The carbon cycle

in the C-IFS model for atmospheric composition and weather prediction

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Copernicus
Europe's eyes on Earth

Funded by the European Union

Implemented by ECMWF

The carbon cycle

Interaction between all the Earth system components

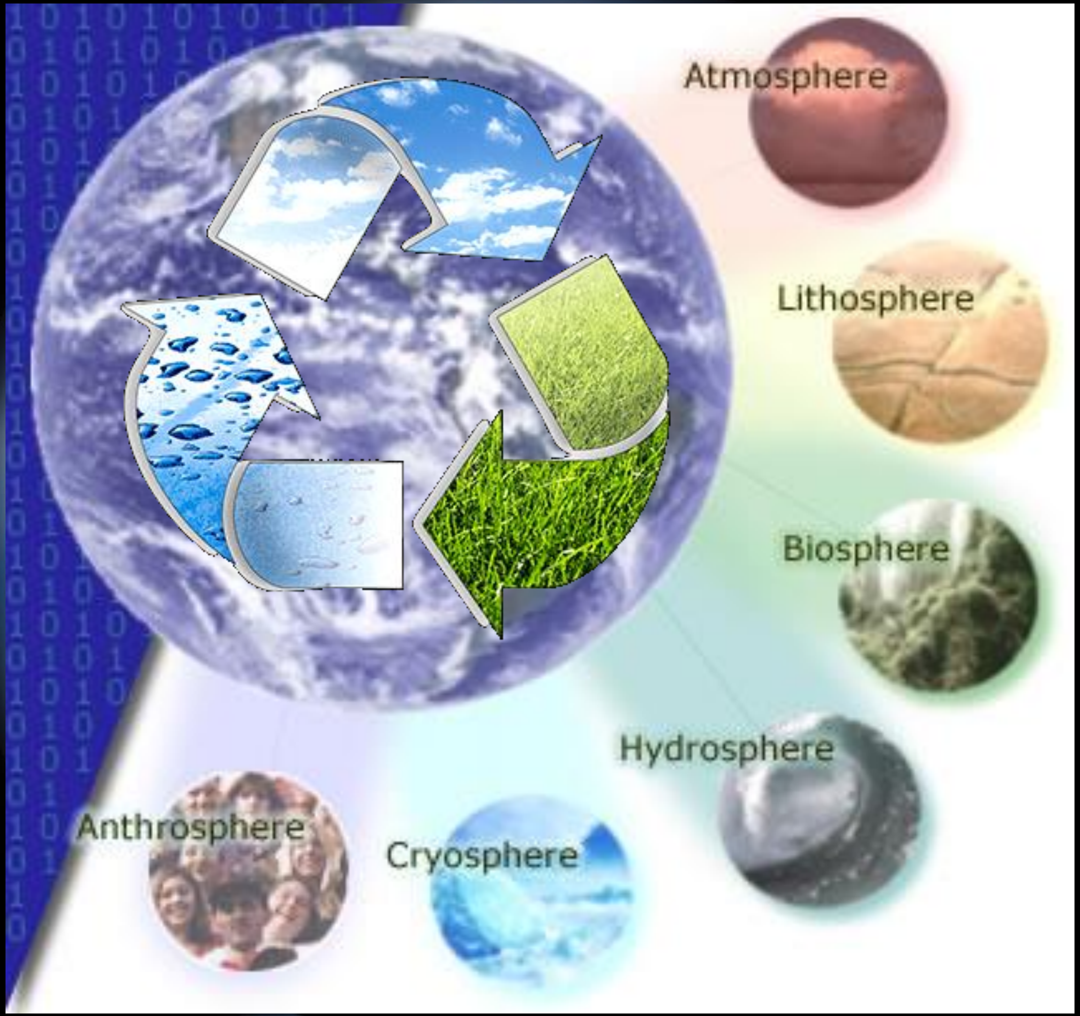
- Carbon reservoirs and their interactions with the atmosphere (focusing on CO_2 primarily).

- Can carbon cycle – climate feedbacks improve atmospheric predictive skill?

Vegetation, radiative transfer, atmospheric chemistry

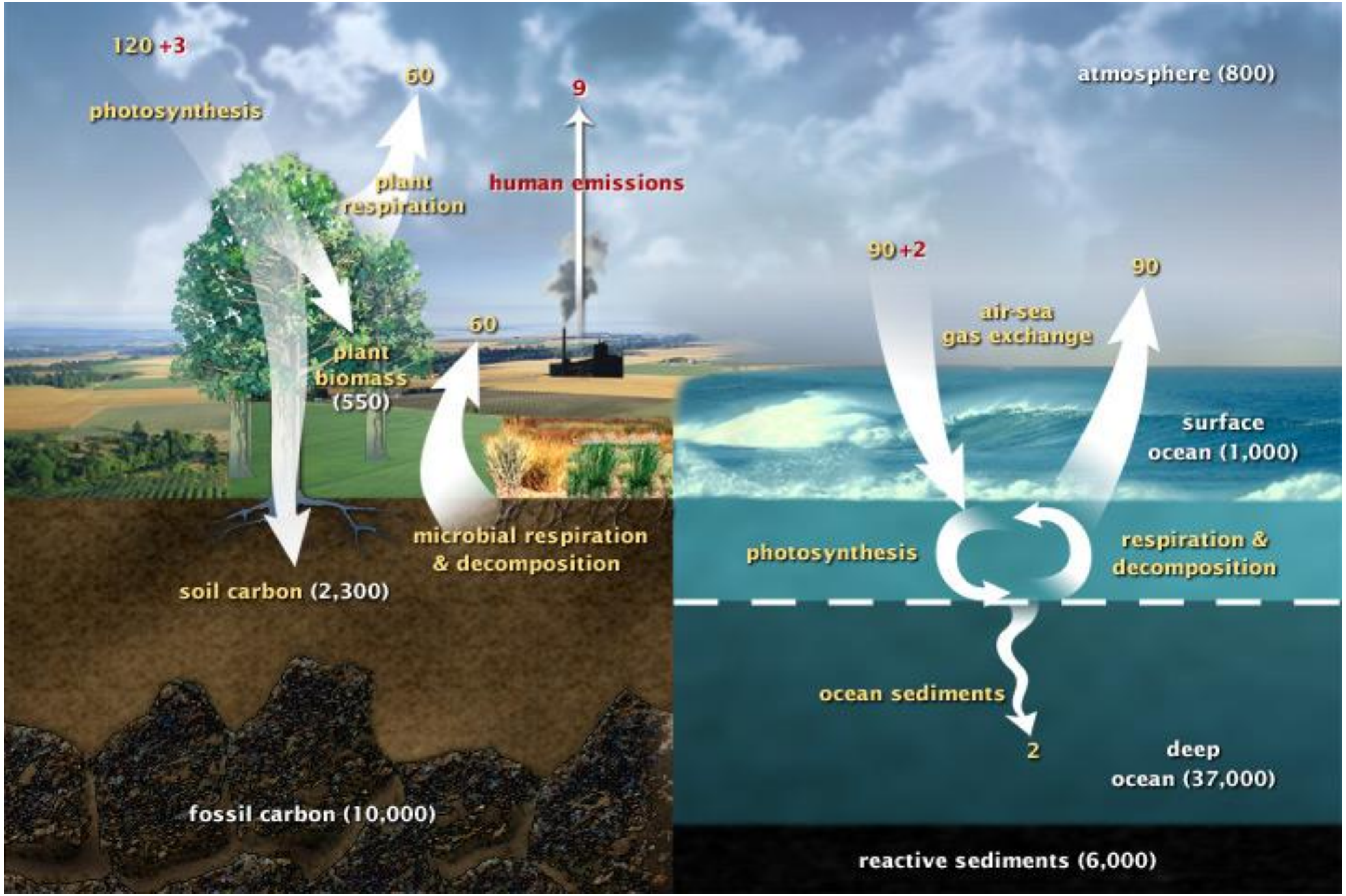
- Atmospheric CO_2 and CH4 analysis and forecast (Copernicus Service)

Funded by the European Union



The 'spheres' of influence on the climate system.
Source from Institute for Computational Earth System Science(ICESS)

The atmospheric reservoir in the fast carbon cycle (annual time-scale)



Source: http://earthobservatory.nasa.gov/Features/CarbonCycle/
(Diagram adapted from U.S. DOE, Biological and Environmental Research Information System.)

Movement of carbon between land, atmosphere, and oceans:

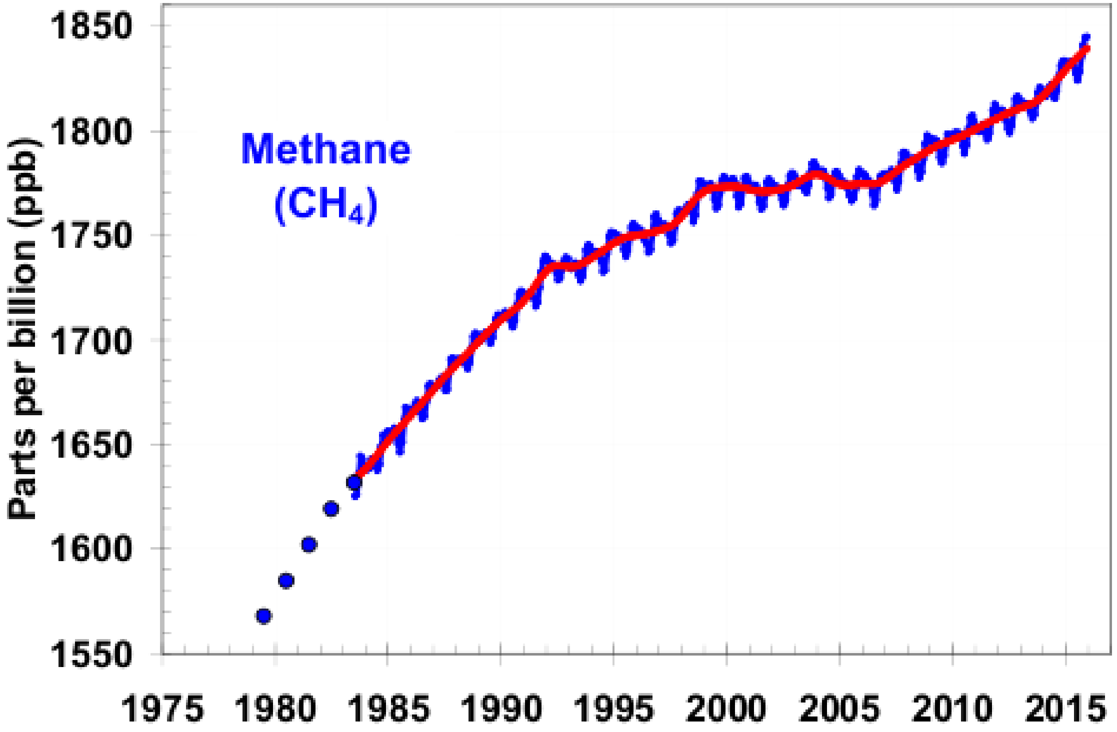
Yellow numbers are **natural (balanced fluxes)**

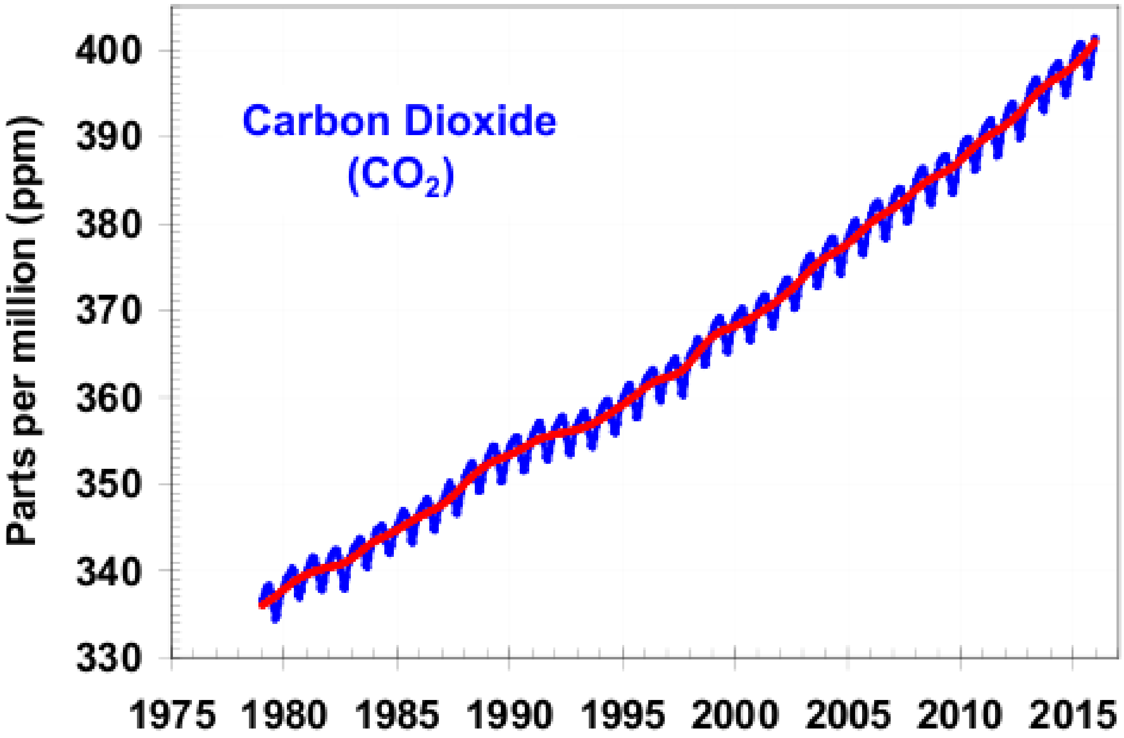
Red are human contributions (perturbing balance)

[Units: in Gigatons of carbon per year]

White numbers: stored carbon [Gigatons of carbon].

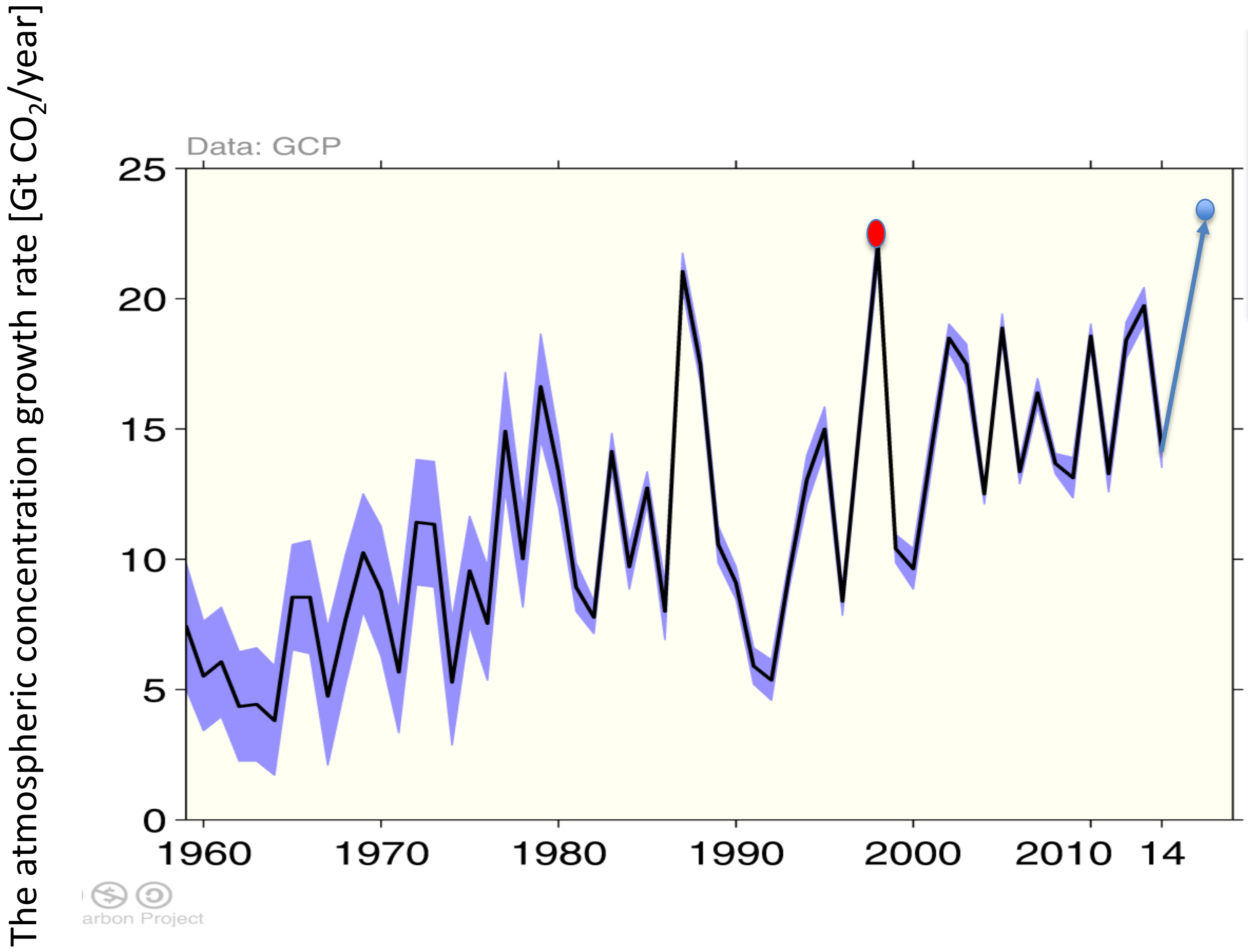
The atmospheric reservoir: surface observations





THE NOAA ANNUAL GREENHOUSE GAS INDEX (AGGI).

