Present and future ocean-atmosphere CO_2 fluxes, and EO measurement needs

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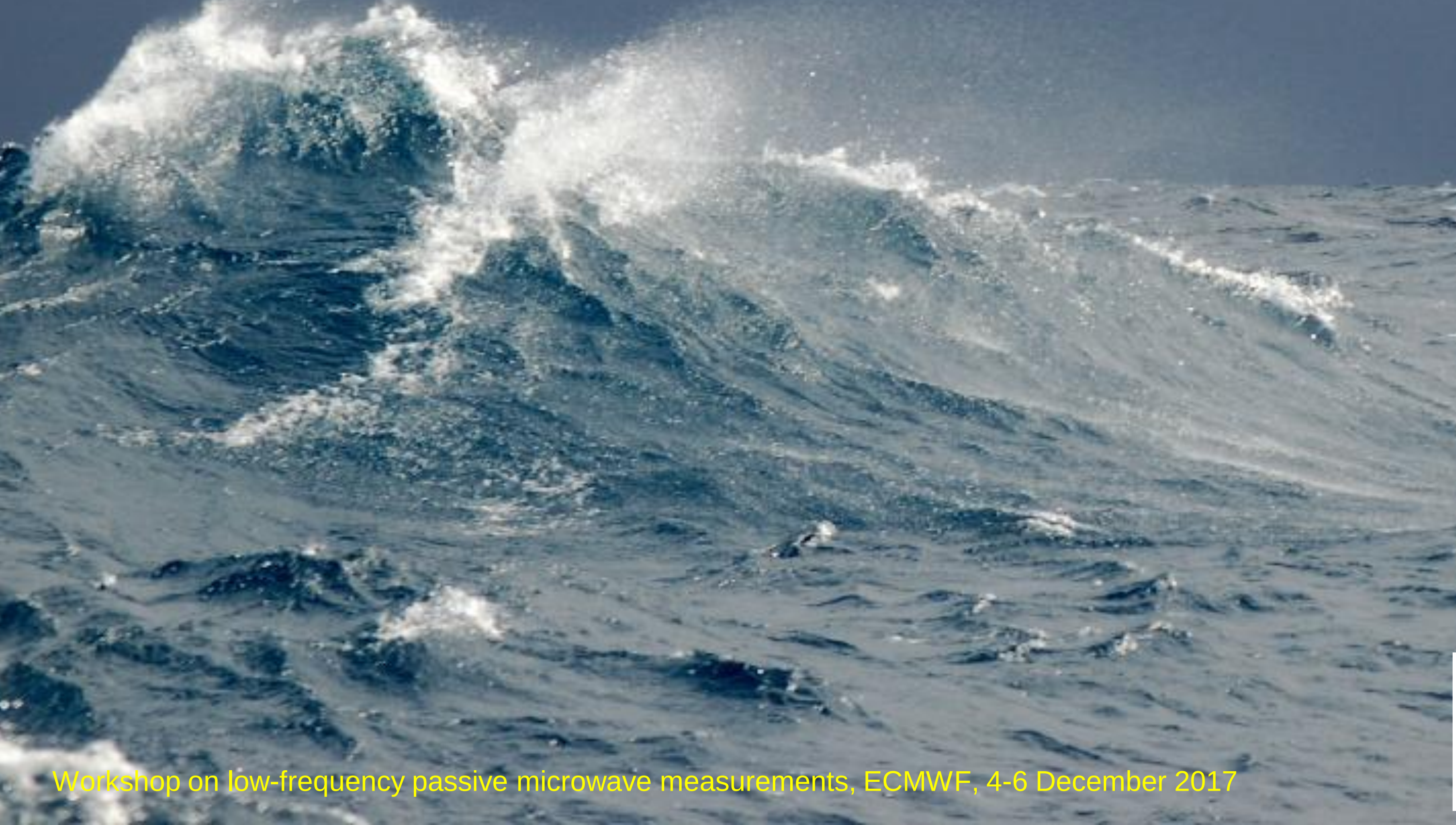

Workshop on low-frequency passive microwave measurements, ECMWF, 4-6 December 2017

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Present and future ocean-atmosphere CO_2 fluxes, and EO measurement need

- Why we are interested – the global carbon budget
- Constructing the ocean sink using in-situ and EO observations
  - Methods
  - Results
- A wish list for the future

Fate of anthropogenic CO_2 emissions (2007–2016)

Sources = Sinks

9.4 GtC/yr

88%

12%

1.3 GtC/yr

4.7 GtC /yr

46%

30%

3 GtC /yr

24%

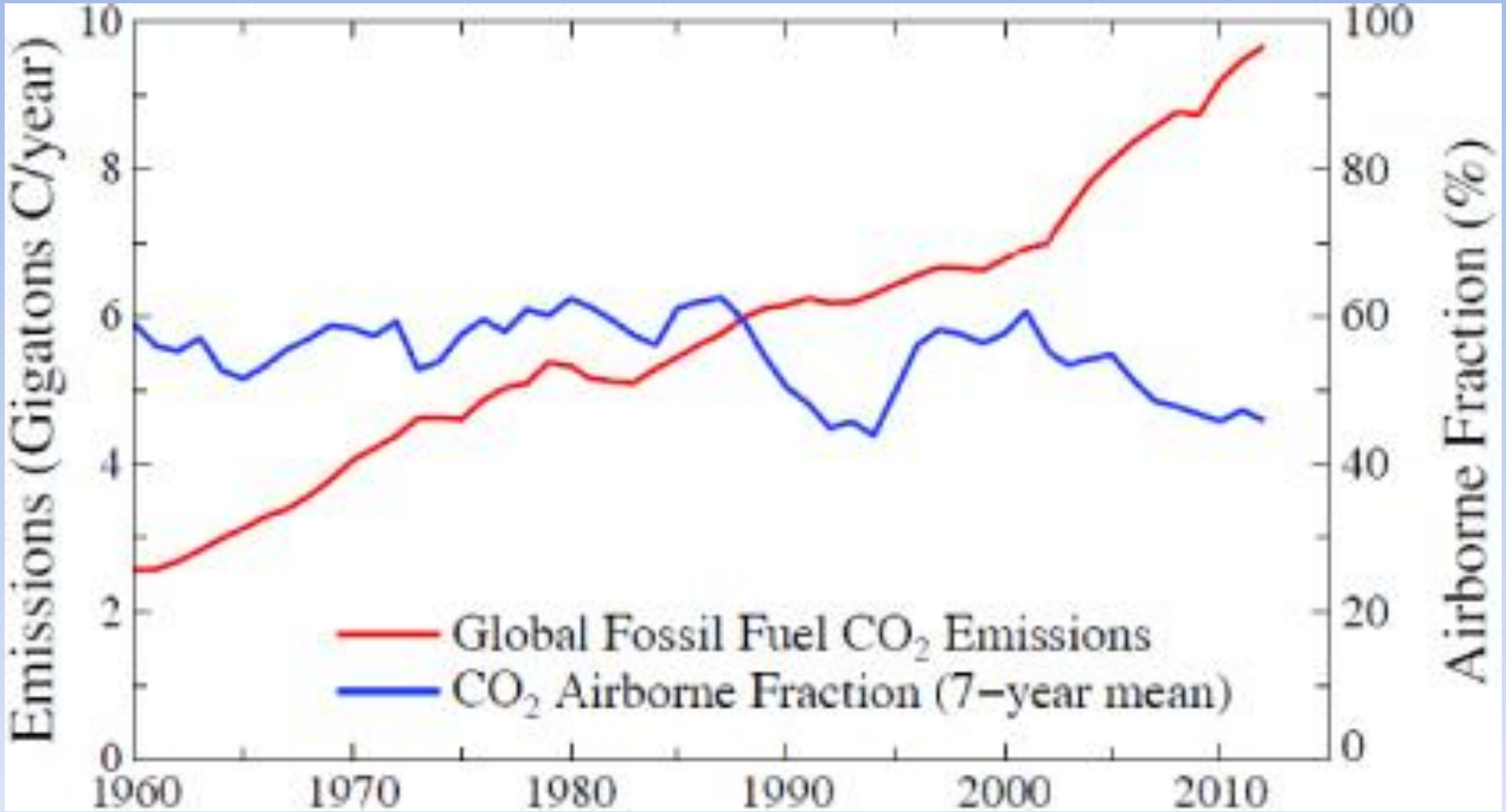
2.4 GtC /yr

Budget Imbalance:
(the difference between estimated sources & sinks)

6%
0.6 Gt GtC /yr

Source: CDIAC; NOAA-ESRL; Houghton and Nassikas 2017; Hansis et al 2015; Le Quéré et al 2017; Global Carbon Budget 2017

