Global Observations of the Carbon Cycle

Background Paper for the GCOS All Panel meeting, 18-22 March 2019.

Box 4: Closing the carbon budget

Targets	Quantify fluxes of carbon-related greenhouse gases to +/- 10% on annual timescales Quantify changes in carbon stocks to +/- 10% on decadal timescales in the ocean and on land, and to +/- 2.5 % in the atmosphere on annual timescales
Who	Operators of GCOS-related systems, including data centres
Time frame	Ongoing
Performance indicator	Regular assessment of uncertainties in estimated fluxes and inventories

1. Background.

The GCOS-IP 2016 produced targets based on closing the cycles of water, carbon and energy with associated uncertainty targets on annual time scales.

The targets for the carbon cycle are given above the cycle ~~i~~as illustrated below (Figure 1).

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The Global Carbon Project (GCP) produces annually a global carbon budget (Le Quére, 2018). This is summarised in Table 1. The current most uncertain parts ~~if~~ of the budget are emissions from land-use change and uptake by the land and ocean sinks. The budget imbalance ~~it~~ is thought to be mainly due to incomplete knowledge of land-use change and uptake by sinks. It is clear that while estimate of some of the fluxes achieve the target uncertainty, others do not.

Table 2 lists the major known sources of uncertainty of the GCP budget terms. Some of these are due to lack of understanding, e.g. responses to diffuse radiation and to variability. Others could, to some extent, be addressed through better observations, e.g. better monitoring of transitions between various land use and land-covers, wood and crop harvest and peat burning, and better monitoring over the vast oceans particularly in the Southern Hemisphere.

It is important to emphasize that these uncertainties are related to the global budget; at subcontinental or (large) country level for land and at sub-basin level and coastal zones for ocean, other uncertainties would apply. These are, while probably more important for the Paris agreement, even less well quantified.

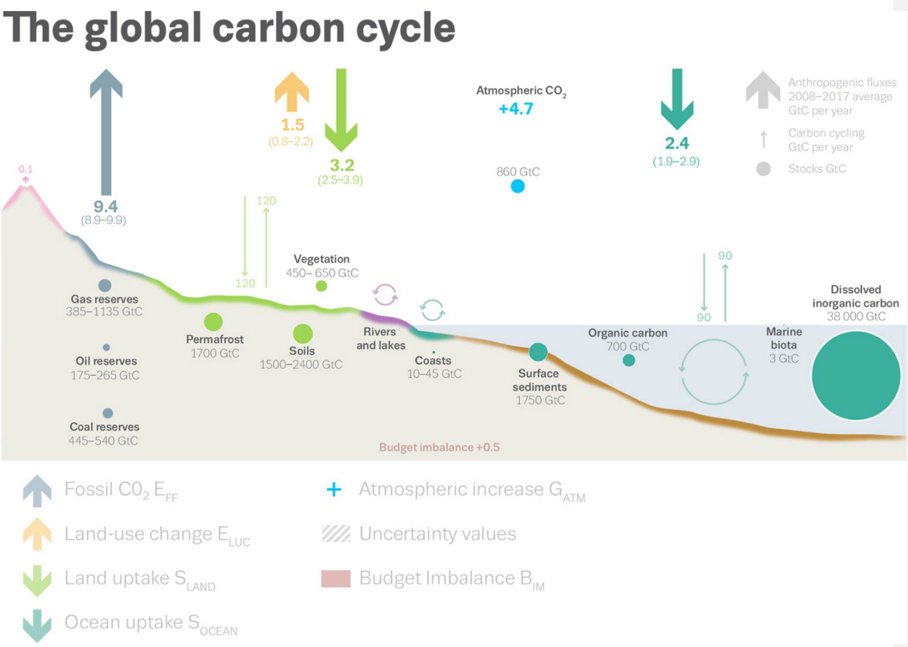

Figure 1 and Table 1, the Carbon Cycle and its uncertainty, (from Le Quére, 2018)

