Coupling of energy, water and carbon cycle: a retrospective and prospective

Ying-Ping Wang CSIRO Environment, Australia

What are the fundamental progresses?

Energy and water cycles
- Penman equation (1948)
- Monin-Obukhov similarity theory (1954)
- Budyko curve (1961)
- Penman-Monteith equation (1965)
- Priestley-Taylor equation (1972)

Carbon cycle
- Cavin cycle (C3) (1950)
- Hatch-Slack pathway (C4) (1966)
- Cowan and Farquhar’s optimization theory (1977)
- Farquhar’s photosynthesis model (1980)

Coupling (leaf water use efficiency)
- Bierhuizen and Slayter model (WUE=Y/T=k/VPD) (1965)
- Farquhar’s theory (1982)

Prologue

We have hundreds of **models** of water and carbon cycles. The coupled energy, water, carbon or even nutrient cycles are included in most advanced earth system **models** for projecting future climate or environmental changes.

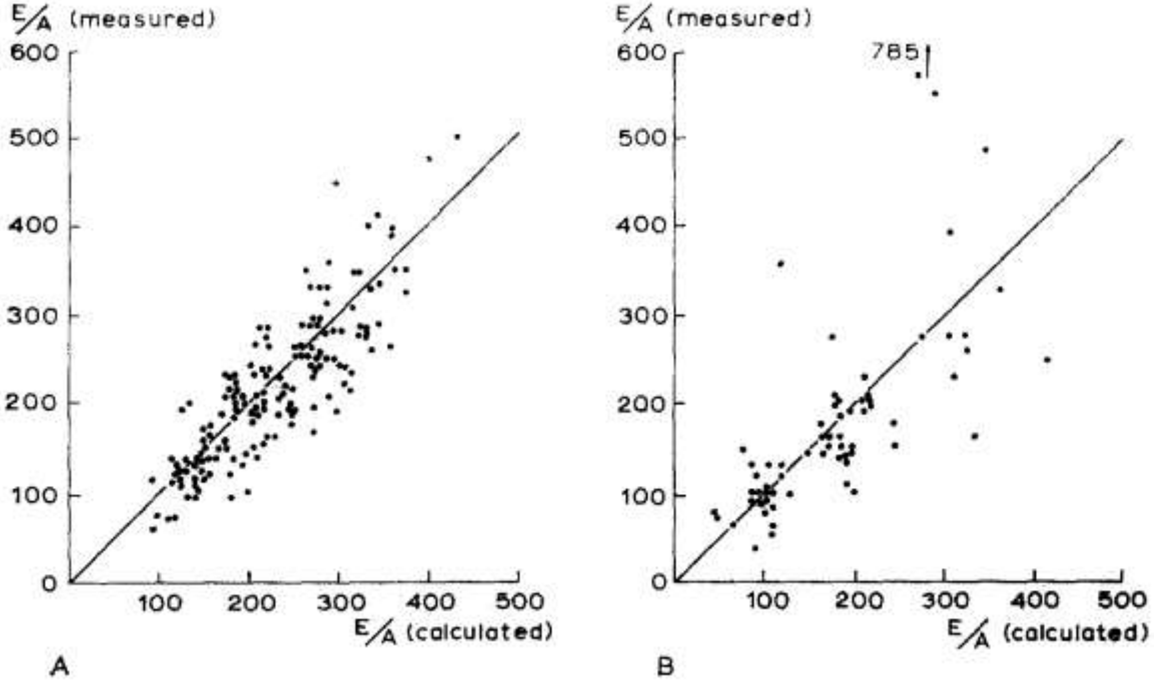
However, much of the fundamentals underpinned those models were developed >40 years ago.

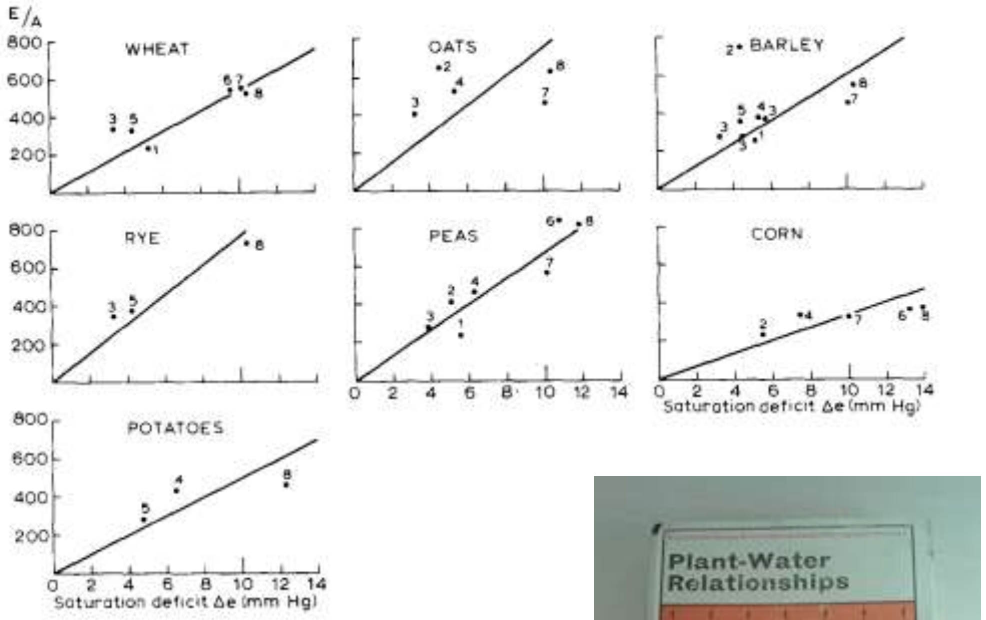
Q: are we making real progress?

Coupling of energy, water and carbon cycles

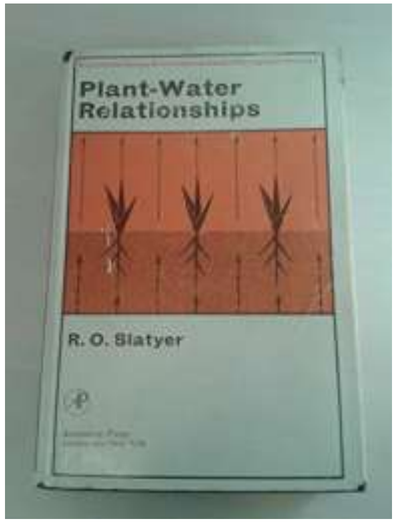
- Coupling of water and energy cycles was recognized, and the physics on latent heat transfer was understood (Black 1762).
- Studies of the coupling of water and carbon cycles were made possible only with the invention of leaf gas exchange (Bierhuizen and Slatyer 1964).
- Including surface conductance into Penman-Monteith equation (1966) started a new era of studies on water and carbon coupling.

Bierhuizen and Slatyer (1965, Agri. Met.)





$$\frac{E}{A} = \frac{1}{WUE} = 0.079\,\frac{\Delta w}{\Delta c}\frac{r_{bc} + r_{sc} + r_m}{r_{bw} + r_{sw}}$$



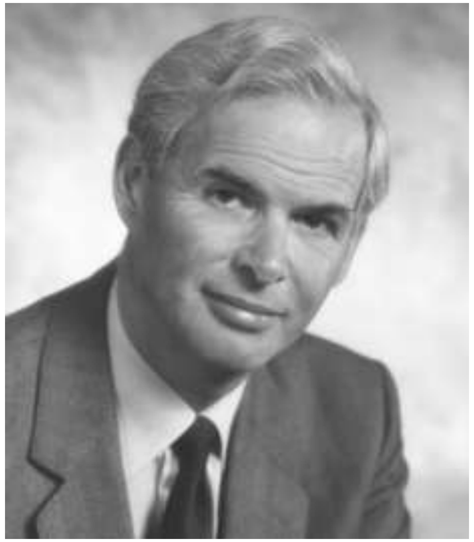
Penman-Monteith equation

Penman equation (1948)

$$\lambda E = \frac{\Delta R_n + 6.43\gamma(1+0.536U)D}{\Delta+\gamma}$$

Penman-Monteith equation (1965)

$$\lambda E = \frac{\Delta(R_n - G) + \rho_a c_p / r_h}{\Delta + \gamma\left(1 + \frac{r_v}{r_h}\right)}$$



John Monteith
(1929-2012)

Monteith (1965) stated: “the parameters r_h and r_v allow the equations of heat and vapor flux derived from a single leaf to be applied to a plant community”

Scaling from leaf to canopy using r_v attracted criticism

A meeting organised by Lloyd Evans in 1962 in Canberra invited a number of prominent scientists, including RJ Taylor, WC Swinbank, CB Tanner, John Philip.

CB Tanner (1963) “derivation of r_s is invalid when the sources and sinks of heat, water vapour and momentum were set **at different levels** of a crop canopy” .

John Philip (1966): “work which is **superficially** mathematical-physical, but which contains **loose** thinking, non-rigorous calculations, uncoordinated physical measurements in the field, and **overinflated** claims”….” is an **artifact** of a somewhat unrealistic analysis, and its physiological significance is **questionable**”.

Advances on canopy meteorology (1980’s)

Thoms AS (1976) (different profiles for heat and momentum transfer).

Denmead OT and EF Bradley (1985). Counter-gradient observed.

