From climate models to earth system models: the stomatal paradigm and beyond

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Academy Colloquium "Stomatal conductance through time: towards accurate estimates of physiological CO_2 –forcing of the climate"

Royal Netherlands Academy of Arts and Sciences
Amsterdam
18 September 2012

NCAR is sponsored by the National Science Foundation

Outline

Atmospheric general circulation model (1970s) → Climate model (1990s) → Earth system model (2010s)

geophysical fluid dynamics

vegetation, biogeophysics

ecosystems, biogeophysics and biogeochemistry, socioeconomic forcings

Stomata

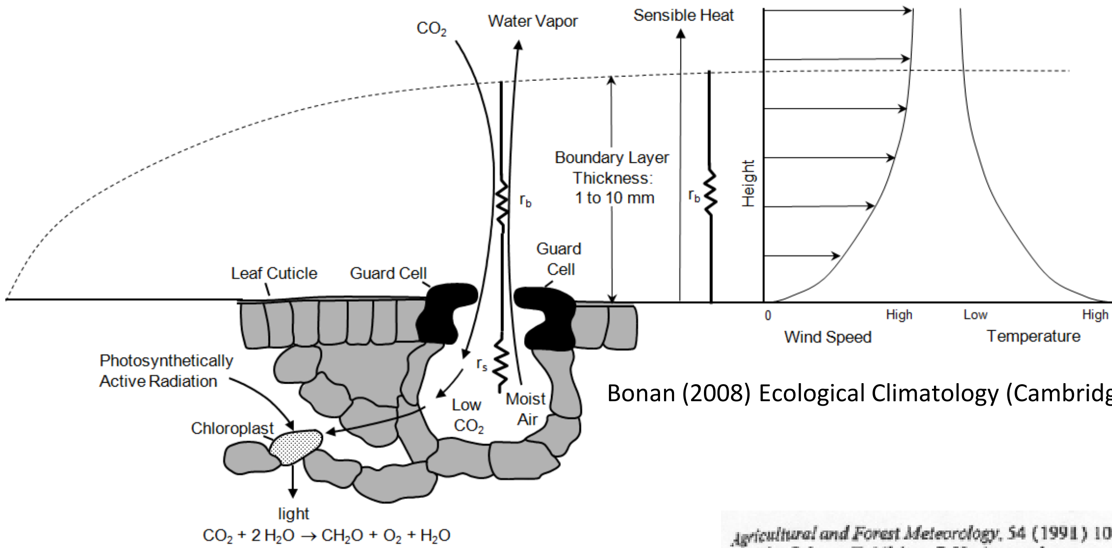
Biosphere feedbacks

- Land use and land cover change
- Carbon cycle
- Reactive nitrogen

Outline

1. Stomata and climate models
2. Biosphere feedbacks
   - Land use and land cover change
   - Carbon cycle
3. Stomata (leaf -> canopy -> globe): the Community Land Model experience
   - Leaf trait databases
   - Within-canopy profile theory and observations
   - Radiative transfer theory
   - Flux tower measurements
   - Empirically upscaled global flux fields

From physiological theory to models



Bonan (2008) Ecological Climatology (Cambridge)

Planta 149, 78–90 (1980)

A Biochemical Model of Photosynthetic CO_2 Assimilation in Leaves of C_3 Species

G.D. Farquhar[1], S. von Caemmerer[1], and J.A. Berry[2]

[1] Department of Environmental Biology, Research School of Biological Sciences, Australian National University, P.O. Box 475, Canberra City ACT 2601, Australia and
[2] Carnegie Institution of Washington, Department of Plant Biology, Stanford, Cal. 94305, USA

Agricultural and Forest Meteorology, 54 (1991) 107–136 107
Elsevier Science Publishers B.V., Amsterdam

Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer*

G. James Collatz[a], J. Timothy Ball[b], Cyril Grivet[a] and Joseph A. Berry[a]
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(Received 1 November 1989; revision accepted 22 October 1990)

Photosynthesis

$$A_n = \left(1 - \frac{\Gamma_*}{C_i}\right) \min\left(W_c, W_j\right) - R_d$$

$$W_c = \frac{V_{c\max} C_i}{C_i + K_c\left(1 + O_i/K_o\right)} \qquad W_j = \frac{J}{4}\left(\frac{C_i}{C_i + 2\Gamma_*}\right)$$

Stomatal conductance

$$g_s = m\frac{A_n h_s}{c_s} + b$$

Atmospheric general circulation models

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. D2, PAGES 2817–2831, FEBRUARY 20, 1995

Land-atmosphere CO_2 exchange simulated by a land surface process model coupled to an atmospheric general circulation model

Gordon B. Bonan
National Center for Atmospheric Research, Boulder, Colorado

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. D11, PAGES 13,213–13,235, JUNE 20, 1998

Atmospheric CO_2 simulated by the National Center for Atmospheric Research Community Climate Model
1. Mean fields and seasonal cycles

S. G. Craig and K. J. Holmén
Department of Meteorology, Stockholm University, Stockholm, Sweden

G. B. Bonan and P. J. Rasch
Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado

Tellus (1996), 48B, 521–542
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TELLUS
ISSN 0280–6509

Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model
Part 1: Surface carbon fluxes

By A. SCOTT DENNING[1*], G. JAMES COLLATZ[2], CHANGAN ZHANG[3], DAVID A. RANDALL[3], JOSEPH A. BERRY[4], PIERS J. SELLERS[2], GREG D. COLELLO[4] AND DONALD A. DAZLICH[3], [1]*School of Environmental Science and Management, University of California, Santa Barbara, CA 93106-5131, USA;* [2]*National Aeronautic and Space Administration, Goddard Space Flight Center, MS 923, Greenbelt, MD 20771, USA;* [3]*Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80521–371, USA;* [4]*Carnegie Institute of Washington, Department of Plant Biology, Stanford, CA 94305, USA*

Tellus (1996), 48B, 543–567
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TELLUS
ISSN 0280–6509

Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model
Part 2: Simulated CO_2 concentrations

By A. SCOTT DENNING[1,*], DAVID A. RANDALL[2], G. JAMES COLLATZ[3] and PIERS J. SELLERS[3], [1]*School of Environmental Science and Management, University of California, Santa Barbara, CA 93106-5131, USA;* [2]*Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80521-1371, USA;* [3]*National Aeronautic and Space Administration, Goddard Space Flight Center, MS 923, Greenbelt, MD 20771, USA*

Physiological feedbacks

Science 8 March 1996:
Vol. 271 no. 5254 pp. 1402-1406
DOI: 10.1126/science.271.5254.1402

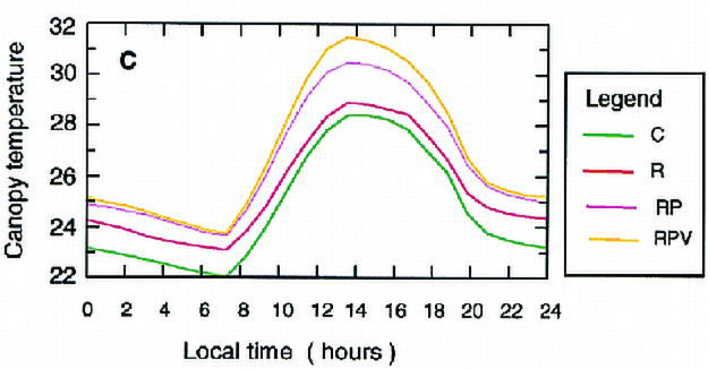
REPORT

Comparison of Radiative and Physiological Effects of Doubled Atmospheric CO_2 on Climate

P. J. Sellers, L. Bounoua, G. J. Collatz, D. A. Randall, D. A. Dazlich, S. O. Los, J. A. Berry, I. Fung, C. J. Tucker, C. B. Field, T. G. Jensen

CO_2 fertilization (RP, RPV) reduces canopy conductance and increases temperature compared with radiative CO_2 (R)

Amazonian evergreen forest, diurnal cycle January



Bounoua et al. (1999) J Climate 12:309-324

Vol 439|16 February 2006|doi:10.1038/nature04504 nature

LETTERS

Detection of a direct carbon dioxide effect in continental river runoff records

N. Gedney[1], P. M. Cox[2], R. A. Betts[3], O. Boucher[3], C. Huntingford[4] & P. A. Stott[5]

Vol 448|16 August 2007|doi:10.1038/nature06059 nature

LETTERS

Indirect radiative forcing of climate change through ozone effects on the land-carbon sink

S. Sitch[1], P. M. Cox[3], W. J. Collins[4] & C. Huntingford[2]

nature Vol 458|23 April 2009|doi:10.1038/nature07949

LETTERS

Impact of changes in diffuse radiation on the global land carbon sink

Lina M. Mercado[1], Nicolas Bellouin[2], Stephen Sitch[2], Olivier Boucher[2], Chris Huntingford[1], Martin Wild[3] & Peter M. Cox[4]

Dynamic global vegetation models

Levis, Samuel, Jonathan A. Foley, David Pollard, 2000: Large-Scale Vegetation Feedbacks on a Doubled CO2 Climate. *J. Climate*, **13**, 1313–1325.
doi: http://dx.doi.org/10.1175/1520-0442(2000)013<1313:LSVFOA>2.0.CO;2

Large-Scale Vegetation Feedbacks on a Doubled CO_2 Climate

Samuel Levis

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Jonathan A. Foley

Climate, People, and Environment Program, Institute for Environmental Studies, University of Wisconsin—Madison, Madison, Wisconsin

David Pollard

Earth System Science Center, The Pennsylvania State University, University Park, Pennsylvania

Letters to Nature

Nature **408**, 184-187 (9 November 2000) | doi:10.1038/35041539; Received 6 January 2000; Accepted 26 September 2000

Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model

Peter M. Cox[1], Richard A. Betts[1], Chris D. Jones[1], Steven A. Spall[1] & Ian J. Totterdell[2]

1. Hadley Centre, The Met Office, Bracknell, Berkshire RG12 2SY, UK
2. Southampton Oceanography Centre, European Way, Southampton SO14 3ZH, UK

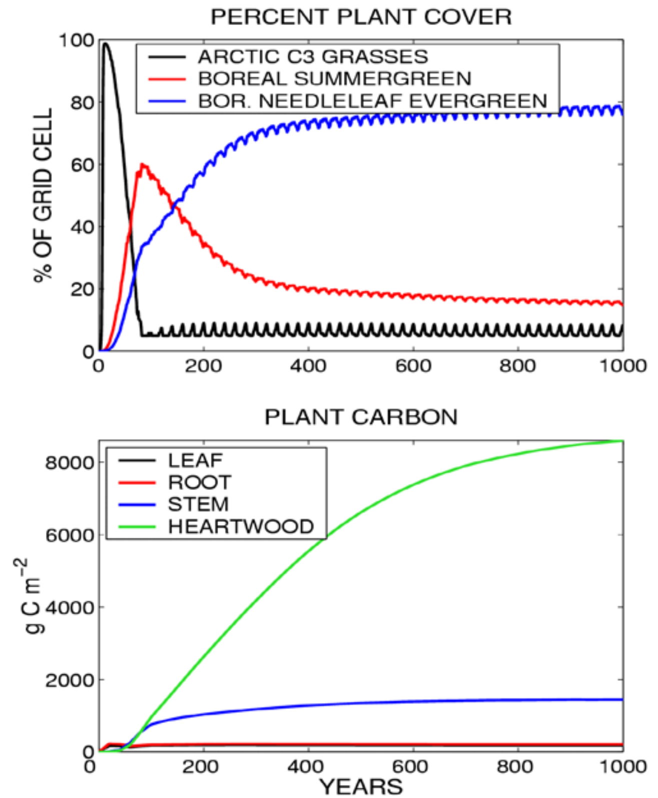
Global Change Biology (2003) 9, 1543–1566, doi: 10.1046/j.1529-8817.2003.00681.x

A dynamic global vegetation model for use with climate models: concepts and description of simulated vegetation dynamics

GORDON B. BONAN*, SAMUEL LEVIS*, STEPHEN SITCH†, MARIANA VERTENSTEIN* and KEITH W. OLESON*

*National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80307, USA, †Potsdam Institut für Klimafolgenforschung (PIK) e.V., Telegrafenberg, PO Box 60 12 03, D-144 12 Potsdam, Germany

