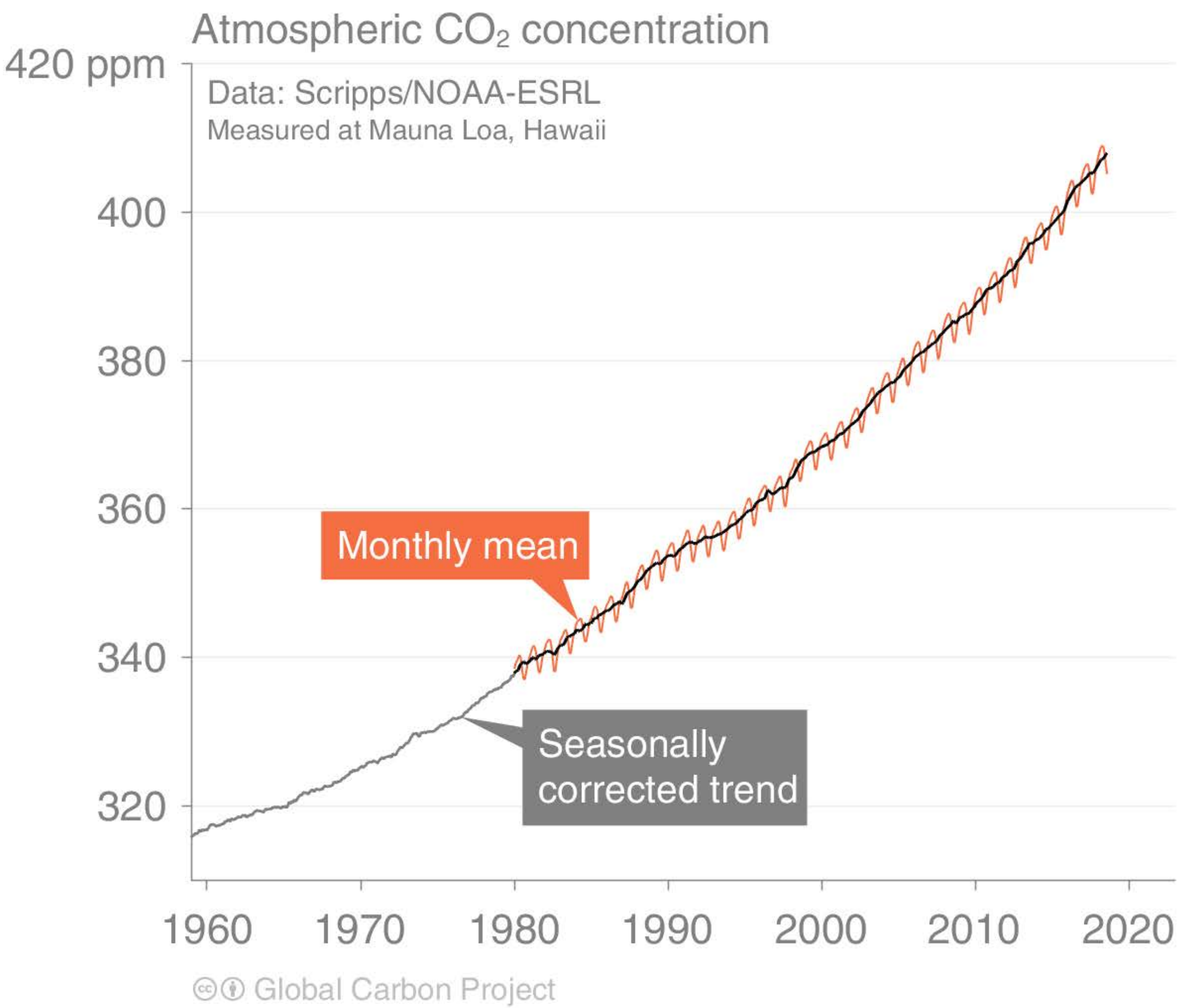
Closing the carbon budget

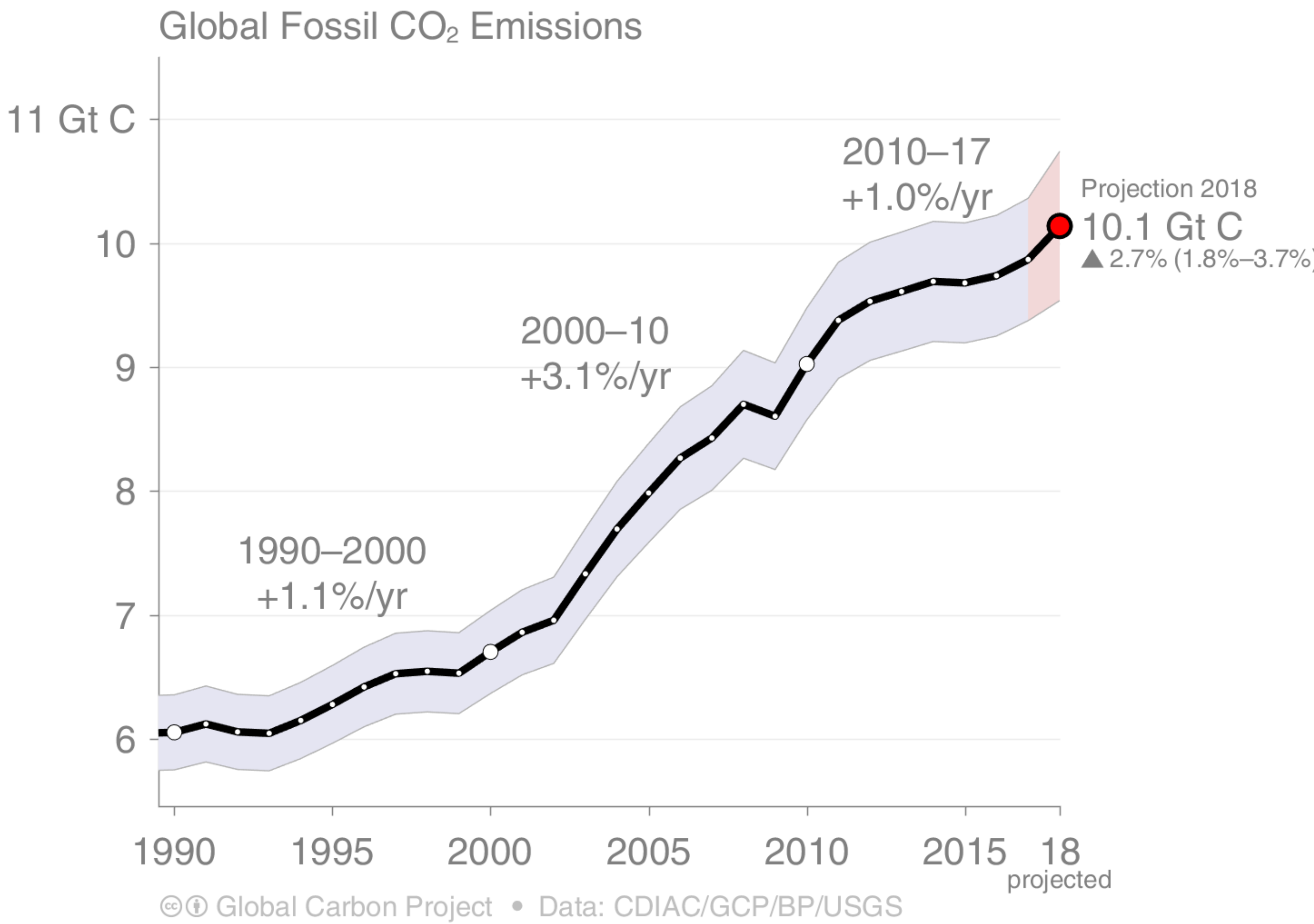
Han Dolman

The issue

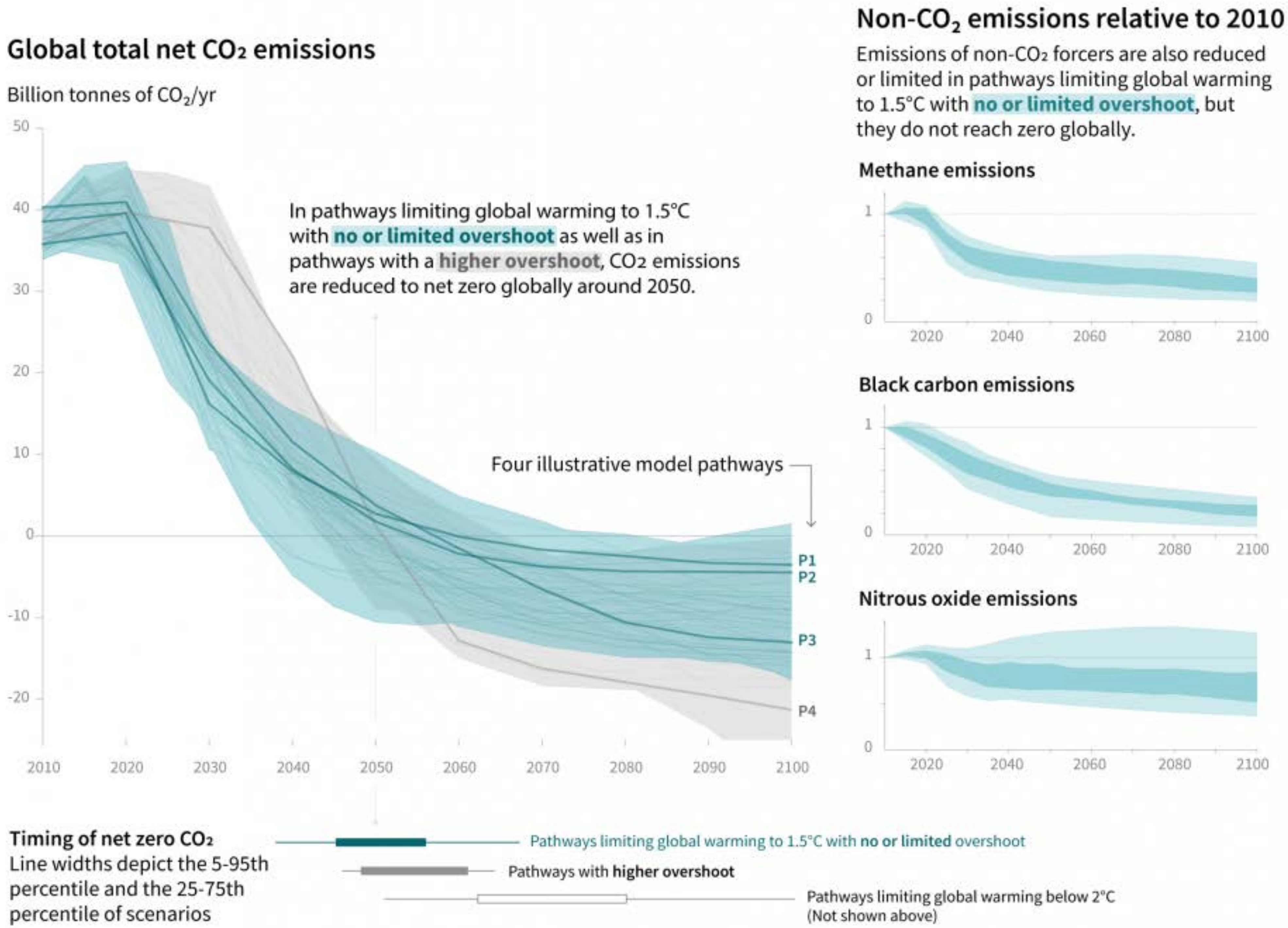


Atmospheric CO_2 concentration
420 ppm
400
380
360
340
320
Data: Scripps/NOAA-ESRL
Measured at Mauna Loa, Hawaii
Monthly mean
Seasonally corrected trend
1960
1970
1980
1990
2000
2010
2020
Global Carbon Project