CO_2 growth rate in the atmospheric reservoir



In 2015 CO_2 increased by 3 ppm
~ 23 $GtCO_2$/year:

(droughts associated and fires during el Nino episodes)

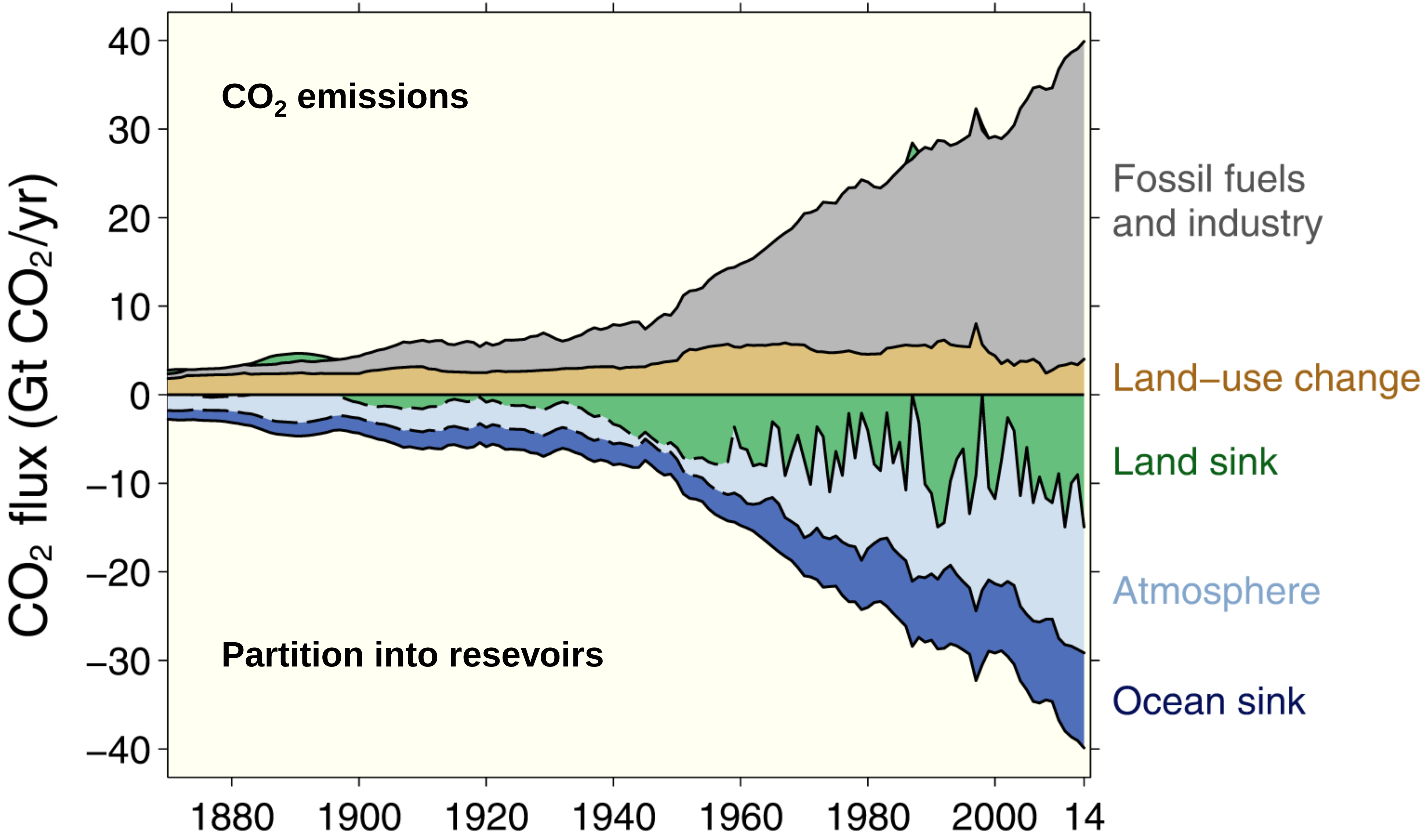
15 $GtCO_2$/year ~ 2 ppm/year on average for last 10 years

In 1997-1998 el Nino
CO_2 increased by 2.8 ppm

Source: NOAA-ESRL; Global Carbon Budget 2015, LeQuere et al., 2015

Global carbon budget

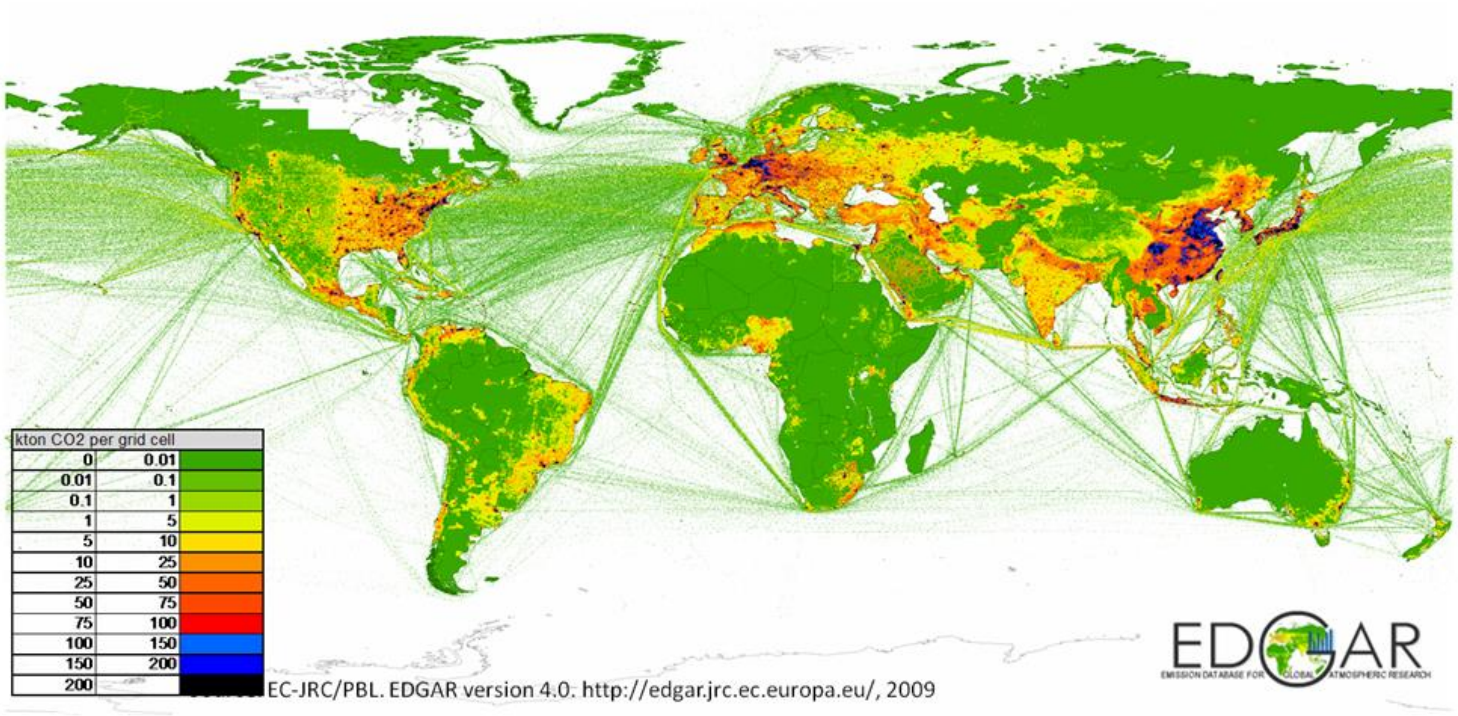
Data: CDIAC/NOAA–ESRL/GCP/Joos et al 2013/Khatiwala et al 2013



Global Carbon Budget 2015, LeQuere et al., 2015

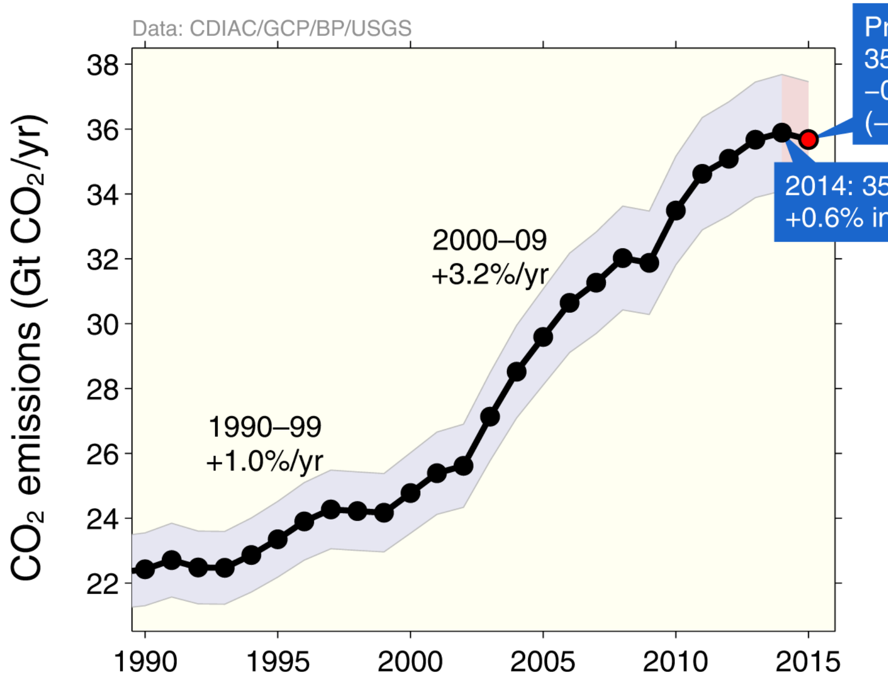
Global Carbon Project

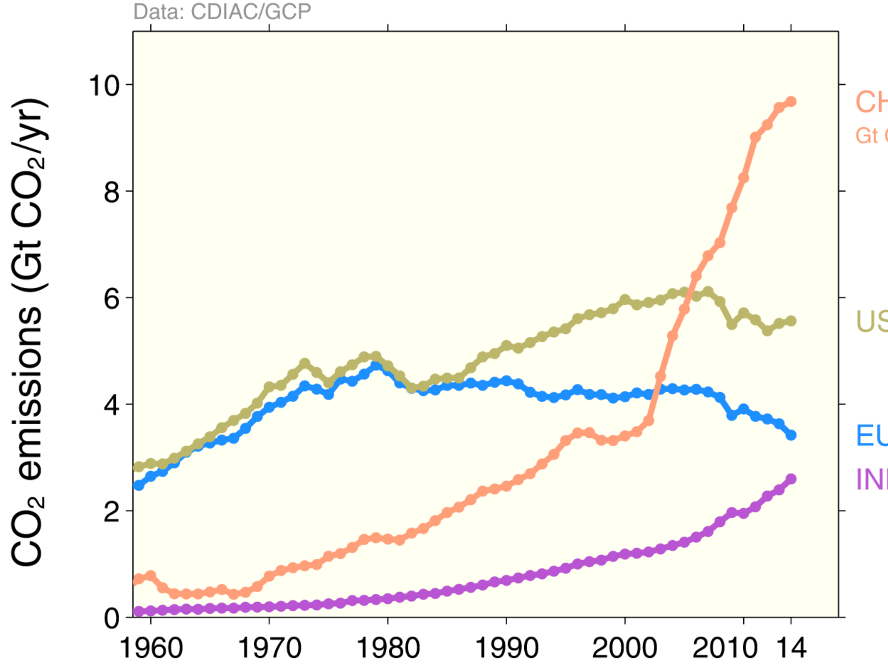
ANTHROPOGENIC FLUXES



EDGAR v4.2 inventory of anthropogenic emissions (excluding land-use change)

Source: EDGAR database

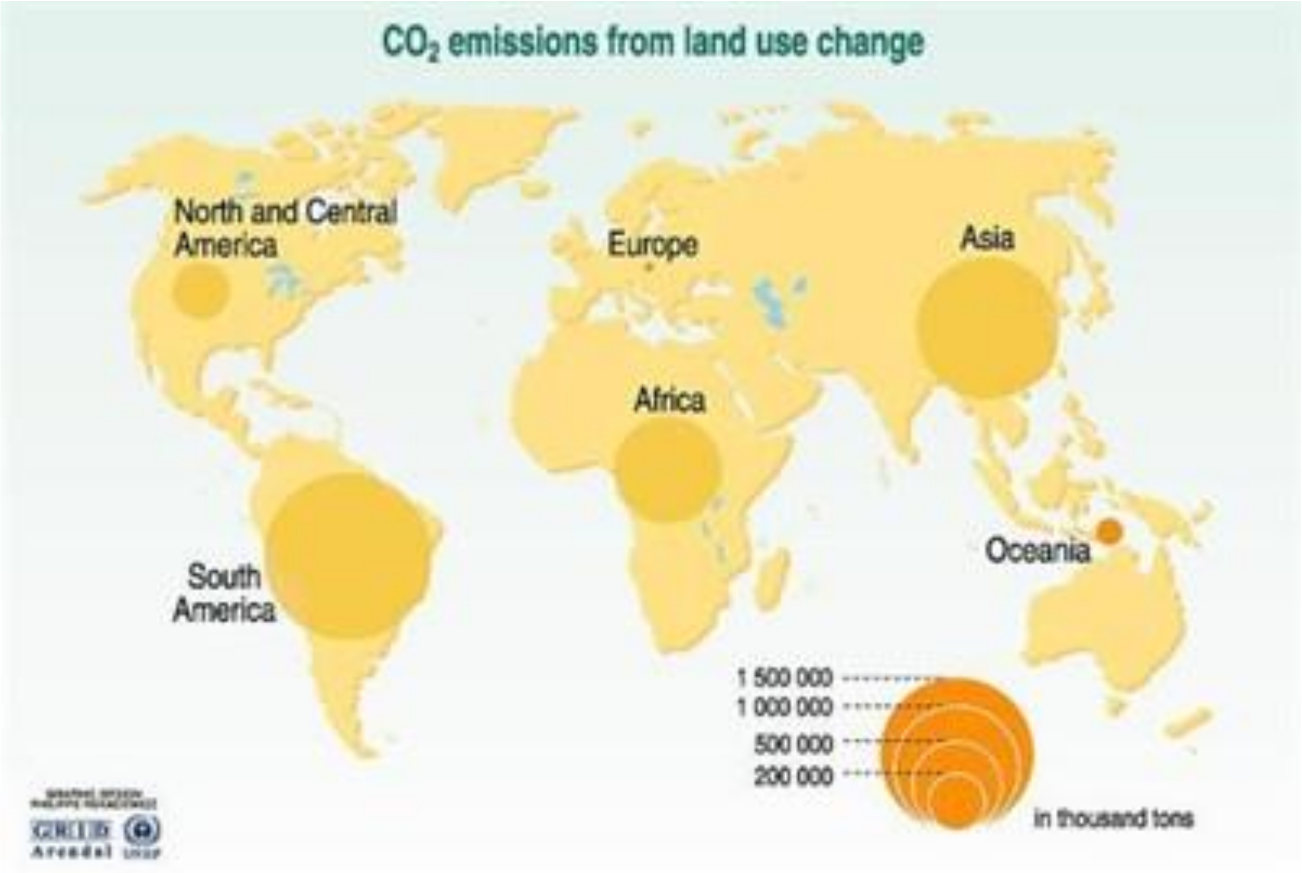




Global Carbon Project

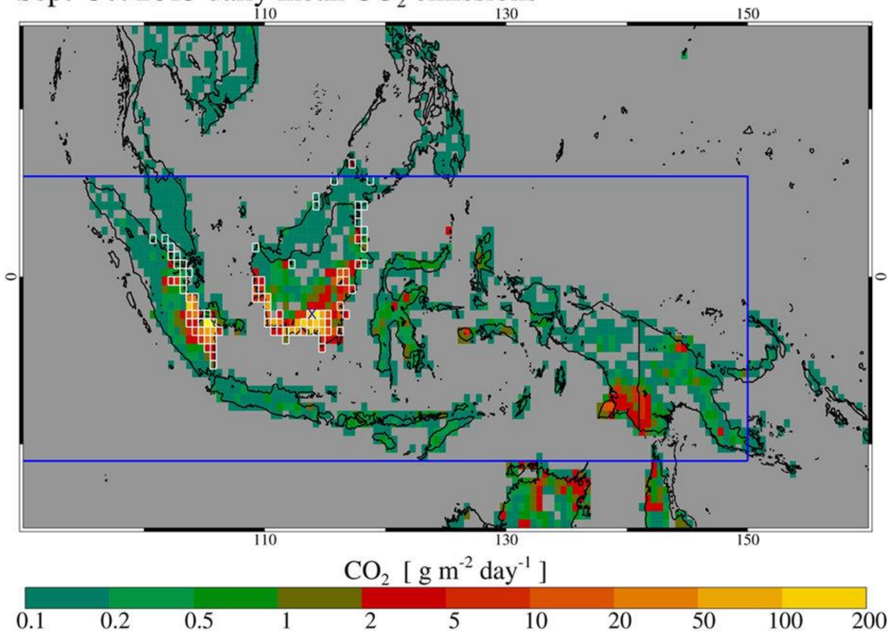
Source: Global Carbon Budget 2015; CDIAC

CO_2 emissions: land-use change

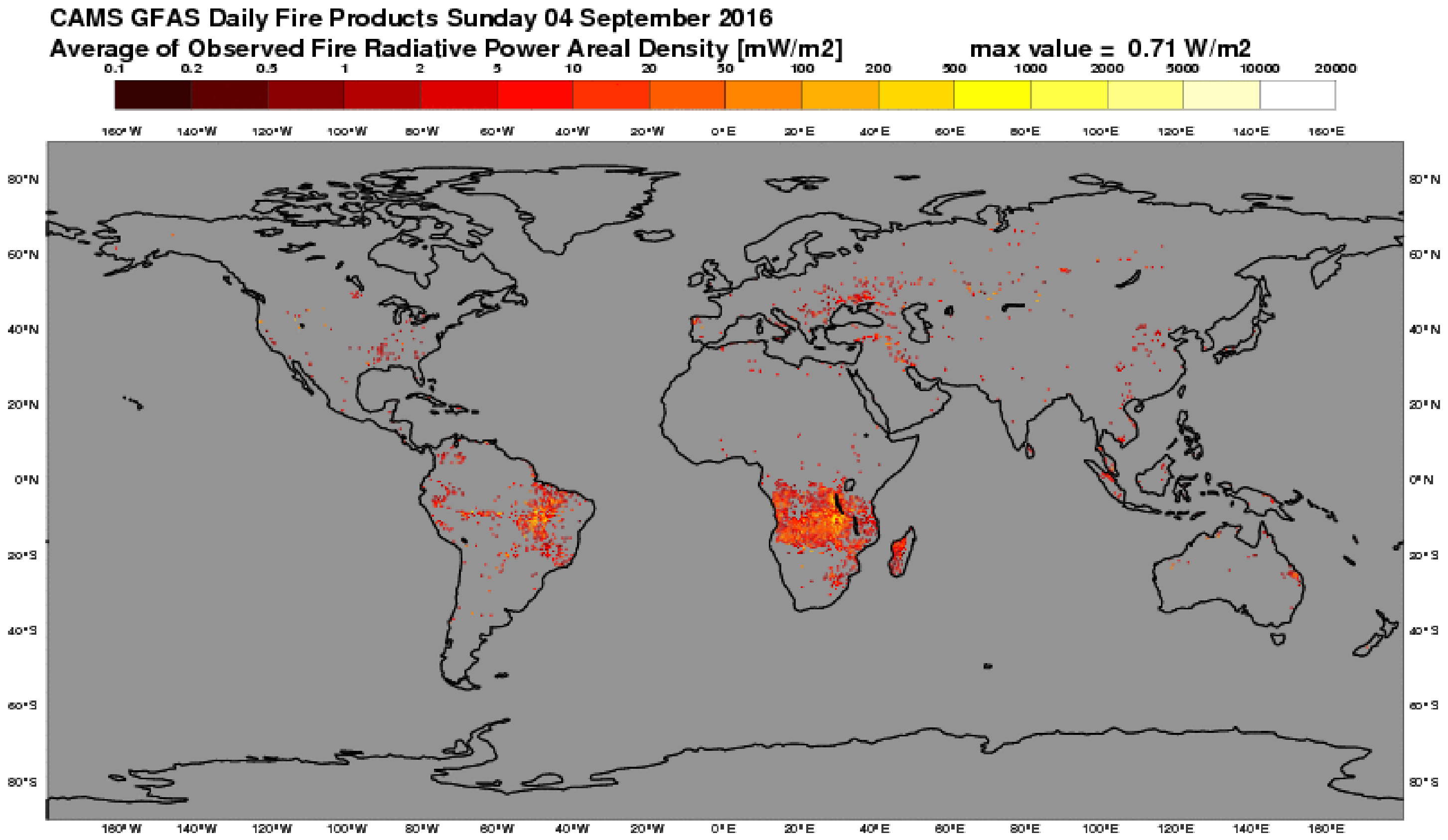


Source : Climate Change Information kit, UNEP IUC, 1997.