Boreal forest succession



Bonan et al. (2003) Global Change Biology 9:1543-1566

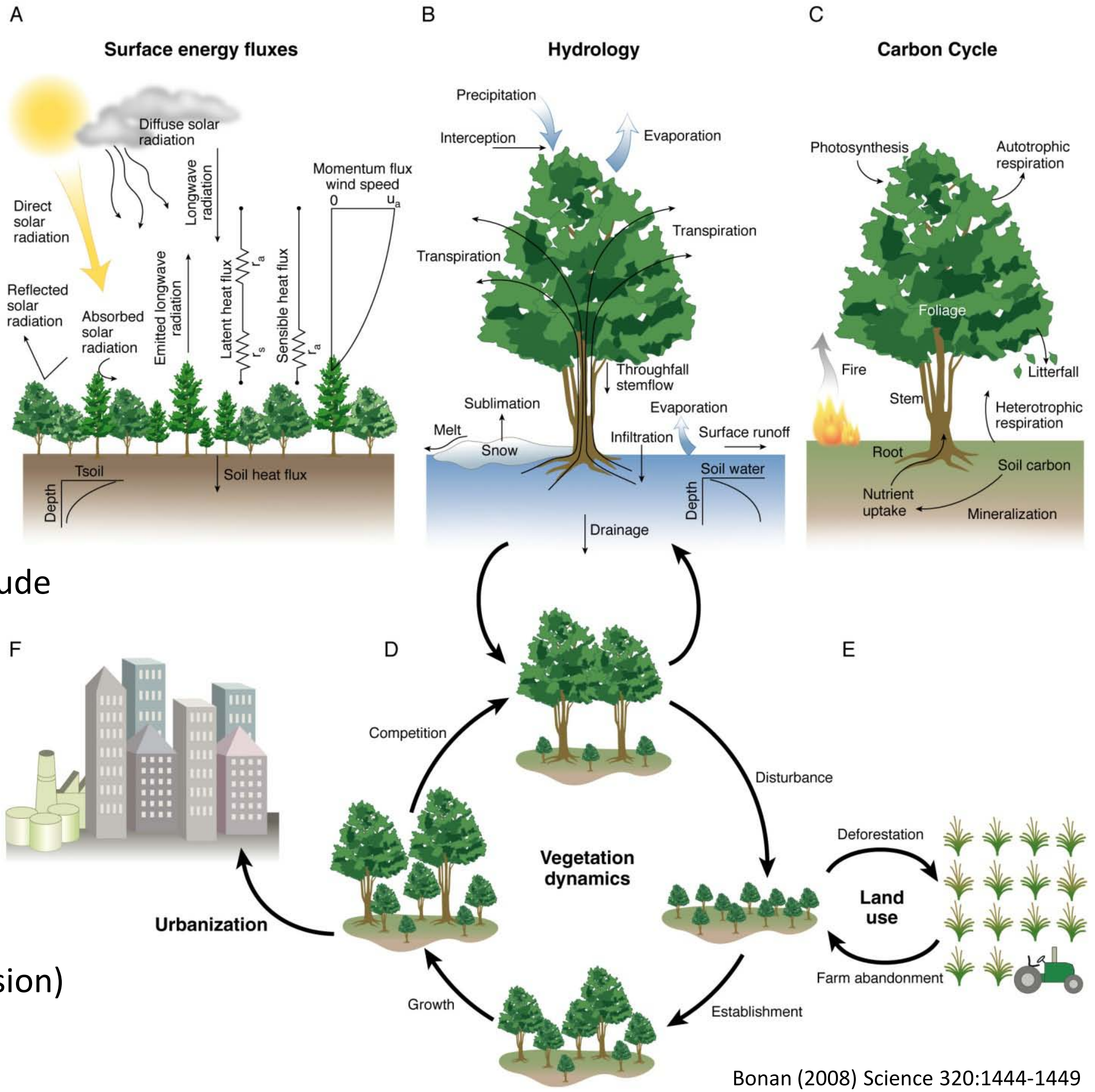
The Community Land Model (CLM4)

Fluxes of energy, water, and carbon and the dynamical processes that alter these fluxes

Oleson et al. (2010) NCAR/TN-478+STR

D. Lawrence et al. (2011) JAMES, 3, doi: 10.1029/2011MS000045

D. Lawrence et al. (2012) J Climate 25:2240-2260



Bonan (2008) Science 320:1444-1449

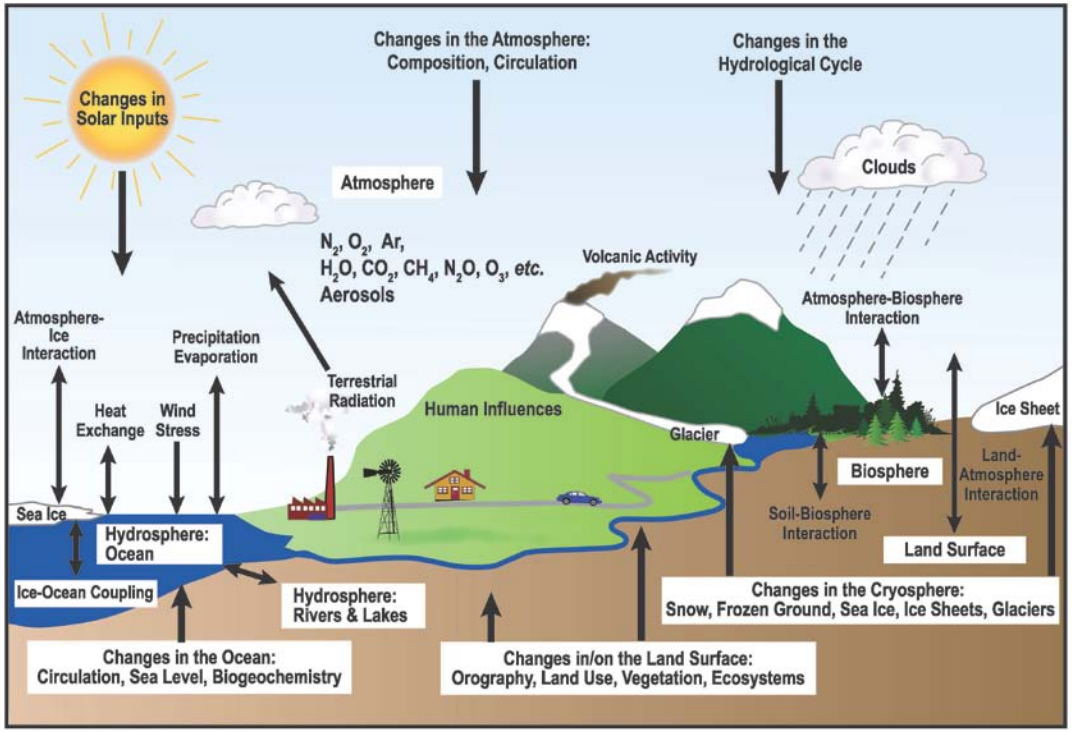
Spatial scale

- 1.25° longitude × 0.9375° latitude (288 × 192 grid)

Temporal scale

- 30-minute coupling with atmosphere
- Seasonal-to-interannual (phenology)
- Decadal-to-century climate (disturbance, land use, succession)
- Paleoclimate (biogeography)

Earth system models



(IPCC 2007)

Earth system models use mathematical formulas to simulate the **physical**, **chemical**, and **biological** processes that drive Earth's atmosphere, hydrosphere, biosphere, and geosphere

A typical Earth system model consists of coupled models of the **atmosphere**, **ocean**, **sea ice**, and **land**

Land is represented by its **ecosystems**, **watersheds**, **people**, and **socioeconomic** drivers of environmental change

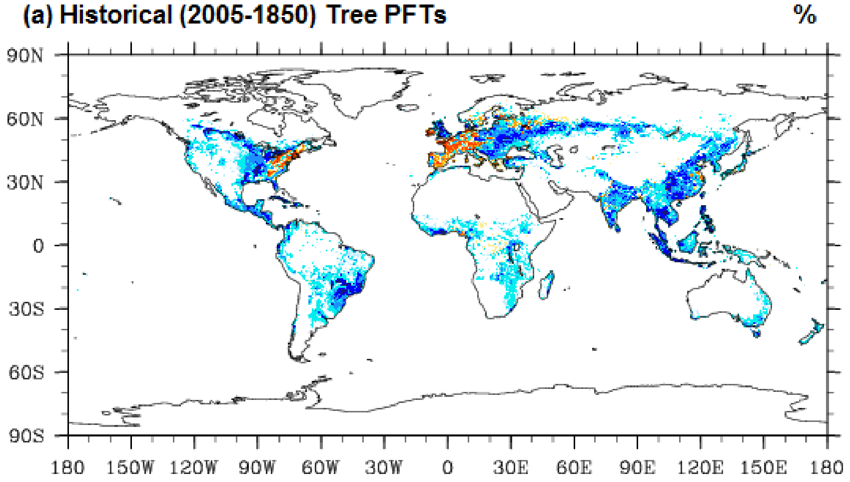
The model provides a comprehensive understanding of the processes by which people and ecosystems **feed back**, **adapt to**, and **mitigate** global environmental change

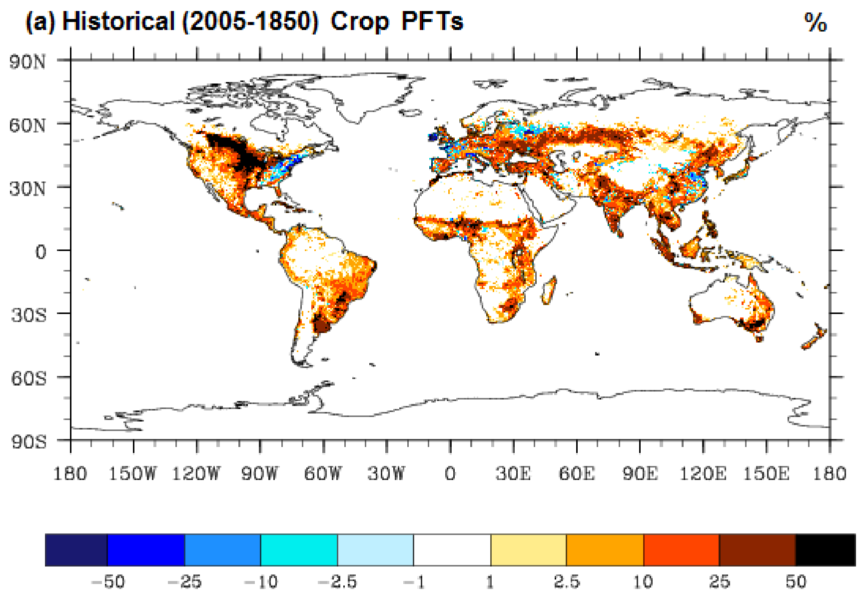
Two prominent biosphere feedbacks

- Land use and land cover change
- Carbon cycle

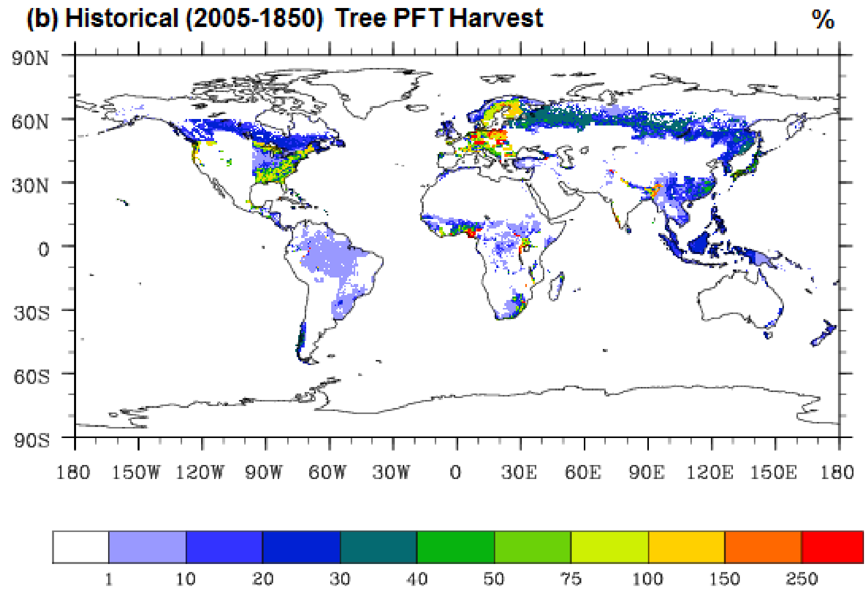
Historical land use and land cover change, 1850 to 2005

Change in tree and crop cover (percent of grid cell)





