Carnegie Insitution
of Washington, Department of Global Ecology

Linking Biochemical Mechanisms to Earth System Processes: ~~Challeges of Scale~~

Joe Berry
Carnegie Institution of Washington
Department of Global Ecology

Collaborators:

Elliott Campbell	Univ. of Iowa/Carnegie Inst.
Jim Collatz	NASA Goddard Space Flight Center
Scott Denning	Colo. State Univ., Atmos. Sciences
Inez Fung	U. C. Berkeley, Atmos Sciences
Randy Kawa	NASA Goddard Space Flight Center
Steve Montzka	NOAA, GMD, Boulder, CO
Nick Parazoo	Colo. State Univ., Atmos. Sciences
Piers Sellers	NASA, Johnson Space Flight Center
Chris Still	U. C. Santa Barbara, Geography
Reto Stockli	Institut f. Atmosphäre und Klima, Zurich
Aaron Wang	Colo. State Univ., Atmos. Sciences
Adam Wolf	Stanford/Carnegie Inst.
Zhengxin Zhu	NASA Goddard Space Flight Center

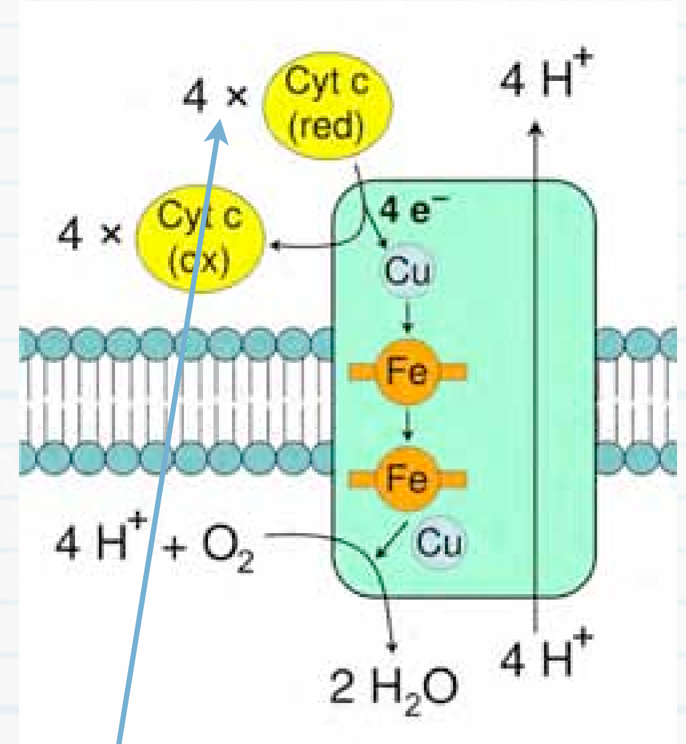
Support:

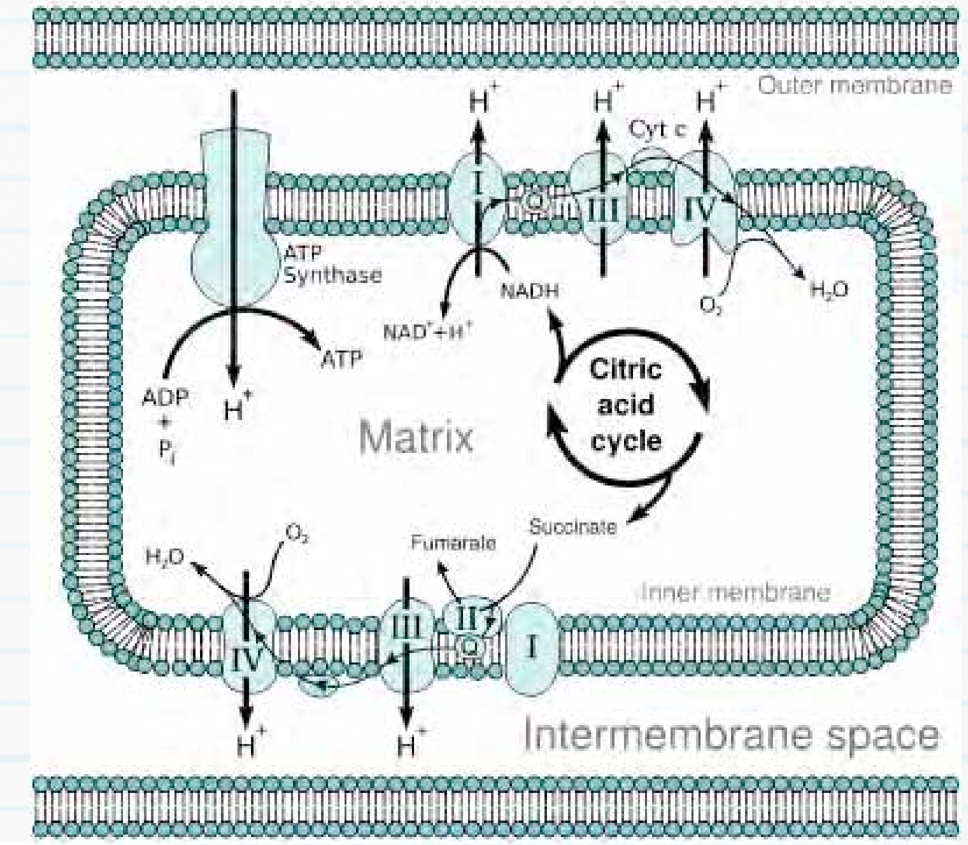
NASA
NOAA

Outline

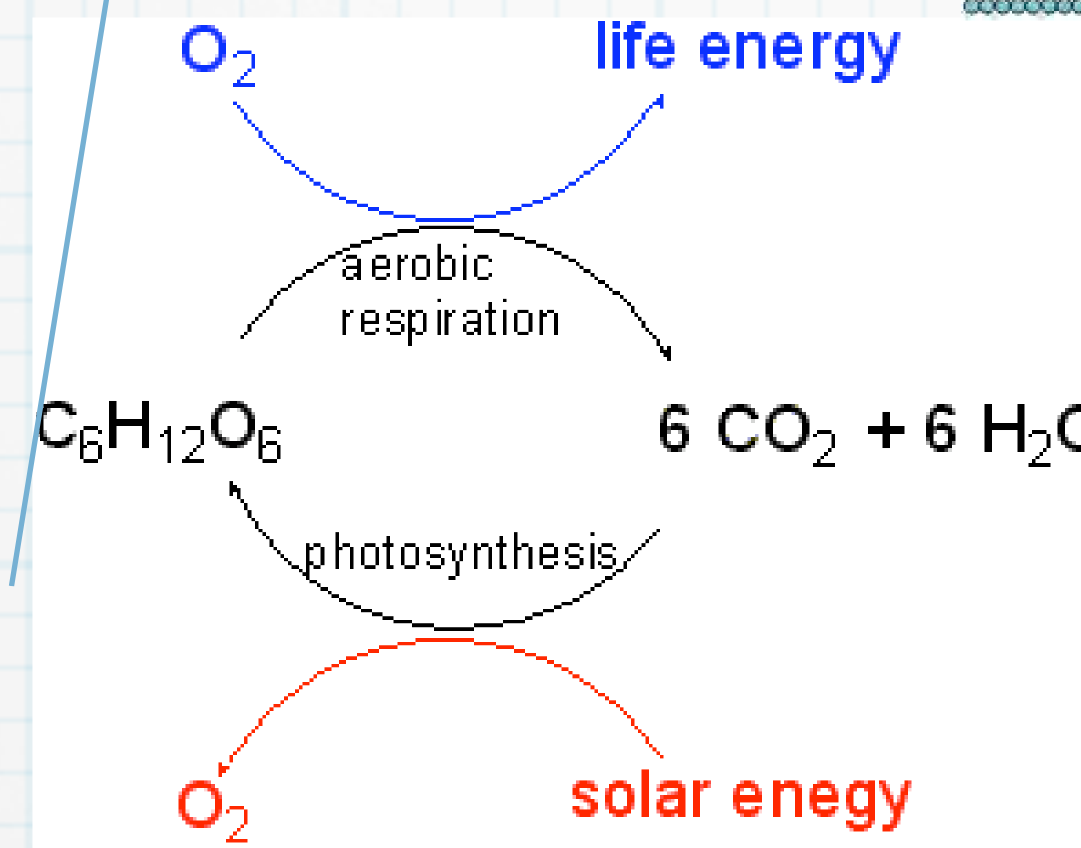
* The molecules
* Their global impact
* Linkage to climate: regulation of surface properties.
* Testing models at appropricate scales
* Carbonyl sulfide as a biospheric tracer
* C_4 photosynthesis in the global carbon cycle.

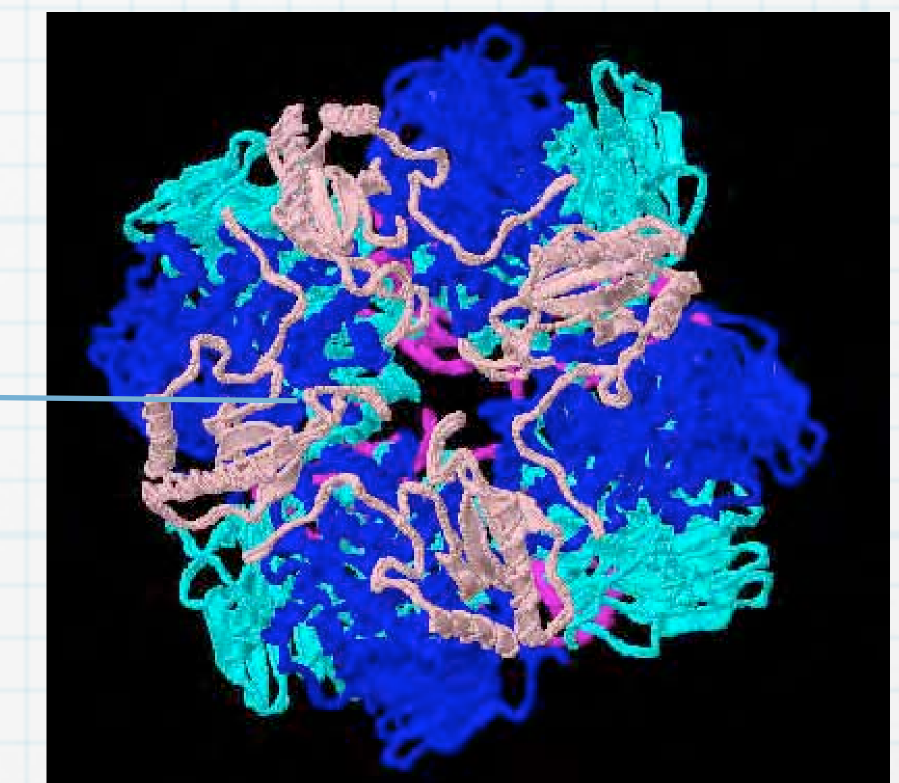
Respiration



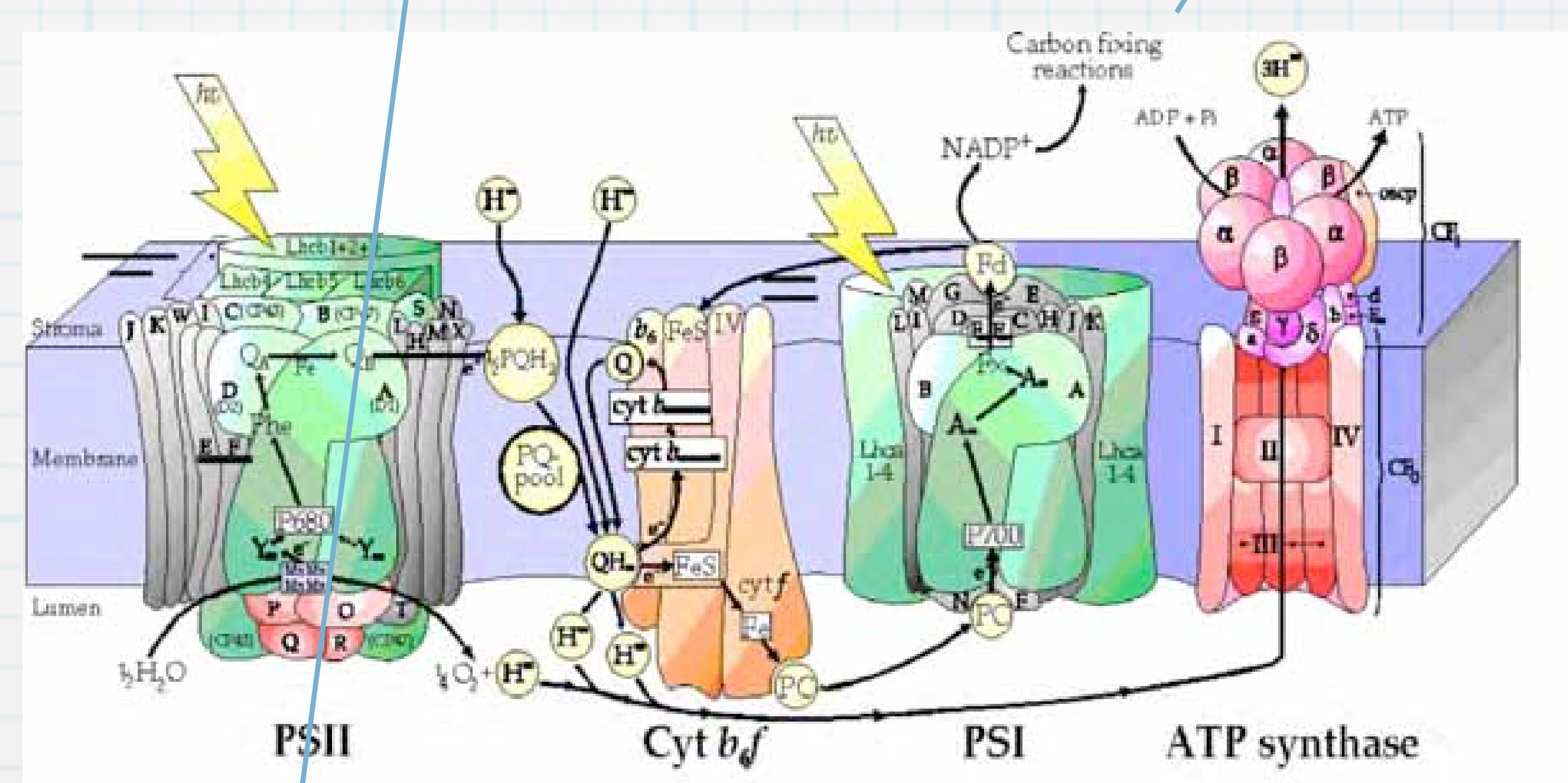


Oygen & Carbon Cycles
Rubisco

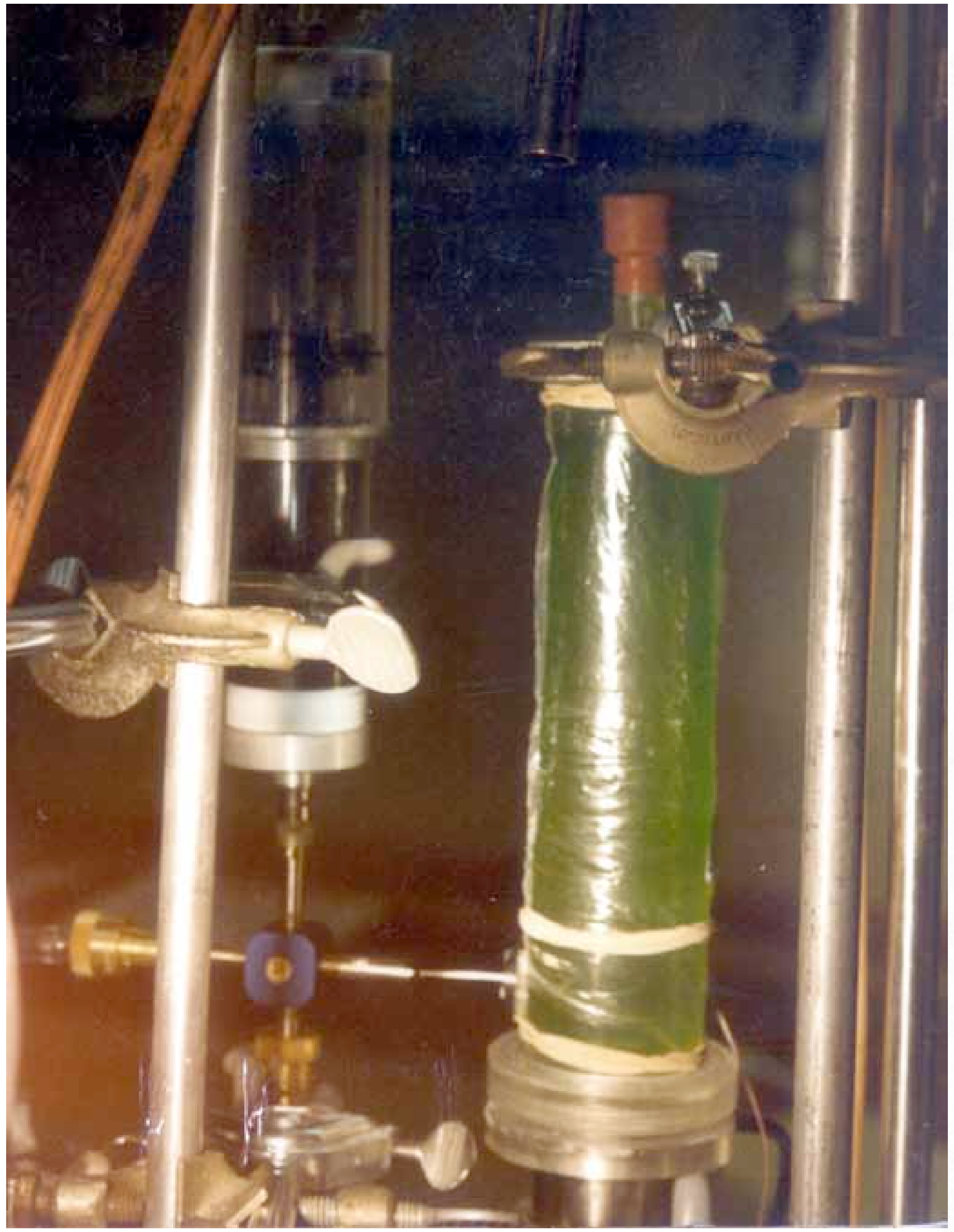


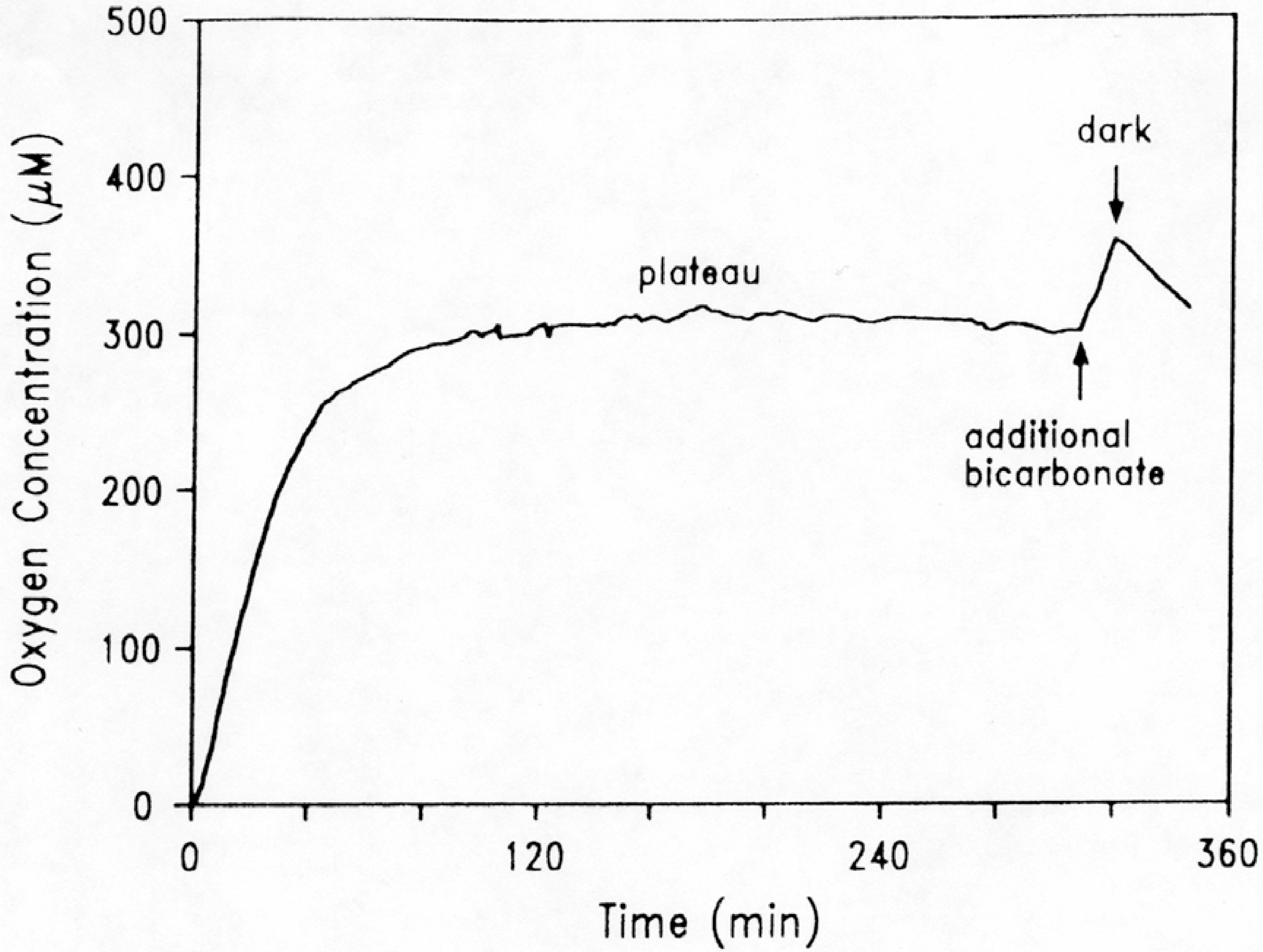


Photosynthesis

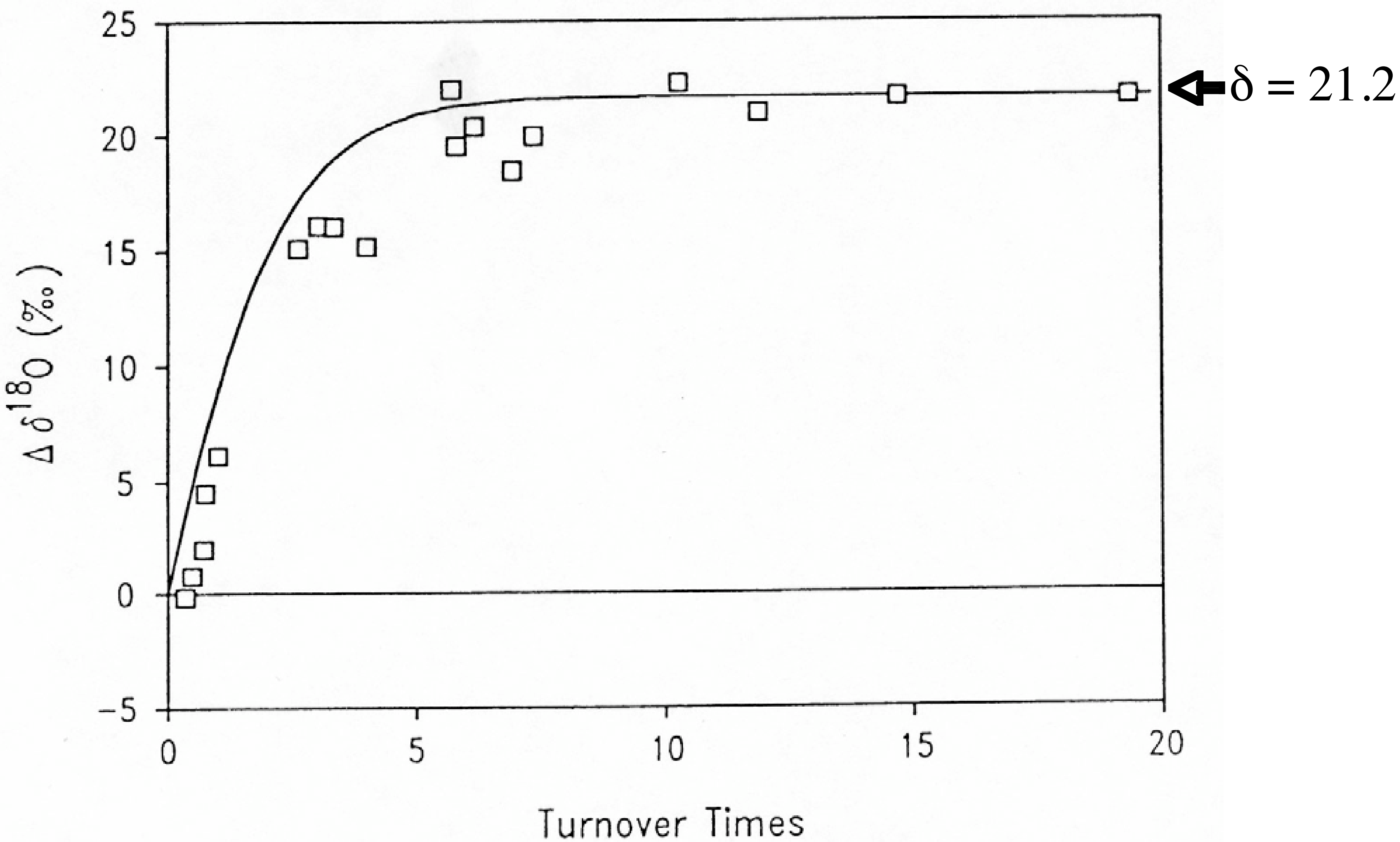


GUY, RD, ML FOGEL, and JA BERRY 1993 Photosynthetic fractionation of stable isotopes of oxygen and carbon. Plant Physiol. 101:37-47.