The underlying issue

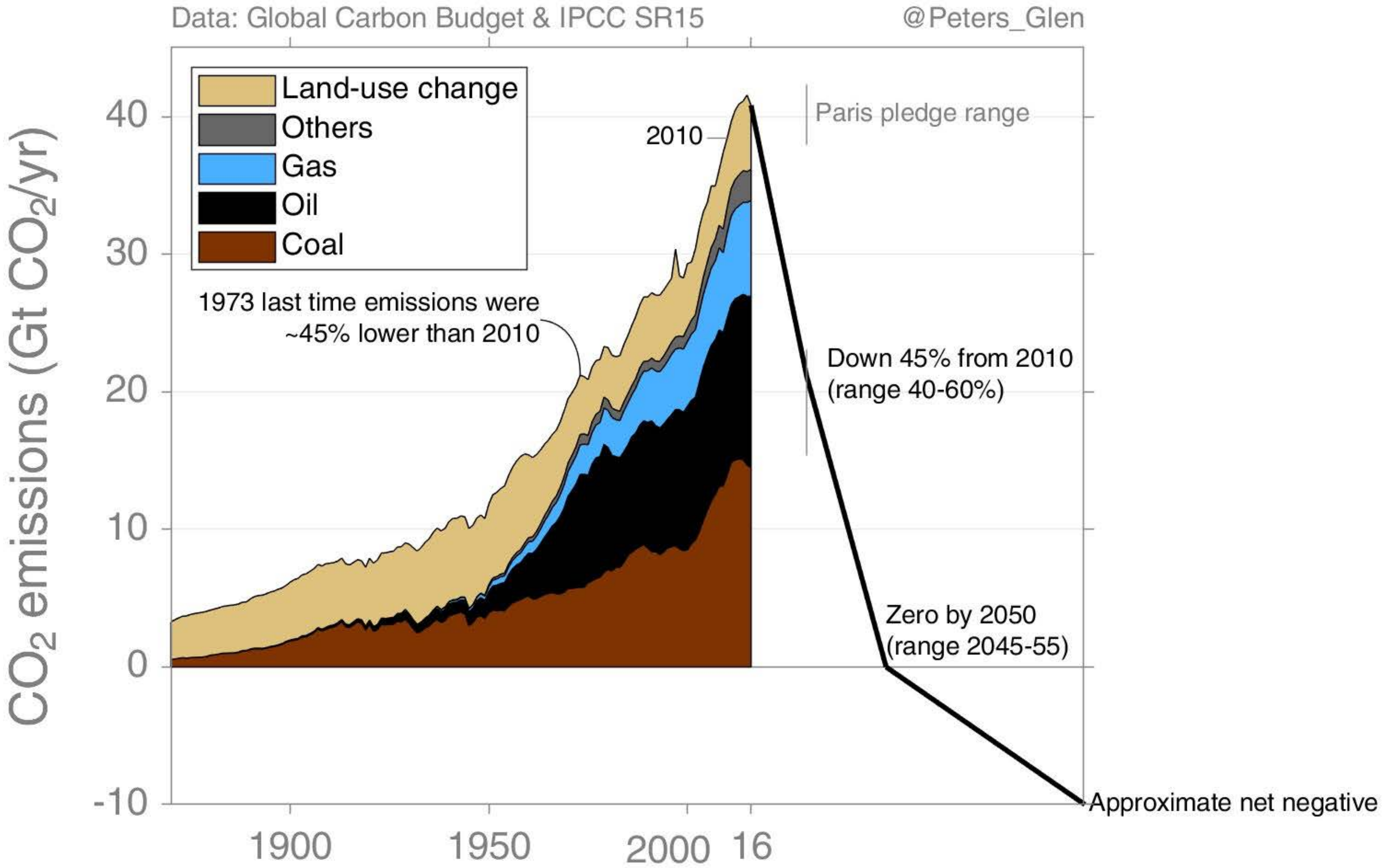


The mitigation urgency



Source: IPCC Special Report on Global Warming of 1.5°C

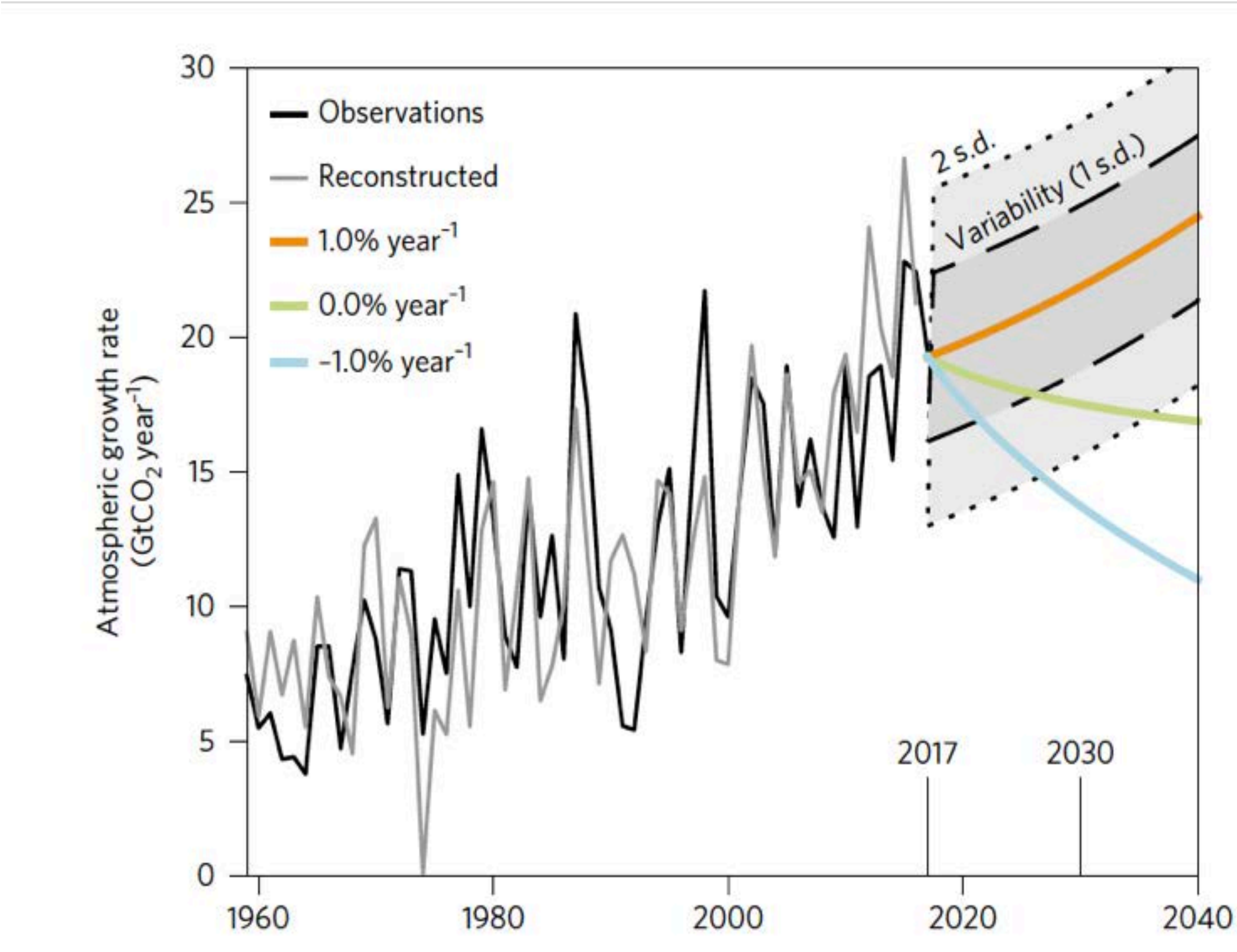
The mitigation challenge



The GCOS Carbon Budget ambition

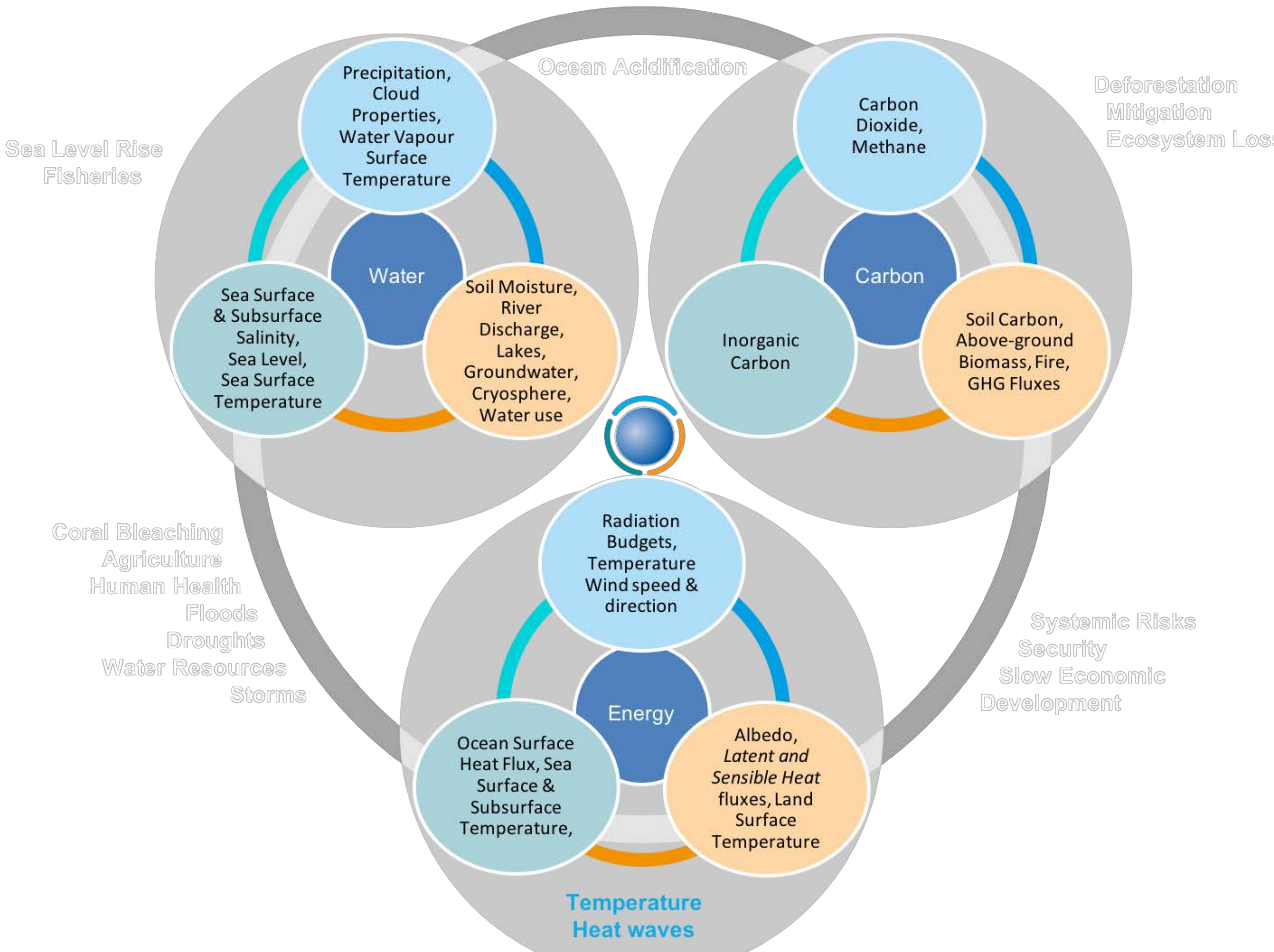
Box 4: Closing the carbon budget	
Targets	Quantify fluxes of carbon-related greenhouse gases to +/- 10% on annual timescales Quantify changes in carbon stocks to +/- 10% on decadal timescales in the ocean and on land, and to +/- 2.5 % in the atmosphere on annual timescales
Who	Operators of GCOS-related systems, including data centres
Time frame	Ongoing
Performance indicator	Regular assessment of uncertainties in estimated fluxes and inventories

Can we do something useful?