CO_2 emissions: land-use change by burning biomass


Sept-Oct 2015 daily mean CO_2 emissions

GFAS daily fire product available 1 day behind real time


CAMS GFAS Daily Fire Products Sunday 04 September 2016

Average of Observed Fire Radiative Power Areal Density [mW/m2] max value = 0.71 W/m2

GFAS CO2 emissions over Indonesia (Sep-Oct 2015):

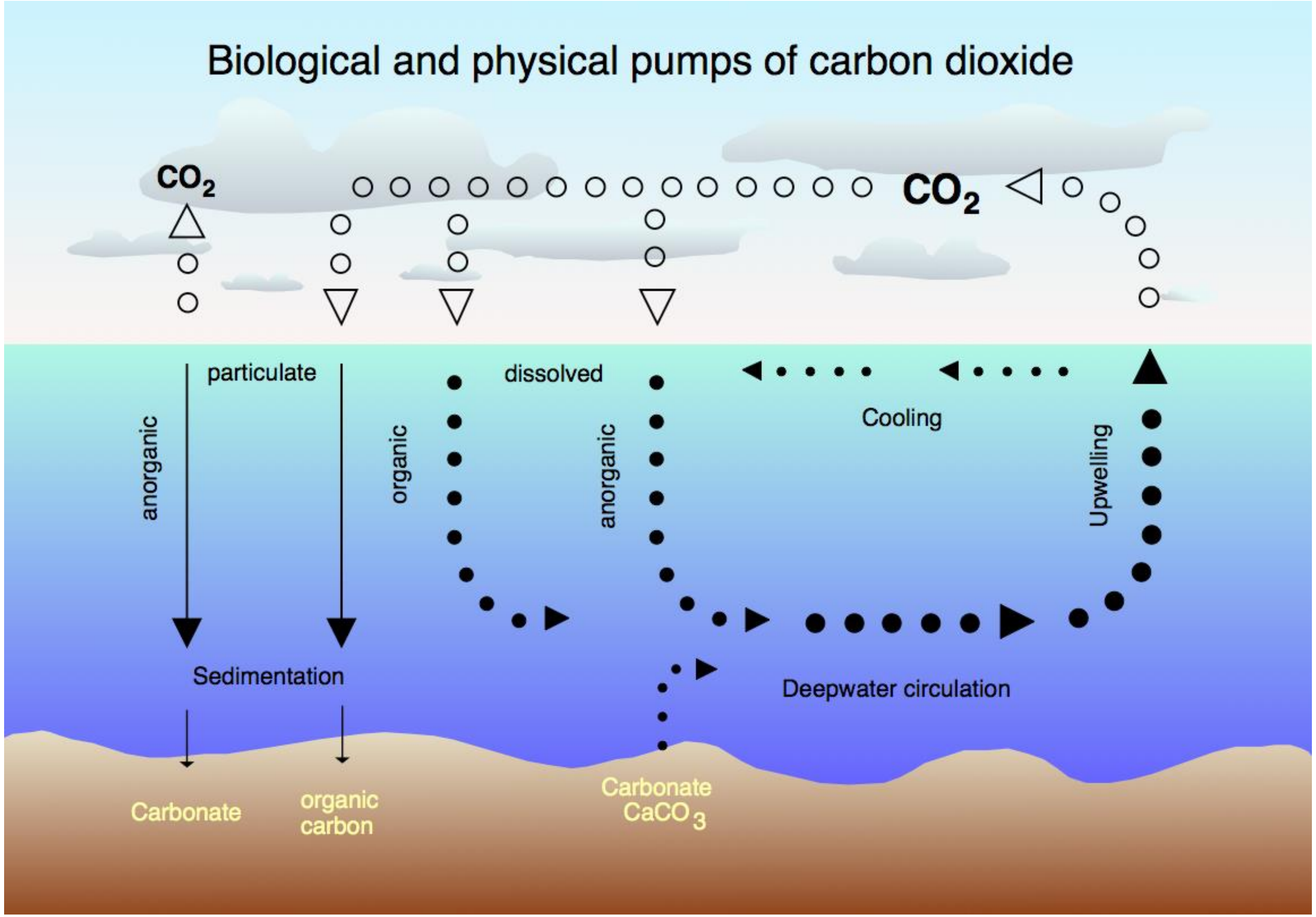
Fires contribute to el Nino signal
in the atmospheric CO_2 growth rate

The ocean reservoir in the carbon cycle

Solubility pump
(inorganic carbon)

Ocean circulation
(long timescales)

Biological pump
(organic carbon)



Wikipedia: Hannes Grobe 21:52, 12 August 2006 (UTC), Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

The CO_2 ocean-atmosphere fluxes

Climatology of monthly mean ocean fluxes from Takahashi et al. (2009) used in C-IFS

Observations of pCO_2 at the surface of the ocean and in the atmosphere with transfer coefficients based on turbulent exchange.

Regions of sources and sinks associated with **upwelling** and **downwelling** regions

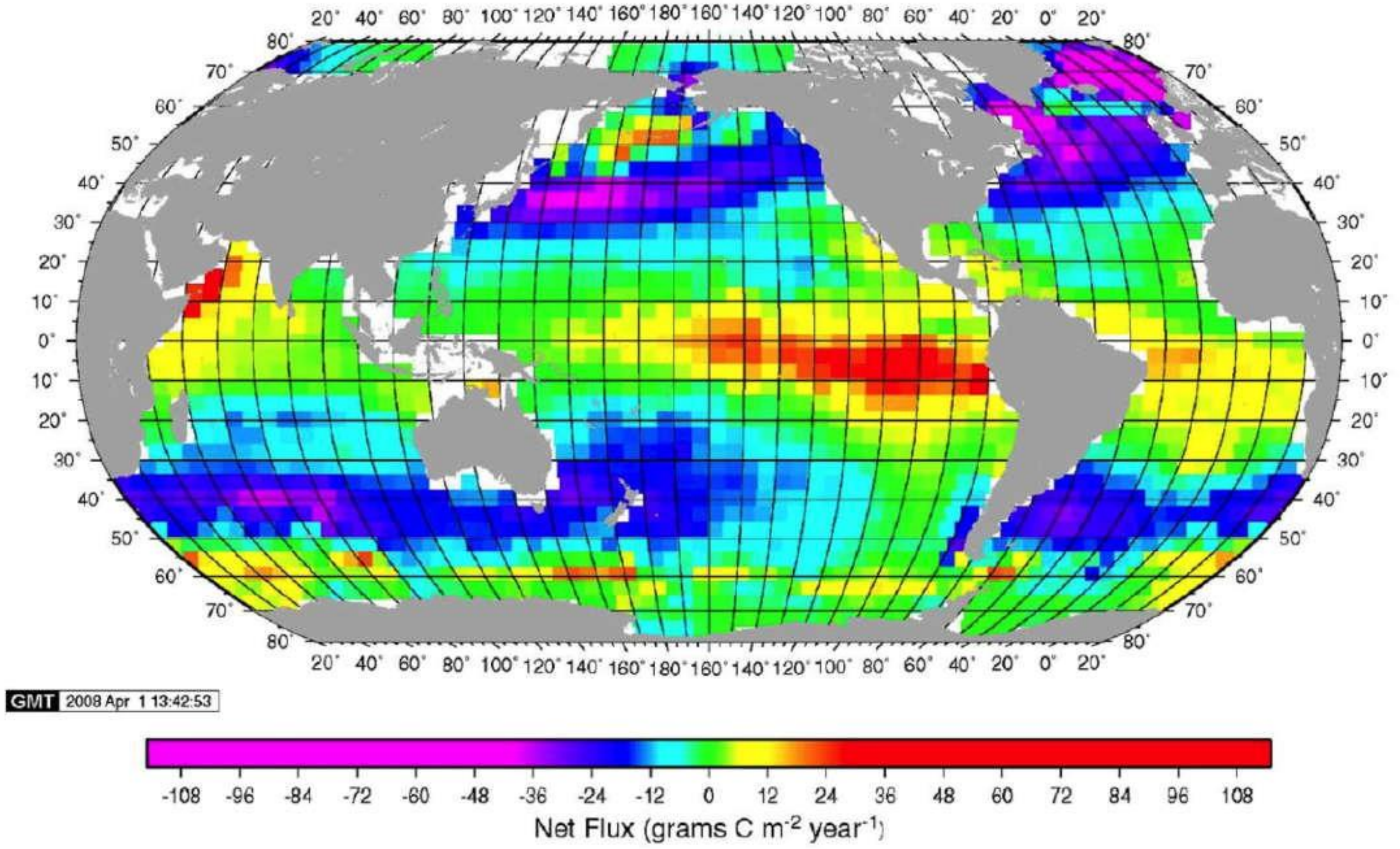


Fig. 13. Climatological mean annual sea–air CO_2 flux (g-C m^{-2} yr^{-1}) for the reference year 2000 (non-El Niño conditions). The map is based on 3.0 million surface water pCO_2 measurements obtained since 1970. Wind speed data from the 1979–2005 NCEP-DOE AMIP-II Reanalysis (R-2) and the gas transfer coefficient with a scaling factor of 0.26 (Eq. (8)) are used. This yields a net global air-to-sea flux of 1.42 Pg-C y^{-1}.

Takahashi et al. (2009)

The terrestrial CO_2 fluxes

- Strong link with water and energy fluxes

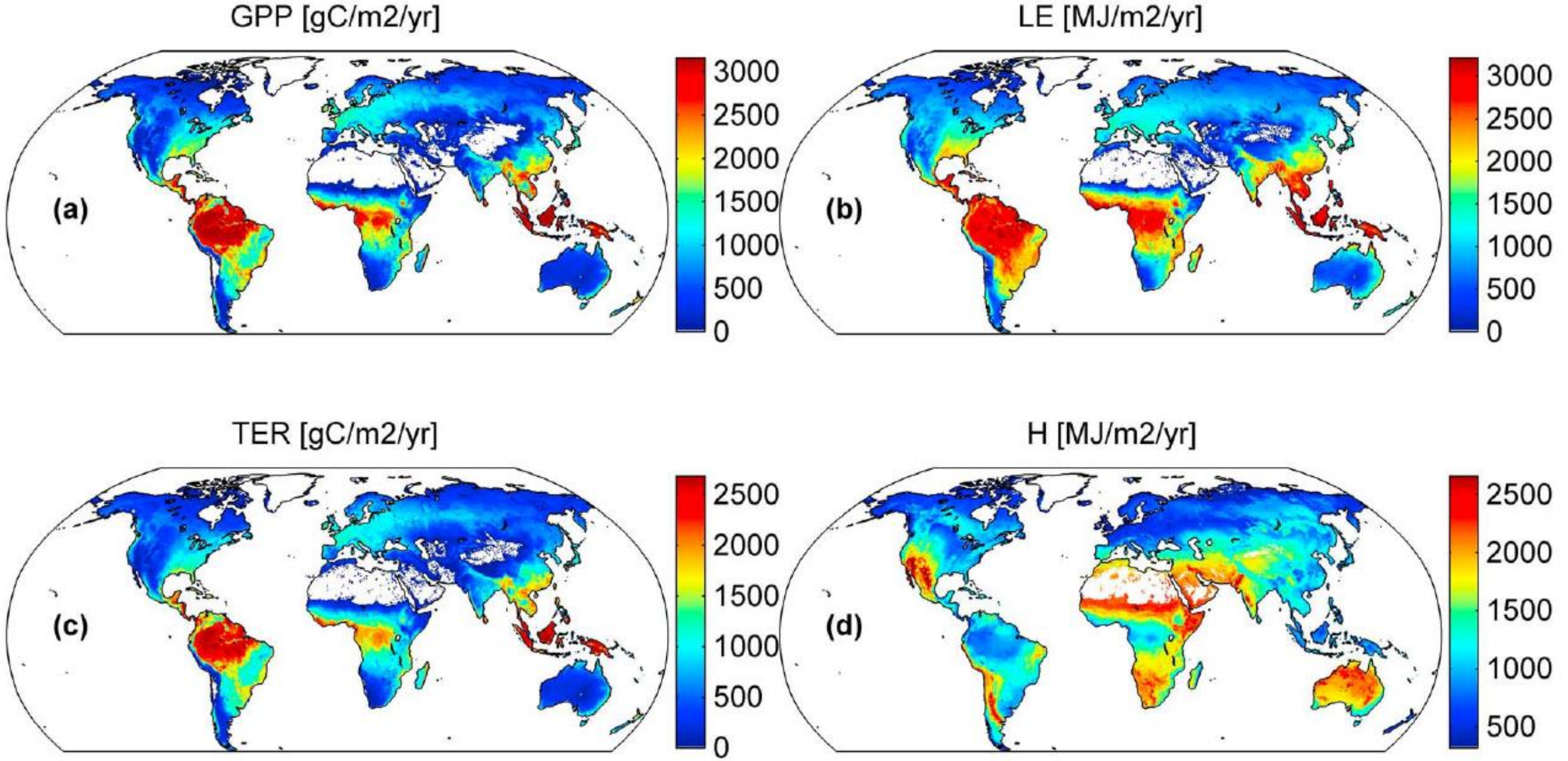


Figure 3. Mean annual (1982–2008) (a) GPP, (b) LE, (c) TER, and (d) H derived from global empirical upscaling of FLUXNET data.

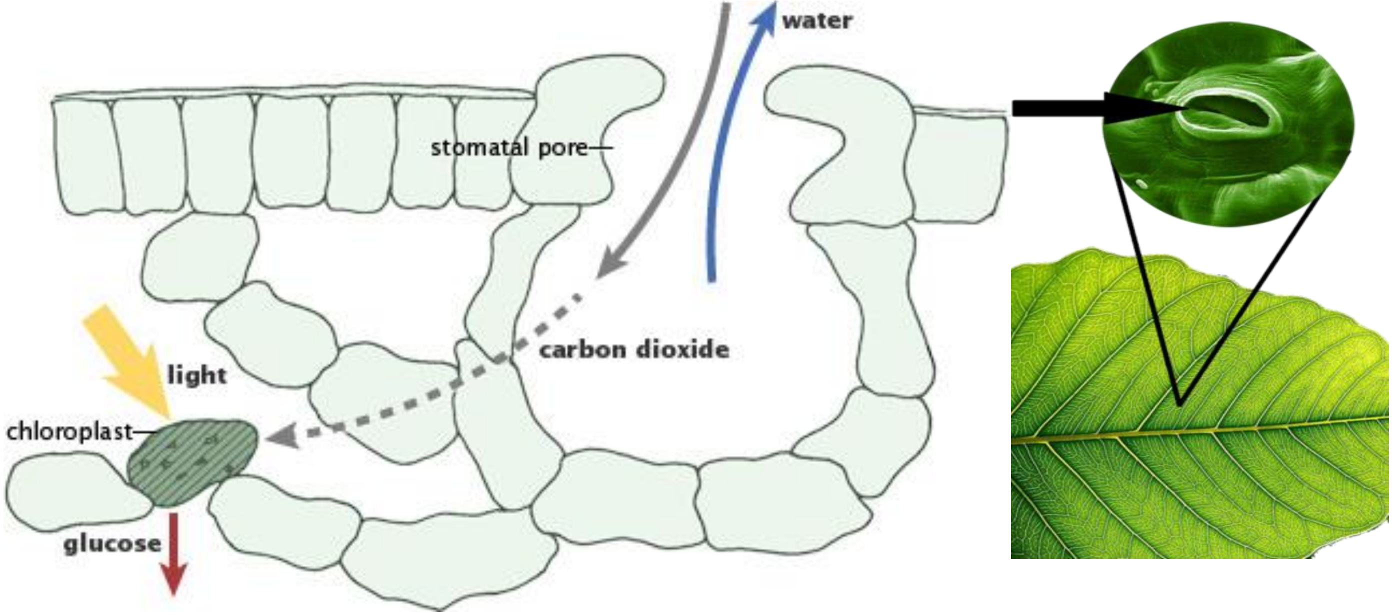
Jung et al. (2011)

Terrestrial carbon flux : Exchange between the biosphere and the atmosphere

Atmospheric CO_2 sink (Gross Primary Production):

Photosynthesis (plants)

$$CO_2 + H_2O + \text{energy} \longrightarrow CH_2O + O_2$$



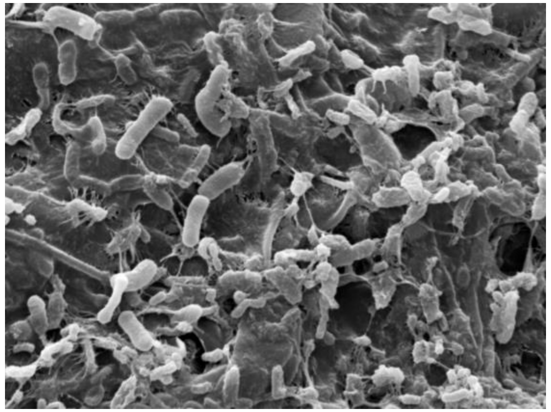
Atmospheric CO_2 source (Ecosystem Respiration):

Respiration (plants, animals)

$$CH_2O + O_2 \longrightarrow CO_2 + H_2O + \text{energy}$$

$$CH_2O \longrightarrow CH_4 + \text{energy}$$ ***in anoxic conditions***

+ decomposition of organic carbon in soil by microbes

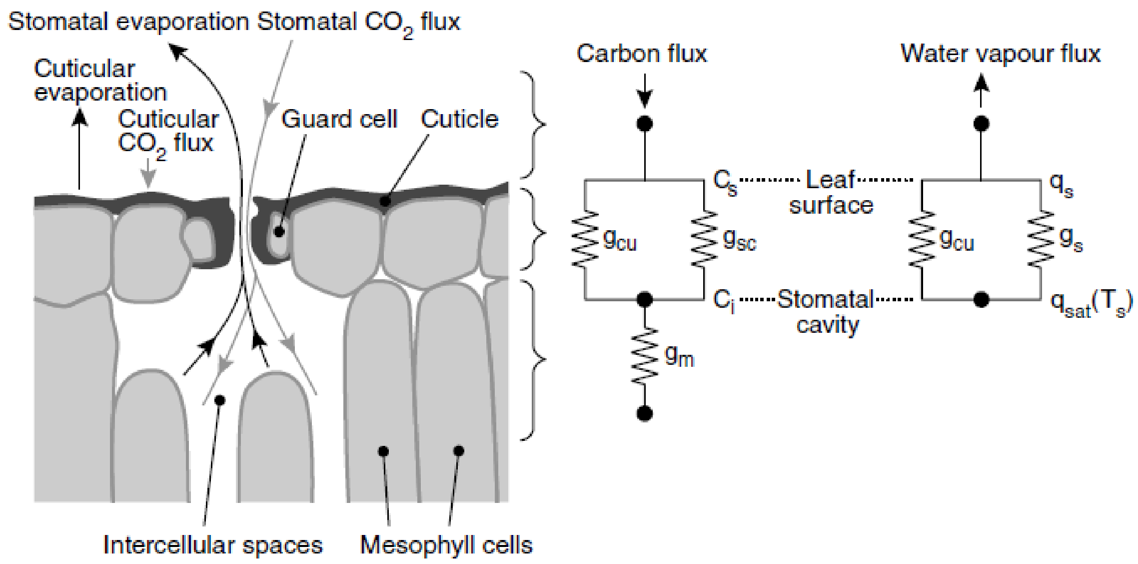


earthobservatory.nasa.gov/Features/CarbonCycle. Illustration adapted from Sellers et al., 1992

Credit: © Raphael Gabriel

Modelling CO$_2$ uptake by plants (GPP) in C-IFS

BOUSSETTA ET AL.: LAND CO$_2$ WITHIN THE ECMWF SYSTEM



$$r_s = \frac{1}{g_s}$$

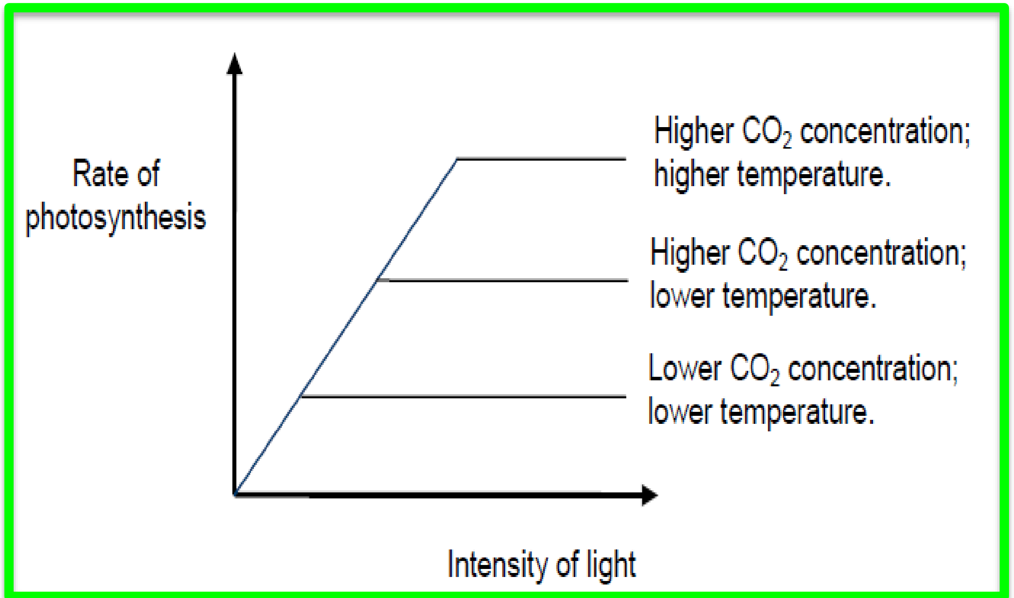
$$g_s = \frac{A_n}{(C_s - C_i)}$$

Environmental factors:

- Temperature
- PAR (solar radiation)
- Soil moisture
- Atm. wv deficit
- Atm. CO2

Biological factors:

- Mesophyll conductance



+ Soil moisture stress function

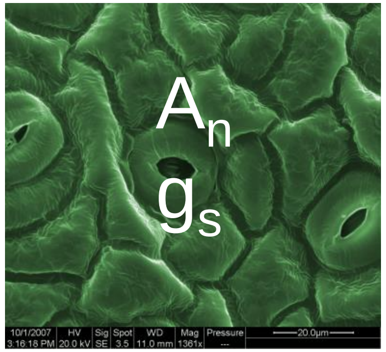
$$C_s - C_i = f(D_s, r_m)$$

$$C_s = 340\,ppm$$

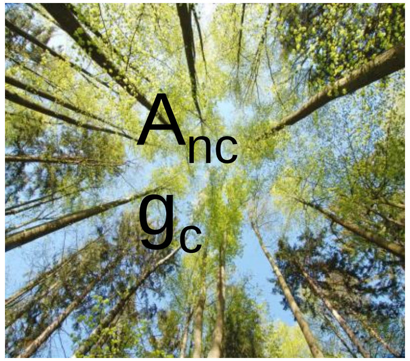
CTESSEL parameterisation based on ISBA-Ags
Jacobs (1994), Calvet et al., 1998,2000, Lafont et al. 2012, Boussetta et al. (2013)

Modelling CO_2 uptake by plants (GPP) in C-IFS

LEAF STOMATA

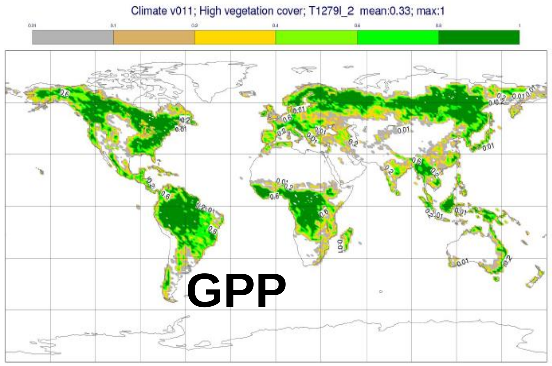


CANOPY



Upscaling to canopy with **LAI** climatology from MODIS

MODEL FLUXES



Upscaling to model grid point with **vegetation dominant type/cover**

CTESSEL parameterisation based on ISBA-Ags Jacobs (1994), Calvet et al., 1998,2000, Lafont et al. 2012, Boussetta et al. (2013)

Modelling soil respiration

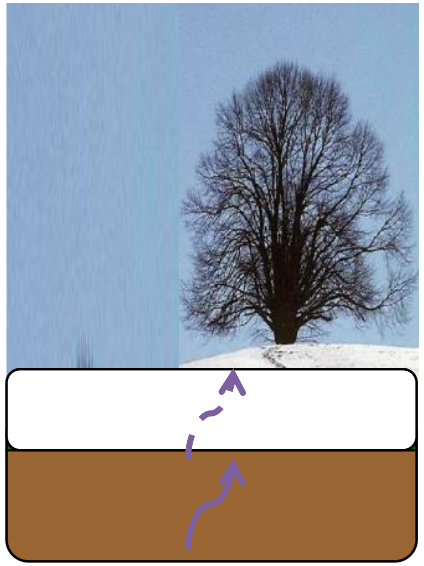
$$\boxed{R_{soil} = R_0 Q_{10}^{(0.1(T_{soil}-25))} f_{sm}} \Rightarrow R_{soil} = R_0 e^{-\alpha.Z_{snow}} Q_{10}^{(0.1(T_{soil}-25))} f_{sm}$$

Environmental factors:

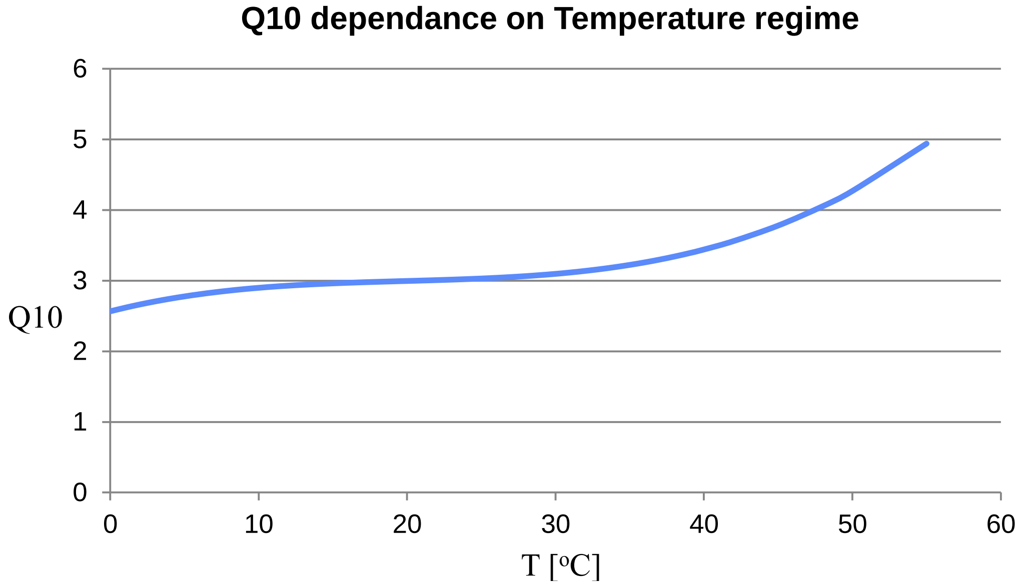
- Temperature
- Soil moisture
- Snow depth

Biological factors:

- Organic carbon in soil and microbial activity (R0 parameter)



Including a snow attenuation effect on the soil CO2 emission

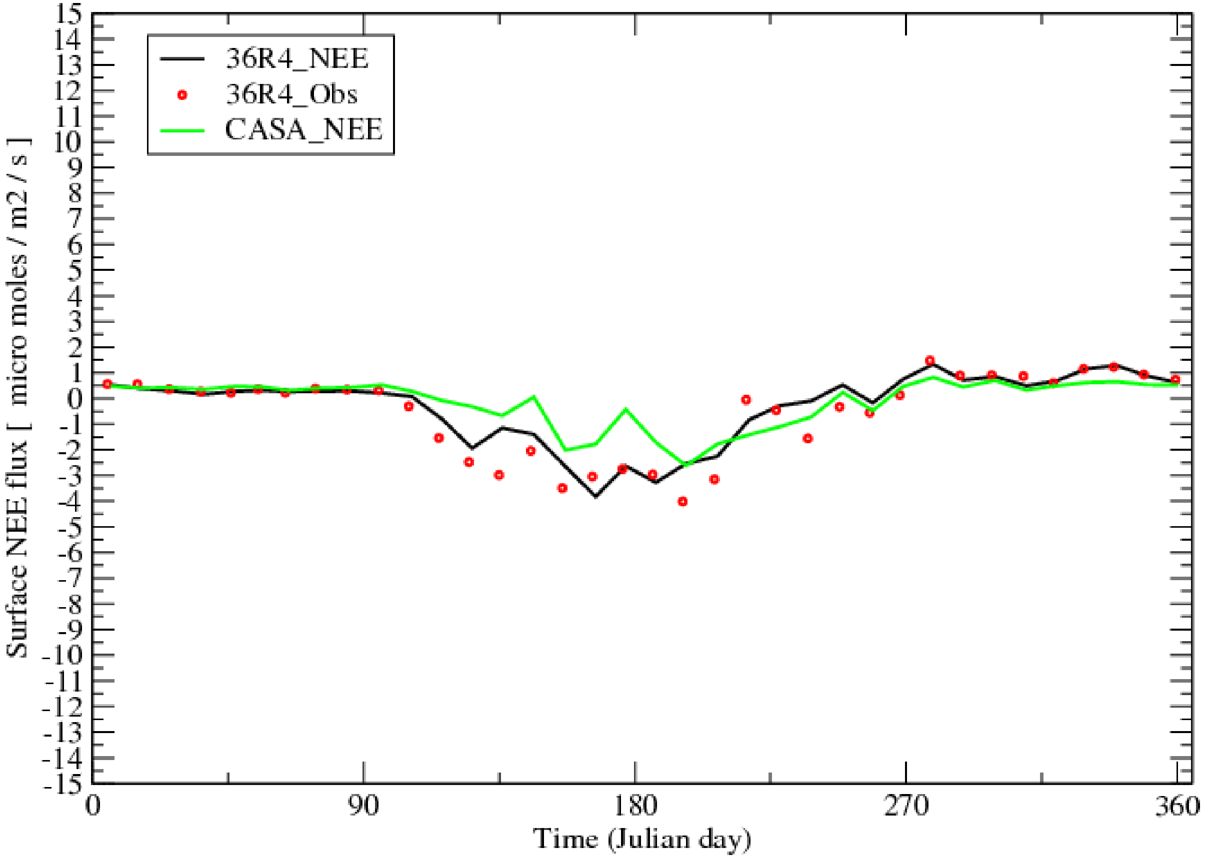


Including a temeperature dependancy on the Q10 parameter (McGuire et al., 1992)

Boussetta et al. (2013)

Evaluation of CO_2 ecosystem fluxes from CTESSEL in IFS

Example of NEE (micro moles /m^2/s) predicted over the site Fi-Hyy (FINLAND) by **CTESSEL (black line)** and CASA-GFED3 (green-line) compared to FLUXNET observations



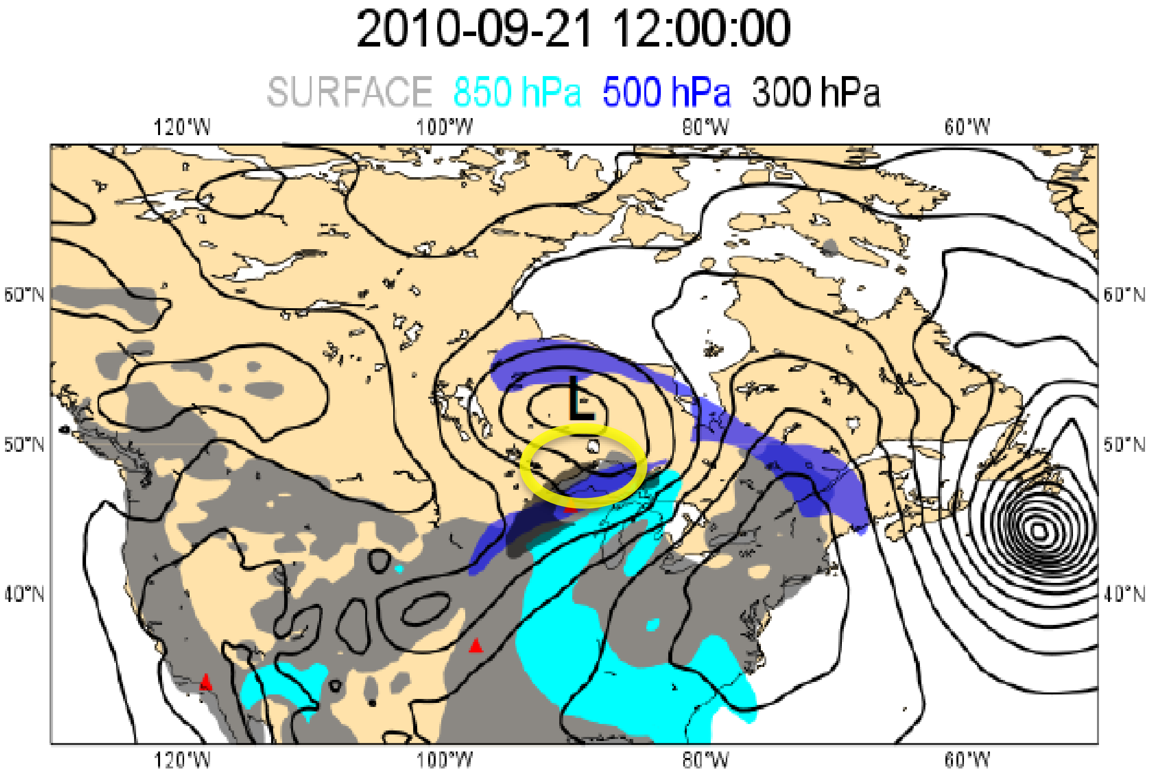
Boussetta et al. (2013)

Scheme	**NEE rmse**	**NEE bias**	**NEE corr**
CTESSEL	3.736	-1.656	0.536
CASA	1.872	0.739	0.297

Modelling atmospheric CO_2 in C-IFS

Synoptic variability of NEE is important for the CO2 synoptic variability in the BL

In the warm sectors of low pressure systems:



synergy between advection and CO_2 ecosystem fluxes:

cloudy **reduction of CO2 uptake** **More CO_2** **Enhanced atmospheric CO_2 anomaly**
warm **increase in respiration**

Agusti-Panareda et al. ACP 2014

Modelling atmospheric CO_2 in C-IFS

CO_2 surface fluxes & column-averaged dry-air mole fraction of CO_2 [ppm]

Transport

IFS model

Fluxes

Vegetation (CTESSEL model)

Source ○

Sink ○

Fires (GFAS) △

Ocean (Takahashi et al 2009)

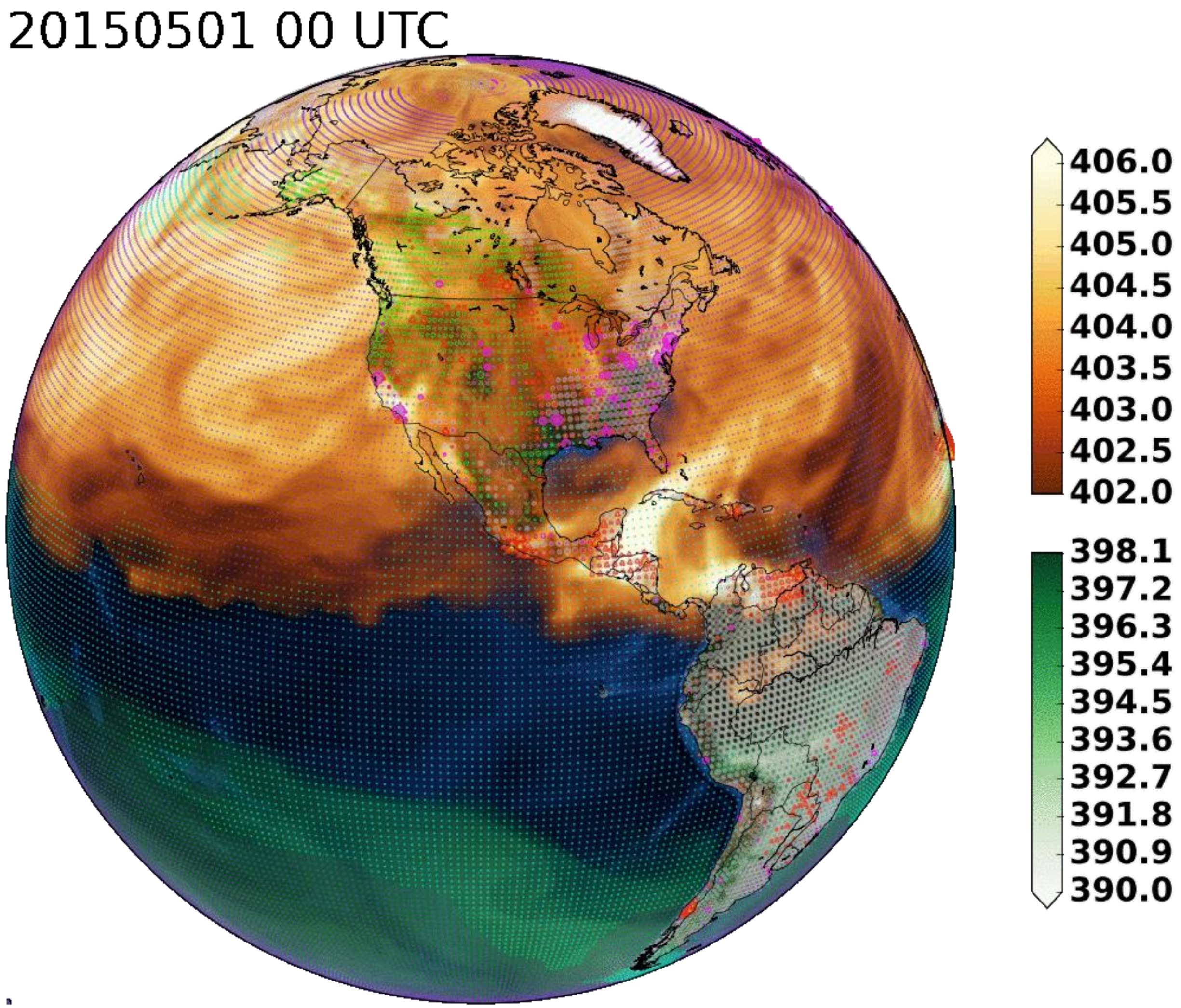
Source ○

Sink ○

Anthropogenic ●

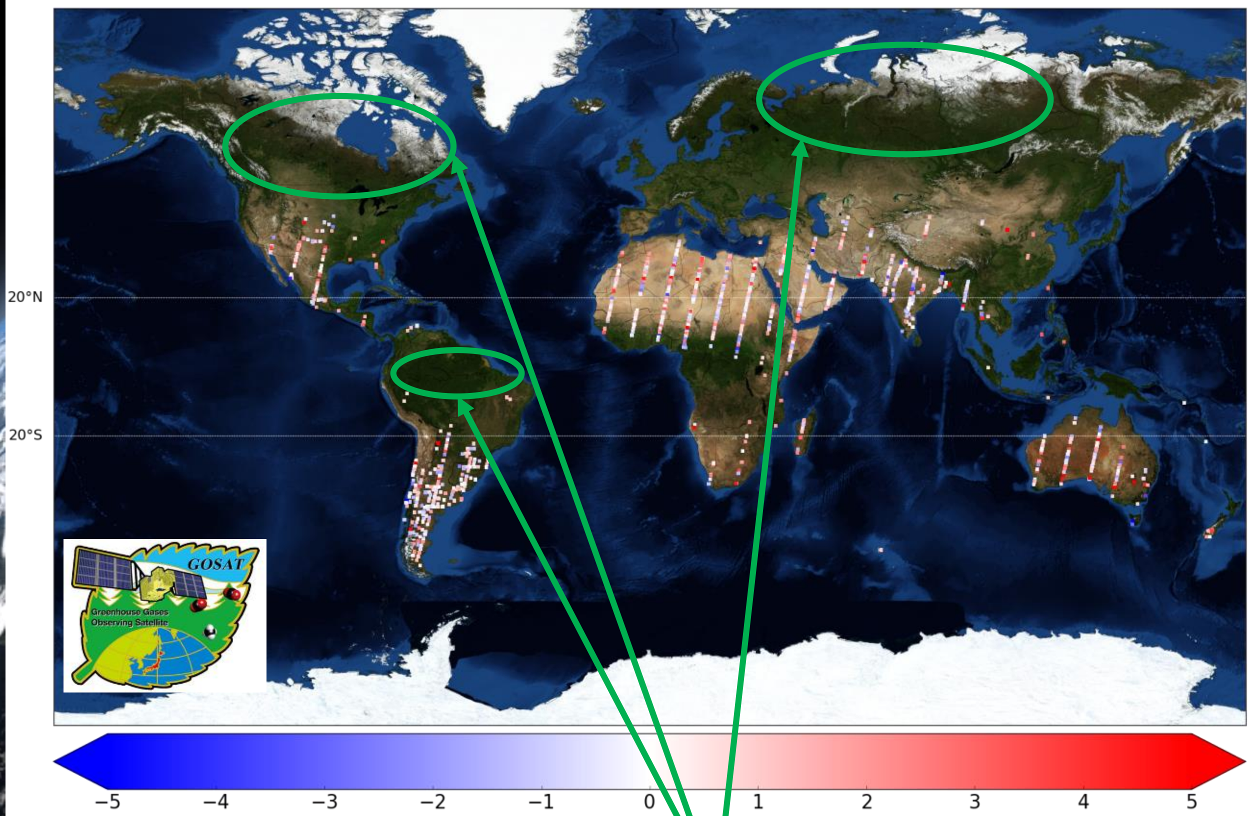
(EDGAR v4.2)

Symbol size reflects the relative flux intensity
(Note that fires have been re-scaled by a factor of 10)