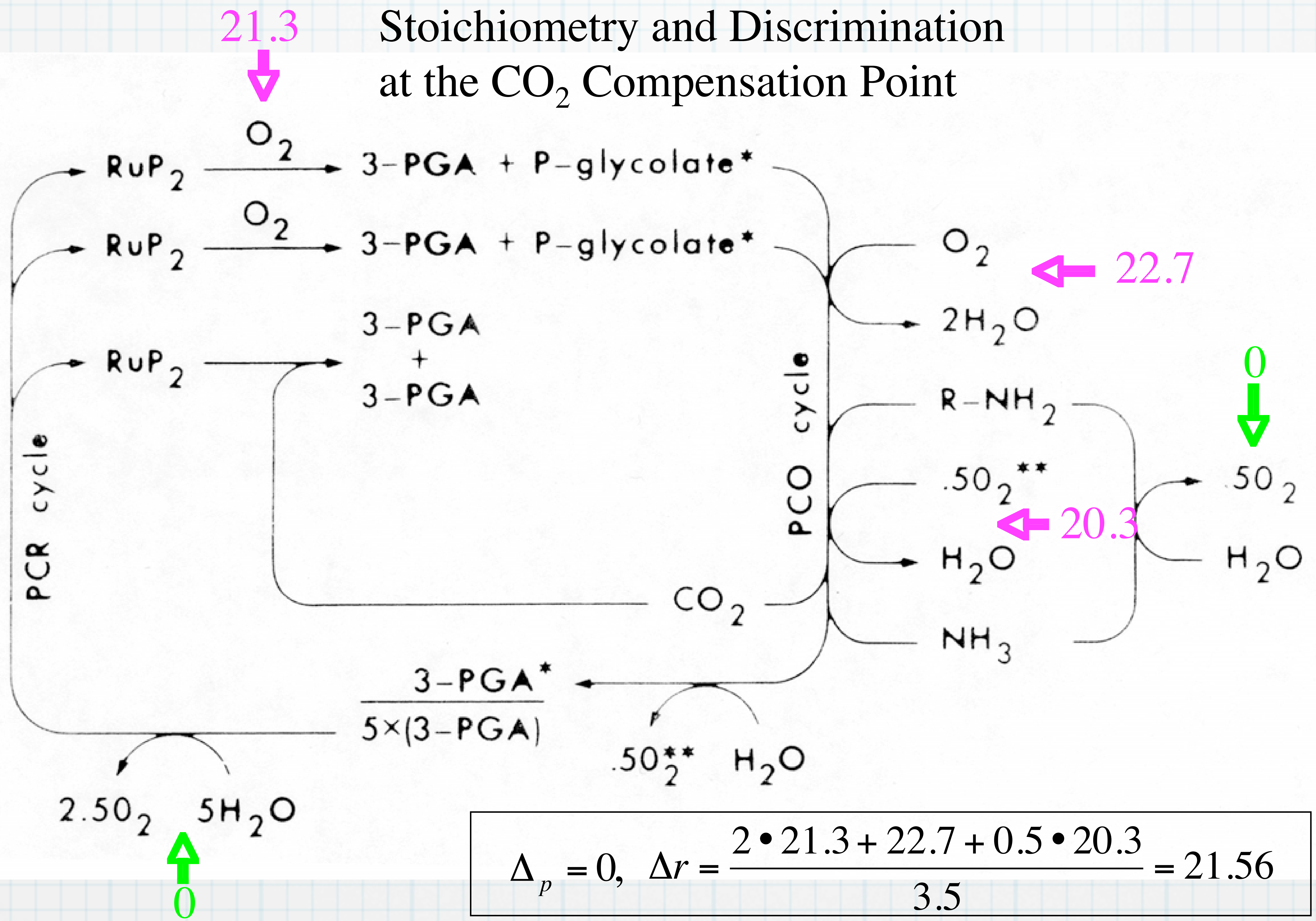




Oxygen Isotopes in the Microcosm

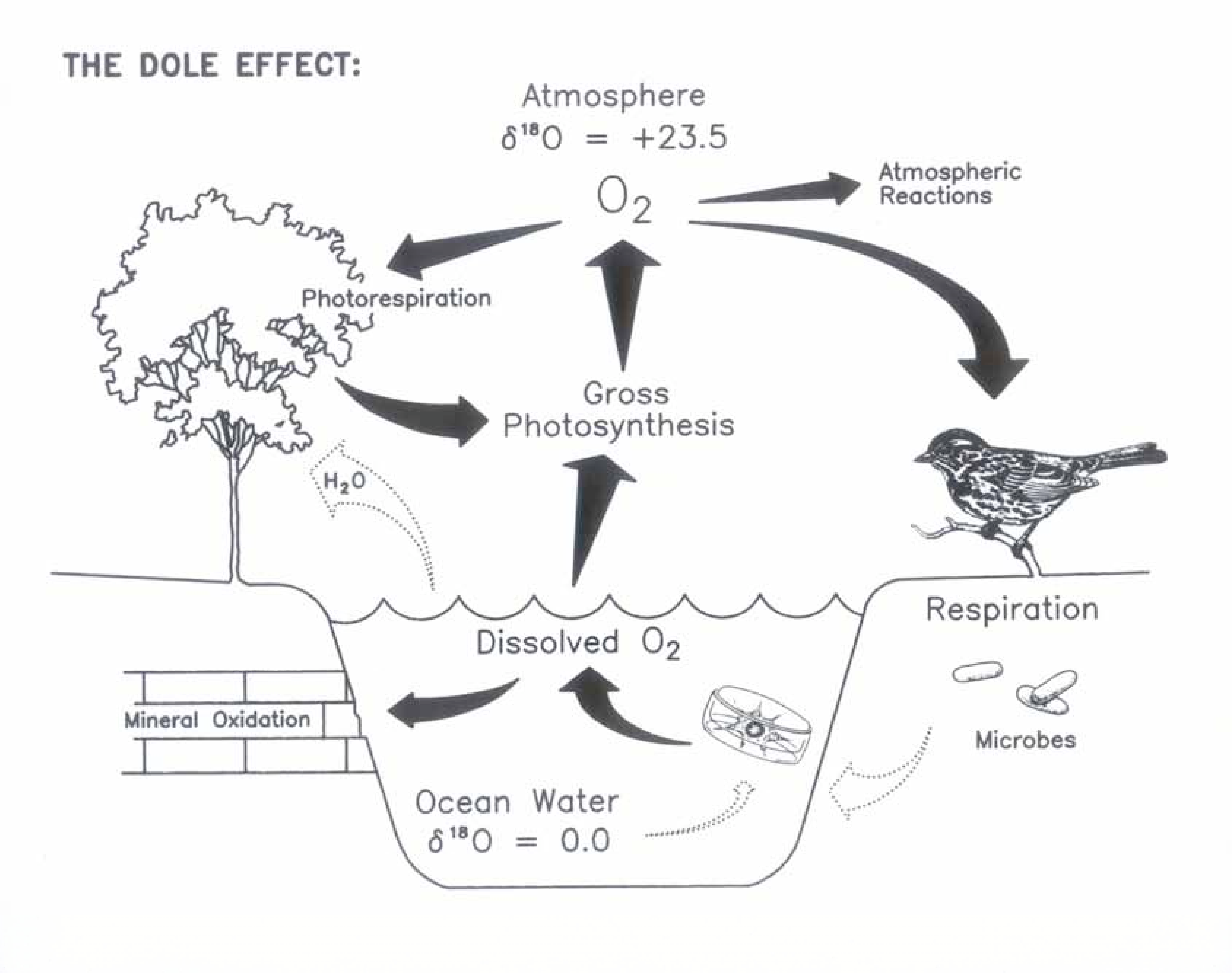


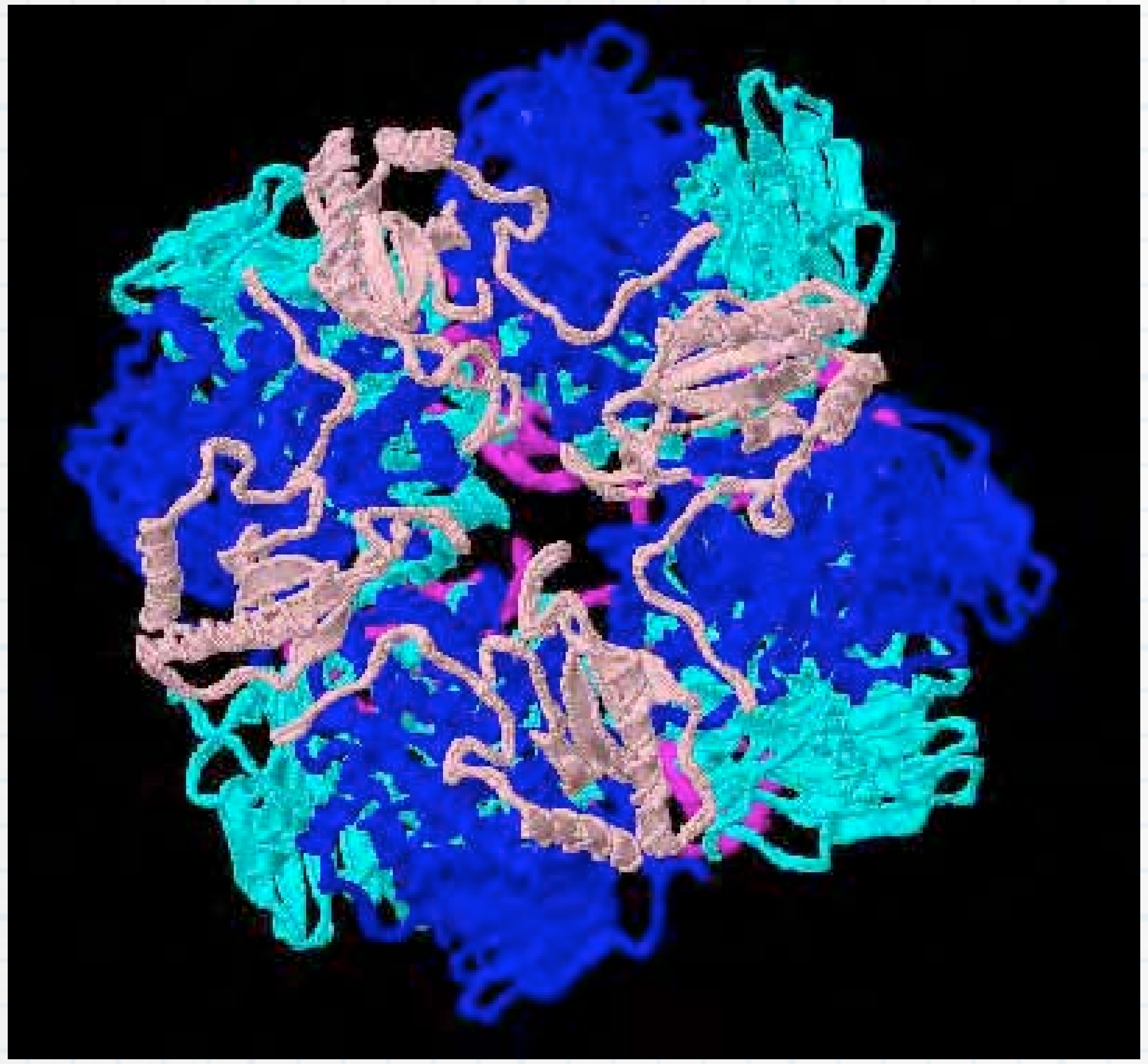
Stoichiometry and Discrimination at the CO_2 Compensation Point



$$\Delta_p = 0,\ \ \Delta r = \frac{2 \bullet 21.3 + 22.7 + 0.5 \bullet 20.3}{3.5} = 21.56$$

The isotopic steady-state achieved in a microcosm is very close to that achieved by the planet.





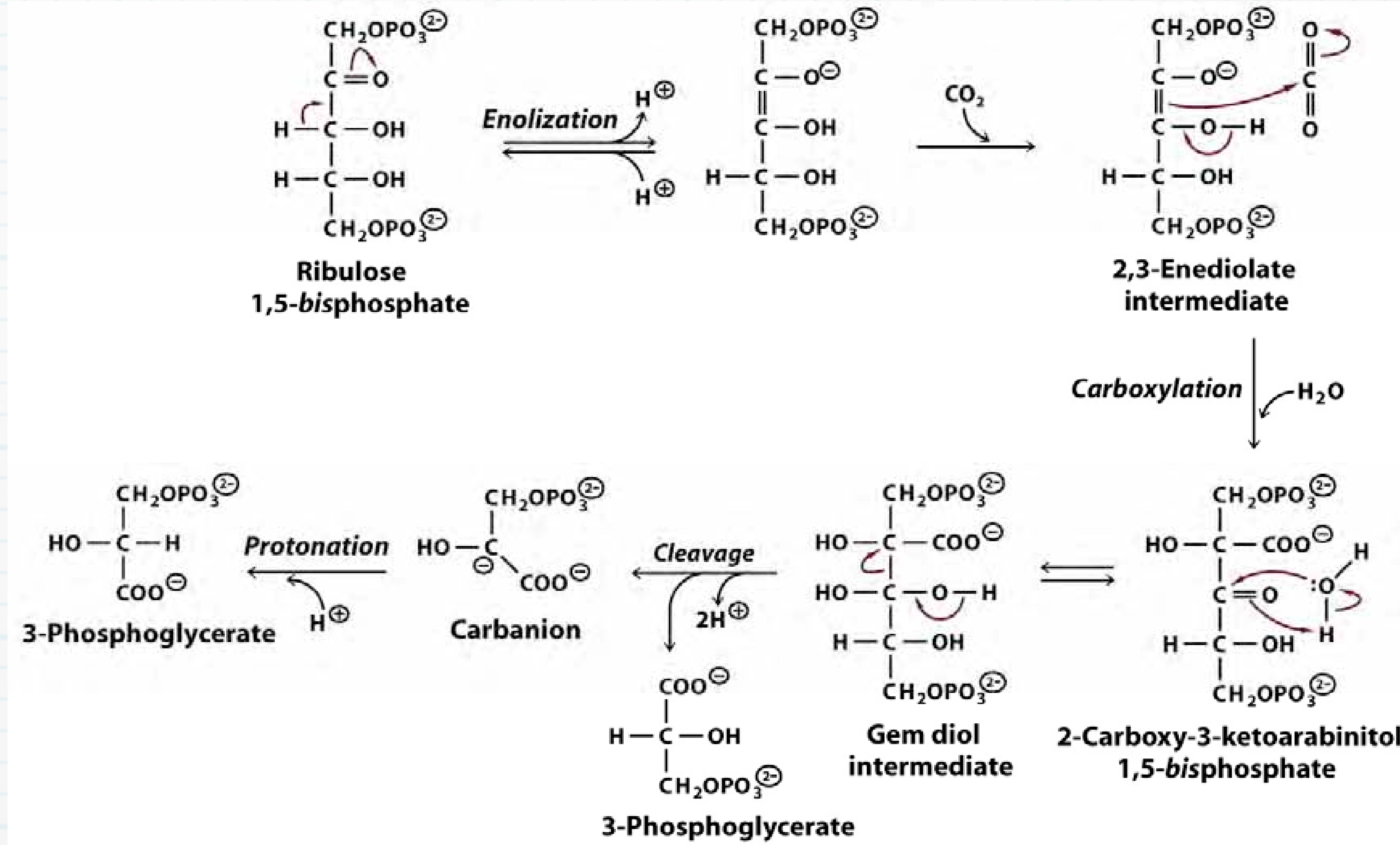
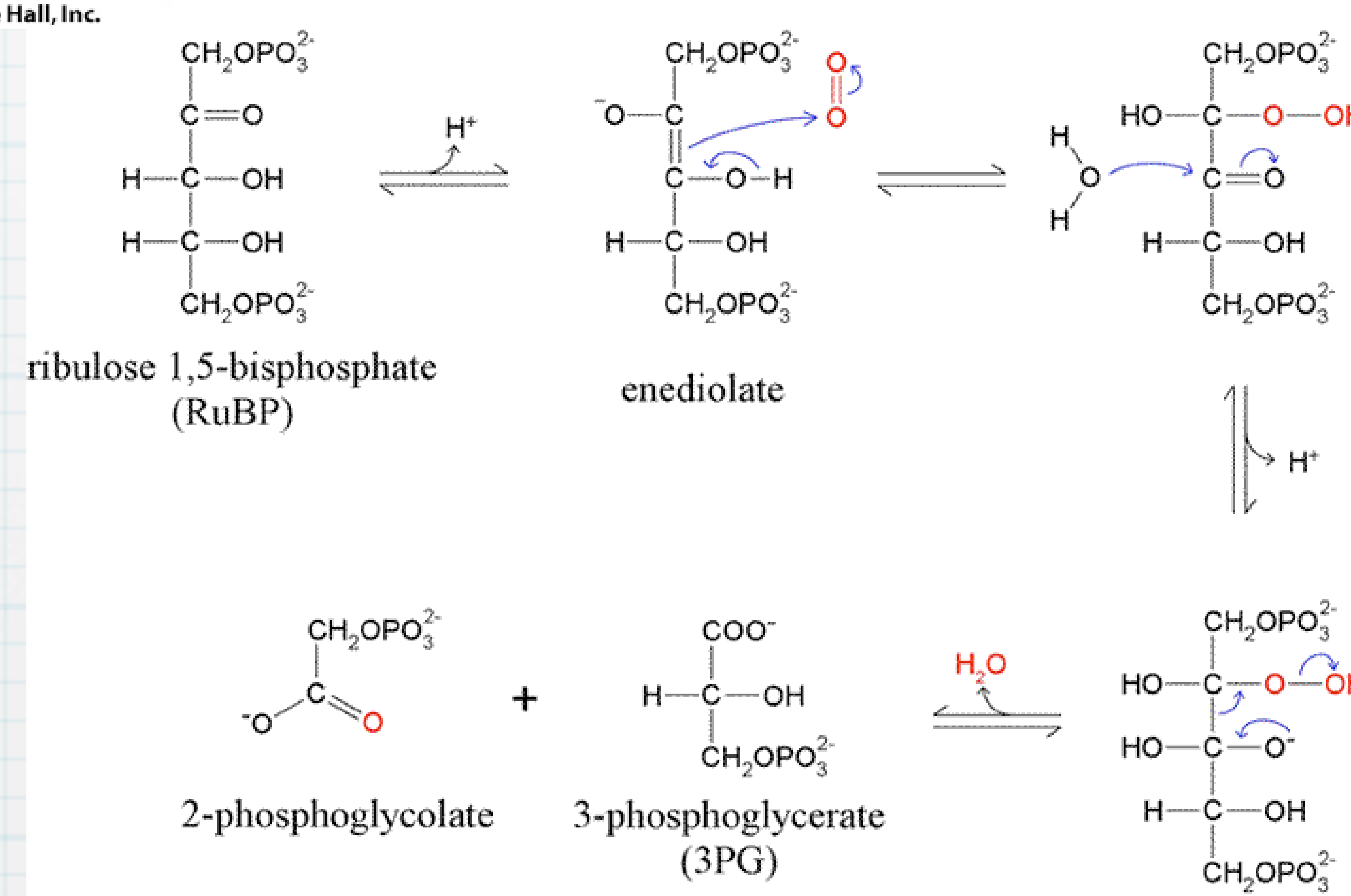
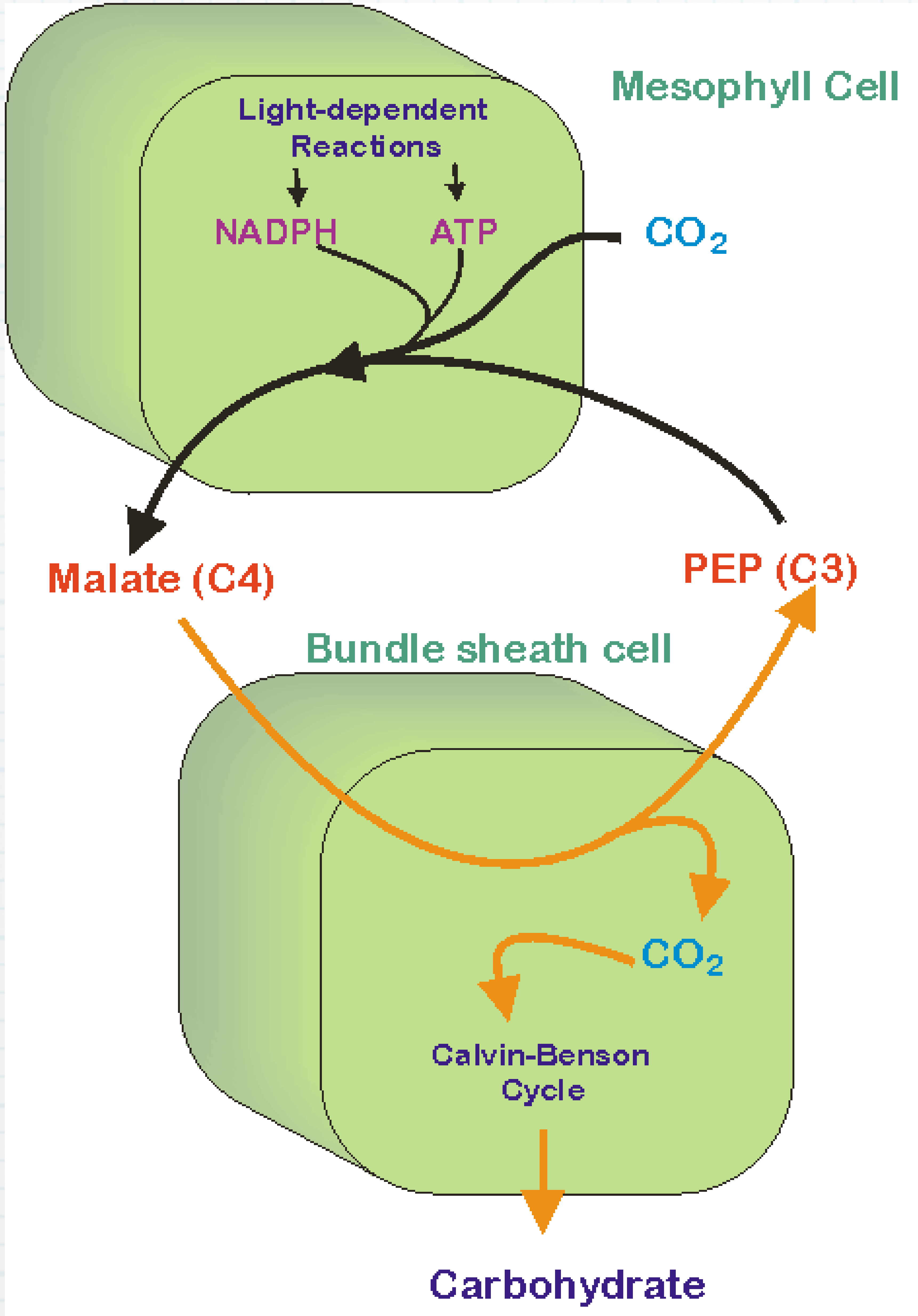


Figure 15-20 Principles of Biochemistry, 4/e

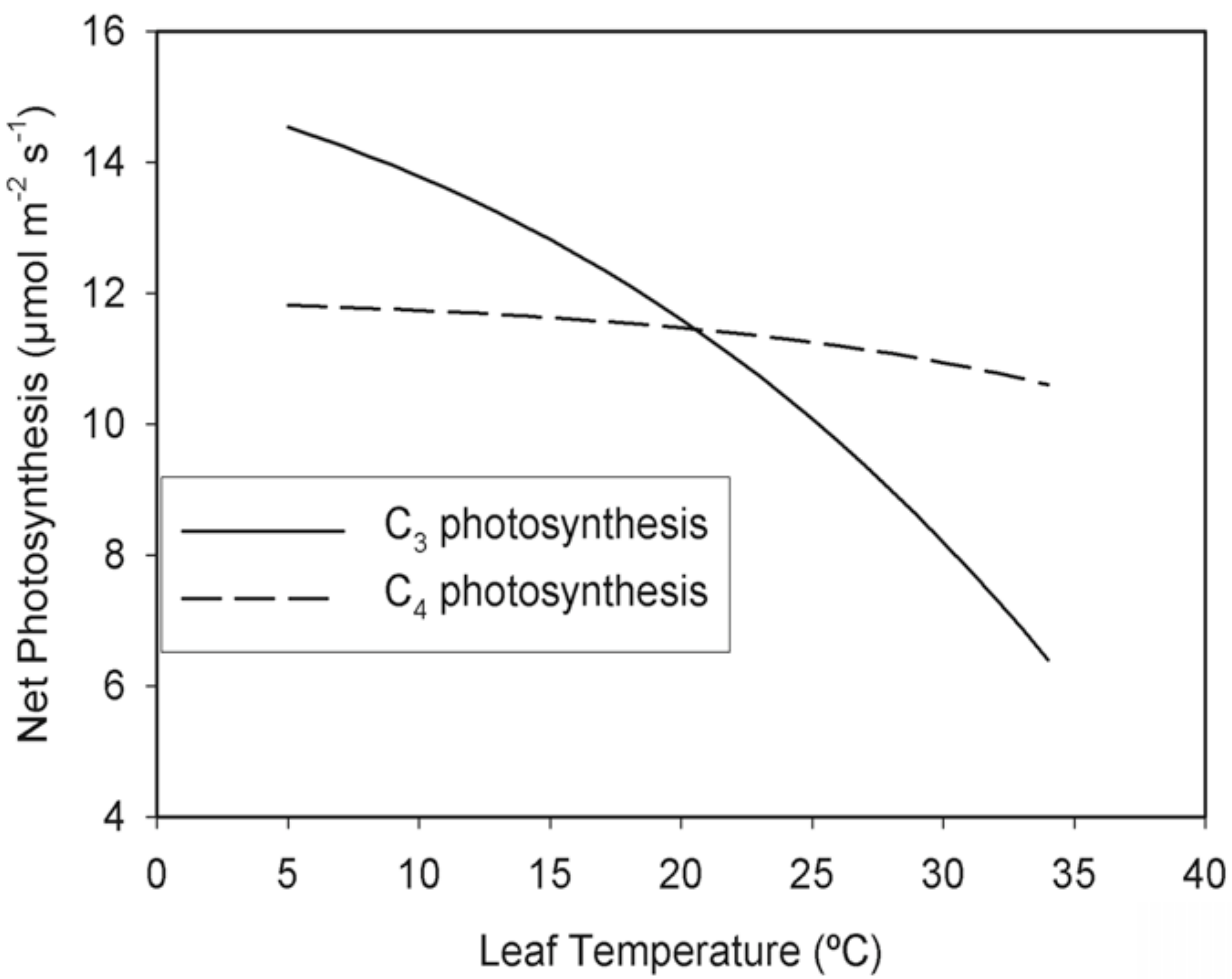


Rubisco

- fixes both CO_2 and O_2
- discriminates aginst ^{13}C containing CO_2
- kinetics, although complex, are well defined by biochemical experiments
- exerts control over CO_2 fixation by leaves
    - Maximum rate ∝ V_{max} Rubisco
    - RuBP supply in non-limiting
    - RuBP rate of supply is limiting

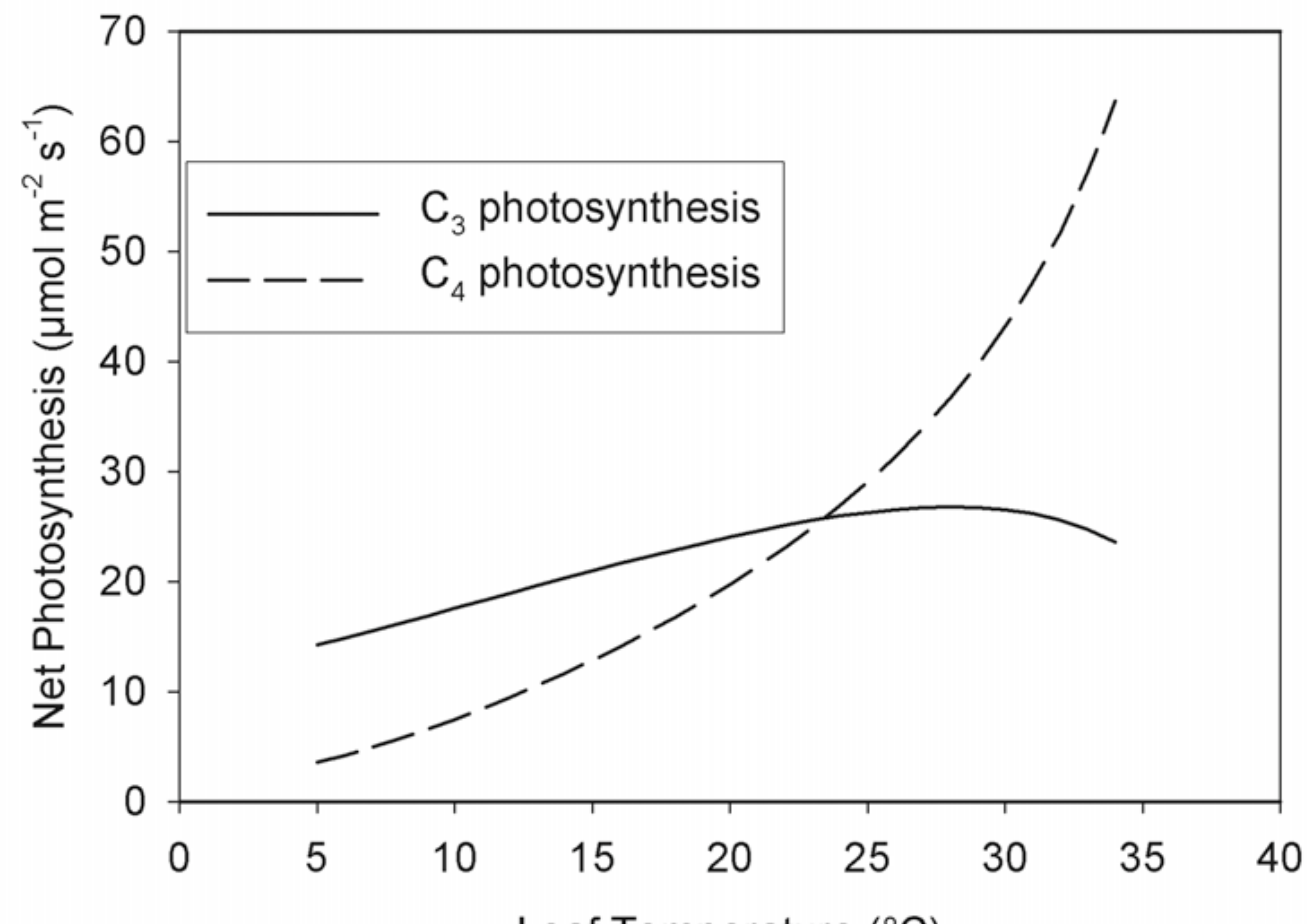


Mesophyll Cell
Light-dependent Reactions
NADPH
ATP
CO_2
Malate (C4)
PEP (C3)
Bundle sheath cell
CO_2
Calvin-Benson Cycle
Carbohydrate



Light-limited conditions

Light-saturated
(Rubisco-limited)
conditions

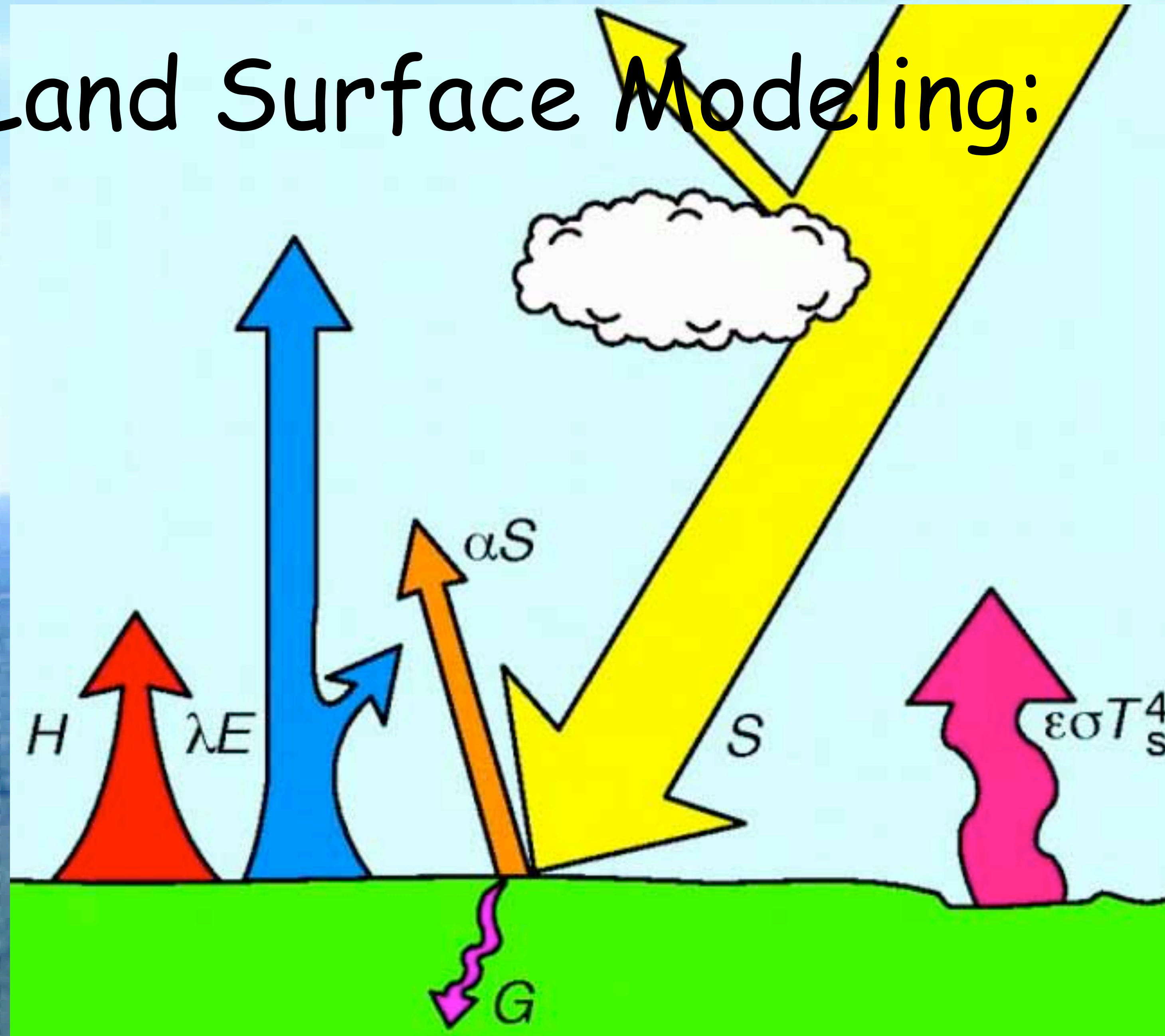


Ehleringer et al. 1997
Collatz et al. 1998
Still et al. 2003

Conculsions 1

- Earth is like a bag of enzymes in some respects.
- Stable isotopes are a good way to see this.
- The kinetics of Rubisco is one key to understanding the short-term dynamics of the biosphere.