Raupach MR (1989) Near field and far field for canopy turbulence.

$$\lambda E = \frac{\Delta(R_n - G) + \rho_a c_p / r_h}{\Delta + \gamma\left(1 + \frac{r_v}{r_h}\right)}$$

→

$$\lambda E = \frac{\Delta \mathrm{Y} R_n^{*} + \rho_a c_p D / r_h}{\Delta + \gamma\left(\frac{r_w}{r_h} + \frac{r_v}{r_h}\right)}$$

Ecosystem evapotranspiration

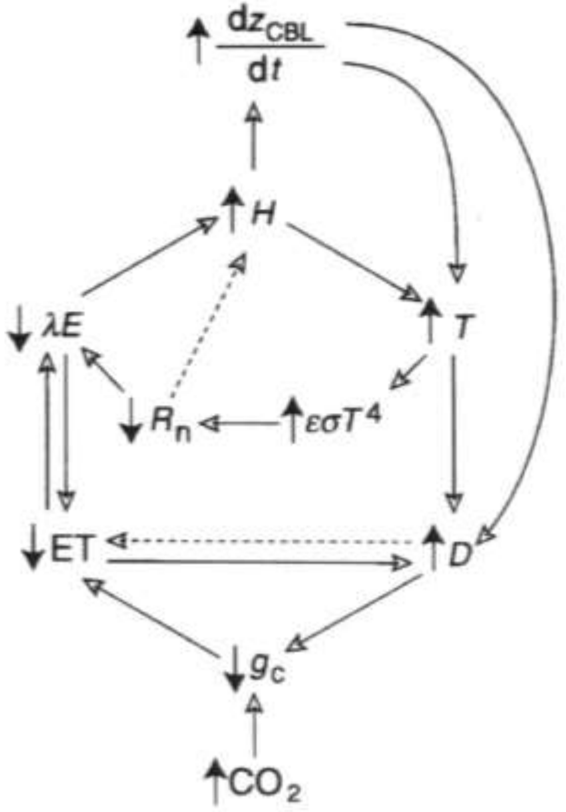
Leaf scale:

Transpiration is a nearly linear function of leaf conductance ($1/r_v$).

Canopy scale:

The first of these involves the humidity of the boundary layer. Drying of the boundary layer in response to increased r_V increases the driving gradient for transpiration, partially compensating for the increase in r_v.

An increase in canopy temperature increases the vapor pressure deficit (D), which tends to increase transpiration and partially counteract the effect of the increase in r_v.



What effect will a small fractional change in stomatal conductance have on the transpiration rate of the transpiring unit?

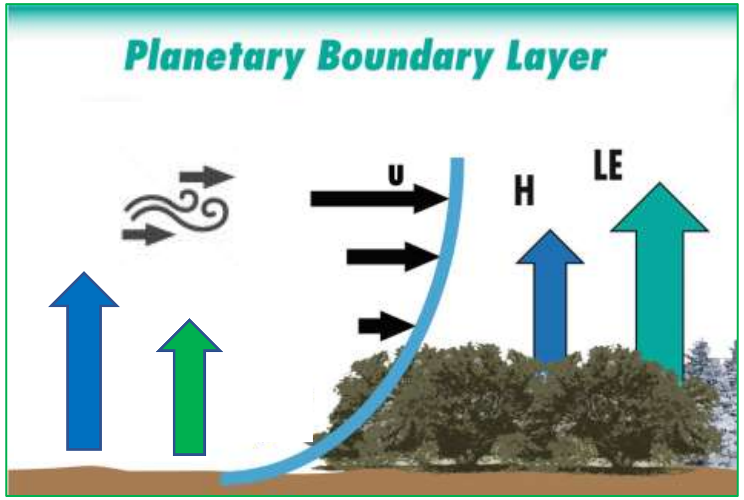
$$E = \Omega_{ci}E_{eq} + (1 - \Omega_{ci})E_{imp} \qquad \Omega_{ci} = (\varepsilon + 1) / (\varepsilon + 1 + r_{ci} / r_{ai})$$

Ω is the decoupling factor （解耦因子） between vegetation and atmosphere

Ω increases with spatial scale, *E* is less controlled by stomatal conductance.

much smaller change

depends on Ω



equal-proportional change

Jarvis and McNaughton (1986)

Surface conductance ($1/r_\mathrm{v}$) is not a simple integral of leaf stomatal conductance($1/r_\mathrm{l}$)

$$\boxed{1/\langle r_v\rangle = \sum a_i/r_{v,i}}$$

$$\omega_i = \frac{1}{r_{v,i} + \varepsilon r_{h,i}}$$

$$\langle r_h\rangle = \frac{\sum a_i \frac{R_{n,i}}{\langle R_n\rangle}\omega_i r_{h,i}}{\sum a_i\,\omega_i}$$

$$\langle r_v\rangle = \frac{\sum a_i \frac{R_{n,i}}{\langle R_n\rangle}\omega_i r_{v,i}}{\sum a_i\,\omega_i}$$

$$\langle r_s\rangle = \frac{\sum a_i \frac{R_{n,i}}{\langle R_n\rangle}\omega_i \left(r_{v,i} - r_{h,i}\right)}{\sum a_i\,\omega_i}$$

Raupach (1991, 1995) and McNaughton (1994)

Key message

- Surface conductance **is not** a simple integral of leaf stomatal conductance if the averaging scheme is applied to a multi-layered canopy
- The averaging scheme for water vapour is different from that for CO_2 or surface temperature

Soil-Plant-Atmosphere-Continuum (SPAC)

To counteract the “over-simplification” by John Monteith (1965), John Philip (1966) proposed and outline soil-plant-atmosphere continuum (SPAC).

- Boundary conditions and energy source
- Initial conditions through the SPAC
- Transfer equations for energy and water (second order pdes)
- Conductivities, diffusivities and other coefficients
- The geometry

Philip then admitted: the problem is too complicated. Simplifications are necessary:

- semi-isothermal
- quasi-stationary
- simplified geometry

SPAC: Ian Cowan’s contribution

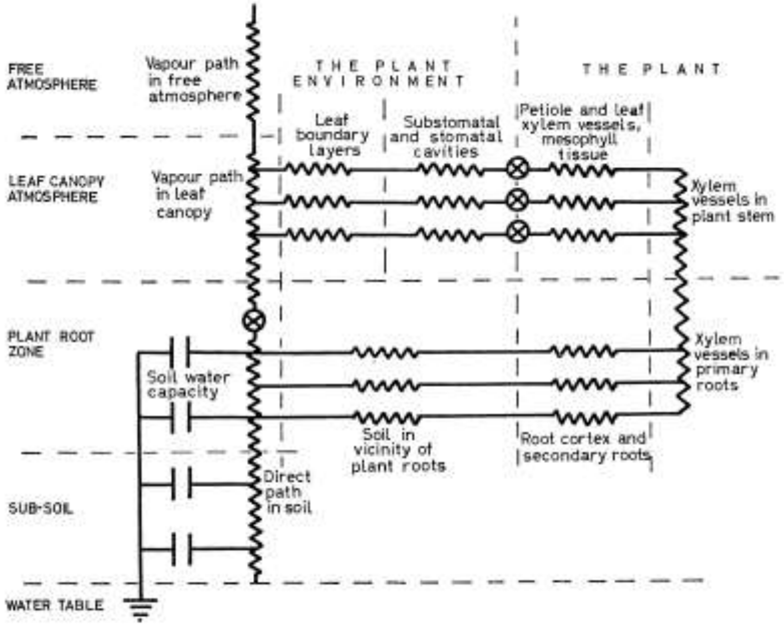
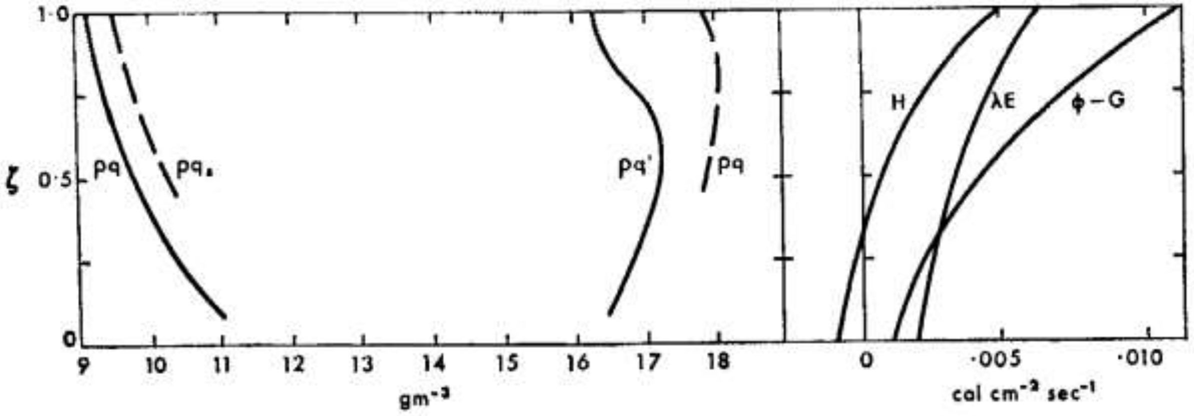


FIG. 1. Representation of pathways of water transport in the soil, plant and atmosphere. Sites of phase change, liquid to vapour, are distinguished by the symbol ⊗.



