual evaporation rates

Strong Evidence for Reduced Solar Radiation

- Some regional analyses of using measured cloud cover give reduced solar radiation of few percent per decade

  (e.g. Chattopadhyay and Hume, 1997; Thomas, 2000; Chen et al., 2005; Shenbin, 2006; Xu et al., 2006)

- Some local & regional studies ascribe observed reduction in solar radiation to increased aerosol concentrations

  (e.g. Askov, 1997; Omran, 1998; Cohen, 2001)

- Regionally varying but widespread increase in aerosols and associated reduction in solar radiation documented in authoritative reviews, and estimated as around 2-3%

  (e.g., Ramanathan et al., 2001; Stanhill and Cohen, 2001)

- IPCC (2007) estimate solar radiation reduction due to sulphate aerosols of -0.2 to -0.8 W m^{-2} since 1750

Consequence of Reducing Solar Radiation on Open Water and Area-average Evaporation

- If all other influences on evaporation, i.e., humidity deficit, wind speed, surface resistance (due to changes in soil moisture, vegetation cover and vigor) remain unaltered, a huge assumption, differentiating actual evaporation rates and combining gives:

$$\left(\frac{\delta\left(\lambda E_{aa}\right)}{\lambda E_{aa}}\right) = 0.84\left(\frac{\left(A_{ow}/A_{veg}\right) + \left[r_{c\lim}\left(1 + 0.536.u_2\right)\right]/250}{1 + \left(r_{c\lim}u_2\right)/110}\right)\left(\frac{\delta\left(\lambda E_{ow}\right)}{\lambda E_{ow}}\right)$$

- In typical conditions (available energy 50-500 W m^{-2}; climatological resistance 20-200 s m^{-1}; wind speed 1-10 m s^{-1}; net longwave radiation -100 to 0 W m^{-2}) the change in area-average evaporation is 10-40% bigger than the change in open water evaporation

Defining "*Humid*" and "*Arid*" Conditions

- Priestley & Taylor (1972) propose estimating evaporation using:

$$(\lambda E_{PT})_{\alpha} = \alpha \frac{\Delta A}{\Delta + \gamma}$$

- In "humid" conditions (water freely available) , P&T used data from five oceanic and four land sites to propose $\alpha = 1.26$
- Jensen et al. (1990) suggested that in "arid" conditions, $\alpha = 1.74$
- Shuttleworth (2006) proposes deriving equivalent values of r_{clim} in humid and arid conditions ($u_2 = 2\ \mathrm{ms}^{-1}$ and T = 15 °C) by setting:

$$\Delta A . \frac{1 + r_{c\,\lim} / (r_a)_{rc}}{\Delta + \gamma\left(1 + (r_s)_{rc} / (r_a)_{rc}\right)} = \alpha \frac{\Delta A}{\Delta + \gamma} \qquad \left[(r_a)_{rc} ; (r_s)_{rc} \text{ for reference crop}\right]$$

- Giving the values: r_{clim} = 60 s m^{-1} for humid conditions
- r_{clim} = 123 s m^{-1} for arid conditions

Complementary Evaporation Hypothesis

- Bouchet (1963) complementary evaporation hypothesis is:

$$\lambda E_{actual} = 2\lambda E_{po} - \lambda E_{p}$$

where λE_{po} is the "true potential evaporation rate" , λE_{p} is the "potential evaporation rate calculated using the actual measured humidity deficit" and λE_{actual} is the actual evaporation rate when less than the potential rate because water is limited."

- Assumes $\lambda E_{po} = \lambda E_{p} = \lambda E_{actual}$ in "humid conditions" regardless of the nature of the evaporating surface , and assumes the effect of the surface can be allowed for by "crop" or "pan" factors

- Usually implemented using "actual" evaporation nomenclature as:

$$\lambda E_{aa} = 2\left(\lambda E_{PT}\right)_{1.26} - \lambda E_{ow} \quad \left[= 2\left(\lambda E_{PT}\right)_{1.26} - \left(K_{pan}\right)^{-1} \lambda E_{pan} \right]$$

