Longer time scale ESM components:

Challenges and Opportunities in Carbon Cycle and Chemistry

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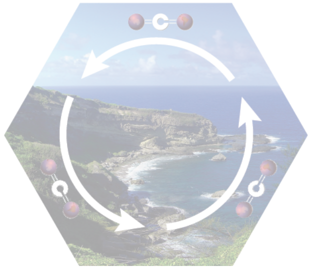
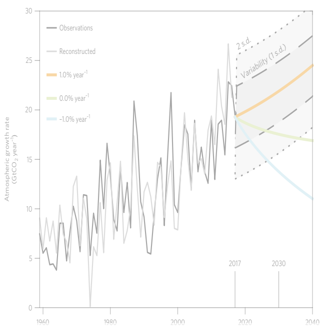
Outline

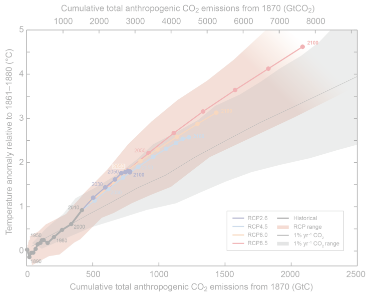
1. Guiding questions in the context of the WCRP GC-Carbon



2. Uncertainties in near-term CO_2 variations



3. Uncertainties in TCRE and remaining carbon budget



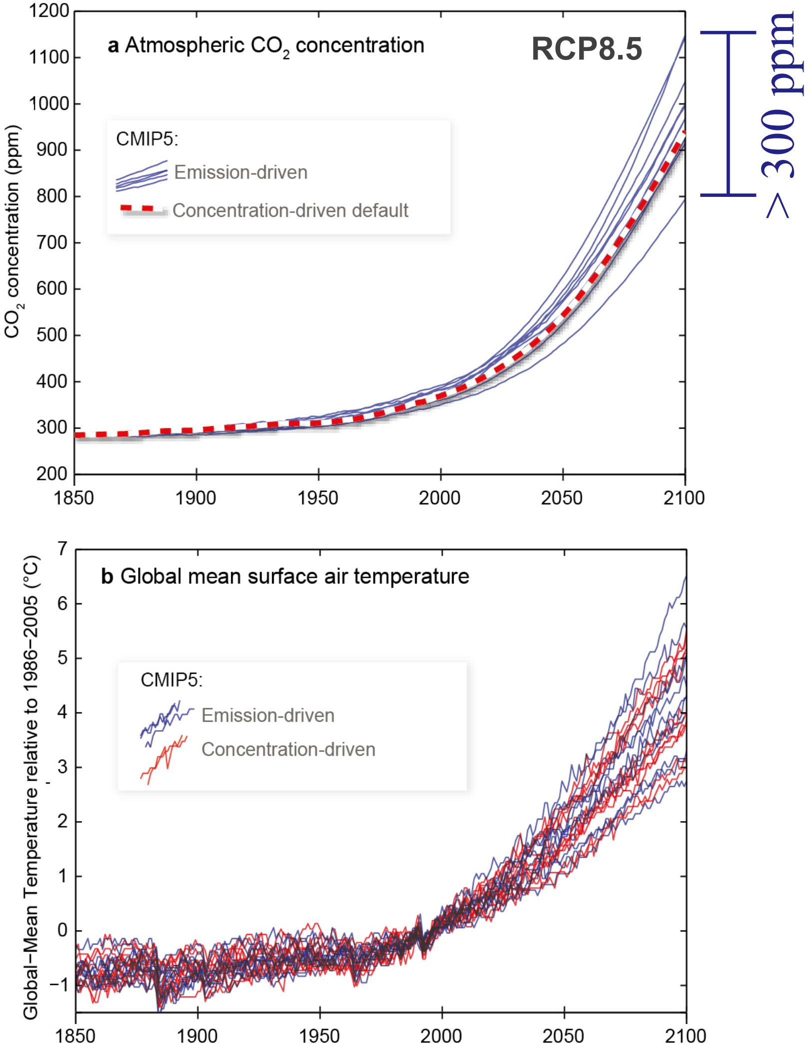
Uncertainty in carbon cycle projections (>300 ppm) is comparable to differences across socio-economic scenarios.

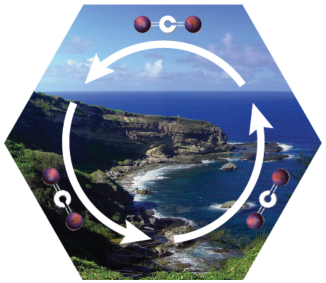
AR5 WG1 SPM:

“Based on ESMs, there is *high confidence* that the feedback between climate and the carbon cycle is positive in the 21st century.”

CMIP5

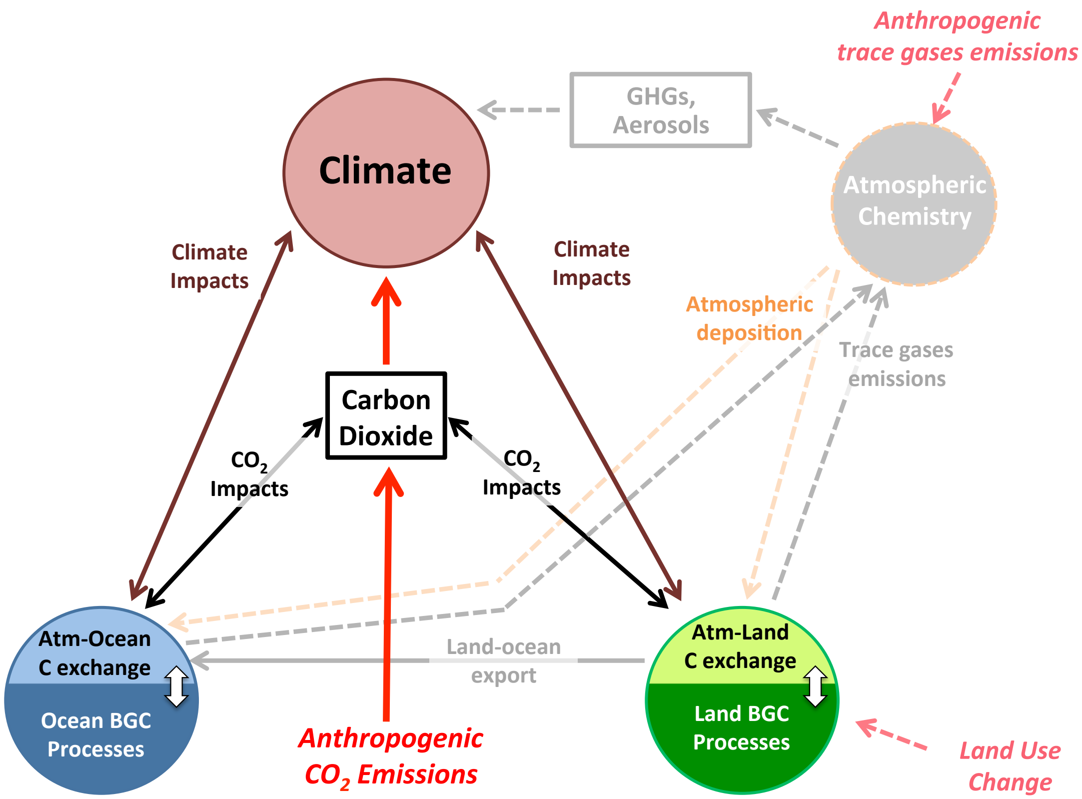
- >40 climate models (AOGCM)
- 10 ESMs (i.e. with BGC components)