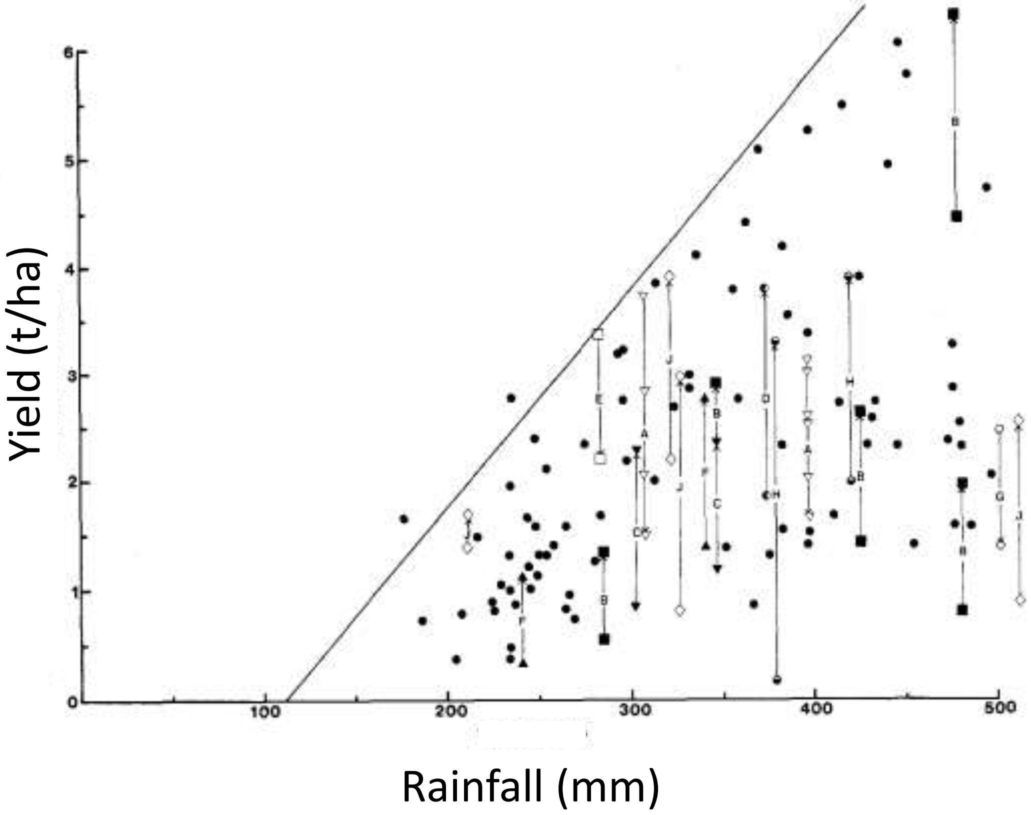
IR Cowan (1965), Transport of water in the soil-plant-atmosphere system. J App Ecol

IR Cowan (1968). Mass, heat and momentum exchange between stands of plants and their atmospheric environment. QJRMS.

Applications of WUE in crop modelling

- $Y = WUE \times T = \frac{k}{D} \times T$ (Tanner and Sinclair 1983)
- $ET = T + E$
- $E = E_{max}(t^{1/2} - (t-1)^{\frac{1}{2}})$ (Philip 1957)
- $\frac{ET}{ET_{max}} = f(\theta_s, l_R)$ (French and Schulz 1985)
- $\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial y}\left(D \frac{\partial \theta}{\partial y}\right) - \frac{\partial K}{\partial y}$ (Philip 1957)

Simulate crop yield without carbon cycle

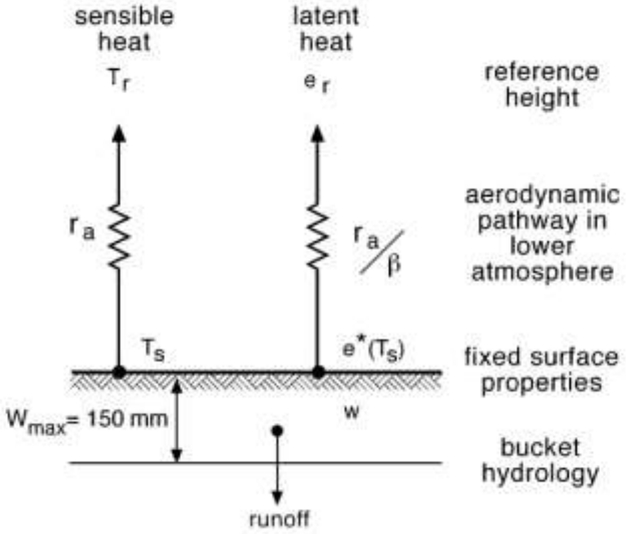


French and Schulz (1984)

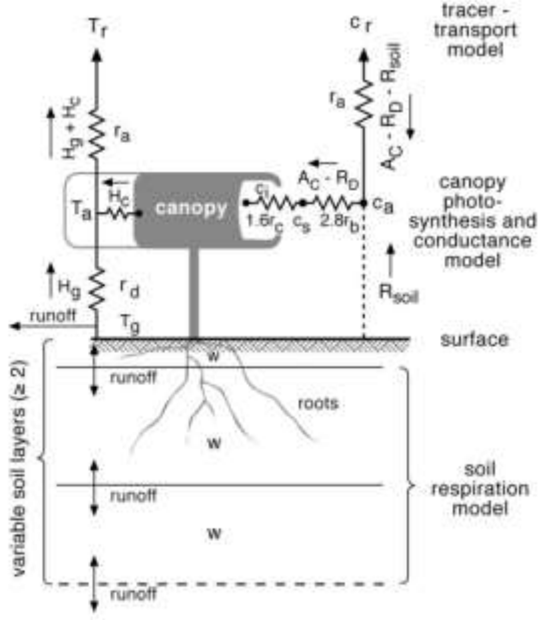
PM equation into global climate models

Dickinson and Henderson-Seller (1988) found that climate models with those early land models were inadequate for assessing the climatic impact of Amazon deforestation.

First generation



Third generation

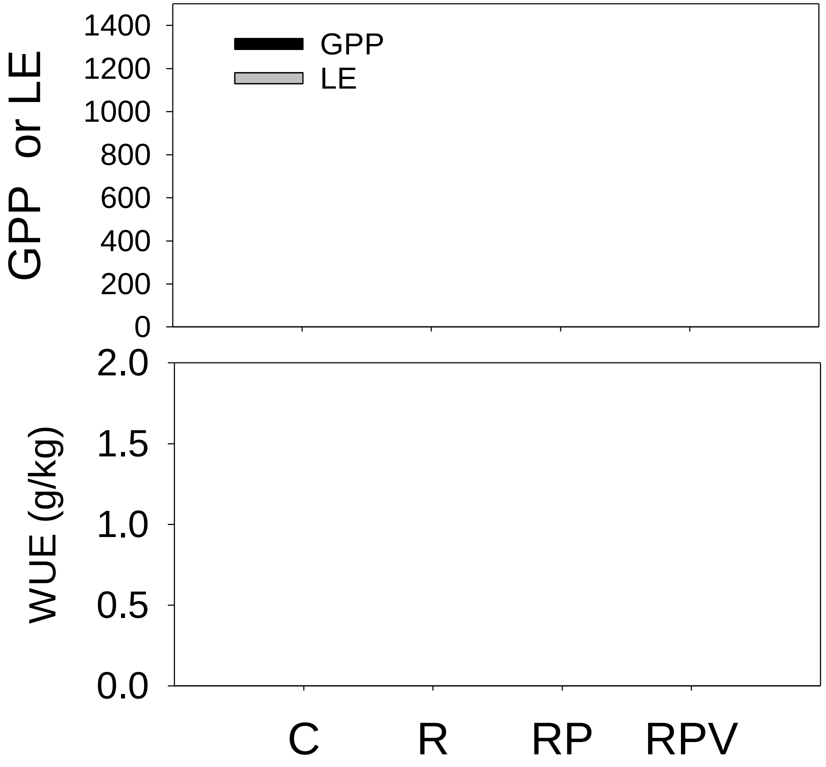


Dickinson and Henderson-Seller (1988); Sellers et al. 1986)

SiB2: Sellers et al. 1995; CLM: Dai et al. 2003; CABLE (Kowalczyk et al. 2006)

Adapted from Pitman 2003

The physiological effects on water, carbon fluxes, WUE and surface T (Bounoua et al. 1999)



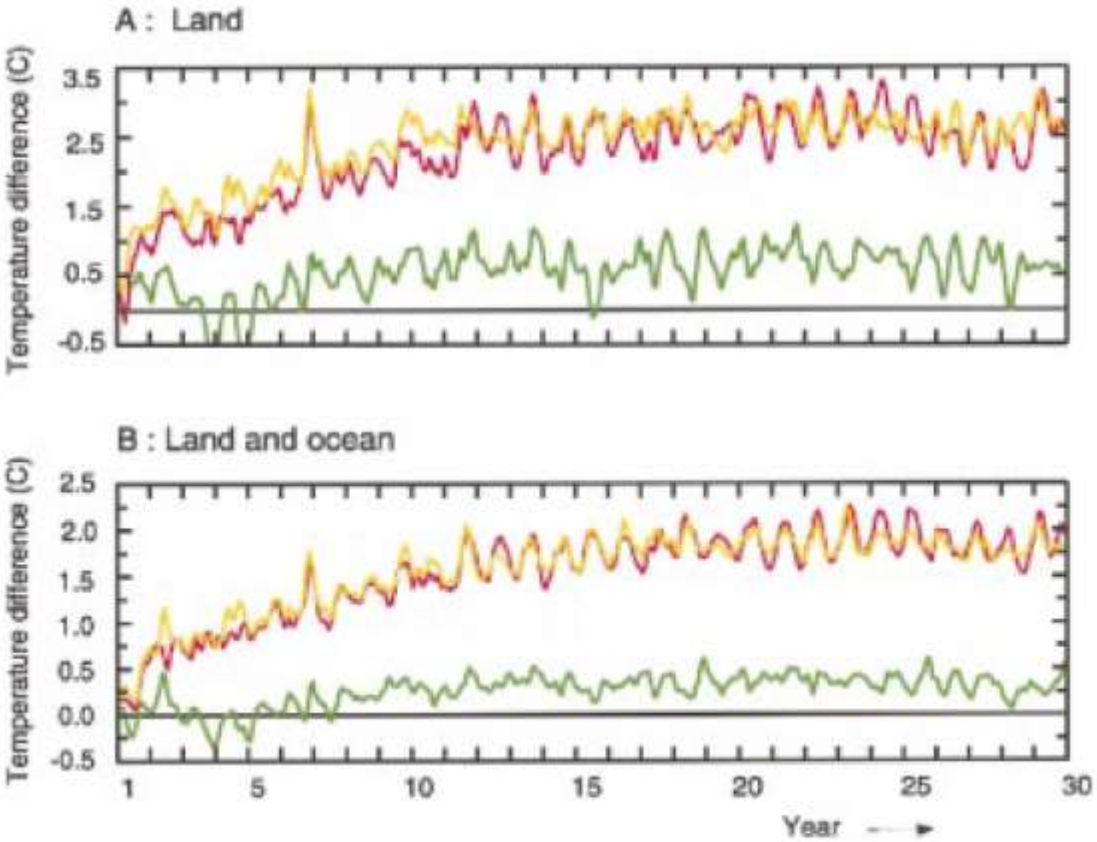


FIG. 3. Three-month running mean temperature difference (PV-C: green), (R-C: red), (RPV-C: orange) for (a) land points and (b) land and ocean points.