Problems with the Complementary Evaporation Hypothesis

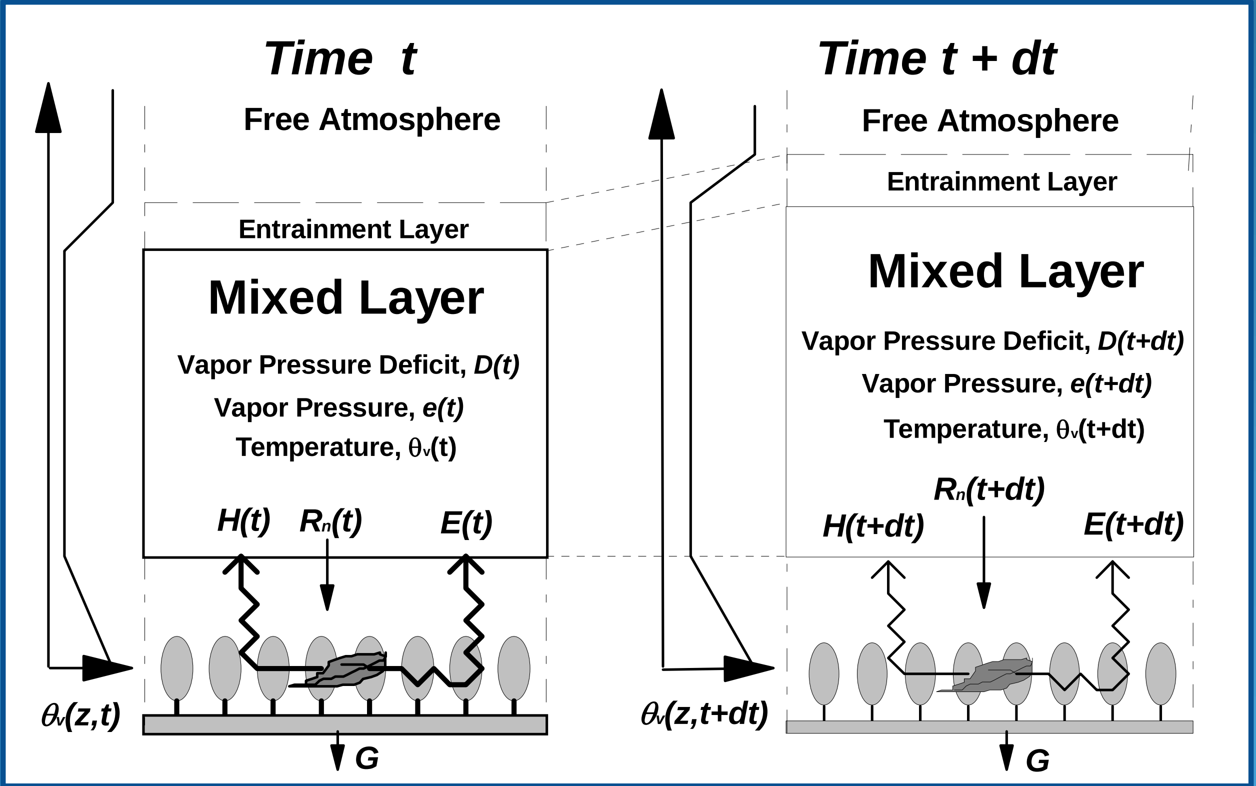
- A relationship which is justified by a hand waving, energy-based argument between the mysterious potential rates that themselves only have an assumed empirically based relationship with actual evaporation rates
- The relationship cannot possibly be universally applicable because the estimated evaporation rates involved
  1. have different wind speed dependency
  2. are for evaporating surfaces with different albedo (despite the justification being energy-based)
- The hand waving justification for the hypothesis is inconsistent with present day understanding of the coupling processes between land surfaces and the developing atmospheric boundary layer

Land-surface Atmosphere Coupling

- The Complementary Evaporation Hypothesis (implicitly) assumes the land surface interacts with a boundary layer of fixed extent that is largely isolated from the remainder of the atmosphere , hence (more evap.) ⇒ (ABL more humid/less warm) ⇒ (less pan evap.)
- In reality, the evaporation from the surface is into an ABL which grows during the day by entraining drier and warmer air from the overlying free atmosphere , with growth rate depending on the strength of the capping inversion and the surface sensible heat flux.
- Because surface evaporation is mainly used to moisten the entrained air, **in humid conditions the change in vapor pressure deficit (VPD) is small, and so the change in open water (and pan) evaporation in humid conditions also small**. **But in arid conditions with dry surfaces the ABL warmed, and VPD/pan evap is high.**

MacNaughton & Spriggs (1989) "***Slab Model***" of Coupled Surface-Atmosphere Interactions

- Assumed ABL very well mixed, surface exchanges controlled by Penman-Monteith Equation, and rate of growth in ABL height proportional to surface sensible heat flux but inversely related strength of inversion



Coupled Land Surface /Atmosphere Model's Evaporation Response to Area-Average Surface Resistance

- Sensitive to initial atmospheric profile & strength of inversion
- Parameterize daily evaporation in terms of:

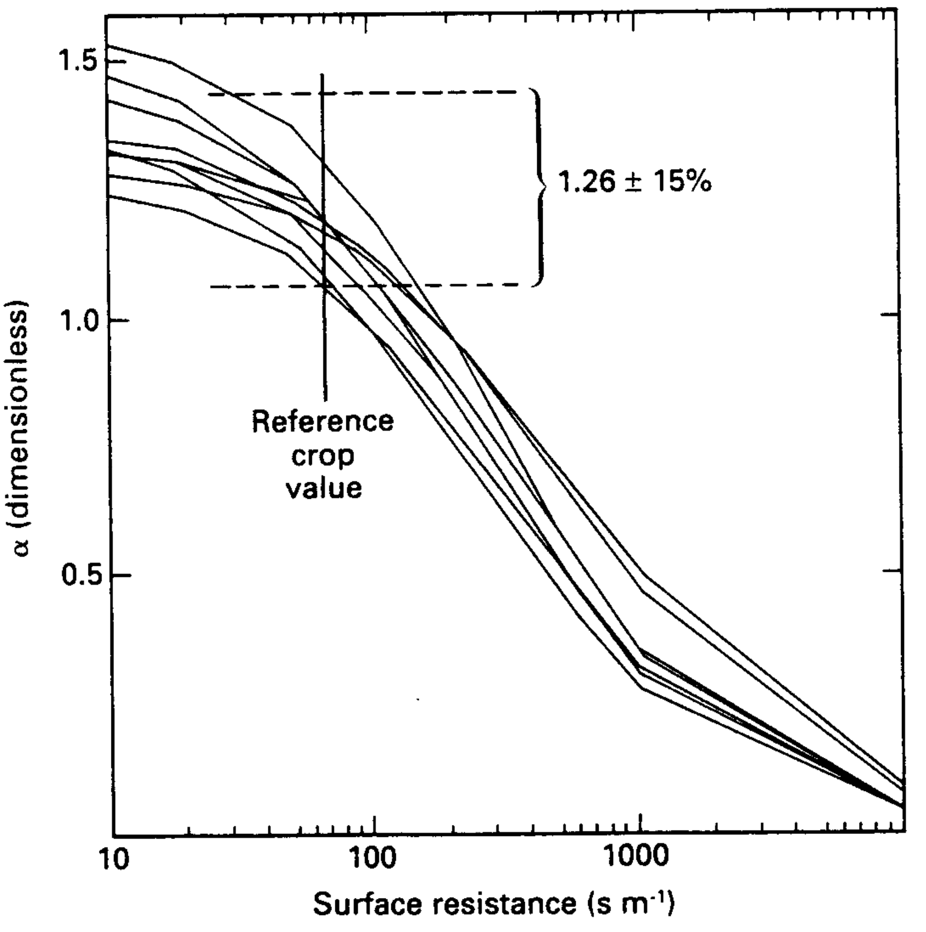
$$\boxed{(\lambda E_{PT})_{\alpha} = \alpha \frac{\Delta A}{\Delta + \gamma}}$$

- Surface Resistance gives:

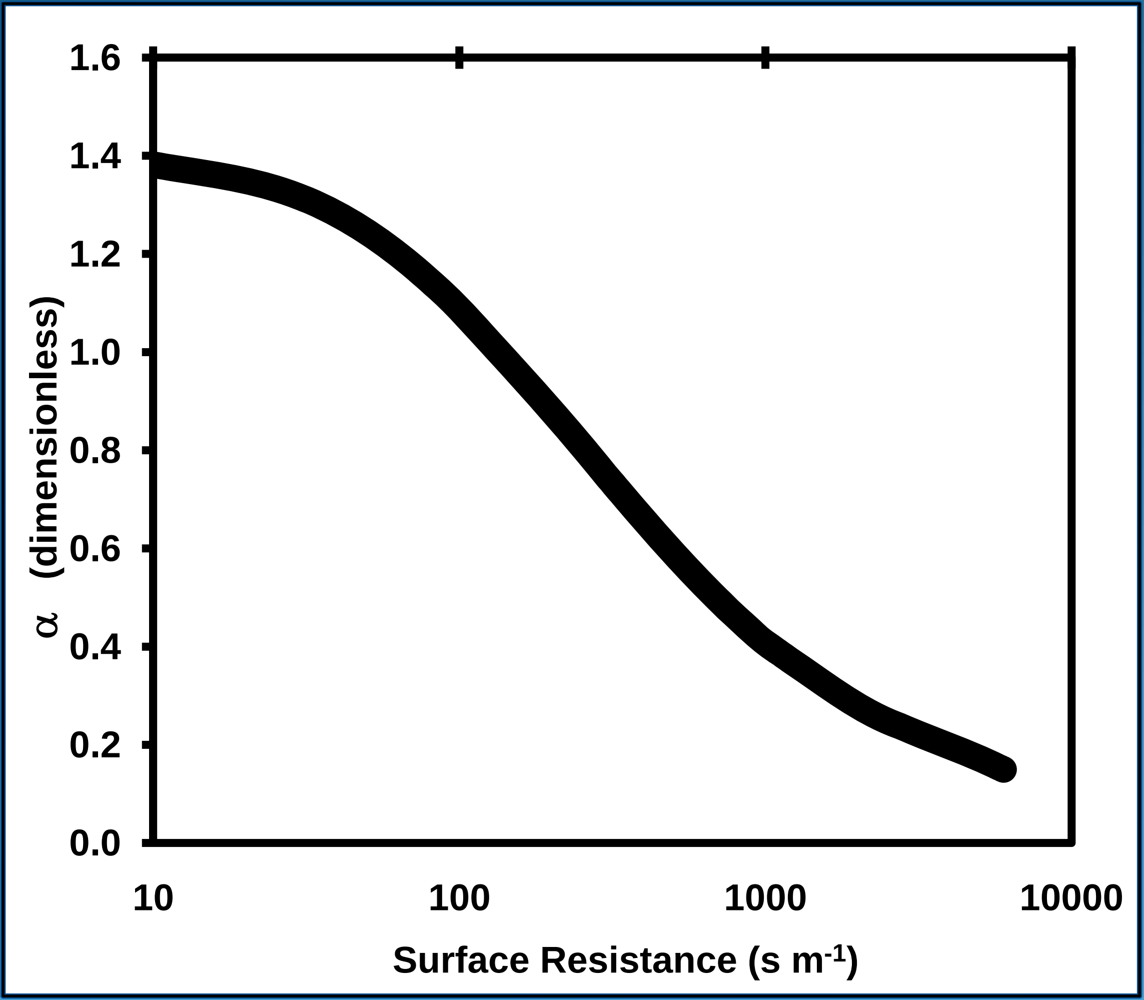
Low ⇒ Little change

Medium ⇒ Progressive fall off

High ⇒ Monotonic, to zero



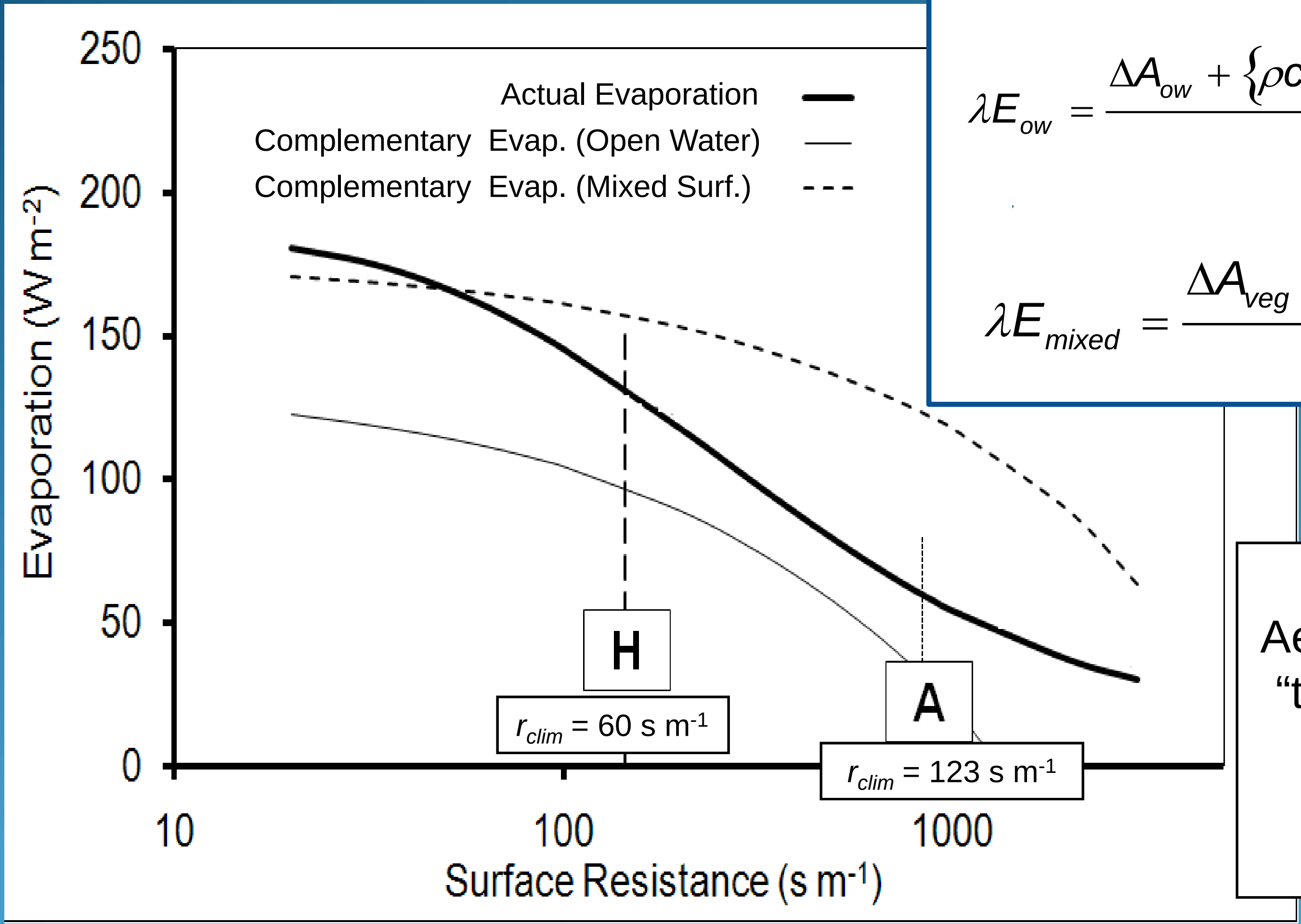
Coupled Land Surface /Atmosphere Model’s Parameterization of Evaporation Response



$$\begin{aligned}\alpha_{M\&S} = {} & 1.26 - 0.24141\left[\ln\left(\frac{(r_s)_{aa}}{70}\right)\right] \\ & - 0.07199\left[\ln^2\left(\frac{(r_s)_{aa}}{70}\right)\right] \\ & + 0.0099\left[\ln^3\left(\frac{(r_s)_{aa}}{70}\right)\right] \\ & + 0.00504\left[\ln^4\left(\frac{(r_s)_{aa}}{70}\right)\right] \\ & - 0.00083\left[\ln^5\left(\frac{(r_s)_{aa}}{70}\right)\right]\end{aligned}$$