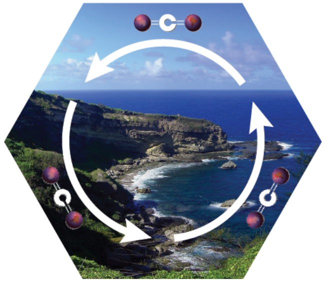


GC: Carbon Feedbacks in the Climate System

Objective: to understand how biogeochemical cycles and feedbacks control CO_2 concentrations and impact on the climate system



Ilyina T. and Friedlingstein P. 2016: White Paper on WCRP Grand Challenge



GC: Carbon Feedbacks in the Climate System

Objective: to understand how biogeochemical cycles and feedbacks control CO_2 concentrations and impact on the climate system

Guiding questions:

1. What are the drivers of land and ocean carbon sinks?
2. What is the potential for amplification of climate change over the 21st century via climate-carbon cycle feedbacks?
3. How do greenhouse gases fluxes from highly vulnerable carbon reservoirs respond to changing climate (including climate extremes and abrupt changes)?

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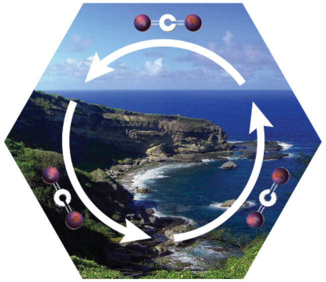


GC: Carbon Feedbacks in the Climate System

Kick-off workshop (Hamburg, Nov. 2017)

Processes on Land

- CO_2 fertilisation and role of nutrients
- Carbon turnover time and response to climate change

Processes in the Ocean

- Ocean mixing, stratification and carbon uptake
- Biological pump and carbon export

Learning from existing records

- New ocean products for comprehensive spatio-temporal
- variability
- Synthesis of surface and satellite measurements as well
- as manipulative experiments
- Focus on interannual to decadal variability not just mean

Improving projections

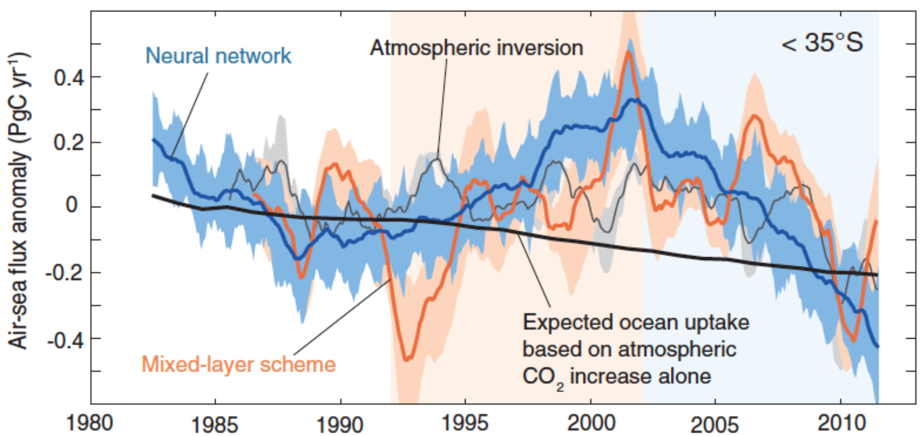
- Extended climate-carbon feedback framework
- Decadal prediction of the carbon cycle

What are the drivers of the land ocean carbon sink?

Ocean: *key mechanisms are identified, but with large uncertainties regarding their strength and multi-year variability*

Southern Ocean is responsible for about half of the ocean carbon sink and dominates its multi-year variability

Observations



Landschützer et al., Science, 2015

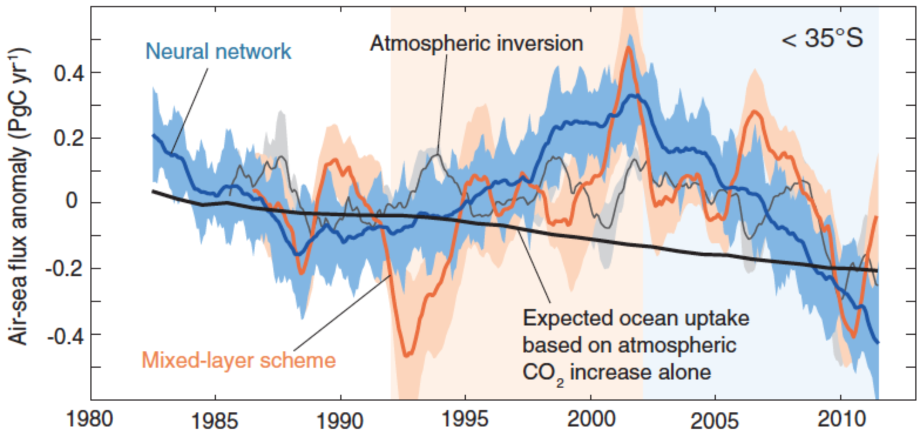
What are the drivers of the land ocean carbon sink?