Land Surface Modeling: The Link to Climate Modeling

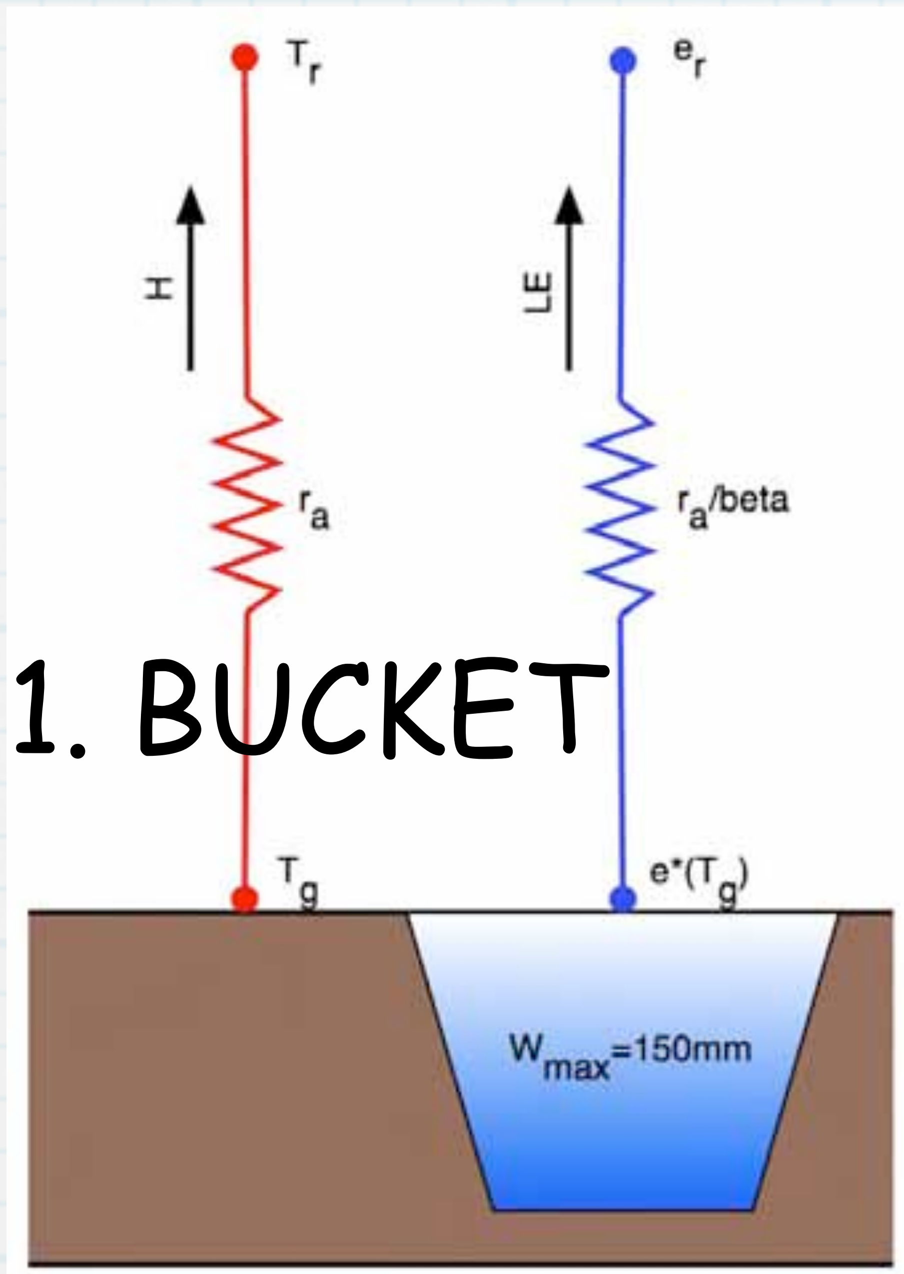


$$R_n = S(1-\alpha) + L_d - \epsilon\sigma T_s^4$$

$$R_n = H + \lambda E + G$$

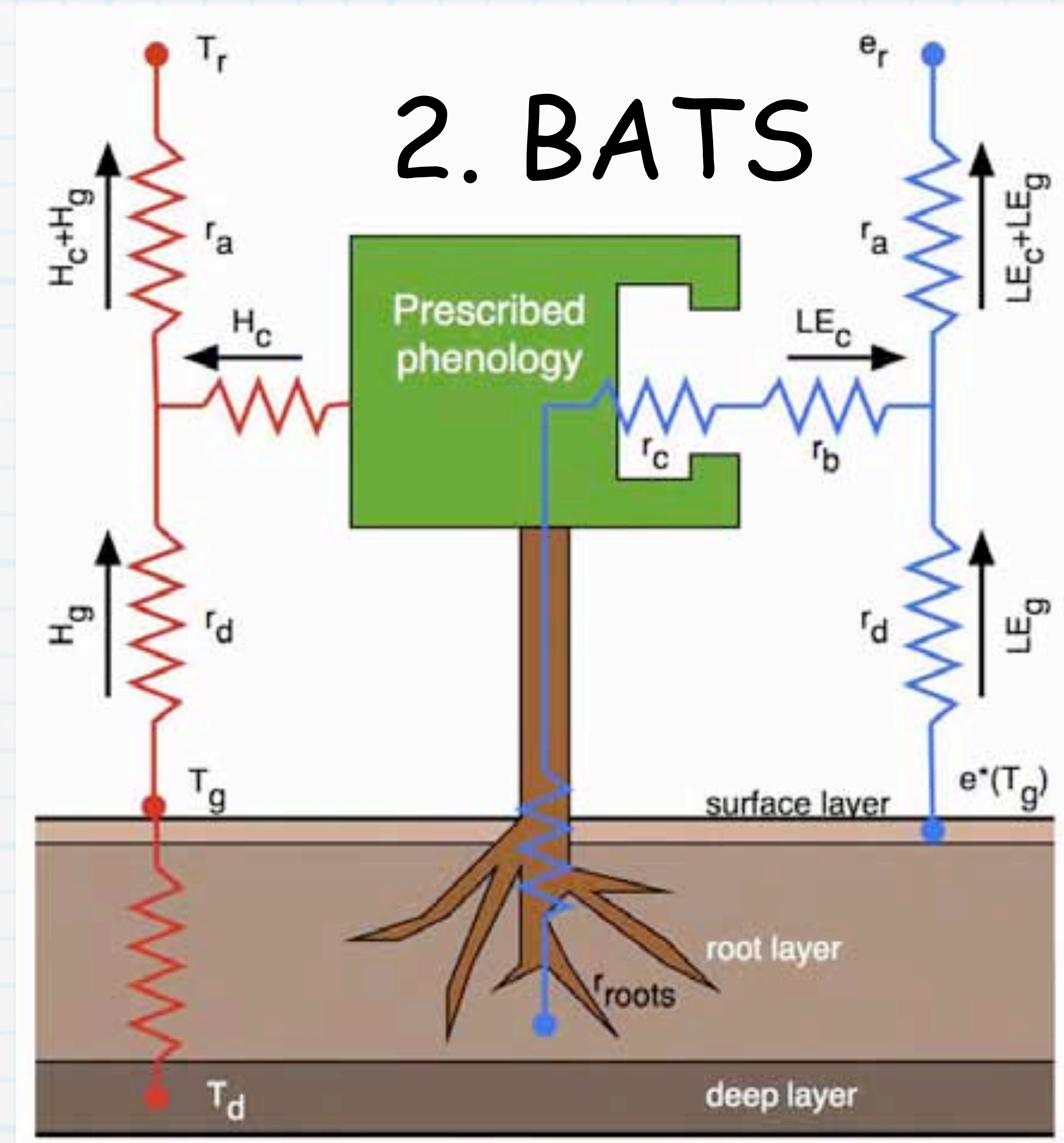
$$P = E + R + \Delta W$$

Mechanistic land surface models
3 Generations of LSM's (after Sellers et al. 1997)



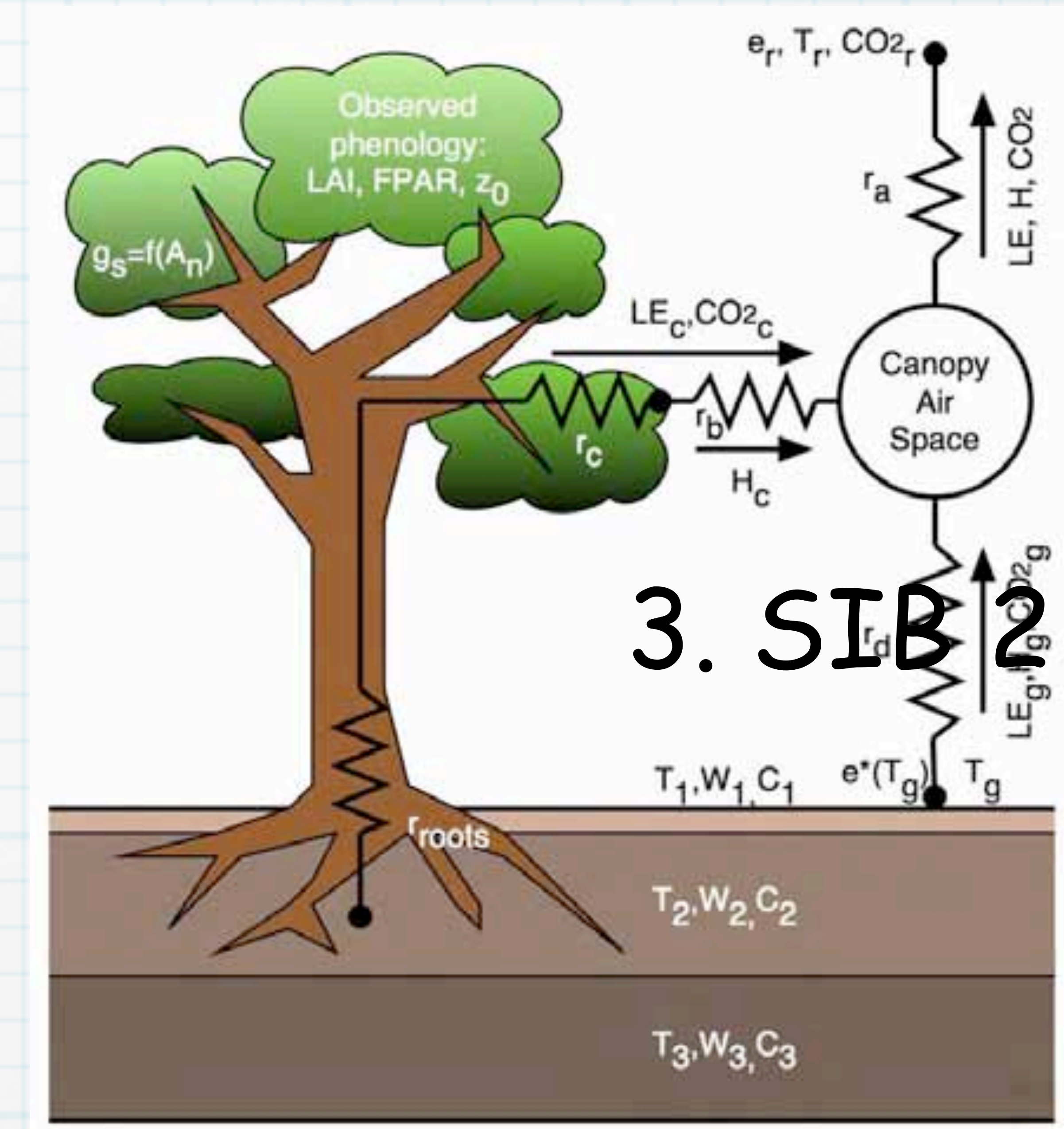
surface radiation balance

Manabe 1969



biophysical control of transpiration

Dickinson 1986
Jarvis 1976
Deardroff 1978



biochemical control of transpiration & carbon exchange

Sellers et al. 1996
Farquhar 1980 Collatz 1991

Solving for Stomatal Conductance (g).

The approach takes advantage of the observation that g is generally highly correlated with the rate of Photosynthesis (A_n), and that we have reasonably good models of Photosynthesis.

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

Where: h_s and c_s are the relative humidity and CO_2 concentrations at the leaf surface, respectively; m an b are regression coefficients, and:

$$A_n = f(\text{PAR},\text{Temp},\text{CO}_2,\text{Stress}, V_{max})$$

$$A \approx \min \begin{cases} J_E \\ J_C \\ J_S \end{cases}$$

C$_3$

$$J_E = a \times \alpha \times Q_p \frac{p_i - \Gamma_*}{p_i + 2\Gamma_*}$$

$$J_C = \frac{V_m (p_i - \Gamma_*)}{p_i + K_c(1 + [O_2]/K_o)}$$

$$J_S = V_m / 2$$

C$_4$

$$J_i = a \alpha_r f Q_p$$

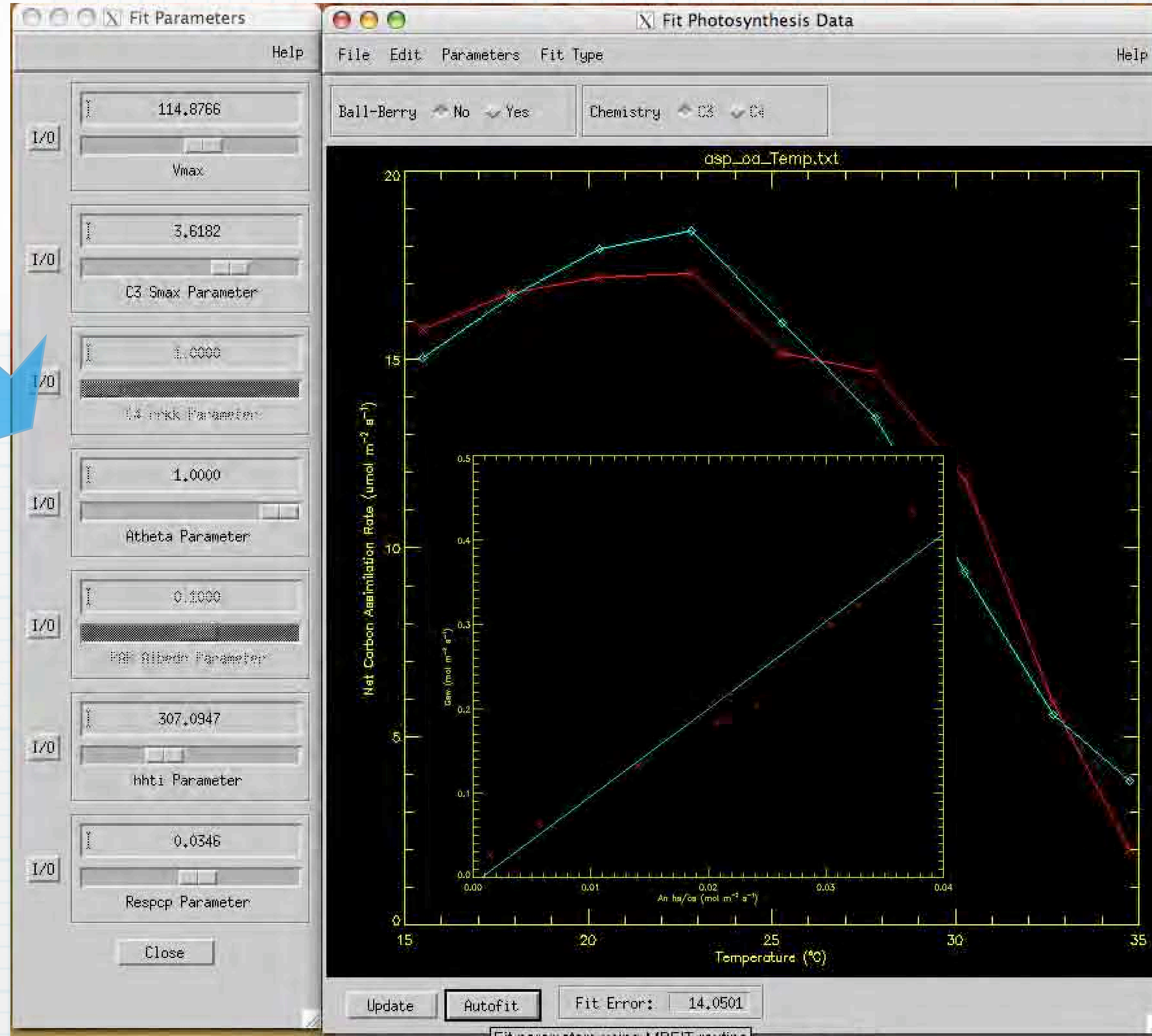
$$J_c = p_i \left(k_p - \frac{L}{p_i} \right) / P$$

$$J_e = V_{max}$$

$$\theta J_P^2 - J_P (J_E + J_C) + J_E J_C = 0$$

and

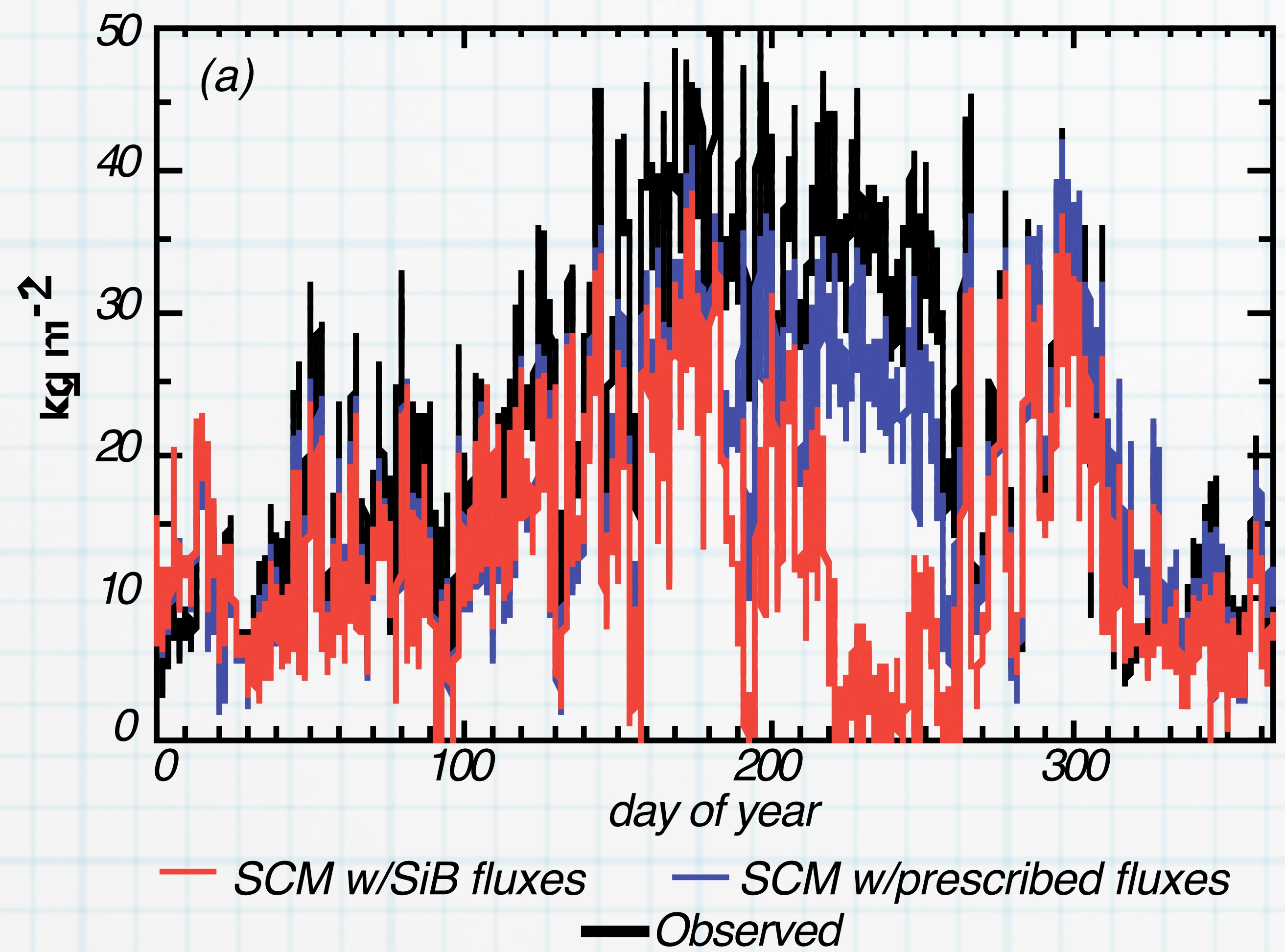
$$\beta A^2 - A (J_P + J_S) + J_P J_S = 0$$

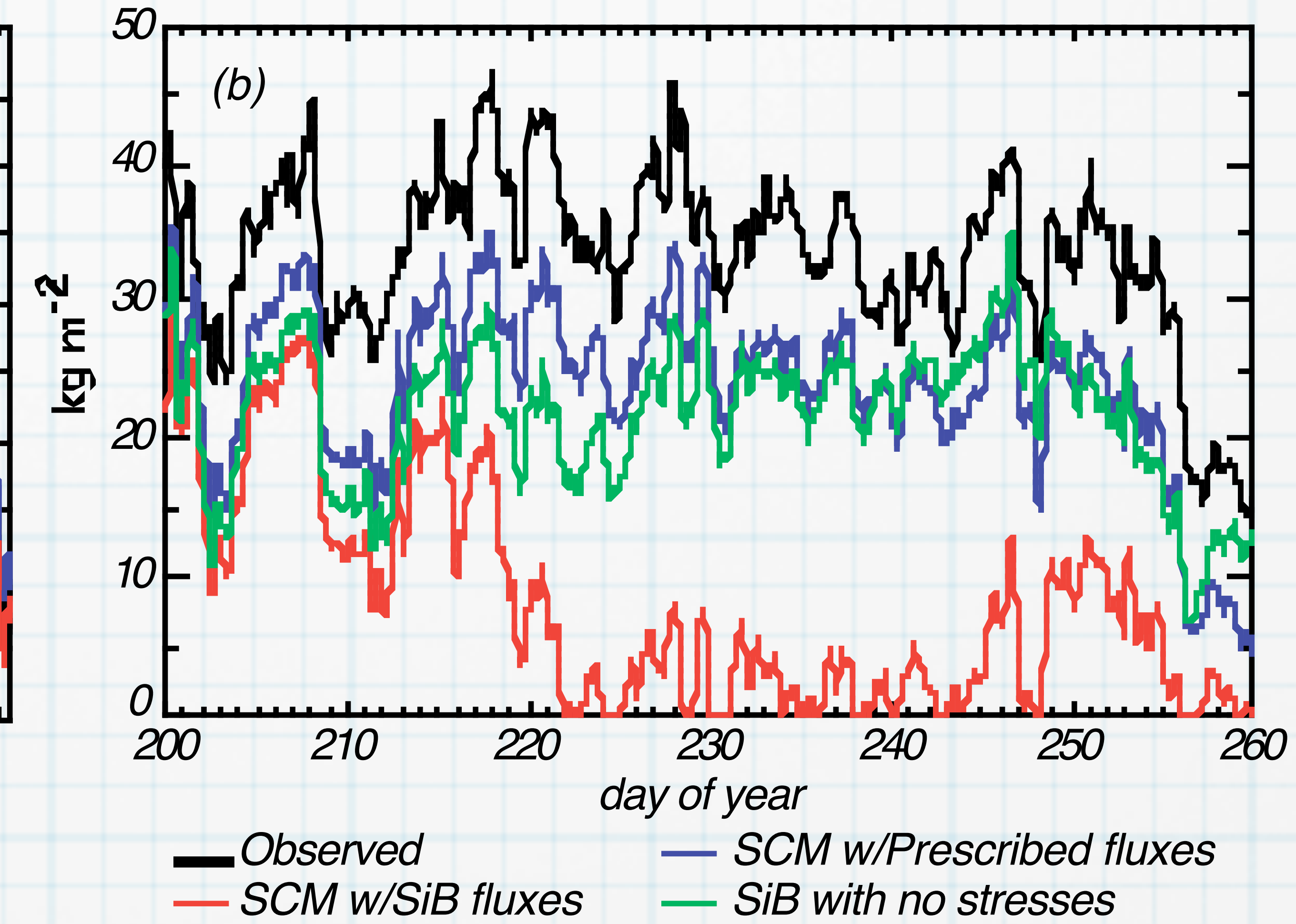

Fit Parameters
Help
I/O
114.8766
Vmax
3.6182
C3 Smax Parameter
1.0000
Atheta Parameter
0.1000
307.0947
hhti Parameter
0.0346
Respcp Parameter
Close
Fit Photosynthesis Data
File Edit Parameters Fit Type
Help
Ball-Berry No Yes
Chemistry C3 C4
asp_oa_Temp.txt
Net Carbon Assimilation Rate (µmol m^{-2} s^{-1})
Temperature (°C)
An hs/cs (mol m^{-2} s^{-1})
Update
Autofit
Fit Error: 14.0501
Fit parameters using MPFIT routine

Pathological Feedback involving Stomata

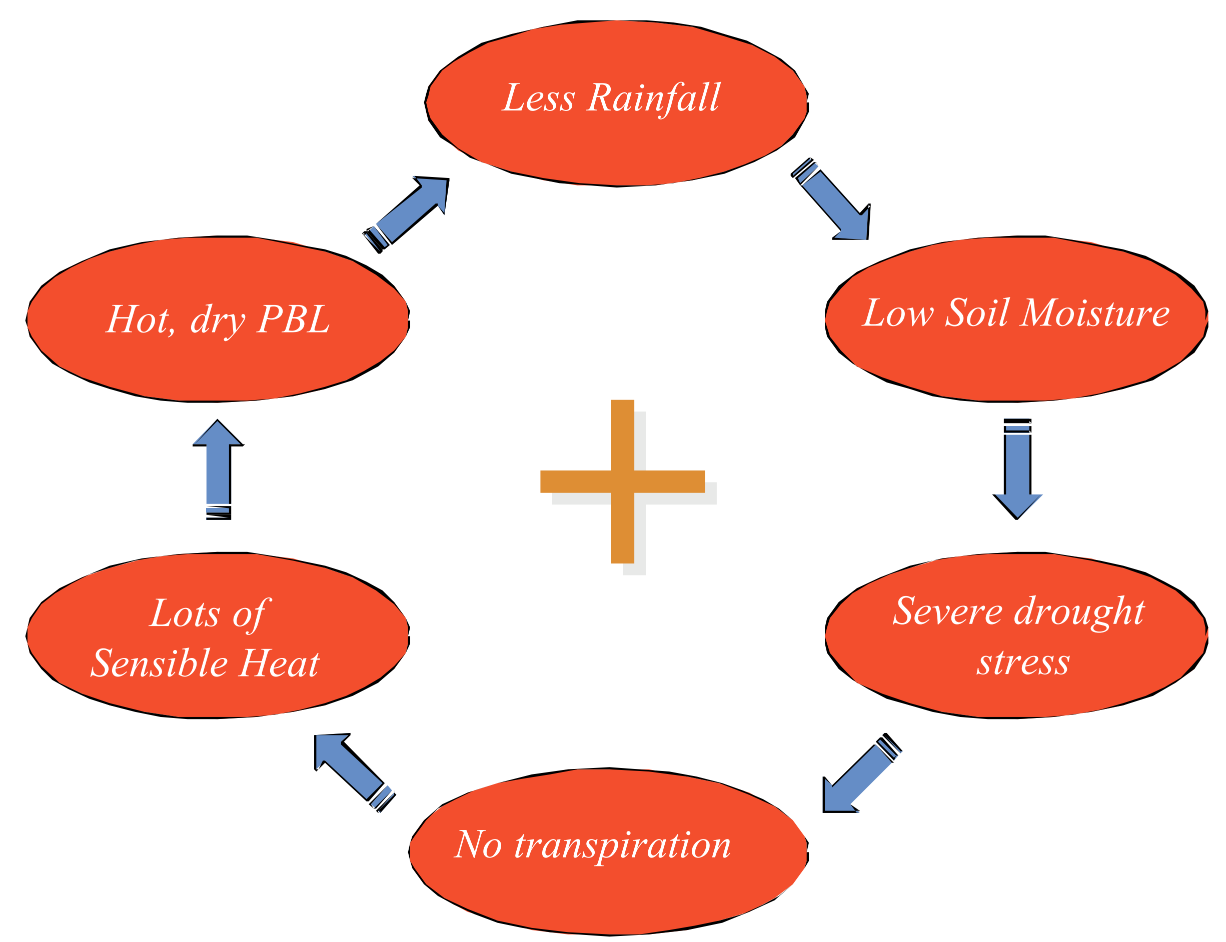
A single column simulation at the ARM region of Kansas/Oklahoma

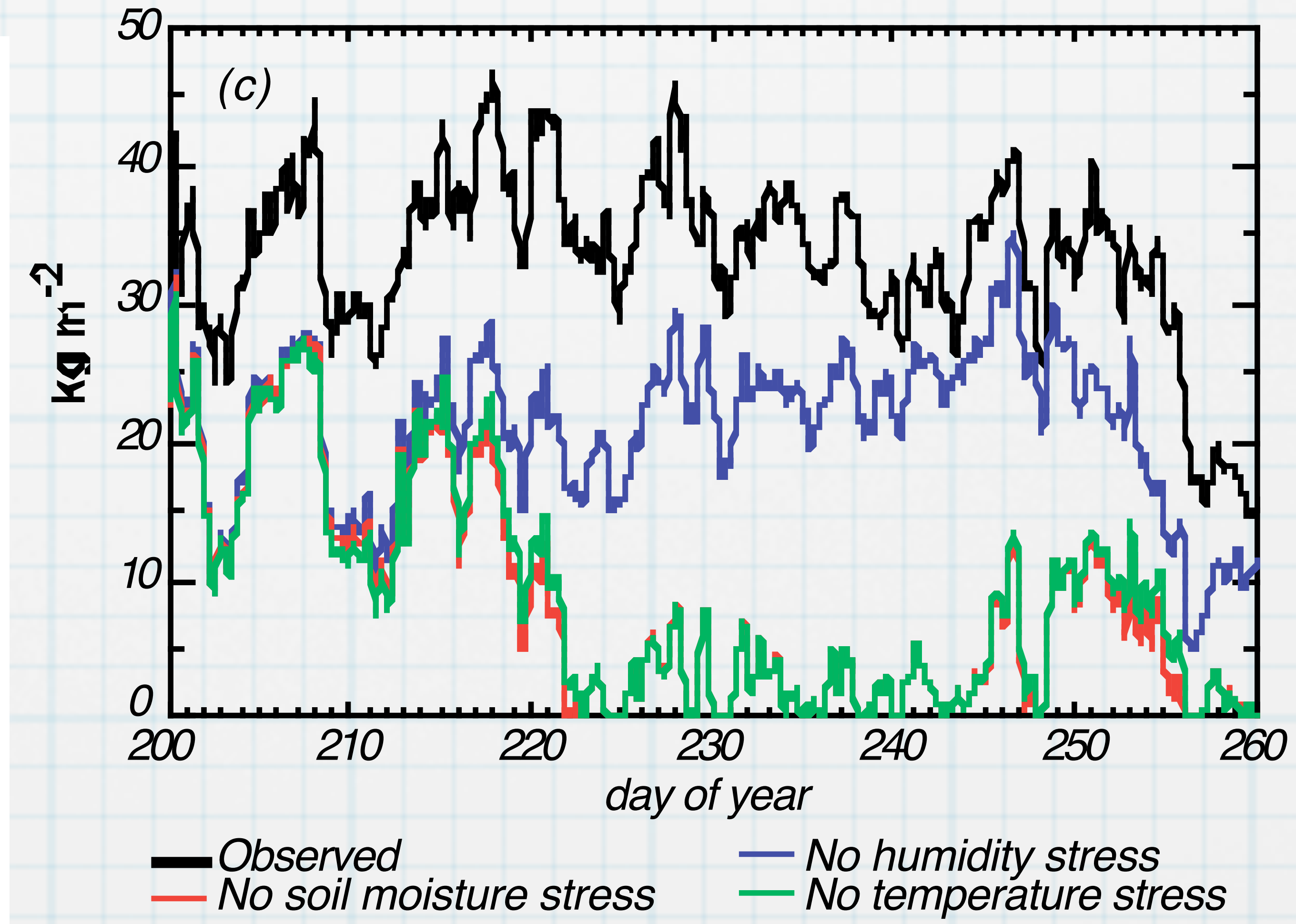
Precipitable Water -- ARM 2000





Precipitation and Ecosystem Stress: A Positive Feedback Loop





(S. Denning, D. Randall and A. Philpott)

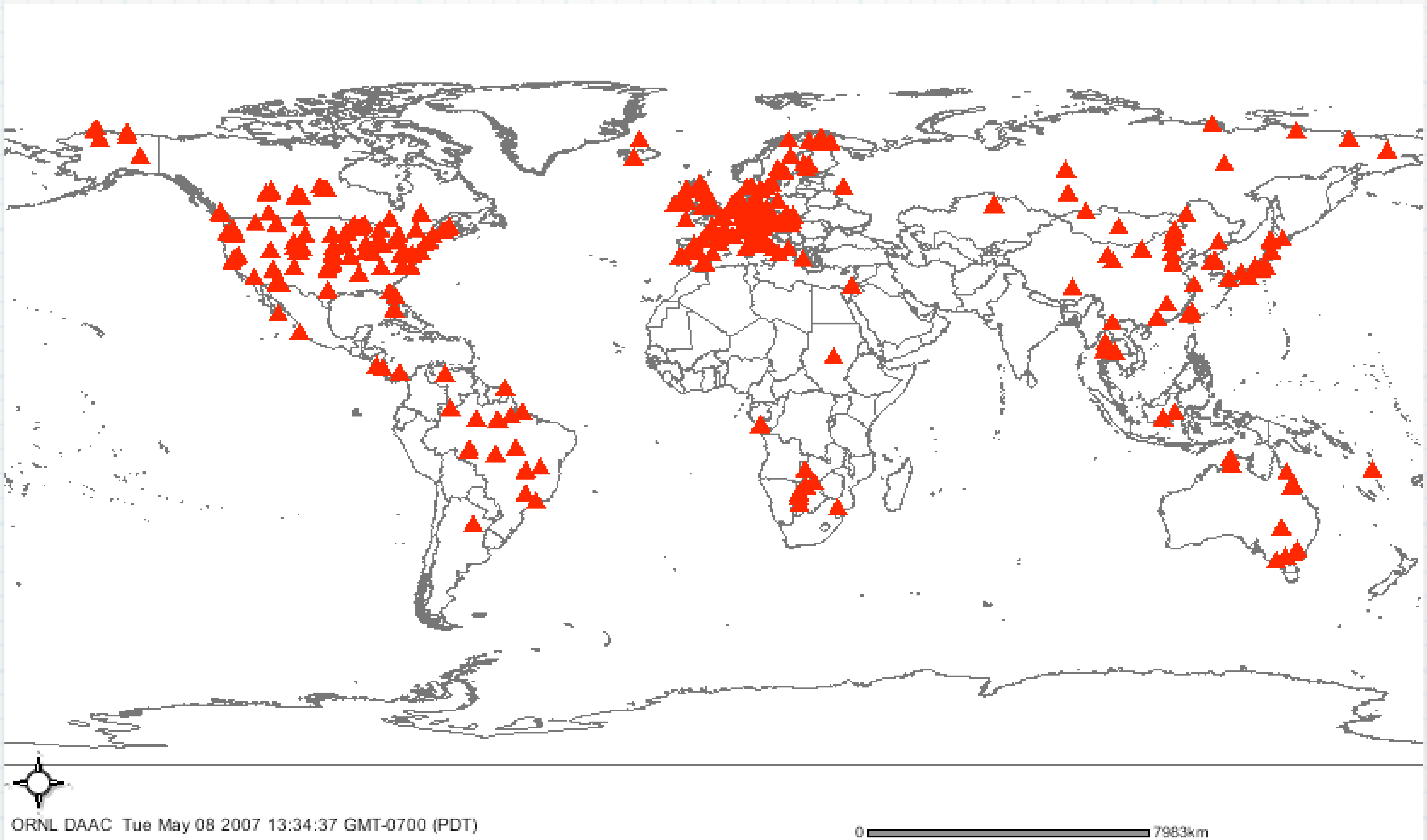
Conclusions II:

- The land surface model is largely based on leaf-scale studies.
- It is generally applied at scales (~10^4 km^2), while validation studies are limited to a scale of a few hectares.
- Sometimes we see pathalogical feedbacks.
- Needs:
  - resolve intermediate scales
  - resolve the component fluxes (respiration and photosynthesis.

