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The Observed Evolution of the Southern Ocean CO_2 sink and its drivers

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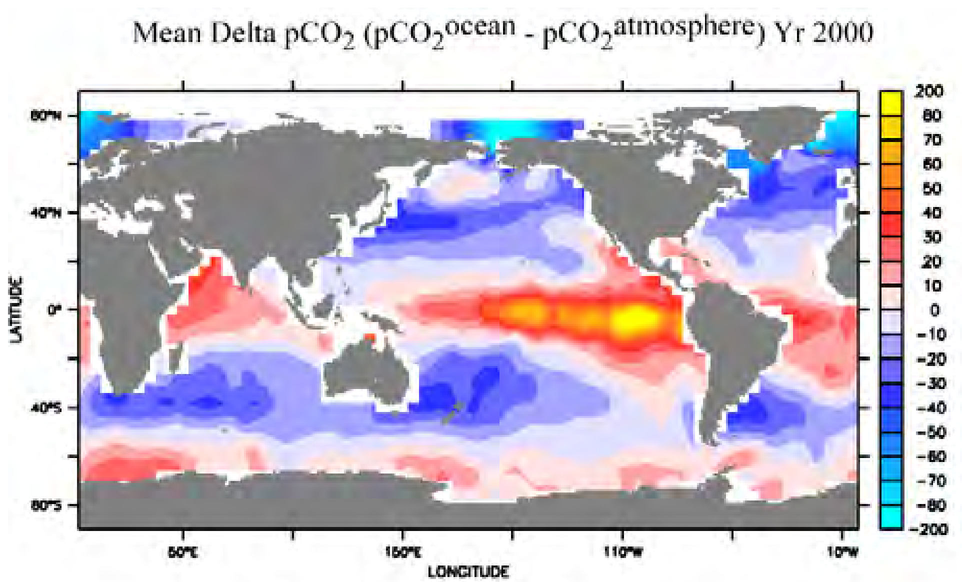
Motivation: Southern Ocean pCO_2 trends

The oceans take up 25% of the atmospheric CO_2 emitted annually

The Southern Ocean takes up about 40% of ocean uptake

Key player in the global carbon cycle and increasing in the future.



Takahashi et al (2009) Climatology

Red (+ve) out of the Ocean

Blue (-ve) into the Ocean

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Motivation: Southern Ocean pCO_2 trends

- Trends
  - Faster than the atmosphere is a decreasing CO2 sink
  - Slower than the atmosphere is an increasing CO2 sink

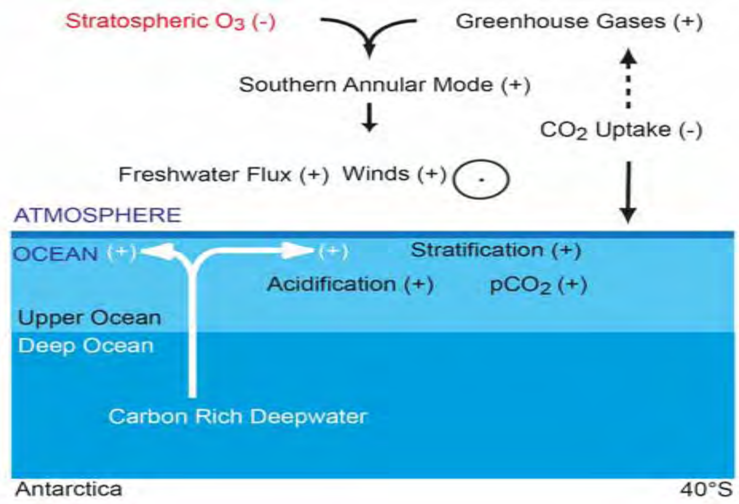
- Takahashi et al (2009) showed in winter that oceanic pCO2 growth rate faster than the atmosphere i.e. decreasing sink of atmospheric CO2

- Metzl (2009) showed that in the Indian Ocean Sector in the summer and winter the ocean growth rate is faster than the atmosphere.