Agusti-Panareda et al. ACP 2014

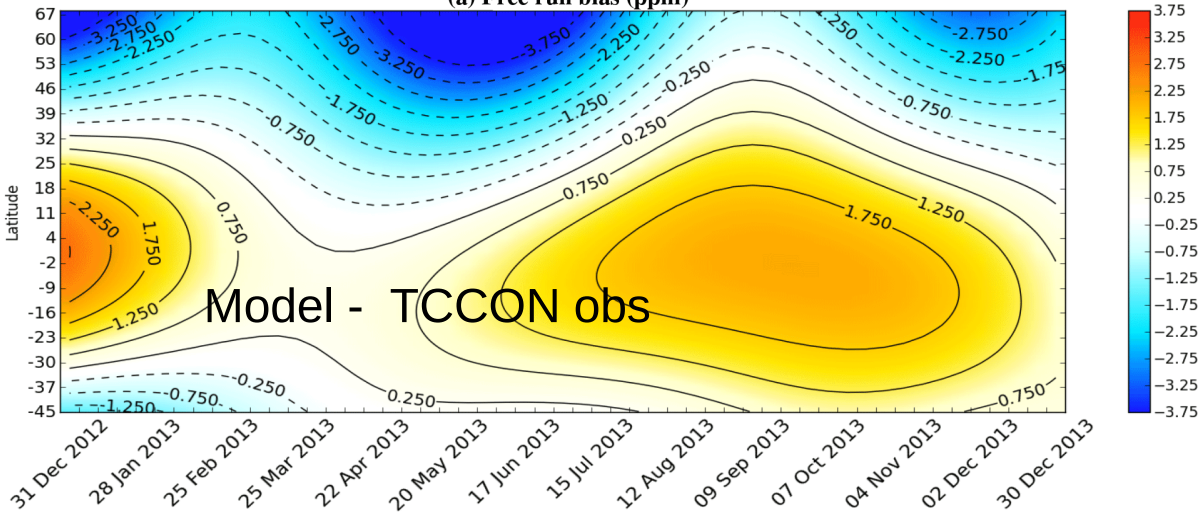
GOSAT analysis (28 November 2014 – 14 December 2014)



Analysis departure (o-a)
In ppm for GOSAT data

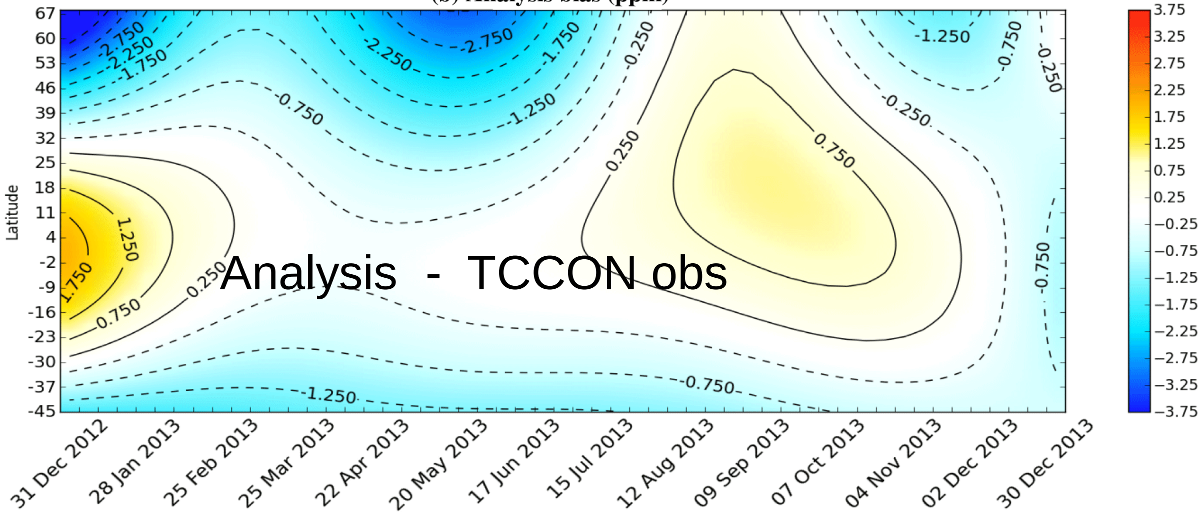
No or few GOSAT data to constrain the analysis in these regions

(a) Free run bias (ppm)



Model - TCCON obs

(b) Analysis bias (ppm)



Analysis - TCCON obs

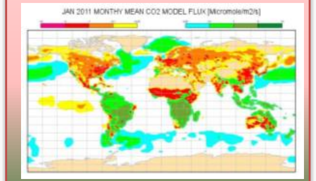
TCCON
total carbon column observing network

Massart et al. ACP 2015

Correcting atmospheric CO_2 biases with Biogenic Flux Adjustment Scheme (BFAS)

ARCHIVED DATA

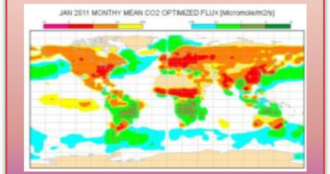
MODELLED FLUXES
CAMS CO_2 FC



BUDGET

EPS FORECAST/HINDCAST

OPTIMIZED FLUXES
MACC (LSCE)

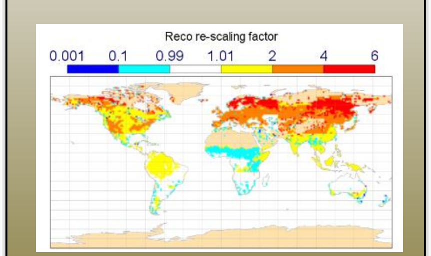


REFERENCE BUDGET

BFAS

Compares budgets

Re-scaling maps for biogenic fluxes from CTESSEL



CAMS CO_2 modelling (IFS)

CO_2 SURFACE FLUXES

CTESSEL model

Adjusted Net Ecosystem Fluxes

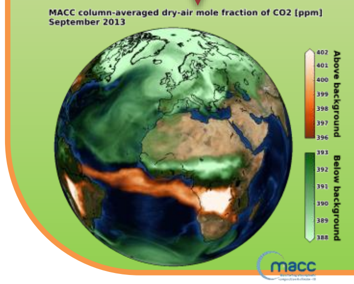
Prescribed

Anthropogenic emissions

Ocean sources/sinks

Fire emissions

TRANSPORT

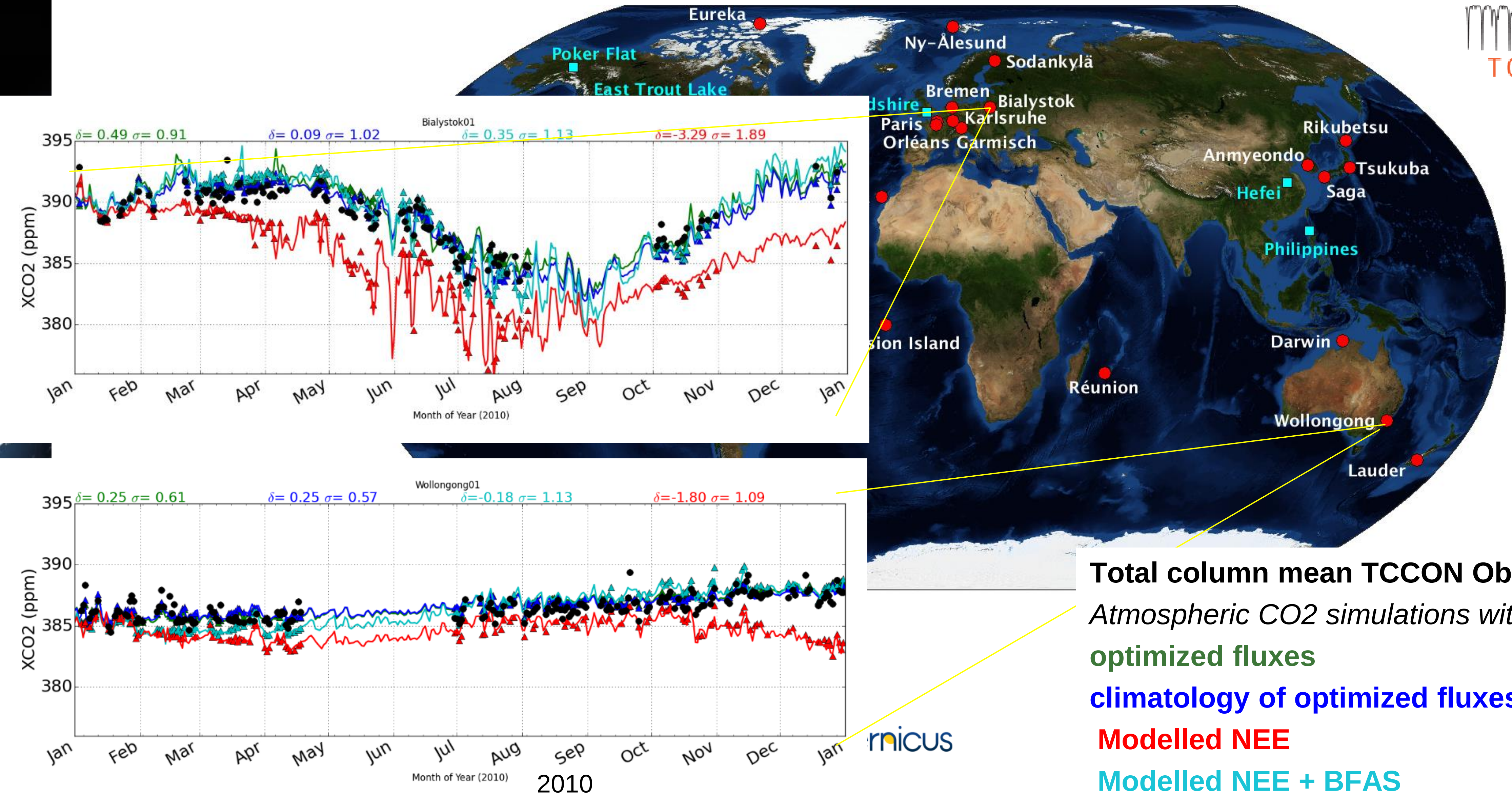


Improved atmospheric CO_2 forecast

Agusti-Panareda et al et al. ACP 2016

Biogenic Flux Adjustment Scheme: Improving the total column CO_2

TCCON



2010

Total column mean TCCON Observations

Atmospheric CO2 simulations with

optimized fluxes

climatology of optimized fluxes

Modelled NEE

Modelled NEE + BFAS

Biogenic Flux Adjustment Scheme: Improving CO_2 synoptic variability

Global Greenhouse Gas Reference Network

March 2010

NOAA/ESRL tall tower Observations

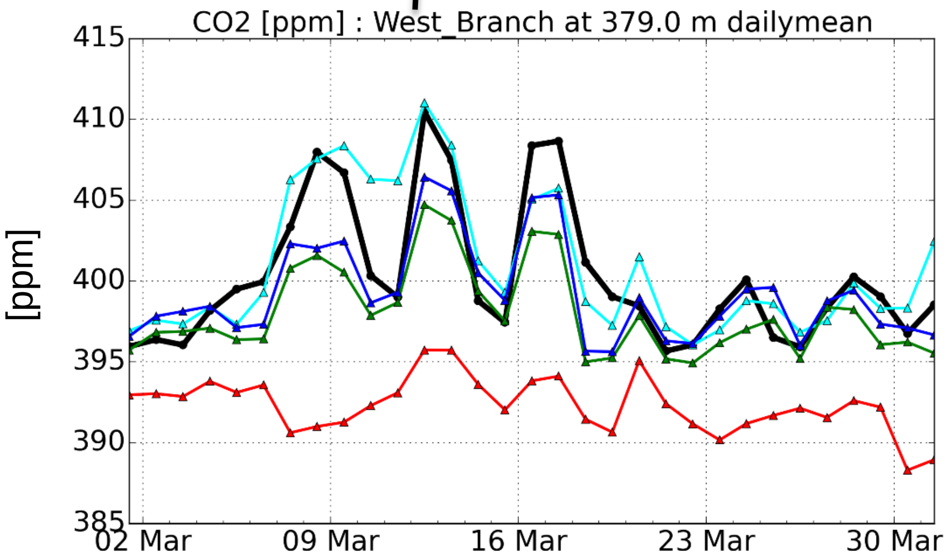
Atmospheric CO2 simulations with

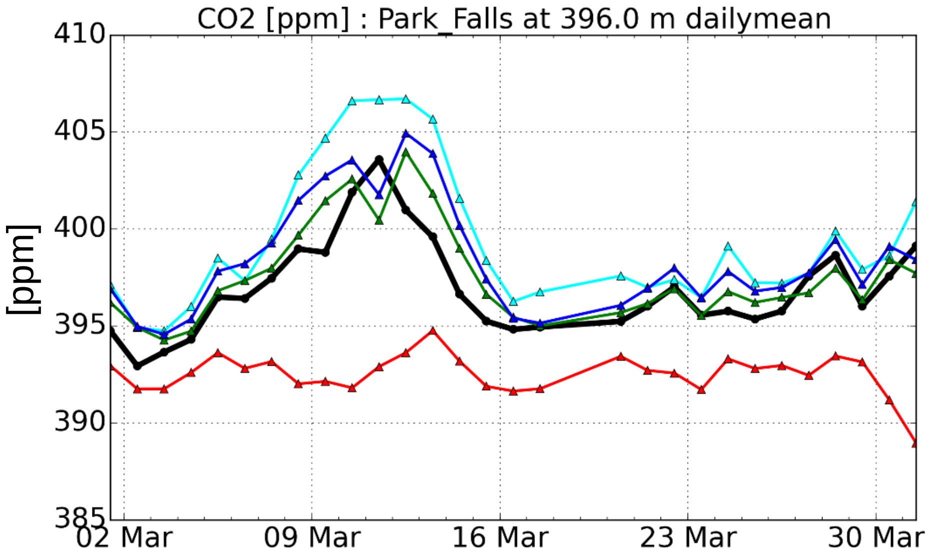
optimized fluxes

climatology of optimized fluxes

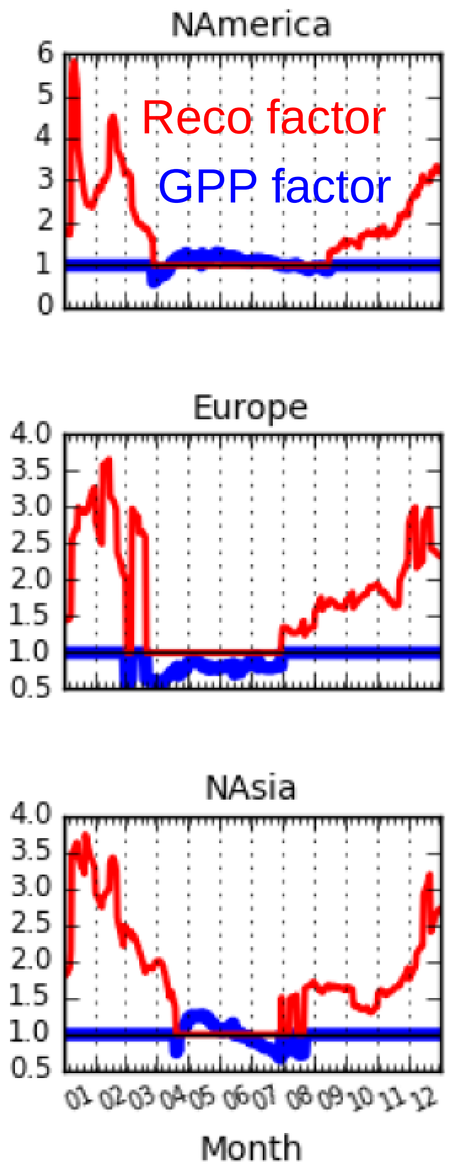
Modelled NEE

Modelled NEE + BFAS

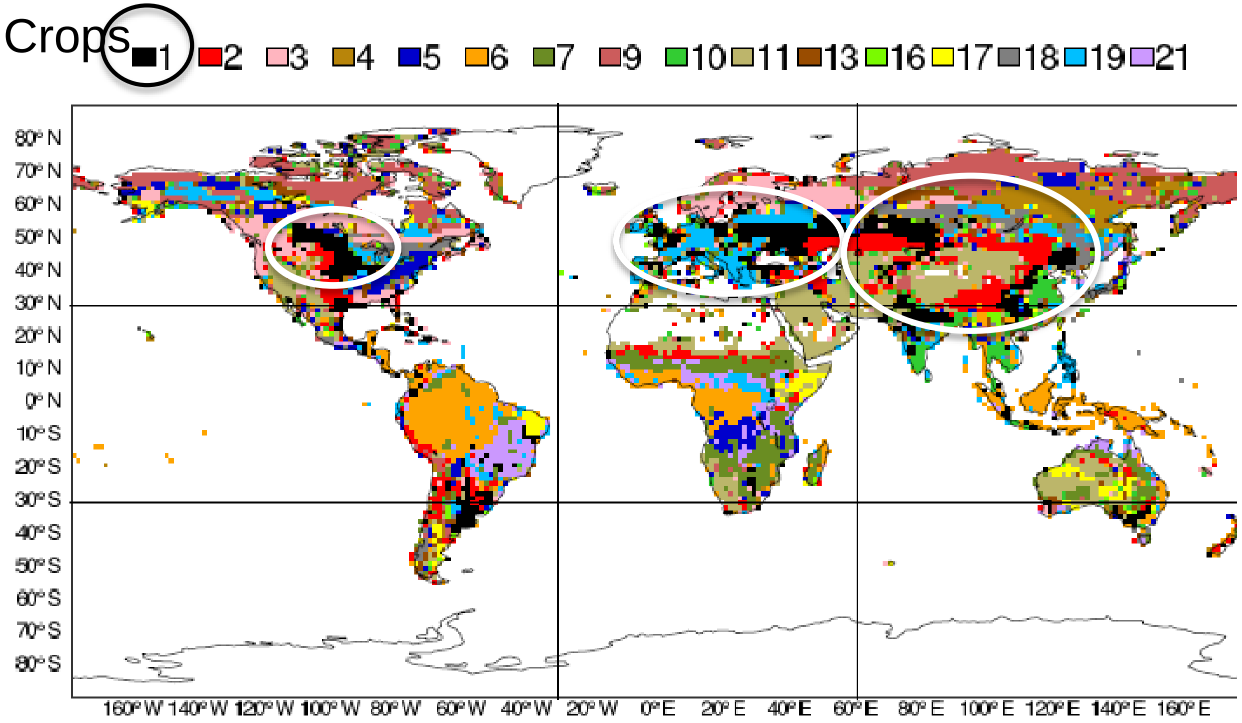




CO_2 Ecosystem Flux Adjustment factors: what can we learn to improve the model?