Testing the Models

Meteorological approaches are widely used to study the energy and carbon balance of ecosystems. (located in a South African savanna)

Flux Sites Around the World



Testing the models

Eddy Covariance

Is considered a "direct measure" of fluxes. It requires few assumptions and can be used within canopies, above forests, or mounted on a jet.

Gas Analyzer (open path) 3D sonic anemometer
both measure at 5-20 Hz

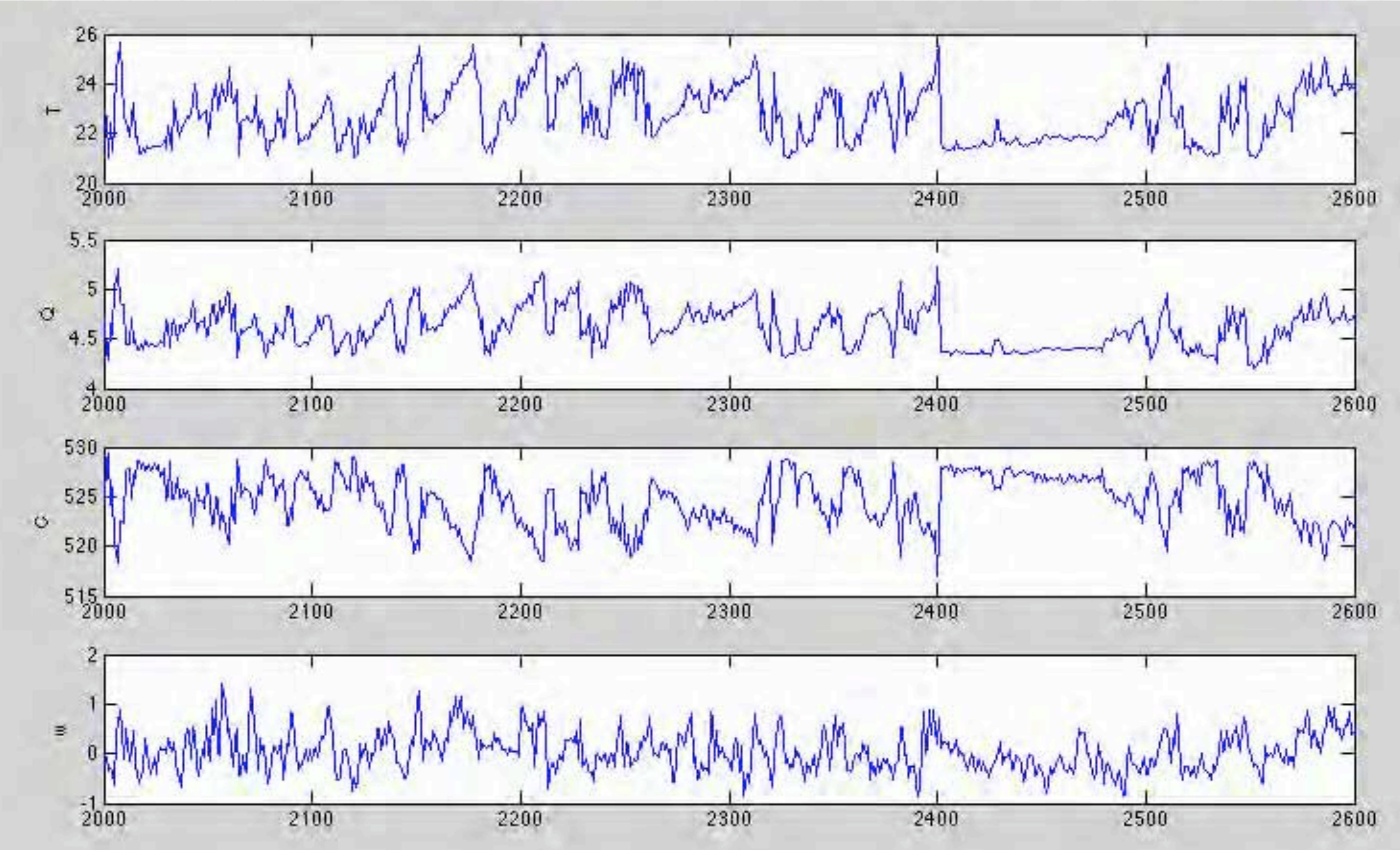
10 Hz. Data

Temperature

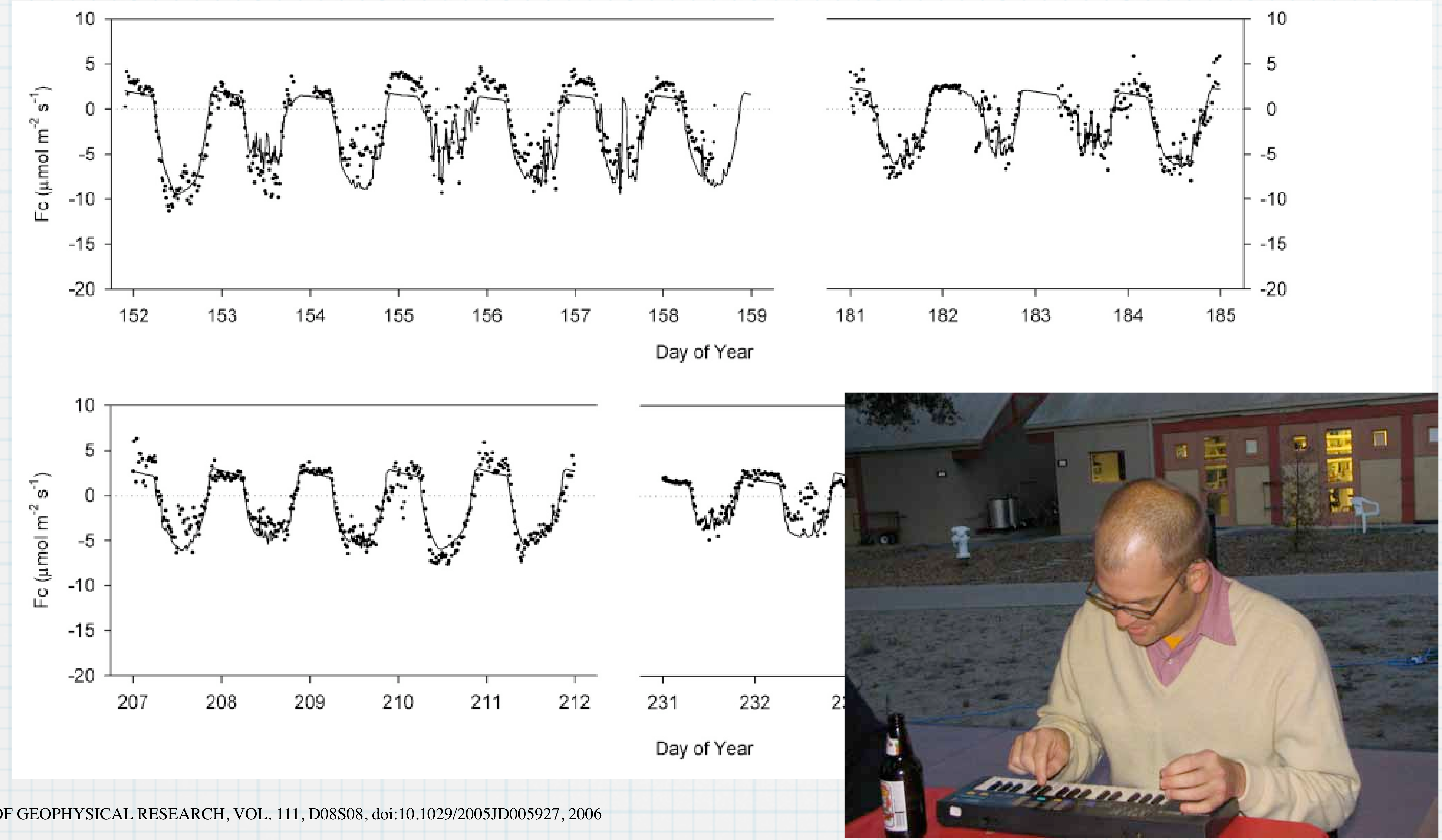
Water Vapor

CO_2

Vertical wind speed



CO_2 fluxes fit by data assimilation



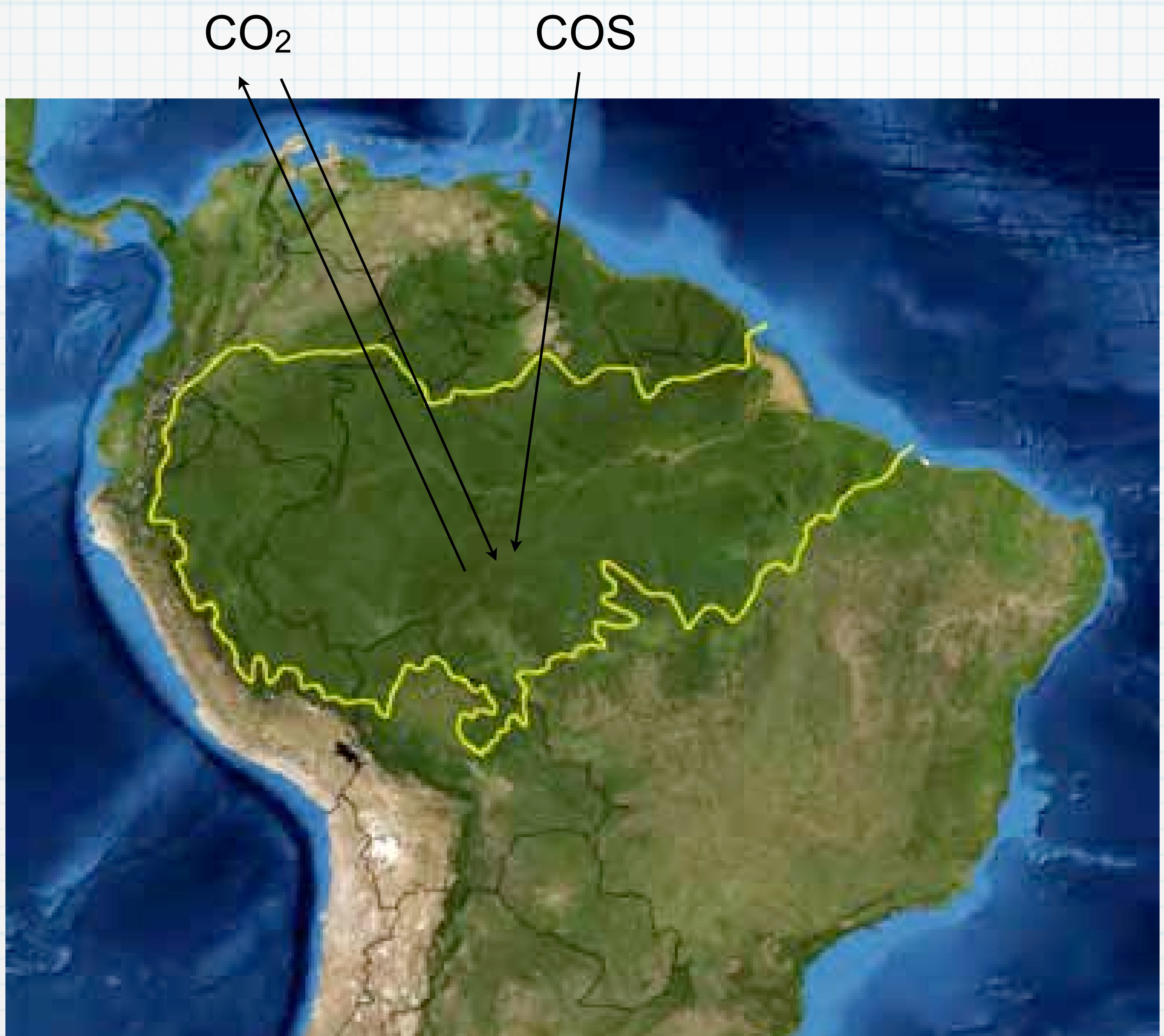
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, D08S08, doi:10.1029/2005JD005927, 2006

Adam Wolf

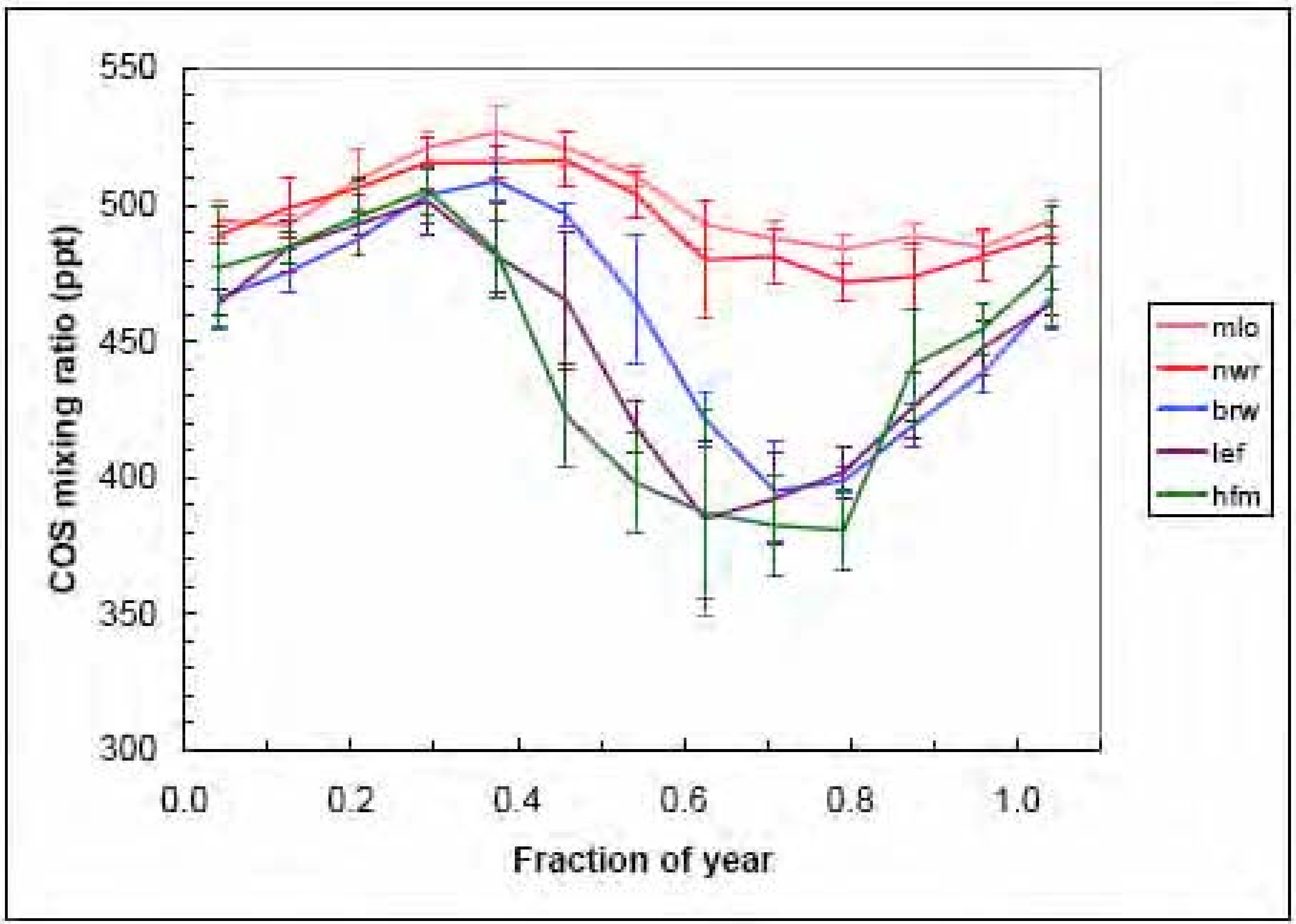
Conclusions III

* Many measurements on-going
* The major focus is carbon, also measure sensible heat, latent heat and mometum transfer.
* Huge jump in scale from the primary leaf measurements - 1 leaf to millions of leaves.
* Largest scale at which we can separate photosynthesis and respiration.
* noisy measurements limit validation & calibration

Carbonyl sulfide (COS): a new tracer for photosynthesis at continental scales.

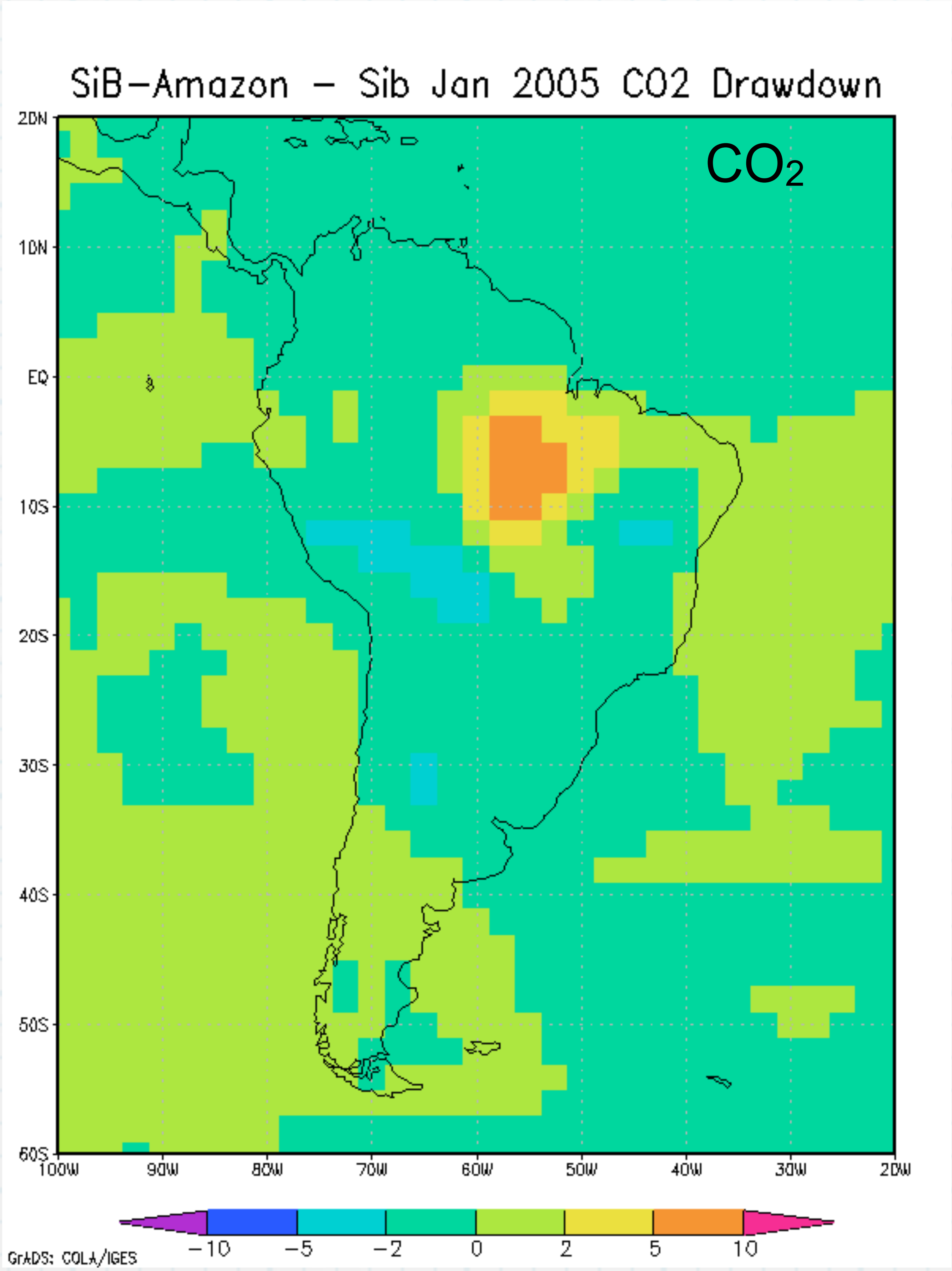


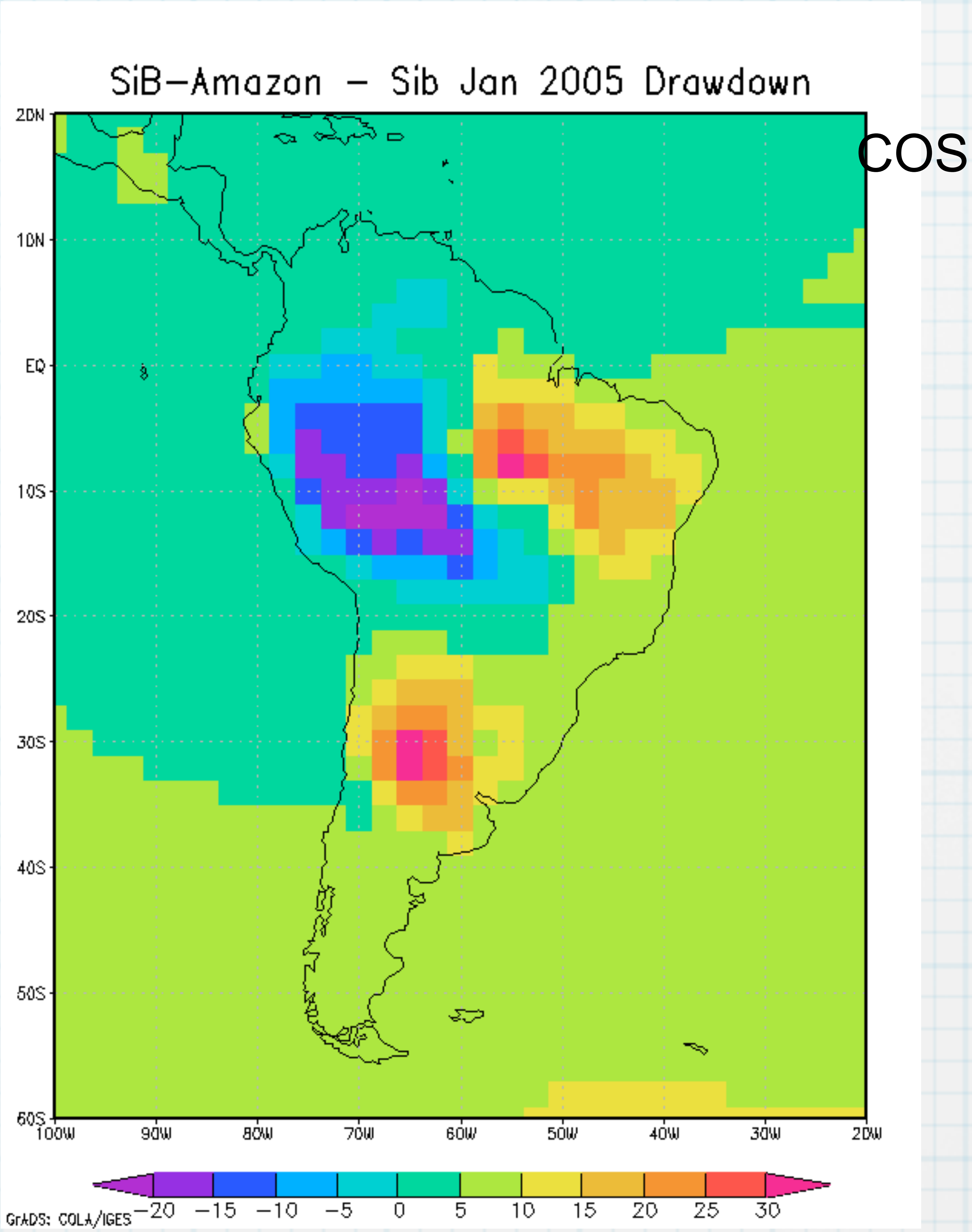
Seasonal cycles of COS



(Steve Montzka)

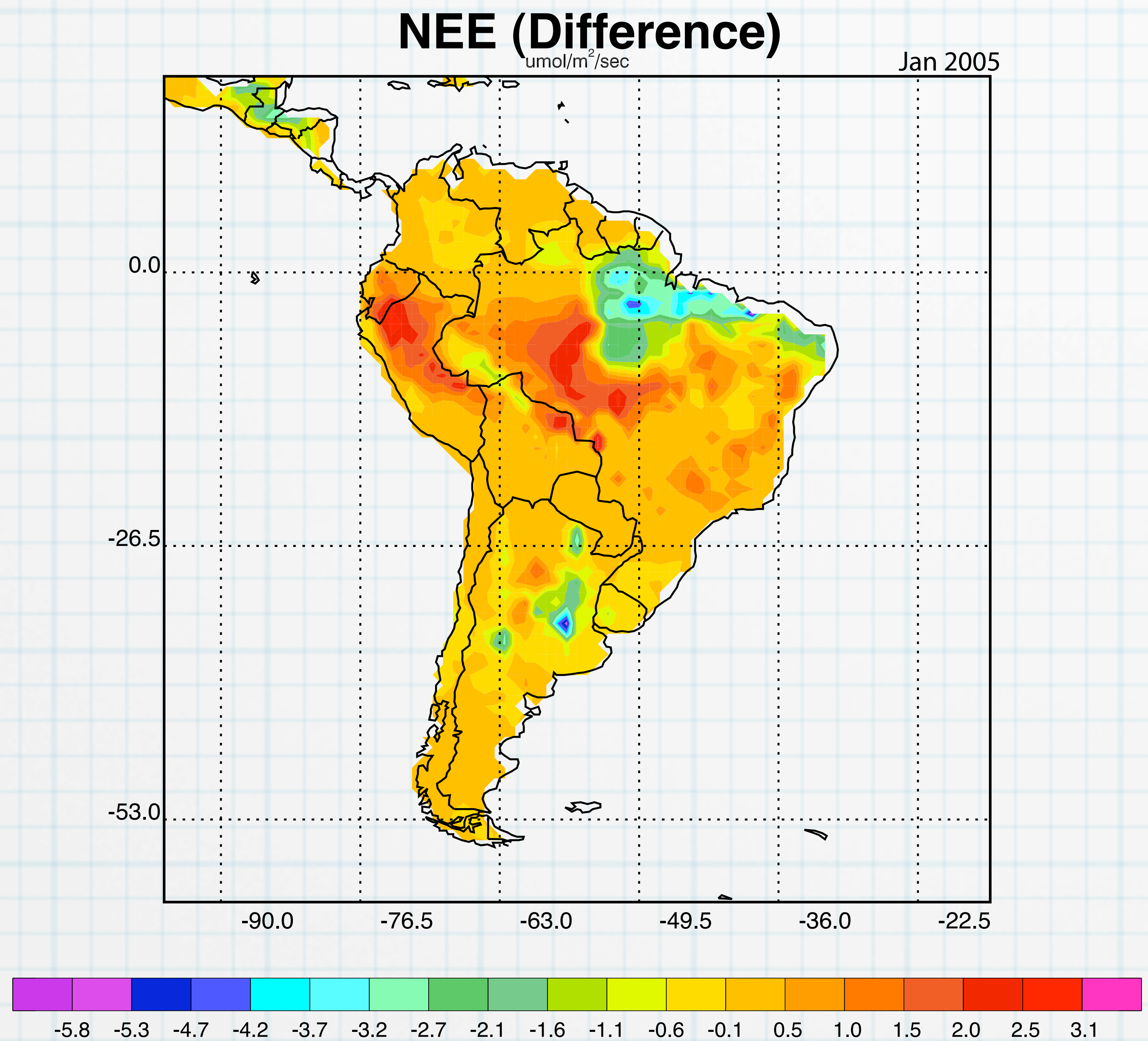
Simulated CO_2 and COS over South America (difference between two surface models in the ABL)