Ocean: *key mechanisms are identified, but with large uncertainties regarding their strength and multi-year variability*

Southern Ocean is responsible for about half of the ocean carbon sink and dominates its multi-year variability

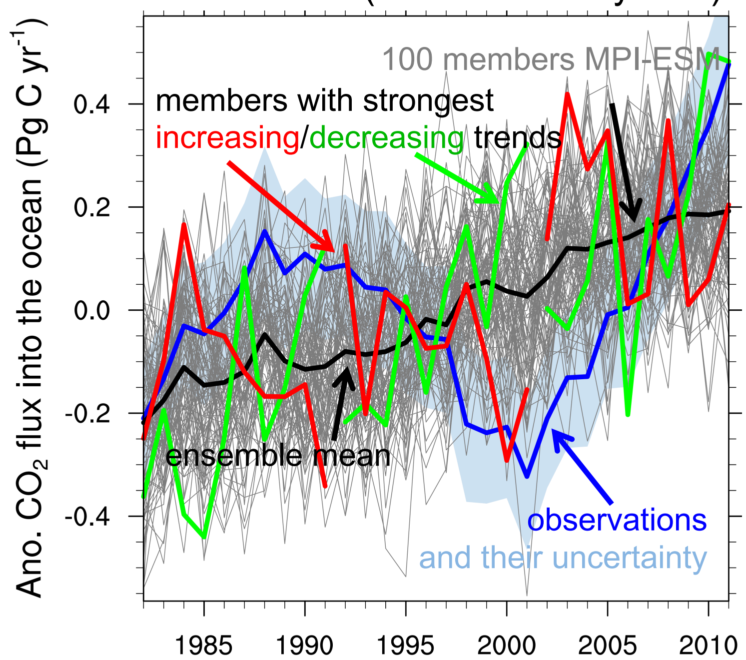
Poor understanding of origins of variability, e.g. due to uncertain relative contribution of biological vs. physical processes

Observations



Landschützer et al., Science, 2015

MPI-ESM (note reversed y-axis)

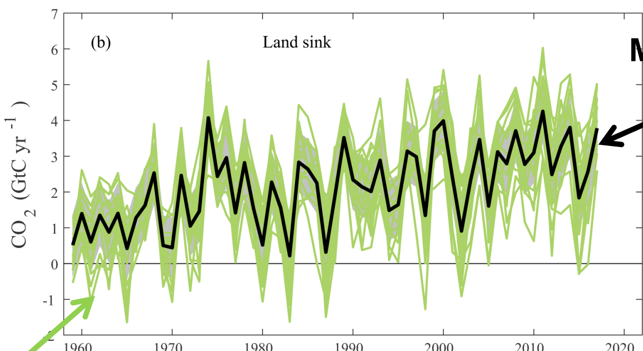


Hongmei Li and Ilyina GRL 2018

What are the drivers of the land ocean carbon sink?

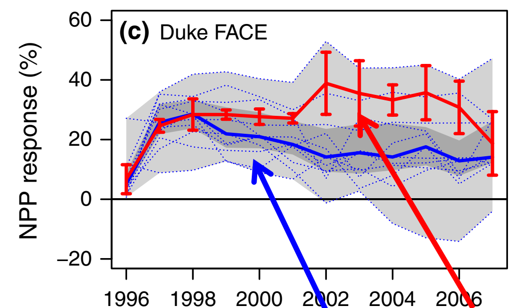
Land: *the main barriers relate to understanding of the actual processes driving the sinks*

Fair global agreement between land carbon models and estimate from global carbon budget



LeQuéré et al., ESSD, 2018

But large uncertainty at the process level, e.g. plant response to CO_2 increase

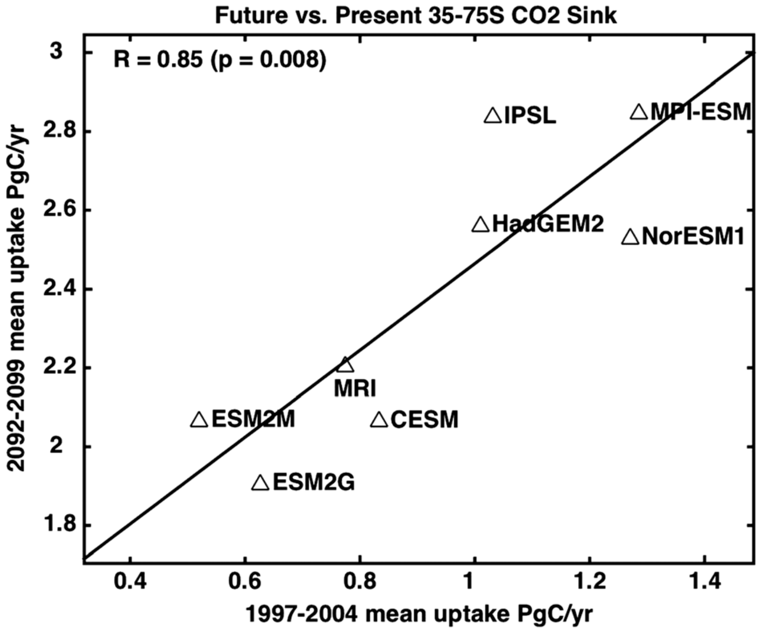


Zaehle et al., New Phyt., 2014

What is the potential for amplification of climate change over the 21st century via climate-carbon cycle feedbacks?

Ocean: How changes in climate, ocean circulation, and biogeochemical mechanisms will affect the ocean's capacity to sequester carbon?