Renormalized to describe all-day (rather than day-time) evaporation

Comparison of Complementary Evaporation with the True Behavior of Actual Evaporation in the Coupled System



$$\lambda E_{ow} = \frac{\Delta A_{ow} + \left\{\rho c_p D_2 \left(1 + 0.536 . u_2\right)\right\} / 250}{\Delta + \gamma}$$

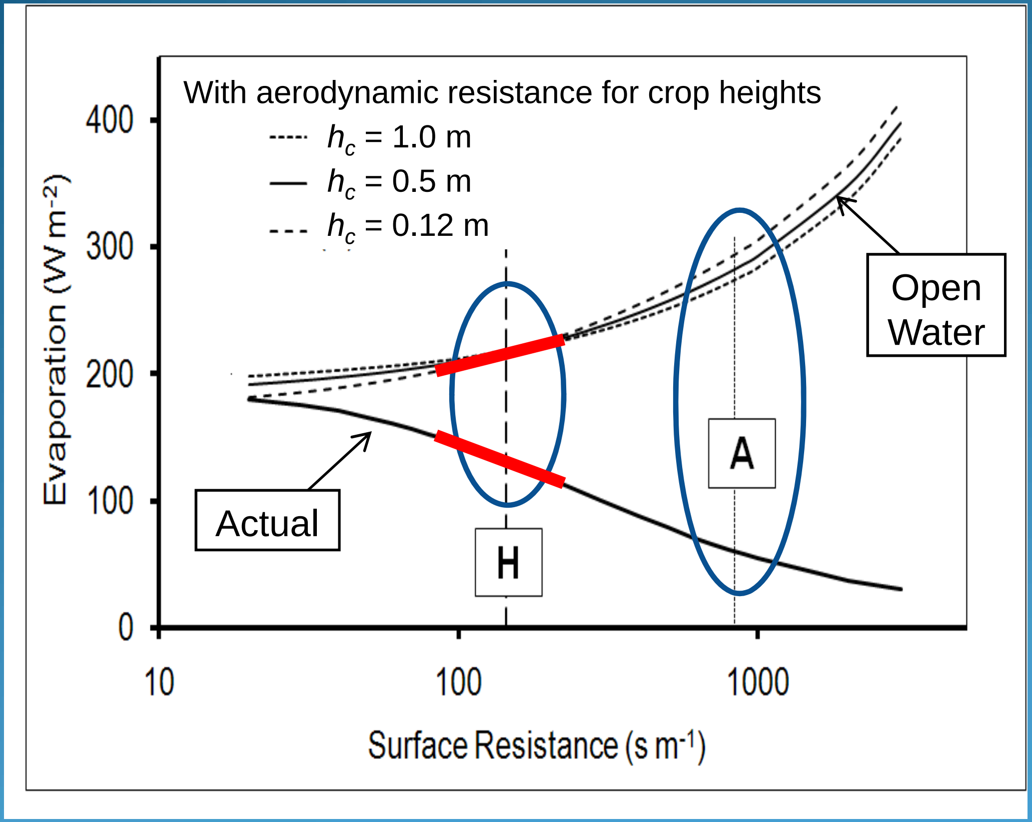
$$\lambda E_{mixed} = \frac{\Delta A_{veg} + \left\{\rho c_p D_2 u_2\right\} / 463}{\Delta + \gamma}$$

Mixed Surface

Aerodynamic resistance "tuned" to compensate for using vegetation albedo with surface resistance of zero

A_{veg} = 200 W m^{-2} ; u = 2 m s^{-1} ; T = 15 °C

Coupled Land Surface /Atmosphere Model's Variation of VPD and Open Water Evaporation



Calculated from

$$\frac{\Delta A_{veg} + \left(\rho c_p D\right)/r_a}{\Delta + \gamma\left(1 + r_s/r_a\right)} = \alpha \frac{\Delta}{\Delta + \gamma} A_{veg}$$

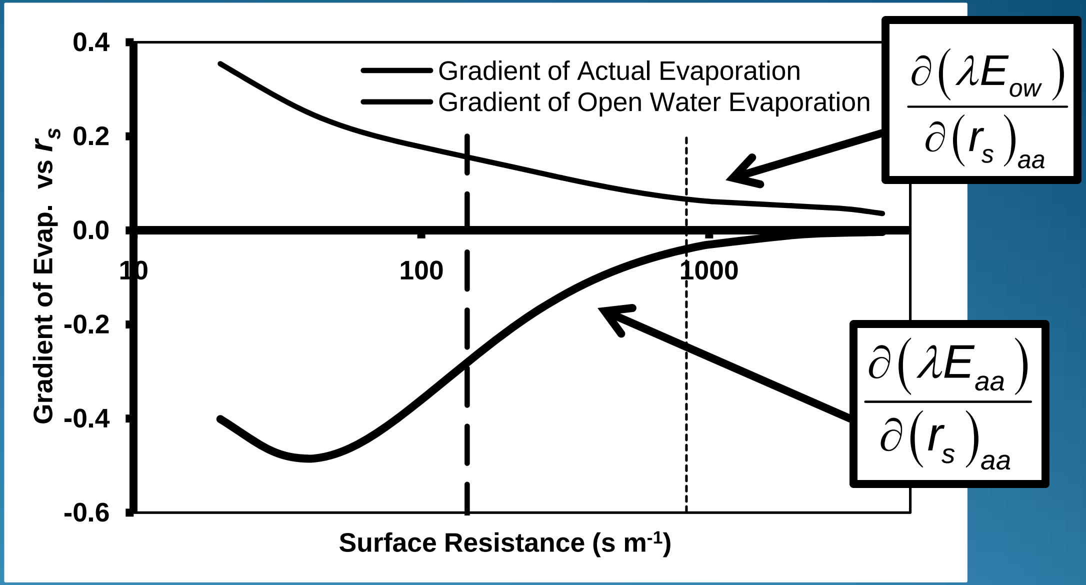
$$D = \frac{\Delta A_{veg}}{\rho c_p}\left[\frac{\alpha_{M\&S}\gamma r_s}{\Delta + \gamma} + \left(\alpha_{M\&S} - 1\right) r_a\right]$$

