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

Anna Agusti-Panareda

Sebastien Massart, Mark Parrington, Miha Ratzinger, Luke Jones, Michail Diamantakis Gianpaolo Balsamo, Souhail Boussetta Emanuel Dutra, Joaquin Munoz-Sabater, Alessio Bozzo, Robin Hogan, Richard Forbes (ECMWF)

Frederic Chevallier, Phillippe Peylin, Natasha MacBean, Fabienne Maignan (LSCE)

Anna.Agusti-Panareda@ecmwf.int
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)

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)

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].

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

**The NOAA Annual Greenhouse Gas Index (AGGI).**
In 2015 CO₂ increased by 3 ppm ~ 23 GtCO₂/year:
(droughts associated and fires during el Nino episodes)

15 GtCO₂/year ~ 2 ppm/year on average for last 10 years

In 1997-1998 el Nino CO₂ increased by 2.8 ppm

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


CO₂ emissions

Partition into reservoirs

Fossil fuels and industry

Land–use change

Land sink

Atmosphere

Ocean sink

Global Carbon Budget 2015, LeQuere et al., 2015
ANTHROPOGENIC FLUXES

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

Source: EDGAR database
CO$_2$ emissions: land-use change
CO₂ emissions: land-use change by burning biomass

GFAS daily fire product available 1 day behind real time

GFAS CO₂ emissions over Indonesia (Sep-Oct 2015): Fires contribute to El Nino signal in the atmospheric CO₂ 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 CO₂ sink (Gross Primary Production):

**Photosynthesis (plants)**

\[
\text{CO}_2 + \text{H}_2\text{O} + \text{energy} \rightarrow \text{CH}_2\text{O} + \text{O}_2
\]

Atmospheric CO₂ source (Ecosystem Respiration):

**Respiration (plants, animals)**

\[
\text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{energy}
\]

\[
\text{CH}_2\text{O} \rightarrow \text{CH}_4 + \text{energy} \quad \text{in anoxic conditions}
\]

+ decomposition of organic carbon in soil by microbes

[Carbon Cycle Illustration](earthobservatory.nasa.gov/Features/CarbonCycle). Illustration adapted from Sellers et al., 1992

Credit: © Raphael Gabriel
Modelling CO₂ uptake by plants (GPP) in C-IFS

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

Biological factors:
- Mesophyll conductance

CTESSEL parameterisation based on ISBA-Ags

\[ r_s = \frac{1}{g_s} \]

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

Rate of photosynthesis

+ Soil moisture stress function

CTESSEL parameterisation based on ISBA-Ags
Modelling CO₂ uptake by plants (GPP) in C-IFS

Modelling soil respiration

\[ R_{soil} = R_0 Q_{10}^{(0.1(T_{soil}-25))} f_{sm} \]

\[ R_{soil} = R_0 e^{-\alpha Z_{snow}} Q_{10}^{(0.1(T_{soil}-25))} f_{sm} \]

**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

\[ \text{Boussetta et al. (2013)} \]
Evaluation of CO₂ ecosystem fluxes from CTESSEL in IFS

Example of NEE (micro moles /m²/s) predicted over the site Fi-Hyy (FINLAND) by CTESSEL (black line) and CASA-GFED3 (green-line) compared to FLUXNET observations.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>NEE rmse</th>
<th>NEE bias</th>
<th>NEE corr</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTESSEL</td>
<td>3.736</td>
<td>-1.656</td>
<td>0.536</td>
</tr>
<tr>
<td>CASA</td>
<td>1.872</td>
<td>0.739</td>
<td>0.297</td>
</tr>
</tbody>
</table>

Boussetta et al. (2013)
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
  - warm
  - reduction of CO2 uptake
  - increase in respiration
  - More CO$_2$
  - Enhanced atmospheric CO$_2$ anomaly

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)
- Source
- Sink

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)

20150501 00 UTC

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

Massart et al. ACP 2015
Correcting atmospheric CO$_2$ biases with Biogenic Flux Adjustment Scheme (BFAS)

**ARCHIVED DATA**
- **MODELLED FLUXES**
  - CAMS CO$_2$ FC

**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
  - 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 CO₂
Biogenic Flux Adjustment Scheme: Improving CO$_2$ synoptic variability

March 2010

NOAA/ESRL tall tower Observations

Atmospheric CO$_2$ 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?

- 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)

CTESSEL improves the LE/H simulations (Photosynthesis-based vs Jarvis approach).
LE/H: When “good” is not enough?
(Interaction with the atmosphere)

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):

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

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

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

<table>
<thead>
<tr>
<th>Aspects</th>
<th>Jarvis model</th>
<th>COTESSEL model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplicity/robustness</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Coupling with carbon cycle &amp; ecosystem CO$_2$ flux</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Feedbacks on vegetation</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Use carbon observations</td>
<td>LAI</td>
<td>LAI, SIF, GPP, atmospheric CO$_2$ for mass balance</td>
</tr>
</tbody>
</table>

The mechanistic approach
CHTESSEL in IFS

\[ r_c = f(r_{cc}) \]

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

Copernicus atmospheric CO$_2$ forecast/analysis
Feedbacks from vegetation: Impact of assimilating LAI on 2m temperature

NRT_LAI_ALB – FCLIM:
November 2010
Severe drought in the Horn of Africa

S. Boussetta
Feedbacks from vegetation: Impact of assimilating LAI on albedo

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

Hot-spots of NEE and GPP variability

NEE (DGVM)

GPP (DGVM)

Koster and Walker (2015)

Jung et al. JGR 2011
During photosynthesis a plant absorbs Photosynthetically Active Radiation (PAR) through its chlorophyll:

- % for ecosystem GPP
- % lost as heat
- % re-emitted as chlorophyll fluorescence (SIF)
A simpler approach with a statistical model

- GPP = a + b \times SIF

- a & b coefficients function of PFTs

Relationship between GPP and SIF is \sim linear

\[ R^2(SIF, GPP) = 0.8 \]

\[ y = -0.88 + 3.55x; \quad r^2 = 0.92 \]
\[ y = 0.35 + 3.71x; \quad r^2 = 0.79 \]
\[ y = -0.17 + 3.48x; \quad r^2 = 0.87 \]

Guanter et al. (2014)

Mac Bean et al. in prep.
Transpiration of water vapour from plants is correlated with CO2 uptake (GPP)

\[ ET = \frac{GPP}{WUE} \]

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

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

(a) VarBC correction with fixed CO$_2$

(b) VarBC correction with variable CO$_2$ from MACC

Engelen and Bauer, 2011
Atmospheric CH$_4$ in the ECMWF model (IFS)

CH$_4$ synoptic variability: 25 to 29$^{th}$ 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: $\text{CH}_4$ oxidation

Parameterization in IFS:

\[ \Delta [\text{H}_2\text{O}] = 2k_1[\text{CH}_4] \]
\[ \Delta [\text{H}_2\text{O}] = k_1(6.8 - [\text{H}_2\text{O}]) \]

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

- Change of $\text{CH}_4$ associated with transport and global $\text{CH}_4$ increase no considered.
- Assumption breaks in polar regions (removal of $\text{H}_2\text{O}$ by condensation).

$2[\text{CH}_4] + [\text{H}_2\text{O}] \sim 6.8 \text{ ppmv}$

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 > 1 year)
  
  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
Thank you