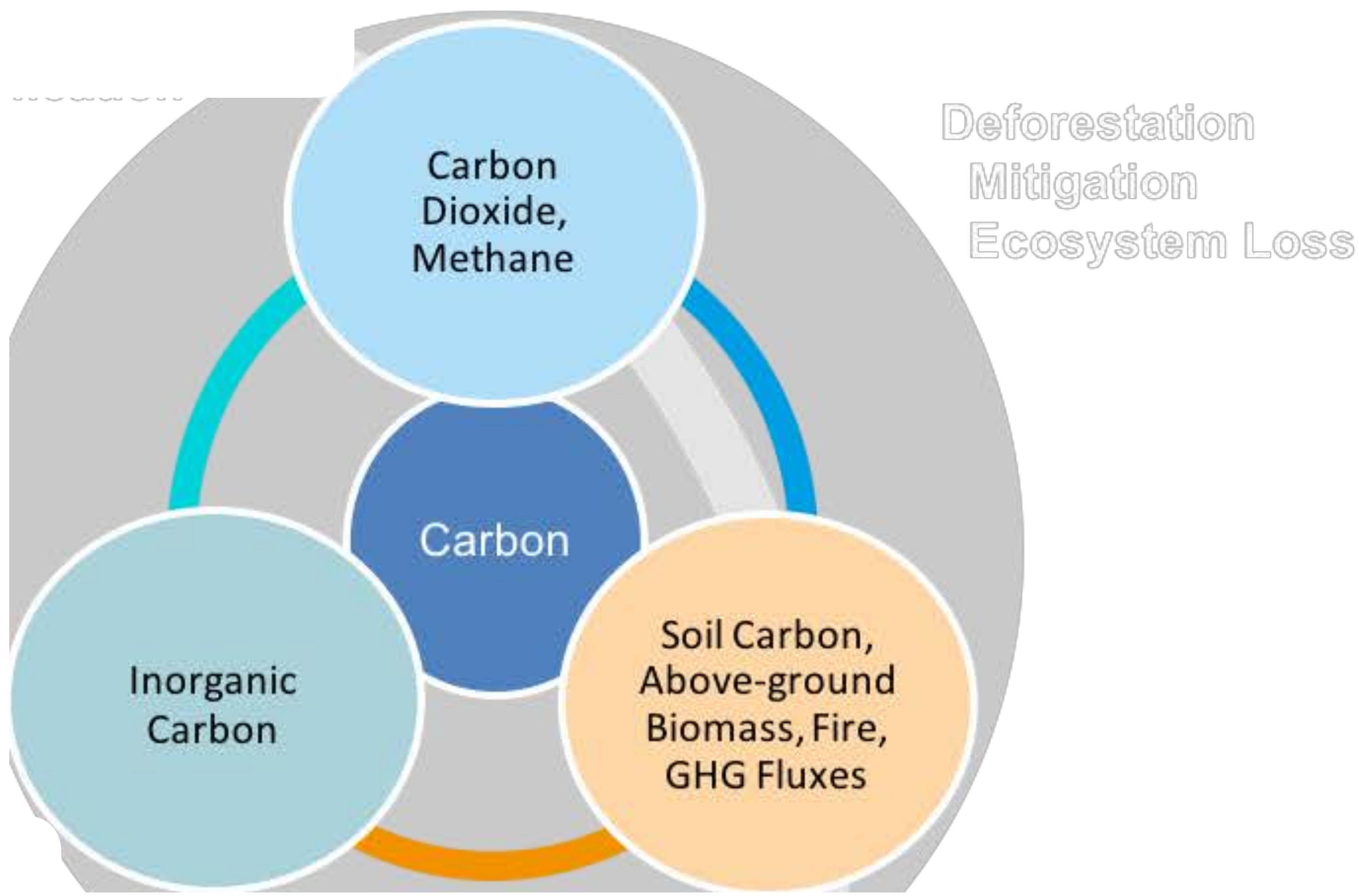


Peters et al., 2017

The GCOS IP Earth System Cycle approach



The GCOS perception of the carbon cycle



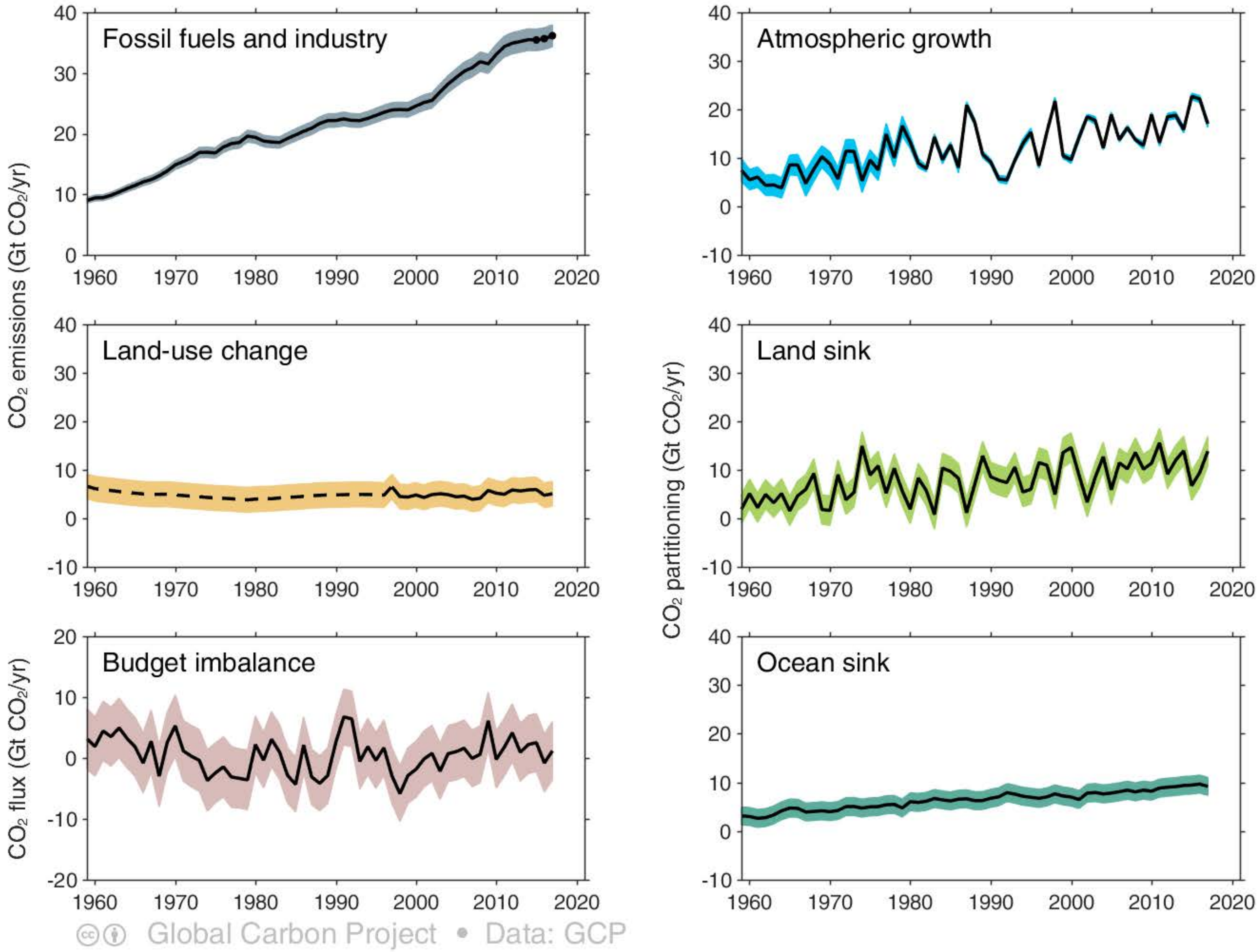
The global carbon cycle

Le Quéré et al , 2019

The fossil fuel emissions overlie and interact with highly dynamic natural carbon cycle that itself is sensitive to climate

Changes in the budget over time

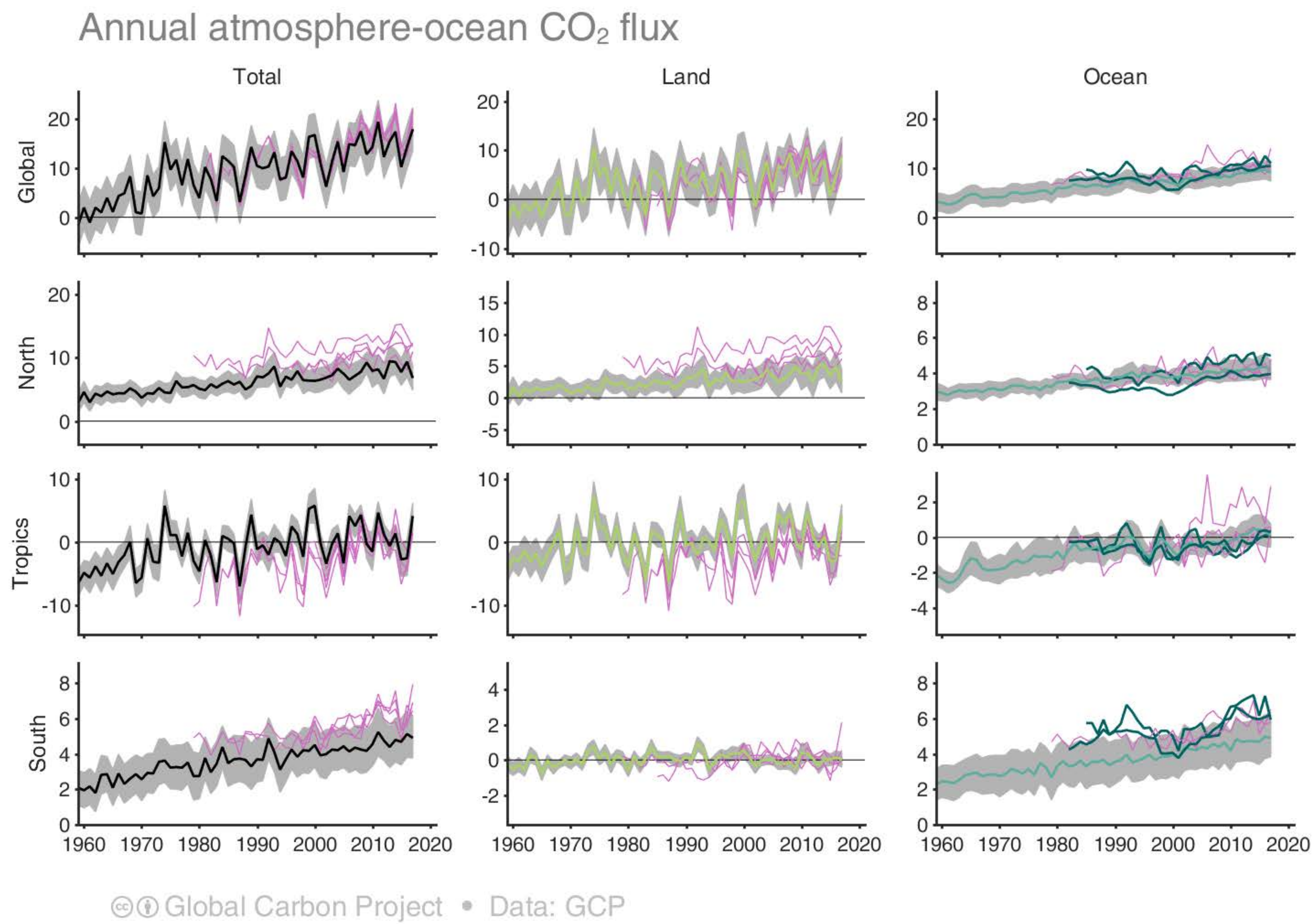
The sinks have continued to grow with increasing emissions, **but climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO_2 in the atmosphere**



The budget imbalance is the total emissions minus the estimated growth in the atmosphere, land and ocean.
It reflects the limits of our understanding of the carbon cycle.
Source: CDIAC; NOAA-ESRL; Houghton and Nassikas 2017; Hansis et al 2015; Le Quéré et al 2018; Global Carbon Budget 2018