Agusti-Panareda et al et al. ACP 2016



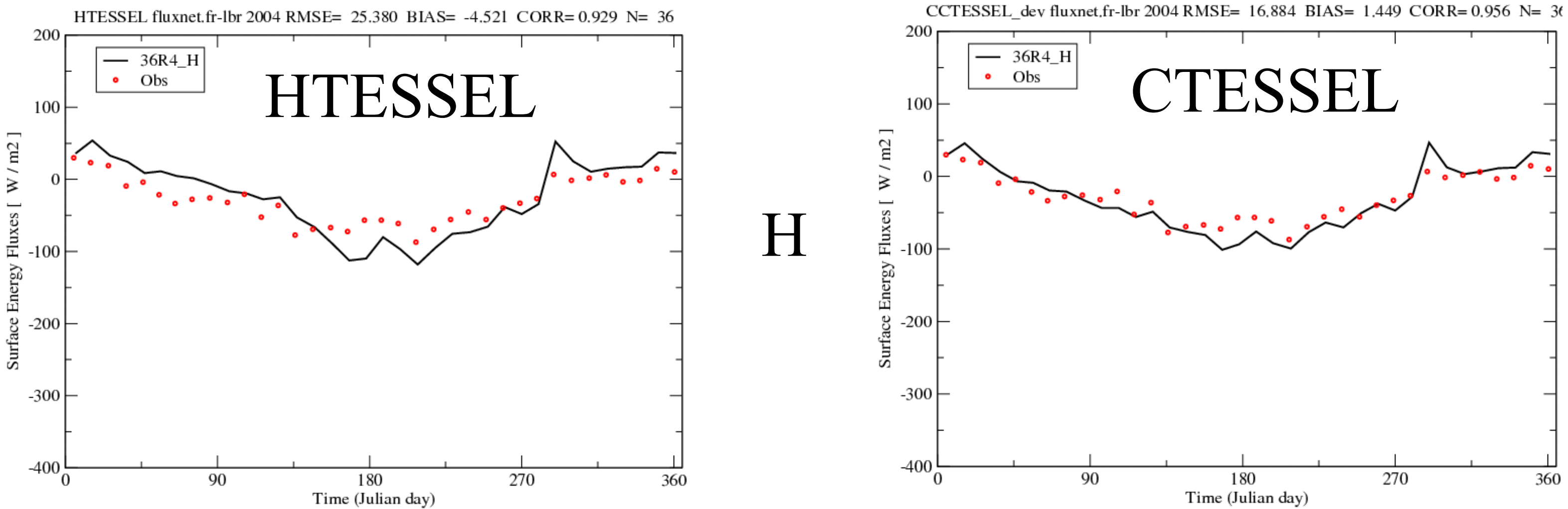
Vegetation code	Vegetation type
1	Crops, mixed farming
2	Short grass
7	Tall grass
9	Tundra
10	Irrigated crops
11	Semidesert
13	Bogs and marshes
16	Evergreen shrubs
17	Deciduous shrubs
3	Evergreen needle leaf trees
4	Deciduous needle leaf Trees
5	Deciduous broadleaf trees
6	Evergreen broadleaf trees
18	Mixed forest/woodland
19	Interrupted forest
21	Tropical savanna (new type)
–	Remaining land points without veg

- Re-tune the reference respiration for crops
- Distinction between C3 and C4 crops necessary
- Revision of vegetation types: A new subtype of interrupted forest for BFAS (tropical savanna)

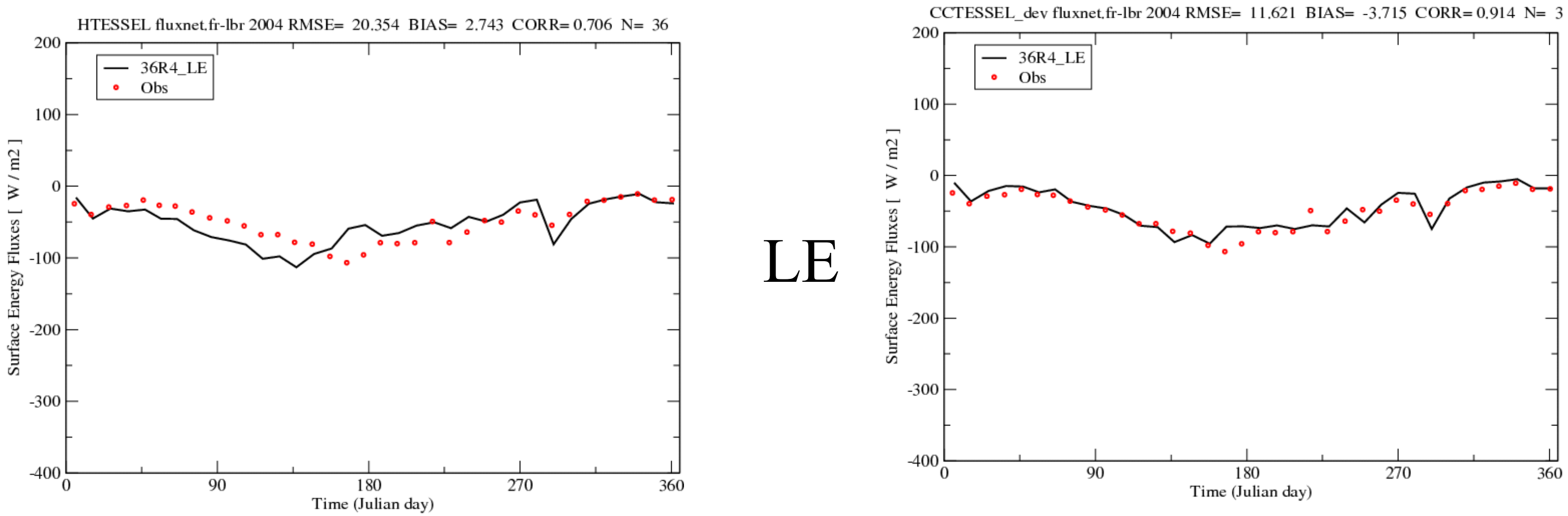
Feedbacks of carbon cycle to NWP:

- **Improvement in representation of vegetation: photosynthesis, phenology, albedo**

Jarvis Vs photosynthesis-based evapotranspiration (offline run)



Surface sensible heat flux (W/m^2) compared with flux-tower observations over Fr-LBr for HTESSEL (left panel) and CTESSEL (right panel)

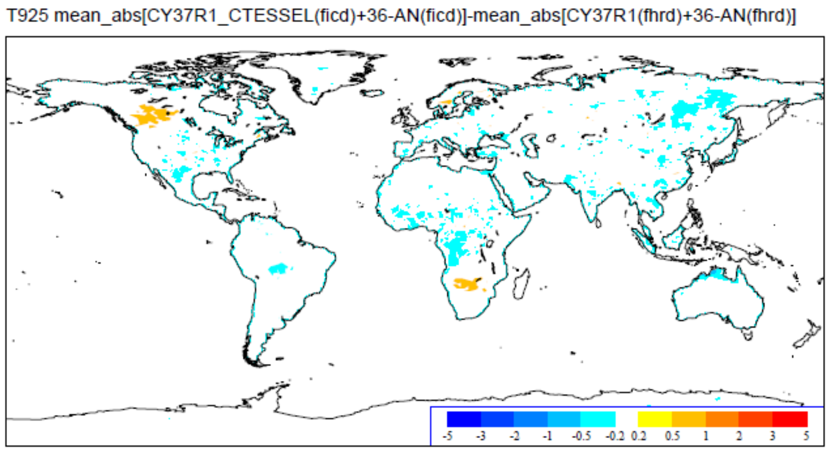


Surface laten heat flux (W/m^2) compared with flux-tower observations over Fr-LBr for HTESSEL (left panel) and CTESSEL (right panel).

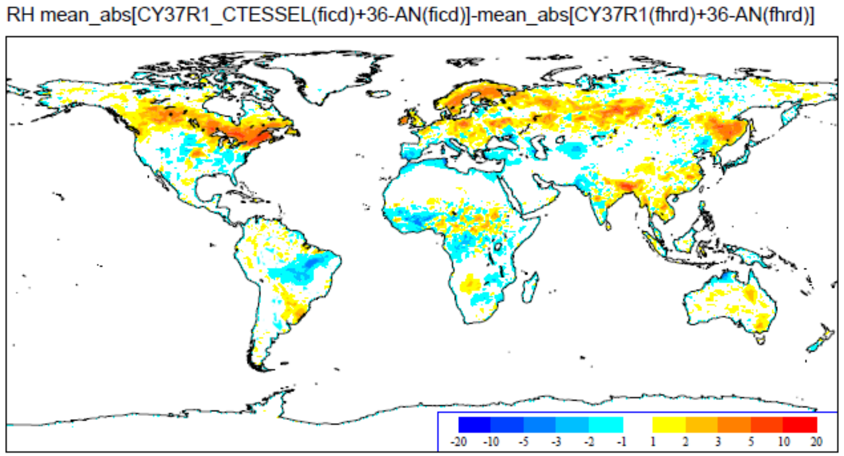
- **CTESSEL improves the LE/H simulations (Photosynthesis-based vs Jarvis approach).**

LE/H: When “good” is not enough?
(Interaction with the atmosphere)

2m T Error differences from the CTL


T925 mean_abs[CY37R1_CTESSEL(ficd)+36-AN(ficd)]-mean_abs[CY37R1(fhrd)+36-AN(fhrd)]

2m Rh Error differences from the CTL


RH mean_abs[CY37R1_CTESSEL(ficd)+36-AN(ficd)]-mean_abs[CY37R1(fhrd)+36-AN(fhrd)]

Having better LE/H heat flux from the surface does not always lead to a better atmospheric prediction ➔ interaction with other processes and compensating errors?

S. Boussetta

Modelling stomatal conductance (empirical vs mechanistic approaches):

$$E = \frac{\beta}{\boxed{r_c} + r_a}(q_a - q_{sat})$$

The Jarvis (statistical) approach
CHTESSEL in IFS (operational)

$$r_c = \frac{r_{S,\min}}{LAI} f_1(R_s) f_2(\bar{\theta}) f_3(D_a)$$

The mechanistic approach
CTESSEL in IFS

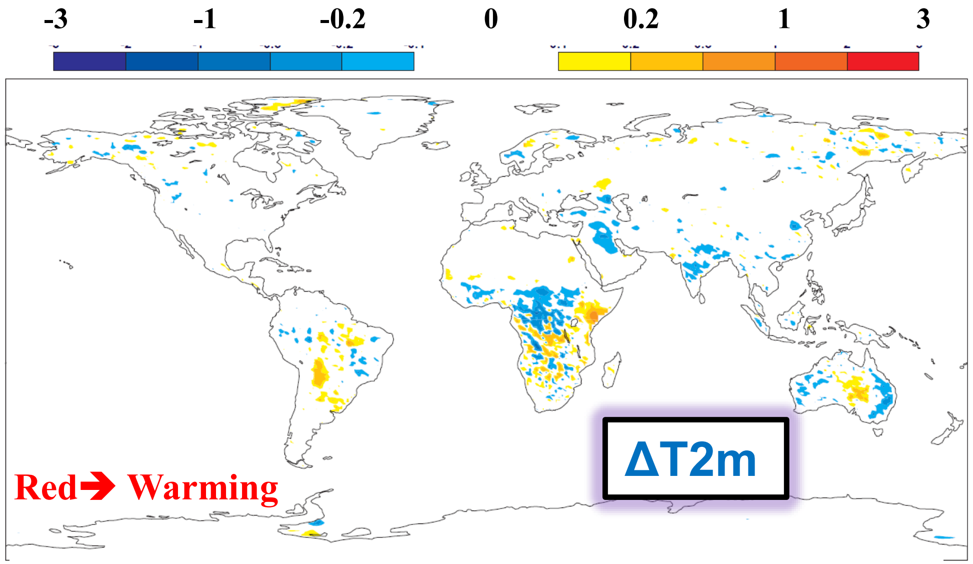
$$r_c = f(r_{cc})$$

$$r_{cc} = \frac{\alpha}{A_n}(C_s - C_i)$$

Copernicus atmospheric CO_2 forecast/analysis

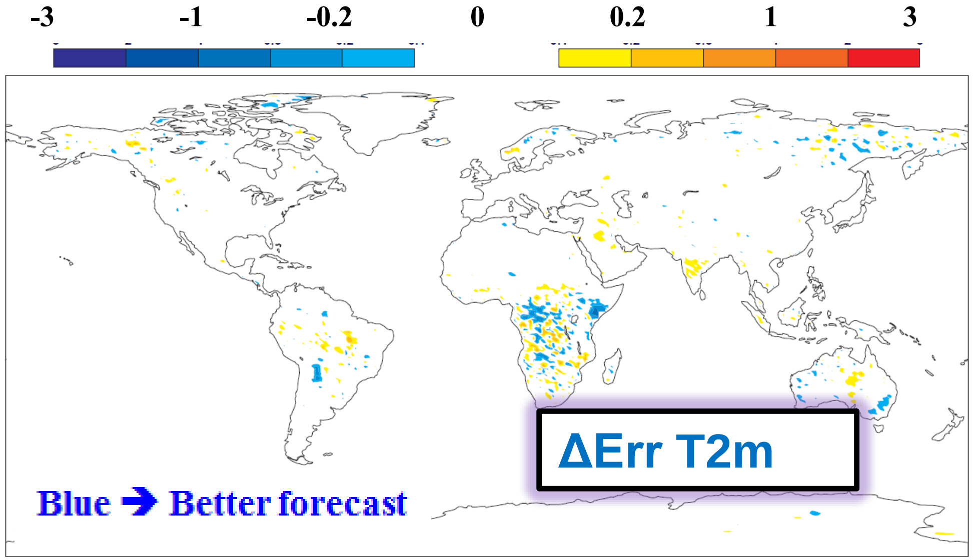
Aspects	Jarvis model	CTESSEL model
Simplicity/robustness	Yes	No
Coupling with carbon cycle & ecosystem CO_2 flux	No	Yes
Feedbacks on vegetation	No	Yes
Use carbon observations	LAI	LAI, SIF, GPP, atmospheric CO_2 for mass balance

Feedbacks from vegetation: Impact of assimilating LAI on 2m temperature



ΔT2m

Red➔ Warming



ΔErr T2m

Blue ➔ Better forecast

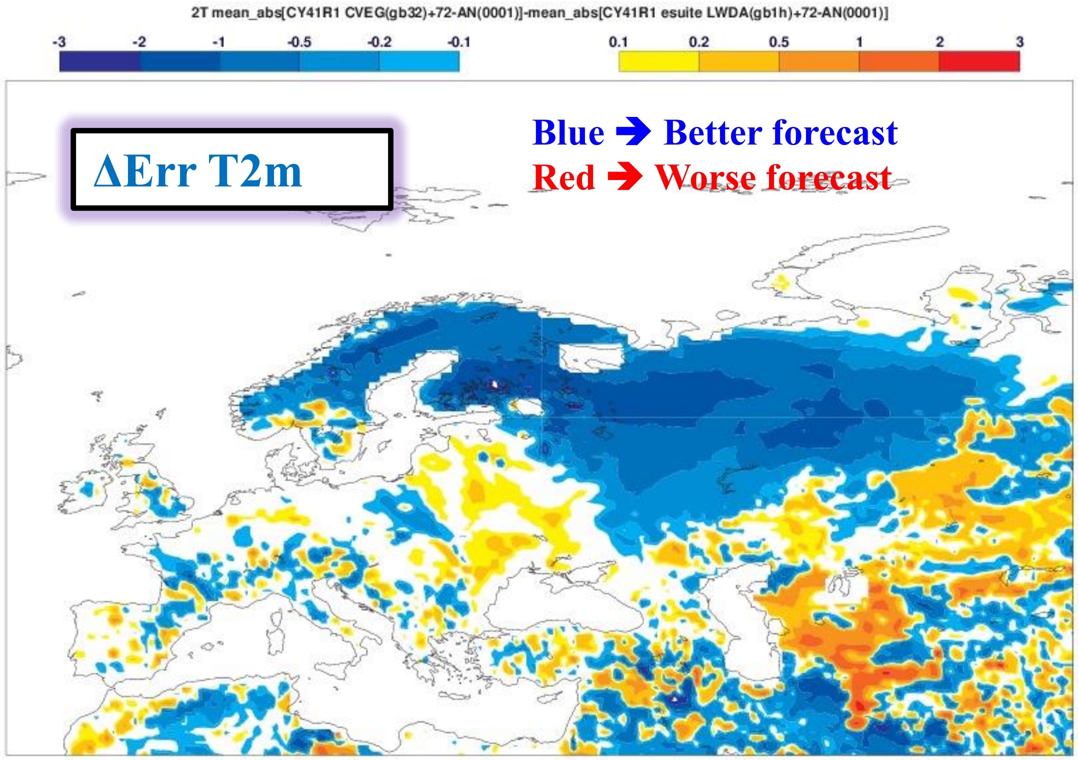
NRT_LAI_ALB – FCLIM:

November 2010

Severe drought in the Horn of Africa

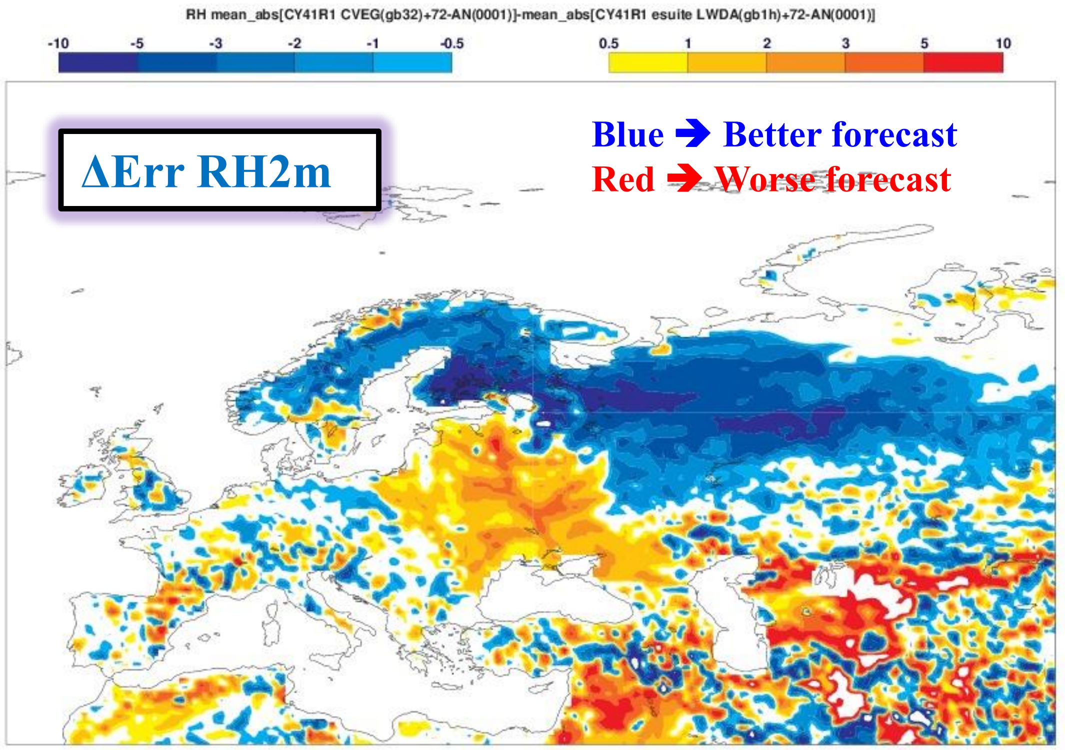
S. Boussetta

Feedbacks from vegetation: Impact of assimilating LAI on albedo



ΔErr T2m

Blue ➔ Better forecast
Red ➔ Worse forecast



ΔErr RH2m

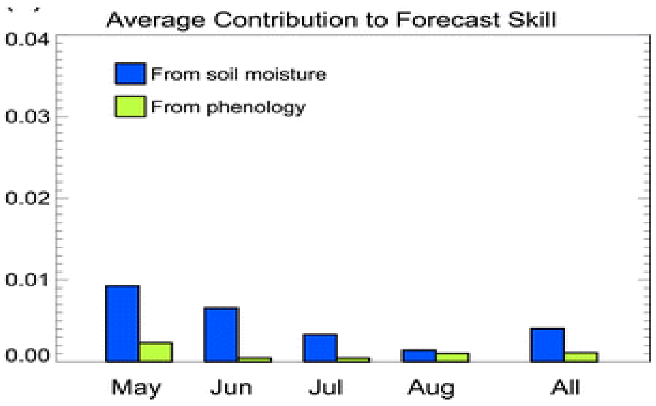
Blue ➔ Better forecast
Red ➔ Worse forecast

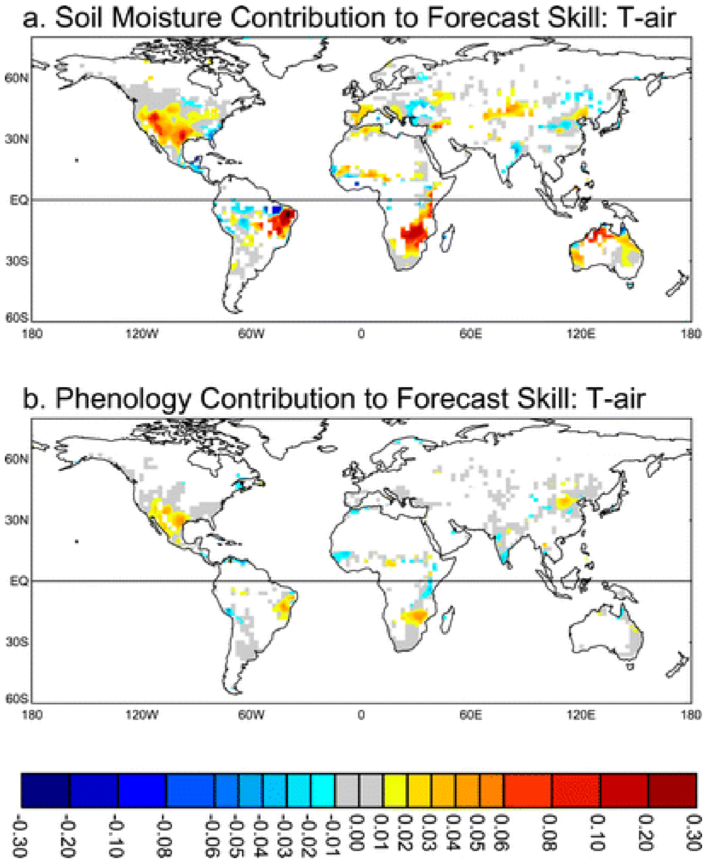
Reduction of cold/moist bias in 3-day FC over northern Europe in March 2015