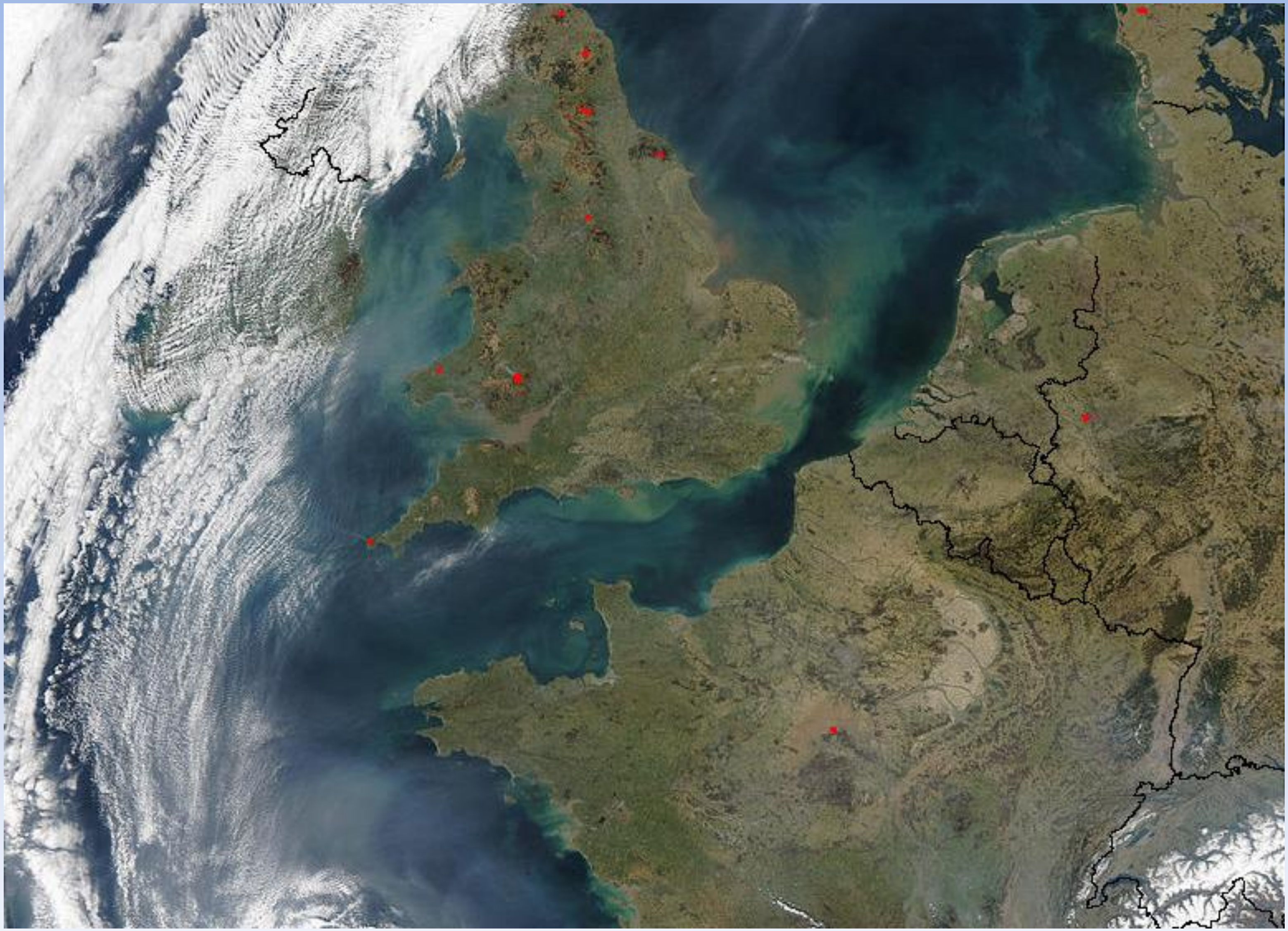
CO_2 emissions and airborne fraction



- The fossil fuel CO_2 source has increased almost fourfold since 1960.
- The "airborne fraction" has remained roughly constant.

It follows that

- The land and ocean sinks must have similarly increased.



- Terrestrial environment is heterogeneous on ~100m scales
  - net CO_2 flux is the small difference between large uptake and release
- The sea is heterogeneous, but on much larger scales.
  - 100 km in open ocean
- Net fluxes are similar to land, but diurnal and seasonal variations much smaller.

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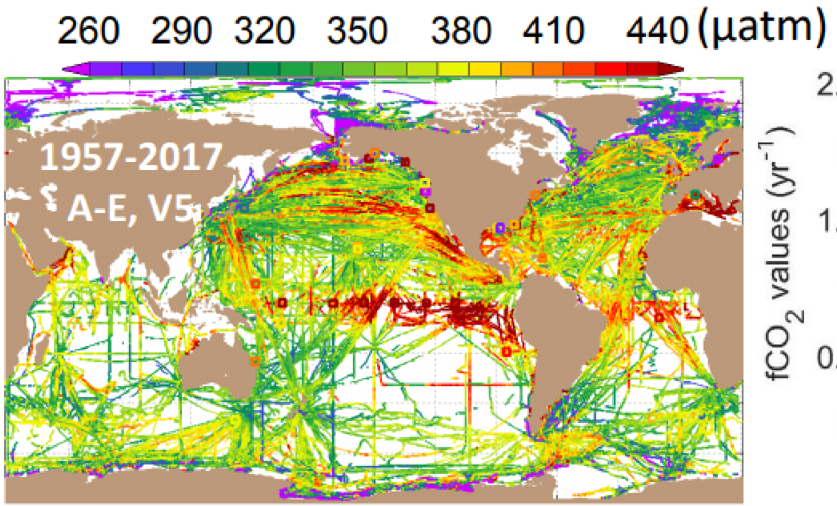
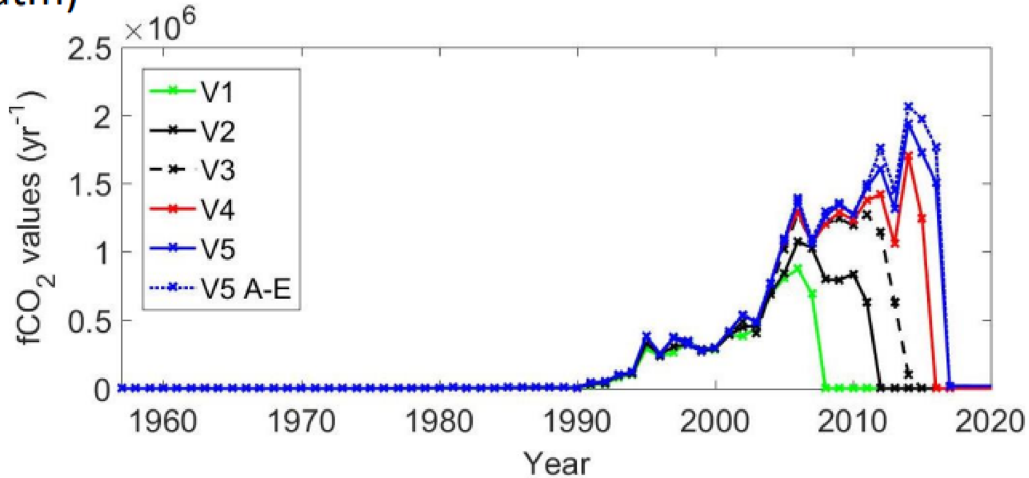
Surface Ocean CO_2 Atlas at 10!

www.socat.info





Global synthesis and gridded products of surface ocean fCO_2
(fugacity of CO_2) in uniform format with quality control;
No gap filling; Annual public releases;
V5: 21.5 million fCO_2 values from 1957-2017, accuracy < 5 µatm (flags A-D);
Plus calibrated sensor data (< 10 µatm, flag E);
Online viewers, downloadable (text, NetCDF), ODV;
Documented in ESSD articles;
Fair Data Use Statement;
Community activity with >100 contributors worldwide.

(Pfeil et al., 2013; Sabine et al., 2013; Bakker et al., 2014, 2016, all in ESSD)

Ocean CO_2 fluxes

- Use the Gas exchange equation at the sea surface: needs complete coverage of ocean surface CO_2 fugacity, fCO_2
- Rapid increase in quantity of surface ocean fCO_2 data since the early 90s.
- Brought together and QC'd under SOCAT in recent years
- Good coverage in the N. Hemisphere, more patchy in the South.
- Neural net or regressions used to create maps of fluxes, using Satellite-derived SST, wind speed, and chlorophyll.

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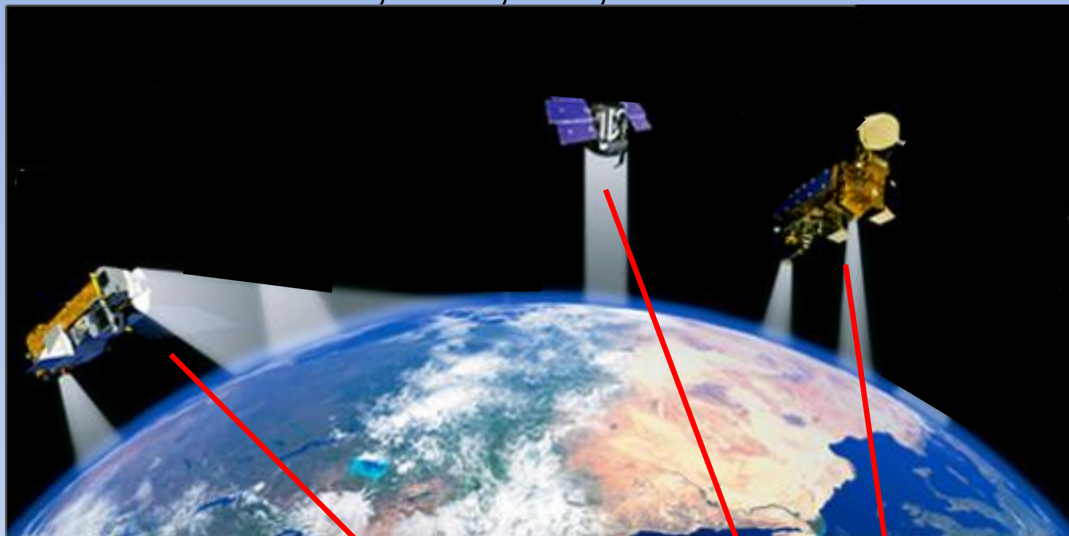
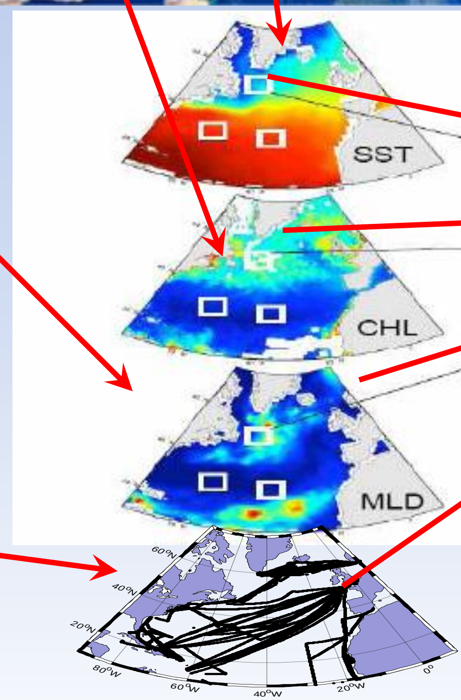
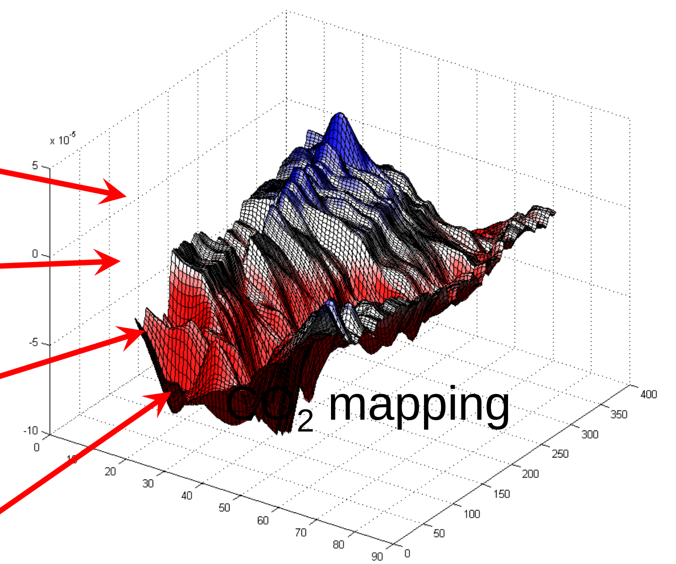
Satellite SST, SSS, Chl, winds