The fully coupled energy, water and carbon cycle into earth system model

- Two groups predicted very different response of land carbon by 21st century, source (Cox et al. 2000) and sink (Friedingstein et al. 2001)
- Fung et al. (2000) advocated the flying leap for carbon, or C4MIP
- By now there are >12 earth system models in CMIP6

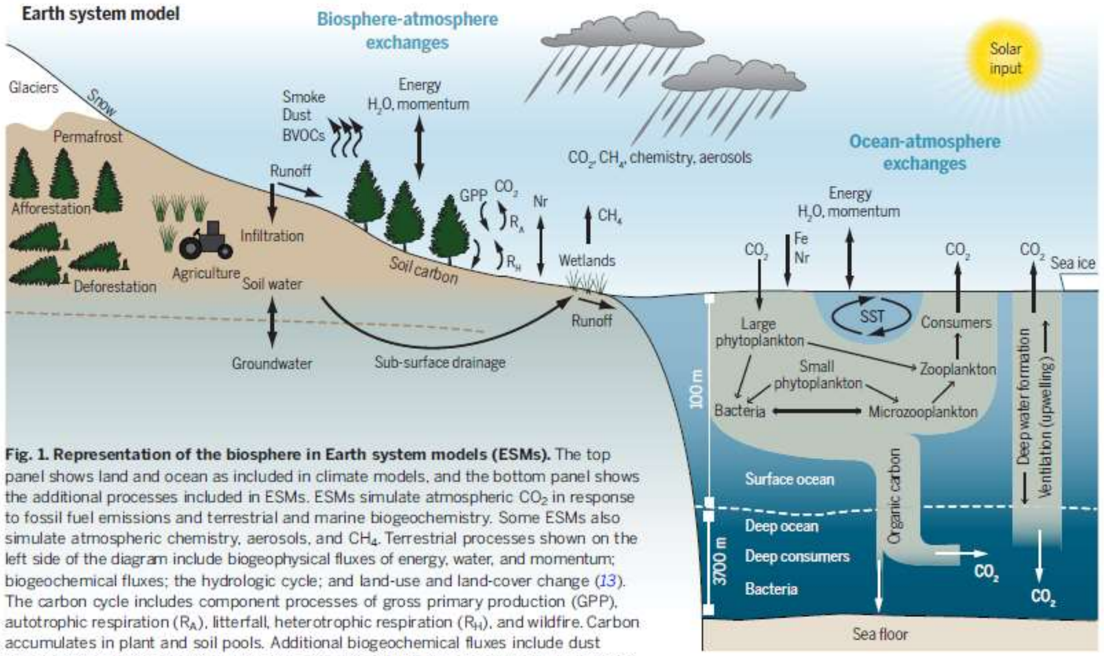


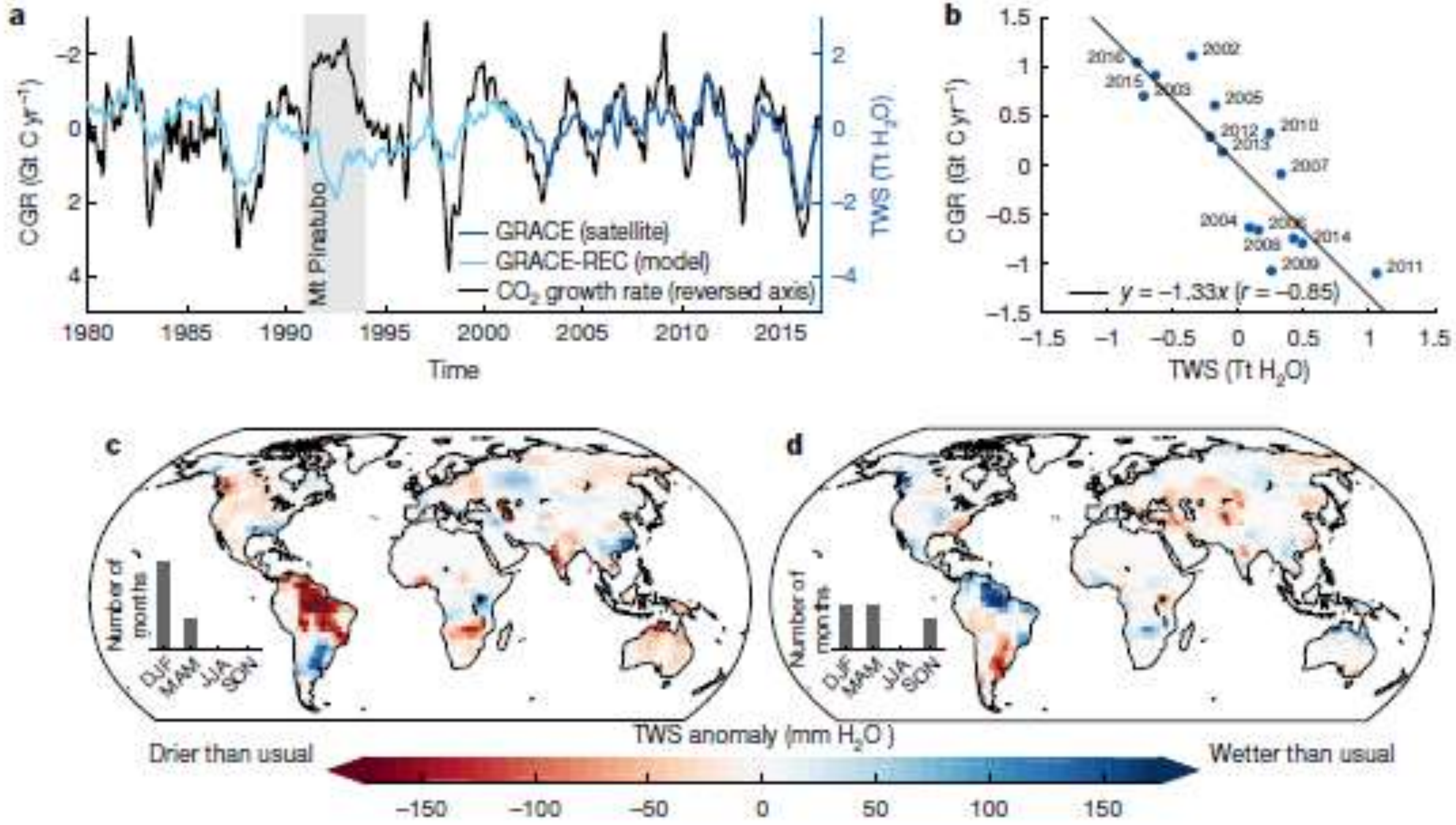
Fig. 1. Representation of the biosphere in Earth system models (ESMs). The top panel shows land and ocean as included in climate models, and the bottom panel shows the additional processes included in ESMs. ESMs simulate atmospheric CO_2 in response to fossil fuel emissions and terrestrial and marine biogeochemistry. Some ESMs also simulate atmospheric chemistry, aerosols, and CH_4. Terrestrial processes shown on the left side of the diagram include biogeophysical fluxes of energy, water, and momentum; biogeochemical fluxes; the hydrologic cycle; and land-use and land-cover change (*13*). The carbon cycle includes component processes of gross primary production (GPP), autotrophic respiration (R_A), litterfall, heterotrophic respiration (R_H), and wildfire. Carbon accumulates in plant and soil pools. Additional biogeochemical fluxes include dust entrainment, wildfire chemical emissions, biogenic volatile organic compounds (BVOCs), the reactive nitrogen cycle (Nr), and CH_4 emissions from wetlands. Ocean processes are shown on the right side of the diagram. Physical processes include sea ice dynamics, ocean mixing and circulation, changes in sea surface temperature (SST), and ocean-atmosphere fluxes. The gray shaded area depicts the marine carbon cycle, consisting of the phytoplankton-based food web in the upper ocean, export and remineralization in the deep sea and sediments, and the physiochemical solubility pump controlled by surface-deep ocean exchange (*100*).