	Component	**Estimated Carbon Fluxes**			**Data Sources**	**Significant ECV**
		Emission GtCyr^{-1}	Uncertainty ± 1 σ	Uncertainty (%)		
	Fossil Fuel and Industrial Emissions	9.4	0.5	5%	Global & National CO2 Emissions from Fossil fuels compiled at CDIAC UNFCCC Inventory Reports BP Statistical Review of World Energy USGS estimates of cement production	Anthropogenic GHG Emissions
	Atmospheric Growth	4.7	0.1	2%	Measurements through NOAA/ESRL	Atmospheric composition CO2
	Land-use change	1.3	0.7	54%	2 'book-keeping' models 12 dynamic global vegetation models (DGVMs)	Land Use Fires Above-ground Biomass
	Land Sink	3	0.8	27%	DGVMs	
	Ocean Sink	2.4	0.5	21%	Global Ocean Biochemistry models constrained by observations	Ocean Carbonate system
	Budget imbalance	0.6				
Not included	**anthropogenic CO and CH_4**	0.07-0.1 GtCyr				Atmospheric Composition CH4 and CO
	Land-ocean aquatic fluxes of C	0.65	0.4			River Discharge (Glaciers)
	Loss of additional sink capacity	0.4	0.3			"Land Use Fires Above-ground Biomass"

Table 2 Major known sources of uncertainty in the carbon cycle (from table 9, Le Quére 2018)

Source of Uncertainty	Source, timescale, region	Reference
Emissions from fossil fuels and industry	energy statistics mainly China	Korsbakken et al. (2016)
	carbon content of coal mainly China	Liu et al. (2015)
Emissions from land-use change	land-cover and land-use change statistics global, in particular tropics	Houghton et al. (2012)
	sub-grid-scale transitions annual to decadal global	Wilkenskjeld et al. (2014)
	vegetation biomass global, in particular tropics	Houghton et al. (2012)
	wood and crop harvest annual to decadal global; SE Asia	Arneth et al. (2017)
	peat burning multi-decadal trend global	van der Werf et al. (2010)
	loss of additional sink capacity global (not included)	Gitz and Ciais (2003)
Ocean sink (SOCEAN)	variability in oceanic circulation, global, in particular Southern Ocean	DeVries et al. (2017)
	anthropogenic changes in nutrient supply global (not included)	Duce et al. (2008)
Land sink (SLAND)	strength of CO_2 fertilisation global	Wenzel et al. (2016)
	response to variability in temperature and rainfall, in particular tropics	Cox et al. (2013)
	nutrient limitation and supply, global	Zaehle et al. (2011)
	response to diffuse radiation, global	Mercado et al. (2009)

2. **Core ECVs**

Carbon cycle and other GHGs	Carbon dioxide, methane, other long-lived GHG, ozone, precursors for aerosol and ozone	Soil carbon, above-ground biomass	Inorganic carbon, nitrous oxide

a. *Atmospheric composition of carbon dioxide CO_2* is well measured.

b. The ocean biogeochemistry of *inorganic carbon* gives the ocean uptake and storage but does not reflect the variability and has large uncertainties.

   i. Variability of ocean CO_2 uptake across air-sea interface in space and time is derived from inorganic carbon measurements and their empirical interpolations using satellite-derived and/or assimilated datasets of ocean surface properties such as temperature and salinity. The flux is less constrained in the Southern Hemisphere and in marginal seas and coastal zones.

   ii. Changes in the carbon storage are derived from shipboard measurements of inorganic carbon and other biogeochemical and physical variables such as oxygen, nutrients, temperature and salinity.

   iii. Large uncertainty in i. and ii. may be reduced by filling in the large spatial and temporal gaps of measurements by ships and buoys with those using emerging sensor technology on autonomous platforms such as profiling floats and ocean gliders.

The variability and size of organic carbon pools, while smaller than the inorganic pools, are also not well observed and also depend on the availability of other nutrients.