Cumulative percent of grid cell harvested

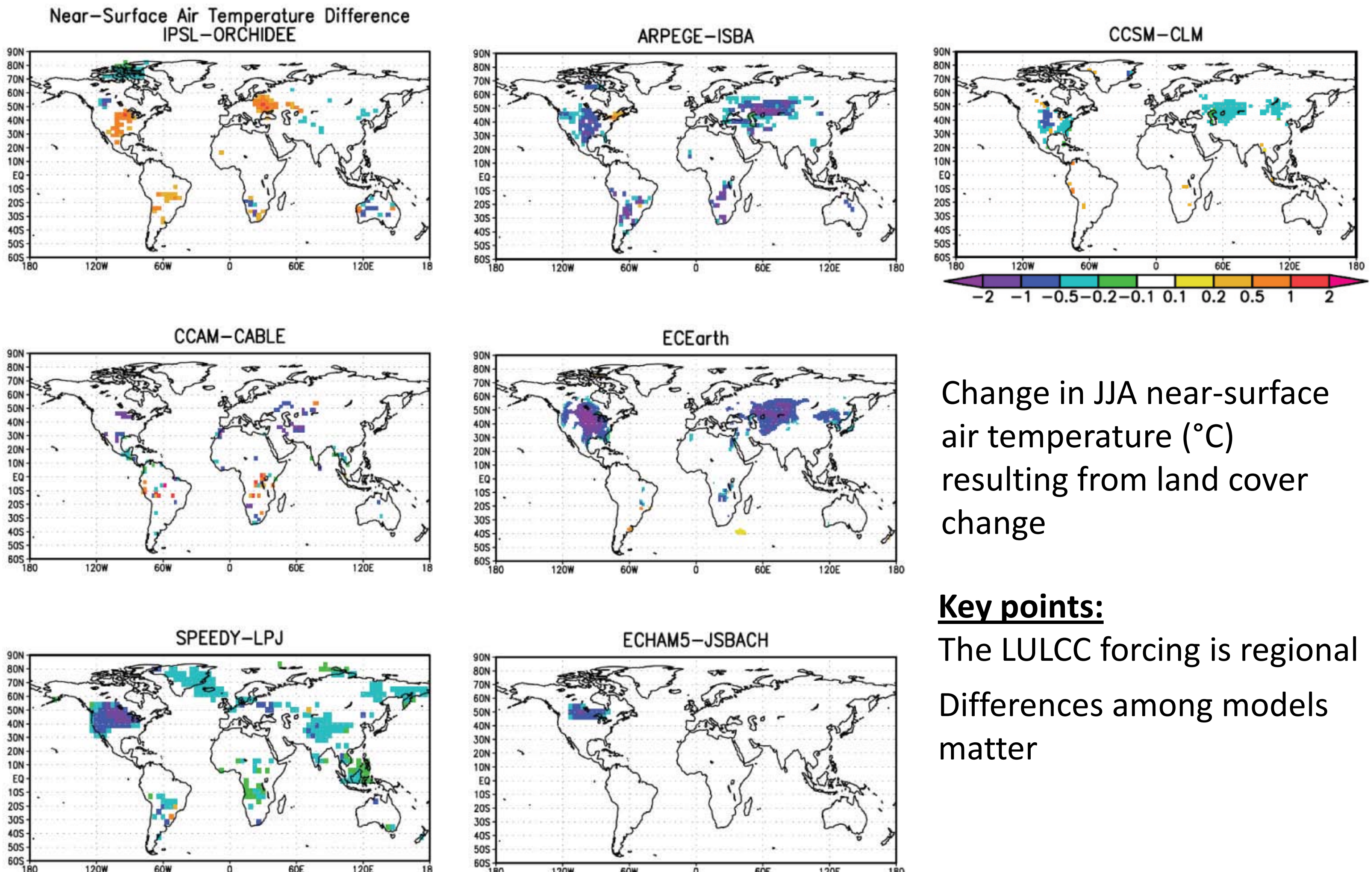


Historical LULCC in CLM4

- ❑ Loss of tree cover and increase in cropland
- ❑ Farm abandonment and reforestation in eastern U.S. and Europe
- ❑ Extensive wood harvest

Lawrence P et al. (2012) J Climate 25:3071-3095

The LUCID intercomparison study



Change in JJA near-surface air temperature (°C) resulting from land cover change

Key points:

The LULCC forcing is regional

Differences among models matter

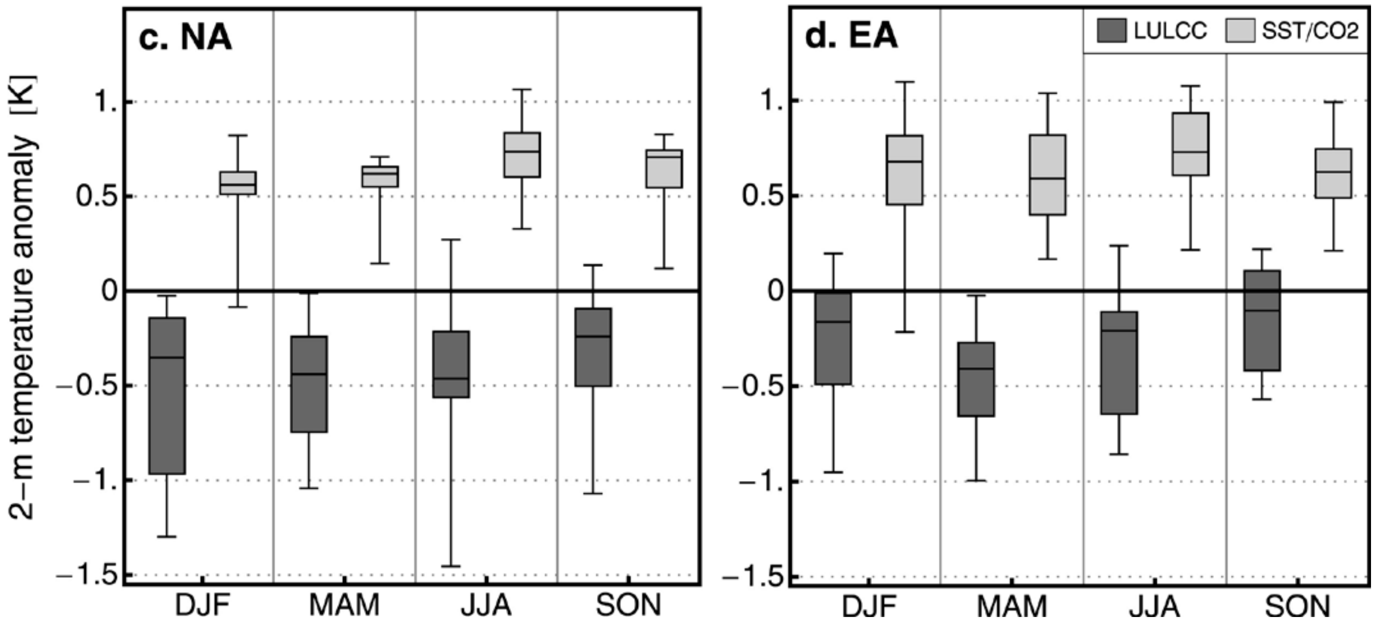
Pitman, de Noblet-Ducoudré, et al. (2009) GRL, 36, doi:10.1029/2009GL039076

LULCC relative to greenhouse warming

Multi-model ensemble of the simulated changes between the pre-industrial time period and present-day

North America

Eurasia



de Noblet-Ducoudré, Boiser, Pitman, et al. (2012) J Climate 25:3261-3281

CO_2 + SST + SIC forcing leads to warming

LULCC leads to cooling

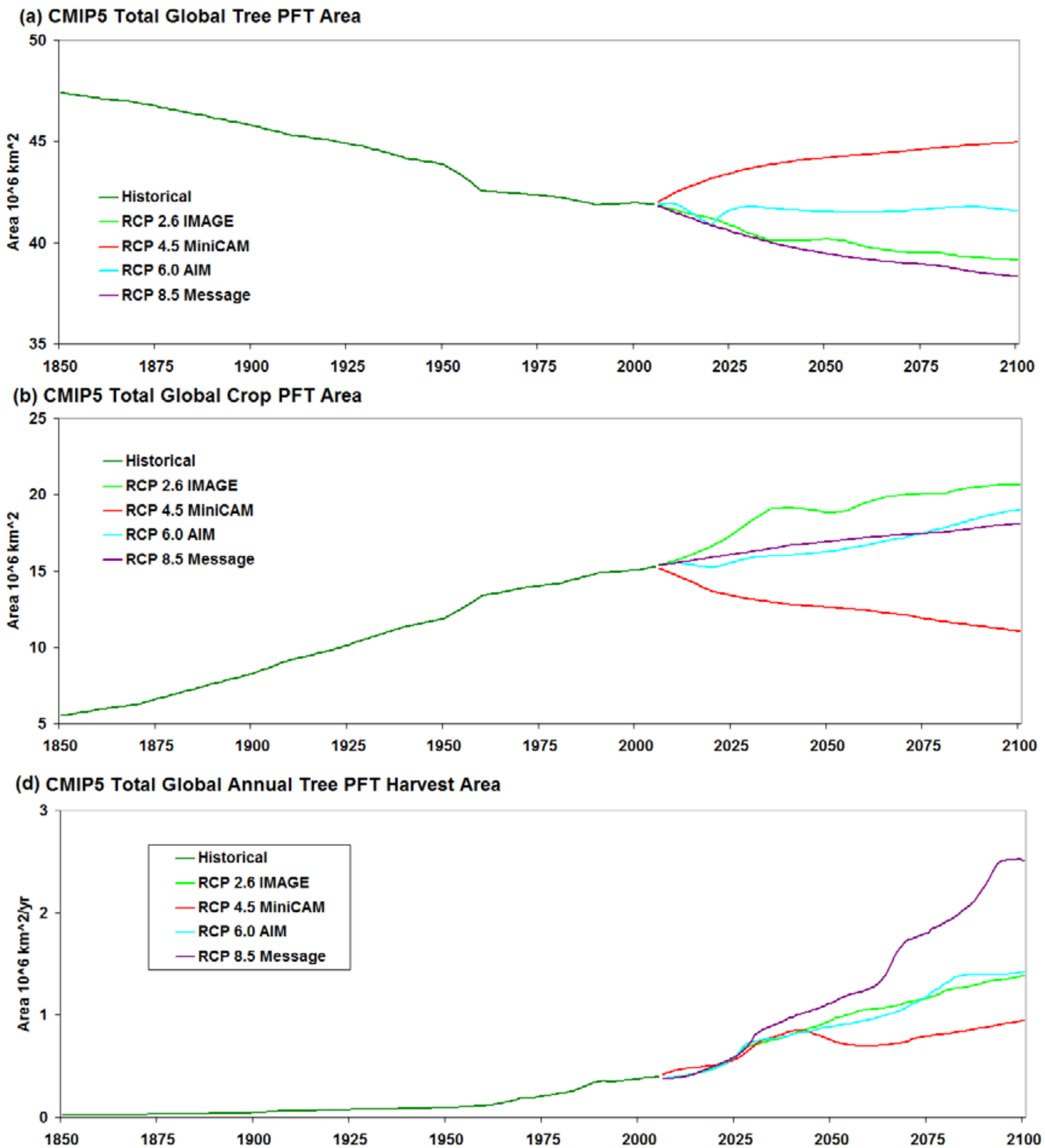
The bottom and top of the box are the 25th and 75th percentile, and the horizontal line within each box is the 50th percentile (the median). The whiskers (straight lines) indicate the ensemble maximum and minimum values.