- Consistent with Le Quéré et al (2007)

- Attributable to a strong SAM over the recent past from modelling

  Lenton et al (2009)



Motivation: Southern Ocean pCO_2 trends

Currently no studies investigate the drivers of observed pCO_2 in the Southern Ocean Seasonal or otherwise

(i) to separate biological and physical changes in the ocean carbon cycle

(ii) to identify the major drivers of change and use this to project how a changing climate may impact on ocean carbon uptake

(iii) to have a powerful tool to assess and validate model simulations

Oceanic pCO2 = f(DIC, ALK, SST, Salinity) **<ALK –ve pCO_2**

We need *two carbon parameters* to characterise the carbon system

DATA/OUTLINE

DATA – very little DIC or ALK measurement in SO most is pCO2 -> ***LDEO_V2009*** *(4.4 million global measurements over 3 decades)*

The Southern Ocean remain heavily undersampled wrt to CO_2

Heavily biased to latter period 1990 – 2009

Triplets for most of the data exist -> pCO2, SST and Salinity

Outline

1) Generate DIC and ALK fields from observations of pCO2, SST and SAL

2) Validate the observed fields of DIC and ALK

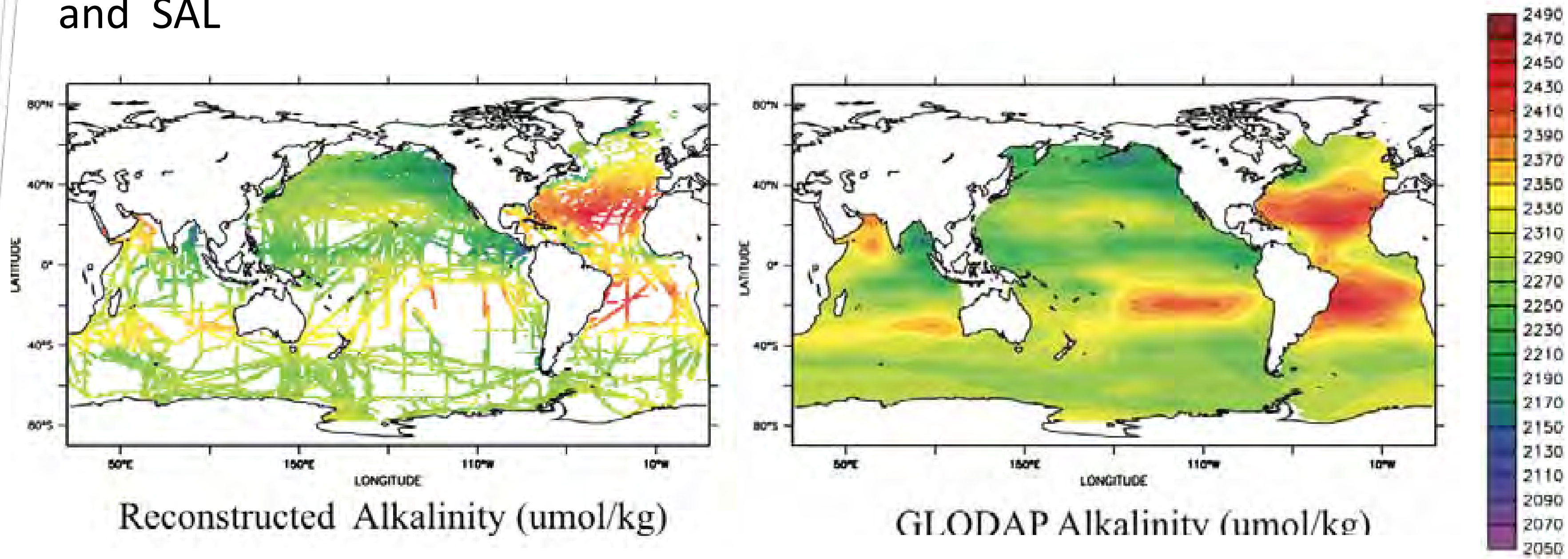
3) Calculate the seasonal and annual trends in the different basins

4) Identify the key drivers of oceanic pCO_2 in the SO sectors

5) Related to stratification and this maybe a future proxy.

Calculating ALK and DIC

ALK = f(SAL, SST) of Lee et al (2006) at each triplet of pCO2, SST and SAL



Reconstructed Alkalinity (umol/kg)