Extending in-situ data to basin-wide coverage





CO_2 mapping

Commercial ships instrumented for CO_2

Spot CO_2 values

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Extending ship data to obtain fCO_2 data with full spatial coverage

Seek relationships (using multiple regressions or neural nets) between ship pCO_2 data and multiple variables:

- Time
- Region, and position within region
- Remote-sensed data: SST, SSS, wind, Chl
- Atmospheric xCO_2
- Climatological seasonal data (surface nutrients)
- Re-analysis and state estimate data (Mixed layer depth)

- $fCO_2 = f(SST, MLD, SSS, (region), (time) \ldots\ldots)$.

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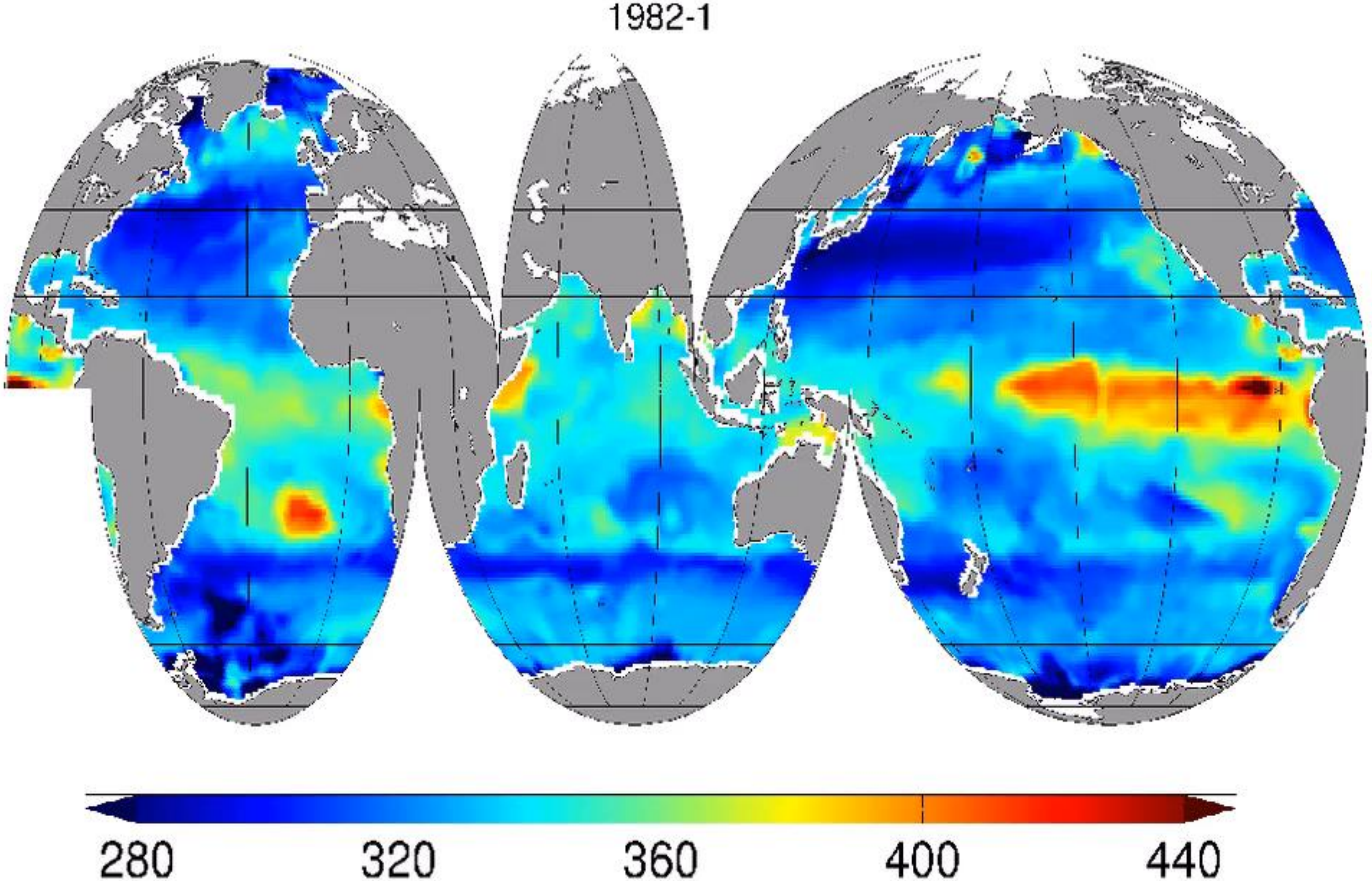

Movie courtesy Peter Landschutzer, ETH Zurich and MPI Hamburg

Uncertainties: sea surface fCO_2

- Realistic-looking reconstructions of surface fCO_2 can be constructed, but how accurate are they?
- Concentrate on the Northern Hemisphere where the data coverage is good.
- Try many different mapping regions and methods of MLR.
- Apply them to model outputs to see how well they reconstruct the "true" pCO_2
- Use "least angle regression" which chooses the most efficient regression among independent variables.

