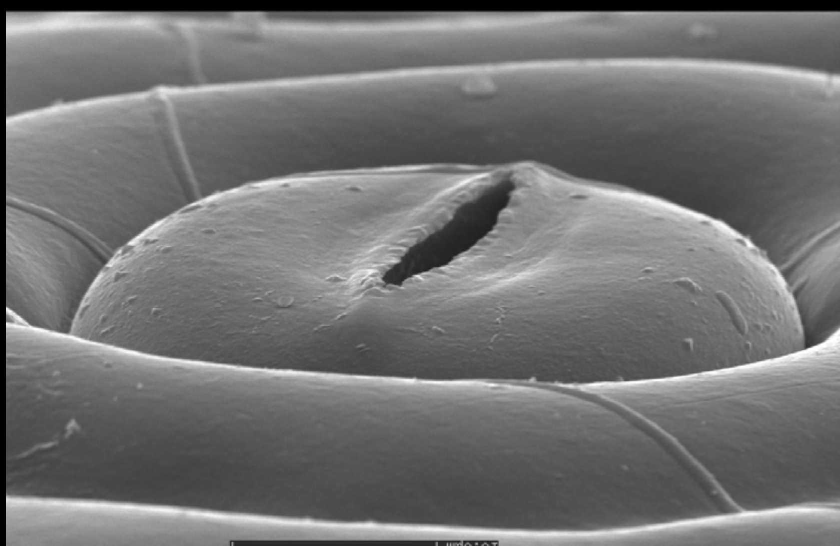
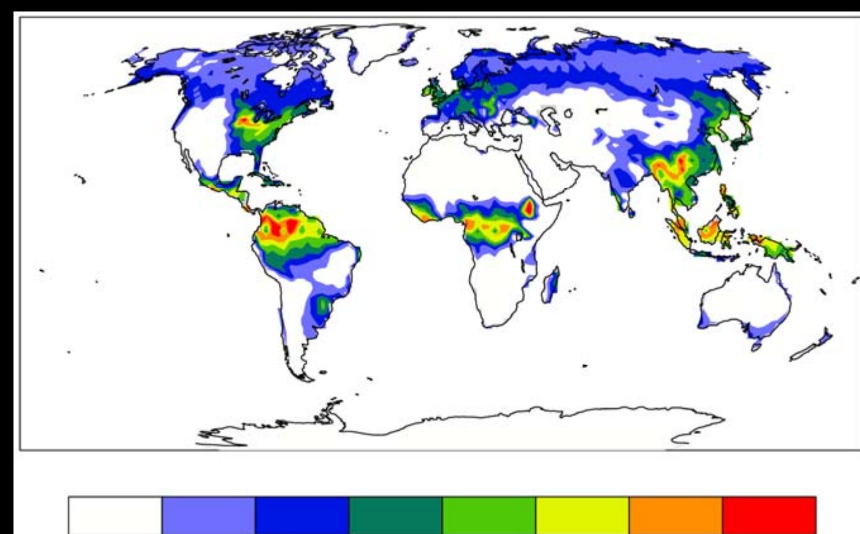
Stomatal conductance models in CLM

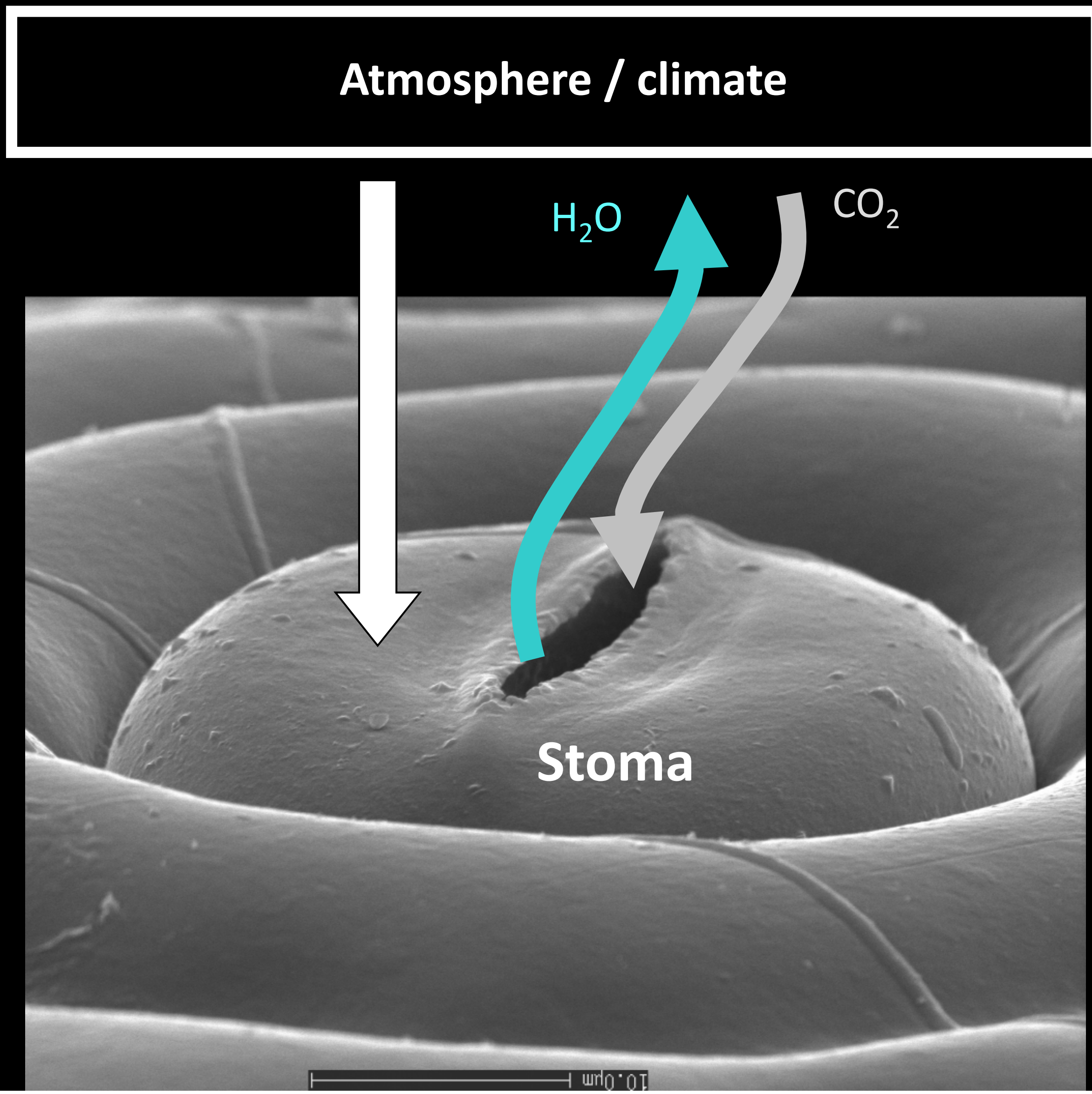
Peter Franks

(*Gordon Bonan, Joe Berry, Danica Lombardozzi*)