Key points:

The LULCC forcing is counter to greenhouse warming

The LULCC forcing has large inter-model spread, especially JJA

21st century land use & land cover change

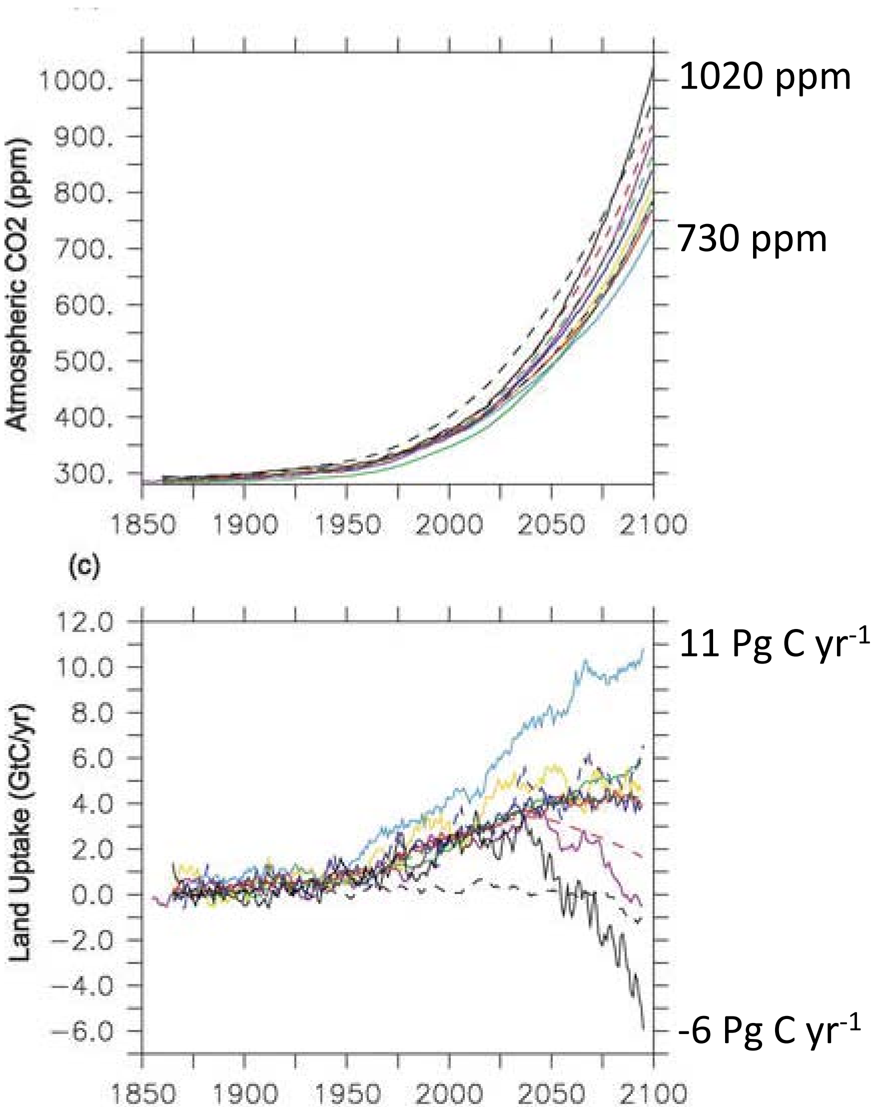


Description

- **RCP 2.6** - Largest increase in crops. Forest area declines.
- **RCP 4.5** - Largest decrease in crop. Expansion of forest areas for carbon storage.
- **RCP 6.0** - Medium cropland increase. Forest area remains constant.
- **RCP 8.5** - Medium increases in cropland. Largest decline in forest area. Biofuels included in wood harvest.

Lawrence P et al. (2012) J Climate 25:3071-3095

C4MIP – Climate and carbon cycle



Carbon cycle-climate feedback

11 carbon cycle-climate models of varying complexity

CO_2 fertilization enhances carbon uptake, diminished by decreased productivity and increased soil carbon loss with warming

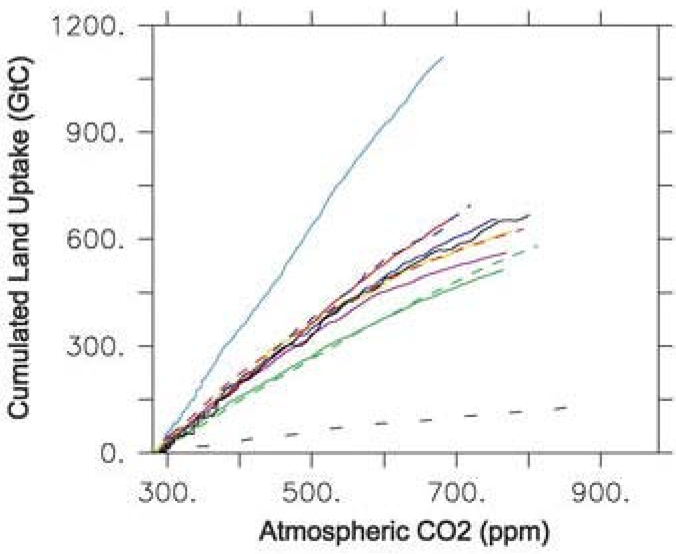
290 ppm difference in atmospheric CO_2 at 2100

17 Pg C yr^{-1} difference in land uptake at 2100

Friedlingstein et al. (2006) J Climate 19:3337-3353

Model uncertainty in feedback is large

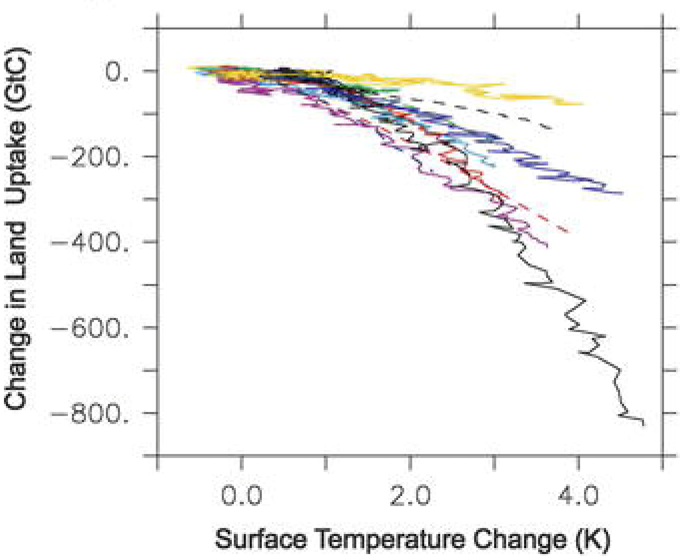
Concentration-carbon feedback



β_L=1.4 Pg C ppm^{-1} [0.2-2.8]

CO$_2$ fertilization enhances carbon uptake

Climate-carbon feedback



γ_L=-79 Pg C K^{-1} [-20 to -177]

Carbon loss with warming

Friedlingstein et al. (2006) J Climate 19:3337-3353

CMIP5 – Climate and carbon cycle

Carbon cycle-climate feedback

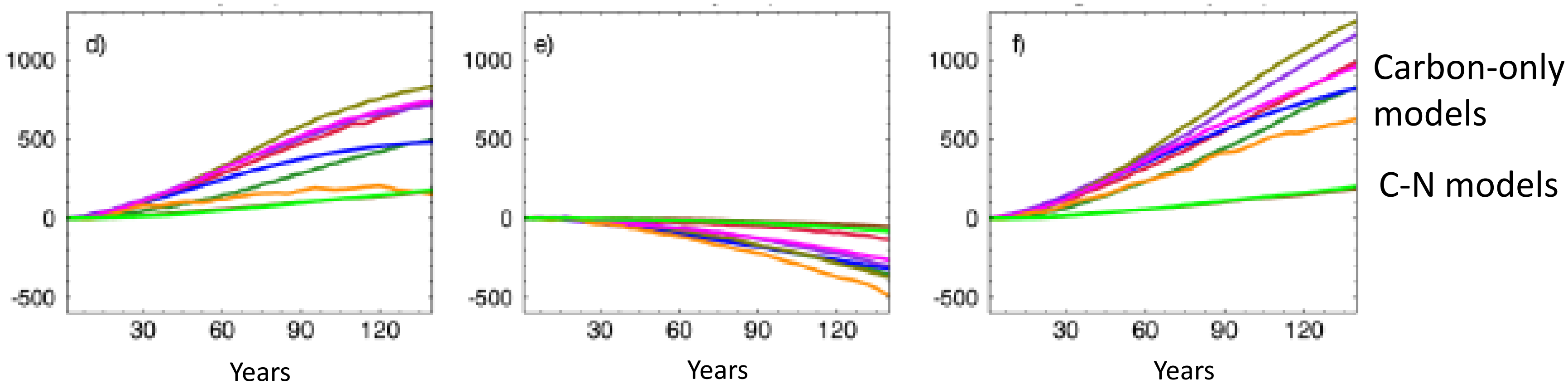
9 Earth system models of varying complexity

140-year simulations during which atmospheric CO_2 increases 1% per year from ~280 ppm to ~1120 ppm

Arora et al. (2012) J Climate, submitted

Cumulative land-atmosphere CO_2 flux (Pg C)

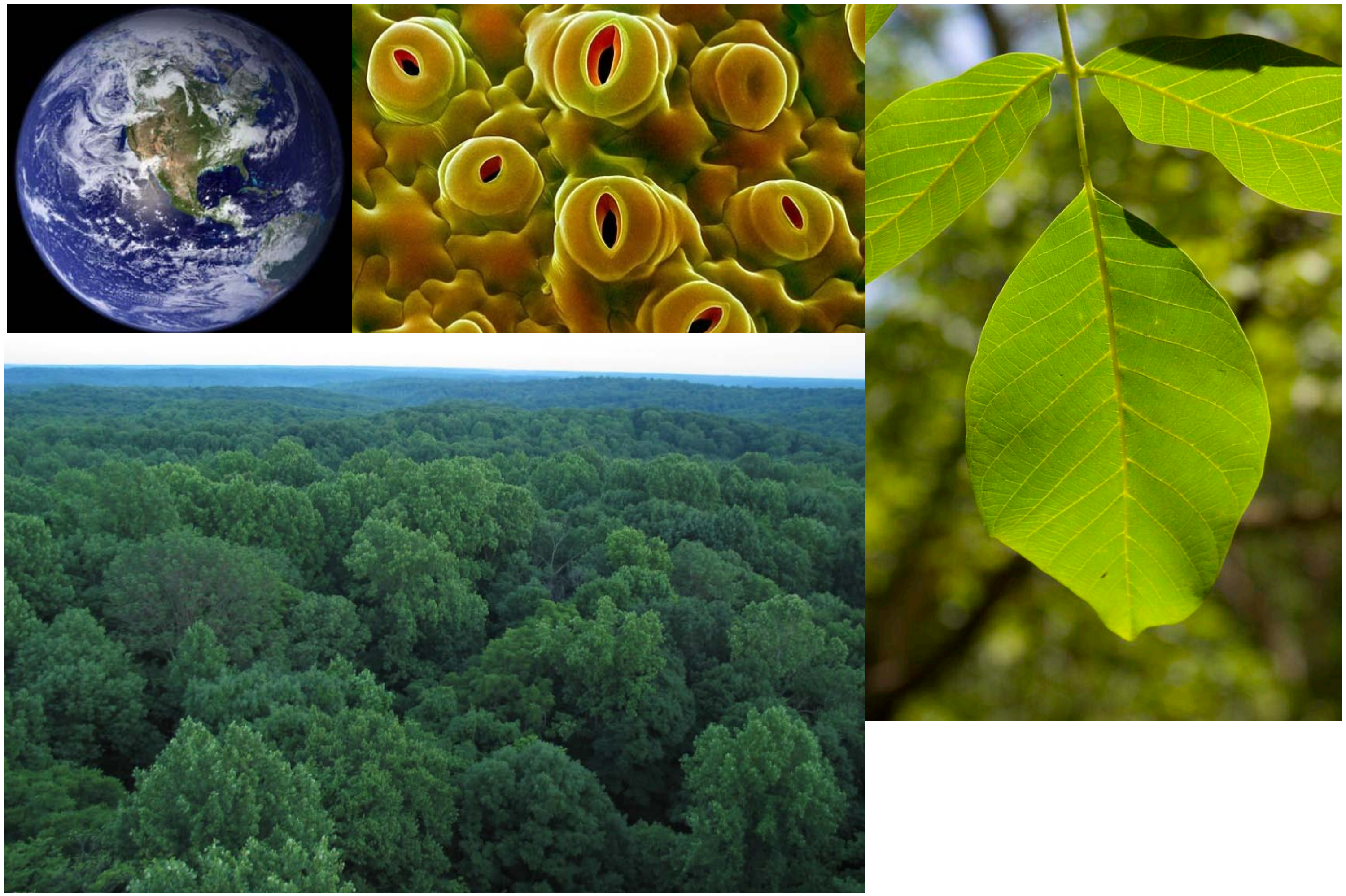
Fully coupled | Climate-carbon coupling | Concentration-carbon coupling



CMIP5: γ_L=-58 Pg C K^{-1} [-16 to -89] β_L=0.9 Pg C ppm^{-1} [0.2-1.5]

C4MIP: γ_L=-79 Pg C K^{-1} [-20 to -177] β_L=1.4 Pg C ppm^{-1} [0.2-2.8]

How well do we scale from leaf to globe?