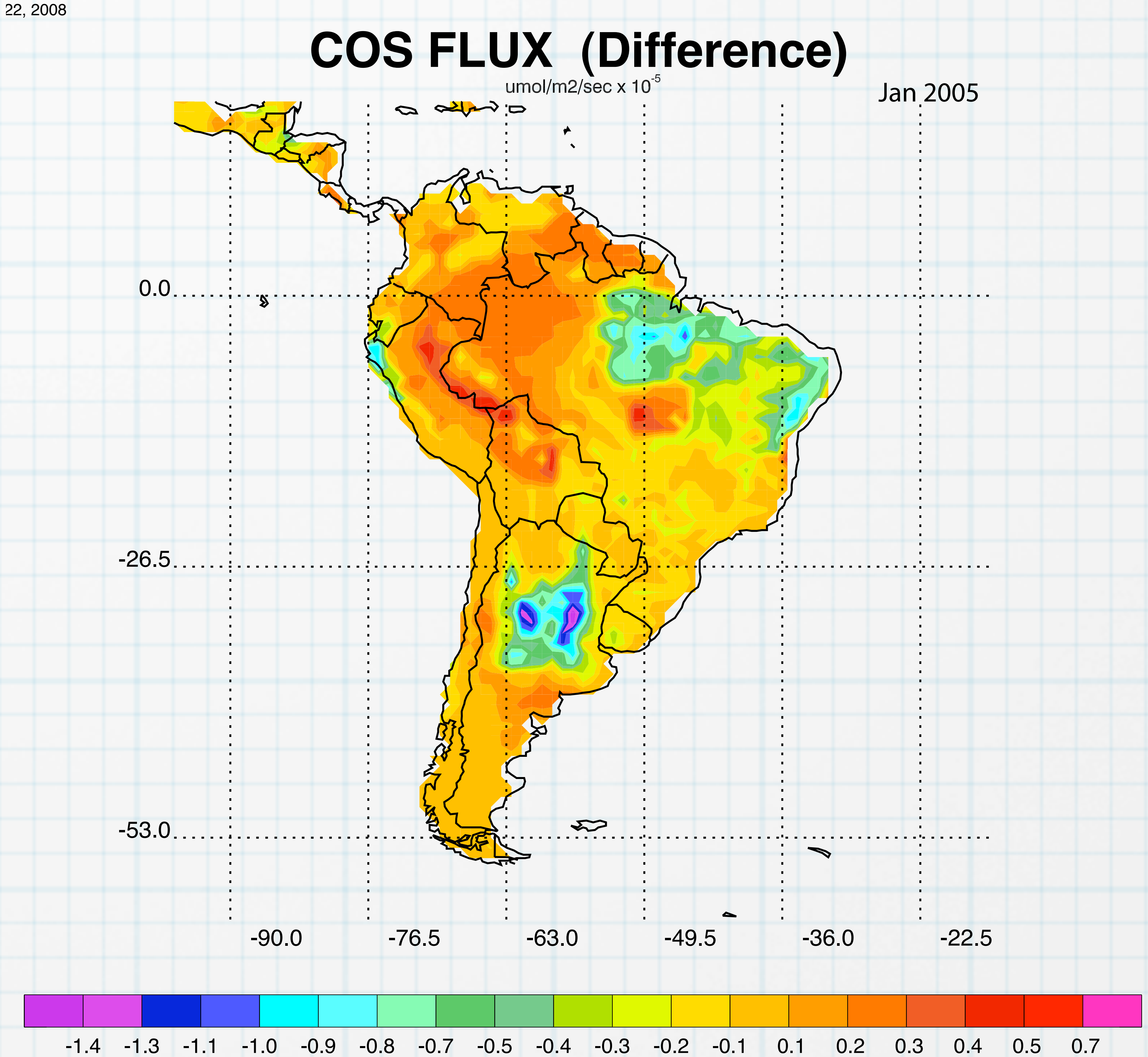




Difference in the simulated surface fluxes

22, 2008



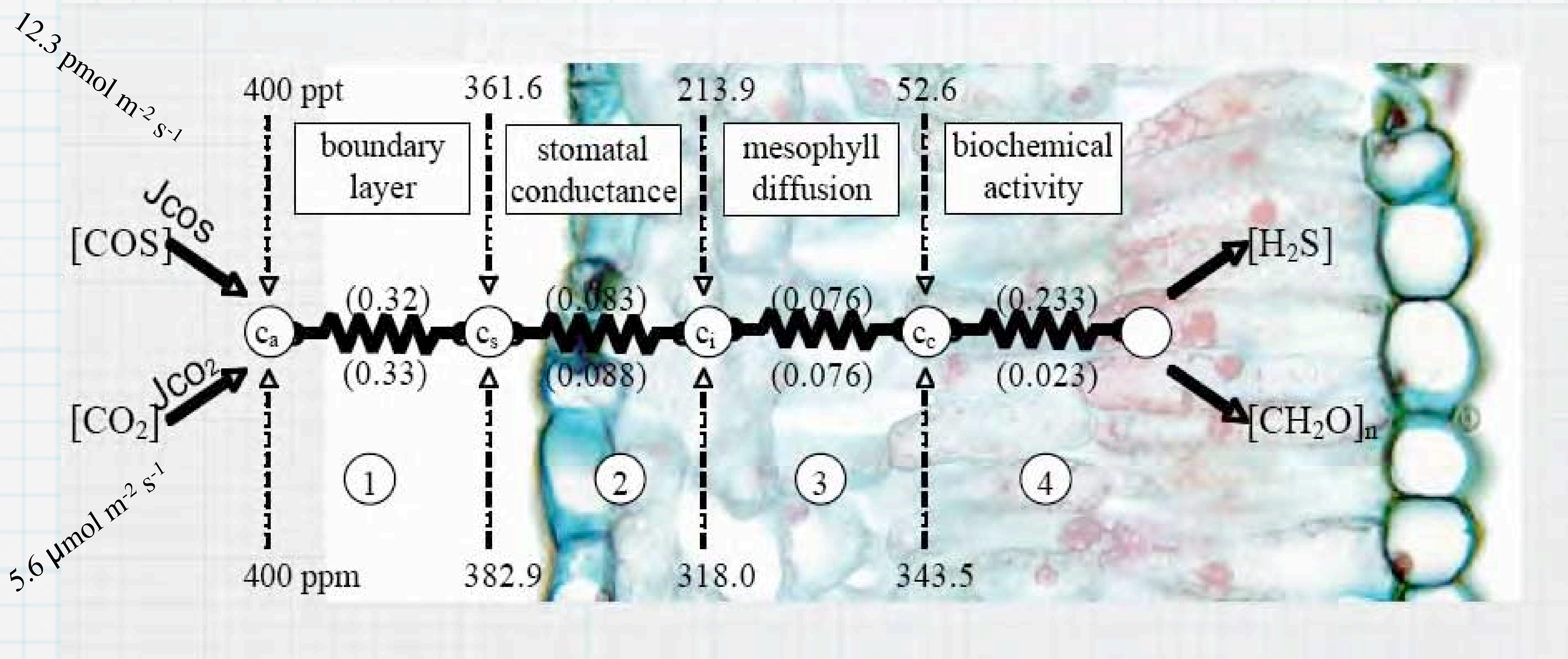


NEE

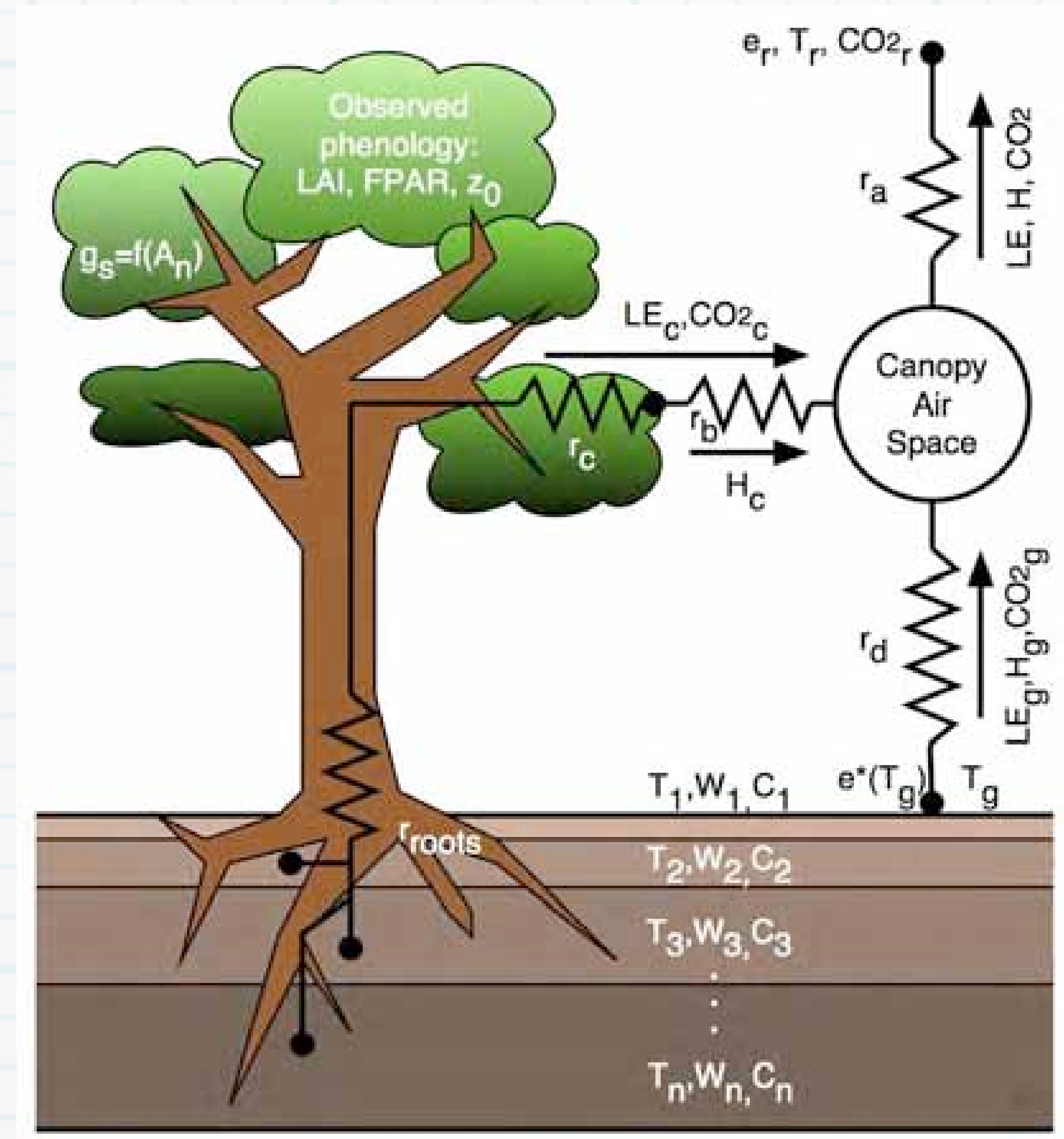
The mechanism of COS uptake

carbonic anhydrase

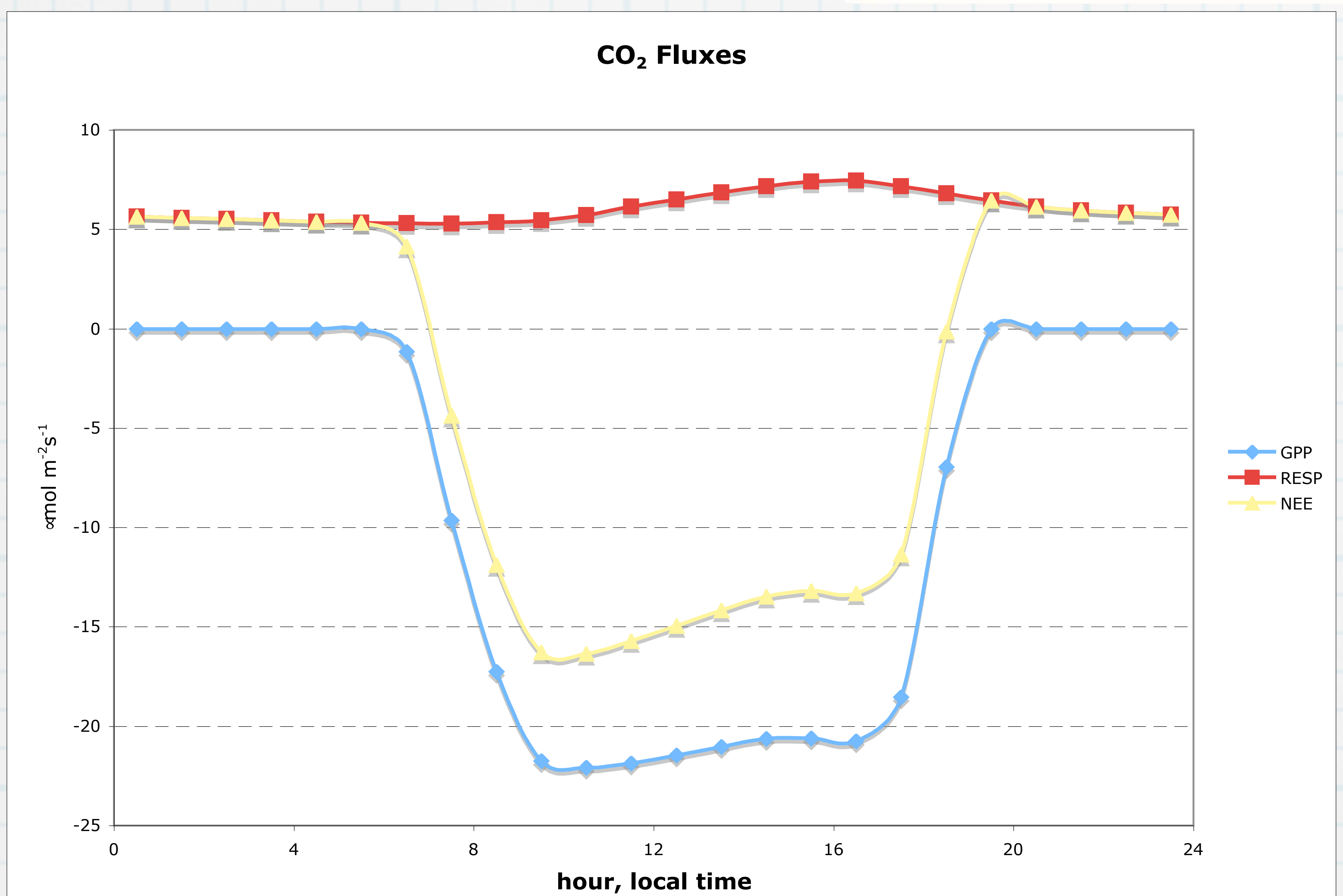
$$COS + H_2O \rightleftharpoons H_2S + CO_2$$



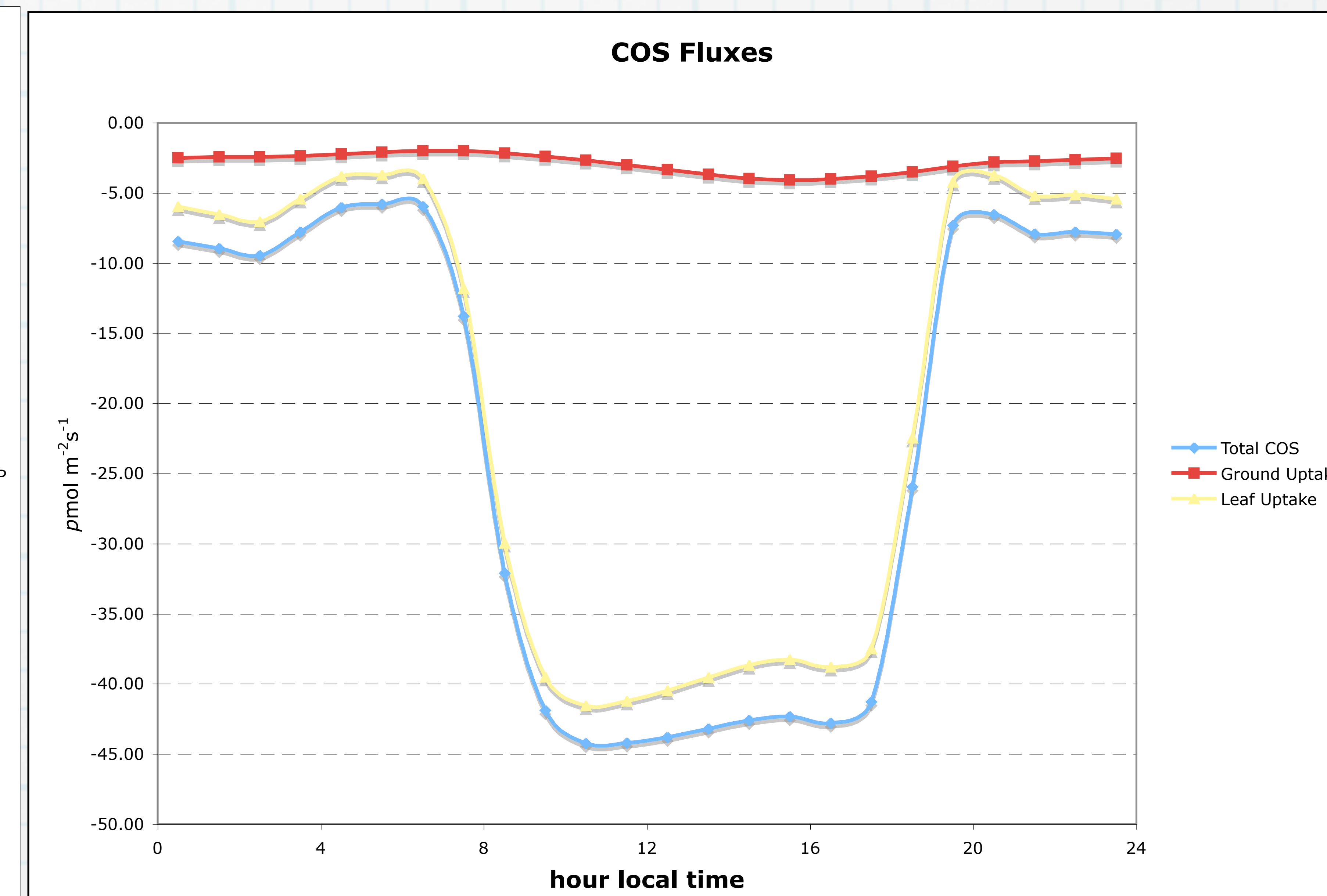
- It should be possible to model COS & CO_2 uptake with a coupled model of photosynthesis and stomatal conductance;
  - Biochemical uptake of COS is limited by Carbonic Anhydrase (CA)
  - Biochemical uptake of CO_2 is limited by Rubisco
  - All other steps are in common
- COS should provide an independent tracer of canopy conductance and photosynthesis that does not become contaminated by co-located sources.



Observed phenology: LAI, FPAR, z0
gs=f(An)
er, Tr, CO2r
ra
LE, H, CO2
LEc,CO2c
rc
rb
Hc
Canopy Air Space
rd
LEg, Hg, CO2g
e*(Tg)
Tg
T1,W1,C1
rroots
T2,W2,C2
T3,W3,C3
Tn,Wn,Cn

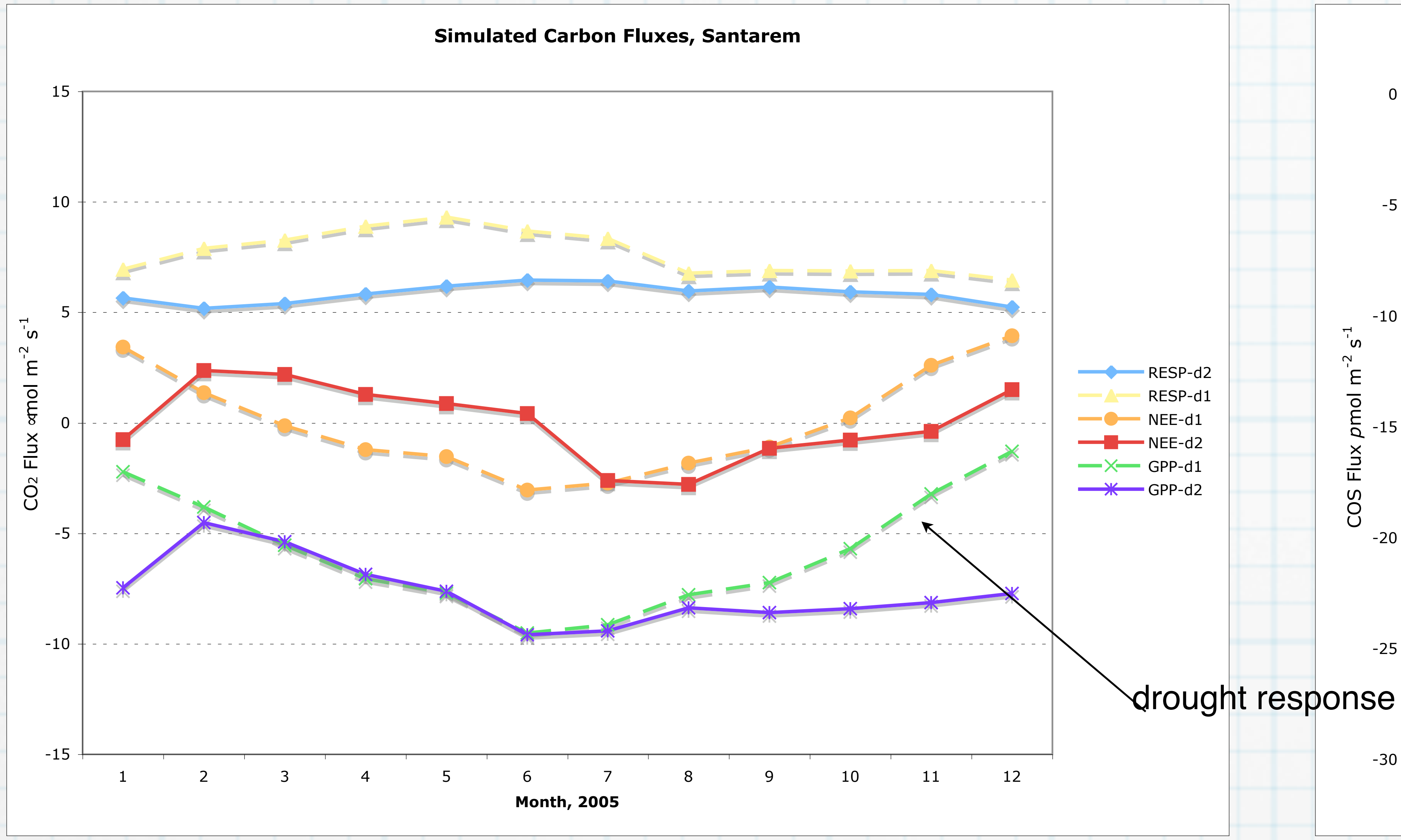


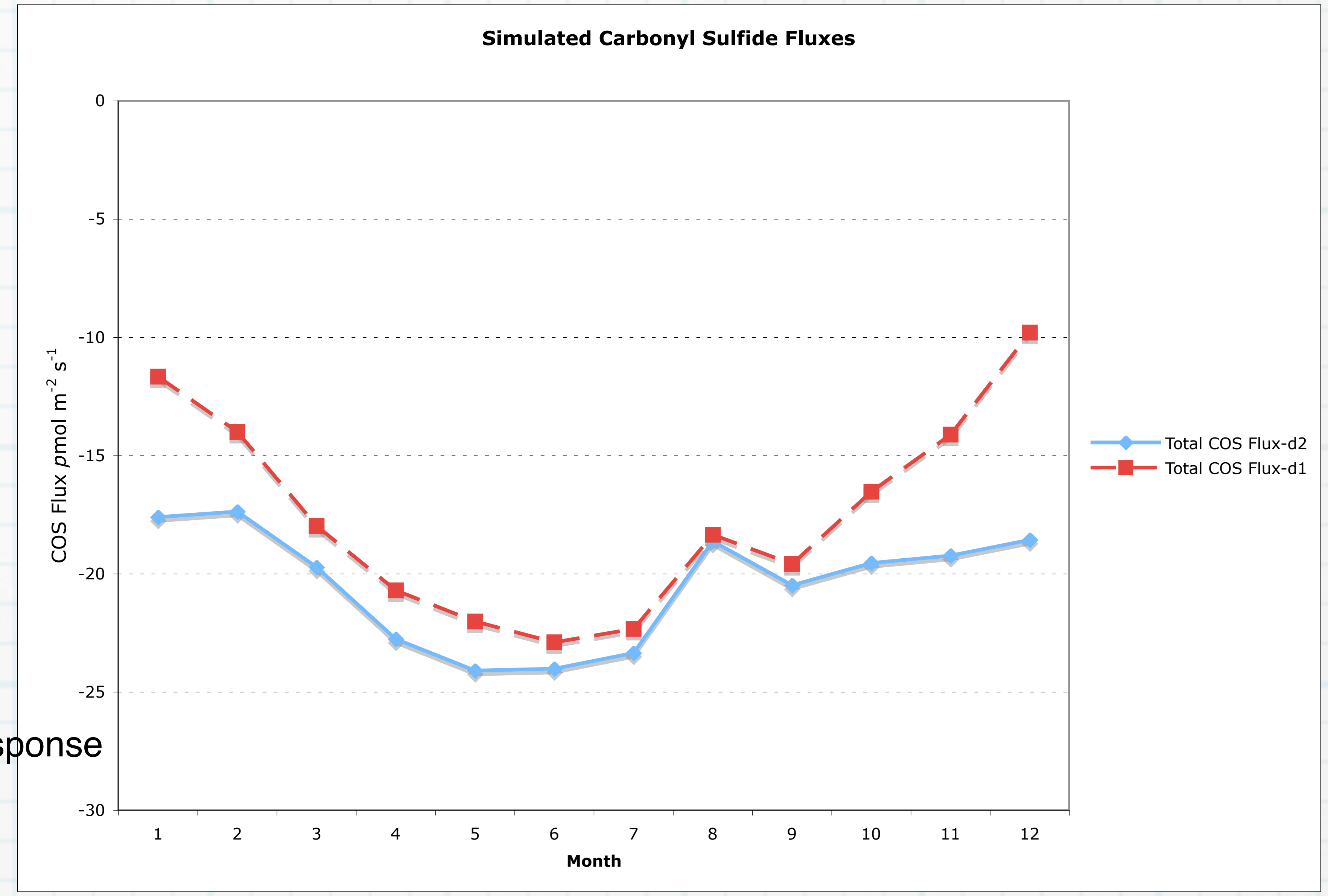
CO2 Fluxes
µmol m-2s-1
hour, local time
GPP
RESP
NEE

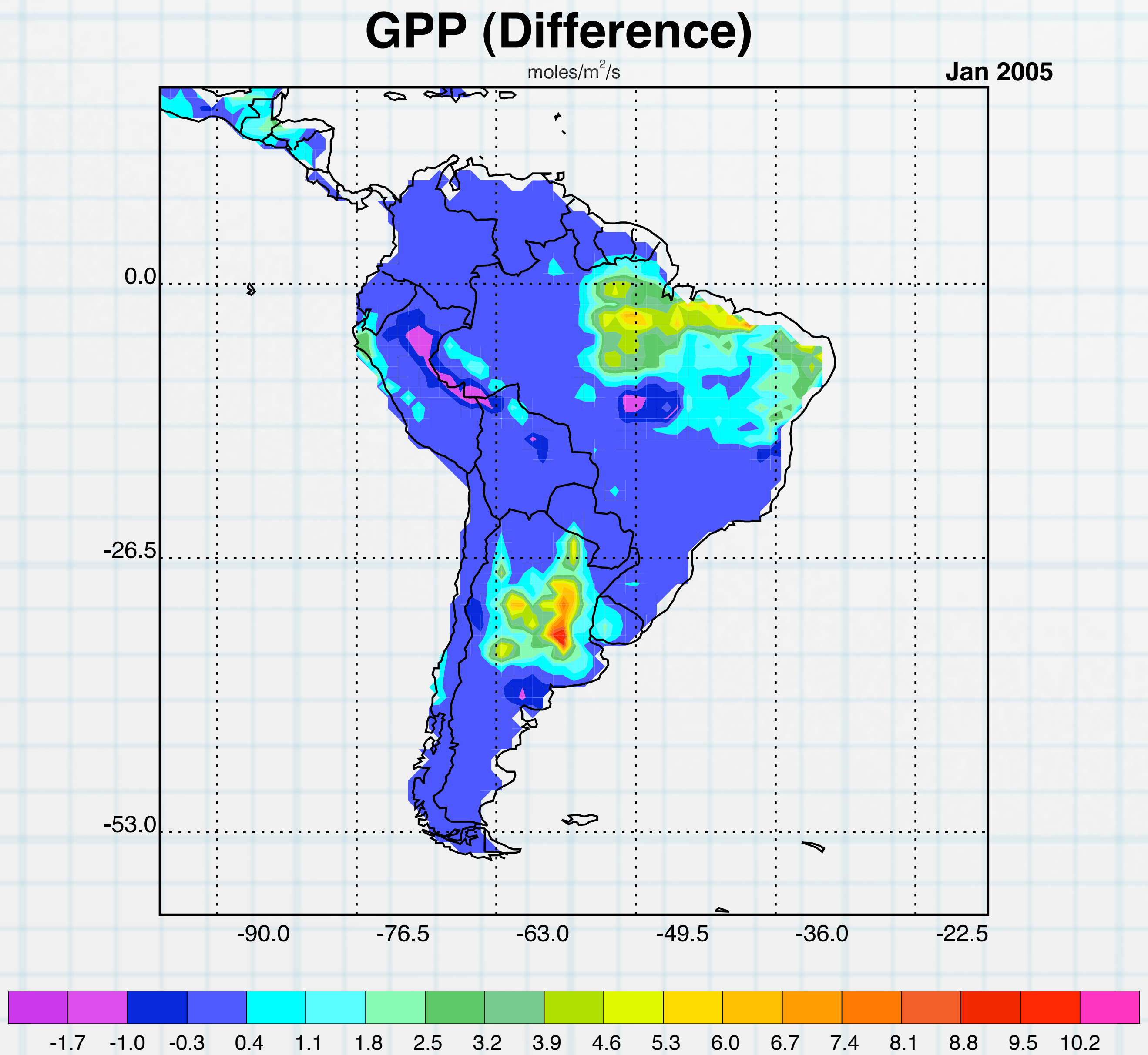


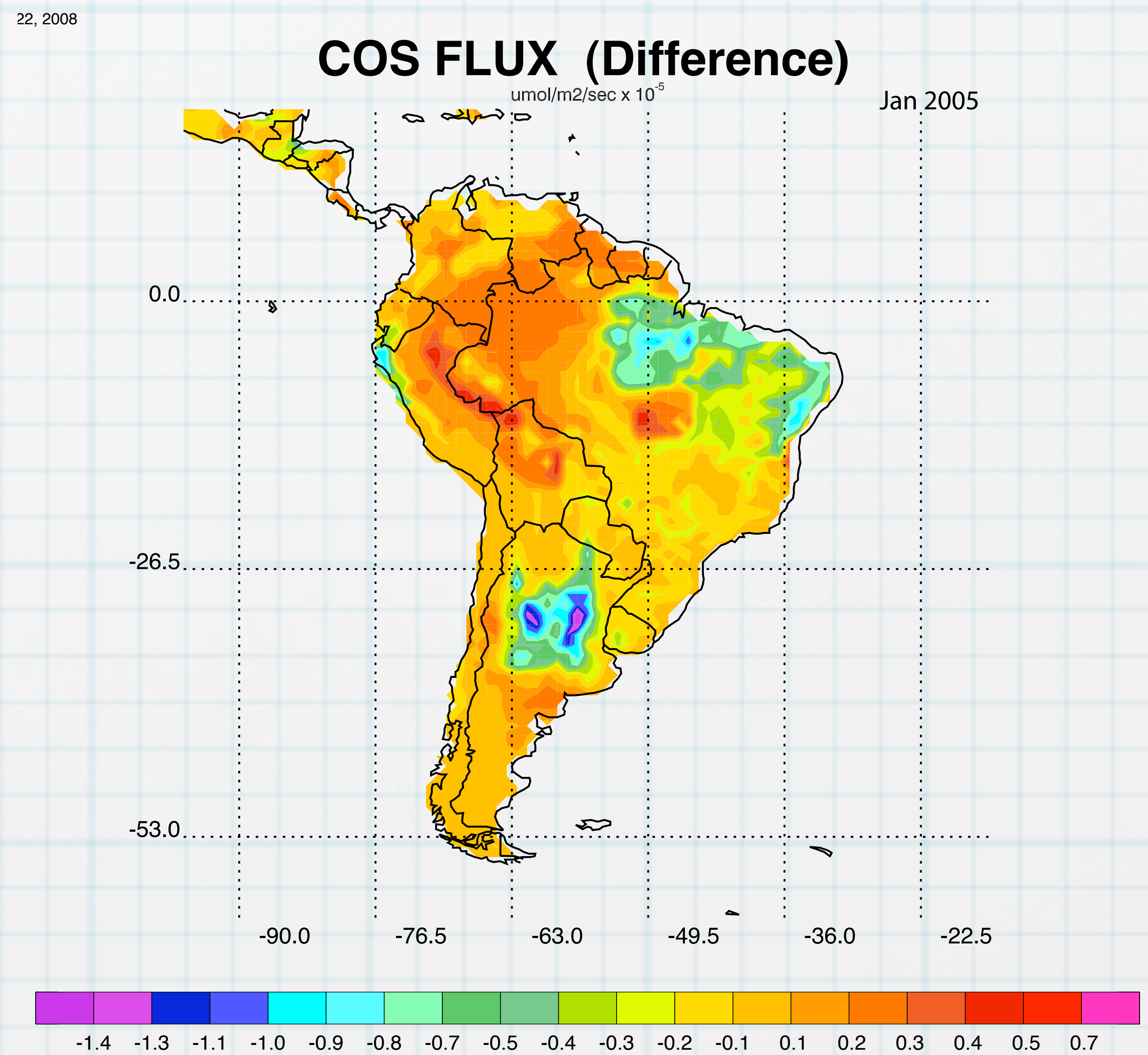
COS Fluxes
pmol m-2s-1
hour local time
Total COS
Ground Uptake
Leaf Uptake