ESMs with overestimated seasonal C-uptake project larger future C-uptake in the South. Ocean



Nevison et al, GRL, 2016

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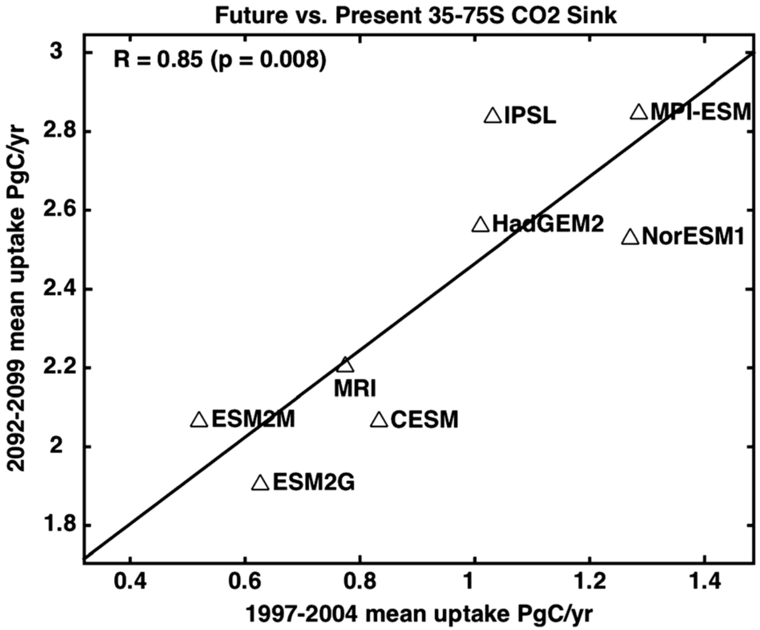
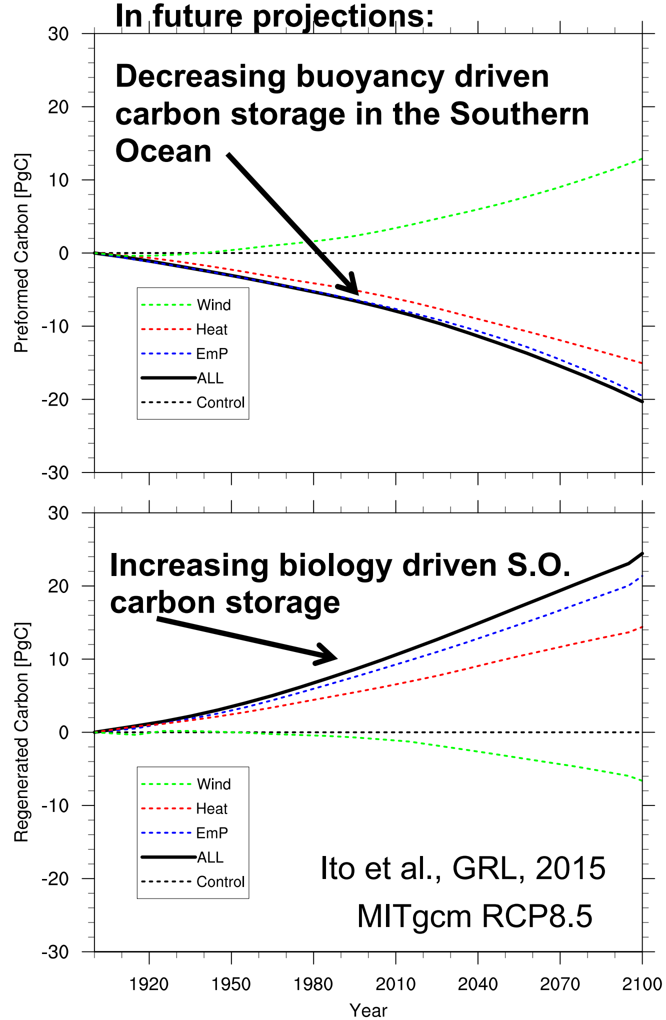


Nevison et al, GRL, 2016

In future projections:



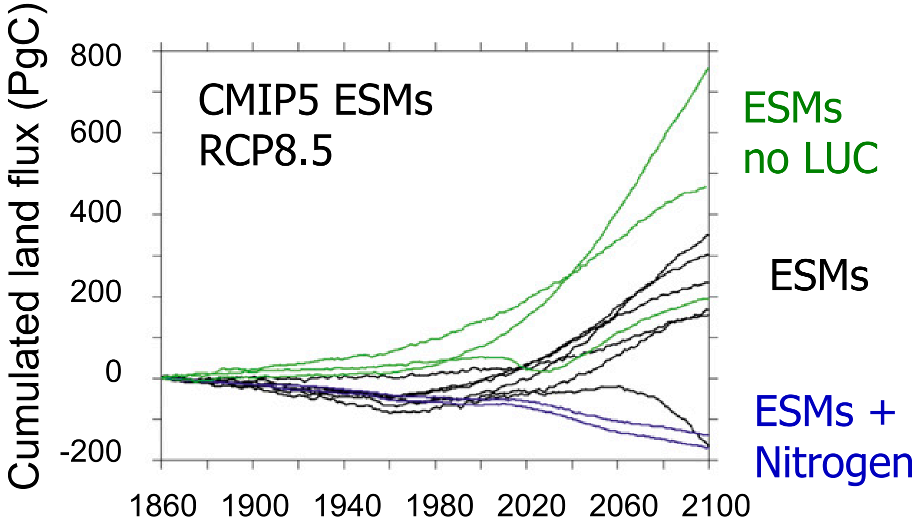
Ito et al., GRL, 2015

MITgcm RCP8.5

What is the potential for amplification of climate change over the 21st century via climate-carbon cycle feedbacks?

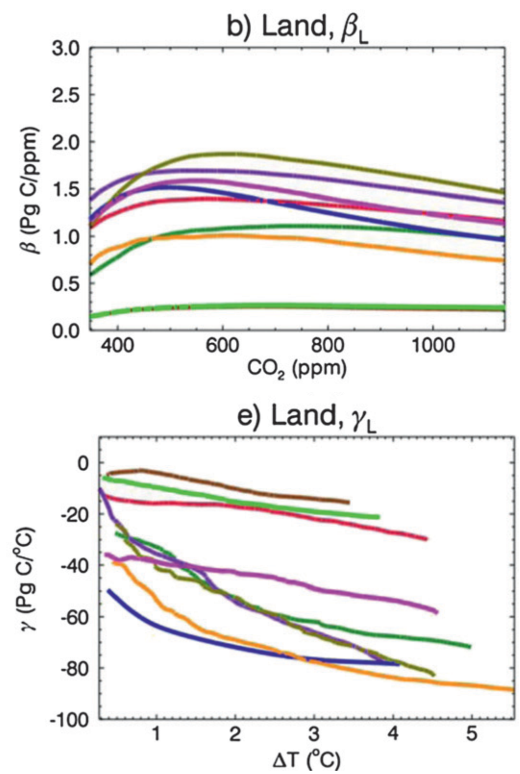
Land: How changes in climate, atmospheric composition, land use will affect the land's capacity to sequester carbon?