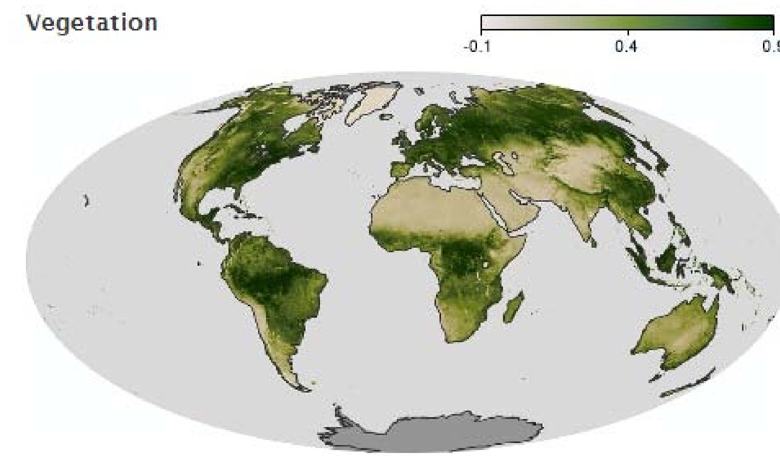
Have we moved beyond stomata as the dominant mechanism to represent biosphere-climate coupling? Global databases of leaf traits and eddy covariance flux datasets allow model testing with observations across multiple scales, from leaf to canopy to global. Such comparisons can reveal limitations in our representation of physiological processes in earth system models.

Multi-scale model evaluation

Canopy fluxes

GPP, latent heat flux

Lasslop et al. (2010) GCB 16:187-208



Global vegetation

GPP, latent heat flux

Jung et al. (2011) JGR, 116, doi:10.1029/2010JG001566

Canopy processes

Theory

Numerical parameterization

Profiles of light, leaf traits, and photosynthesis

Leaf traits

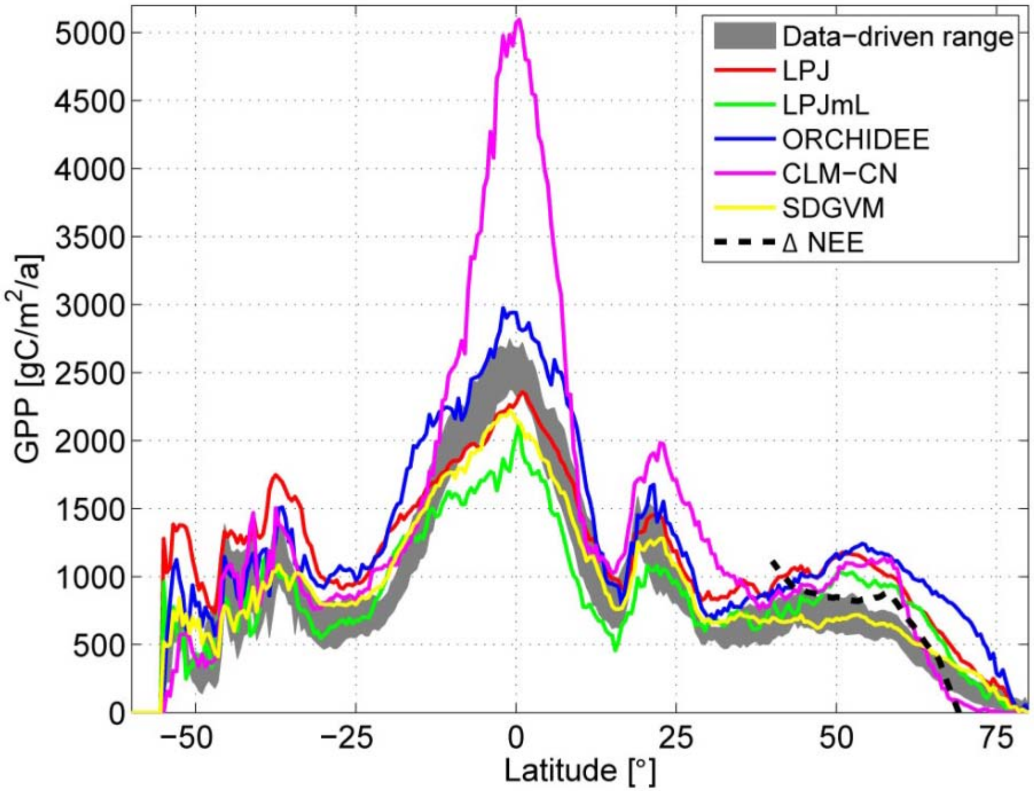
Nitrogen concentration, V_{cmax}

Kattge et al. (2009) GCB 15:976-991

Consistency among parameters, theory, and observations across scales (leaf, canopy, global)

Gross primary production biases

CLM4 (purple line) overestimates annual gross primary production (GPP) compared with data-driven estimates and other models



Beer et al. (2010) Science 329:834-838

Causes of GPP bias

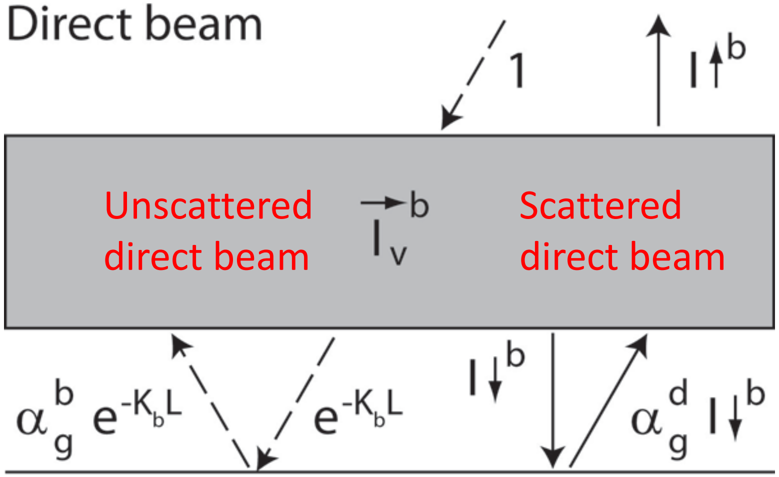
Model structural error
Canopy radiative transfer
Photosynthesis-stomatal conductance
Canopy integration

Model parameter uncertainty
V_{cmax}

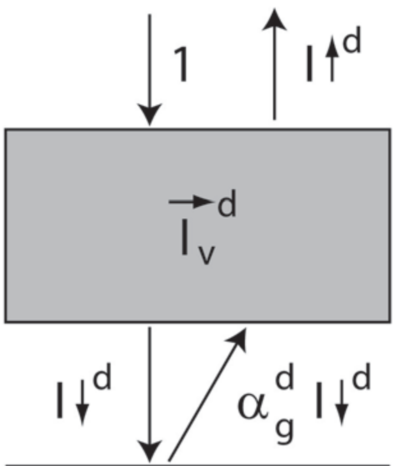
Bonan et al. (2011) JGR, doi:10.1029/2010JG001593
Bonan et al. (2012) JGR, doi:10.1029/2011JG001913

Two-stream radiative transfer

Direct beam



Diffuse



Radiative transfer uses the two-stream approximation (Dickinson, Sellers)

But how to partition absorbed radiation to sunlit and shaded leaves?

Common Land Model (CoLM) uses analytical solution for two-stream approximation

A Two-Big-Leaf Model for Canopy Temperature, Photosynthesis, and Stomatal Conductance

YONGJIU DAI
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ROBERT E. DICKINSON
School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia

YING-PING WANG
CSIRO Atmospheric Research, Aspendale, Victoria, Australia

Dai et al. (2004) J Climate 17:2281-2299

Community Land Model (CLM4) uses ad-hoc partitioning

An Improved Canopy Integration Scheme for a Land Surface Model with Prognostic Canopy Structure

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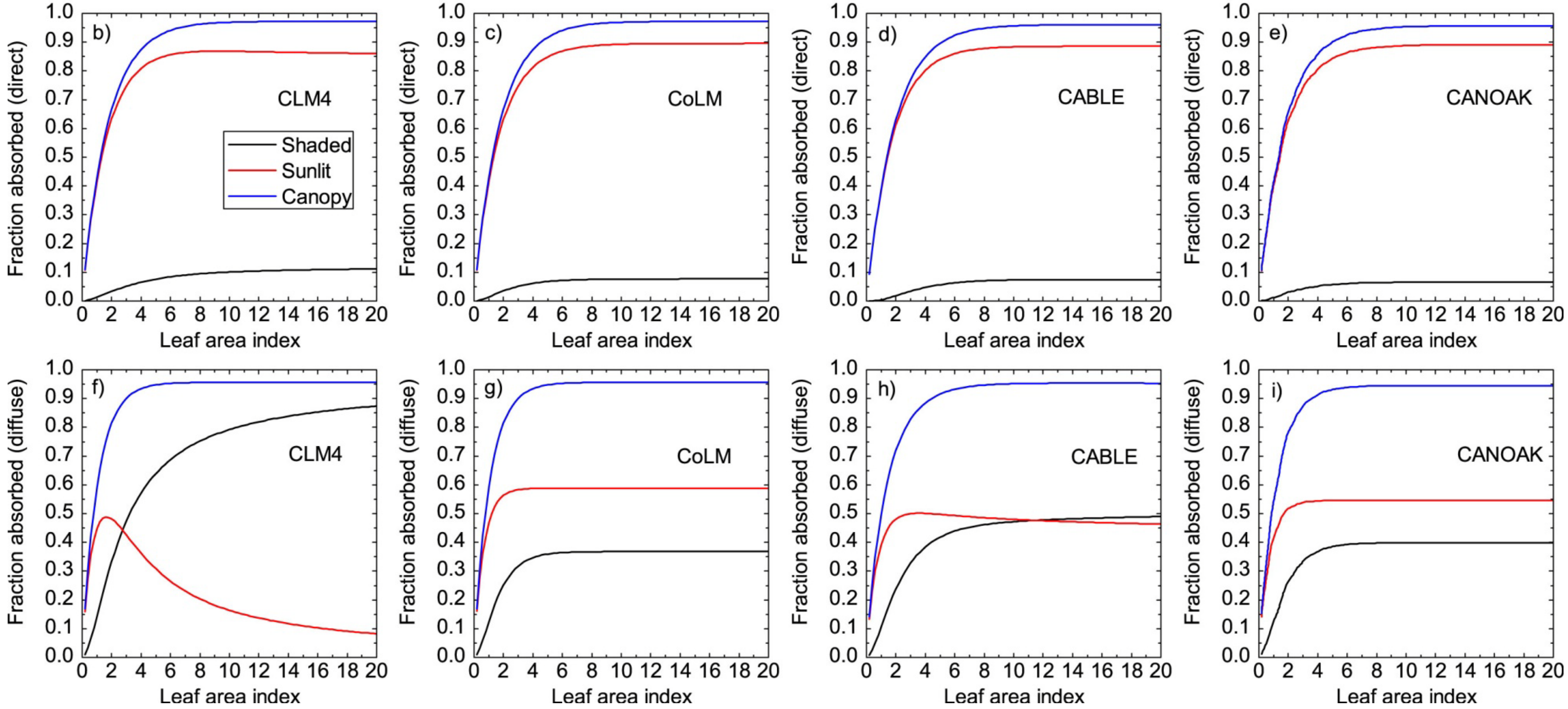
NIKLAUS E. ZIMMERMANN
Department of Landscape Research, Swiss Federal Research Institute WSL, Birmensdorf, Switzerland

Thornton & Zimmermann (2007) J Climate 20:3902-3923

CLM4 radiative transfer error



CLM4 has similar total absorption of direct beam and diffuse radiation as other models, but the partitioning of absorbed radiation between sunlit and shaded leaves is inconsistent. This is most evident for diffuse radiation