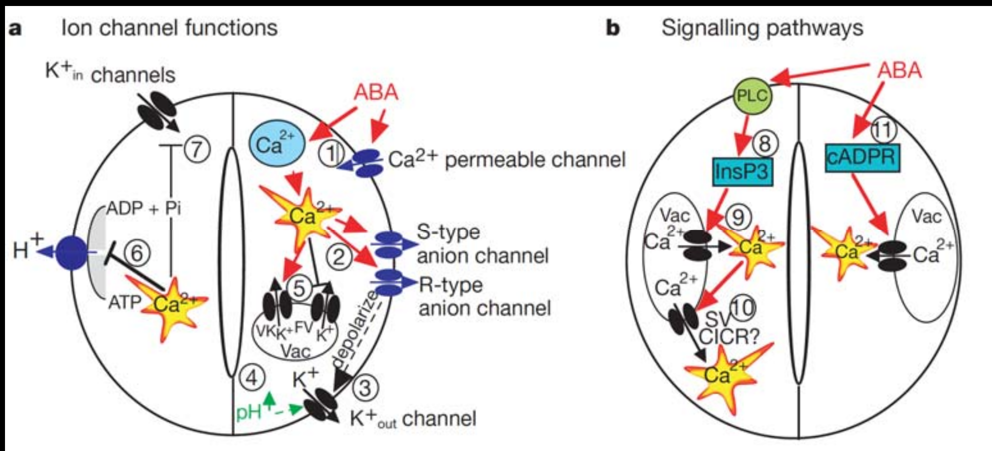


Vegetation and atmosphere are coupled via stomata

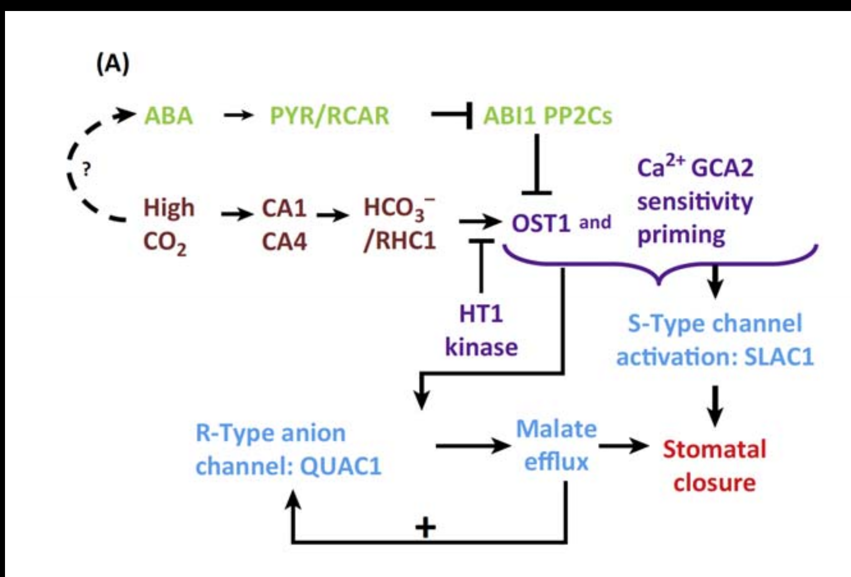


Where to begin with modeling stomatal conductance?

Molecular signaling

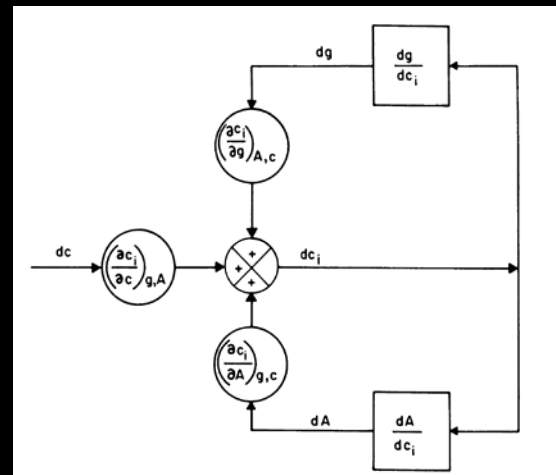


Schroeder et al. 2001

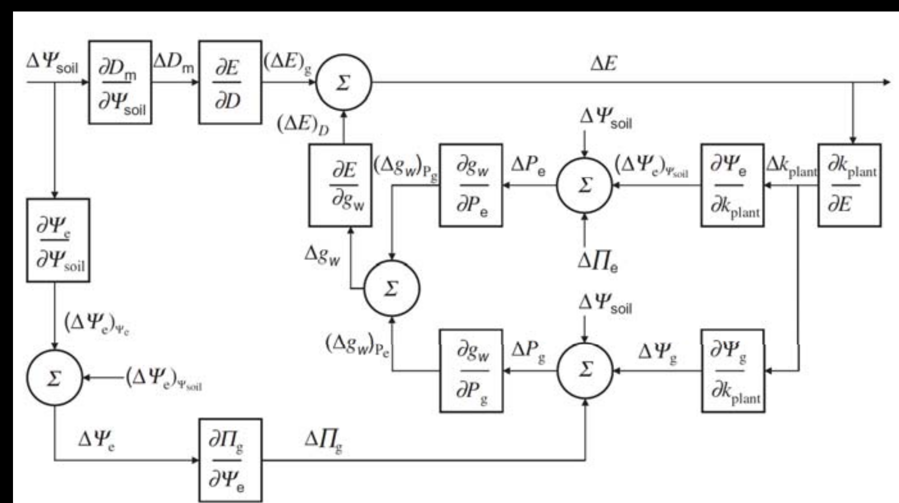


Engineer et al. 2016

Biophysical control theory



Farquhar et al. 1978

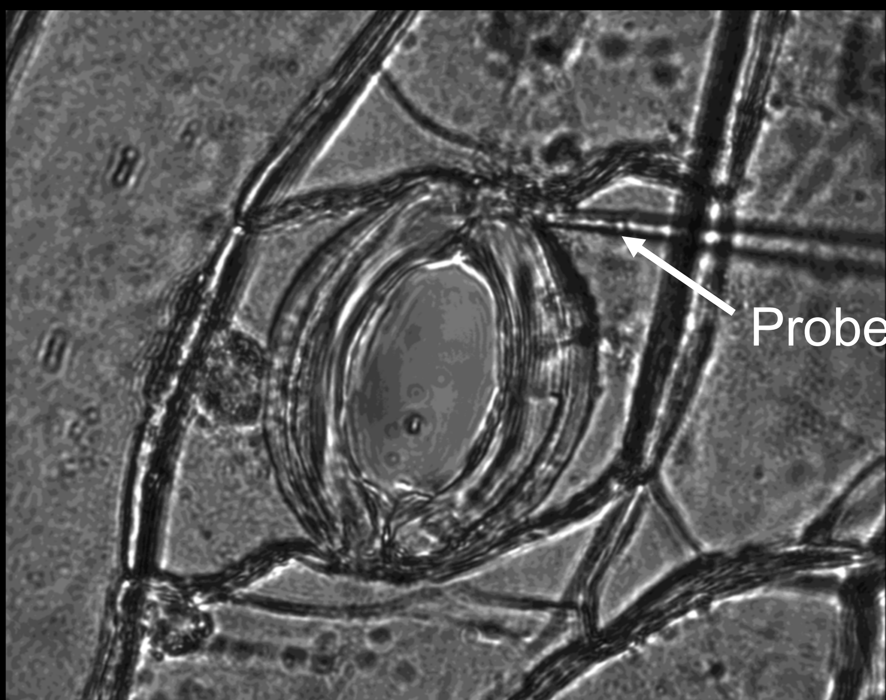


Franks et al. 2007

There are well-developed molecular signaling and biophysical models of stomatal aperture regulation, but they require exhaustive and very specific molecular and/or biophysical information to parameterize, some of it exceptionally difficult to measure.