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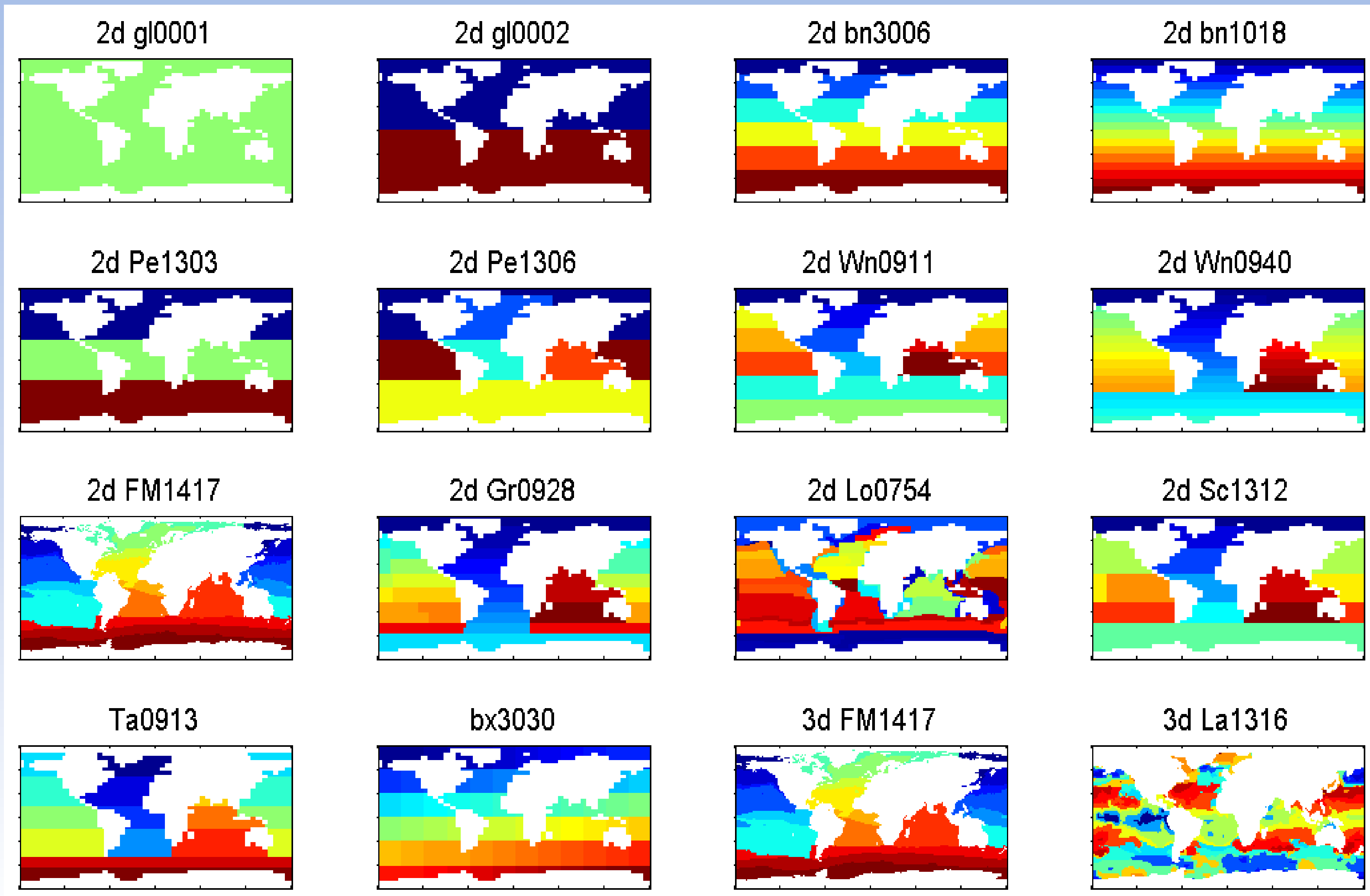
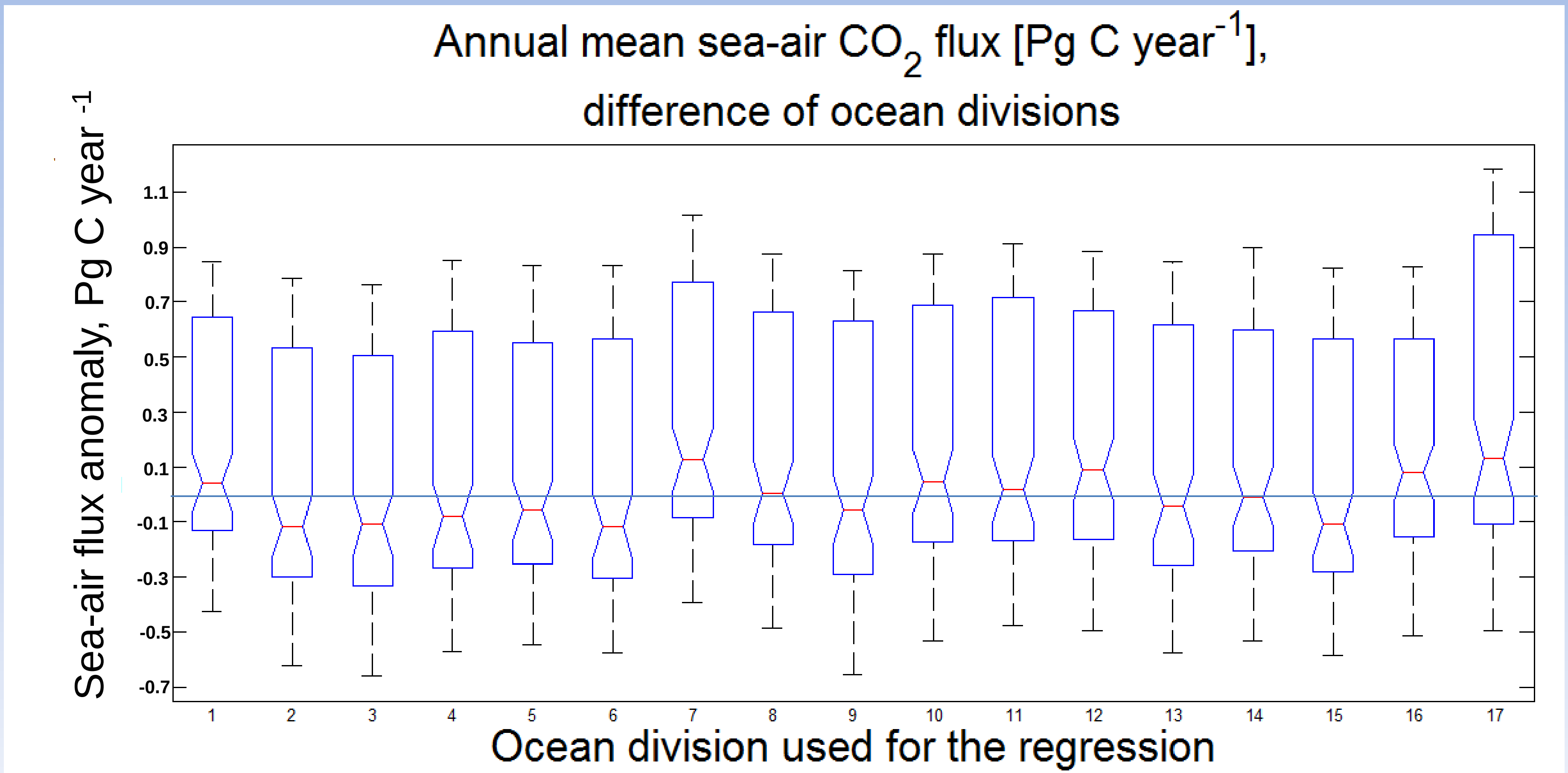
Ocean divisions

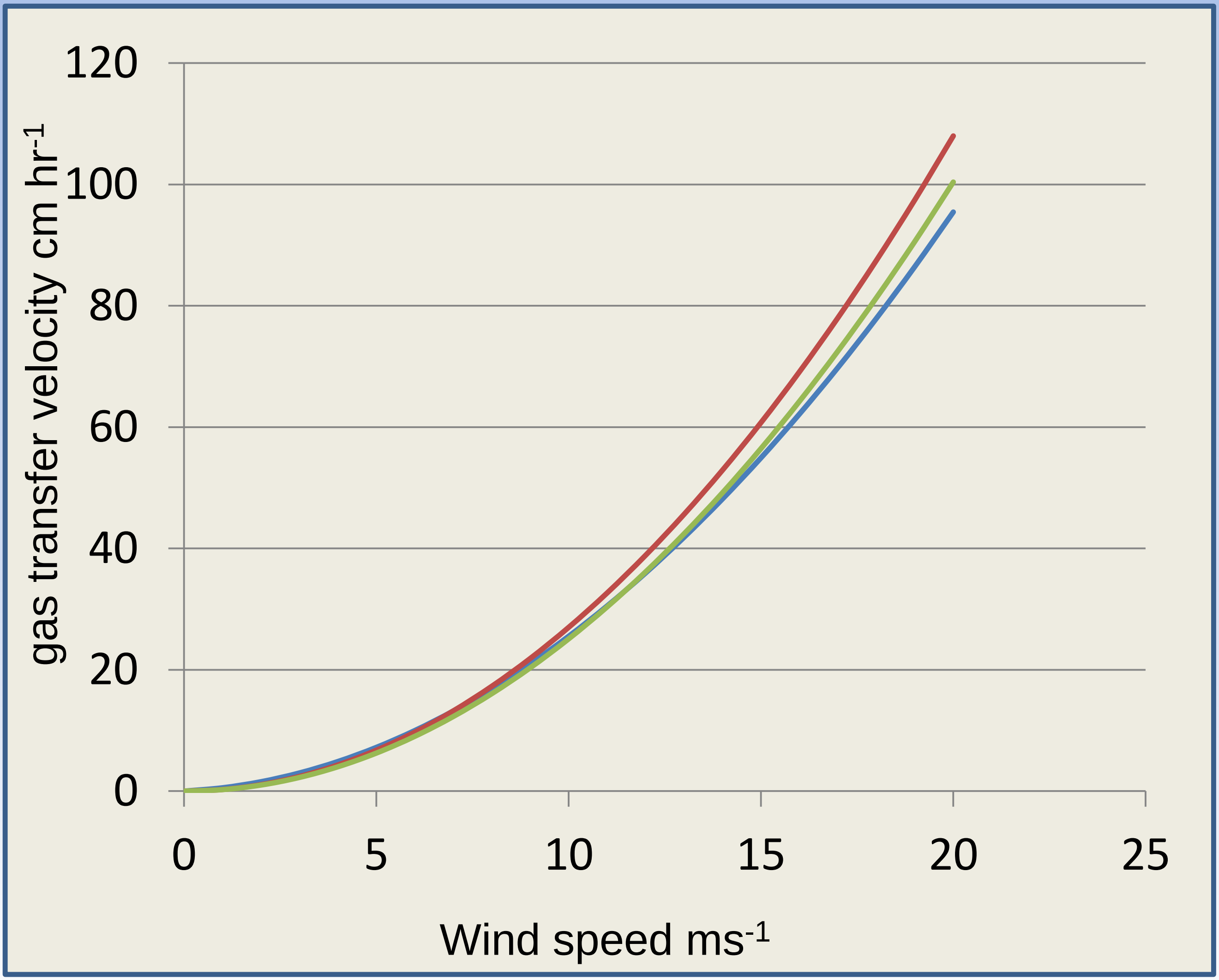


Flux uncertainty due to **ocean divisions**



Standard deviation for the northern hemisphere is 6%, ~0.07 Pg C year^{-1}

Gas transfer parameterizations since 2000



Flux calculation

- We use the FluxEngine developed by Shutler and colleagues: http://www.oceanflux-ghg.org/Products/FluxEngineA
- CCMP 6-hourly winds from satellite capture high wind speed events
- Accurate land mask, ice mask
- Accurate SSTs to account for SOCAT “inlet temperatures”, corrected to 1m.
- Correction for surface temperature skin effect (important! 0.4 PgC yr^{-1} globally, see Woolf et al, JGR **121**, 1229-1248, 2016).