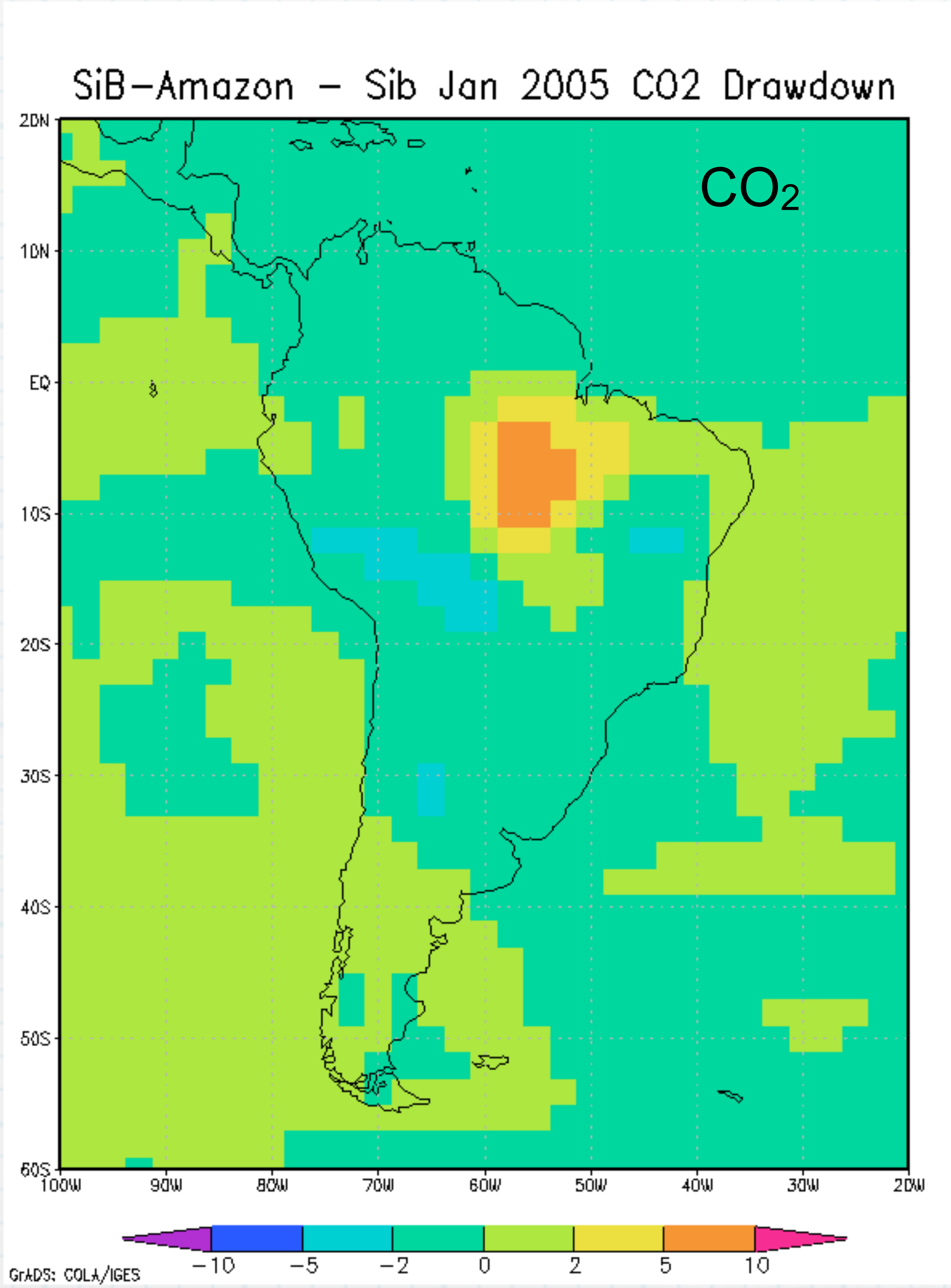
The differnce between the models

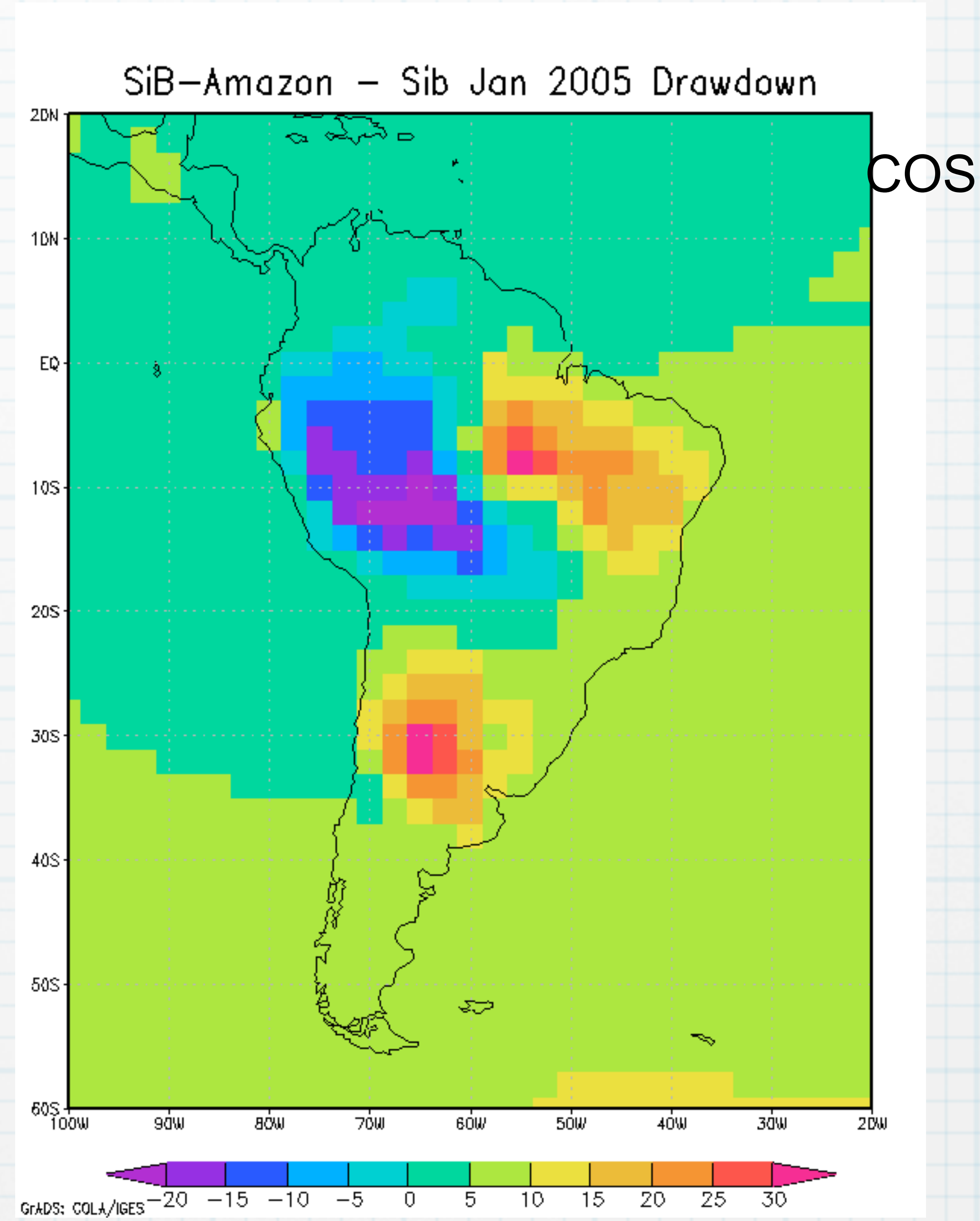


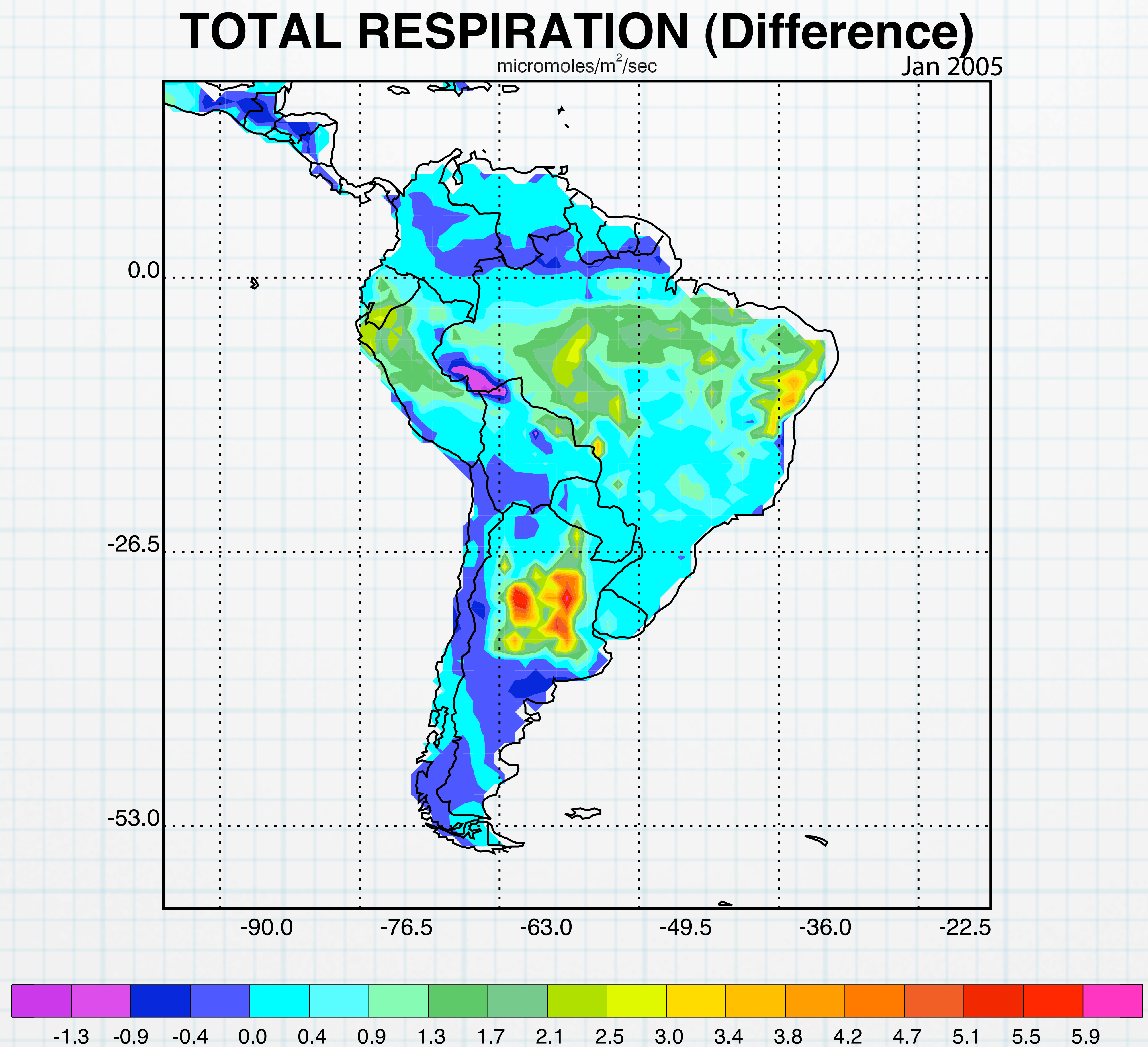




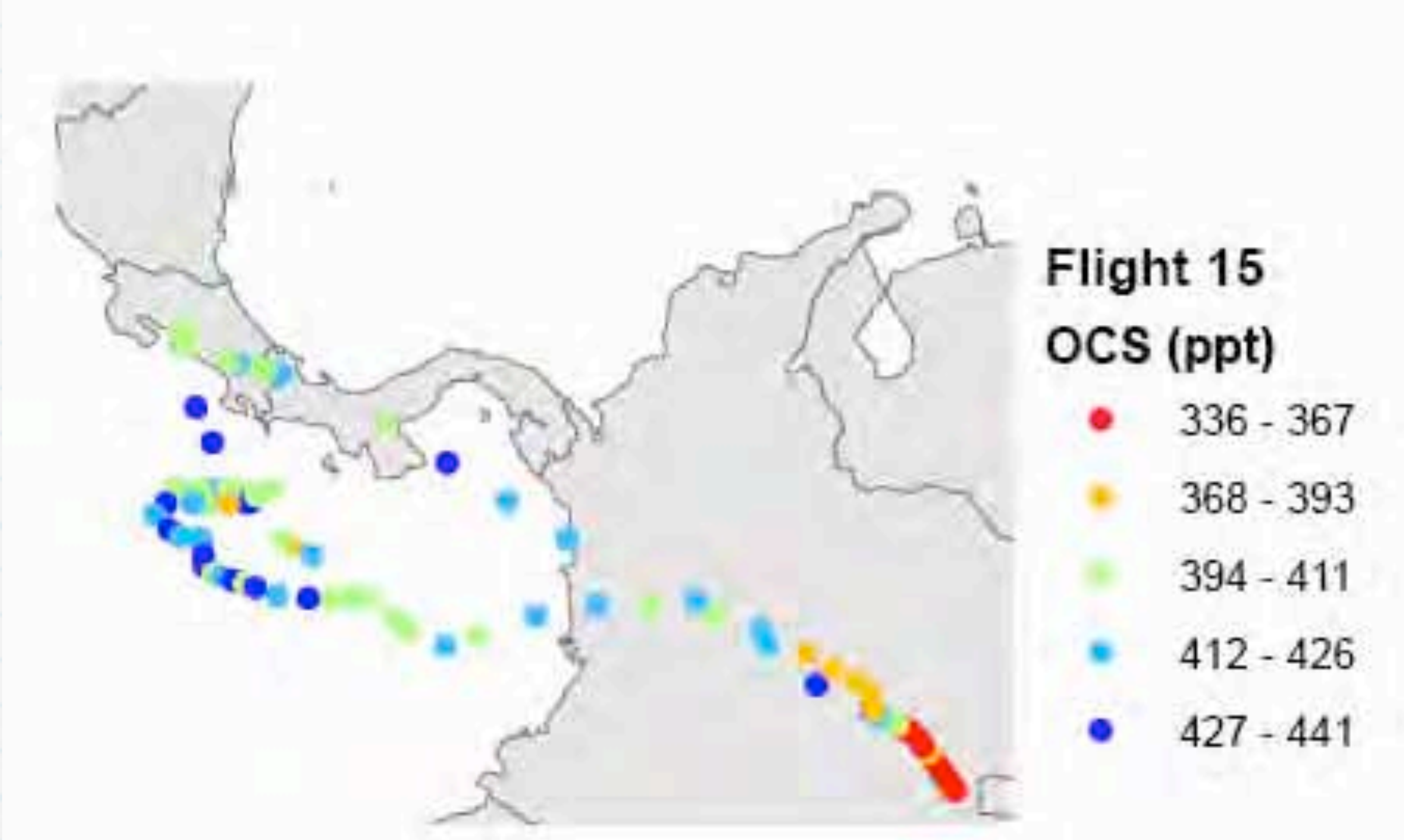



SiB-Amazon – Sib Jan 2005 CO2 Drawdown
CO_2
20N
10N
EQ
10S
20S
30S
40S
50S
60S
100W
90W
80W
70W
60W
50W
40W
30W
20W
-10
-5
-2
0
2
5
10
GrADS: COLA/IGES

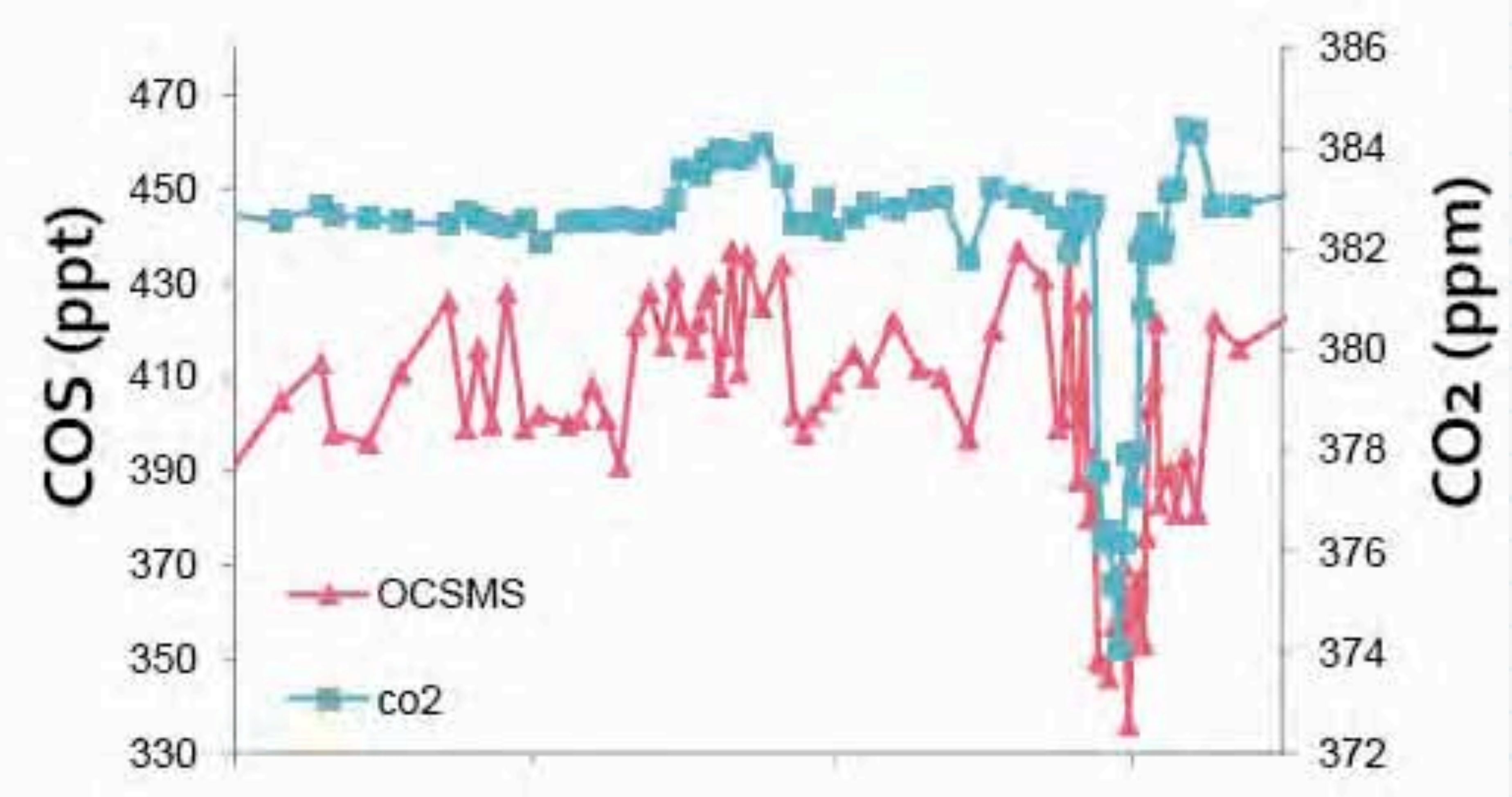

SiB-Amazon – Sib Jan 2005 Drawdown
COS
20N
10N
EQ
10S
20S
30S
40S
50S
60S
100W
90W
80W
70W
60W
50W
40W
30W
20W
-20
-15
-10
-5
0
5
10
15
20
25
30
GrADS: COLA/IGES



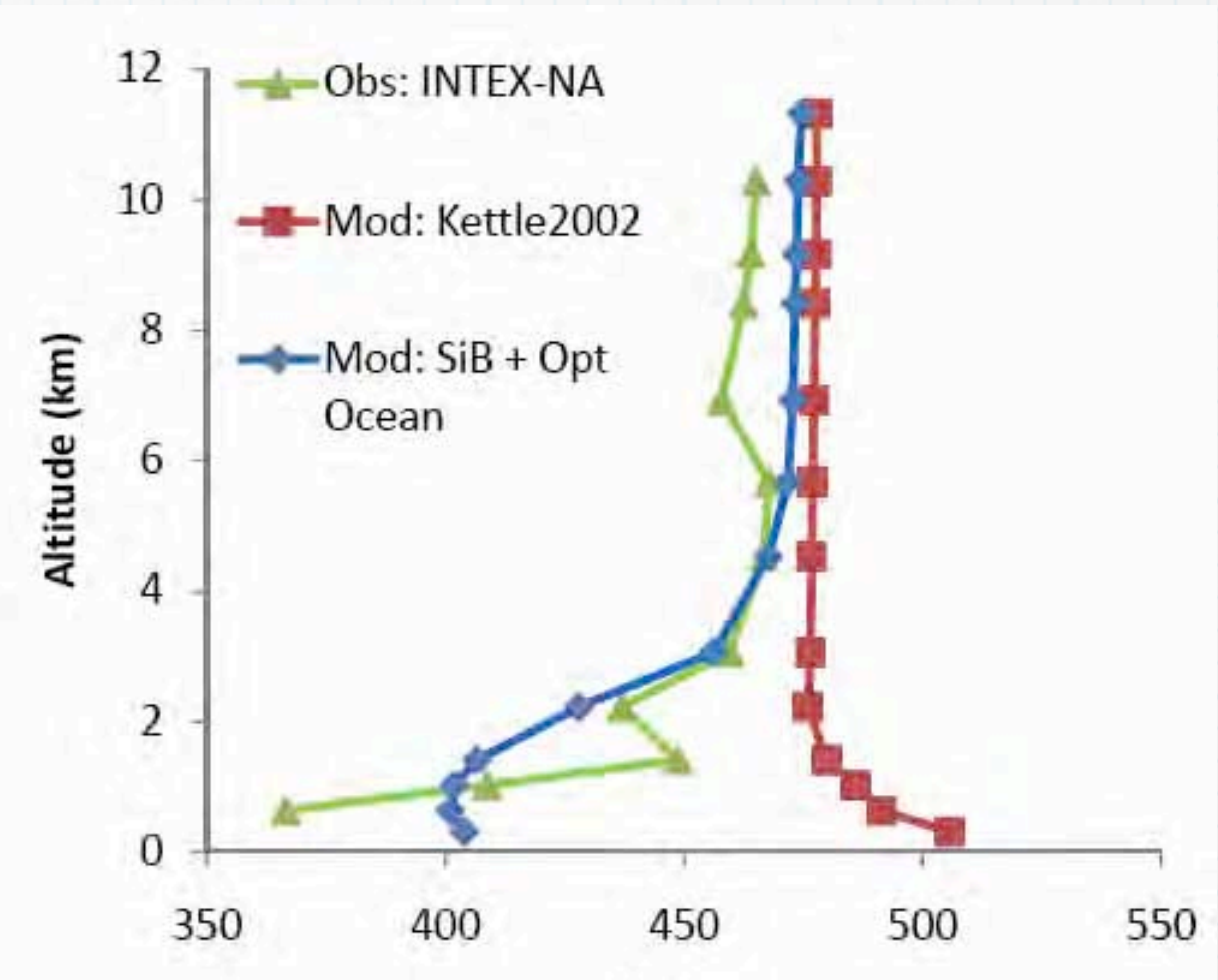
TOTAL RESPIRATION (Difference)
micromoles/m2/sec
Jan 2005
0.0
-26.5
-53.0
-90.0
-76.5
-63.0
-49.5
-36.0
-22.5
-1.3
-0.9
-0.4
0.0
0.4
0.9
1.3
1.7
2.1
2.5
3.0
3.4
3.8
4.2
4.7
5.1
5.5
5.9



Flight 15
OCS (ppt)
336 - 367
368 - 393
394 - 411
412 - 426
427 - 441



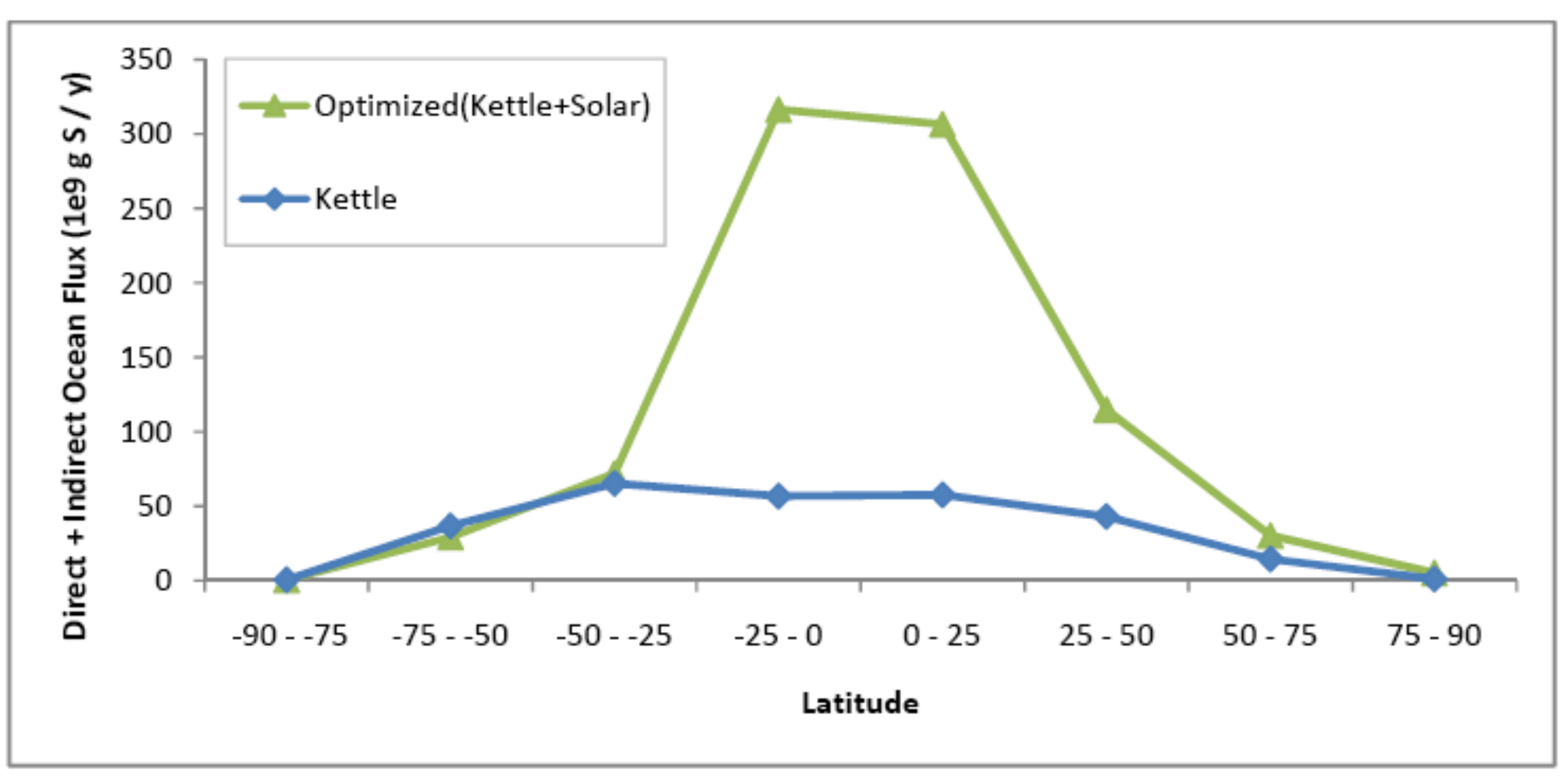
COS (ppt)
CO2 (ppm)
OCSMS
co2



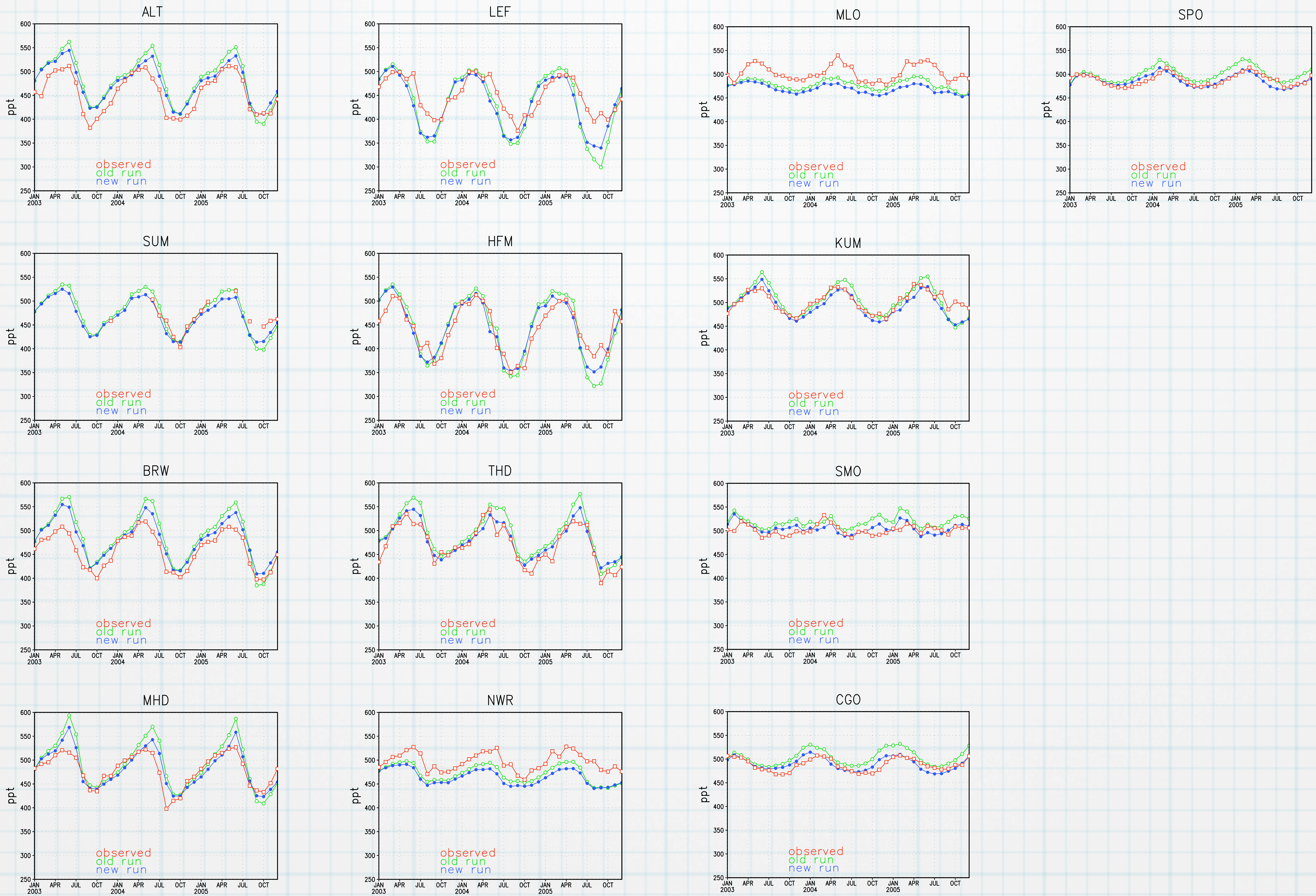
Obs: INTEX-NA
Mod: Kettle2002
Mod: SiB + Opt Ocean
Altitude (km)

Table 1. A compillation of the global sources and sinks used for PCTM simulations of atmospheric COS (units are 1.0e+09g of Sulfur).

Sources	K2002	This Study
Direct COS Flux from Oceans	39	39
Indirect COS Flux as DMS from Oceans	81	81
Indirect COS Flux as CS_2 from Oceans	156	156
Direct Anthropogenic Flux	64	64
Indirect Anthropogenic Flux from CS_2	116	116
Indirect Anthropogenic Flux from DMS	0.5	0.5
Biomass Burning	11	136
Additional (photochemical) Ocean Flux		600
Sinks		
Destruction by OH Radical	-94	-101
Uptake by Canopy	-238	-738
Uptake by Soil	-130	-355
Net Total	-5	-2.5



Optimized(Kettle+Solar)
Kettle
Direct + Indirect Ocean Flux (1e9 g S / y)
350
300
250
200
150
100
50
0
-90 - -75
-75 - -50
-50 - -25
-25 - 0
0 - 25
25 - 50
50 - 75
75 - 90
Latitude


ALT
LEF
MLO
SPO
SUM
HFM
KUM
BRW
THD
SMO
MHD
NWR
CGO
ppt
600
550
500
450
400
350
300
250
observed
old run
new run
JAN 2003
APR
JUL
OCT
JAN 2004
APR
JUL
OCT
JAN 2005
APR
JUL
OCT

Conclusions IV

* Simulation experiment indicates that COS could be a powerful tracer of photosythesis and respiration
* Observations of COS in the atmosphere support the simulations, but observations are very sparse.
* To do this, we have had to make major changes in the accepted global budget.
* COS feedback on climate might be influenced by forests.

The Role of C_4 photosynthesis in the global carbon cycle.

- How are C_4 and C_3 plants distributed on the planet?
- C_4-CO_2 has and isotopic tracer that could be used:
  - to validate the bottom-up analysis
  - to examine transport.