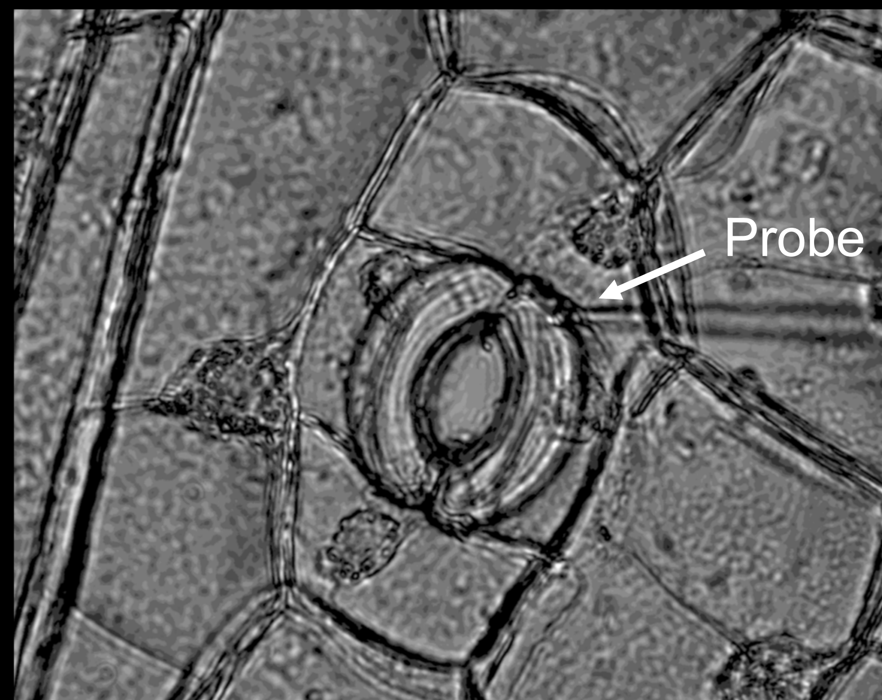
When fully parameterized, these models are a powerful tool for specific applications e.g. guiding genetic engineering of crop water-use efficiency.

T. virginiana 3.5 MPa pressure



Control

T. virginiana 3.5 MPa pressure



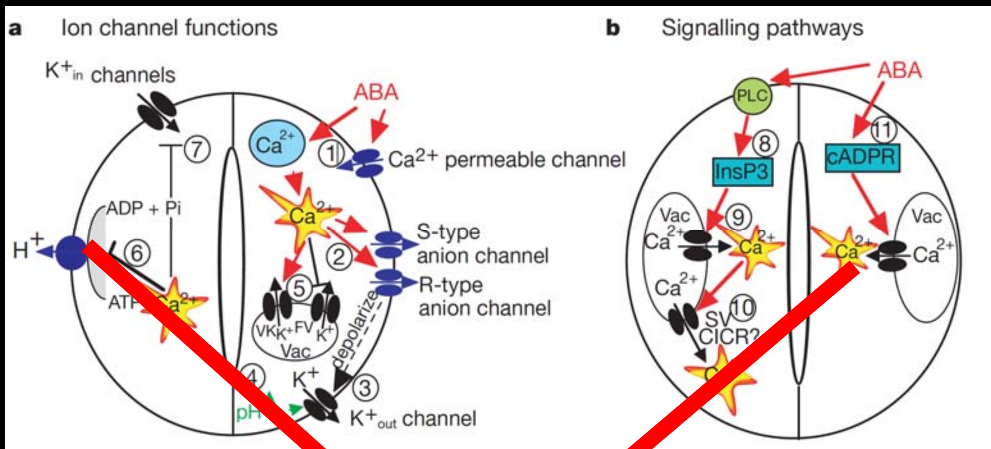
ABA-treated

10 υm

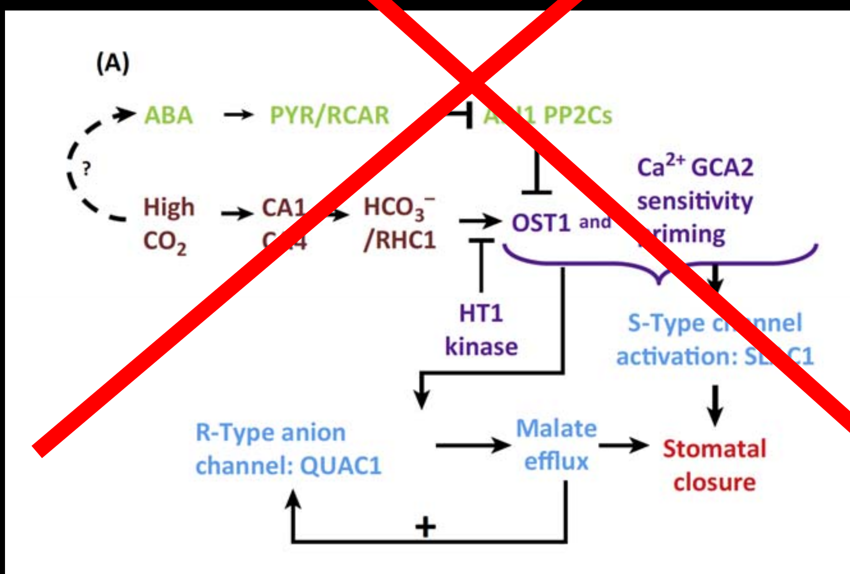
P. Franks (Plant Physiology)

For the global scale, molecular models are too complex and species-specific, and control theory requires too many unknown parameters.

Molecular signaling

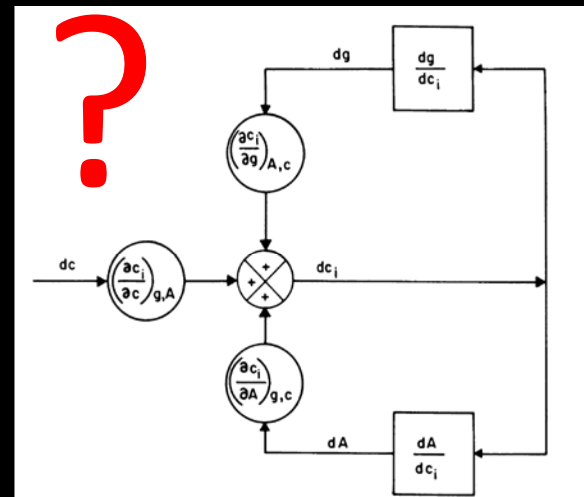


Schroeder et al. 2001

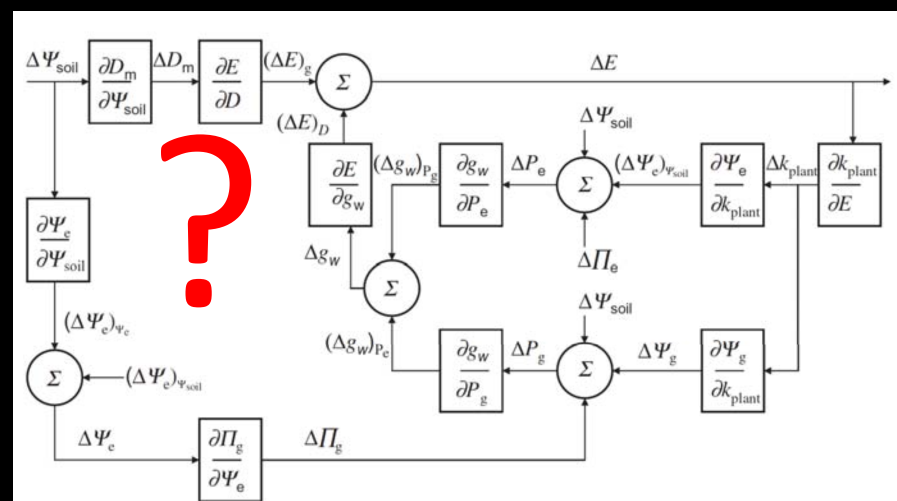


Engineer et al. 2016

Biophysical control theory



Farquhar et al. 1978



Franks et al. 2007

How complex do stomatal conductance models need to be?