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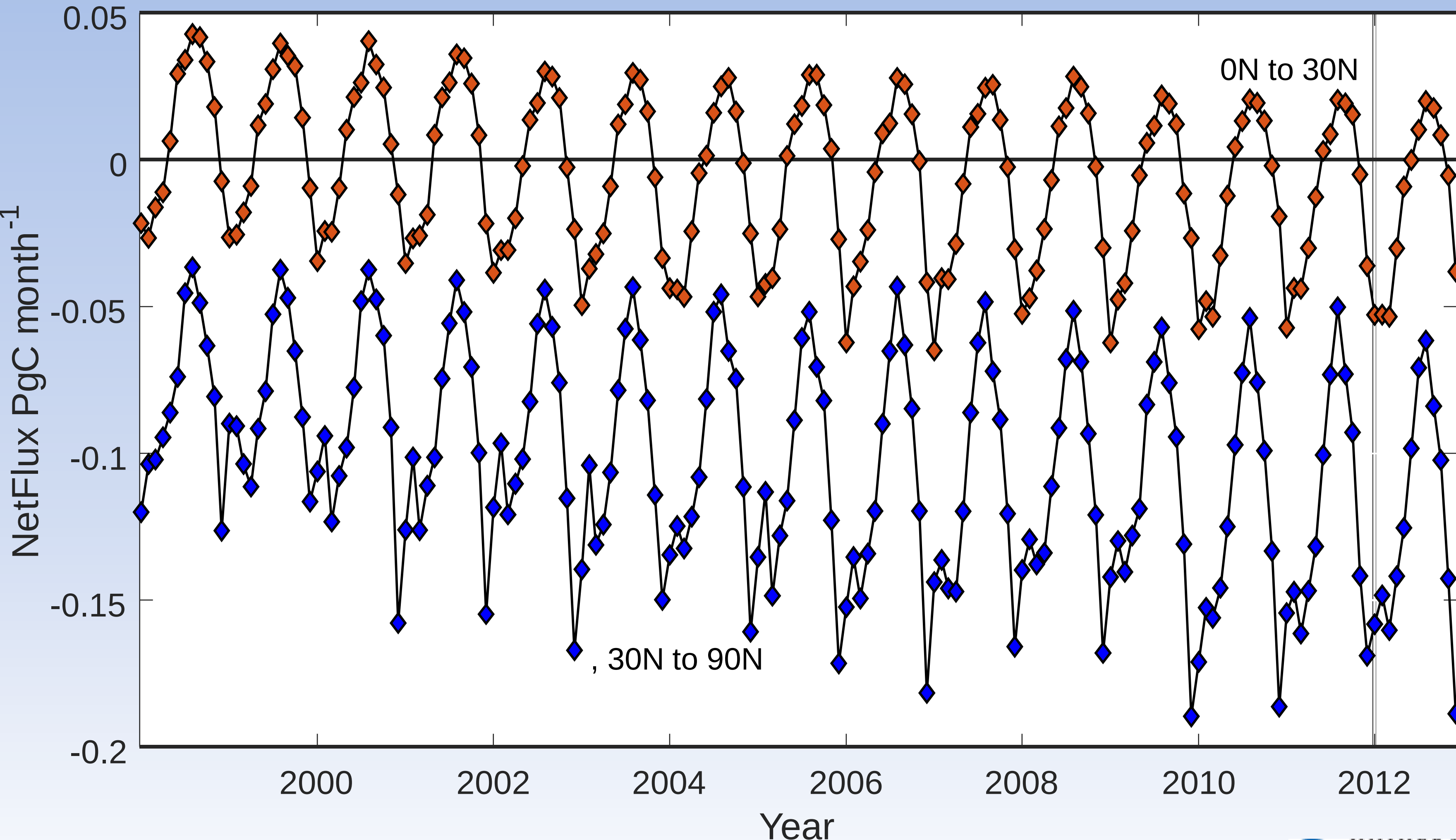
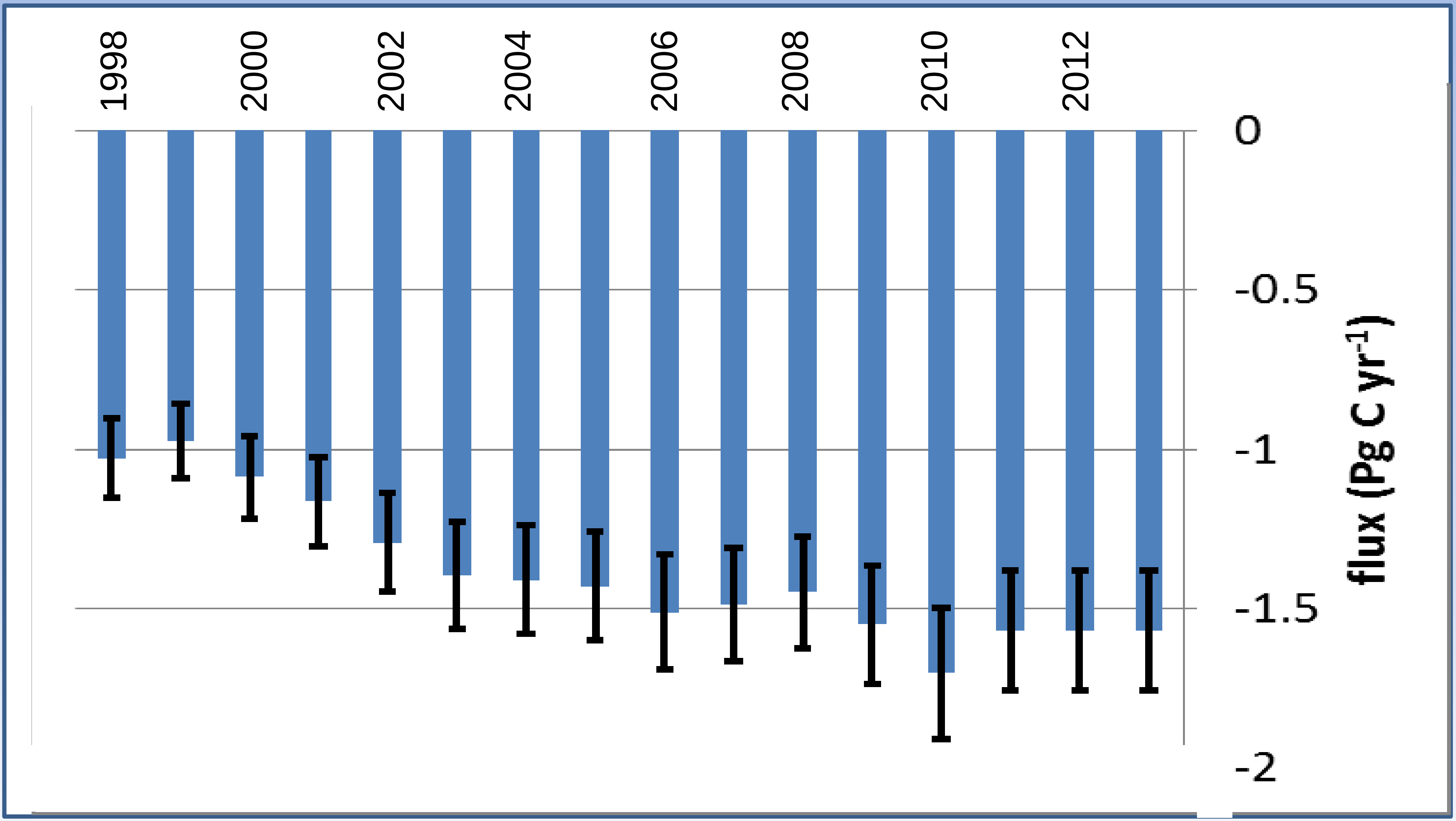
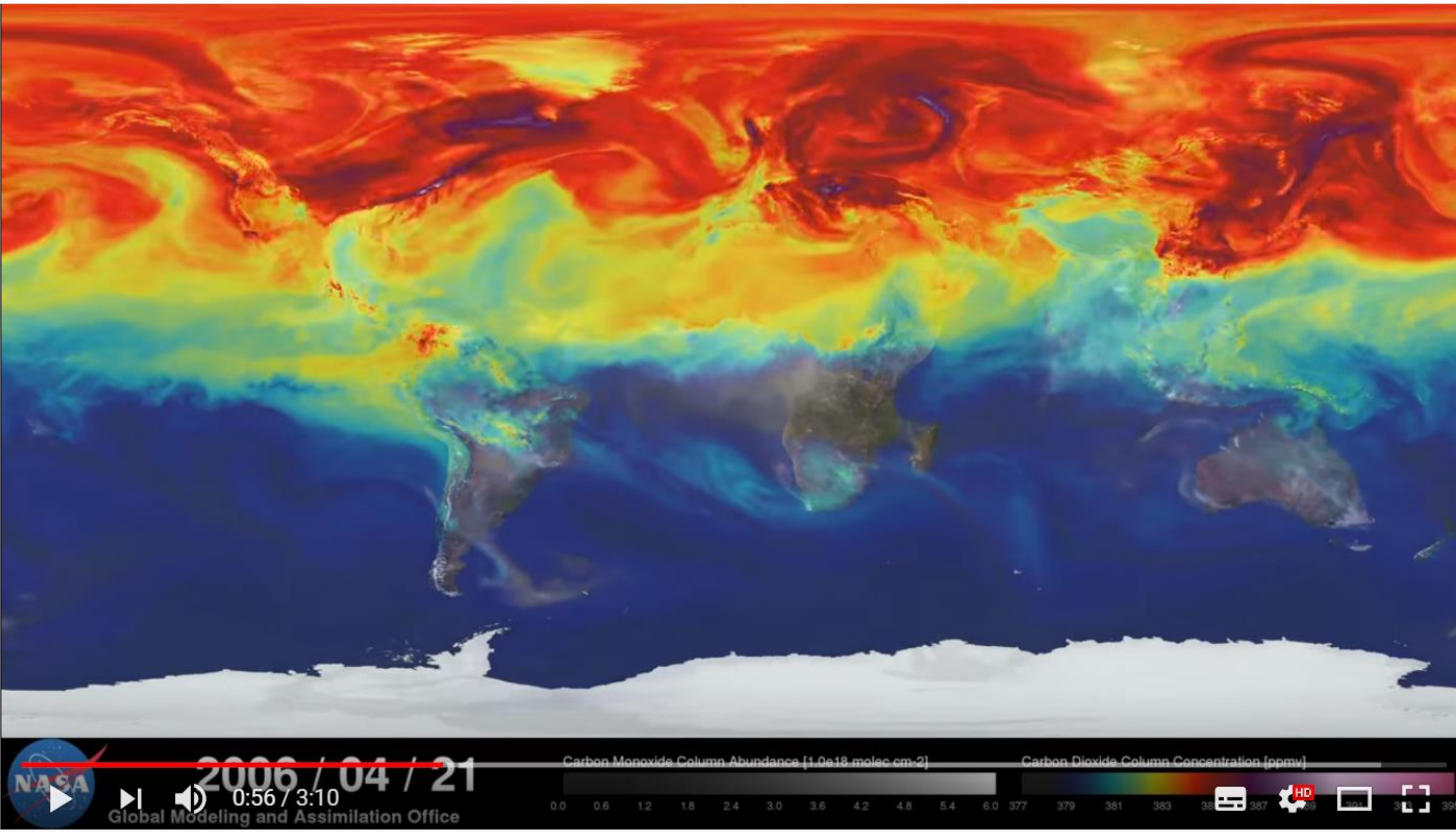
Monthly ocean fluxes, 0-30N and 30N-90N