$$\lambda E_{ow} = \frac{\Delta A_{ow} + \left[\rho c_p D_2\left(1 + 0.536 u_2\right)\right]/250}{\Delta + \gamma}$$

A_{veg} = 200 W m^{-2} ; u = 2 m s^{-1} ; T = 15 °C

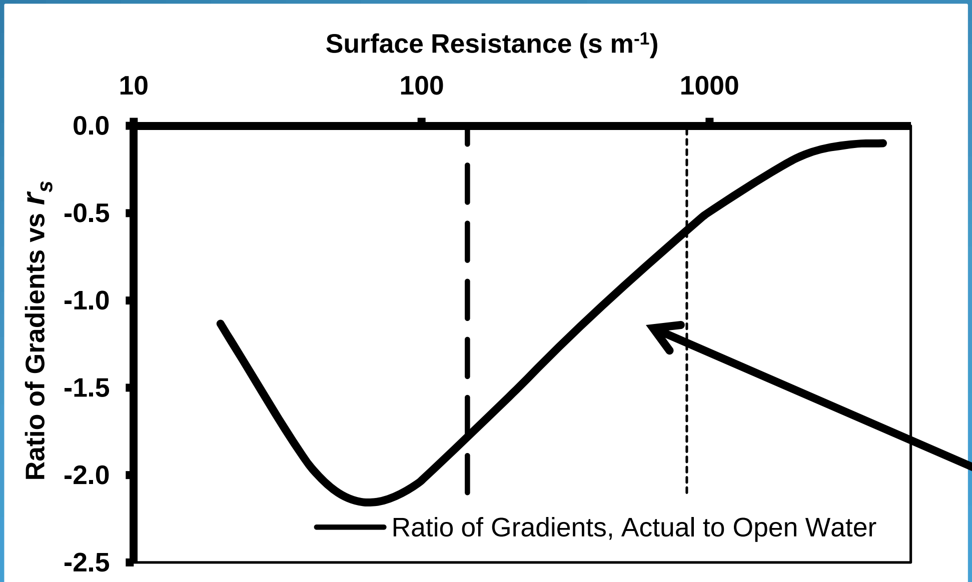
Note the different rates of change with surface resistance between Actual Evaporation and Open Water Evaporation which vary with conditions

Relative Rates of Change of Actual and Open Water Evaporation with Area-Average Surface Resistance



$$\frac{\partial\left(\lambda E_{ow}\right)}{\partial\left(r_s\right)_{aa}}$$

$$\frac{\partial\left(\lambda E_{aa}\right)}{\partial\left(r_s\right)_{aa}}$$

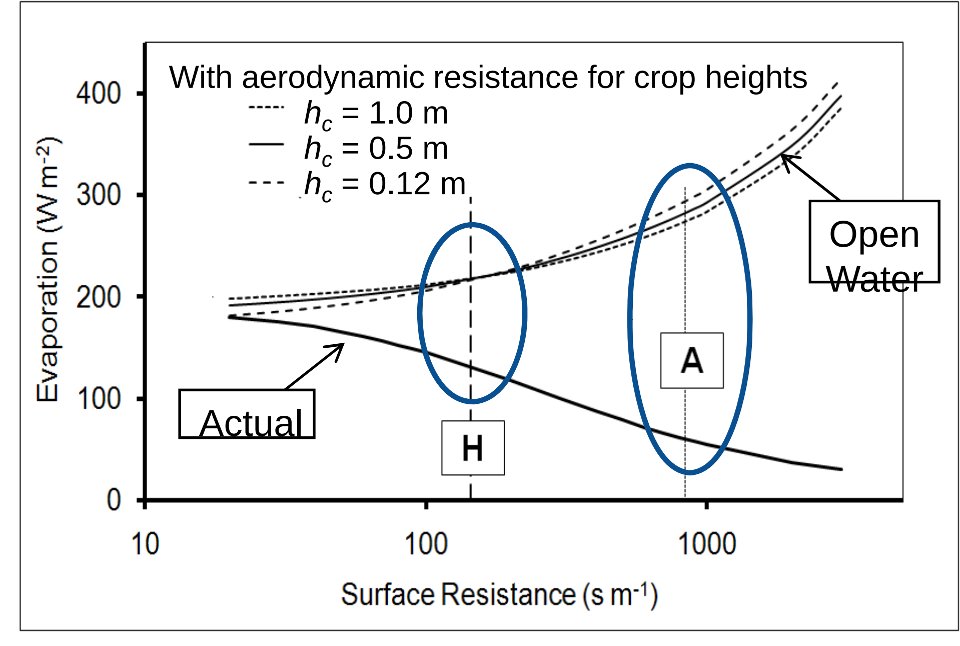


These calculations are made when

A_{veg} = 200 W m^{-2} ; u = 2 m s^{-1} ; T = 15 °C

$$\text{Ratio} = \left(\frac{\partial\left(\lambda E_{aa}\right)}{\partial\left(r_s\right)_{aa}}\right) \Bigg/ \left(\frac{\partial\left(\lambda E_{ow}\right)}{\partial\left(r_s\right)_{aa}}\right)$$