Total land and ocean fluxes

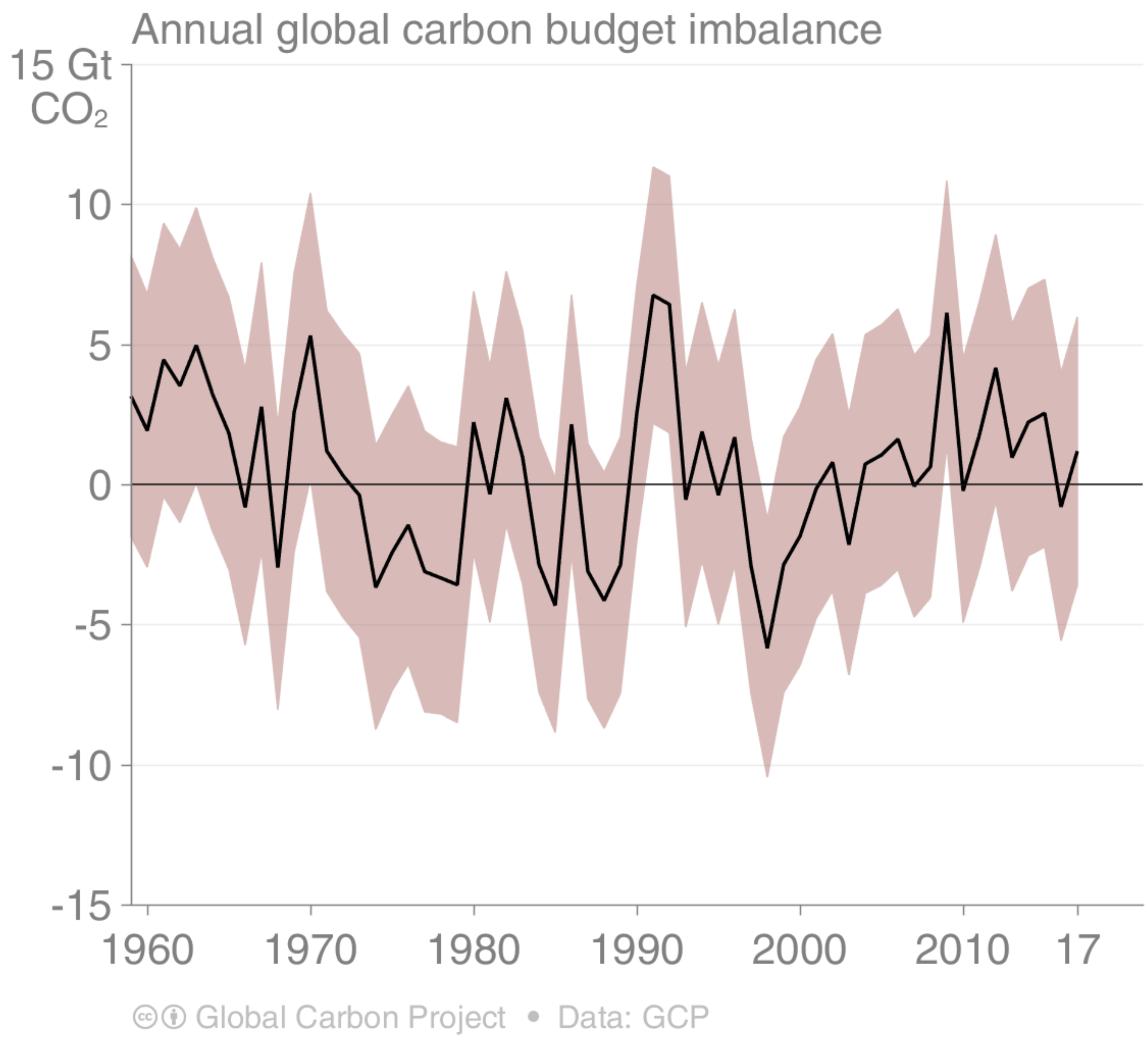
Total land and ocean fluxes show more interannual variability in the tropics



Source: Le Quéré et al 2018 (see Table 4 for detailed references)

Remaining carbon budget imbalance

Large and unexplained variability in the global carbon balance caused by uncertainty and understanding hinder independent verification of reported CO_2 emissions



positive values mean overestimated emissions and/or underestimated sinks

The budget imbalance is the carbon left after adding independent estimates for total emissions, minus the atmospheric growth rate and estimates for the land and ocean carbon sinks using models constrained by observations

Source: Le Quéré et al 2018; Global Carbon Budget 2018

Wat do the uncertainties and imbalances mean in the real world?

Annual Emission 2017 (in Gt C yr^{-1}, source Global Carbon atlas)

India 0.672

Germany 0.212

EU 0.97

Morocco 0.0172

China 2.683

US 1.437

Budget imbalance and ranges of the GCP budget (Gton Cyr^{-1})

Overall budget imbalance: 0.5
Uncertainty in

Sources

Fossil	0.5	(9.9)
Land use	0.7	(1.4)

Sinks

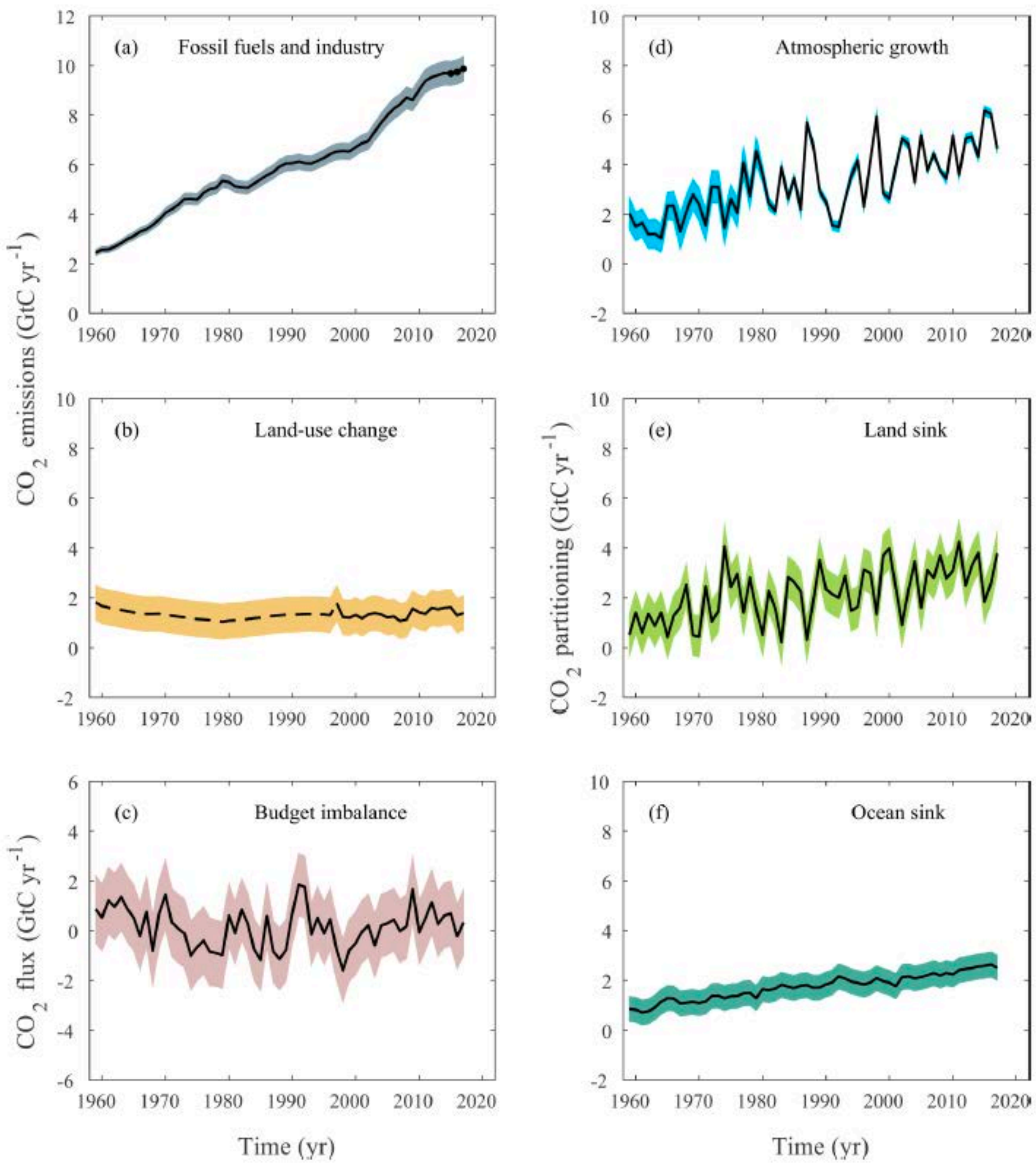
Atmosphere	0.2	(4.6)
Ocean	0.5	(2.5)
Land	0.8	(3.8)

What causes the budget imbalance

“We cannot attribute the cause of the variability in the budget imbalance with our analysis, only to note that the budget imbalance is unlikely to be explained by errors or biases in the emissions alone because of its large semi-decadal variability component, a variability that is untypical of emissions and has not changed in the past 50 years in spite of a nearly tripling in emissions. Errors in $\mathbf{S_{LAND}}$ **and** $\mathbf{S_{OCEAN}}$ are more likely to be the main cause for the budget imbalance”