Future land sink in RCP scenario very uncertain. Not even sure about the sign !



Friedlingstein et al., J. Clim, 2014

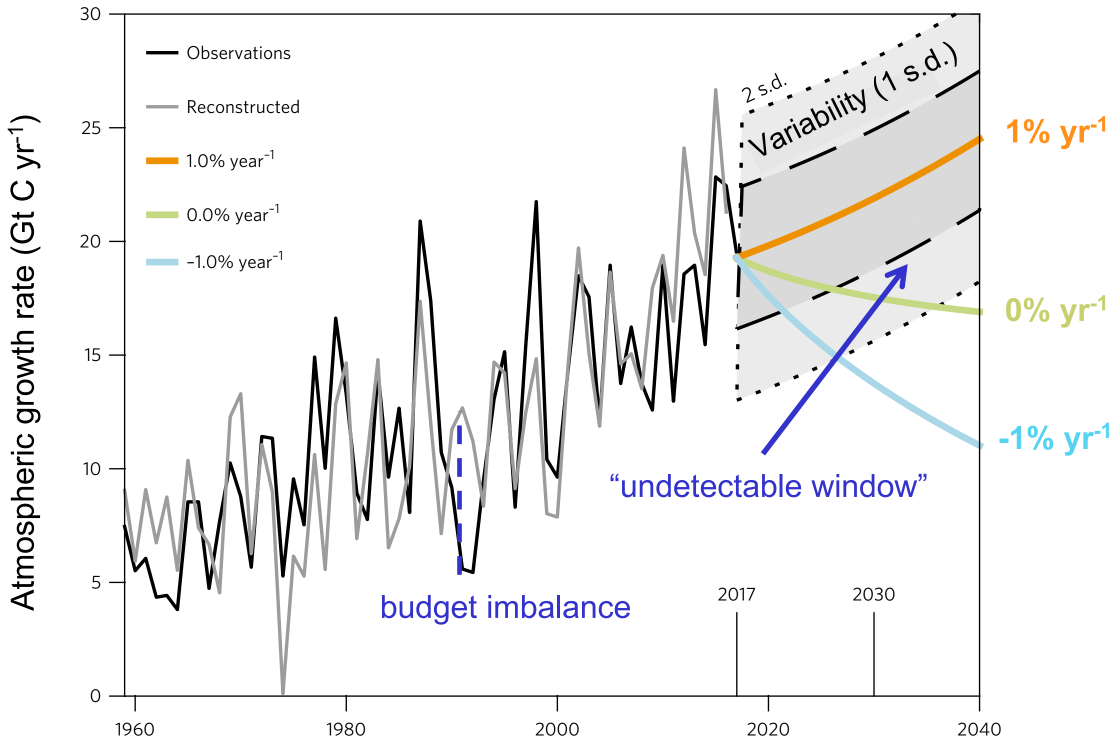
Large uncertainty on land carbon response to CO_2 (β) and climate (γ)



Arora et al., J. Clim, 2013

Uncertainty in near-term CO_2 changes

Near-term changes in emissions may not be detectable in atmospheric CO_2 observations over several years due to natural variability and process uncertainty



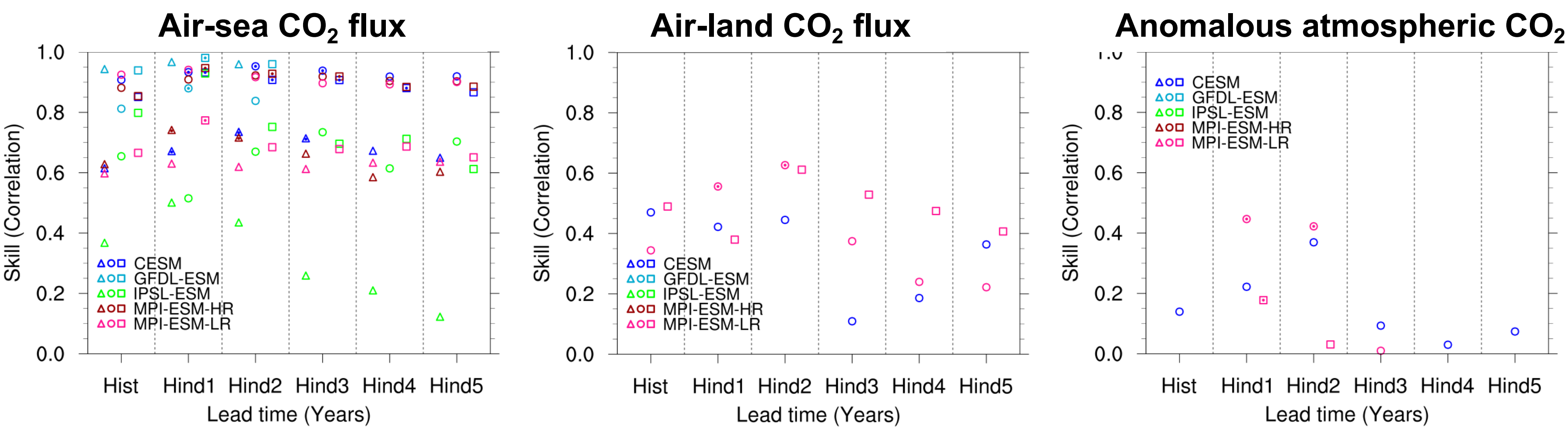
Peters et al., Nature Climate Change 2017

Near-term predictability horizons for CO_2 fluxes in a multi-model framework

△ Observational product (only for air-sea CO_2 flux)