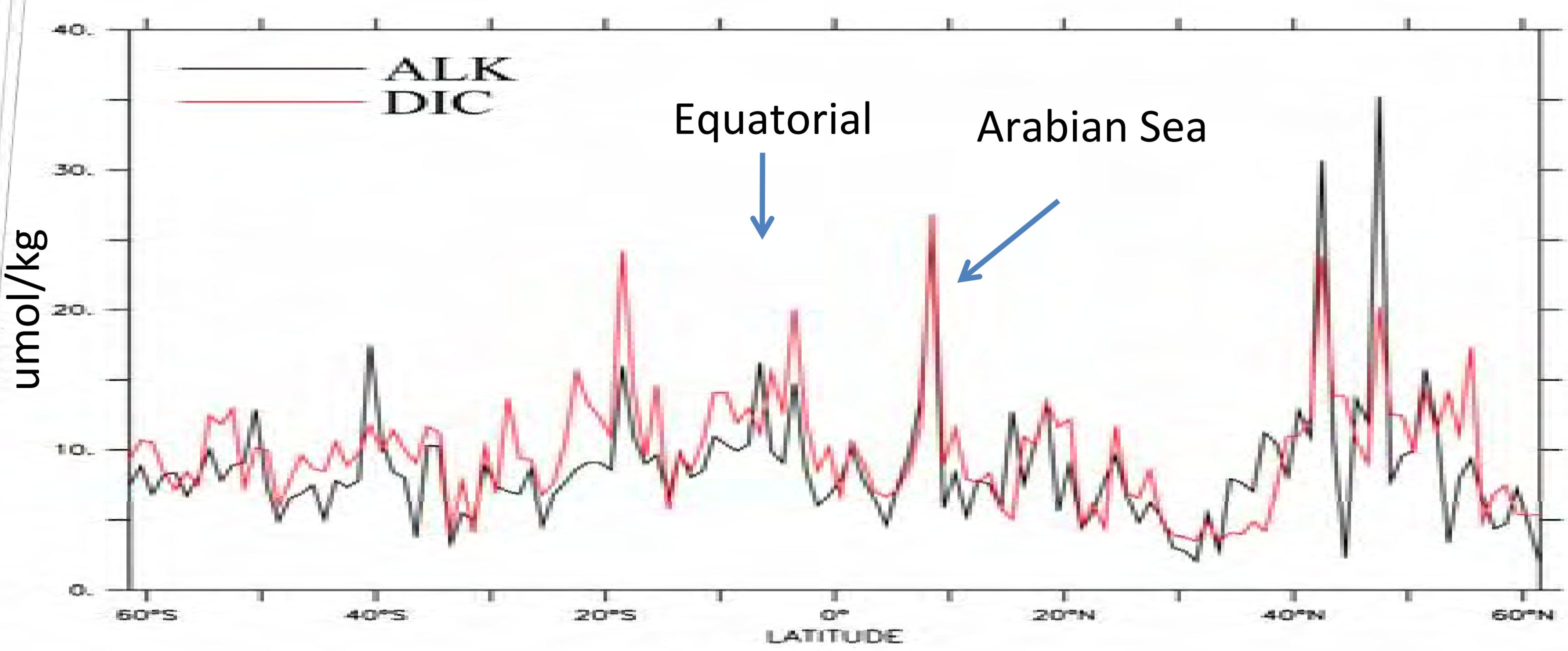
GLODAP Alkalinity (umol/kg)

Standard Equations of carbonate chemistry to generate DIC

All data were then averaged on to a 1x1 degree /monthly grid to reduce the impact of high frequency variability and coastal data removed (<200m)