Le Quéré et al , 2019

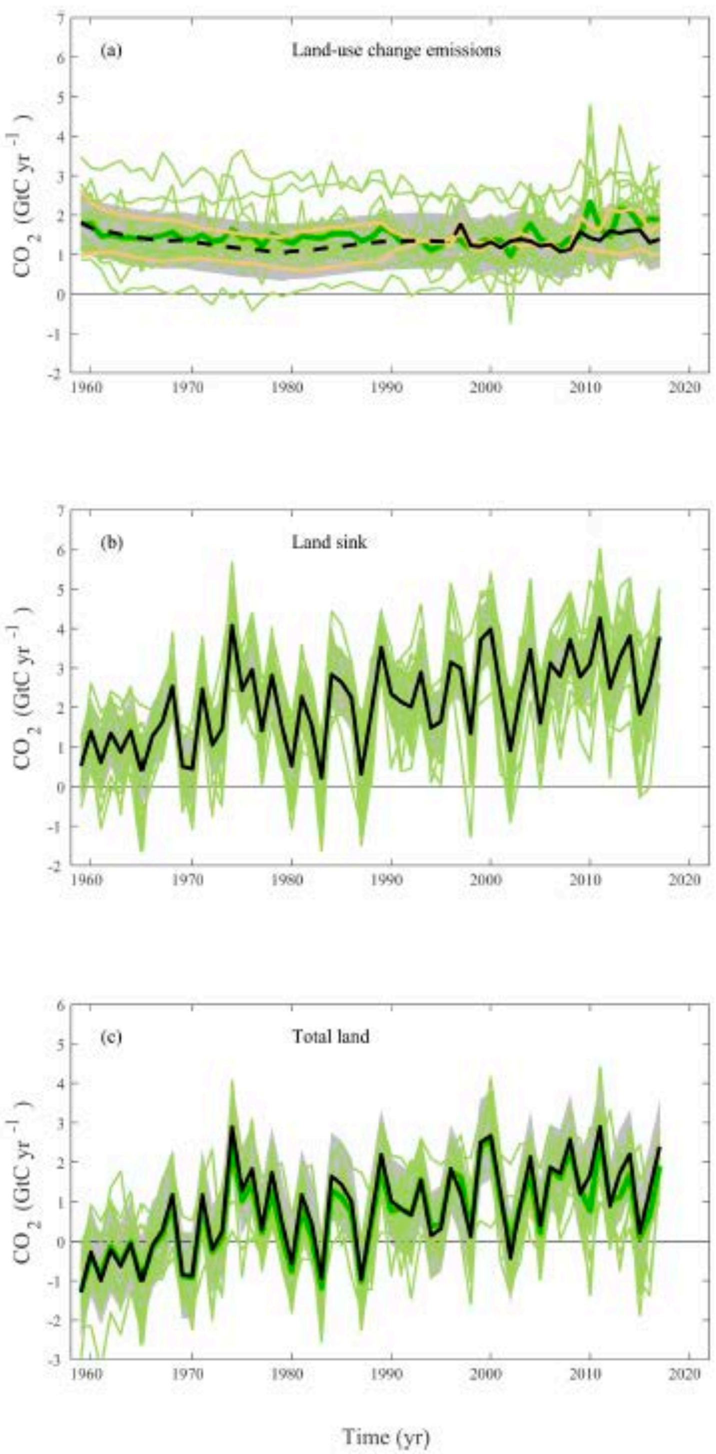
More on uncertainties



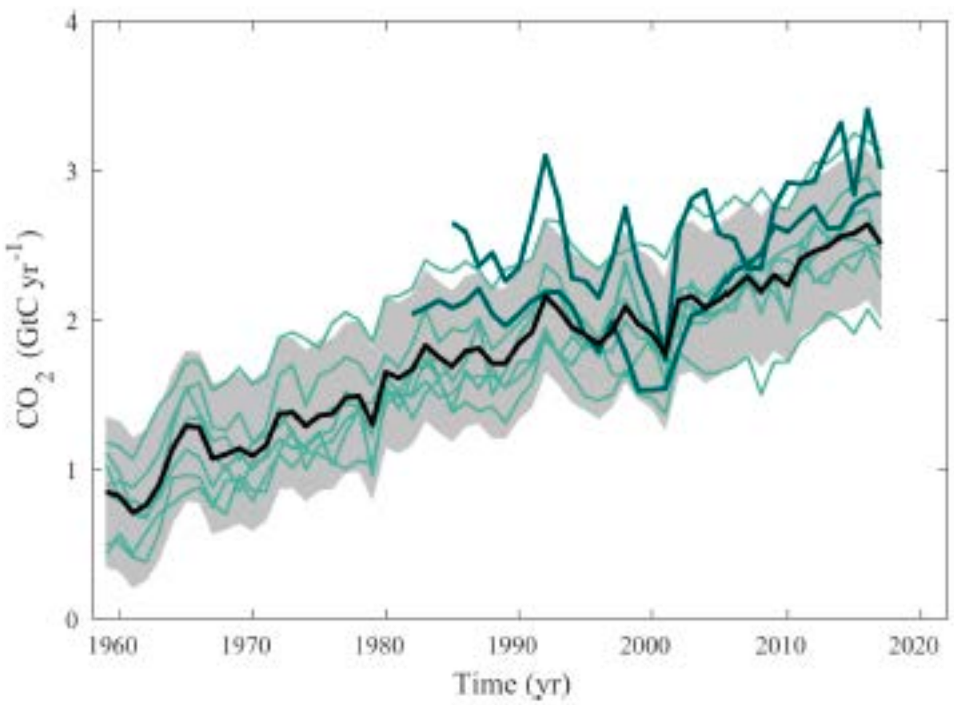
Le Quéré et al , 2019

Land and ocean sink

Land

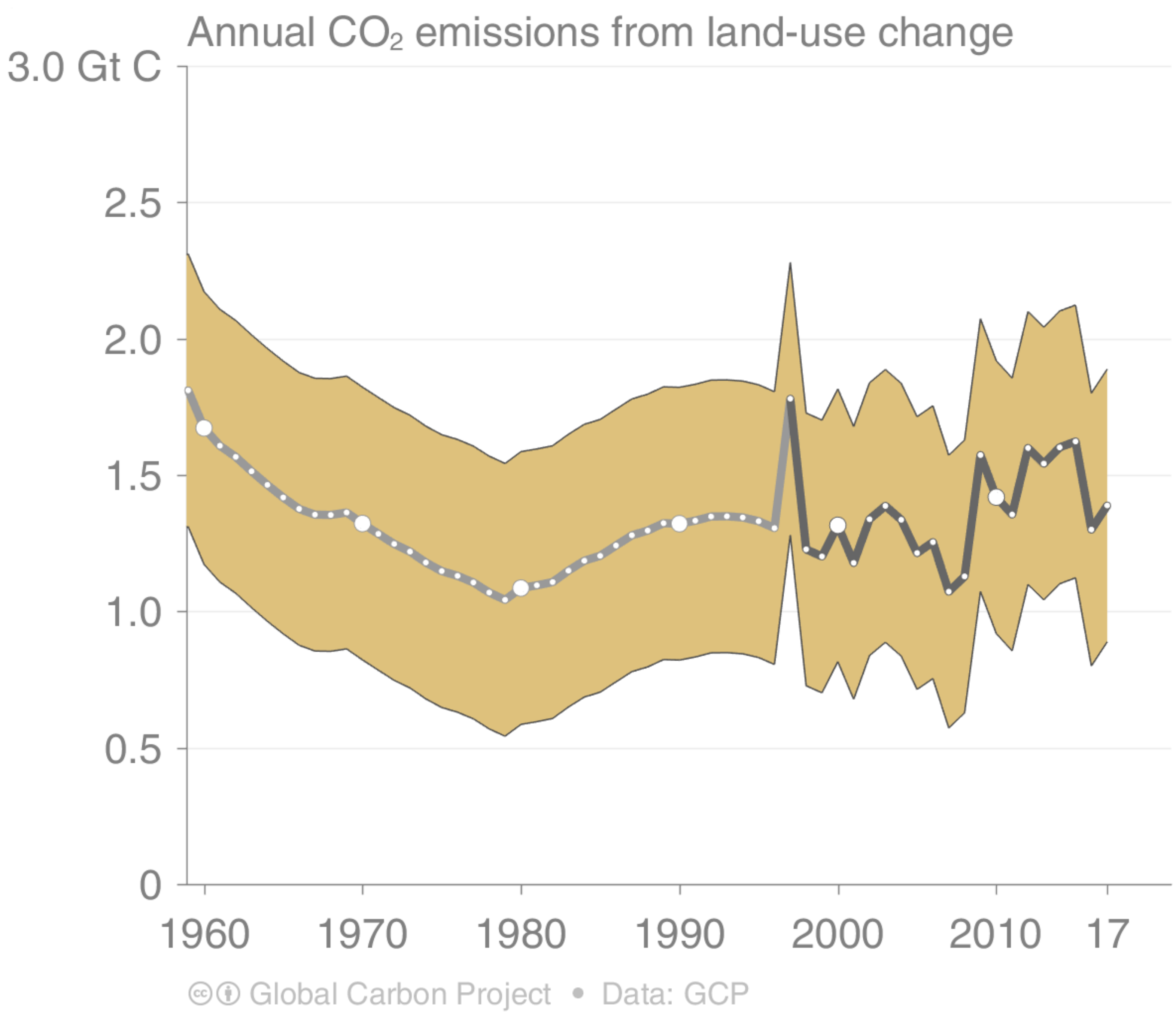


Ocean



Le Quéré et al , 2019

Land use change



Ocean carbon cycle

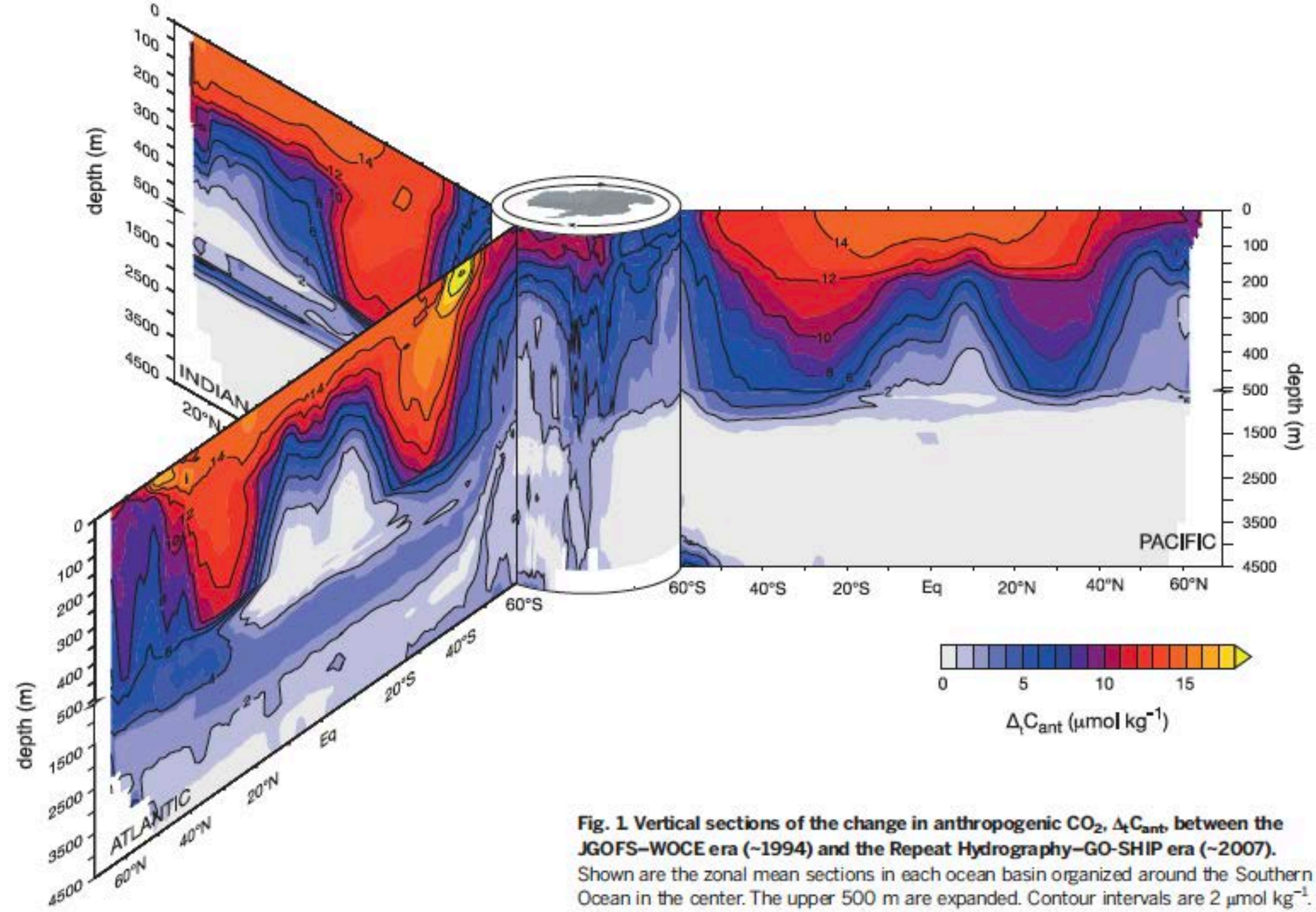


Fig. 1. Vertical sections of the change in anthropogenic CO_2, $\Delta_t C_{ant}$, between the JGOFS–WOCE era (~1994) and the Repeat Hydrography–GO-SHIP era (~2007). Shown are the zonal mean sections in each ocean basin