○ Global Carbon Budget estimates

□ ESM assimilation simulation



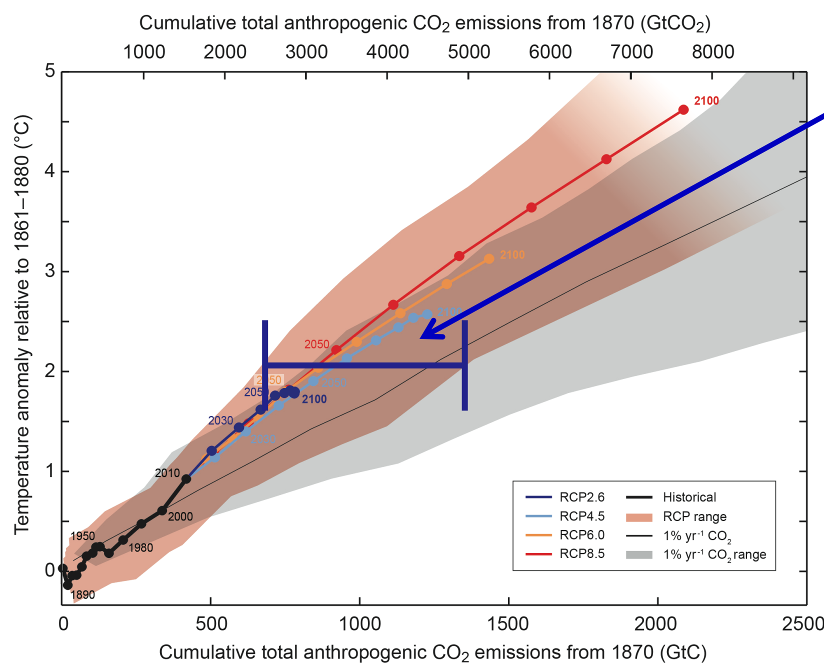
Ilyina et al., in prep.

Predictability of 2-3 years is expected in initialized ESM-based prediction systems for CO_2 fluxes and variations in atmospheric CO_2 growth rate

Implications for climate projections

Large uncertainty in CO_2 emissions compatible with a given climate target

Budget for the 2° C target is about 700GtC to 1300GtC.
Given 550 GtC emitted so far, that's 15 to 75 years of current emissions.



Uncertainty

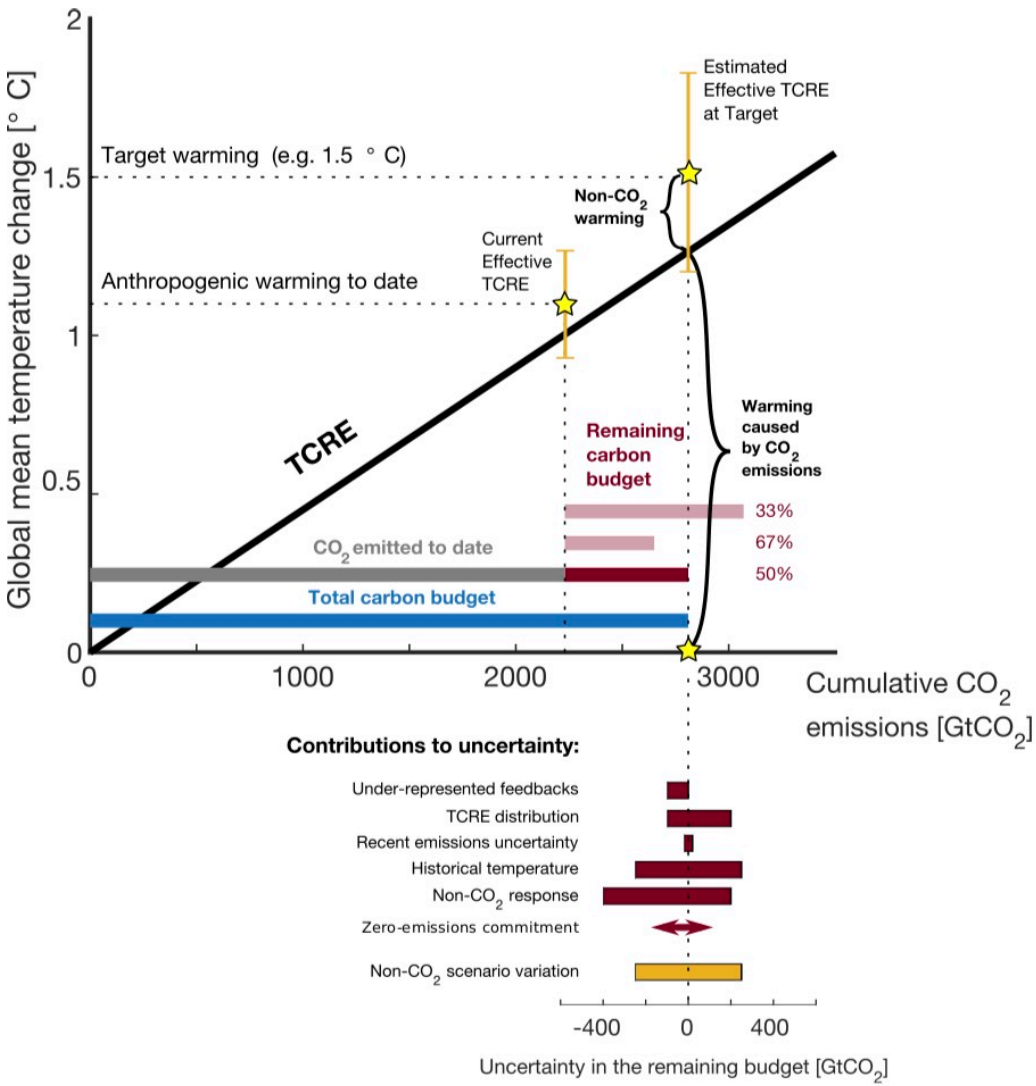
- Carbon feedbacks (CO_2 emissions ➔ CO_2 concentration)
- Climate feedbacks (CO_2 concentrations ➔ climate response)

AR5 WG1 SPM:

"Cumulative total emissions of CO_2 and global mean surface temperature response are approximately linearly related. Any given level of warming is associated with a range of cumulative CO_2 emissions."

Rogelj et al. Nature, 2019
Matthews et al. in prep.