~~b.~~c. Terrestrial uptake and land use change emissions are derived from models with large uncertainties.
   i. *Land use/cover* can be derived from satellites and is improving
   ii. Large uncertainties in *aboveground biomass* are being addressed though new satellite missions (e.g. in tropical regions)
   iii. *Wild fires* are mapped but their carbon loss is more uncertain
   iv. Changes in *soil carbon* are not monitored, this is particularly important for *peat lands*, *other wetlands* and *permafrost.*
   v. *River discharge* currently is not well reported globally and the carbon content of these waters is not well observed.

~~c.~~d. *Anthropogenic emissions of greenhouse gases* are reported and achieve a reasonable accuracy. The largest regions of uncertainty are China and India.

Key Questions to start addressing (list is non exhaustive)

1) Can addressing these gaps be *prioritised* in terms of improving the estimates of the carbon cycle?
2) What *practical* steps can be undertaken/recommended in the short term?
3) Are the existing ECV requirements *adequate*? Do they capture the scales needed?
4) Can we formulate recommendations for improved data *availability*, or novel observation techniques?
5) Next steps?

First steps are to review current ECV requirements and data sets (see IP). Example questions that can be asked:

   i. Relation land use change and carbon?
   ii. Lateral fluxes,
   iii. Uncertainties in anthropogenic emissions (e.g.China, India)
   iv. Is soil carbon essential?
   v. How well are ocean fluxes prescribed regionally?
   vi. Are the ECV's prescribed at the scale where it matters?
   vii. Gaps? Inconsistencies? Do we see obvious gaps, datasets with very large uncertainties, inconsistencies in scales?

3. **Framing Discussion session**:
   Integration, how do the disparate observations of the ECVs in the Atmosphere Terrestrial and Ocean come together.

   a. *Diverse variables and target scales. Are they comparable/interoperable?*

b. *Measurement approaches and accuracies (inc. satellite, in situ). Can we formulate recommendations for improved data availability, or novel observation techniques?*
c. *Connecting at the interfaces (Atmosphere-Ocean, Land Ocean, Atmosphere-Land). Can we define (and thus observe) ECVs at the interfaces? What role do they play in global and regional budgets?*
d. *Make a list of priority data sets that need to be acquired to achieve he overall goal of 10% of the annual flux?*

4. **Next steps:**

a. *Recommend analyses or intercomparisons (engaging WCRP, etc)*
b. *Opportunities (e.g new technologies, process studies (engaging WCRP, etc)*
c. *Next steps. (e.g. workshops, task team).*

Main Carbon Cycle related ECV product requirements						
ECV	ProducC	Frequency	Resolution	Required measurement uncertainty	Stability (per decade)	Standards/ references

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Carbon dioxide, Methane and other greenhouse gases[i]	Tropospheric CO_2 column	4 h	5–10 km/NA	1 ppm	1.5 ppm/decade	ESA CCI CMUG tables (http://www.esa-cmug-cci.org/)
	Tropospheric CO_2	4 h	5–10 km/5 km	1 ppm	1.5 ppm	
	Tropospheric CH_4 column	4 h	5–10 km/NA	10 ppb	7 ppb	
	Tropospheric CH_4	4 h	5–10 km/5 km	0.5 ppb	0.7 ppb	
	Stratospheric CH_4	Daily	100–200 km/2 km	5%	0.3%	
Inorganic carbon	Interior ocean carbon storage. At least 2 of: DIC, TA or pH	Decadal	Every 20°	TA/DIC ± 2 µmol pH ± 0.005		
	pCO_2 (to provide air–sea flux of CO_2)	Weekly to decadal	Every 10° (denser in the coastal domain, surface)	±2 µatm		
Above-ground biomass	Maps of AGB	Annual	500 m-1 km (based on satellite observations of 100–200 m)	< 20% error for biomass values > 50 t/ha, and 10 t/ha for biomass values ≤ 50 t/ha	10%	No agreed standards but see: GOFC-GOLD (2015b) GFOI (2013)
Land cover	Maps of land cover	Annual	250 m	15% (maximum error of omission and commission in mapping individual classes), location accuracy better than 1/3 IFOV with target IFOV 250 m	15% (maximum error of omission and commission in mapping individual classes), location accuracy better than 1/3 IFOV with target IFOV 250 m	No agreed standards but see GLCN (2014) and GOFC-GOLD (2015(a))
	Maps of high-resolution land cover	5 year	10–30 m	5% (maximum error of omission and commission in mapping individual classes), location accuracy better than 1/3 IFOV with target IFOV 10–30 m	5% (maximum error of omission and commission in mapping individual classes), location accuracy better than 1/3 IFOV with target IFOV 10–30 m	
	Maps of key IPCC land use, related changes and land-management types	1–10 years (including historical data)	10–1 000 m (depending on time period)	20% (maximum error of omission and commission in mapping individual classes), location accuracy better than 1/3 IFOV with target IFOV	20% (maximum error of omission and commission in mapping individual classes), location accuracy better than 1/3 IFOV with target IFOV	IPCC (2006)
Soil carbon	% carbon in soil	5–10 years	20 km			
	Mineral soil bulk density to 30 cm and 1 m	5–10 years	20 km			
	Peatlands total depth of profile, area and location	5–10 years	2 m vertical 20 m horizontal	10%		
Fire	Burnt Areas	24 hours	30 m	15% (error of omission and commission), compared to 30-m observations		None