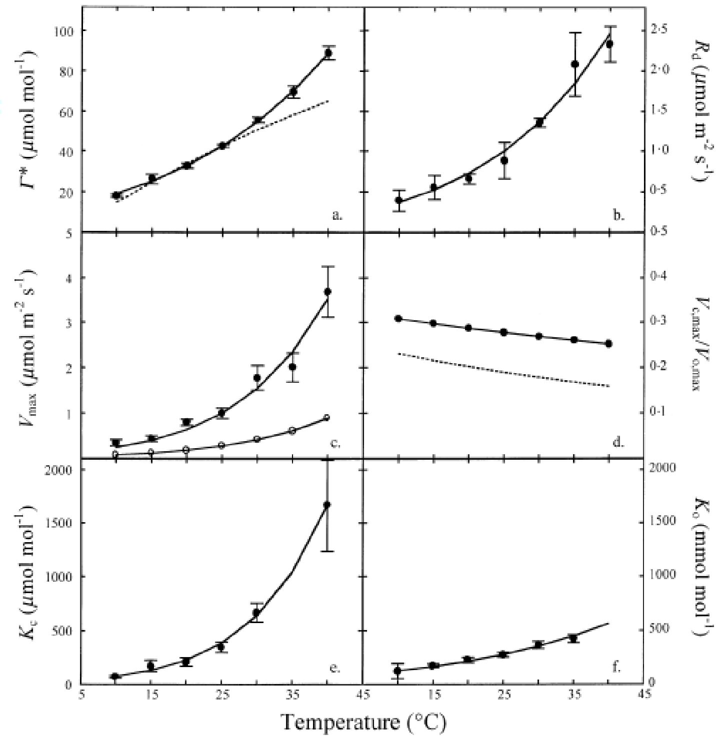
Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

Rubisco kinetics

Plant, Cell and Environment (2001) **24**, 253–259

Improved temperature response functions for models of Rubisco-limited photosynthesis

C. J. BERNACCHI, E. L. SINGSAAS,* C. PIMENTEL,† A. R. PORTIS JR & S. P. LONG



Plant, Cell and Environment (2003) **26**, 1419–1430

In vivo temperature response functions of parameters required to model RuBP-limited photosynthesis

C. J. BERNACCHI[1], C. PIMENTEL[1,*] & S. P. LONG[1]

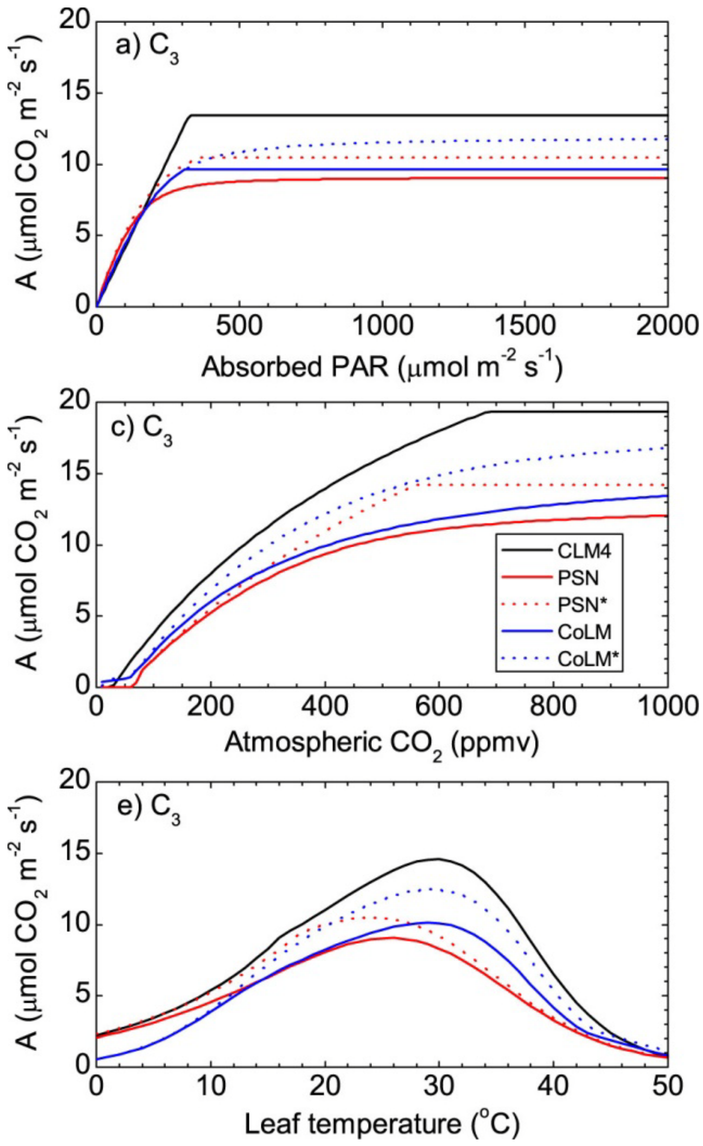
[1]*Departments of Plant Biology and of Crop Sciences, University of Illinois, Urbana, IL 61801, USA*

Plant, Cell and Environment (2002) **25**, 1167–1179

Temperature response of parameters of a biochemically based model of photosynthesis. II. A review of experimental data

B. E. MEDLYN[1,2], E. DREYER[3], D. ELLSWORTH[4], M. FORSTREUTER[5], P. C. HARLEY[6], M. U. F. KIRSCHBAUM[7], X. LE ROUX[8,9], P. MONTPIED[3], J. STRASSEMEYER[5], A. WALCROFT[8,10], K. WANG[11] & D. LOUSTAU[1]

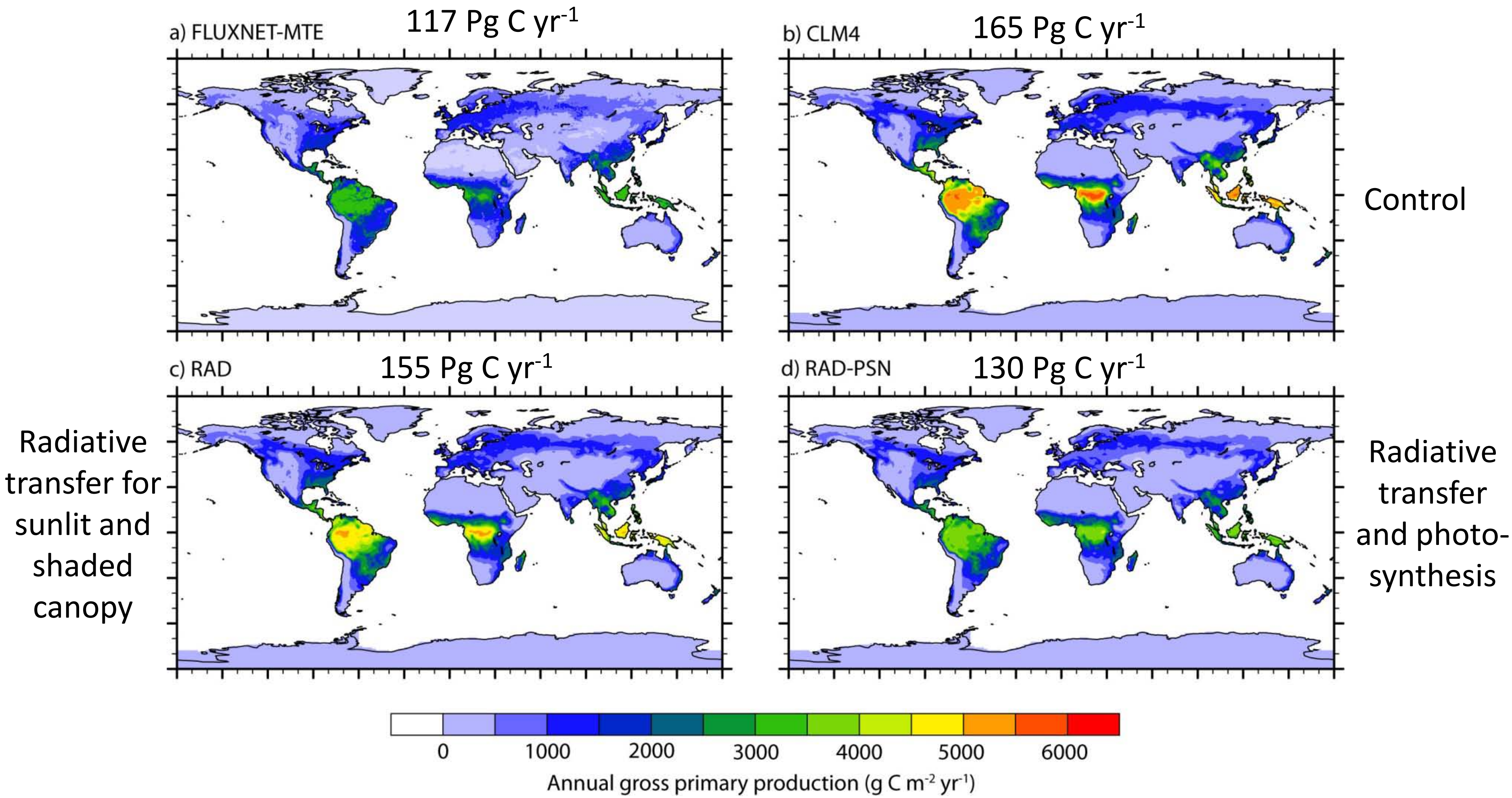
Parameter choices matter



Synthesis-derived leaf photosynthesis parameters (PSN) reduce photosynthetic rate compared with CLM4

Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

Gross primary production bias reduction

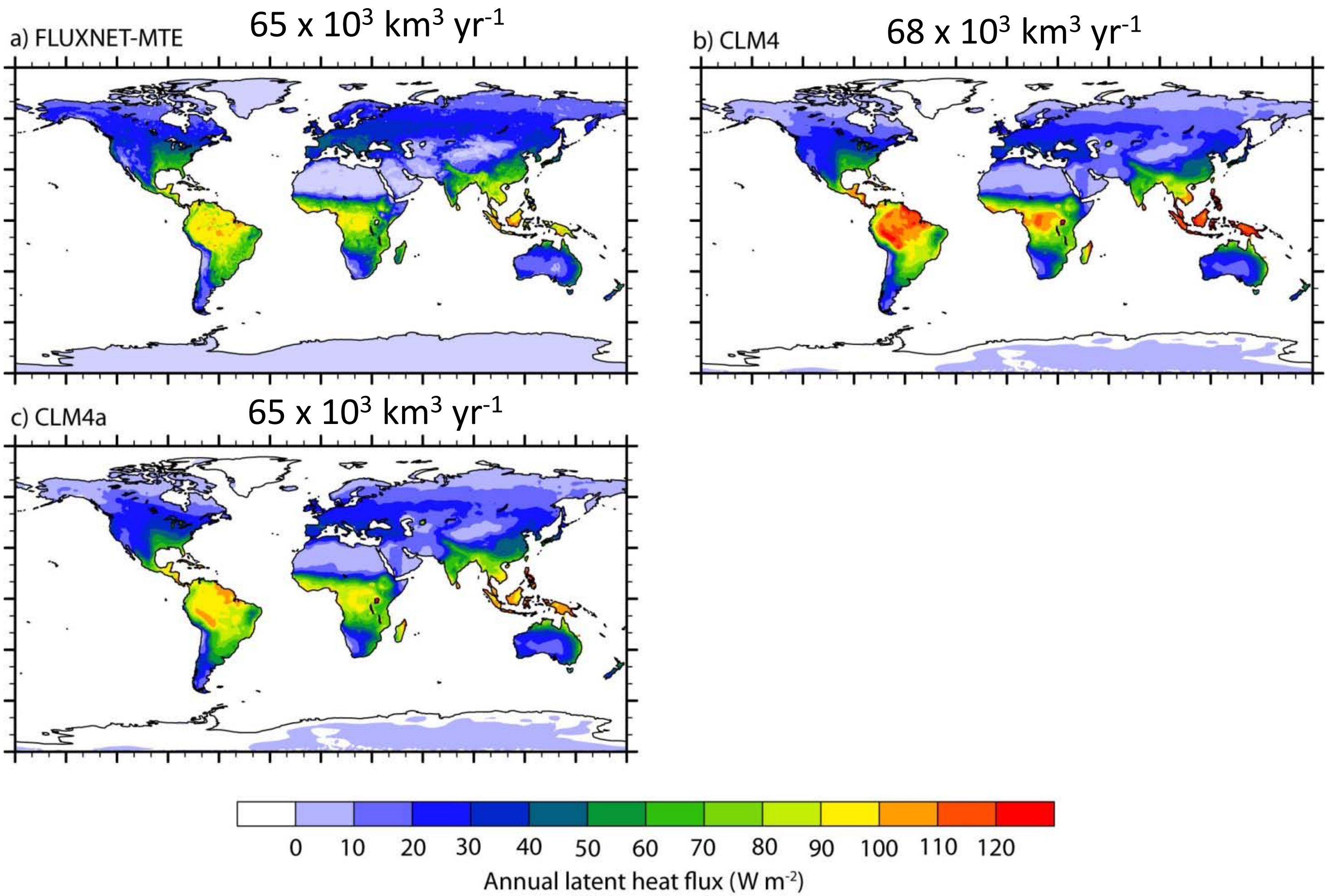


CLM4 overestimates GPP. Model revisions improve GPP. Similar improvements are seen in evapotranspiration

FLUXNET-MTE data from Martin Jung and Markus Reichstein (MPI-BGC, Jena)

Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

Improved annual latent heat flux



Model improvements (CLM4a) reduce ET biases, especially in tropics, and improve monthly fluxes

Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

Is the CLM4 photosynthetic capacity consistent with observations?