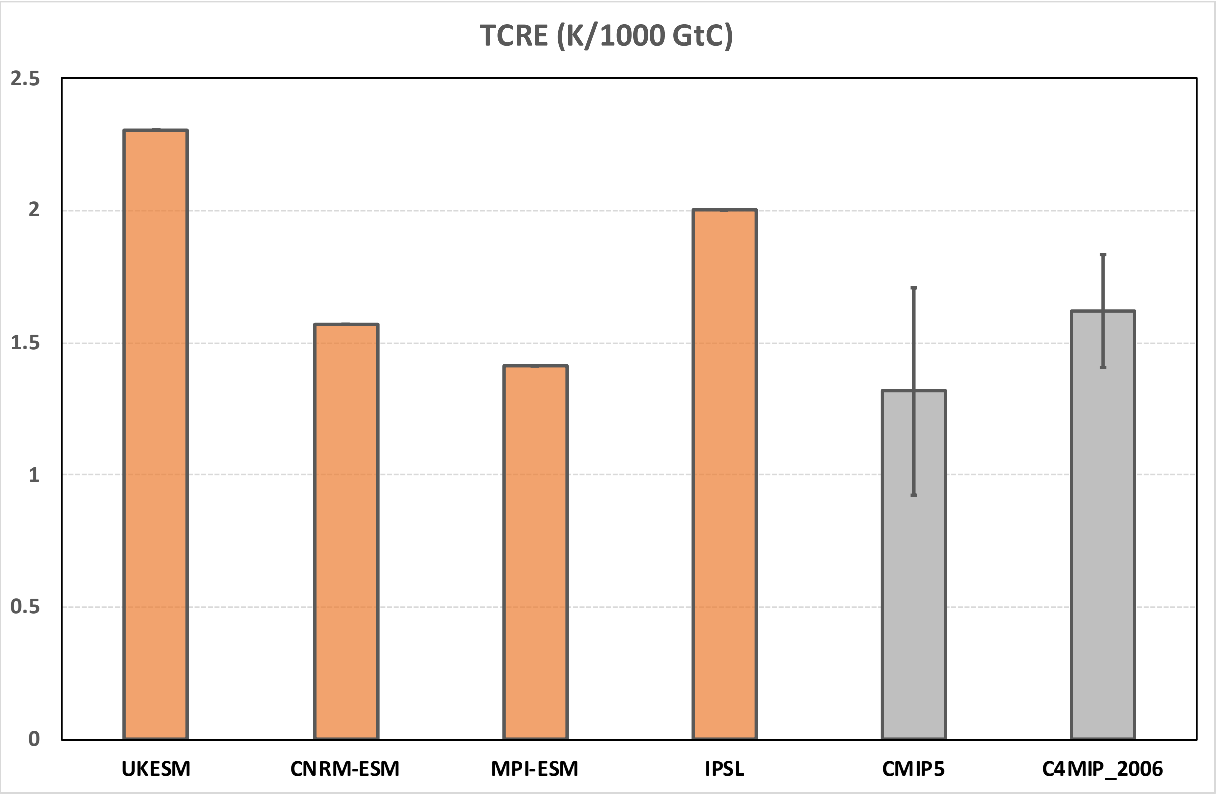
Relationship between the TCRE and the total and remaining carbon budgets