Bonan and Doney 2018

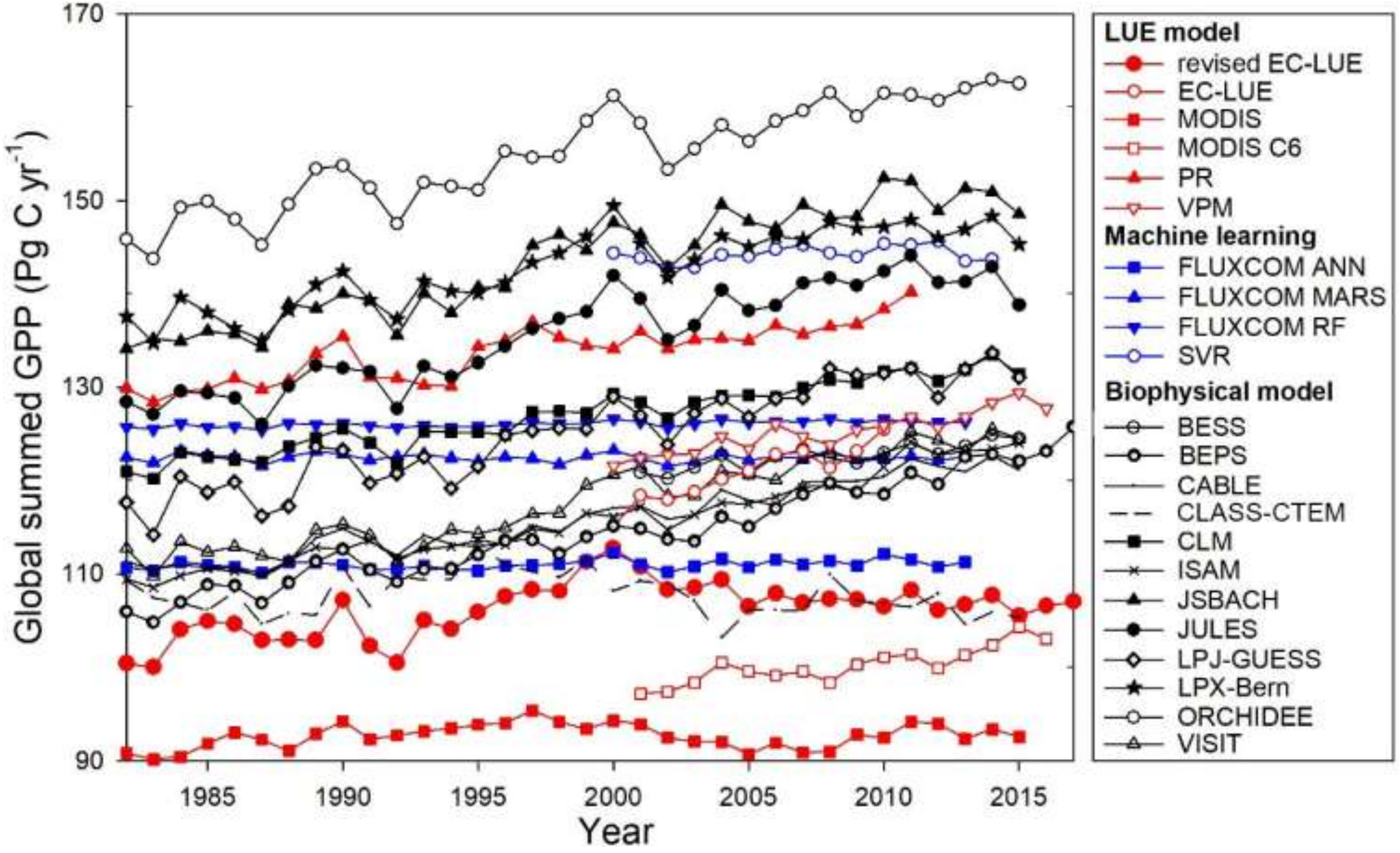
Tools for studying the coupled water and carbon cycles

- Global land surface model/earth system models
- Remote-sensing based models
- Observational based data analysis including machine learning

Observational evidence of a strong water-carbon coupling (Humphrey et al. 2018)



Comparison of GPP estimates

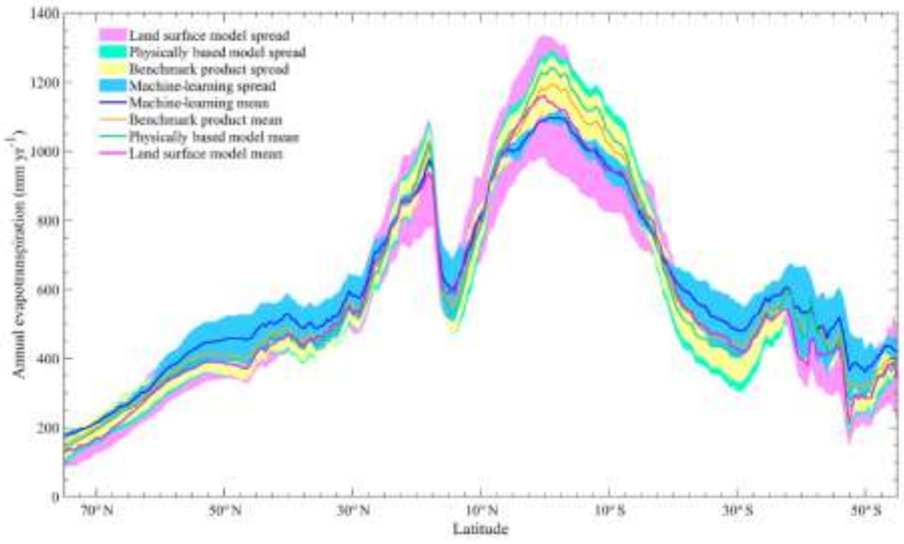


Large discrepancy

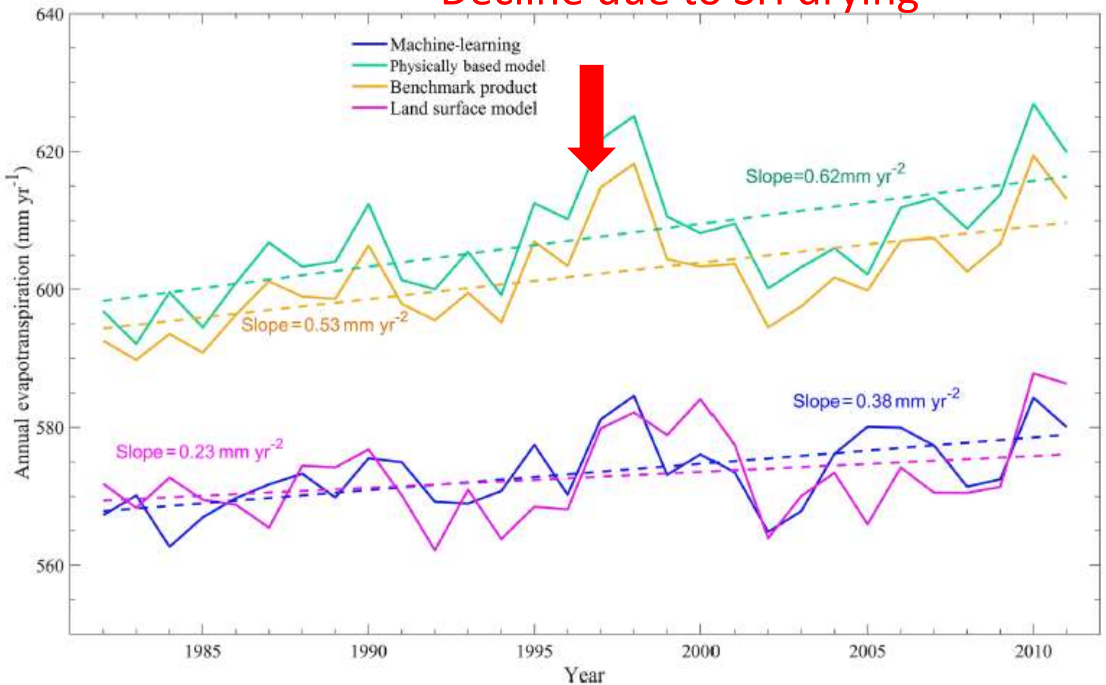
LSM>ML>LUC

Zheng et al. 2020

Latitudinal pattern and trend (Pan et al. 2020)



