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

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The carbon cycle
Interaction between all the Earth system components

• Carbon reservoirs and their interactions with the atmosphere (focusing on CO₂ primarily).

• Can carbon cycle – climate feedbacks improve atmospheric predictive skill?
Vegetation, radiative transfer, atmospheric chemistry

• Atmospheric CO₂ 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

**Methane (CH₄)**

**Carbon Dioxide (CO₂)**

*THE NOAA ANNUAL GREENHOUSE GAS INDEX (AGGI).*
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


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

Source: Global Carbon Budget 2015; CDIAC
CO$_2$ emissions: land-use change
CO$_2$ emissions: land-use change by burning biomass

GFAS daily fire product available 1 day behind real time

Sept-Oct 2015 daily mean CO$_2$ emissions

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 CO₂ ocean-atmosphere fluxes

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

Observations of pCO₂ 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
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.
Terrestrial carbon flux: Exchange between the biosphere and the atmosphere

Atmospheric CO$_2$ 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 CO$_2$ 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

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

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

Biological factors:
- Mesophyll conductance

CTESSEL parameterisation based on ISBA-Ags

\[
\begin{align*}
G_{s} &= \frac{A_{n}}{(C_{s} - C_{i})} \\

r_{s} &= \frac{1}{g_{s}}
\end{align*}
\]
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

Q10 dependance on Temperature regime

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

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

<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:**

<table>
<thead>
<tr>
<th>cloudy</th>
<th>reduction of CO2 uptake</th>
<th>More CO$_2$</th>
<th>Enhanced atmospheric CO$_2$ anomaly</th>
</tr>
</thead>
<tbody>
<tr>
<td>warm</td>
<td>increase in respiration</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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

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 CO$_2$

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 CO₂ synoptic variability

March 2010

NOAA/ESRL tall tower Observations

Atmospheric CO₂ simulations with optimized fluxes
climatology of optimized fluxes
Modelled NEE
Modelled NEE + BFAS
CO₂ 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)

Agusti-Panareda et al. et al. ACP 2016
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?
Modelling stomatal conductance (empirical vs mechanistic approaches):

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

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

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

The mechanistic approach
CTESSEL in IFS

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

<table>
<thead>
<tr>
<th>Aspects</th>
<th>Jarvis model</th>
<th>CTESSEL 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 CO₂ 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 CO₂ for mass balance</td>
</tr>
</tbody>
</table>
Feedbacks from vegetation: Impact of assimilating LAI on 2m temperature

NRT_LAI_ALB – FCLIM:

November 2010

Severe drought in the Horn of Africa
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 x SIF
- a & b coefficients function of PFTs

The relationship between GPP and SIF is approximately linear.

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

\[ y = -0.88 + 3.55x; \quad r^2 = 0.92 \]
\[ y = 0.35 + 3.71x; \quad r^2 = 0.79 \]
\[ y = -0.17 + 3.48x; \quad r^2 = 0.87 \]
Transpiration of water vapour from plants is correlated with CO2 uptake (GPP)

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

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

GPP

ET

WUE

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

Myhre, Shindell et al. (2015) IPCC report AR5, Chapter 8
Using variable CO$_2$ for the assimilation of the thermal IR

Reduction of bias correction in varBC: IASI channel $\sim$ 700 hPa

VarBC correction with fixed CO$_2$

VarBC correction with variable CO$_2$ from MACC

Engelen and Bauer, 2011
Atmospheric CH₄ in the ECMWF model (IFS)

CH₄ synoptic variability: 25 to 29th of March 2010

Average total column CH₄ [ppb]

Mid-tropospheric CH₄ [ppb] at 400 hPa
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).

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

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

S. Massart