GMO

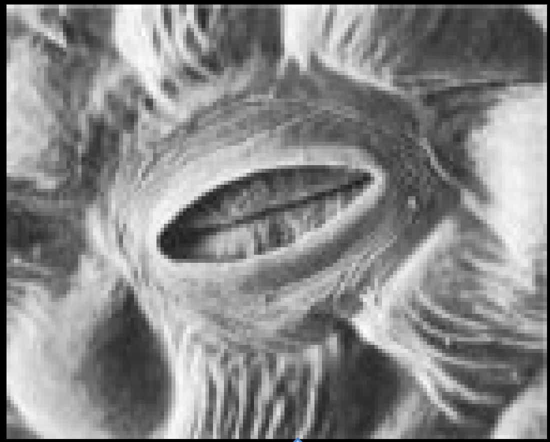
CLM

GCM

The basics are simple:

Darkness
Dry soil
High CO_2
Low humidity
Low temp.

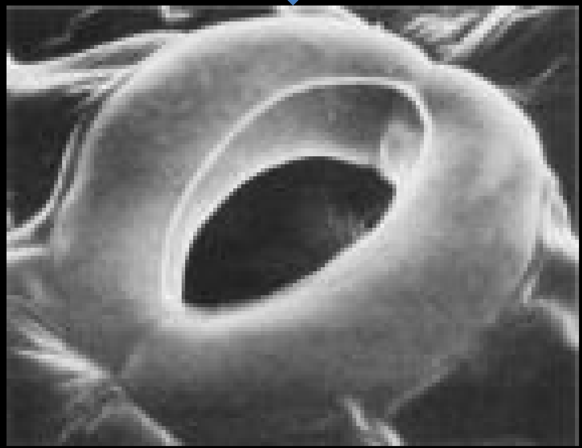
Close



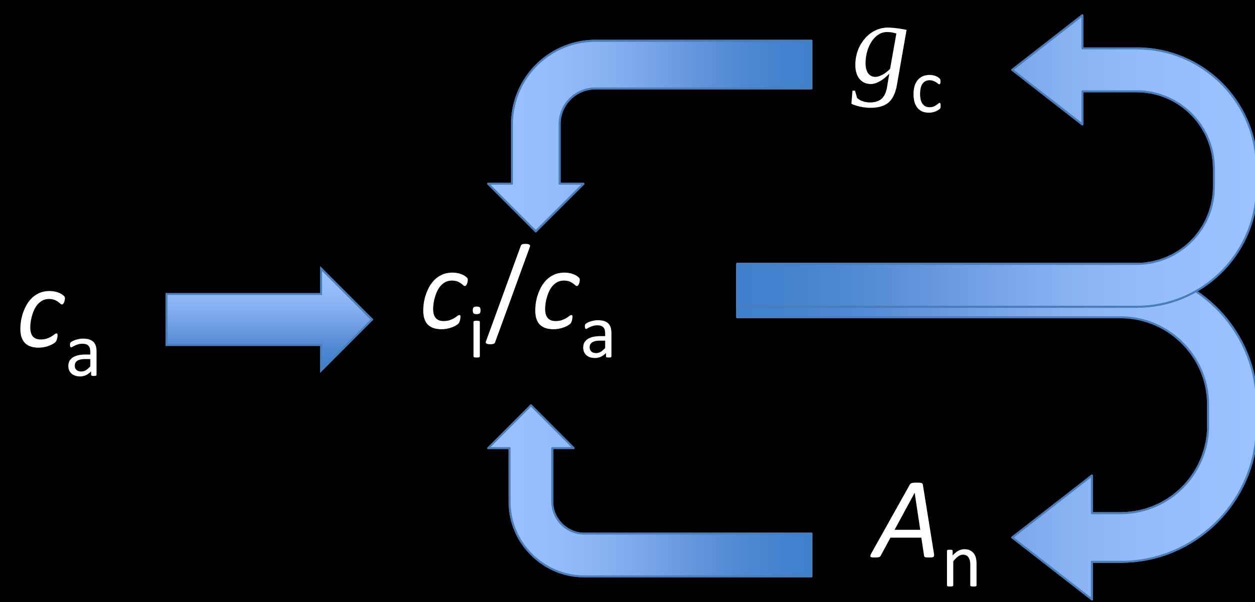
Stomatal conductance, g

Light
Wet soil
Low CO_2
High humidity
High temp.

Open



Stomatal conductance models must integrate the interdependence of net CO_2 assimilation (A_n) and stomatal conductance to water vapor (g_w) or CO_2 (g_c)



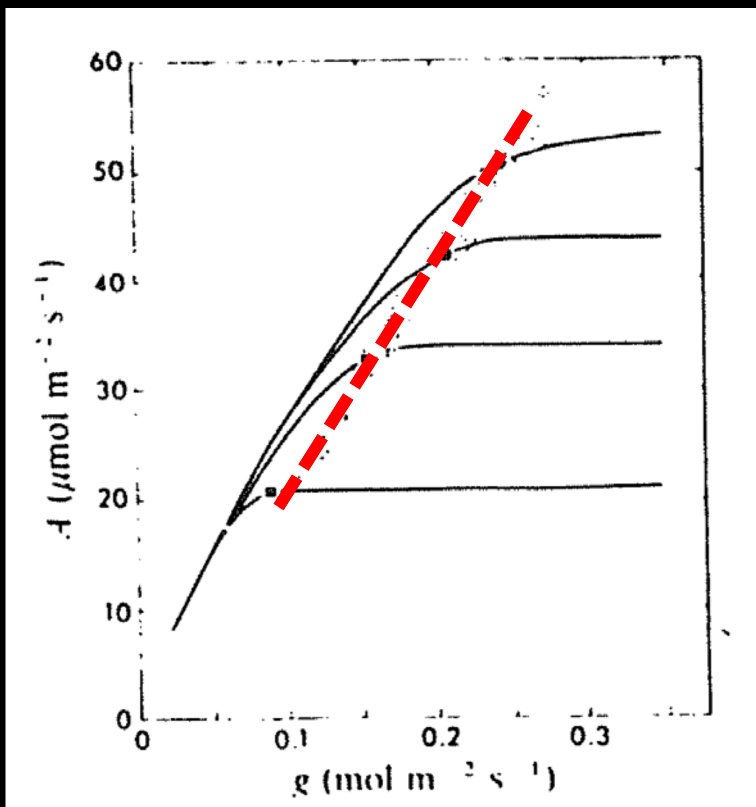
A_n and g_c tend to control (roughly) the ratio of atmospheric to leaf internal CO_2 concentration, c_i/c_a

A good foundation for any stomatal conductance model:

The steady state leaf gas exchange equation

$$g_{\mathrm{w}} = \frac{A_{\mathrm{n}}}{c_{\mathrm{a}}} \cdot \frac{1.6}{\left(1 - c_{\mathrm{i}} / c_{\mathrm{a}}\right)} \qquad (1)$$

In 1978 Wong *et al.* noted that, for constant c_a, under a variety of conditions,