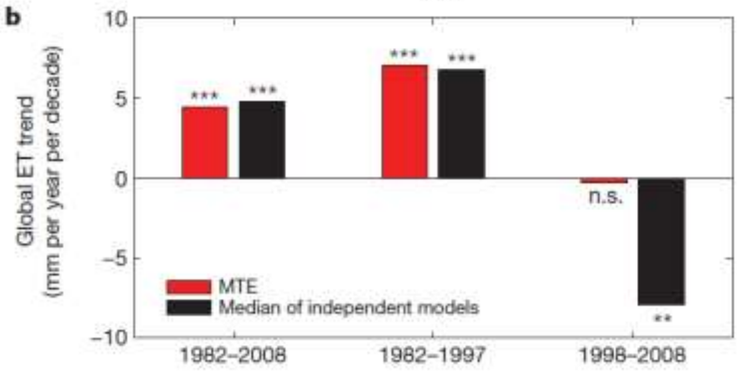
Decline due to SH drying



Consistent latitudinal pattern

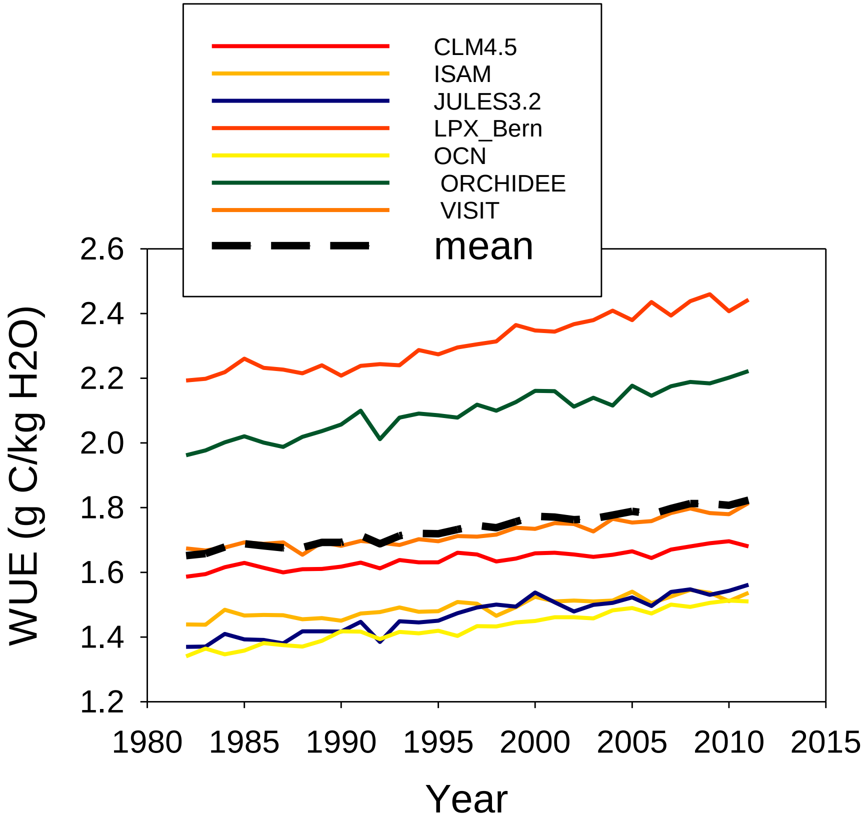
Trend

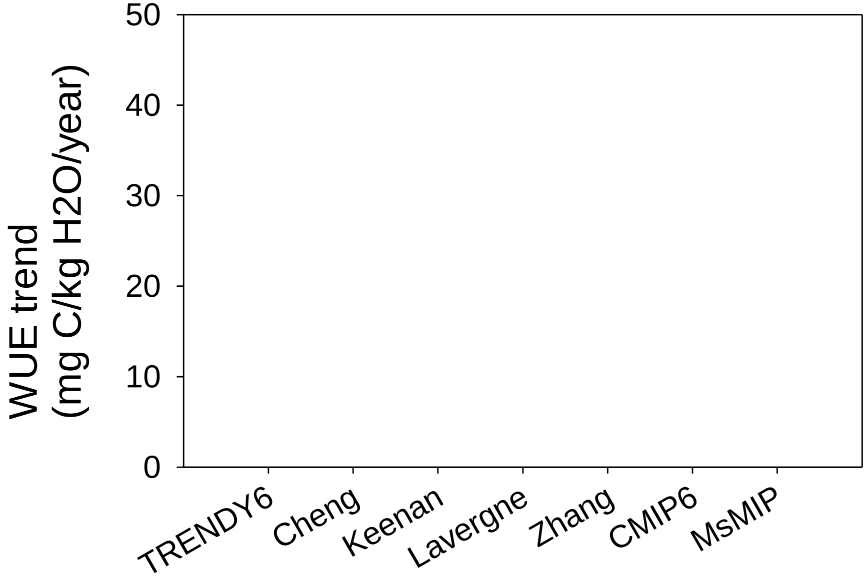
LSM, ML <benchmarking < physical model



Jung et al. 2010

Global WUE and its trend

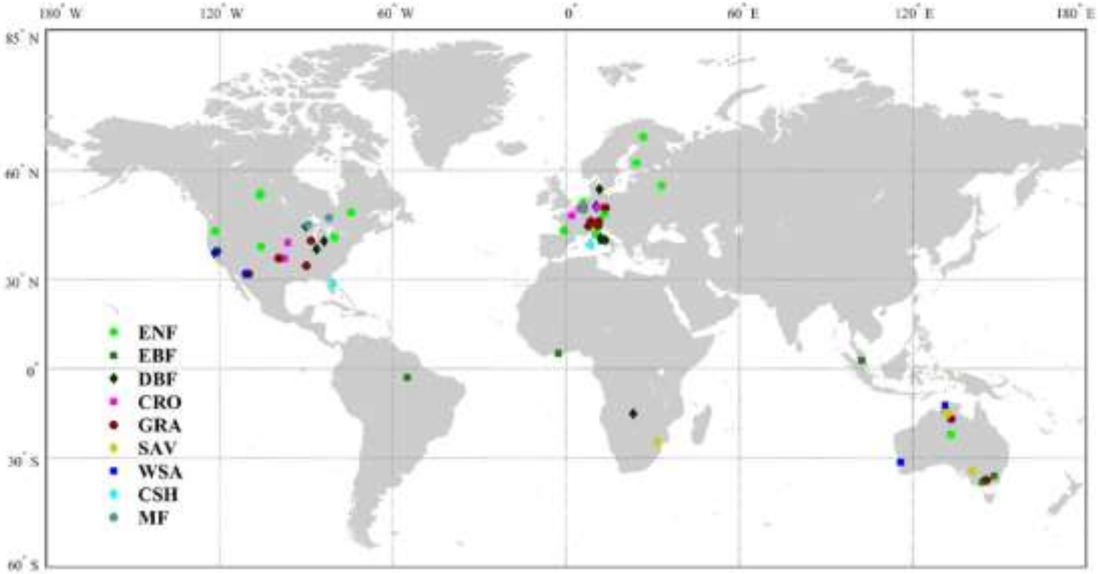




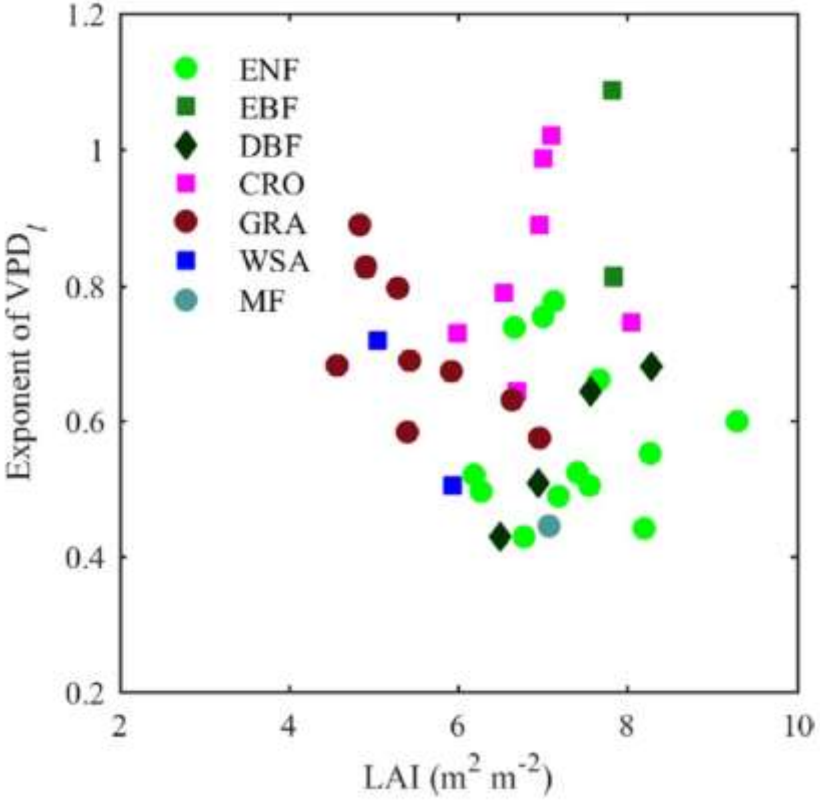
Leaf stomatal conductance at suboptimal or complexity in scaling up?

$$\textbf{\textit{Leuning model}}: \boldsymbol{G_s} \propto \frac{1}{D}; \quad \textbf{\textit{Medlyn model}}: \boldsymbol{G_s} \propto \frac{1}{\sqrt{D}}$$

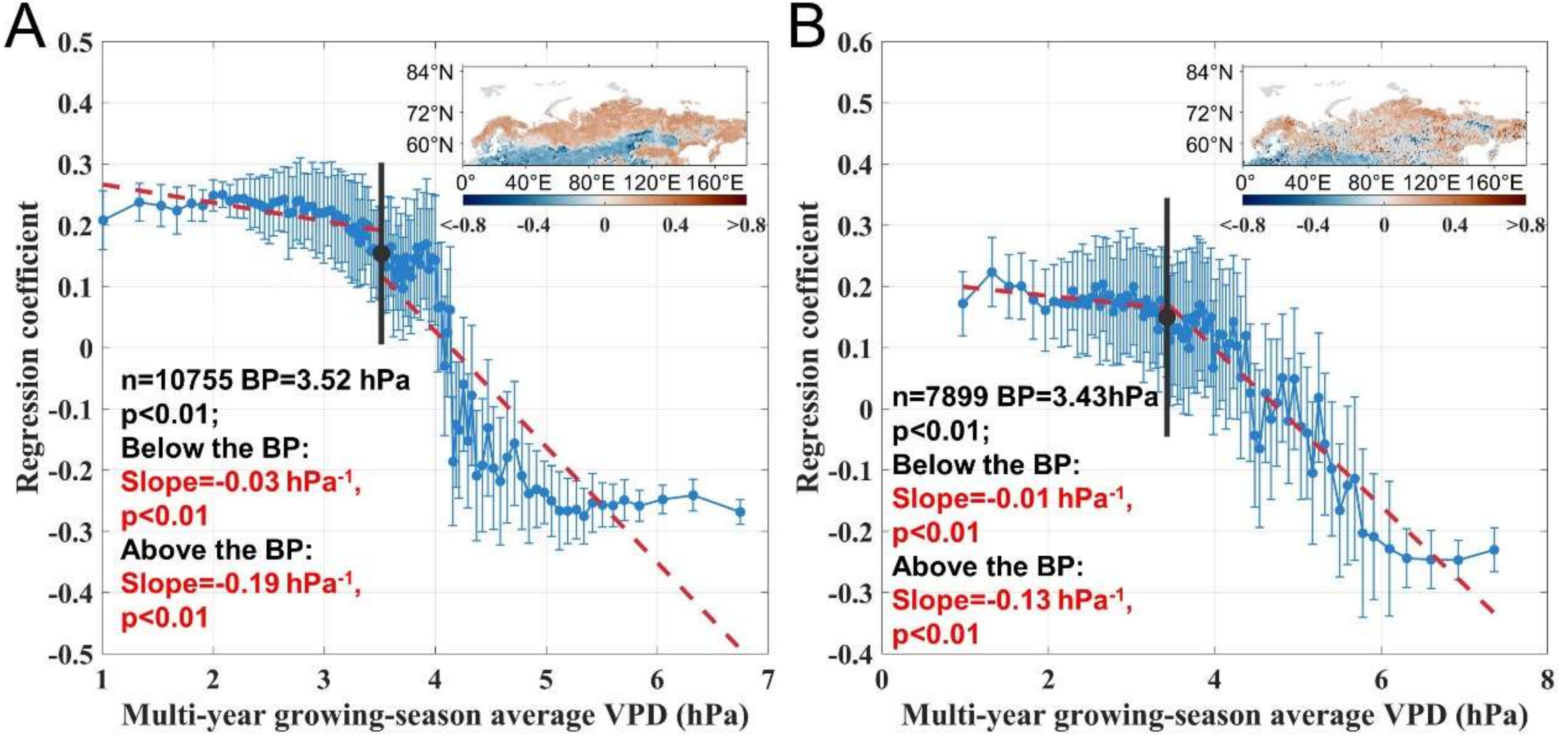
$$G_s = G_0 + G_1 \frac{\mathrm{GPP}}{C_a VPD_l^m}$$