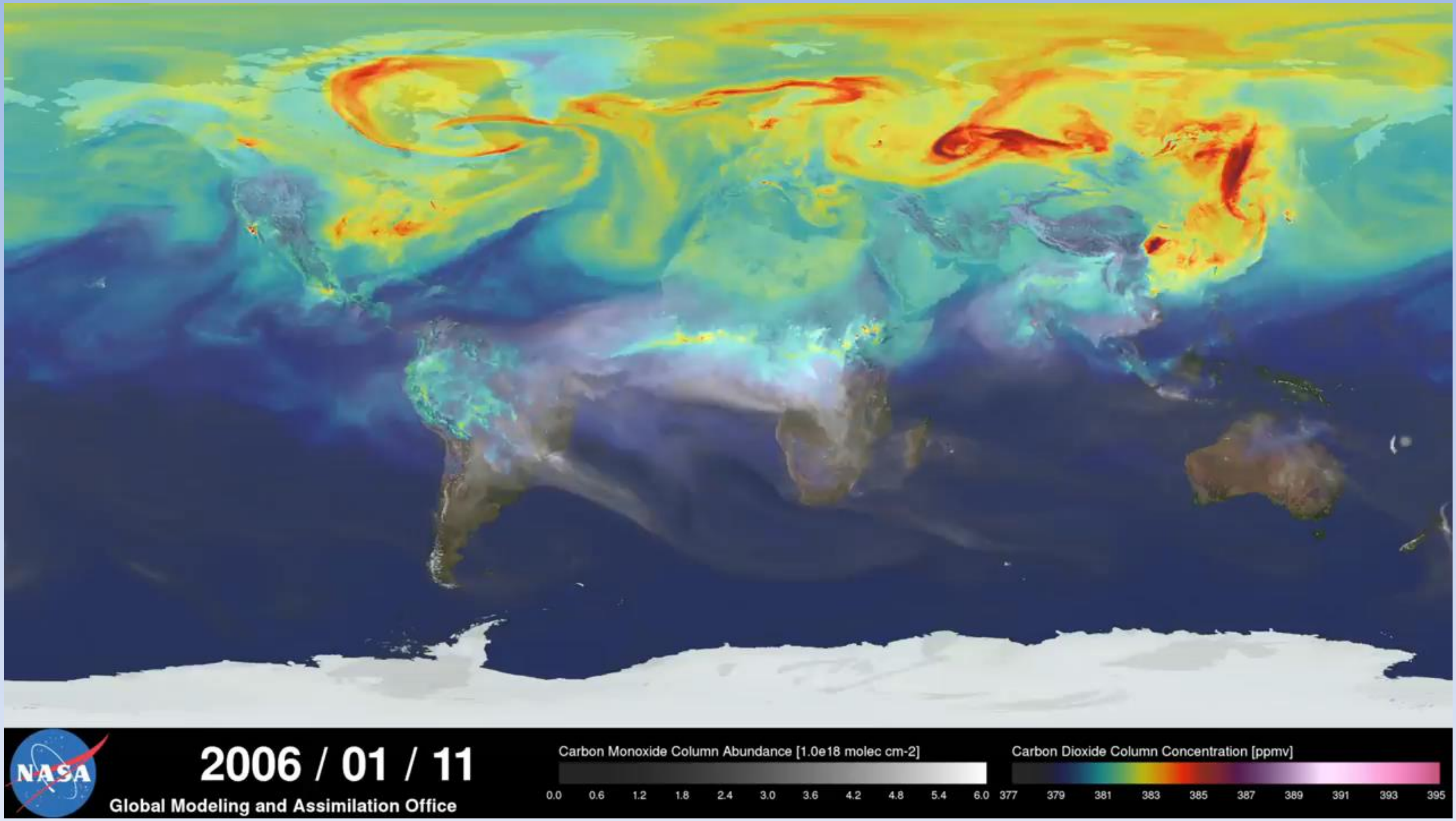


N. Hemisphere ocean sink (PgC yr^{-1})




NASA
2006 / 04 / 21
0:56 / 3:10
Global Modeling and Assimilation Office
Carbon Monoxide Column Abundance [1.0e18 molec cm-2]
0.0 0.6 1.2 1.8 2.4 3.0 3.6 4.2 4.8 5.4 6.0
Carbon Dioxide Column Concentration [ppmv]
377 379 381 383

- JPL high-res



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N. Hemisphere land flux by atmospheric inversion

- Use atmospheric transport model and inversion scheme, with standard priors.
- use N. H ocean observations as a well-observed prior.
- Aggregate northern and southern hemisphere sinks are well resolved, hence a value for the net NH land sink.

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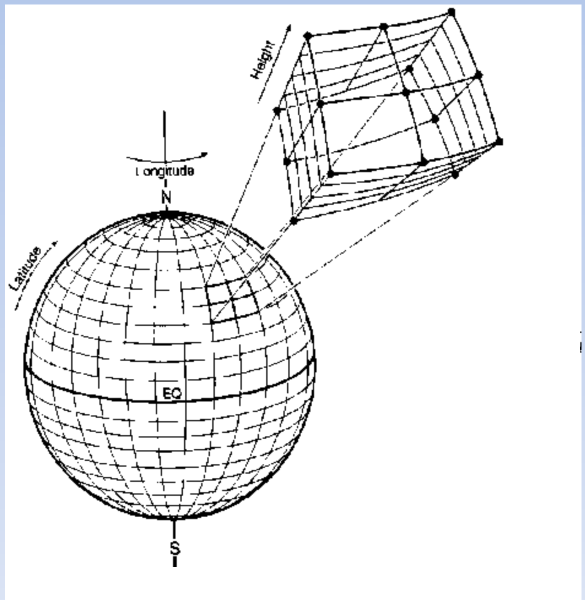
Transport MODEL : GEOS-Chem v9.02

http://acmg.seas.harvard.edu/geos/index.html



CO_2 Simulation : Nassar et al. 2010; Suntharalingam et al. 2005

Resolution : 2° (lat) x 2.5° (lon) ; 47 vertical levels

Spin up and simulation:2004-2012

Initial Prior CO_2 fluxes

Fossil: CDIAC, Andres et al. 2011

Ocean: **Climatology(Takahashi et al.,2009) ;**

Land: Biomass burning (Van der Werf et al. 2006);
Balanced Biosphere(Olsen et al. 2004);
Remaining fluxes based on Nassar et al. 2010.

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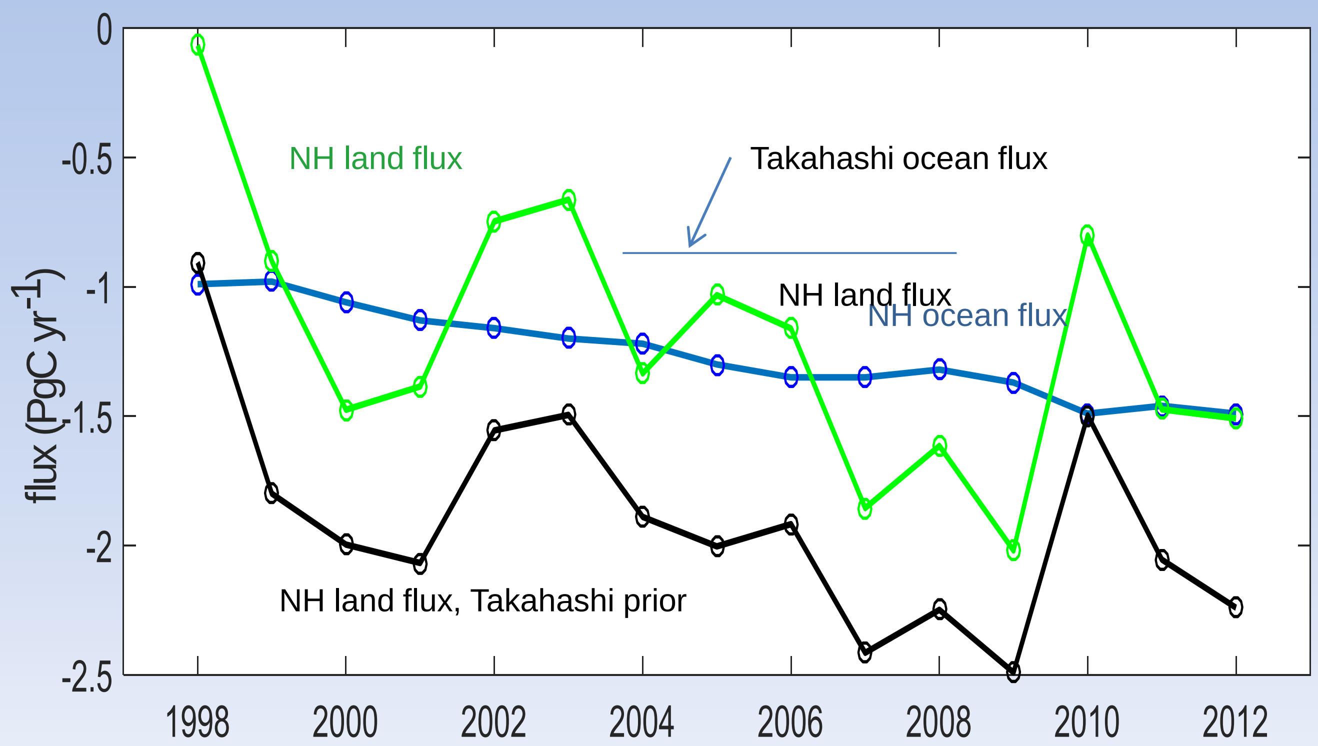
Aggregated observational estimate of N. Hemisphere land fluxes, using inverse atmospheric calculation



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Constraints from the ocean CO_2 flux reconstructions on global carbon cycle

- We can accurately (1-σ < 10%) constrain the ocean CO_2 sink in the Northern hemisphere (and the tropics)
- It has substantially increased since late 90s and in 2012 stood at ~1.5 PgC yr^{-1}.
- Combined with coarse latitudinal atmospheric inversion, gives values and trend for the N. Hemisphere terrestrial sink, which is around 1 PgC yr^{-1} smaller than other studies.
- S. Hemisphere sink has also increased – (land tropics + S hemisphere oceans?).