To match observed GPP, CLM4 needs to infer strong N reduction of GPP (with therefore reduced photosynthetic capacity)

How does this compare with observations of photosynthetic capacity, including N limitation?

Global databases of leaf traits provide an answer

Global Change Biology (2009) **15**, 976–991, doi: 10.1111/j.1365-2486.2008.01744.x

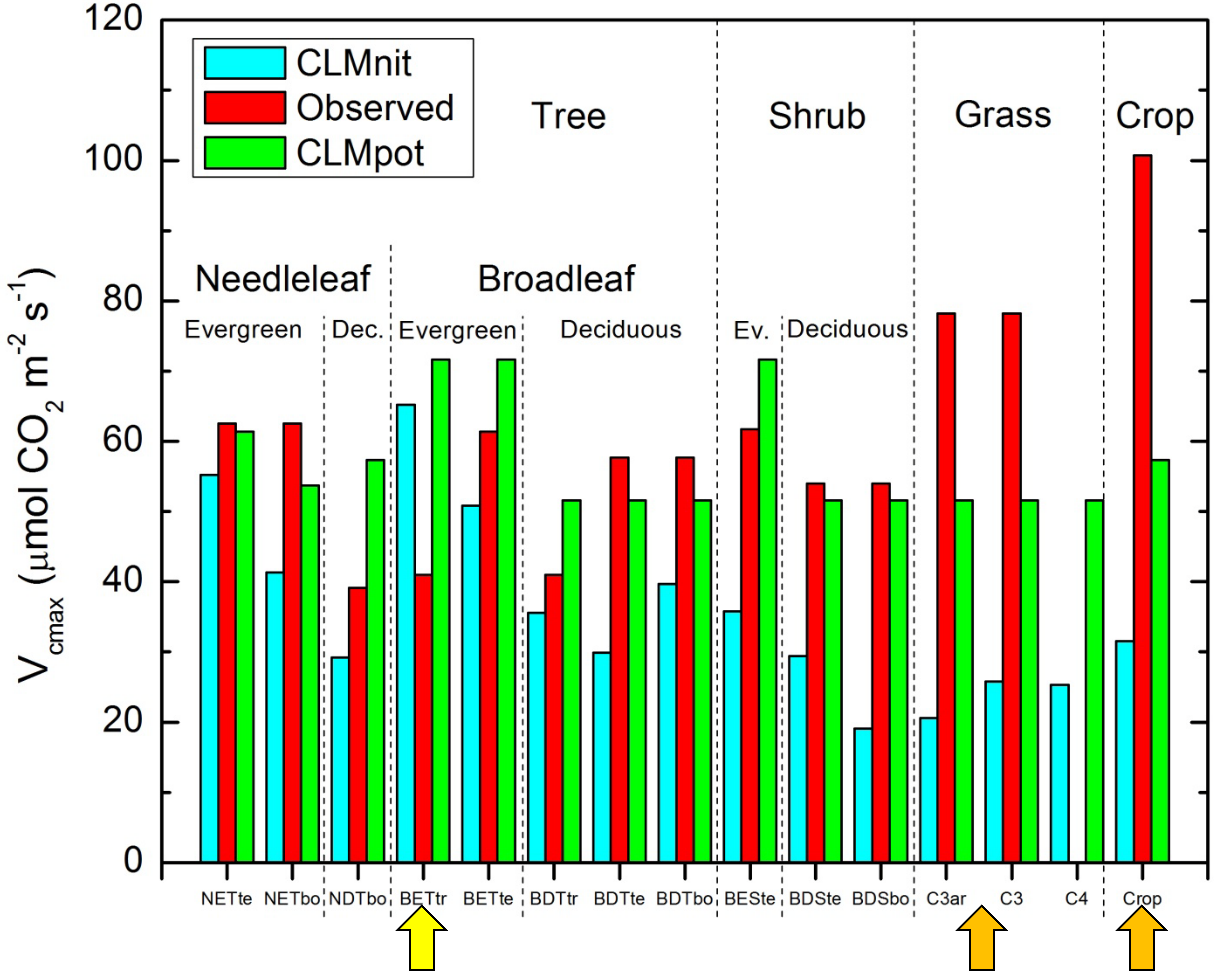
Quantifying photosynthetic capacity and its relationship to leaf nitrogen content for global-scale terrestrial biosphere models

JENS KATTGE*, WOLFGANG KNORR†, THOMAS RADDATZ‡ and CHRISTIAN WIRTH*
*Max-Planck-Institute for Biogeochemistry, Hans-Knöll Street 10, 07745 Jena, Germany, †QUEST, Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, BS8 1RJ, UK, ‡Max Planck Institute for Meteorology, Bundesstraße 53, 20146 Hamburg, Germany

- Derived the relationship between photosynthetic parameter V_{cmax} and leaf N from V_{cmax} (723 data points) and A_{max} (776 data points) studies
- Used measured leaf N in natural vegetation to estimate V_{cmax} for various PFTs
- Most comprehensive estimates of V_{cmax} available
- Includes the effects of extant N availability

CLM4 photosynthetic capacity

Observed and model V_{cmax} (25 °C) for CLM plant functional types



- CLM4 reduces a potential GPP for simulated N availability (Thornton & Zimmermann, 2007, J Climate 20:3902-3923)
- CLM4 realized V_{cmax} after N down-regulation is less than Kattge observed V_{cmax}, except for tropical forest
- CLM4 potential V_{cmax} before N down-regulation is comparable to Kattge observed V_{cmax}, with some exceptions

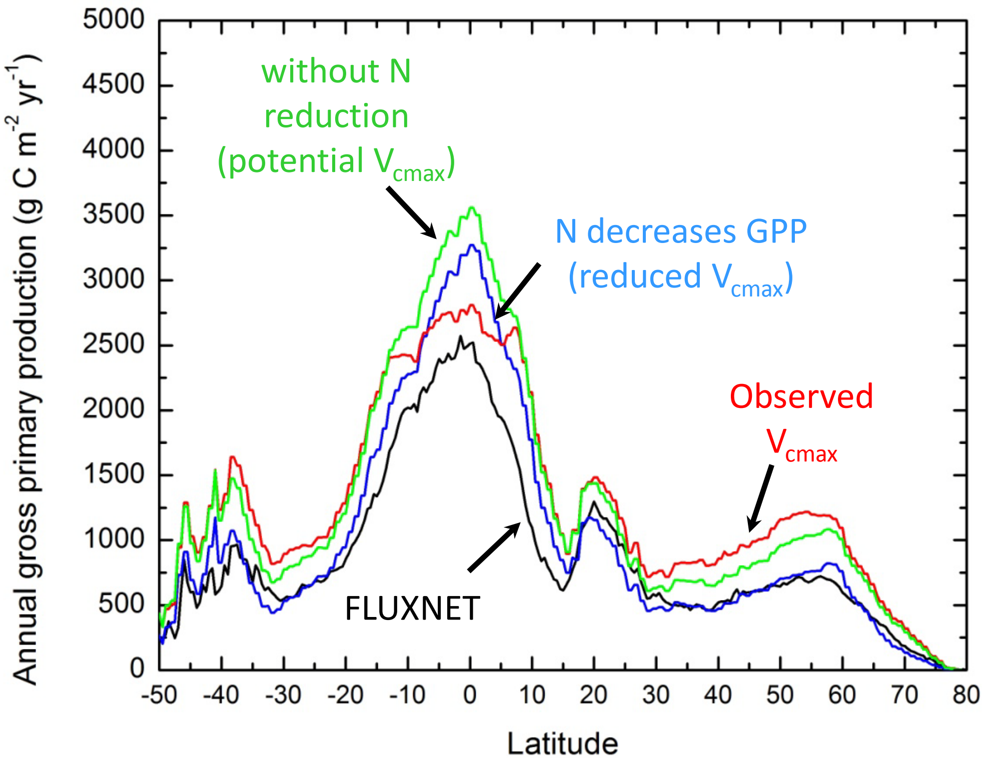
CLM4 requires low V_{cmax}

What happens when we use these V_{cmax} values?

Best simulation uses low V_{cmax}. When we remove the N down-regulation, the model is too productive

Kattge observed V_{cmax} increases GPP except in the tropics, which declines because of lower V_{cmax}

Why is GPP so high if we are using the correct enzyme-limited photosynthetic capacity? What is missing in the model?



Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

Here, we provide a solution to this discrepancy between the leaf trait database and the FLUXNET database in CLM4

Canopy light absorption

Hypothesis: CLM4 is too productive (high GPP) in the absence of N down-regulation because of deficiencies in the canopy parameterization. The CLM nitrogen down-regulation compensates for this deficiency

Model simulations

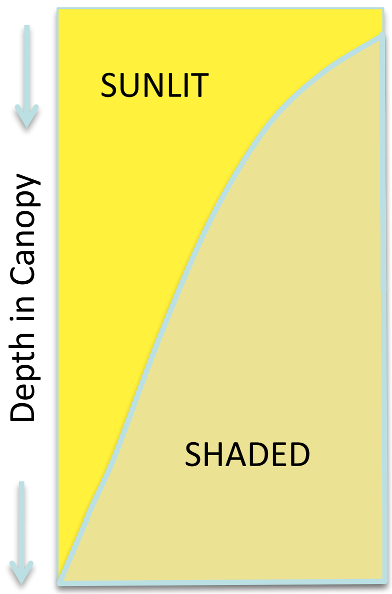
- Without C-N biogeochemistry
- With satellite leaf area and prescribed V_{cmax}

Investigate why CLM requires low V_{cmax} and why it performs poorly with the Kattge et al. (2009) values

Photographs of Morgan Monroe State Forest tower site illustrate two different representations of a plant canopy: as a “big leaf” (below) or with vertical structure (right)

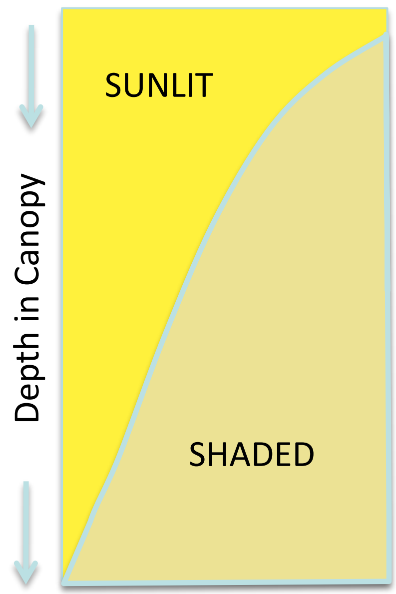
Multi-layer canopy

CLM4



- Two "big-leaves" (sunlit, shaded)
- Radiative transfer integrated over LAI (two-stream approximation)
- Photosynthesis calculated for sunlit and shaded big-leaves

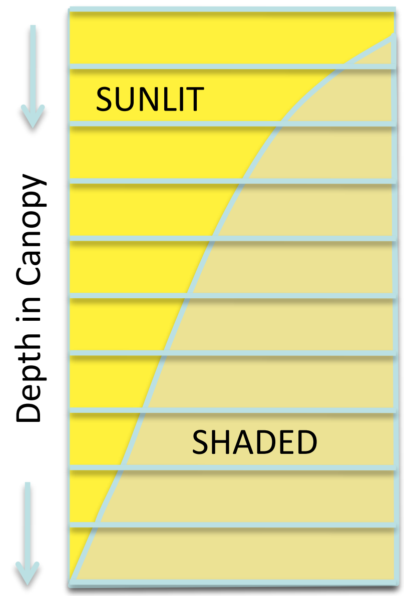
CLM4a



Same model structure as CLM4, but with revisions described by Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

- Corrected radiative transfer for sunlit and shaded canopy
- Corrected A and g_s
- Nitrogen scales exponentially with K_n=0.11