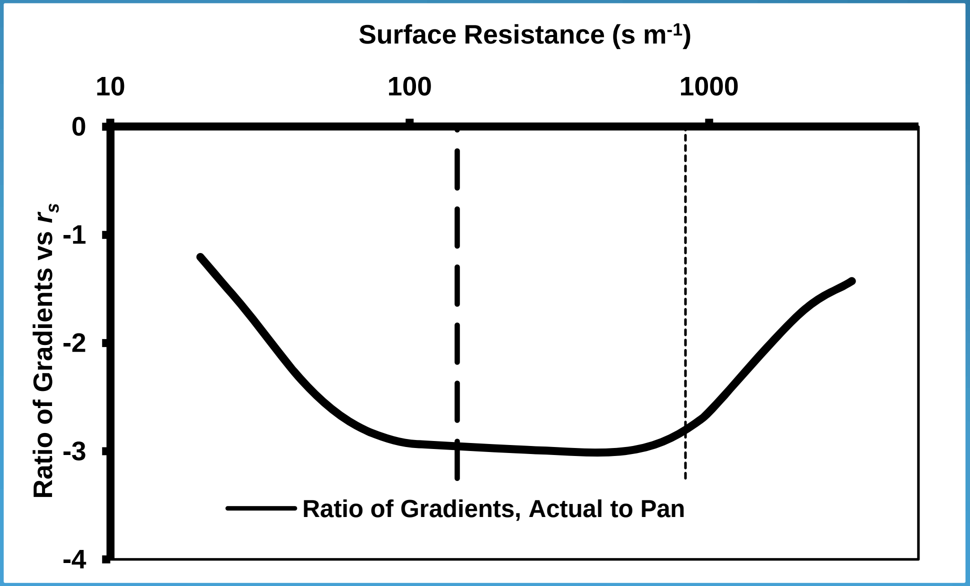
Relative Rate of Fractional Change of Actual and Open Water Evaporation with Area-Average Surface Resistance



$$\text{Ratio} = \left(\frac{\delta(\lambda E_{aa})}{\lambda E_{aa}} \right) \Bigg/ \left(\frac{\delta(\lambda E_{ow})}{\lambda E_{ow}} \right)$$

These calculations are made when

A_{veg} = 200 W m^{-2} ; u = 2 m s^{-1} ; T = 15 °C



$\text{Ratio} = \left(\frac{\delta(\lambda E_{aa})}{\lambda E_{aa}}\right) \Big/ \left(\frac{\delta(\lambda E_{ow})}{\lambda E_{ow}}\right)$ in a Range of Conditions

Wind Speed (m s^{-1})	Ratio at 5°C in Humid Conditions			
	100 W m^{-2}	200 W m^{-2}	300 W m^{-2}	400 W m^{-2}
1	-2.44	-2.38	-2.35	-2.34
2	-1.99	-1.94	-1.92	-1.91
3	-1.72	-1.68	-1.67	-1.66
4	-1.54	-1.51	-1.50	-1.49
5	-1.43	-1.39	-1.38	-1.38

Wind Speed (m s^{-1})	Ratio at 15°C in Humid Conditions			
	100 W m^{-2}	200 W m^{-2}	300 W m^{-2}	400 W m^{-2}
1	-3.82	-3.70	-3.67	-3.65
2	-3.05	-2.97	-2.94	-2.92
3	-2.60	-2.53	-2.51	-2.50
4	-2.30	-2.24	-2.23	-2.22
5	--2.09	-2.04	-2.02	-2.02