Matthews et al. in prep.
Rogelj et al. Nature, 2019

Transient climate response to cumulative carbon emissions

$\mathbf{TCRE = \alpha / (1 + \beta + \alpha^*\gamma)}$

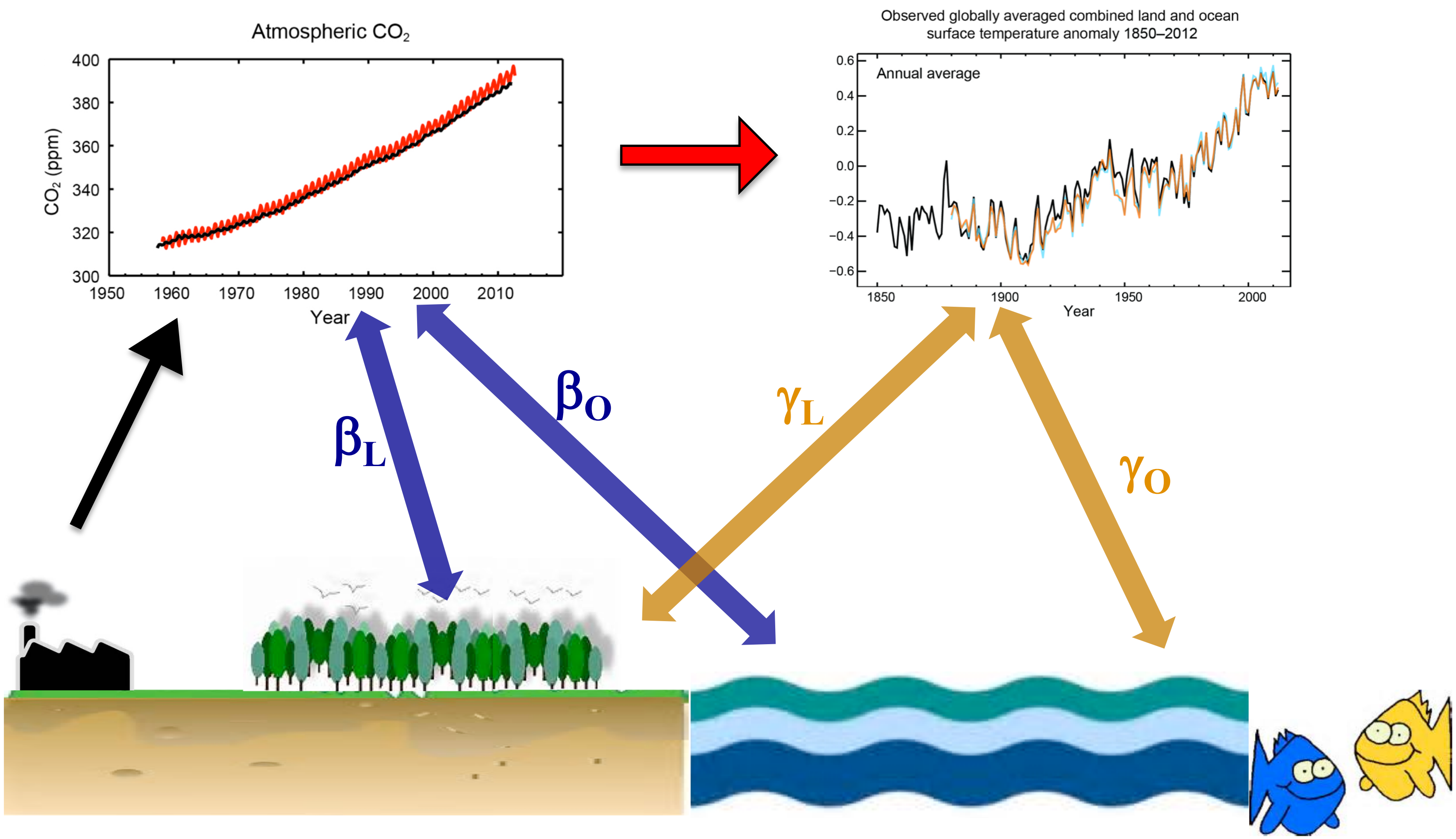


- High TCRE implies lower emissions allowed
- Stems mainly from high climate sensitivity

P. Friedlingstein, C. Jones, et al., in prep.

Carbon cycle feedbacks

- most feedbacks known (or suspected) for decades
- no or little direct observations
- basic or insufficient understanding of processes
- uncertain magnitude



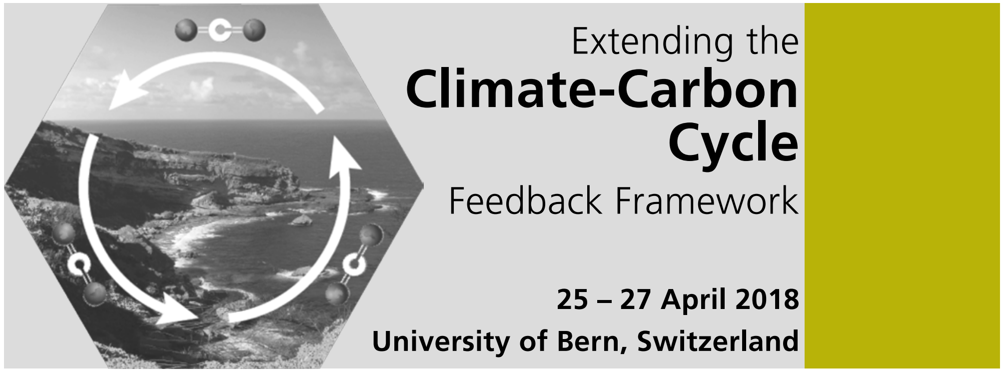
β : concentration carbon cycle feedback – **Negative Feedback**

γ : climate carbon cycle feedback – **Positive Feedback**

Process-oriented climate-carbon cycle feedback framework

- Current β/γ framework (Friedlingstein et al., 2006) is scenario dependent, based only on global temperature, ignores different time-scales, and regional responses.
- A process-oriented climate-carbon cycle feedback framework has been developed at the GC workshop:

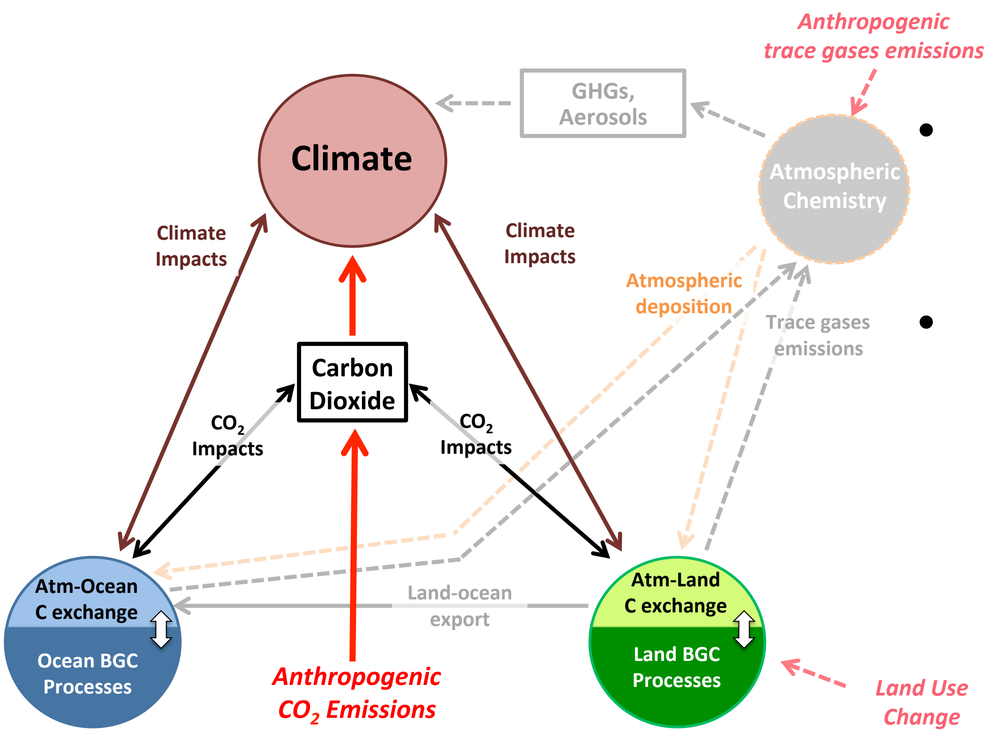
WCRP World Climate Research Programme



- Determine sources of uncertainty to analyse where the uncertainty stems from

Vivek Arora, et al., in prep.

Gaps in coupling between ESM components



- Including atmospheric chemistry of CH_4 and N_2O for interactive gas cycles in ESMs
- Improving representation of aerosol-cloud interactions (e.g. cloud microphysics, aerosols radiative properties)

Summary

- Challenges in projecting climate-carbon cycle interactions and feedbacks are associated with knowledge gaps in process understanding and with the role of multi-year variability.
- Opportunities arise from the development of new comprehensive observational products, hybrid modeling using ML, process-oriented experiments, large ensembles, initialized prediction systems, high resolution model.
- Improving coupling between existing components will enable the full spectrum of climate-relevant interactions within the Earth system.