organized around the Southern Ocean in the center. The upper 500 m are expanded. Contour intervals are 2 μmol kg^{-1}.

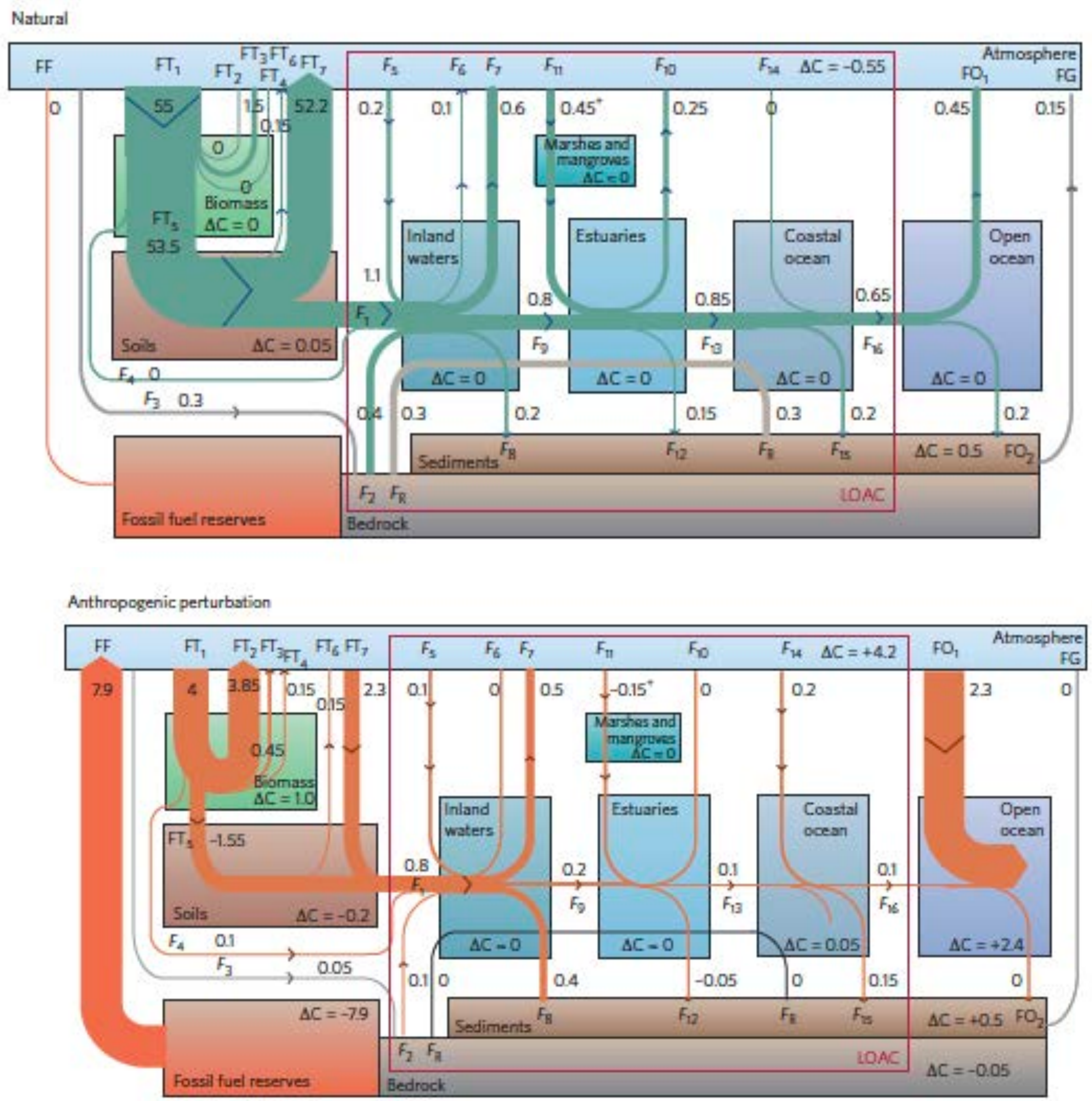
The ocean carbon budget

Table 2. Global CO_2 budget for both the period 1800 to 1994 and the decadal period from 1994 to 2007. In comparison to previous budgets (*1*), we include explicitly also the potential loss of natural CO_2 from the ocean as a component of the budget. The potential contribution of changes in the land-to-ocean carbon fluxes through aquatic systems (*46*) is not considered here.