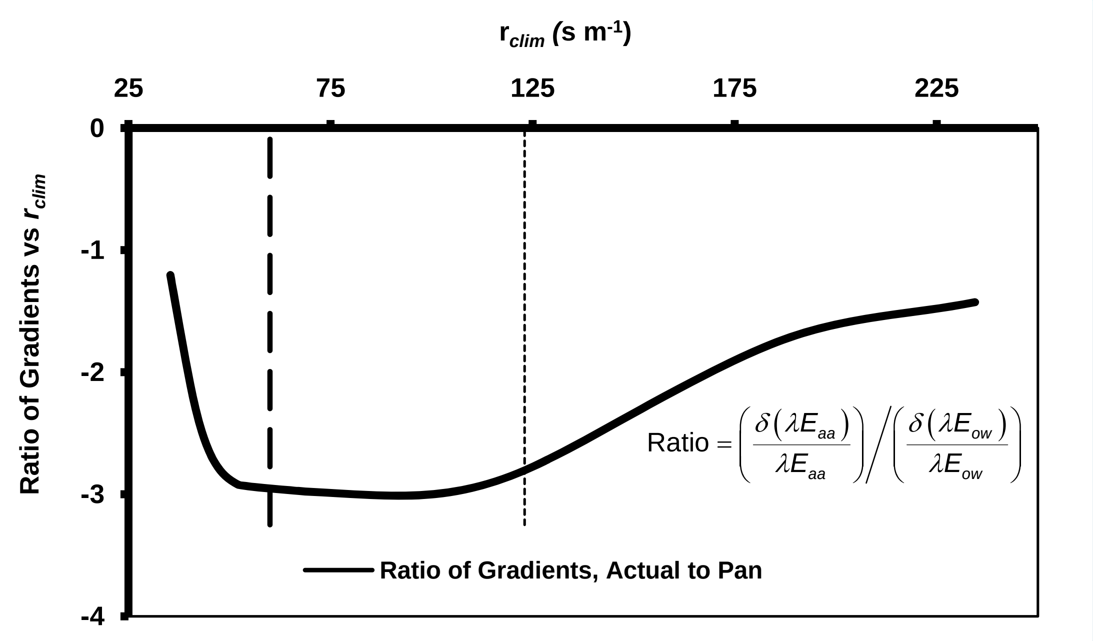
Wind Speed (m s^{-1})	Ratio at 25°C in Humid Conditions			
	100 W m^{-2}	200 W m^{-2}	300 W m^{-2}	400 W m^{-2}
1	-7.99	-7.74	-7.65	-7.61
2	-6.27	-6.08	-6.02	-5.99
3	-5.26	-5.11	-5.06	-5.04
4	-4.59	-4.47	-4.43	-4.41
5	-4.12	-4.01	-3.98	-3.98

Wind Speed (m s^{-1})	Ratio at 5°C in Arid Conditions			
	100 W m^{-2}	200 W m^{-2}	300 W m^{-2}	400 W m^{-2}
1	-2.71	-2.65	-2.63	-2.63
2	-2.33	-2.29	-2.28	-2.27
3	-2.11	-2.08	-2.07	-2.06
4	-1.96	-1.94	-1.93	-1.92
5	-1.86.	-1.84	-1.83	-1.82

Wind Speed (m s^{-1})	Ratio at 15°C in Arid Conditions			
	100 W m^{-2}	200 W m^{-2}	300 W m^{-2}	400 W m^{-2}
1	-3.42	-3.34	-3.31	-3.30
2	-2.86	-2.80	-2.78	-2.77
3	-2.54	-2.49	-2.47	-2.46
4	-2.32	-2.28	-2.27	-2.26
5	-2.16	-2.13	-2.12	-2.11

Wind Speed (m s^{-1})	Ratio at 25°C in Arid Conditions			
	100 W m^{-2}	200 W m^{-2}	300 W m^{-2}	400 W m^{-2}
1	-4.81	-4.68	-4.64	-4.61
2	-3.90	-3.80	-3.77	-3.75
3	-3.36	-3.29	-3.26	-3.25
4	-3.01	-2.95	-2.92	-2.91
5	-2.76	-2.70	-2.69	-2.68

Relative Rate of Fractional Change in Actual and Open Water Evaporation with Climatological Resistance



The value of area-average surface resistance can be derived iteratively from climatological resistance using:

$$\{(r_s)_{aa}\}_{n+1} = \frac{\Delta + \gamma}{\{\alpha_{M\&S}\}_n \gamma}\left\{r_{c\,\mathrm{lim}} - \left(\{\alpha_{M\&S}\}_n - 1\right) r_a\right\}$$

$$\{\alpha_{M\&S}\}_{n+1} = 1.26 - 0.24141\left[\ln\left(\frac{\{(r_s)_{aa}\}_{n+1}}{70}\right)\right] - 0.07199\left[\ln^2\left(\frac{\{(r_s)_{aa}\}_{n+1}}{70}\right)\right] + 0.0099\left[\ln^3\left(\frac{\{(r_s)_{aa}\}_{n+1}}{70}\right)\right]$$

$$+ 0.00504\left[\ln^4\left(\frac{\{(r_s)_{aa}\}_{n+1}}{70}\right)\right] - 0.00083\left[\ln^5\left(\frac{\{(r_s)_{aa}\}_{n+1}}{70}\right)\right]$$

Main Conclusions

- Most likely pan-evaporation has been reduced because **both** surface radiation is less (due to aerosol absorption or greater cloud cover), **and** area-average evaporation has increased. But measurement of change in radiation is needed to separate these two contributions.
- Bouchet's Complementary Evaporation Hypothesis unsuitable for relating changes in pan- and area-average evaporation because :
  - (a) uses the outdated "potential" description of evaporation;
  - (b) ignores differences in albedo and wind speed dependency;
  - (c) ignores understanding of coupled land-atmosphere processes
- There are large difference between the changes in actual- and pan-evaporation induced by changes in surface resistance. When humid, small induced change in pan-evaporation hard to identify separately?
- Climatological resistance could be used to diagnose changes in the meteorological influences on evaporation, and its analysis may even allow calculation of changes in area-average evaporation