Wong, Cowan, Farquhar, *Nature*, 1978

$$g_w \propto A_n \qquad (2)$$

From Eq. (1), this implies constant c_i/c_a

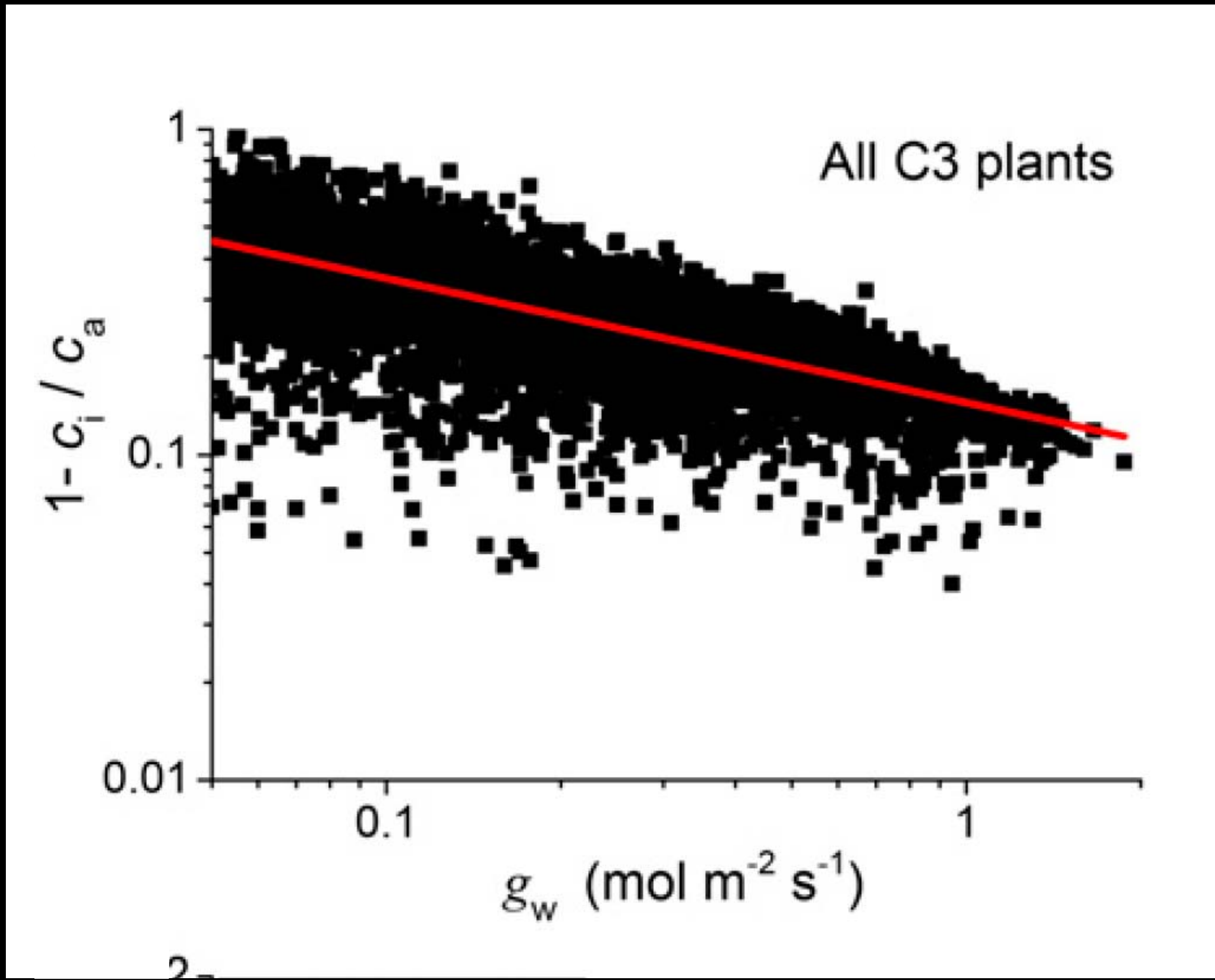
But c_i/c_a is not exactly constant.

e.g.

1) It declines with drier air or soil (improving water-use efficiency)
2) Different plant functional types operate with different mean c_i/c_a.

	Sunflower crop	Temperate broadleaf	Dry land conifer
			
Typical c_i/c_a	0.8	0.7	0.6

Globally, $(1-c_i/c_a)$, a proxy for water-use efficiency, declines with mean stomatal conductance



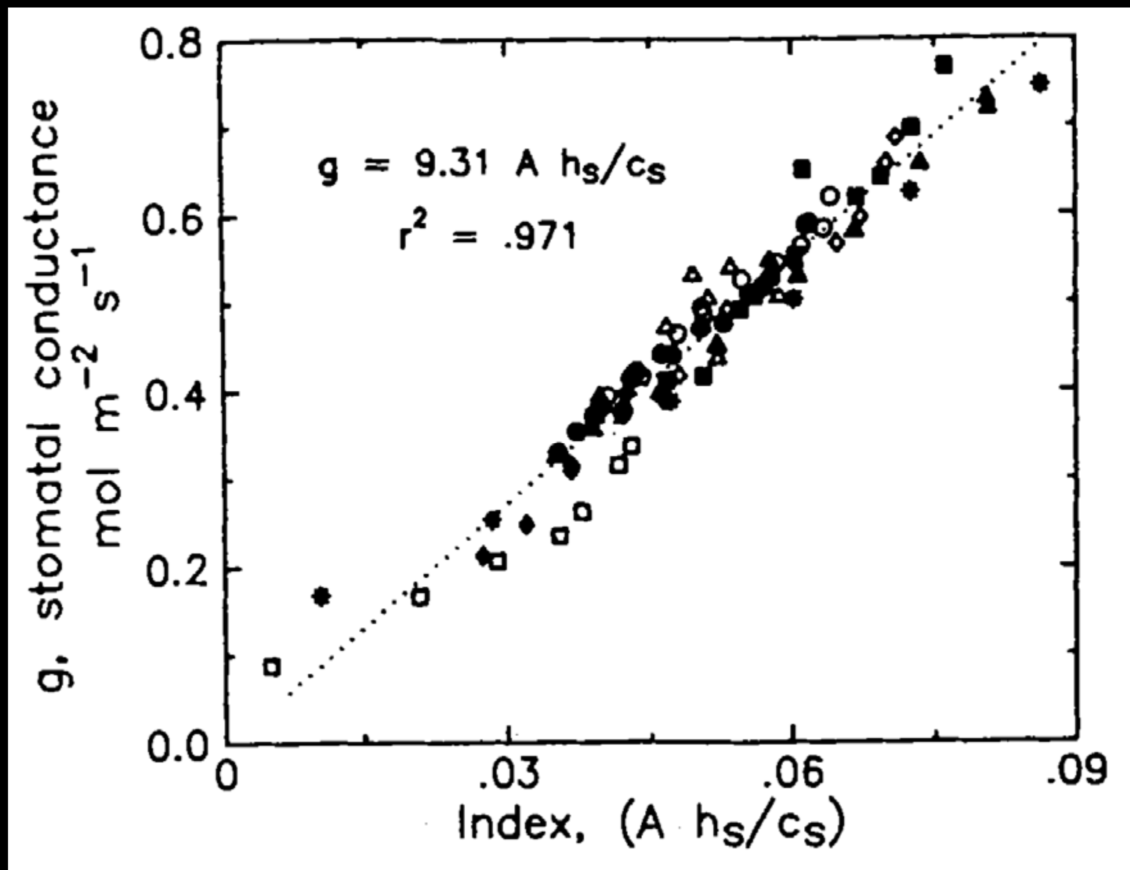
Franks et al. 2017 *Plant Physiology*

In 1987, Tim Ball and Joe Berry reasoned that, because g_w is sensitive to humidity and c_a, then a more complete description of stomatal behavior is

$$g_{\mathrm{w}} \propto \frac{A_{\mathrm{n}} H_{\mathrm{s}}}{c_{\mathrm{s}}} \qquad (3)$$

where H_s and c_s are relative humidity and CO_2 concentration at the leaf surface, respectively.