CO_2 sources and sinks	1800 to 1994 (Pg C)*	1994 to 2007 (Pg C)†	
Constrained sources and sinks			
(1) Emissions of C_{ant} from fossil fuel and cement production	244 ± 20	94 ± 5‡	
(2) Increase of CO_2 in the atmosphere	−165 ± 4	−50 ± 1§	
(3a) Uptake of C_{ant} by the ocean	−118 ± 19	−34 ± 4‖	
(3b) Loss of natural CO_2 by the ocean	7 ± 10¶	5 ± 3#	
(3) Net ocean CO_2 uptake	−111 ± 21	−29 ± 5	2.23
Inferred terrestrial balance			
(4) Net terrestrial balance [−(1)−(2)−(3)]	32 ± 30	−15 ± 7	
Terrestrial balance			
(5) Emissions of C_{ant} from land use change	100 to 180	16 ± 6**	
(6) Terrestrial biosphere sink [−(1)−(2)−(3)] −(5)	−68 to −148	−31 ± 9	2.38

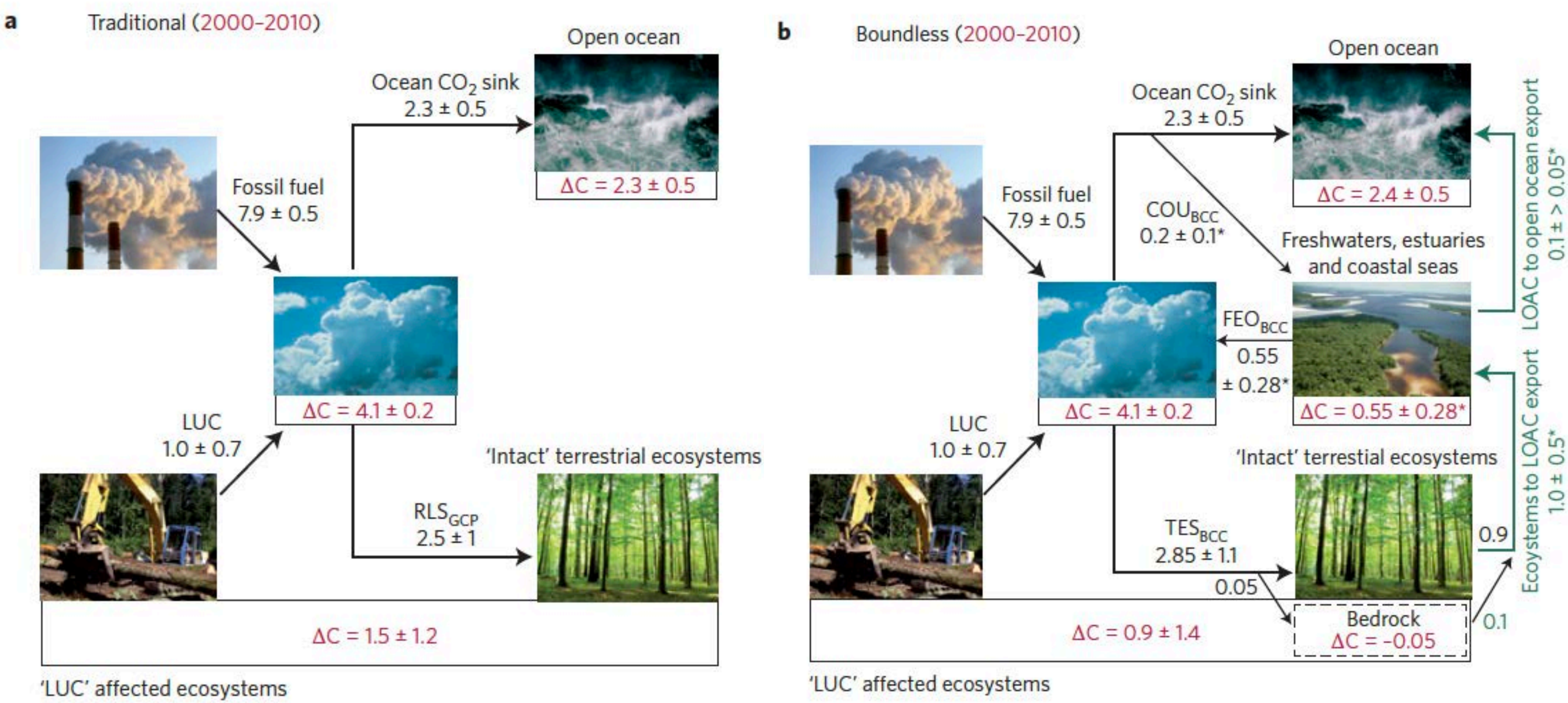
*Budget as listed in (*1*), except for 3b. †The numbers correspond to the period from mid-1994 to mid-2007. ‡Boden *et al.* (*5*). §Dlugokencky and Tans (*37*). ‖This study. ¶Keeling (*38*); Sabine and Gruber (*47*). #See text, based on Landschützer *et al.* (*39*). **Average of Houghton and Nassikas (*4*) and Hansis *et al.* (*48*).

The importance of lateral transport



Regnier et al., 2013

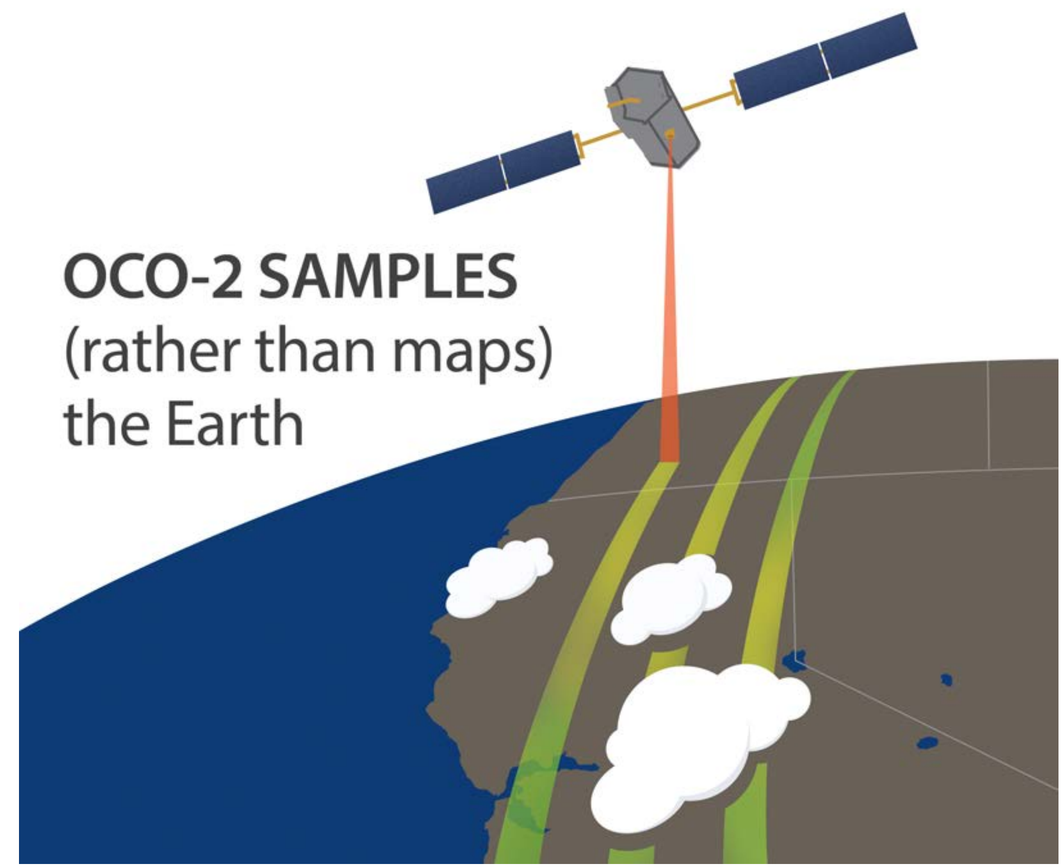
Lateral transport has implications for the land budget



$$TES_{BCC} = RLS_{GCP} + FEO_{BCC} - COU_{BCC}$$

Developments

- New satellites, GOSAT, OCO-2, planned several others
- New observations (SIF>GPP)
- *In situ* infrastructure ICOS, ….
- Inventory agencies are starting to take on top down estimates (inversions)
- EU-ESA taskforce on global monitoring system
- City observations, modelling



Some questions for discussion

- Do the diverse variables and target scales yield sufficient constraints on the carbon cycle that are comparable, consistent or interoperable?
- Do the measurement (including satellite, in situ) provide the needed precision, accuracy, resolution, and coverage needed to monitor both natural and anthropogenic changes in the carbon cycle?
- Do we aim to provide a multi service approach to carbon data, i.e. do we cater for science and policy oriented applications ?
- Can we formulate recommendations for novel observation techniques or analysis techniques that will improve data availability?
- Can we define (and thus observe) ECVs at the interfaces Atmosphere-Ocean, Land Ocean, Atmosphere-Land) to constrain carbon fluxes stocks and fluxes on global and regional scales?

The wider world and the GCOS ECVs

- Relationship of land use change and carbon uptake and emission?
- Lateral fluxes (land-ocean-atmosphere),
- Uncertainties in anthropogenic emissions (e.g.China, India, and rapidly developing world)
- How well are ocean fluxes known regionally?
- Are the ECV's prescribed at the scale where it matters?
- Gaps? Inconsistencies? Do we see obvious gaps, datasets with very large uncertainties, or inconsistencies in scales?