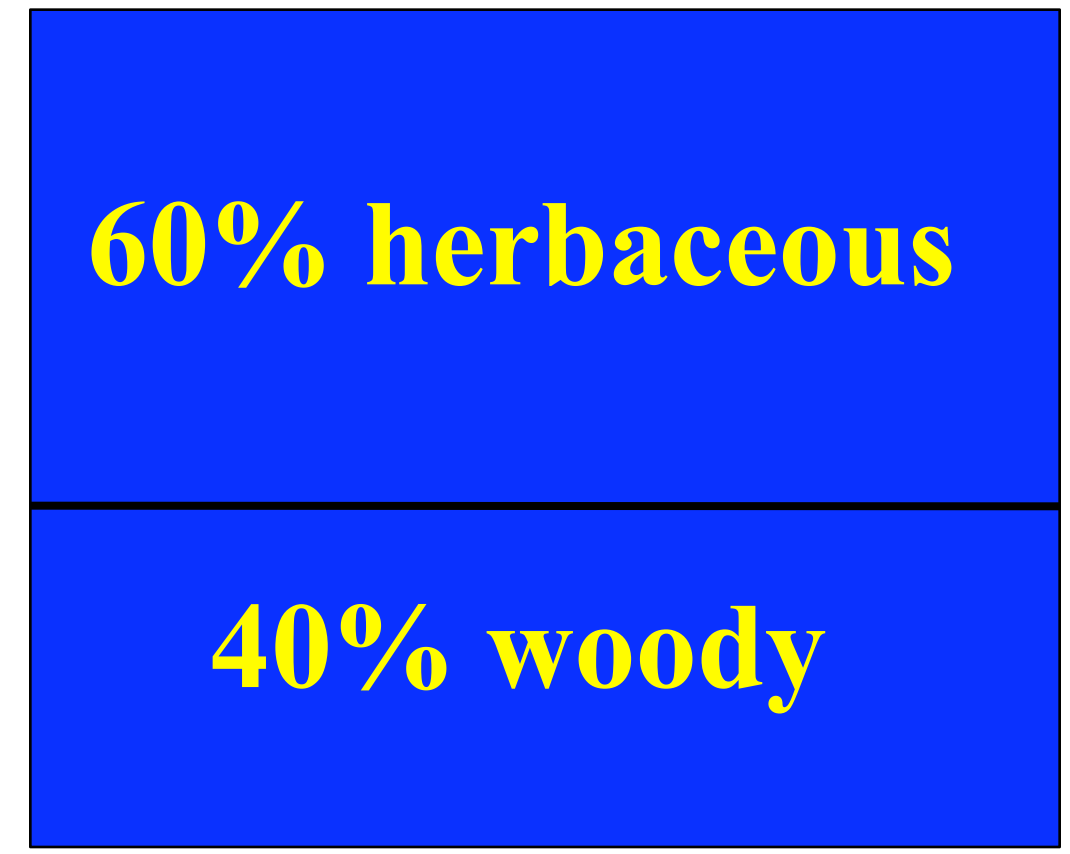
Creating a distribution of C_3 and C_4 vegetation for ecological and biogeochemical applications

Components

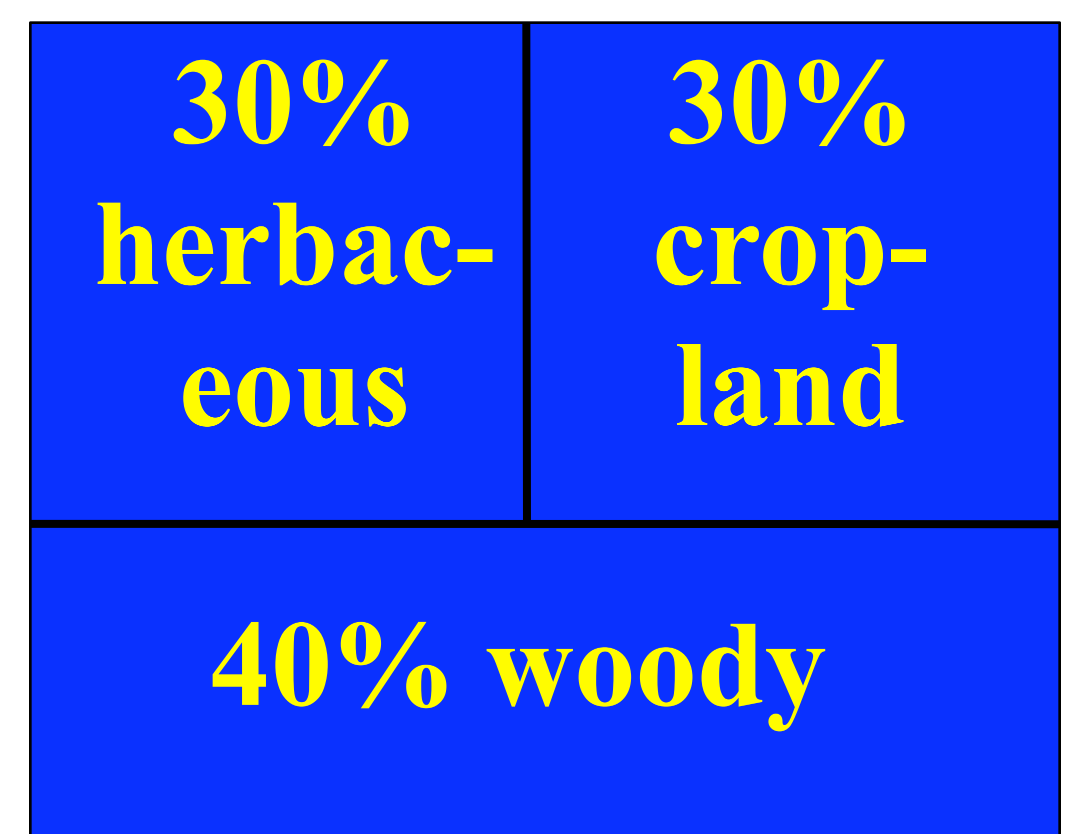
1. C_4 bioclimatology

2. Remote sensing of woody and herbaceous vegetation coverage (MODIS VCF- Hansen et al 2003).

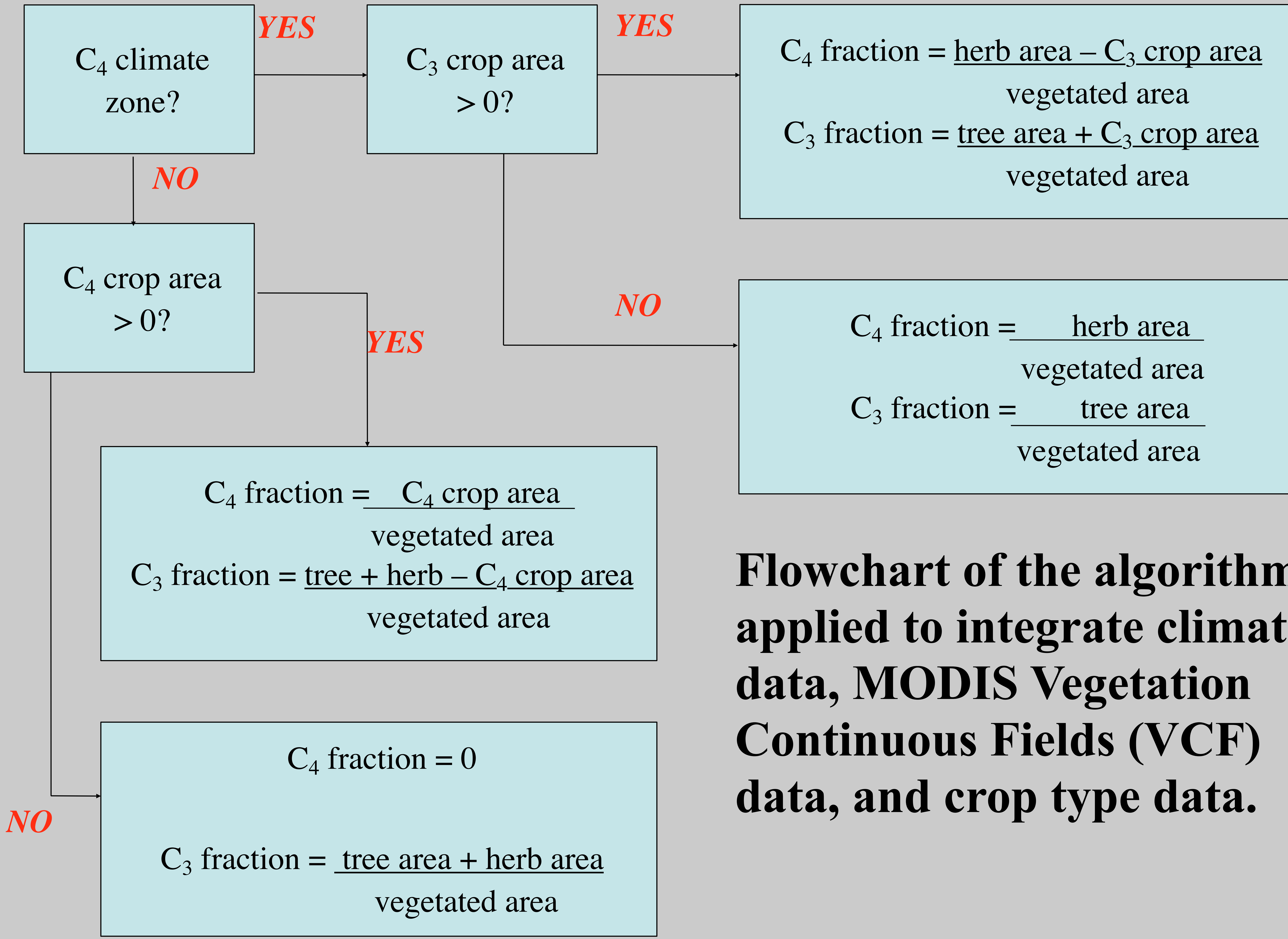
3. Global crop type fractions (Leff et al. 2004) .



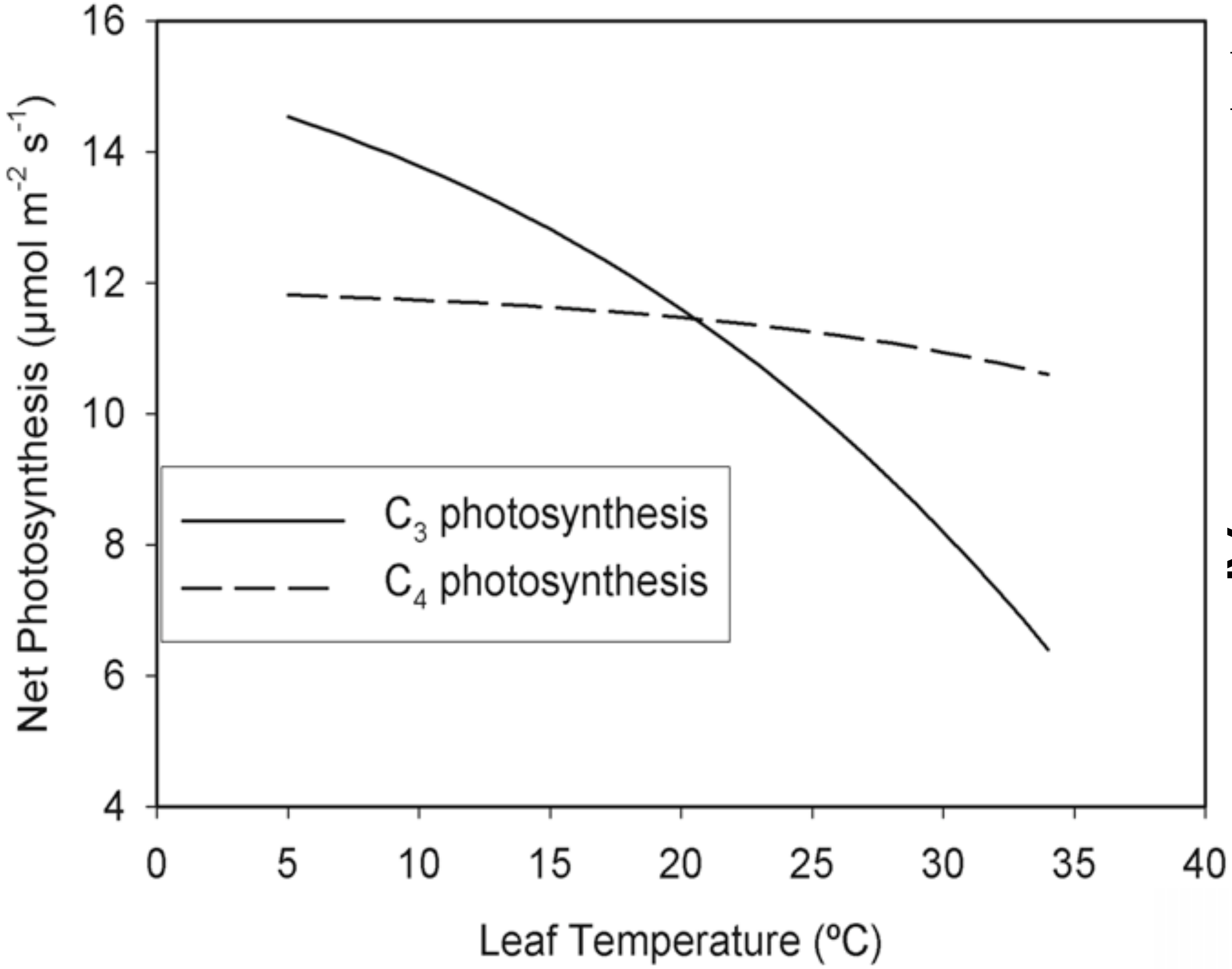
Growth forms in land grid cell



Land grid cell with herb crops



Flowchart of the algorithm applied to integrate climate data, MODIS Vegetation Continuous Fields (VCF) data, and crop type data.



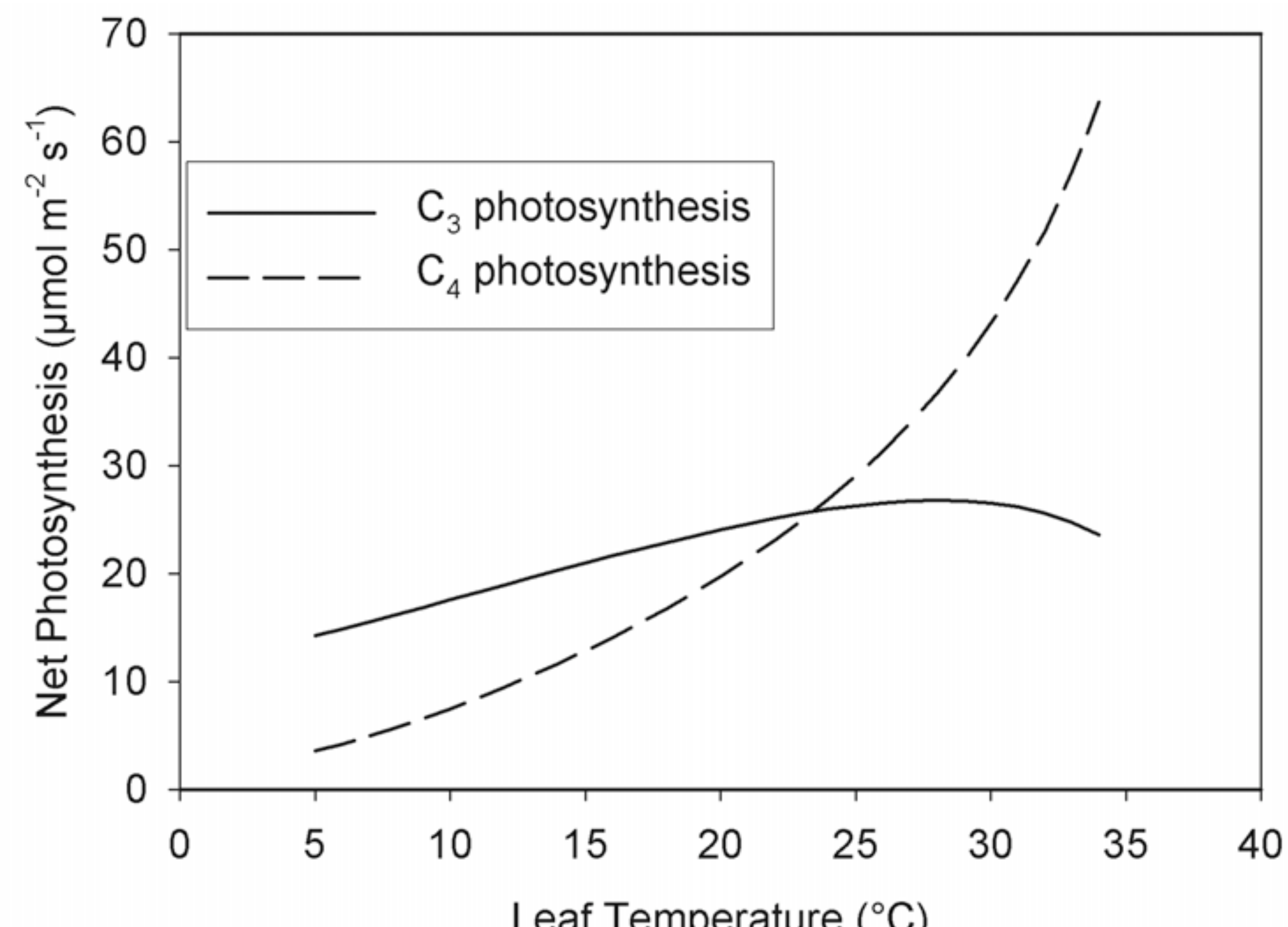
Light-limited conditions

C4 bioclimatic criteria

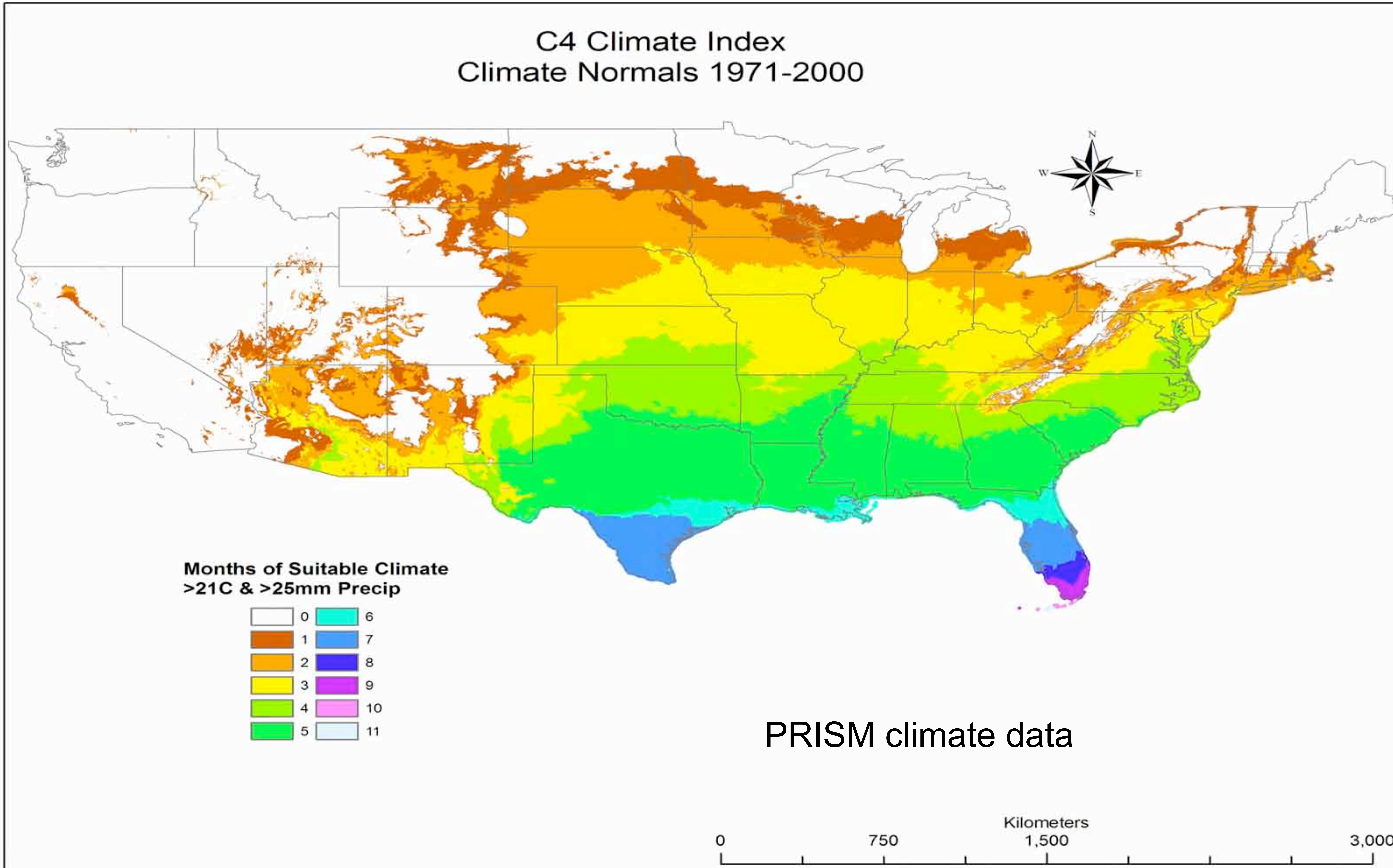
> 21ºC mean monthly temperature

≥ 25mm precipitation in the same month

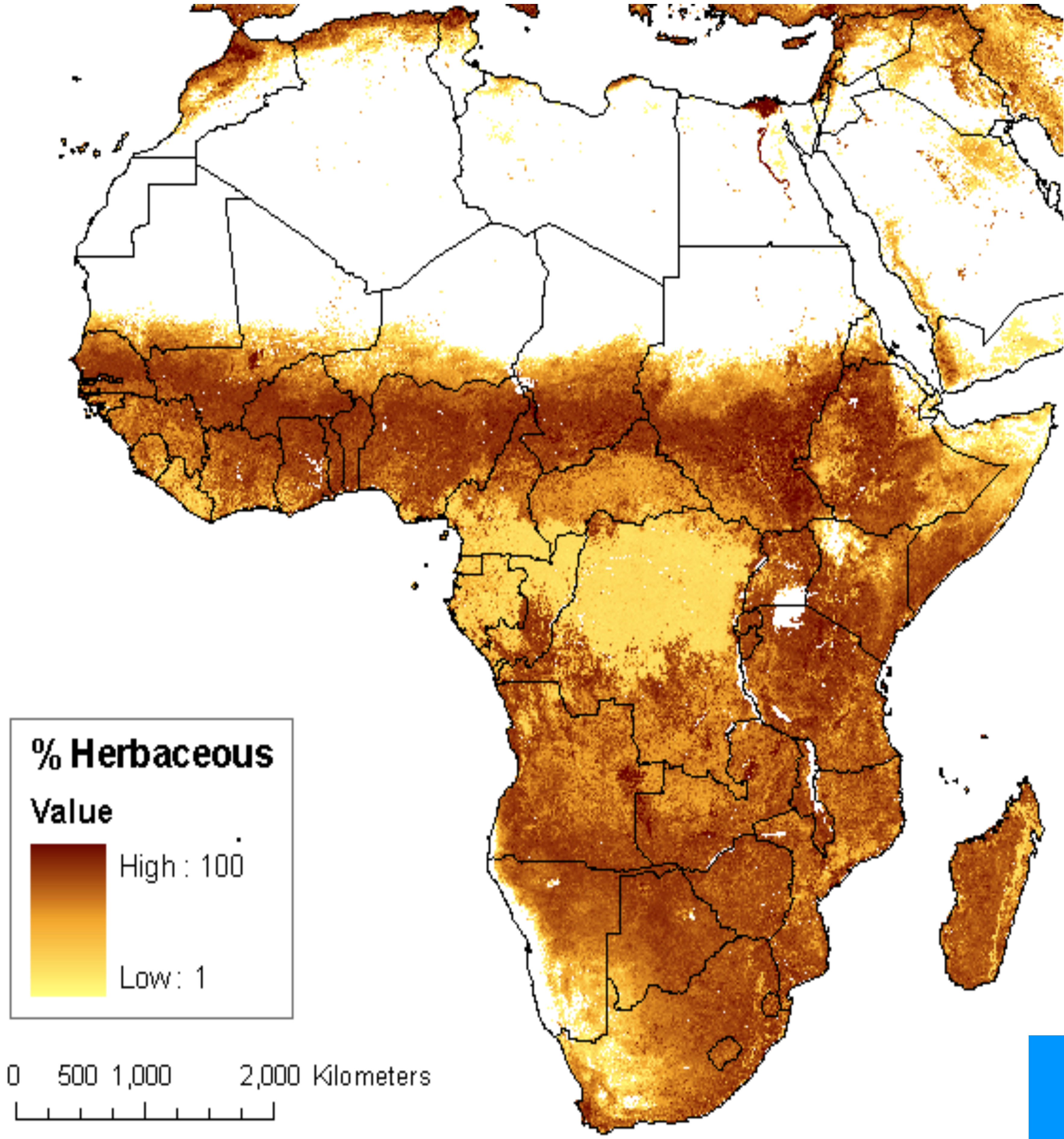
Light-saturated (Rubisco-limited) conditions



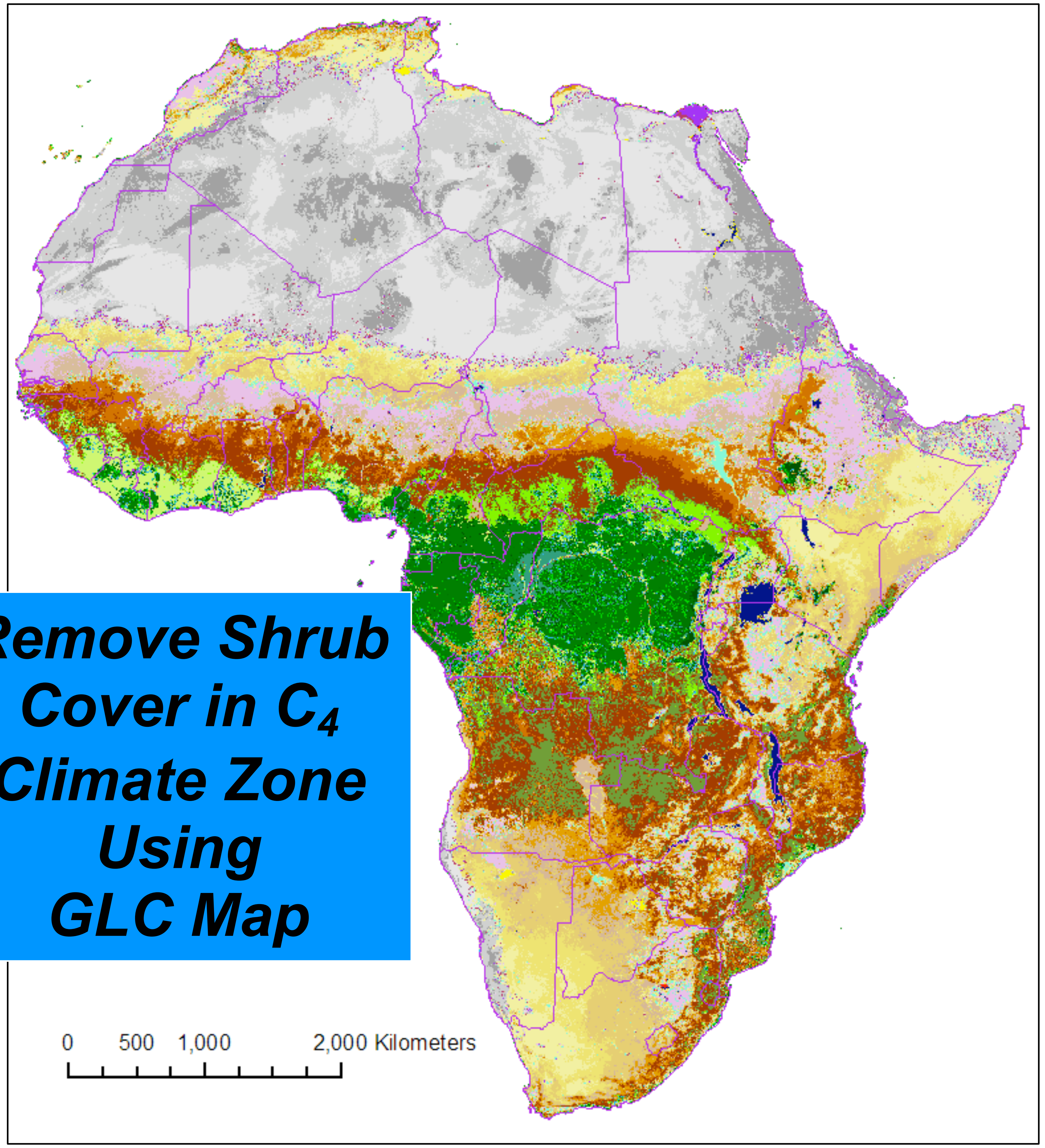
Ehleringer et al. 1997
Collatz et al. 1998
Still et al. 2003


C4 Climate Index
Climate Normals 1971-2000
N
W
E
S
Months of Suitable Climate
>21C & >25mm Precip
0
1
2
3
4
5
6
7
8
9
10
11
PRISM climate data
Kilometers
0
750
1,500
3,000

MODIS VCF maps (growth form)

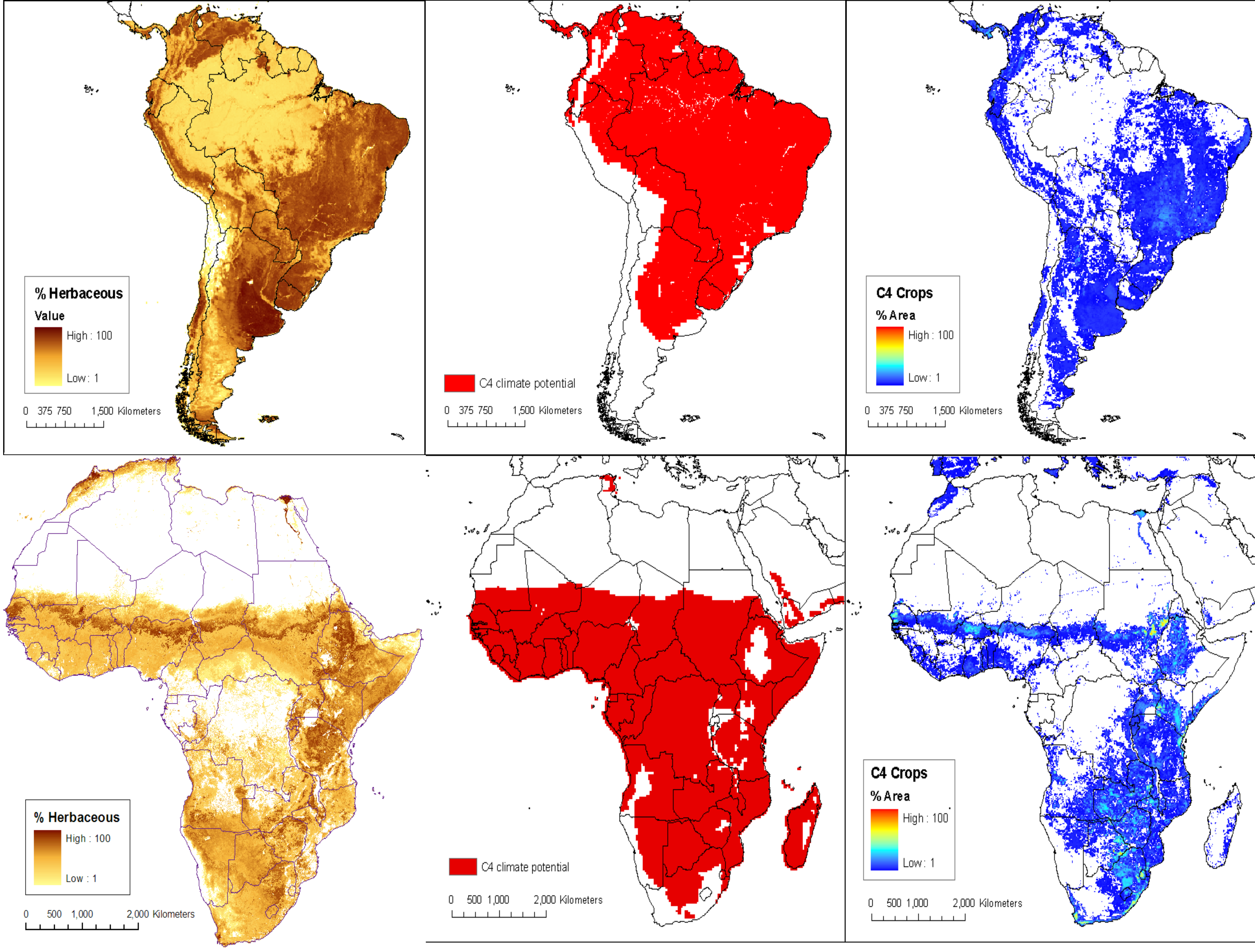


Land-cover map for Africa for the year 2000, derived from SPOT data.