For a surprisingly wide range of conditions, Ball & Berry found close correlation between g_w and $A_n H_s/c_s$



Ball et al. (1987)

Ball & Berry formulated their model as

$$g_{\mathrm{w}} = g_1 \cdot \frac{A_{\mathrm{n}} H_{\mathrm{s}}}{c_{\mathrm{s}}} + g_0 \qquad (4)$$

Slope
(constant)

intercept
(approx. zero)

Ball-Berry model

$$g_{\mathrm{w}} = g_1 \cdot \frac{A_{\mathrm{n}} H_{\mathrm{s}}}{c_{\mathrm{s}}} + g_0$$

- Successfully implemented in CLM since 1995 by combining with the Farquhar photosynthesis model and solving iteratively for A_{n} and g_{w} .

But the full potential of the Ball-Berry model in CLM has not been explored.

- CLM traditionally run with only one average g1 slope value for C3 vegetation (9) and C4 vegetation (4)

Ball-Berry slope parameter g_1 (or *m*) ranges from ~3 to 18

Table 3. *Literature survey of coefficients, m, of the Ball–Berry–Collatz stomatal conductance equation*

m	Taxon	Reference[Q46]
8.1	Populus tremuloides	Berry, 1995
9.5	*Quercus alba*	Harley and Baldocchi, 1995
9.5	*Acer rubrum*	Harley and Baldocchi, 1995
7.2–11.1	*Eucalyptus grandis*	Leuning, 1990
13.5	*Populus tremuloides*	Nikolov *et al.*, 1995
16.0	*Quercus ilex* (well watered)	Sala and Tenhunen, 1996
5.4	*Quercus ilex* (drought)	Sala and Tenhunen, 1996
9.3–18.0	*Eucalyptus grandis*	Leuning, 1995
8.9	*Quercus douglasii*	Xu and Baldocchi, 2003
10.0	*Acer saccharum*	Ellsworth *et al.*, 1994
13.4	*Acer saccharum*	Ellsworth and Reich, 1993
12.0	*Acer saccharum*	Tjoelker *et al.*, 1995
8.7	*Pinus flexilis*	Nikolov *et al.*, 1995
10.0	*Arbutus unedo*	Harley and Tenhunen, 1991
12.7	*Fagus sylvatica*	Medlyn *et al.*, 2001
10.1	Phillyea augustifolia	Medlyn *et al.*, 2001
8.2	*Pistacia lentiscus*	Medlyn *et al.*, 2001
6.2	*Quercus ilex*	Medlyn *et al.*, 2001
9.4	*Betula*	Medlyn *et al.*, 2001
2.9–6.4	*Picea abies*	Medlyn *et al.*, 2001
9.8	*Plantanus orientalis*	Kosugi *et al.*, 2003
9.3	*Liriodendron tulipifera*	Kosugi *et al.*, 2003
5.8	*Cercidiphyllum japonicum*	Kosugi *et al.*, 2003

Baldocchi & Xu

With more representative g_1 values for global biomes/PFTs the Ball-Berry stomatal conductance model could be implemented in CLM with much improved performance.

In parallel developments, a second semi-empirical stomatal conductance model has been proposed by a group led by Belinda Medlyn.

The “Medlyn” model is

$$g_{\mathrm{w}} = 1.6\left(1 + \frac{g_{1\mathrm{M}}}{\sqrt{D_s}}\right)\frac{A_{\mathrm{n}}}{c_{\mathrm{s}}} + g_0 \qquad (5)$$

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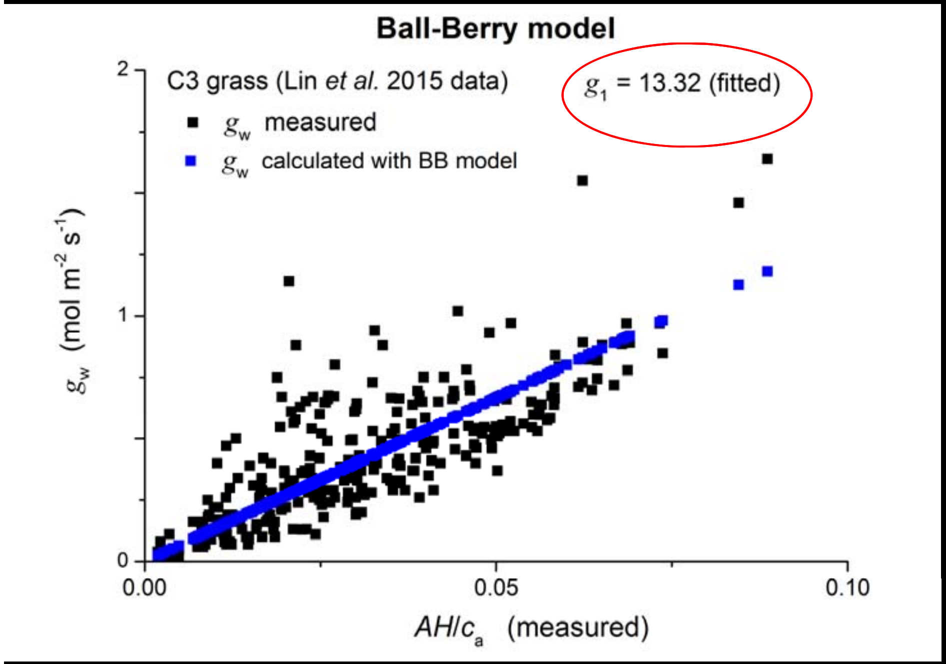
$$g_{\mathrm{w}} = 1.6\left(1 + \frac{g_{1\mathrm{M}}}{\sqrt{D_s}}\right)\frac{A_{\mathrm{n}}}{c_{\mathrm{s}}} + g_0 \qquad (5)$$

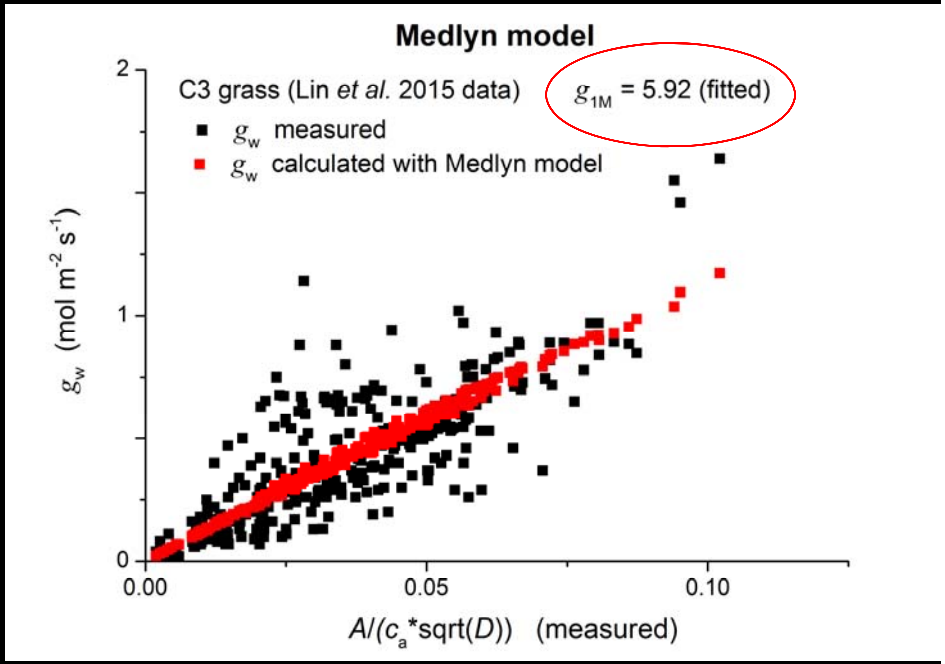
- Uses vapor pressure deficit at the leaf surface (D_s) instead of H_s
- Like the Ball-Berry model it is rooted in the leaf gas exchange equation, but is said additionally to incorporate elements of water-use efficiency optimization.