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EO measurement needs for CO_2 fluxes

- Ideally: pH and TA at the air-sea interface
- Accurate gas transfer velocities – (sea surface information: scatterometry, passive microwave, SAR, → wind, waves, whitecapping, effect of slicks?)
- Ice cover
- SST -- surface skin and "foundation temperature"
- SSS
- Chlorophyll

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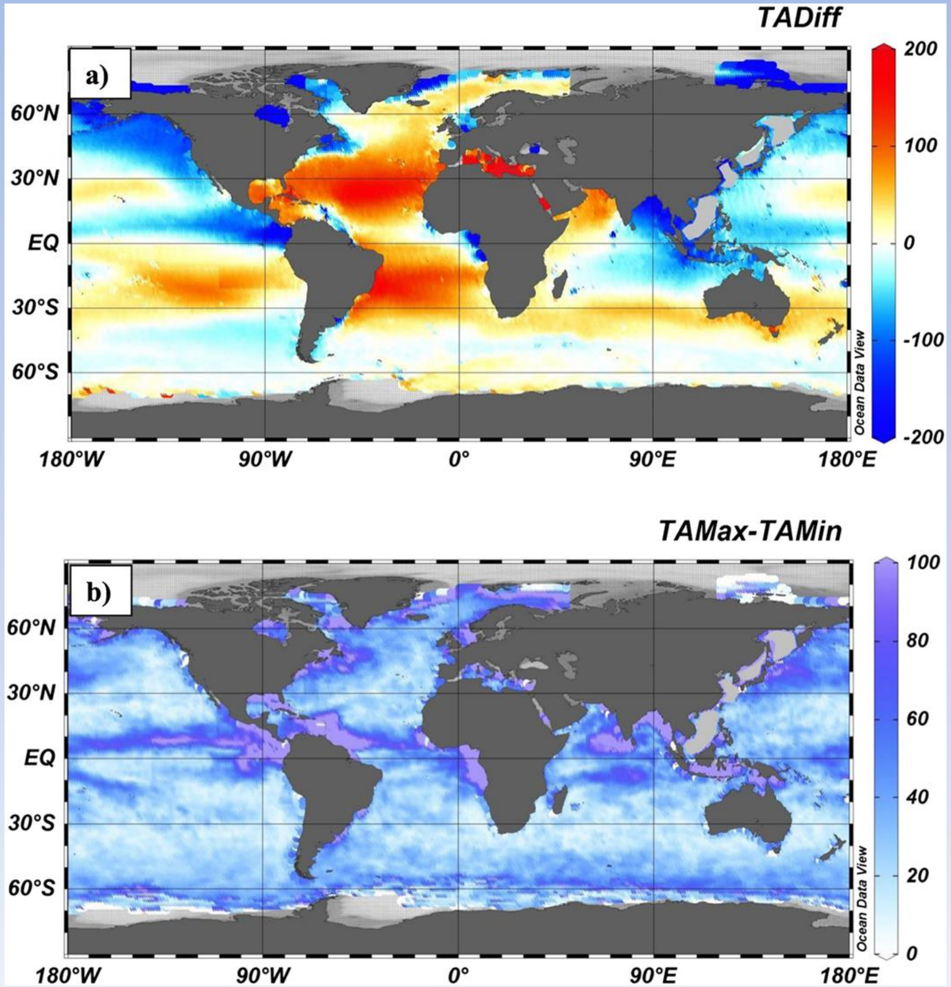
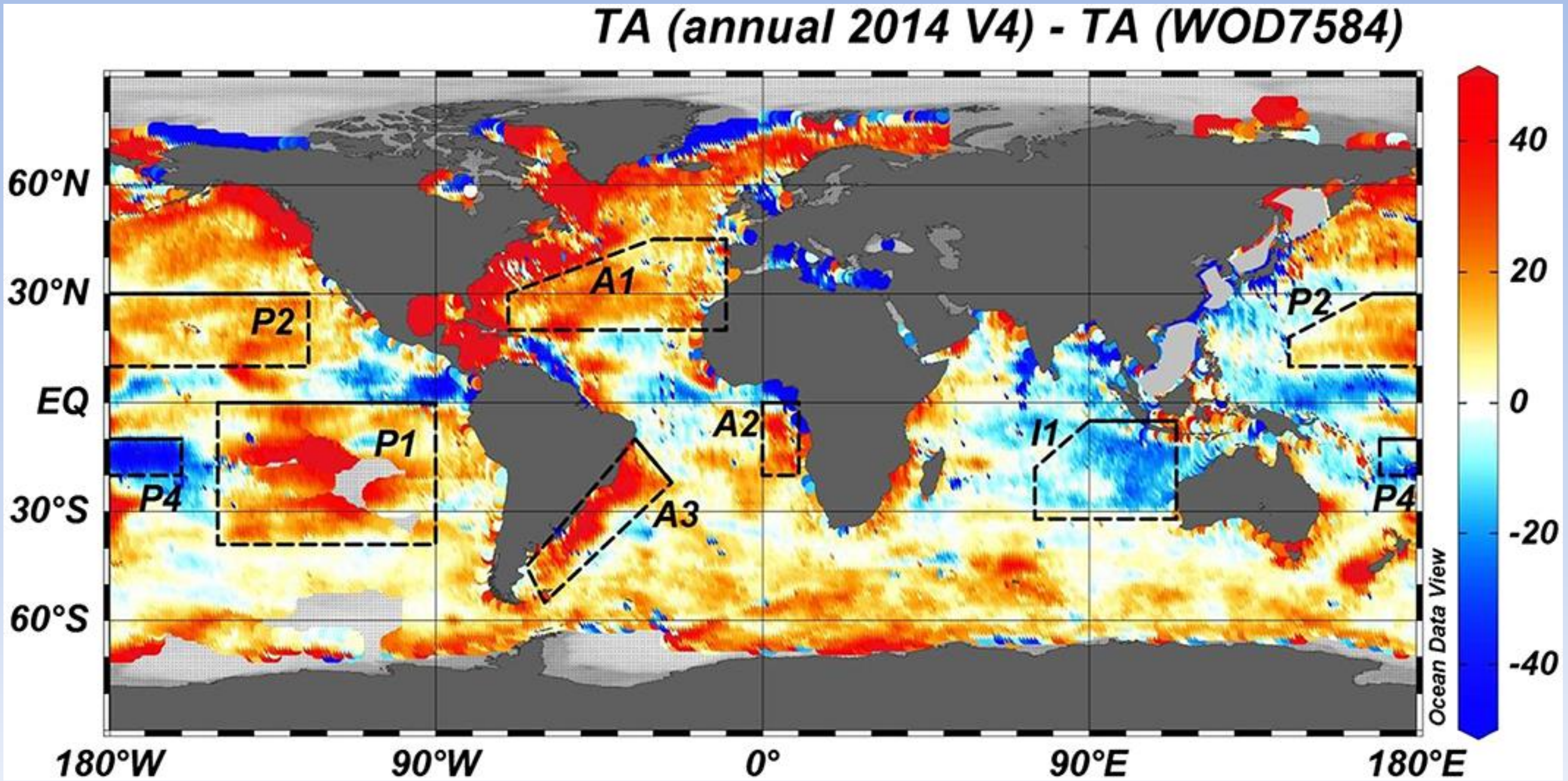
Alkalinity from space: Global variability of total alkalinity, and amplitude of the seasonal cycle. (Aquarius, 2014)



From Fine et al, 2017: Geophysical Research Letters
Volume 44, Issue 1, pages 261-267, 5 JAN 2017 DOI: 10.1002/2016GL071712
http://onlinelibrary.wiley.com/doi/10.1002/2016GL071712/full#grl55372-fig-0002

Changes in ocean total alkalinity over recent decades: from Aquarius satellite data (2014) compared to Conkright et al climatology