Main Carbon Cycle related ECV product requirements

ECV	ProducC	Frequency	Resolution	Required measurement uncertainty	Stability (per decade)	Standards/ references
	Active fire maps	6 hours at all latitudes from polar-orbiting and 1 hour from geostationary	0.25-1 km (polar); 1–3 km (geo)	5% error of commission 10% error of omission Based on per-fire comparisons for fires above target threshold of 5 MW/km² equivalent integrated FRP per pixel (i.e. for a 0.5 km² pixel the target threshold would be 2.5 MW, for a 9 km² pixel it would be 45 MW).		
	Fire radiative power	6 hours at all latitudes from polar-orbiting and 1 hour from geostationary	0.25-1 km (polar) 1–3 km (geo)	10% integrated over pixel. Based on target detection threshold of 5 MW/km² equivalent integrated FRP per pixel (i.e. for a 0.5 km² pixel the target threshold would be 2.5 MW, for a 9 km² pixel it would be 45 MW).and with the same detection accuracy as the Active Fire Maps.		
Anthropogenic greenhouse-gas fluxes	Emissions from fossil fuel use, industry, agriculture and waste sectors	Annual	By country and sector	Globally 5% Nationally 10%		IPCC (2006) IPCC (2013)
	Emissions/ removals by IPCC land categories	Annual	By country/region	Globally 15% Nationally 20%		
	Estimated fluxes by inversions of observed atmospheric composition – continental	Annual	1 000–10 000 km	10%		Maps for modelling and adaptation
	Estimated fluxes by inversions of observed atmospheric composition – national	Annual	100–1 000 km	30%		
	High-resolution CO_2 column concentrations to monitor point sources	4 hourly	1 km	1ppm		
River discharge	River discharge	Daily	Per river	10 % (relative)		ISO/TC 113: WMO (2010) WMO (2008(a)) WMO (2009)
	Water Level	Daily	100 m	10 cm	1 cm/yr	
	Flow velocity	Few times per	Per river	10 % (relative)		

Main Carbon Cycle related ECV product requirements						
ECV	ProducC	Frequency	Resolution	Required measurement uncertainty	Stability (per decade)	Standards/ references
	Cross-section	year for station calibration				

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[i] [i] These requirements for global products have been derived by AOPC to support understanding of fluxes of greenhouse gases. GAW is developing requirements of the ground-based segment that would support this (Task Team on Observational Requirements and Satellite Measurements as regards Atmospheric Composition and Related Physical Parameters, http://www.wmo.int/pages/prog/arep/gaw/TaskTeamObsReq.html). GCOS will coordinate with GAW to ensure compatibility of all observational requirements.