The Ball-Berry and Medlyn models are structurally and physiologically similar.

Do they perform similarly?

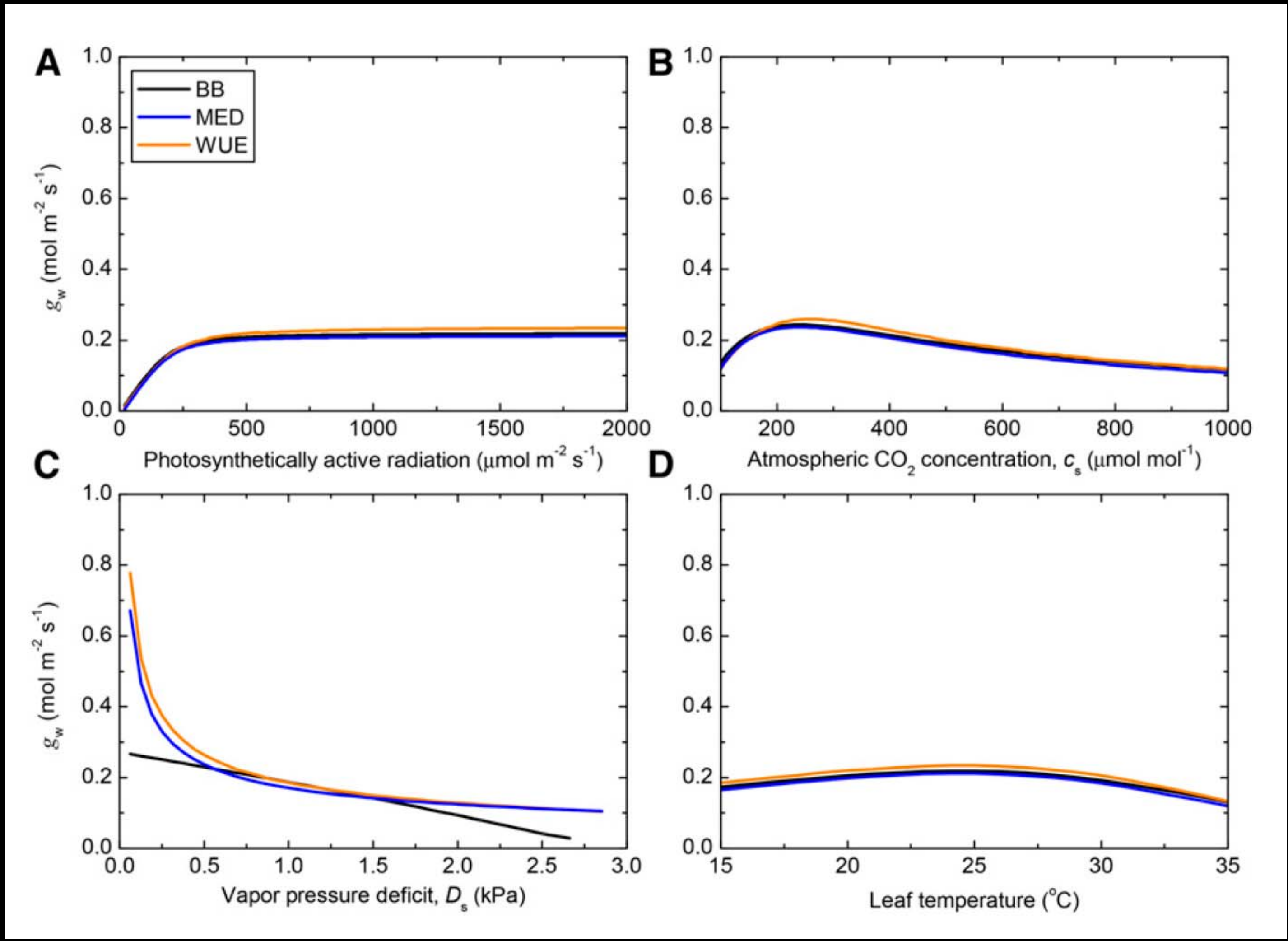
Ball-Berry and Medlyn models fitted to the same data





In this case, if g_1 = 13.32, the corresponding g_{1M} is 5.92

Similar performance of Ball-Berry and Medlyn models at the leaf scale (g_1 = 9; g_{1M} = 2.8 $(kPa)^{0.5}$)



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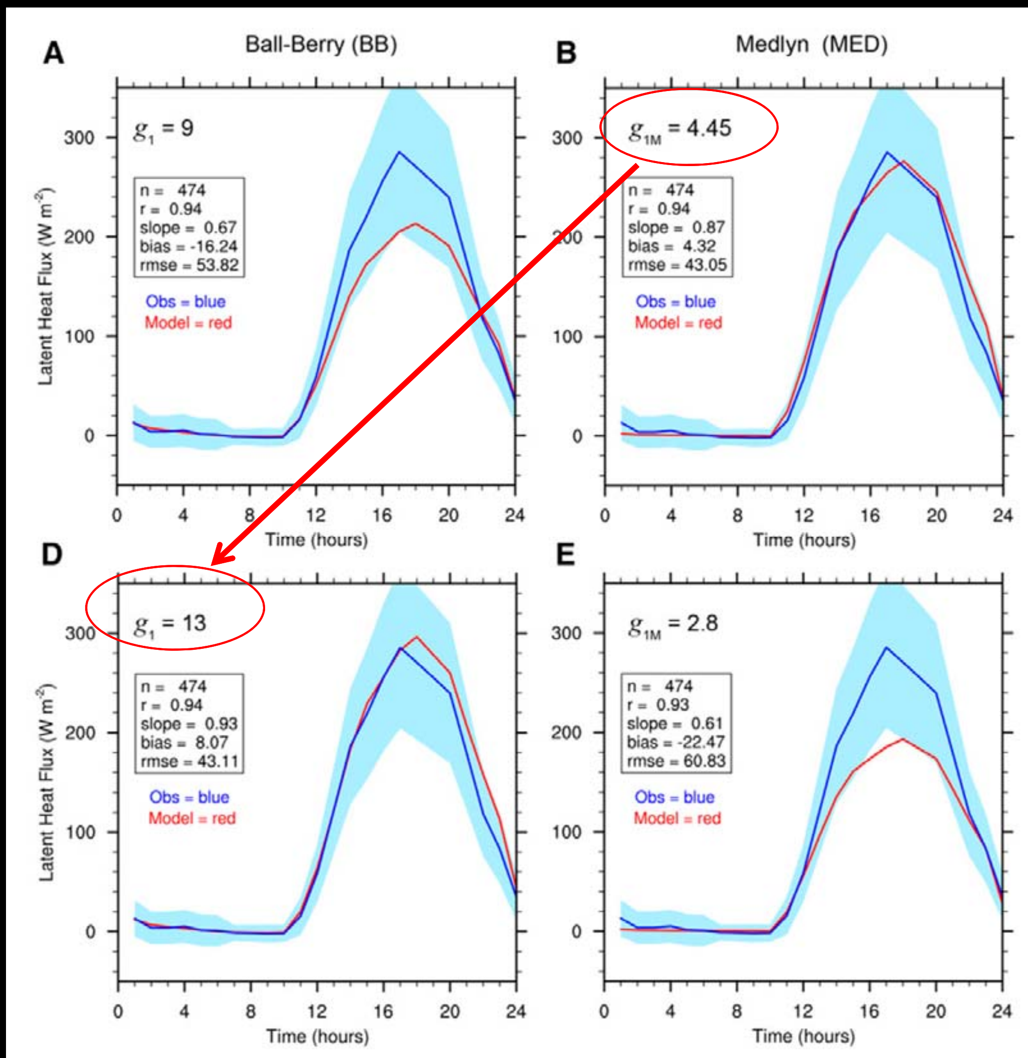
Similar performance at the canopy scale IF comparable g_1 and g_{1M} values are used.