S. Boussetta

Impact of dynamic vegetation on monthly forecast in semi-arid regions

Improved skill of monthly forecast 2m-T with soil moisture and dynamic phenology compared to fc with climatologies



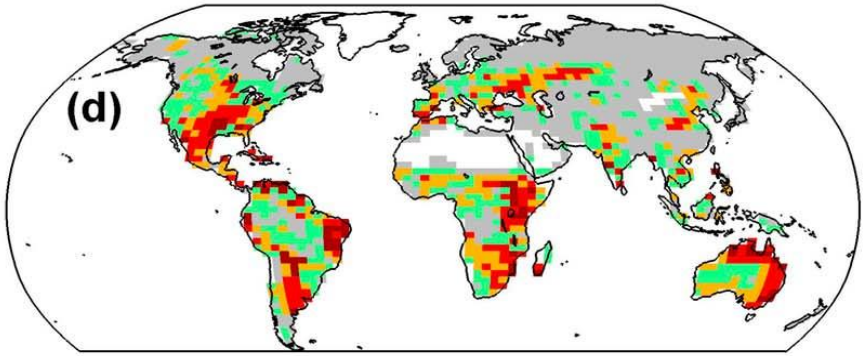

a. Soil Moisture Contribution to Forecast Skill: T-air

b. Phenology Contribution to Forecast Skill: T-air

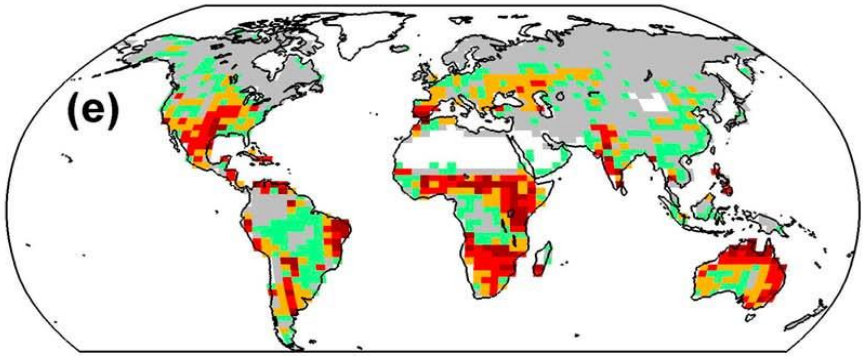
Koster and Walker (2015)

Hot-spots of NEE and GPP variability

NEE (DGVM)



GPP (DGVM)

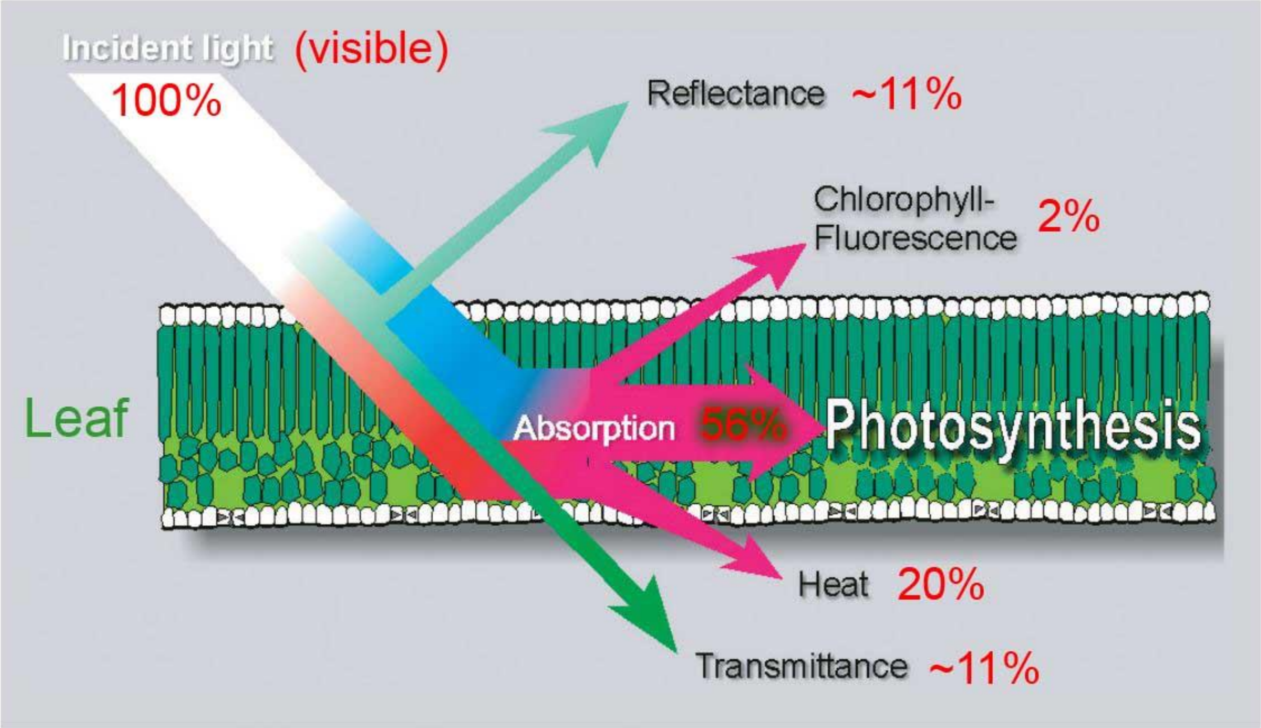


Jung et al. JGR 2011

Using carbon observations to improve carbon and NWP: Fluorescence as a proxy for GPP

During photosynthesis a plant absorbs Photosynthetically Active Radiation (PAR) through its chlorophyll:

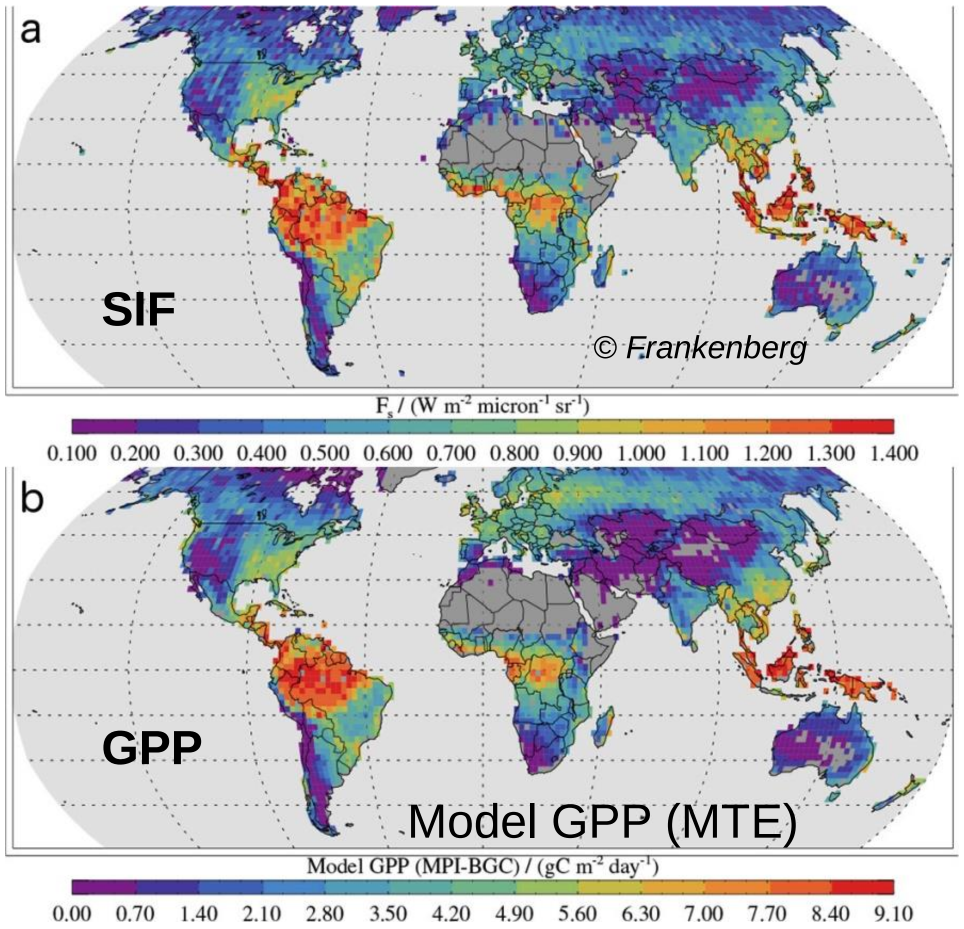
- % for ecosystem GPP
- % lost as heat
- % re-emitted as chlorophyll fluorescence (SIF)



How light energy falling on a leaf is partitioned. About 78% of the incident radiation is absorbed, while the rest is either transmitted or reflected at the leaf's surface. About 20% is dissipated through heat and only 2% emitted as fluorescence, as a by-product of photosynthetic reactions occurring within the leaf itself.

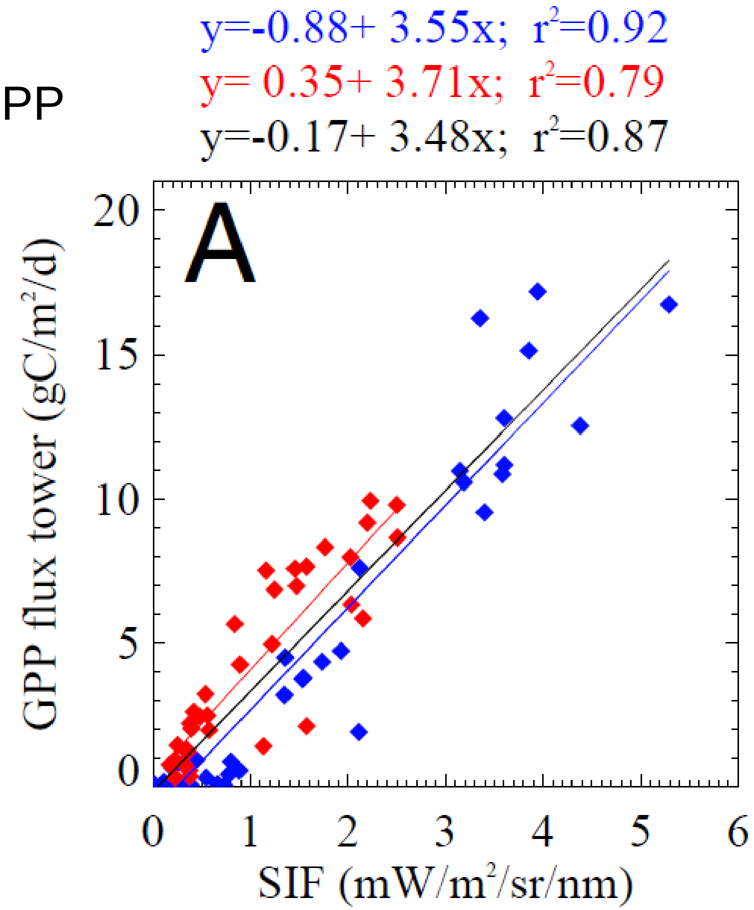
Mapping Photosynthesis from Space - a new vegetation-fluorescence technique
ESA bulletin. Bulletin ASE. European Space Agency. 11/2003; 116:34-37.

A simpler approach with a statistical model



Relationship between GPP and SIF is ~ linear

R^2(SIF, GPP) =0.8



Guanter et al. (2014)

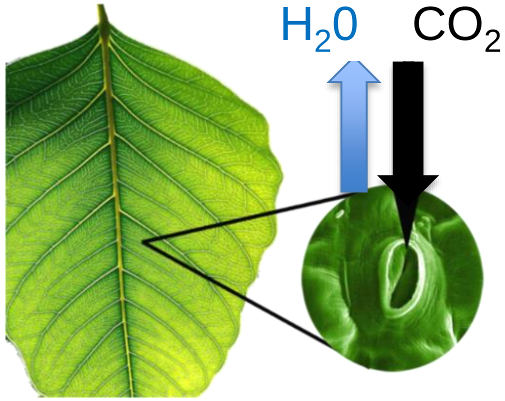
- GPP = a + b x SIF
- a & b coefficients function of PFTs

Mac Bean et al. in prep.

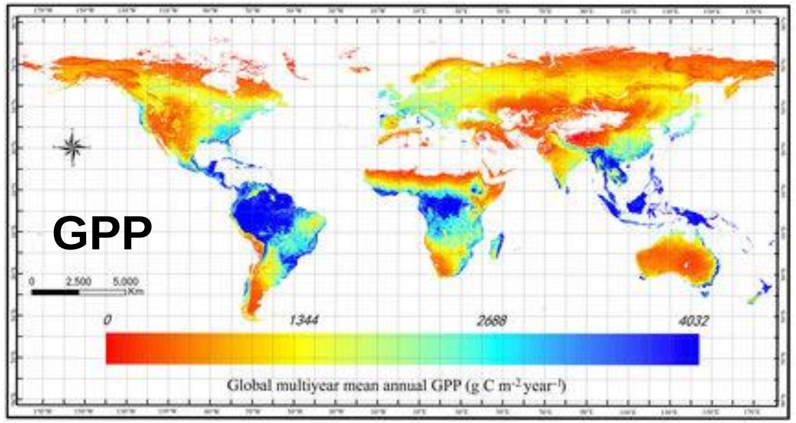
Transpiration of water vapour from plants is correlated with CO2 uptake (GPP)

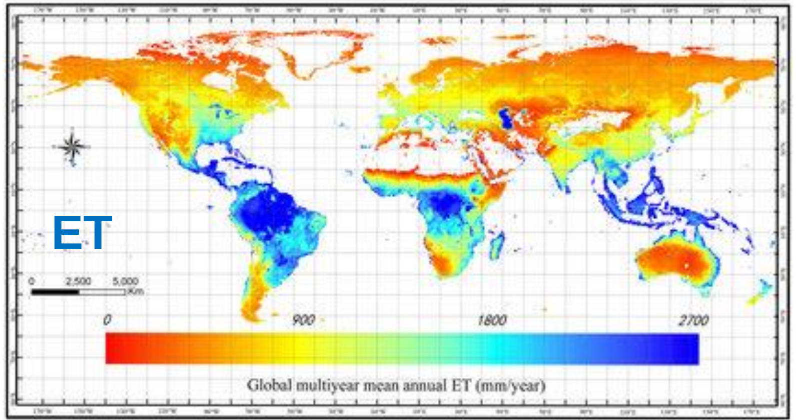
Figure 36-3 Biological Science, 2/e
© 2005 Pearson Prentice Hall, Inc.

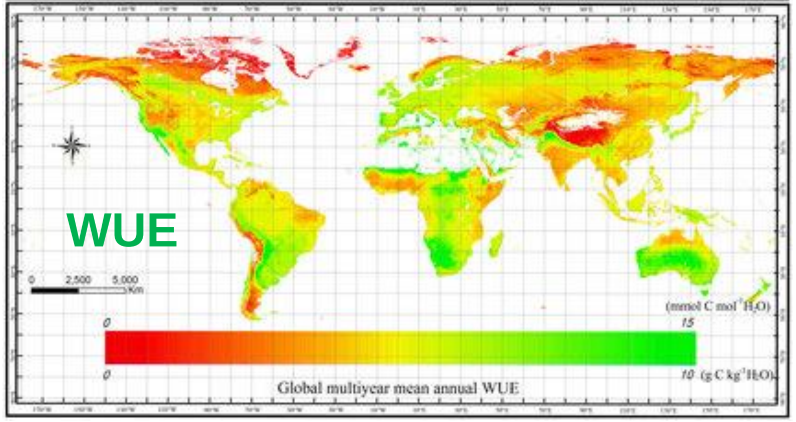
$$ET = \frac{GPP}{WUE}$$



Improving GPP and WUE in models should lead to a better ET





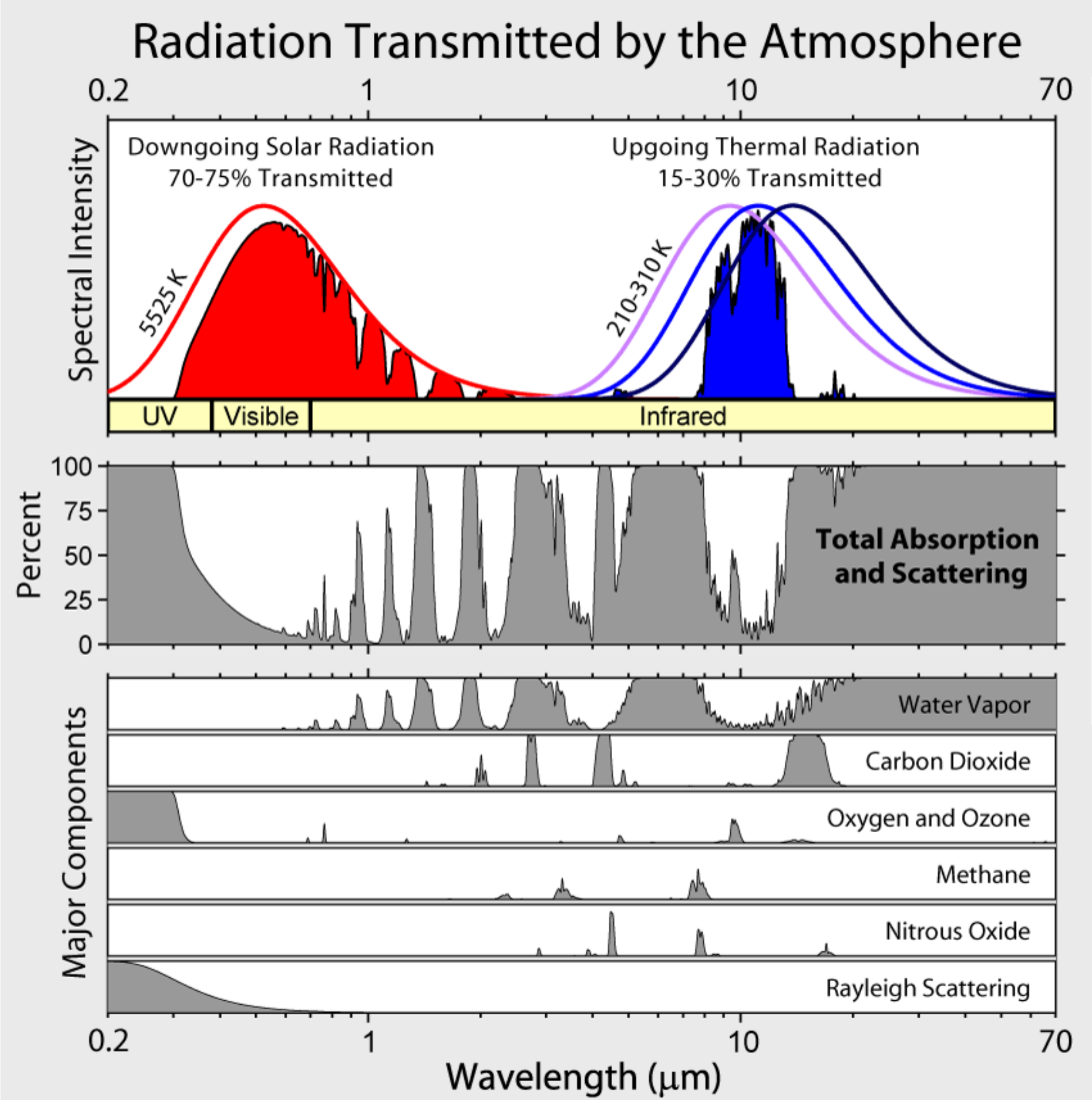


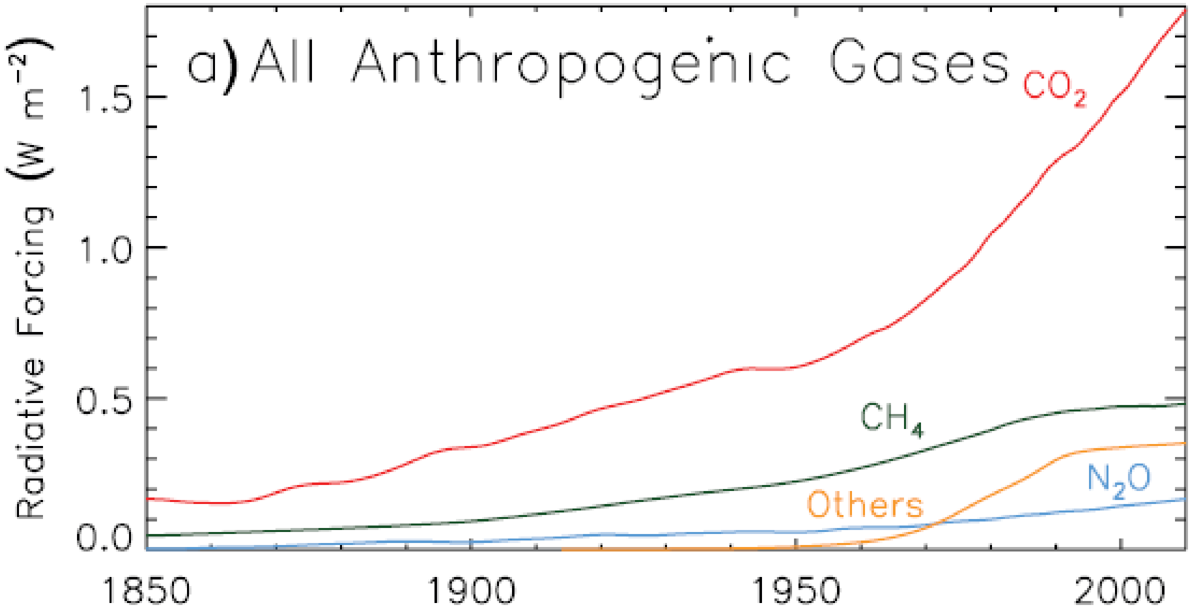
Tang et al. Nature 2014

Feedbacks of carbon cycle to NWP:

- Thermal infrared radiative transfer in model and data assimilation

Radiative forcing of greenhouse gases





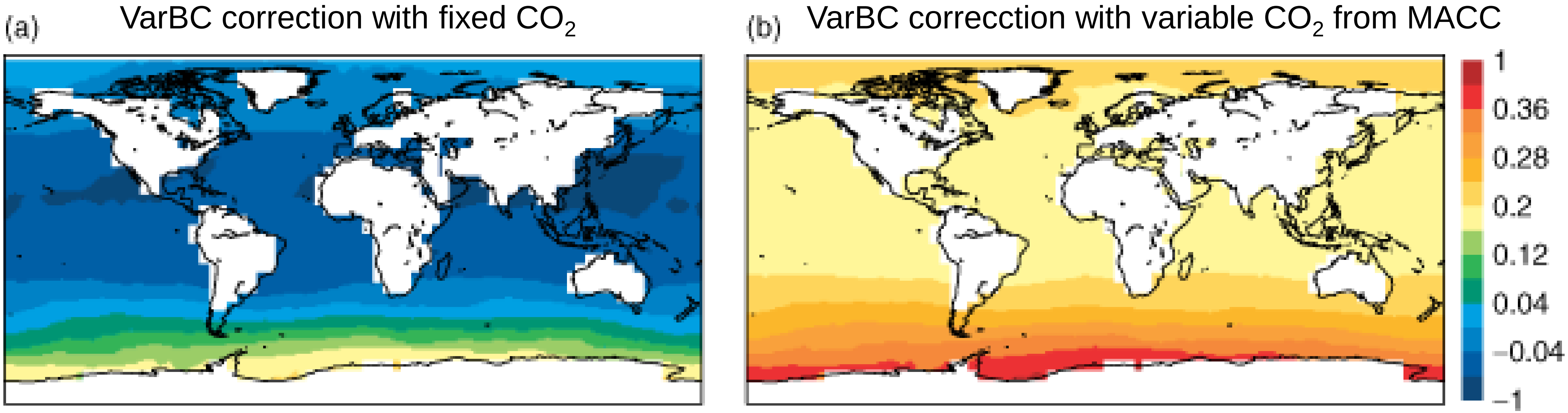
Myhre, Shindell et al. (2015) IPCC report AR5, Chapter 8

Shortwave: atmosphere is mostly transparent

Longwave: atmosphere is mostly opaque

Using variable CO_2 for the assimilation of the thermal IR

Reduction of bias correction in varBC: IASI channel ~ 700 hPa



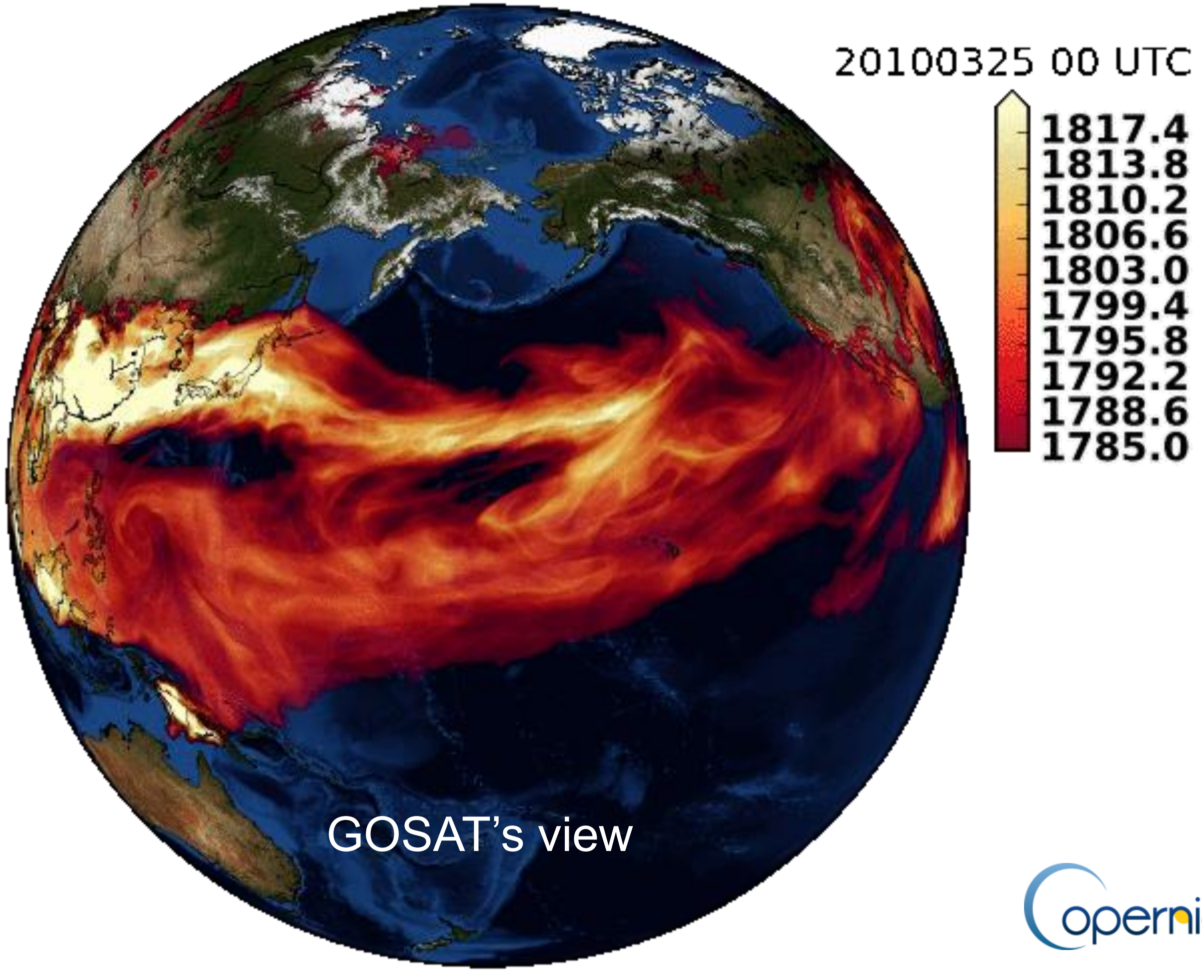
Engelen and Bauer, 2011

Atmospheric CH_4 in the ECMWF model (IFS)

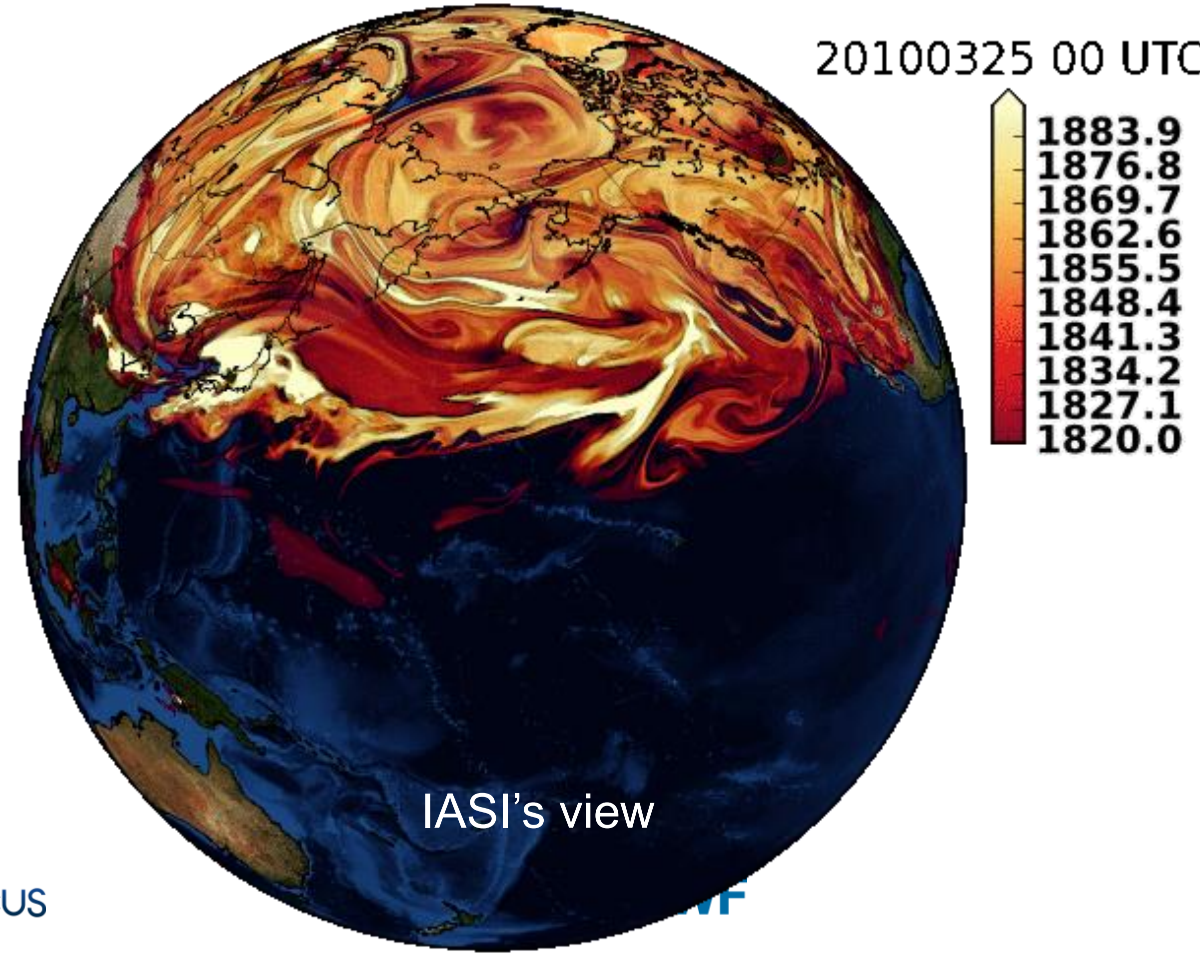
CH_4 synoptic variability: 25 to 29th of March 2010

Average total column CH_4 [ppb]

Mid-tropospheric CH_4 [ppb] **at 400 hPa**



GOSAT's view



IASI's view

Chemical production of water vapour : CH_4 oxidation

$$2[CH_4] + [H_2O] \sim 6.8\,\mathrm{ppmv}$$

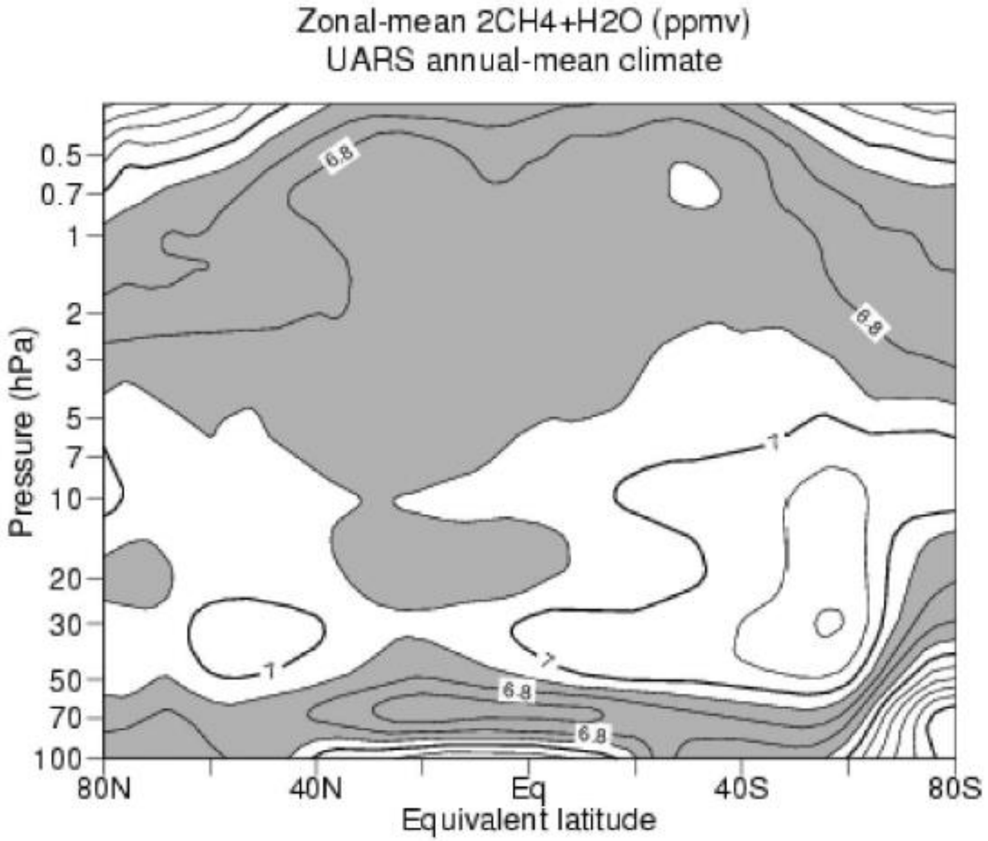
Parameterization in IFS:

$$\Delta[H_2O] = 2k_1[CH_4]$$

$$\Delta[H_2O] = k_1(6.8 - [H_2O])$$

Simmons, Randel et al. 1998,
Brasseur and Solomon 1984
Monge-Sanz et al. 2013

- Change of CH_4 associated with transport and global CH_4 increase no considered.
- Assumption breaks in polar regions (removal of H_2O by condensation).



Randel et al. 1998

http://www.ecmwf.int/sites/default/files/elibrary/2015/9211-part-iv-physical-processes.pdf

Summary

- **Carbon cycle is at the heart of climate change (long time scales > 1year)**

  Climatologies of atmospheric composition in NWP

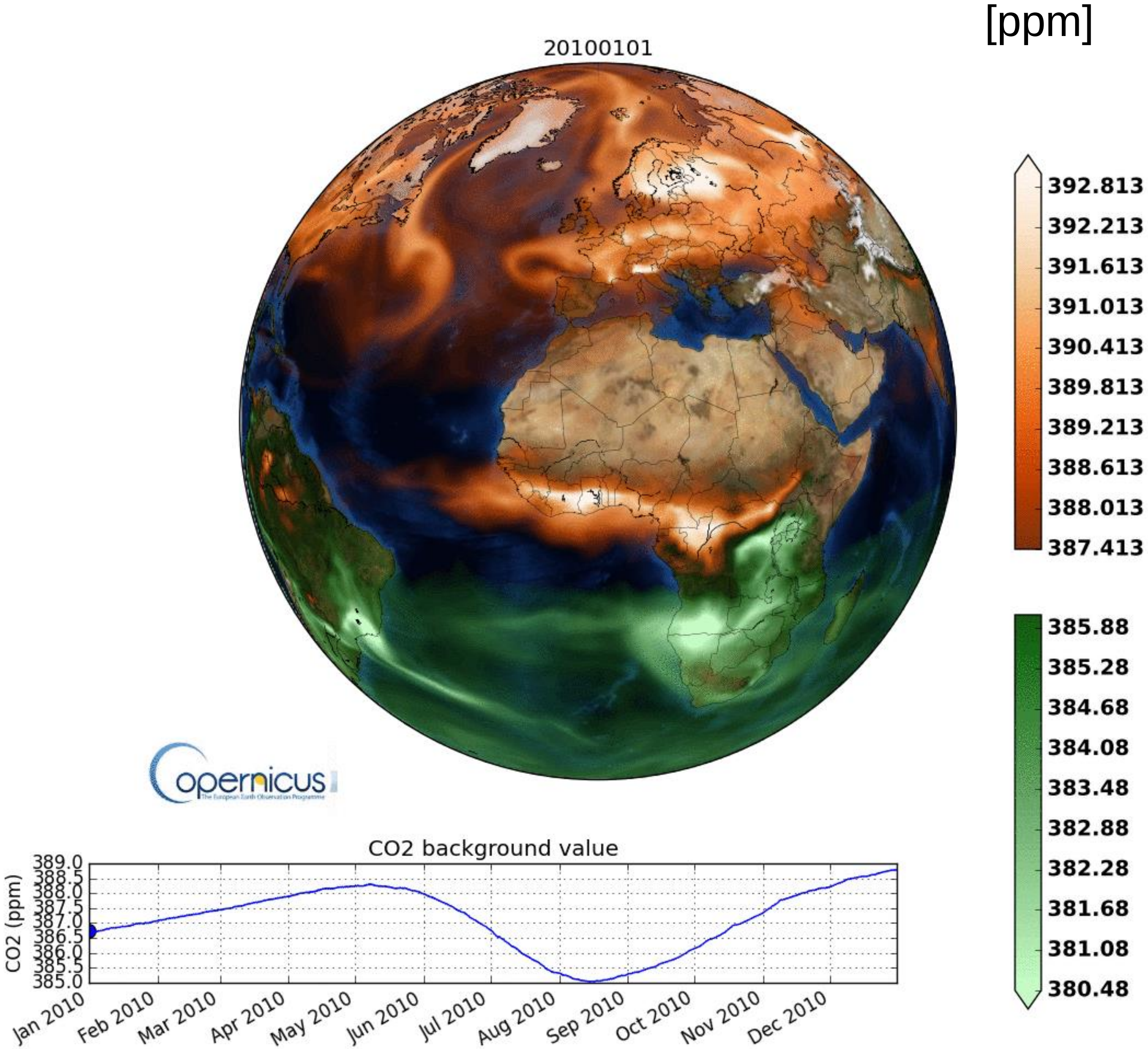
- **Processes on shorter time-scales relevant for NWP (1-day to 1-year):**

  Dynamic vegetation model to link water, energy and carbon cycles.
  Explore impact on skill for long (**monthly, seasonal**) and **high resolution** forecasts?

- **Copernicus Atmosphere Monitoring Service future work on carbon cycle could benefit NWP:**

  - Explore use of chlorophyll fluorescence retrievals from satellites to evaluate/constrain photosynthesis in the model (impact on carbon, water and energy fluxes).

  - Score carbon, water and energy fluxes using eddy covariance observations in near-real time



S. Massart

Thank you

Copernicus
Europe's eyes on Earth

Implemented by ECMWF