Validation of DIC and ALK

Comparison of Bottle Data CDIAC and CARINA (<10m) with calculated DIC and ALK



Mean Zonal Standard Deviation of DIC and ALK

Error of 8 umol/kg for ALK and 9 umol/kg for DIC

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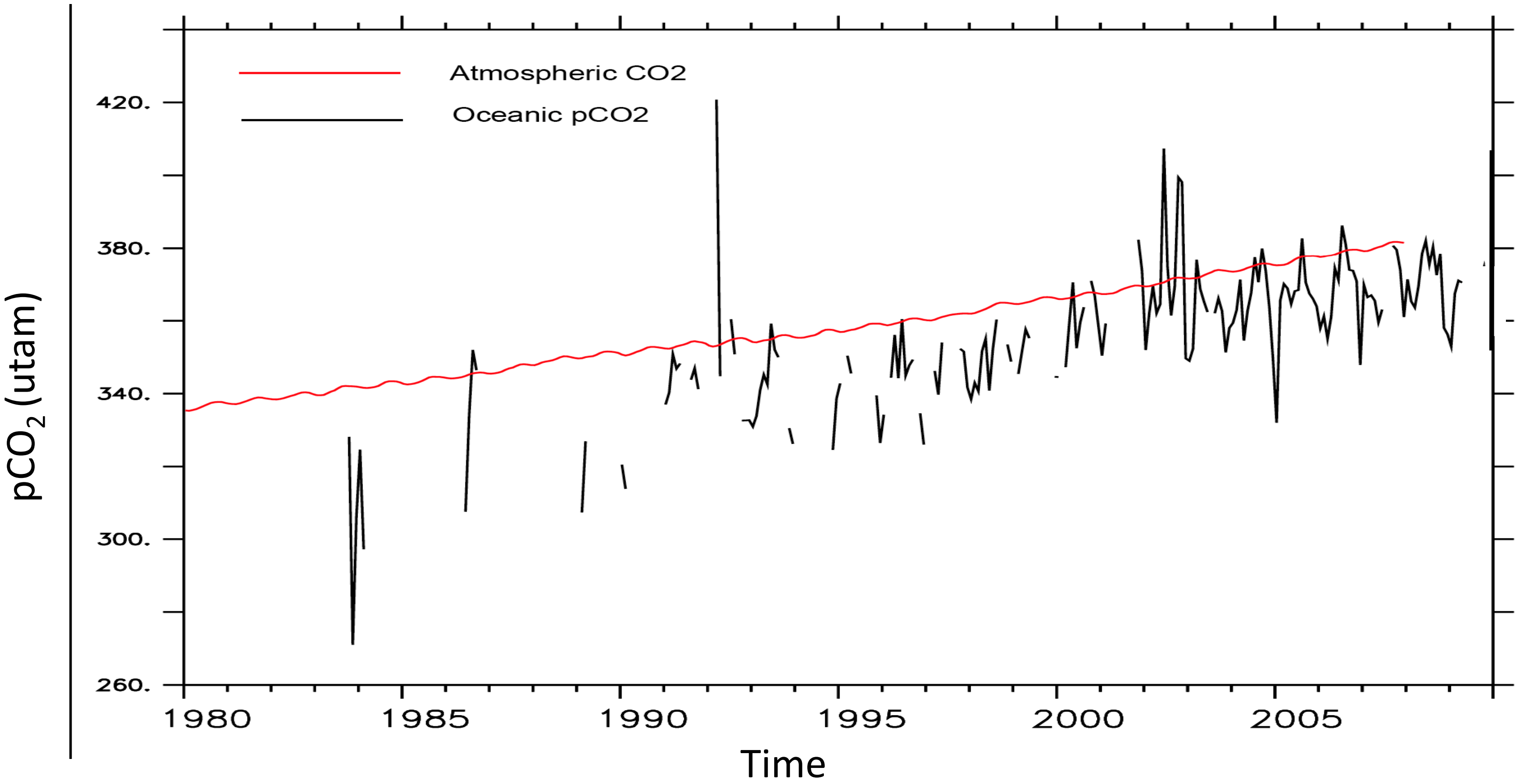
Basin Scale Response Southern Ocean 45S:62S