Harvard forest canopy (Broadleaf forest PFT)



Default values for g_1 and g_{1M} for broadleaf forest are not comparable, but in this case Medlyn performs better

Adjusting g_1 to be comparable with the default g_{1M} results in a similarly good fit

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Interchangeable g_1 and g_{1M} values for different PFTs

Table II. *Interchangeable water-use efficiency indexes*

Values for g_{1M} (see Eq. 3) are shown for different plant functional types, as used when implementing the Medlyn et al. (2011) stomatal model in CABLE (De Kauwe et al., 2015; Kala et al., 2015) and in the CLM4.5 simulations in Figures 9 and 10 below. These values are based on those given by Lin et al. (2015) but differ slightly in some cases. Equivalent approximate values are derived from g_{1M} for λ, g_1, and mean c_i/c_a using Equations 4, 5, and 9 (25°C, $H = 0.8$, $\Gamma^* = 40\ \mu$mol mol^{-1}). In the model implementation, $g_0 = 0$, as was the case for Lin et al. (2015) when determining g_{1M} from gas-exchange data. Plant types with lower values for g_{1M}, g_1, λ, or c_i/c_a have comparatively higher water-use efficiency.

Plant Type	g_{1M}	g_1	λ	c_i/c_a
	$kPa^{0.5}$		*mmol water μmol^{-1} CO_2*	
C_3 crop	5.79	16.5	4.47	0.88
C_3 grass	5.25	15.1	3.68	0.87
Shrub	4.70	13.8	2.95	0.85
Deciduous broadleaf tree	4.45	13.1	2.64	0.85
Evergreen broadleaf tree	4.12	12.3	2.26	0.84
Evergreen needleleaf tree	2.35	7.88	0.74	0.75
Deciduous needleleaf tree	2.35	7.88	0.74	0.75
Arctic tundra	2.22	7.55	0.66	0.74
C_4 grass	1.62	6.05	0.35	0.67

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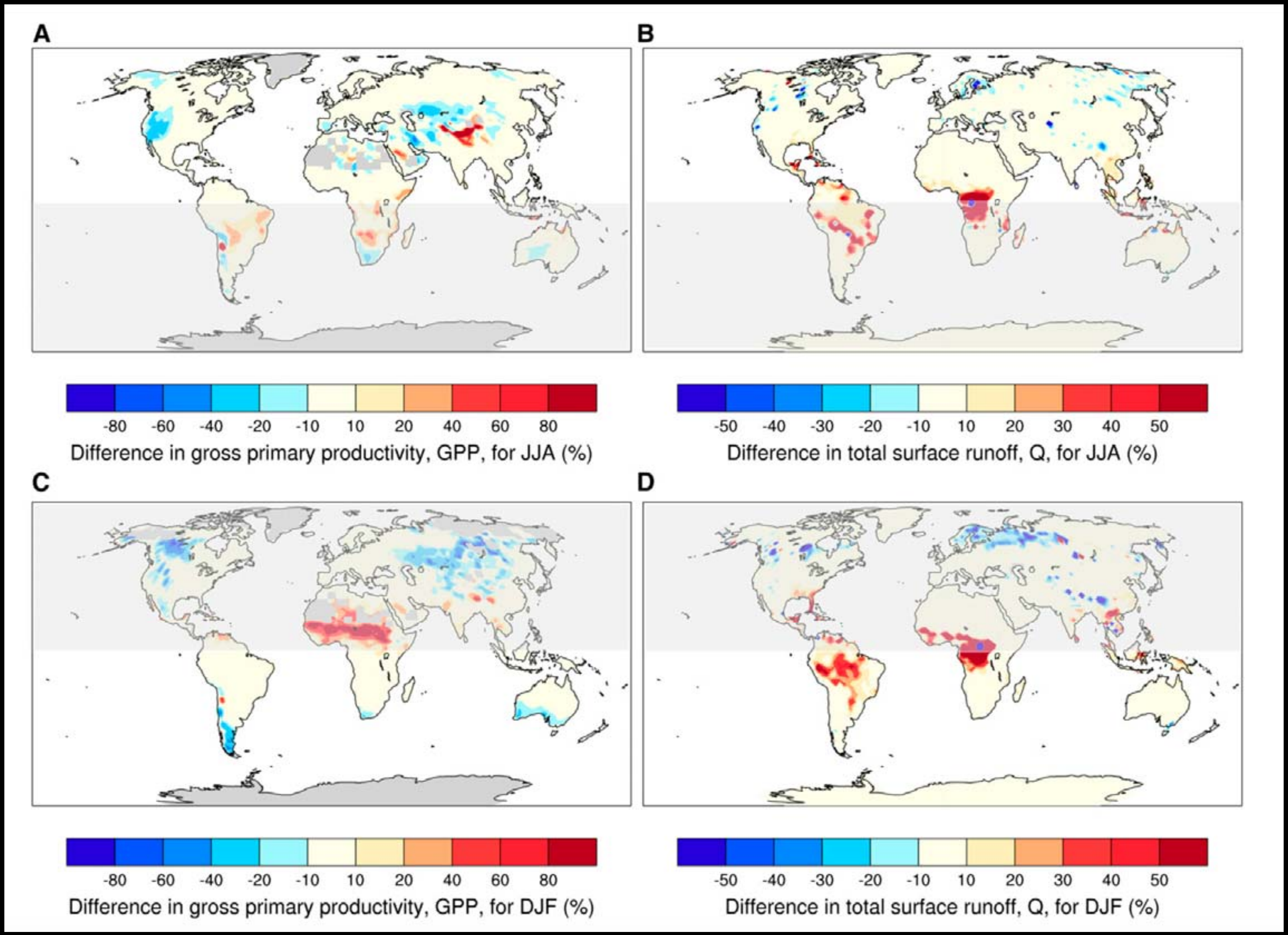
Comparing CLM outputs with PFTs formulated with comparable g_1 or g_{1M} values (little difference between the two).

(Satellite phenology and atmospheric forcing data for 1991 to 2010, CRU-NCEP)



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Stomatal Function across Temporal and Spatial Scales: Deep-Time Trends, Land-Atmosphere Coupling and Global Models

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Conclusions:

- Hybrid physiological-empirical models like Ball-Berry and Medlyn are an ideal balance of moderate complexity, moderate ease of parameterization and broad PFT representation suitable for CLM.

- Ball-Berry and Medlyn models are structurally similar and perform similarly in CLM when parameterized comparably.

- Yes, improvements are possible and needed, e.g. for extremely moist or dry conditions, but more immediately, representative measure of g_1 and g_{1M}.