Lin et al. 2018 AFM (77 sites)

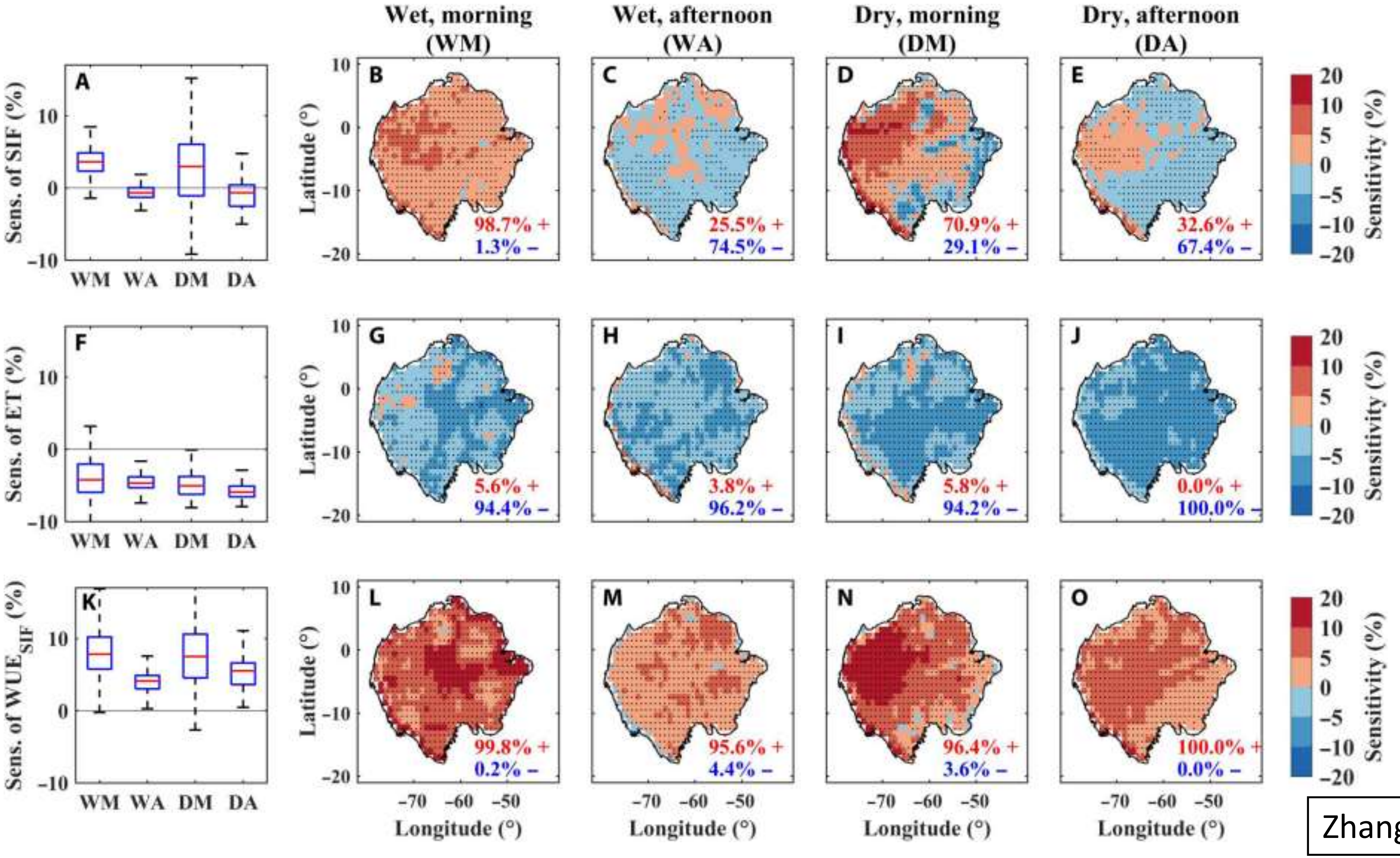


Positive response of GPP to VPD cannot be explained by the current model



Zhong et al. 2023

Positive sensitivity of SIF-based WUE to VPD (Zhang et al. 2023)



Zhang et al. 2023

Unresolved issues

- Lack of sufficient data to constrain global simulation. For example, no observationally-based estimates of global ET are available. All ET data products are generated by models, Precipitation data have large uncertainties.

- Lack of systematic benchmarking/calibration

- Under-sample regions or ecosystems

- Missing processes/errors in the inputs, such as precipitation

- Scaling issues remain

A personal prospective: where

- Machine learning will become more widely used;

- Nowcast and forecast with data assimilation will be used in studying policy-related questions;

- Advances in global science: why responses of some key processes vary with scale (both time and space)? Some new theories likely emerge as more observational evidence is gathered

- Importance of scales in studying the coupling
- (energy; days to weeks, water: month to year; carbon year to century).

Q: Are we making progress?

A: Yes! I have more observations than every before, more models than ever before. We also have evidence of a strong coupling of energy, water and carbon cycles at regional, and global scales.

We have nearly completed SPAC as outlined by John Philip in 1966 with a few twists and turns, including the late development of plant hydraulics
(Tuzet, Perrier, Leuning 2003)

Models

A model is a useful (and often indispensable) framework on which to organize our knowledge …… . the quantitative consequences of any model **can be no more reliable** than the a priori agreement between the assumptions of the model and the known facts about the real phenomenon.”.

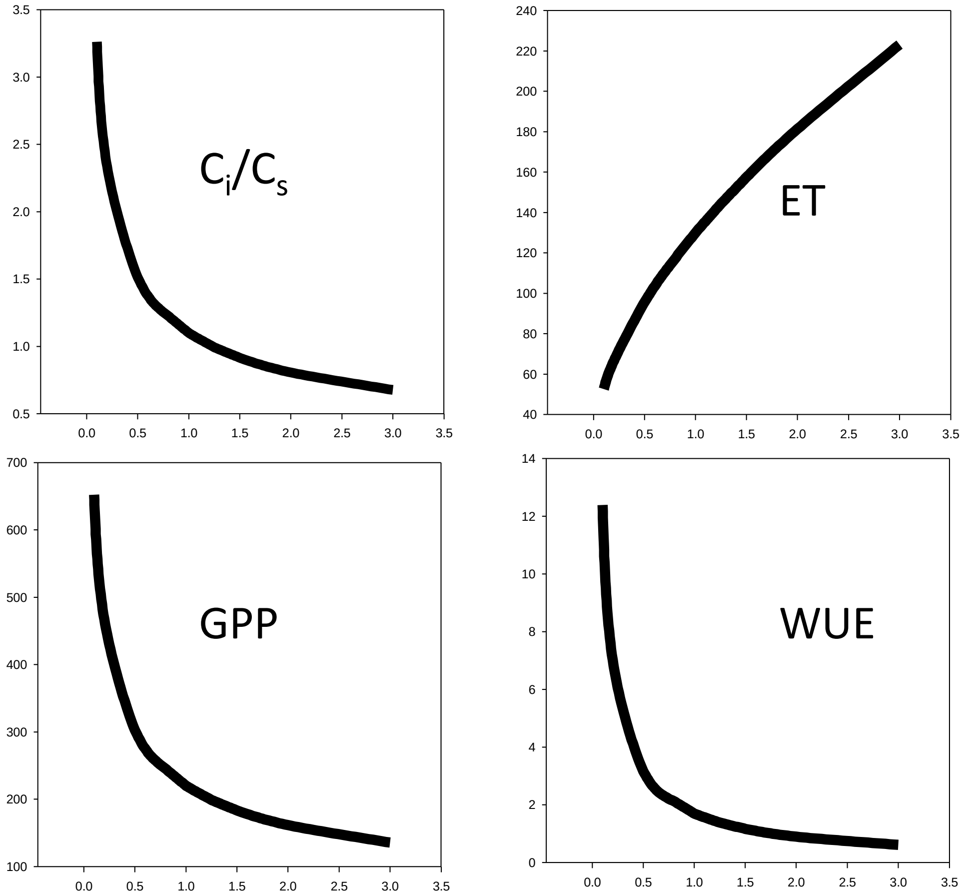
(John Philip, 1966 Annu. Rev. Plant. Physiol. 1966, p258).

Acknowledgment

I was helped by several colleagues in preparing this talk, particularly Lu Zhang Xu Liang.

I have been really fortunate to have known or worked with some eminent scientists in the field, Monteith, Jarvis, Cowan, Farquhar, Philip, Denmead, Raupach, Leuning, Finnigan, McNaughton, Norman etc. They all have major influences on me directly or indirectly.