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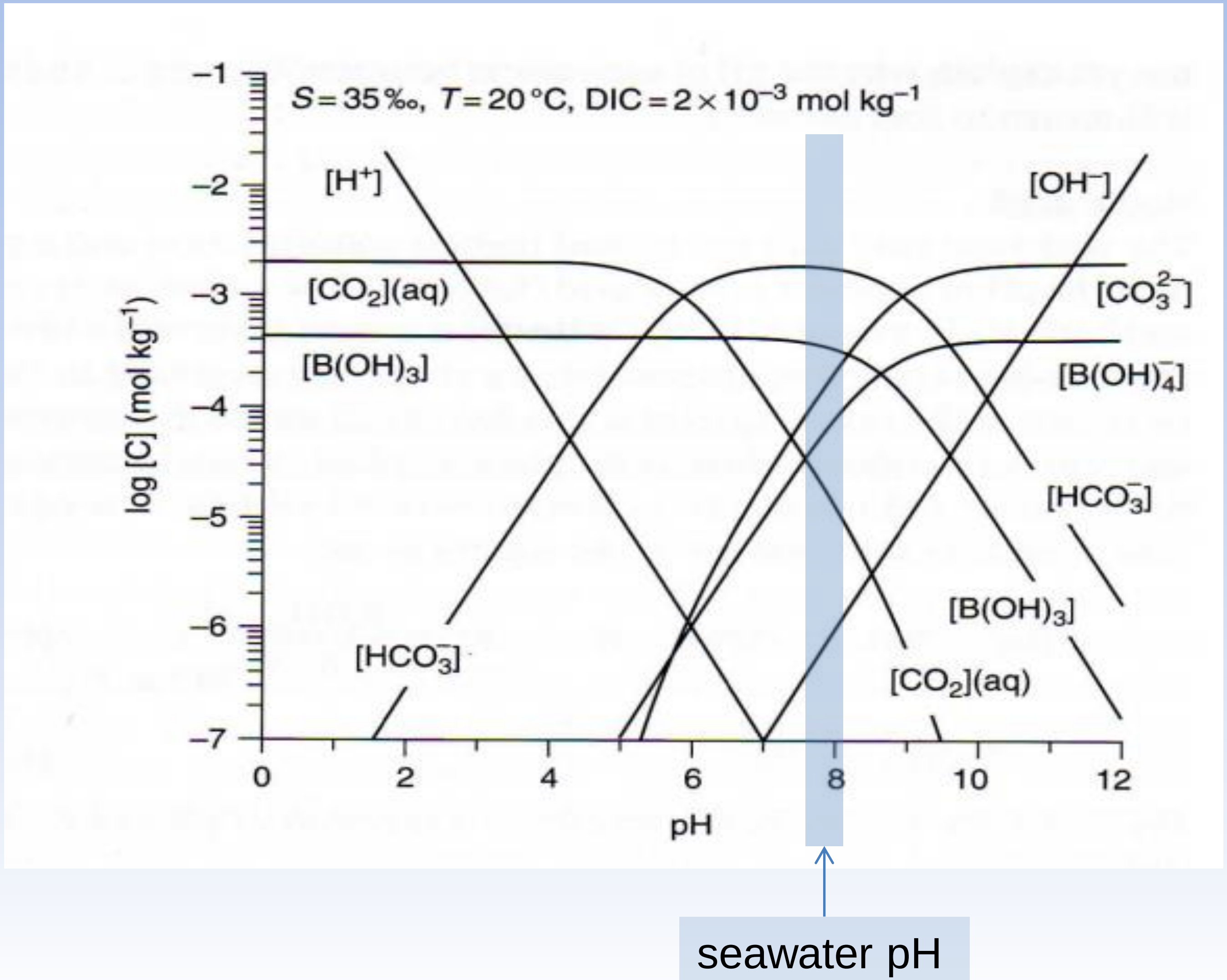
Can we directly observe marine carbonate / pH from space?



Carbonate/bicarbonate ion IR spectra

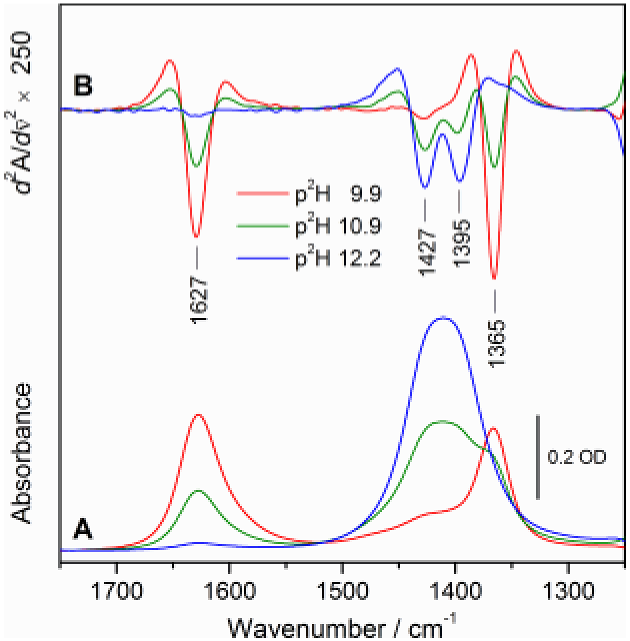
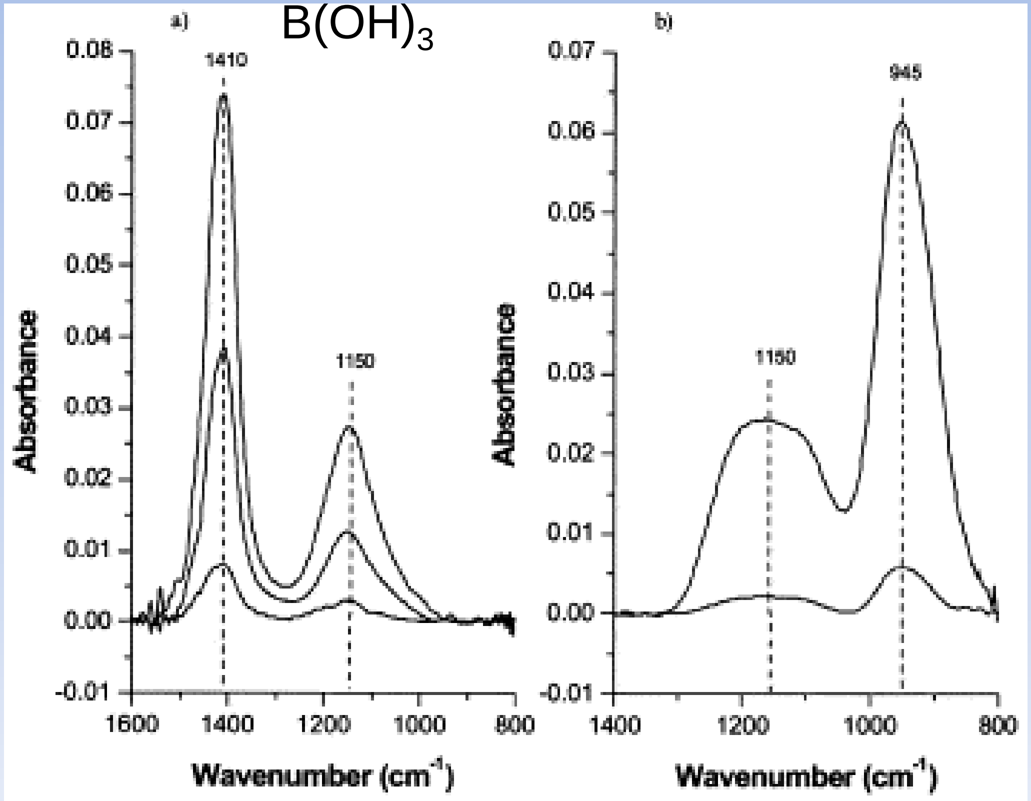


Figure S1. Absorption (A) and second derivative (B) spectra of 100 mM carbonate/bicarbonate in ^2H_2O medium at p^2H 9.9 (red), 10.9 (green) and 12.2 (blue).

Baldassarre, M. and A. Barth (2014). "The carbonate/bicarbonate system as a pH indicator for infrared spectroscopy." Analyst **139(9): 2167-2176.**

Borate/boric acid IR spectra



Future work to improve ocean-atmosphere CO_2 fluxes

- Full assimilation / re-analysis framework incorporating the carbon cycle, assimilating biogeochemical observations from in-situ and EO.
- Improved Surface layer alkalinity
- Improved gas exchange parameterization – using information on the sea surface (whitecaps, slicks, spray)
- Combine EO observations with improved coverage of in-situ observations using autonomous platforms.

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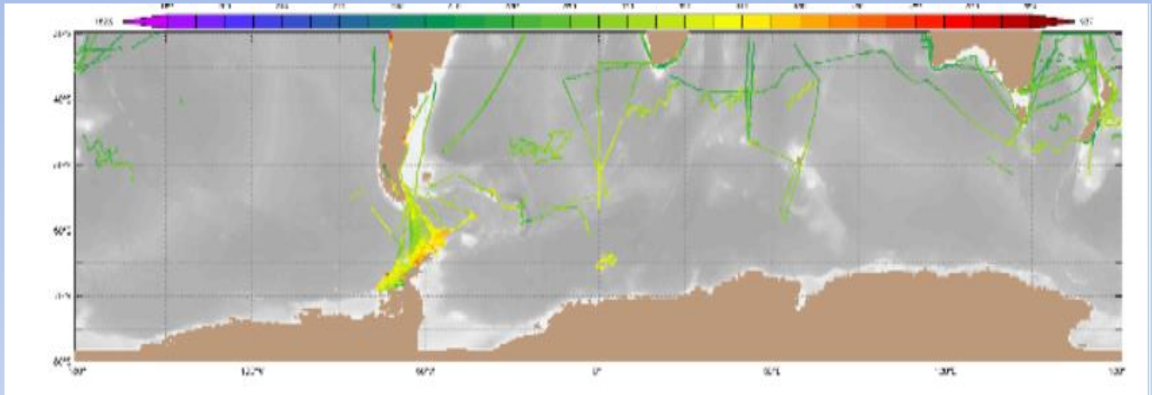
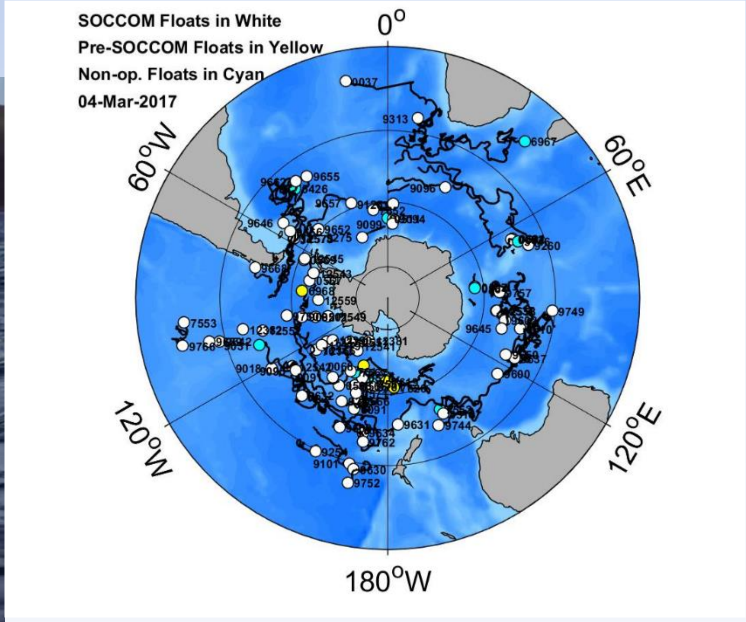
- Autonomous instruments for data-poor regions such as the Southern Ocean?





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