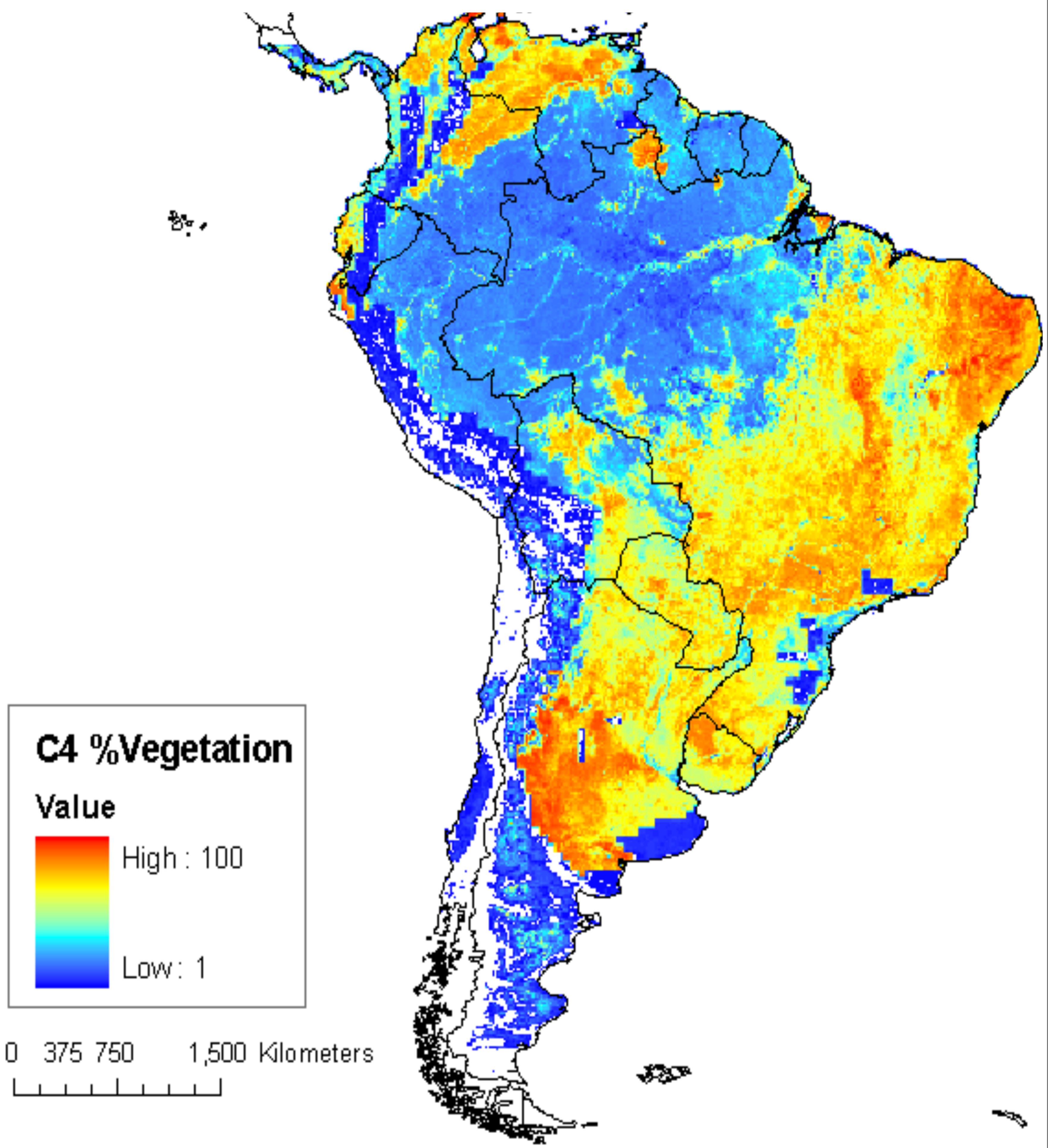
Remove Shrub Cover in C_4 Climate Zone Using GLC Map

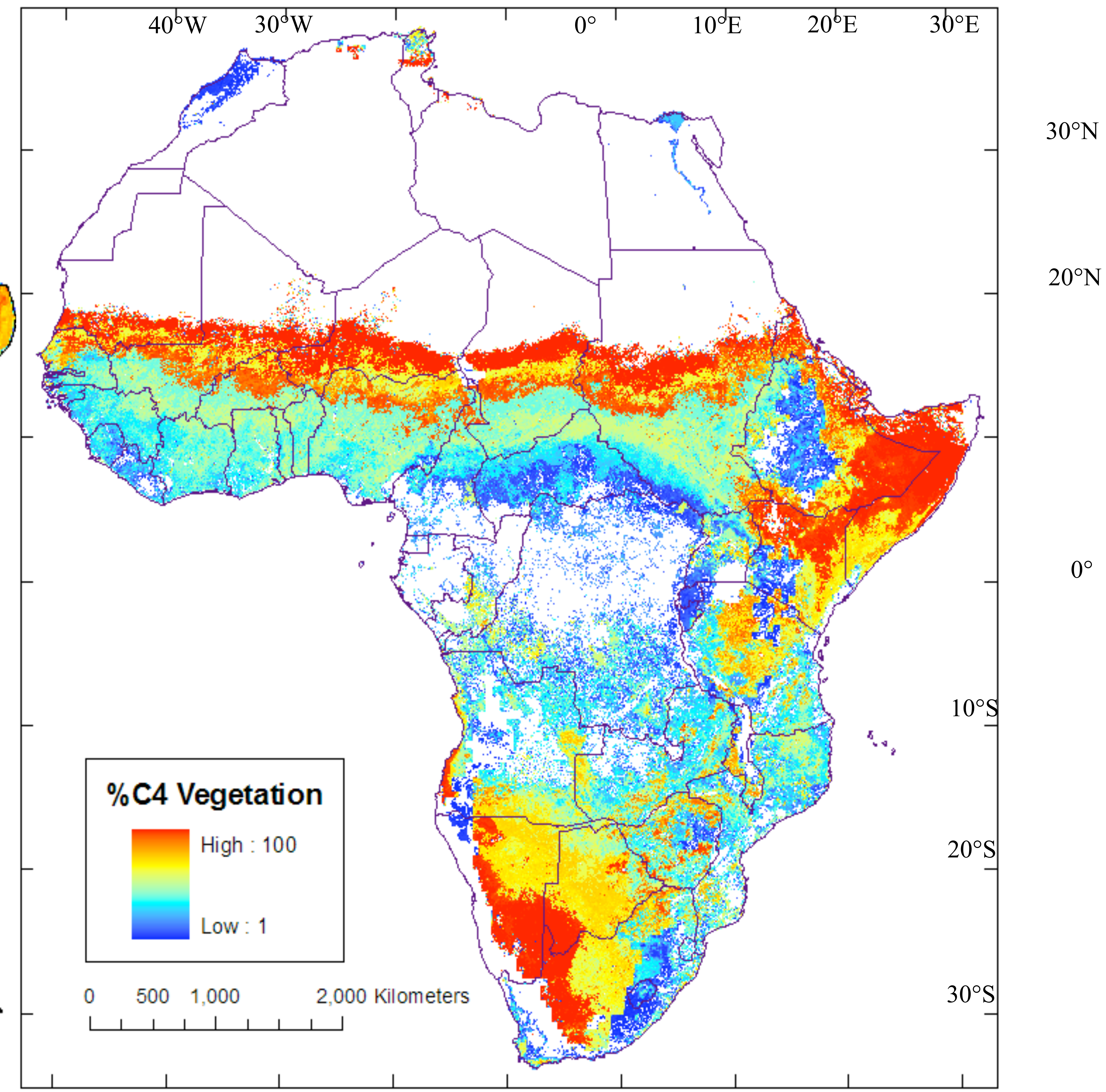
The VCF products are basically a tree/non-tree view of the world - need to correct to remove shrubs from the herbaceous layer



% Herbaceous
Value
High : 100
Low : 1
0 375 750 1,500 Kilometers
C4 climate potential
0 375 750 1,500 Kilometers
C4 Crops
% Area
High : 100
Low : 1
0 375 750 1,500 Kilometers
% Herbaceous
High : 100
Low : 1
0 500 1,000 2,000 Kilometers
C4 climate potential
0 500 1,000 2,000 Kilometers
C4 Crops
% Area
High : 100
Low : 1
0 500 1,000 2,000 Kilometers

The C_4 percentage of vegetation





R.L. Powell and C.J. Still, An improved methodology to predict the carbon isotopic composition of terrestrial vegetation using remote sensing derived datasets and a novel application to wildlife migration (in prep)

Table 1. Areal Coverage of C_3 and C_4 Vegetation

Photosynthetic Pathway	Total Global Coverage, million km^2	Coverage in Croplands, million km^2
C_4	18.8	2.3
C_3	87.4	11.8

C4 plants account for ~23% of global gross primary productivity

Still et al. GBC 2003

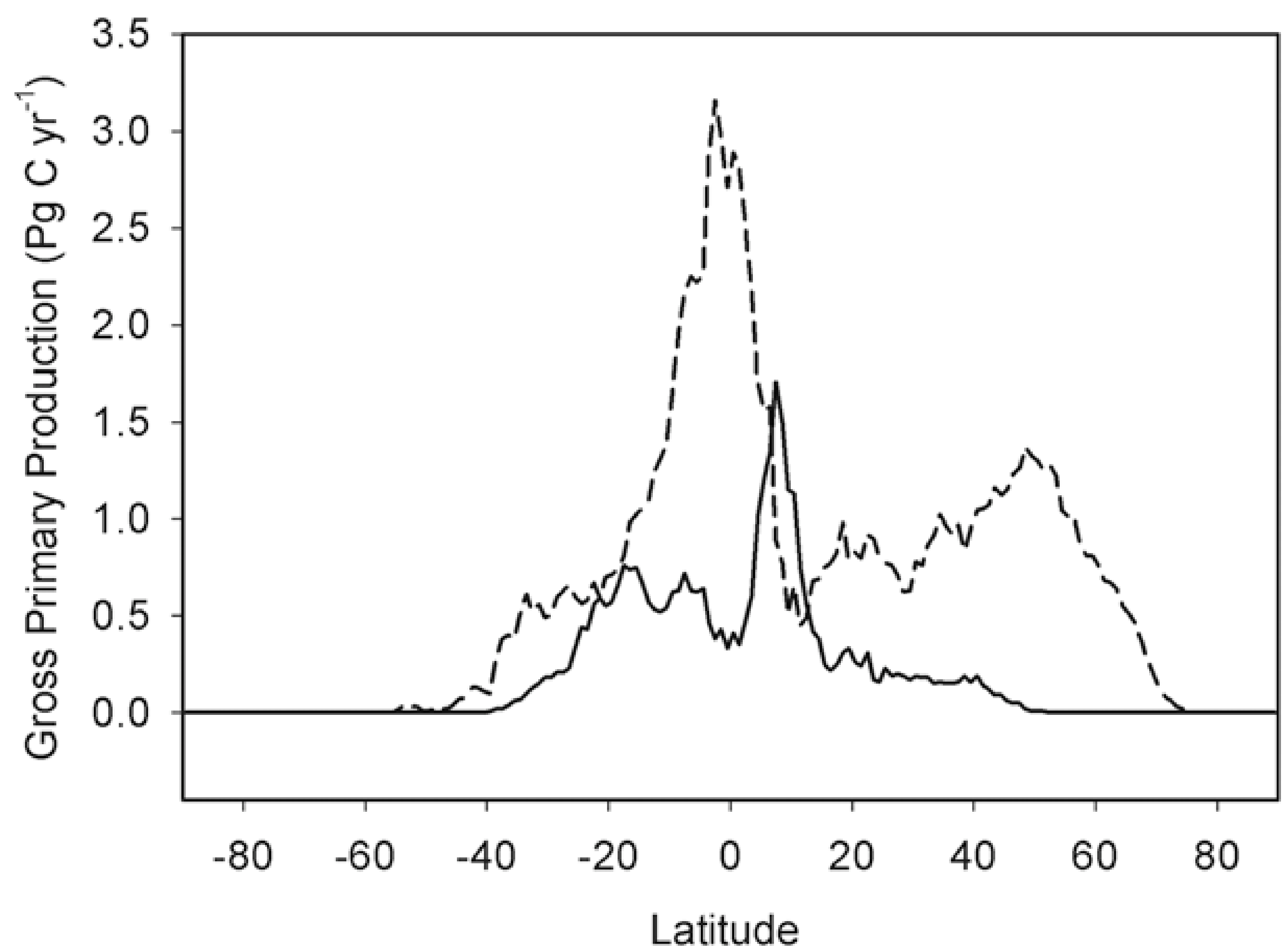
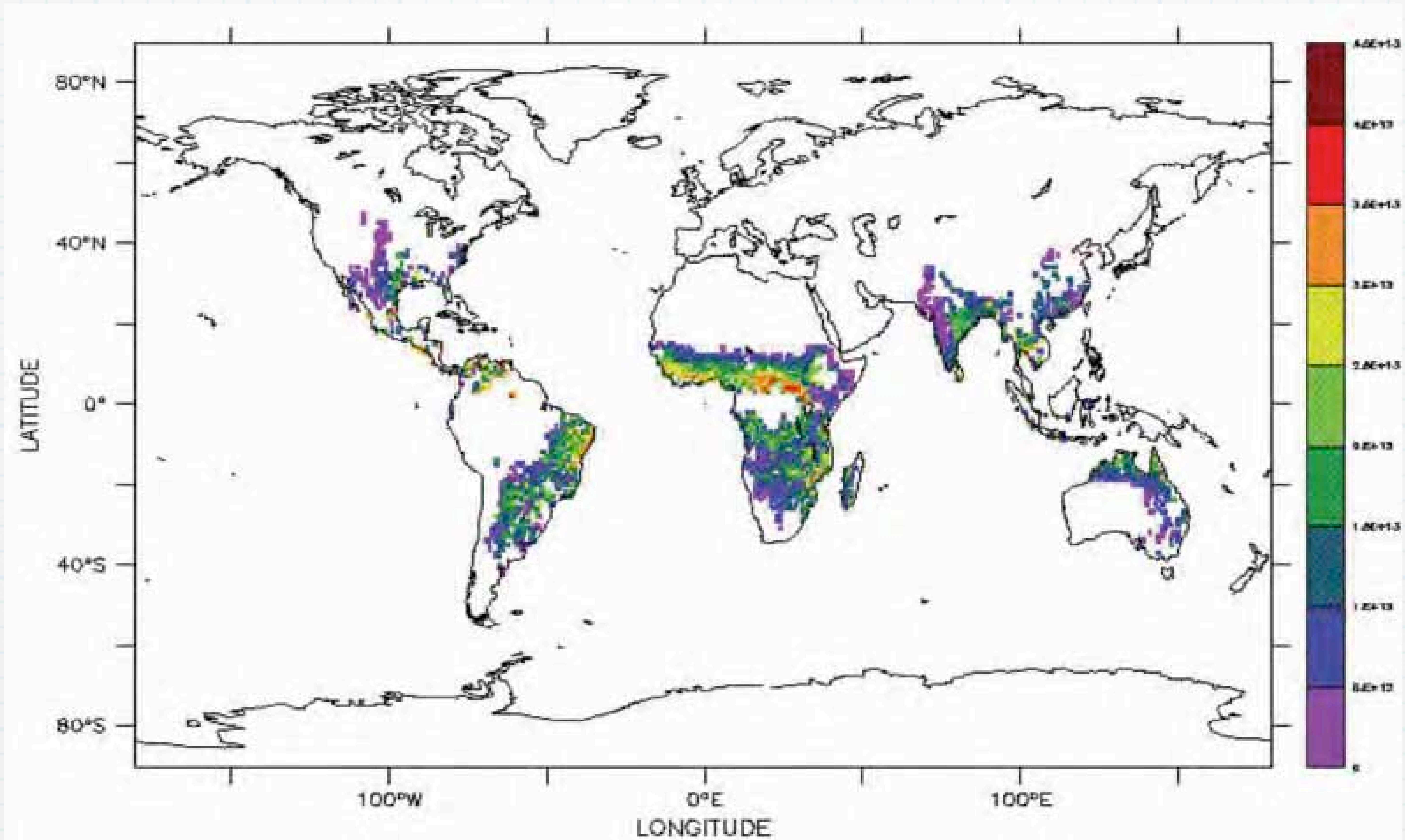


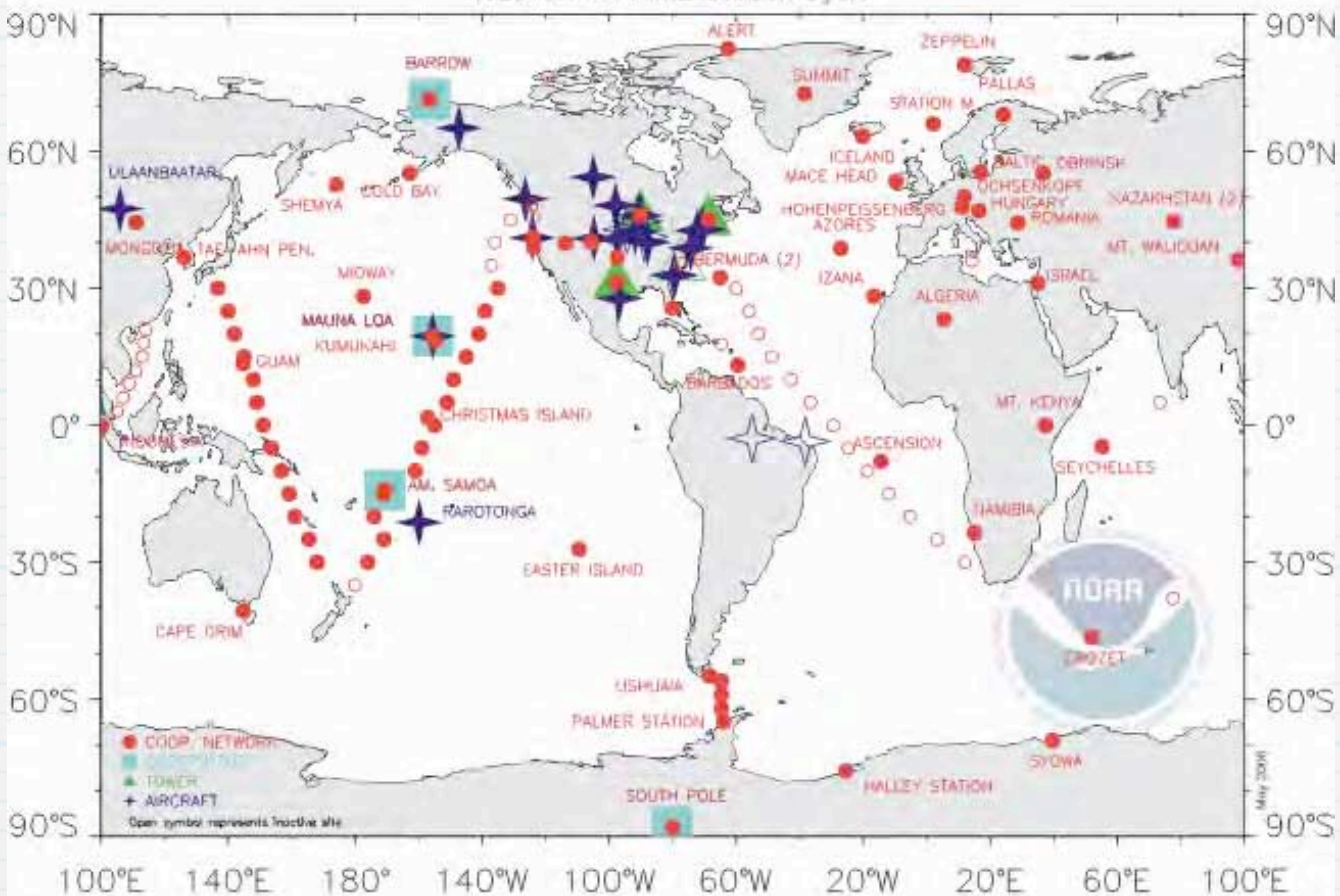
Figure 4. C_3 and C_4 annual gross primary production (GPP) by latitude. C_4 GPP is the solid line; C_3 GPP is the dashed line. Units are petagrams of carbon per year.

A map of GPP by C_4 plants



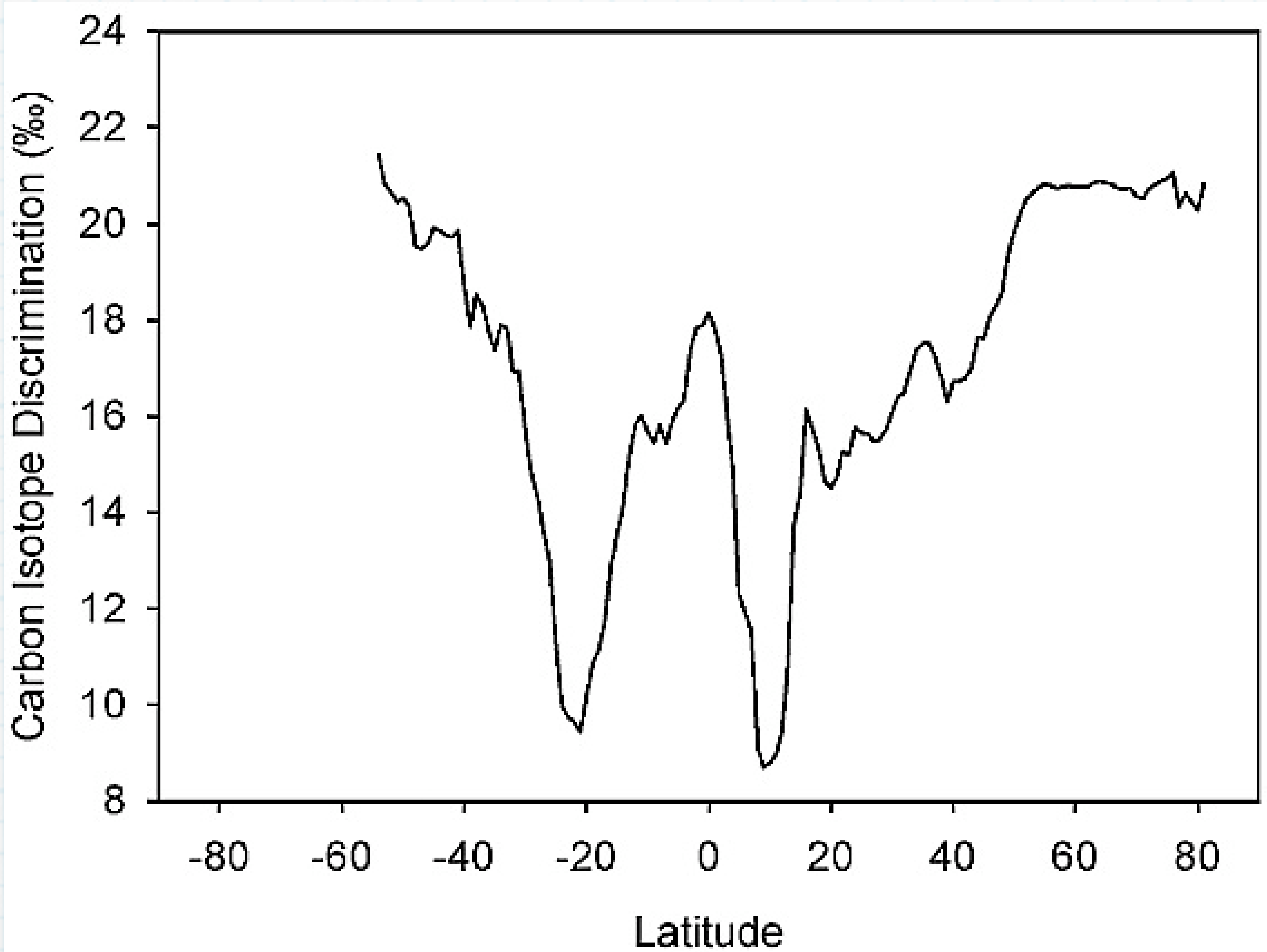
Measurement Programs

NOAA ESRL GMD Carbon Cycle



GMD Carbon Cycle operates 4 measurement programs. Semi-continuous measurements are made at 4 GMD baseline observatories and from tall towers. Discrete samples from the cooperative air sampling network and aircraft are measured at GMD. Presently, atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, nitrous oxide, sulfur hexafluoride, and the stable isotopes of carbon dioxide and methane are measured. Contact: Dr. Pieter Tans, NOAA ESRL GMD Carbon Cycle, Boulder, Colorado, (303) 497-6678 (pieter.tans@noaa.gov, http://www.cmdl.noaa.gov/ccgg).

Latitudinal Variation in photosynthetic discrimination



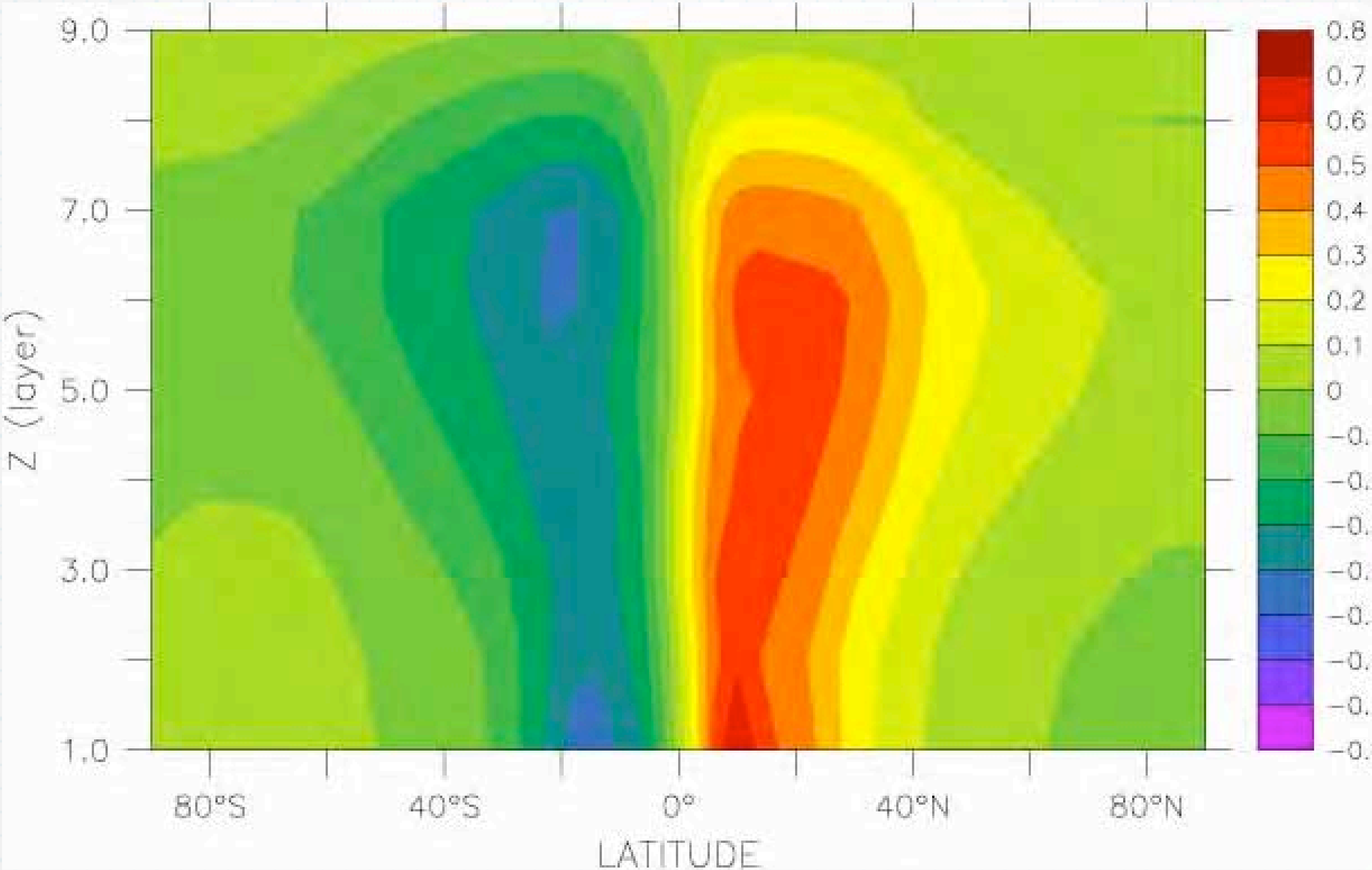
-28
-26
-24
-22
-20
-18
Delta notation

No Clear Evidence for C_4!

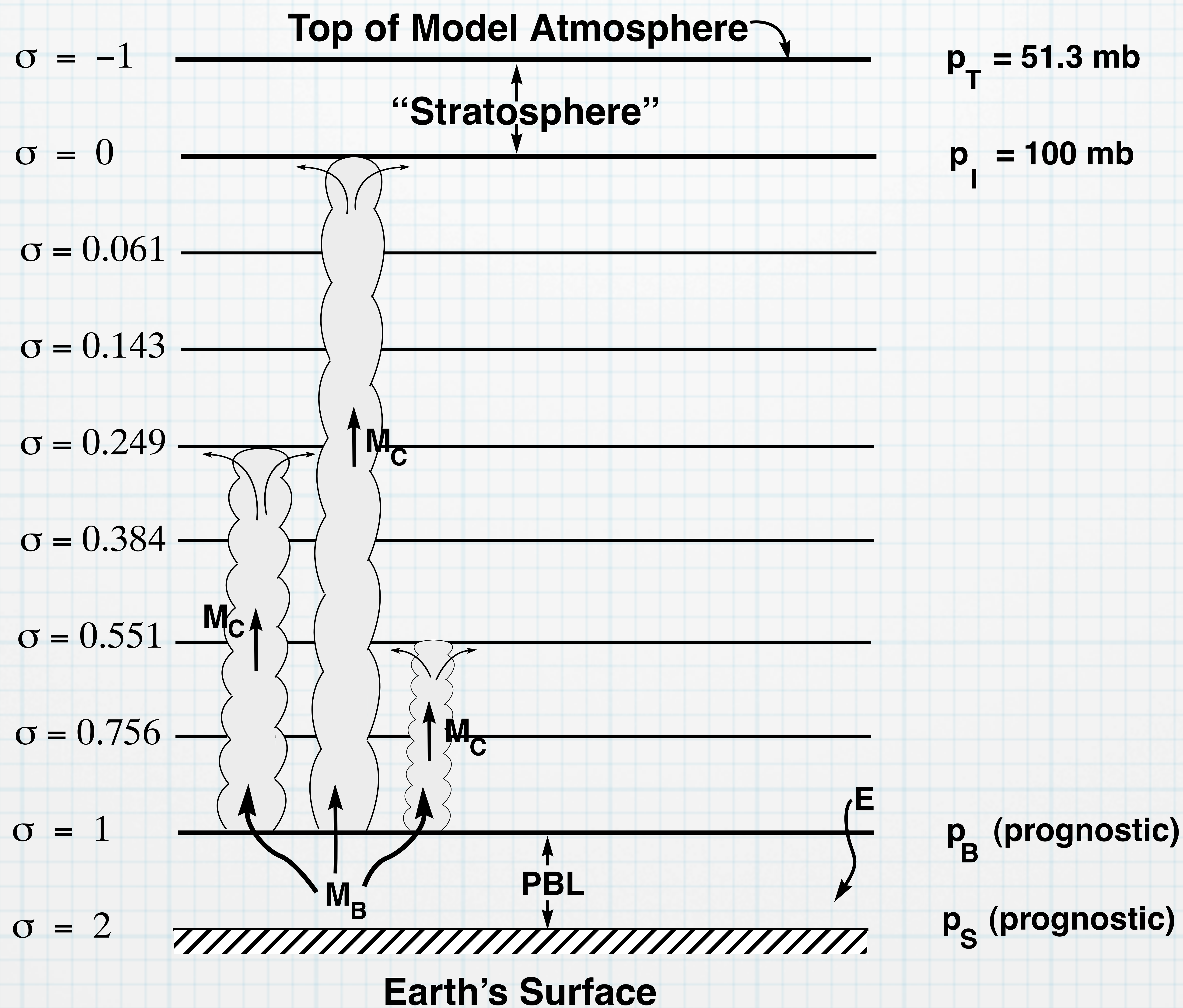
BAKWIN ET AL: ISOTOPIC DISCRIMINATION BY TERRESTRIAL BIOLOGY

Station	Location	δ_{bio}
BAL	Baltic Sea	-24.5
BMX	Bermuda	-24.1
CGO	Cape Grim, Tasmania	-20.8
GMI	Guam	-18.6
HUN	Hungary tower	-24.5
ITN	North Carolina tower	-24.4
IZO	Tenerife	-27.2
KEY	Key Biscayne, Florida	-22.7
KUM	Cape Kumukahi, Hawaii	-23.9
LEF	Wisconsin tower	-24.4
MHT	Mace Head, Ireland	-25.5
MID	Midway Island	-23.7
NWR	Niwot Ridge, Colorado	-24.6
SHM	Shemya Island, Alaska	-25.8
TAP	Tae-ahn Penninsula, Korea	-25.0
UTA	Utah desert	-23.2
UUM	Gobi desert	-26.2

Vertical Section (April-June)



(Chris Still & Inez Fung, unpublished)


Top of Model Atmosphere
σ = −1
p_T = 51.3 mb
"Stratosphere"
σ = 0
p_I = 100 mb
σ = 0.061
σ = 0.143
σ = 0.249
σ = 0.384
σ = 0.551
σ = 0.756
σ = 1
σ = 2
M_C
M_C
M_C
M_B
E
PBL
p_B (prognostic)
p_S (prognostic)
Earth's Surface

Conclusions V

- C_4 is a significant component of the carbon cycle.
- Nevertheless, we don't see a seasonal signal in the background atmosphere
- The C_4 signal goes up the ICTZ
- What about the C_3 signal in the tropics?

Conclusions

- Bio-molecules matter, and have snuck into some climate models.
- We lack a continuum of measurements to test and validate models at larger scales
- Lack of a mechanistic understanding of the control of stomatal conductance of leaves is important.
- Atmospheric trace gases and stable isotopologs of CO_2 and O_2 are useful tracers for biospheric processes
- These may also be useful tracers of circulation.
- noisy measurements limit validation/calibration