Response of GPP, ET and WUE to VPD



Increasing VPD

Important contributors to the divergence among different approaches

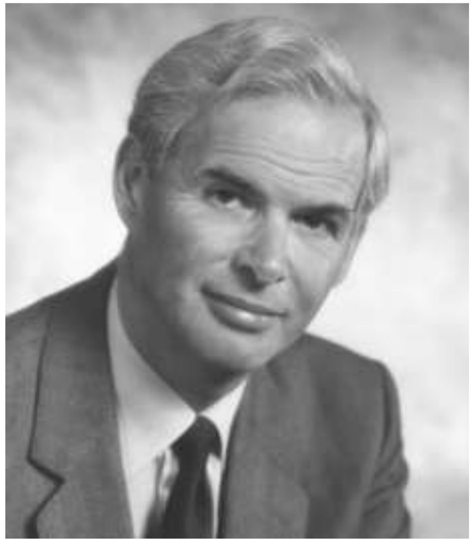
- Different responses of ET and GPP to VPD
- Impact of soil water stress
- Different sensitivities of ET and photosynthesis to CO2
- Vegetation dynamics
- Land use change

Stomatal conductance

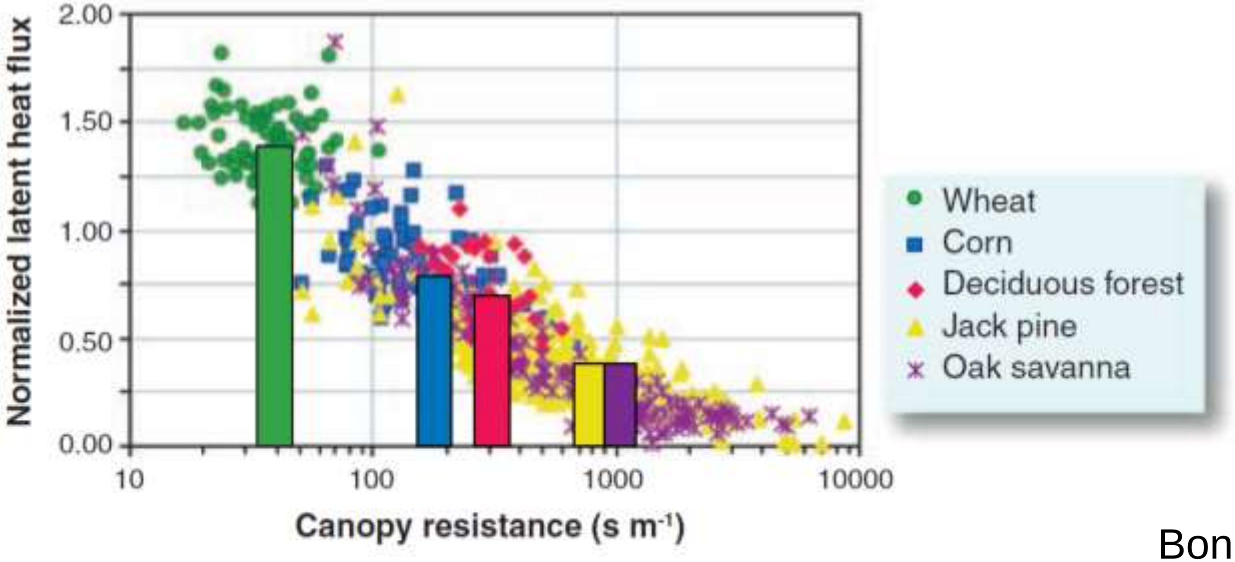
$$g^{-1} = \rho\,(q_s^{*} - q_s)/E$$

Penman-Monteith equation

$$E = \frac{\Delta Q_{\mathrm{ne}} + \gamma \mathrm{Ce}\, \bar{u}_1 \rho (q_2^{*} - \bar{q}_2)}{[\Delta + \gamma(1 + \mathrm{g}^{-1}\mathrm{Ce}\, \bar{u}_1)]}$$

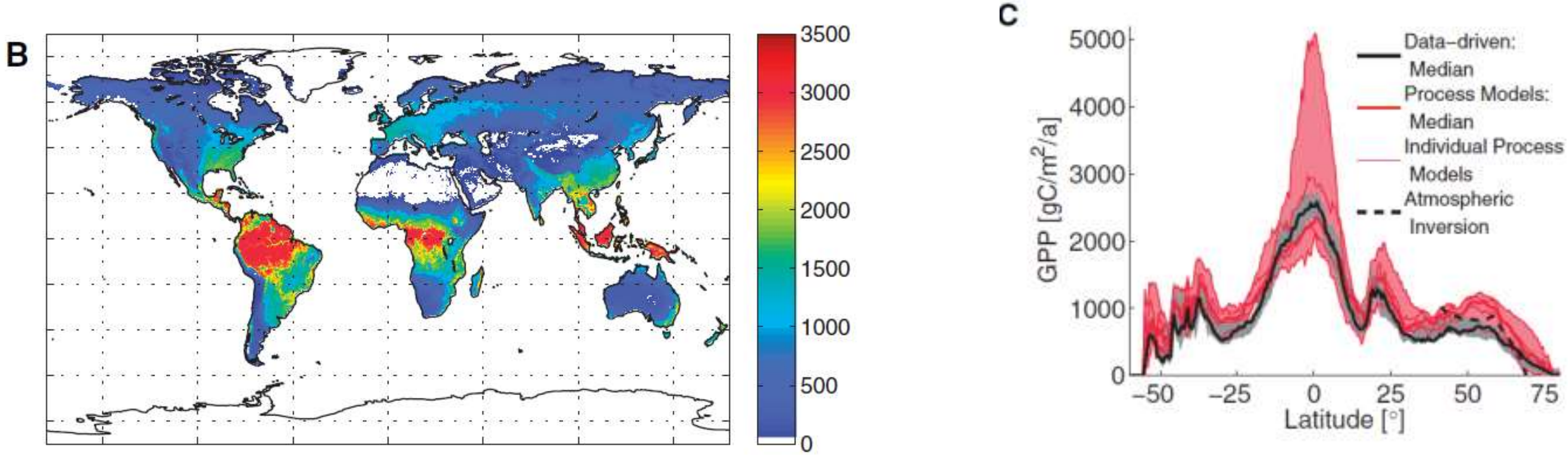


John Monteith
(1929-2012)



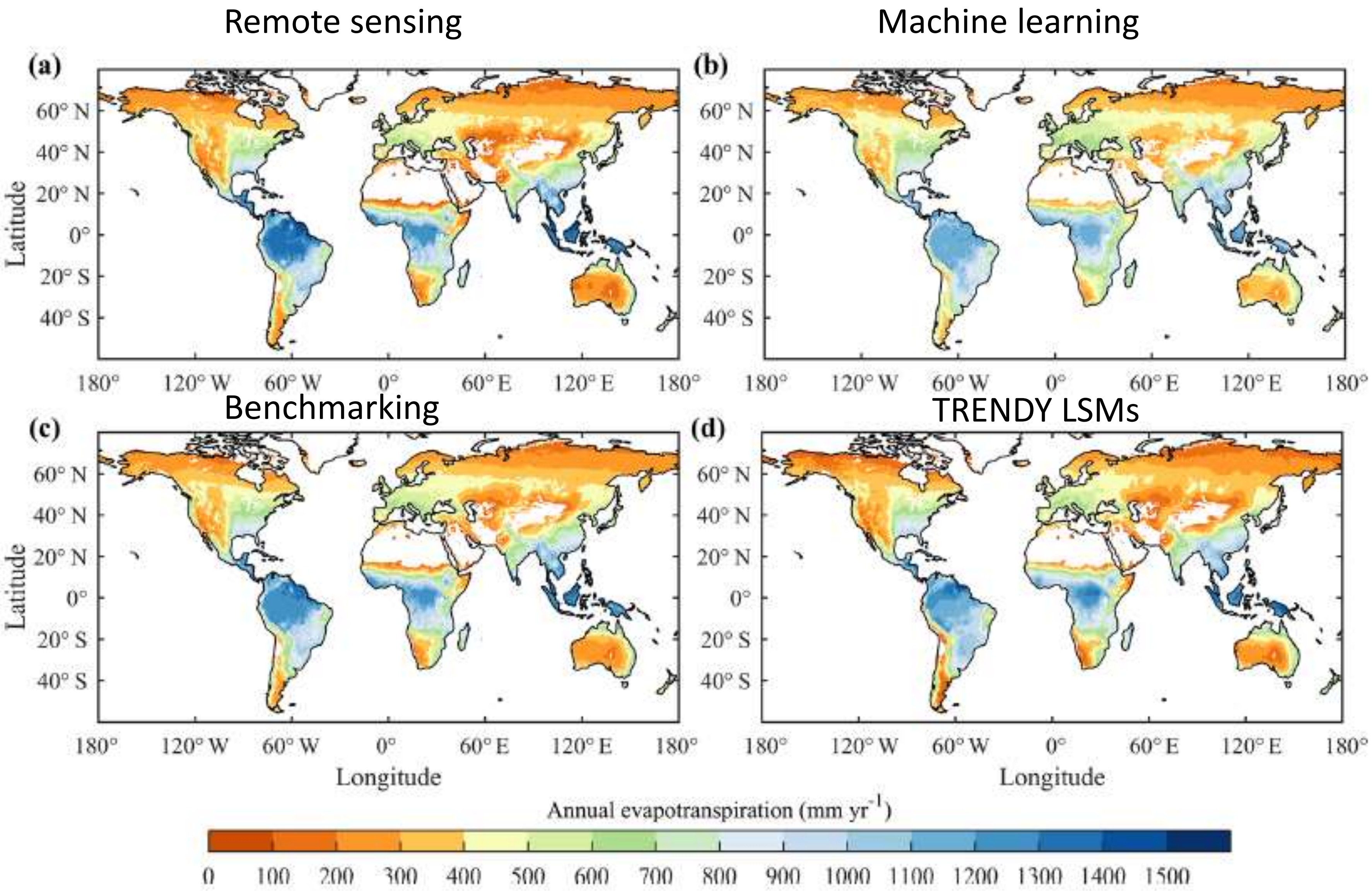
Bonan (2008)

Global pattern of gross primary production



Beer et al. 2010, Science

Comparison of global ET estimates (mm/yr) (Pan et al. 2020)



Remote sensing

Machine learning

Benchmarking

TRENDY LSMs

Ecosystem Evapotranspiration

The humidity response of stomata, leading to increased r_v in response to increased D, tends to close stomata further as a consequence of the drying of the boundary layer caused by the initial closing.

The increase in canopy temperature tends to decrease R_n

ET is more sensitive to changes in g_s in aerodynamically rough (forests) than aerodynamically smooth (crops) canopies

Regional Evapotranspiration

Moving beyond the scale of the local ecosystem to the scale of tens to hundreds of kilometers, two new sets of feedbacks potentially modulate the effects of increased CO_2 on stomatal conductance.

These are related to the planetary or convective boundary layer (CBL) and to the mesoscale circulations generated by contacts between contrasting surface types.