CLM4b

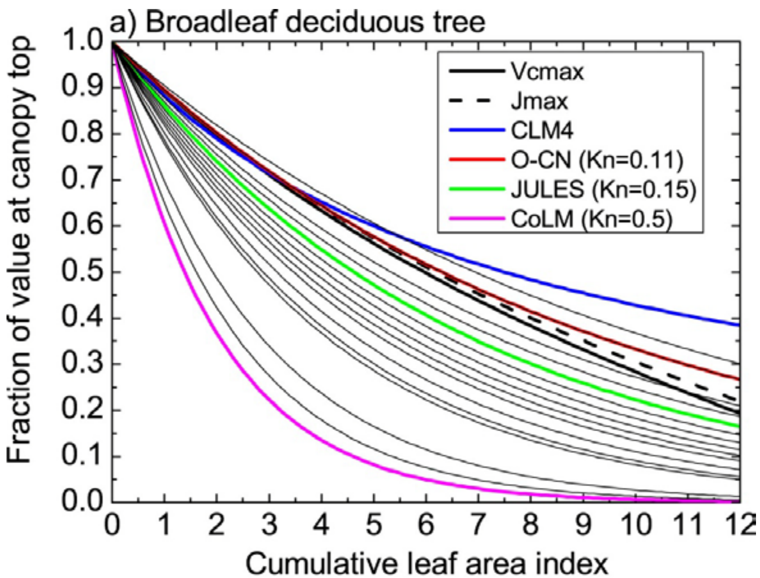


CLM4a and multi-layer canopy

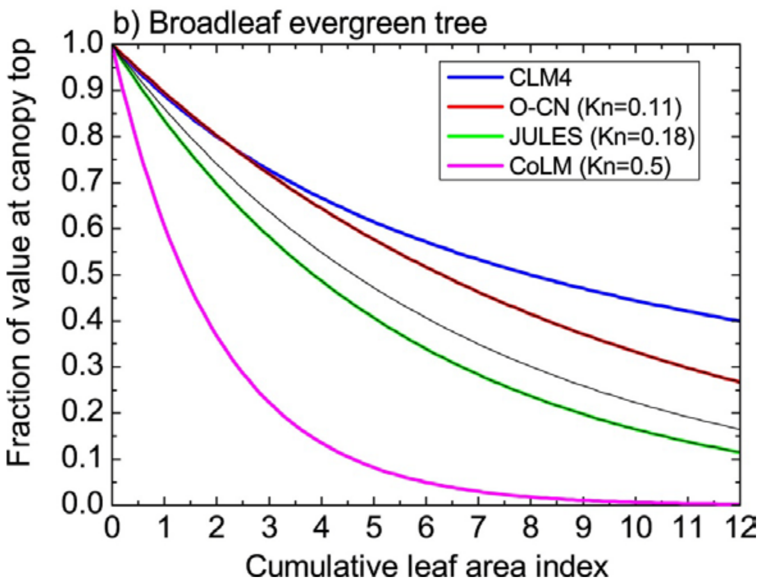
Multi-layer model

- Two-stream approximation for light profile
- Resolves direct and diffuse radiation
- Resolves sunlit and shaded leaves
- Explicit definition of leaf properties with depth
- Nitrogen scaled exponentially with K_n dependant on V_{cmax} (Lloyd et al. 2010)
- V_{cmax} from Kattge et al. (2009)
- Bonan et al. (2012) JGR, doi:10.1029/2011JG001913

Canopy scaling, V_{cmax}



Niinemets & Tenhunen (1997) Plant Cell Environ 20:845-866
Lloyd et al. (2010) Biogeosci 7:1833-1859



CLM4 has a shallower decline than in other models (O-CN, JULES, CoLM) or in observations

CLM4 has no canopy scaling for shrubs, grasses, and crops (only for trees), but foliage N is observed to decrease with depth in the canopy for these PFTs

CLM4a: K_n=0.11

CLM4b: Observations across multiple forest sites suggest K_n scales with V_{cmax}:

$$\ln K_n = 0.00963\ V_{cmax} - 2.43$$

Lloyd et al. (2010) Biogeosciences 7:1833-1859

Leaf-to-canopy scaling using two-leaf canopy

Plant, Cell and Environment (1997) **20,** 537–557

Simple scaling of photosynthesis from leaves to canopies without the errors of big-leaf models

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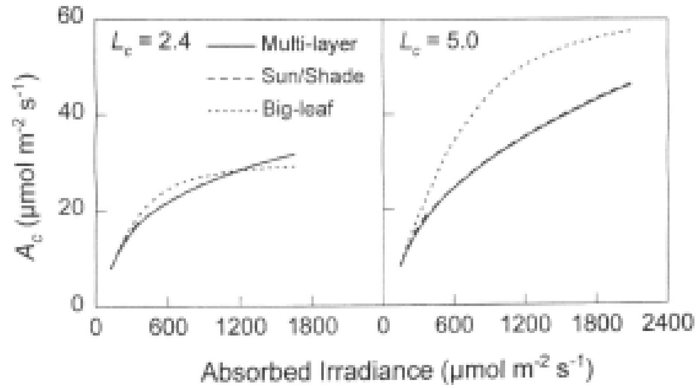
Environmental Biology, Research School of Biological Sciences, Institute of Advanced Studies, The Australian National University, Canberra, ACT, Australia



ELSEVIER

Agricultural and Forest Meteorology 91 (1998) 89–111

AGRICULTURAL AND FOREST METEOROLOGY

A two-leaf model for canopy conductance, photosynthesis and partitioning of available energy I: Model description and comparison with a multi-layered model

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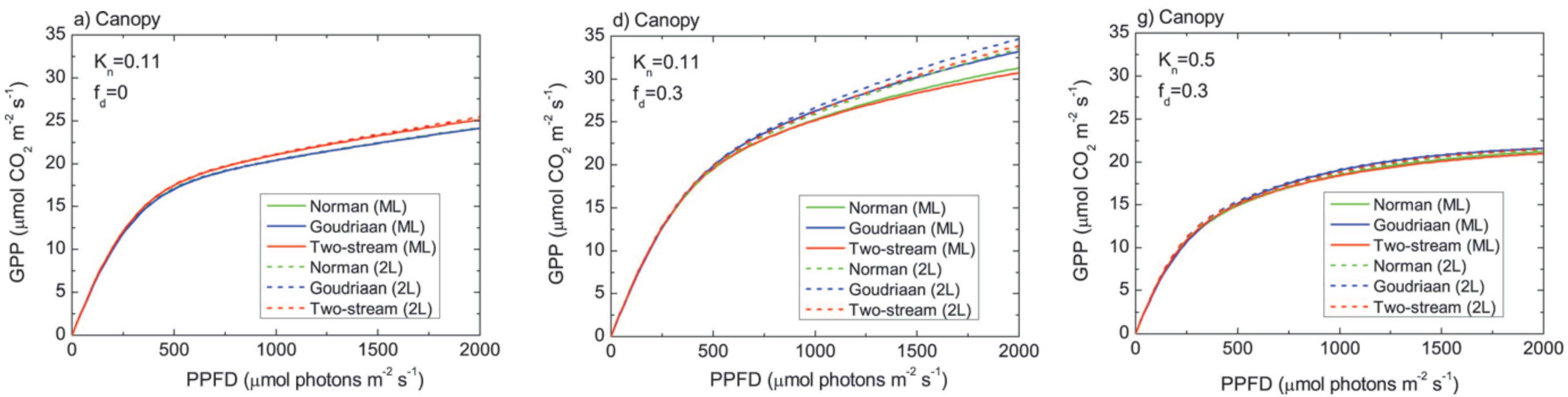
[b] *CSIRO Land and Water, FC Pye Laboratory, Canberra, ACT 2601, Australia*

Diffuse radiation for shaded leaves is problematic

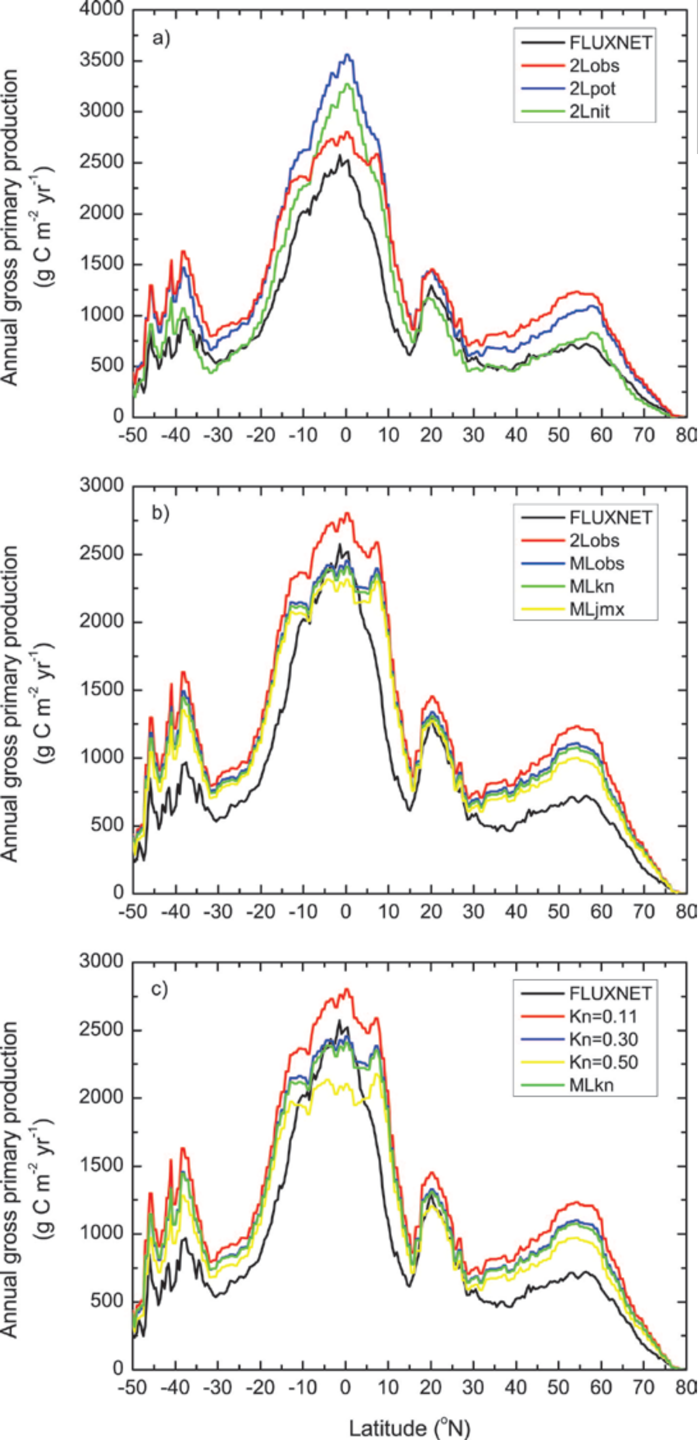


Shallow gradient (K_n=0.11)
With no diffuse radiation (f_d=0), two-leaf canopy (2L) replicates multi-layer canopy (ML). True for all three radiation models (Norman, Goudriaan, two-stream).

With higher diffuse fraction (f_d=0.3), the two-leaf canopy overestimates GPP compared with the multi-layer canopy for all three radiation models (related to light absorption by shaded leaves)

Steep gradient (K_n=0.5)
The decline in photosynthetic capacity compensates for the error in shaded leaf radiation so that the two-leaf and multi-layer canopies are similar

Bonan et al. (2012) JGR, doi:10.1029/2011JG001913



Three ways to get similar GPP

Use low (N-reduced) V_{cmax} and a two-leaf canopy

2Lobs = 161 Pg C yr^{-1}

2Lpot = 161 Pg C yr^{-1}

2Lnit = 129 Pg C yr^{-1}

But wrong V_{cmax}

Use "observed" V_{cmax} and a multi-layer canopy

2Lobs = 161 Pg C yr^{-1}

MLkn = 144 Pg C yr^{-1}

MLjmx = 138 Pg C yr^{-1}

Canopy light response curves at individual tower sites are also improved

Use "observed" V_{cmax} and a two-leaf canopy with high K_n

2Lobs (K_n=0.11) = 161 Pg C yr^{-1}

2Lobs (K_n=0.30) = 146 Pg C yr^{-1}

MLkn = 144 Pg C yr^{-1}

But wrong K_n

Bonan et al. (2012) JGR, doi:10.1029/2011JG001913

Conclusions

- Inclusion of stomata (and coupling with photosynthesis) was key step from atmospheric general circulation model -> climate model -> earth system model
- Earth system models now include many ecological feedbacks, each with many uncertainties. However, stomata and uncertainty in how to represent physiological processes remains key to Earth system simulation
- The CLM4 experience shows the need to combine theory, observations, and modeling and to test models across scales (leaf, canopy, global)