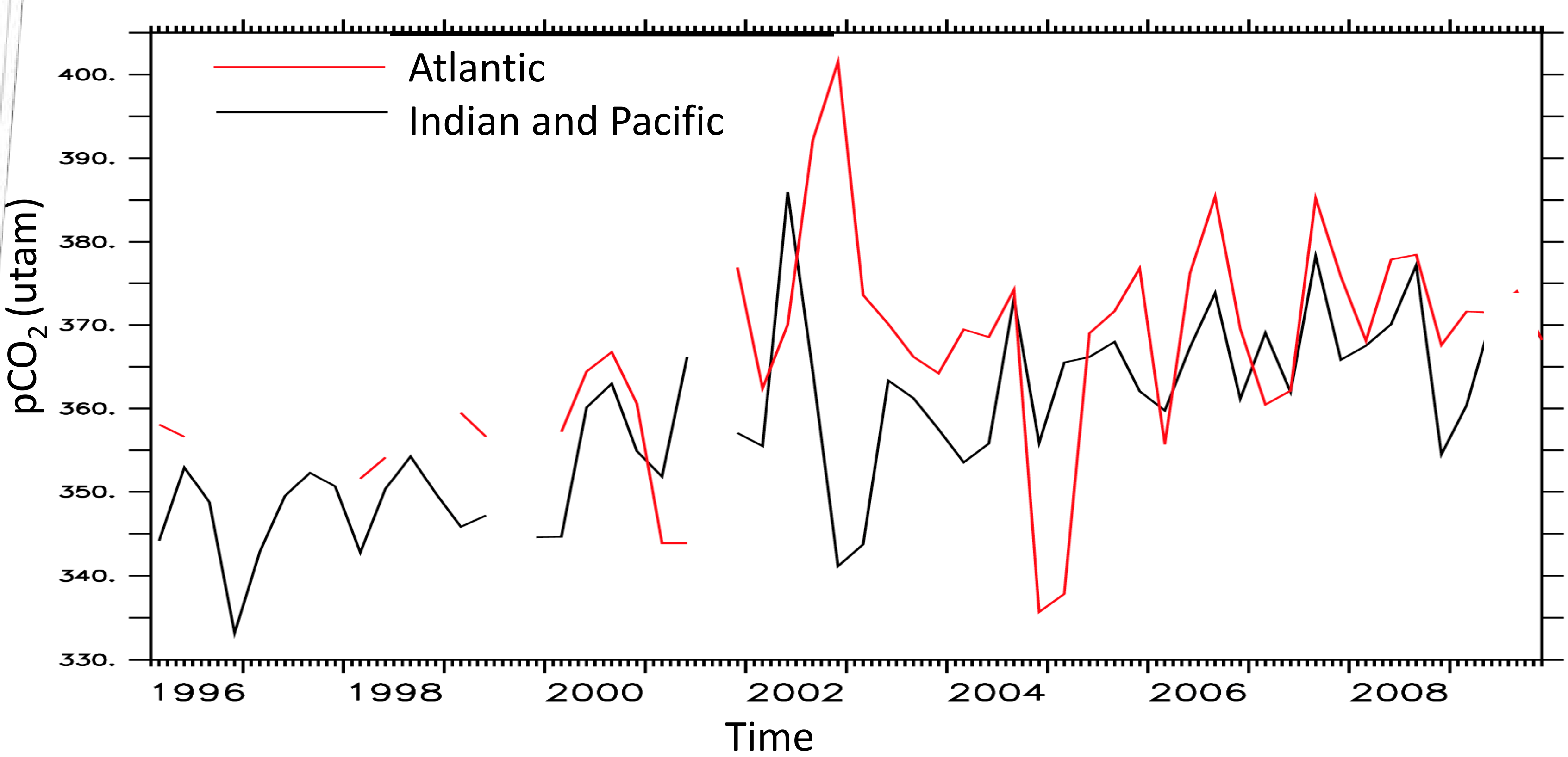


Prior to 1996 limited temporal coverage: focus on 1996-2008

- note Takahashi et al (2009) 1980s

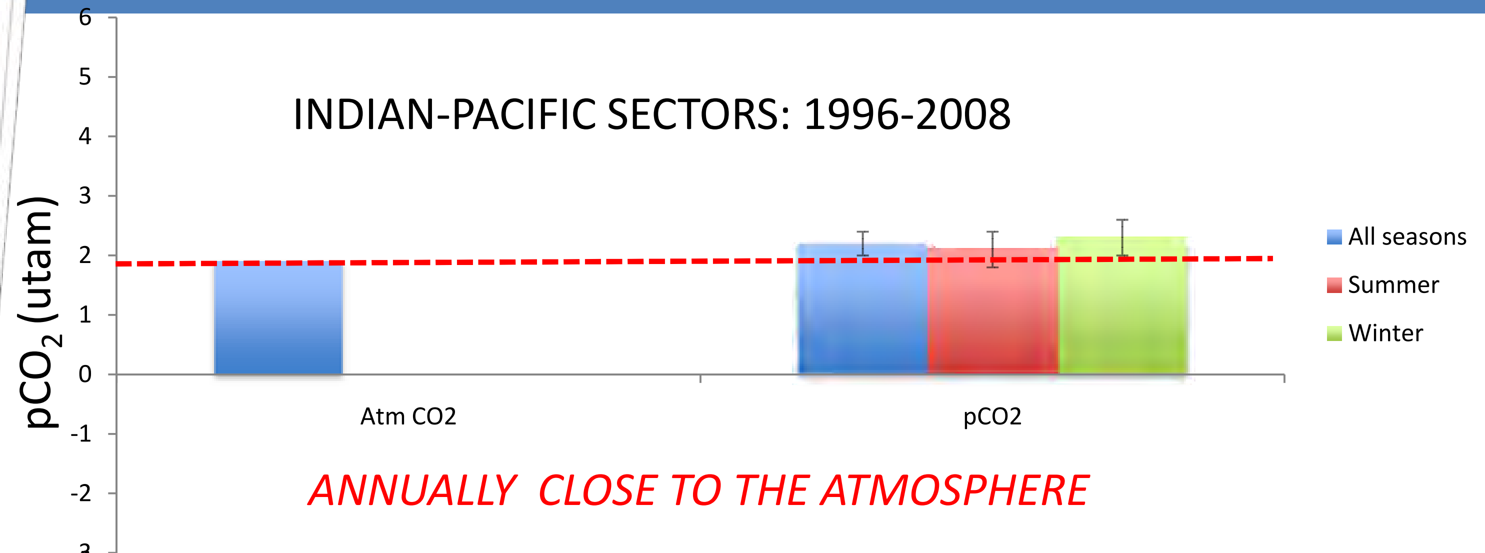
Seasonal Scale Response Southern Ocean: 45S:62S

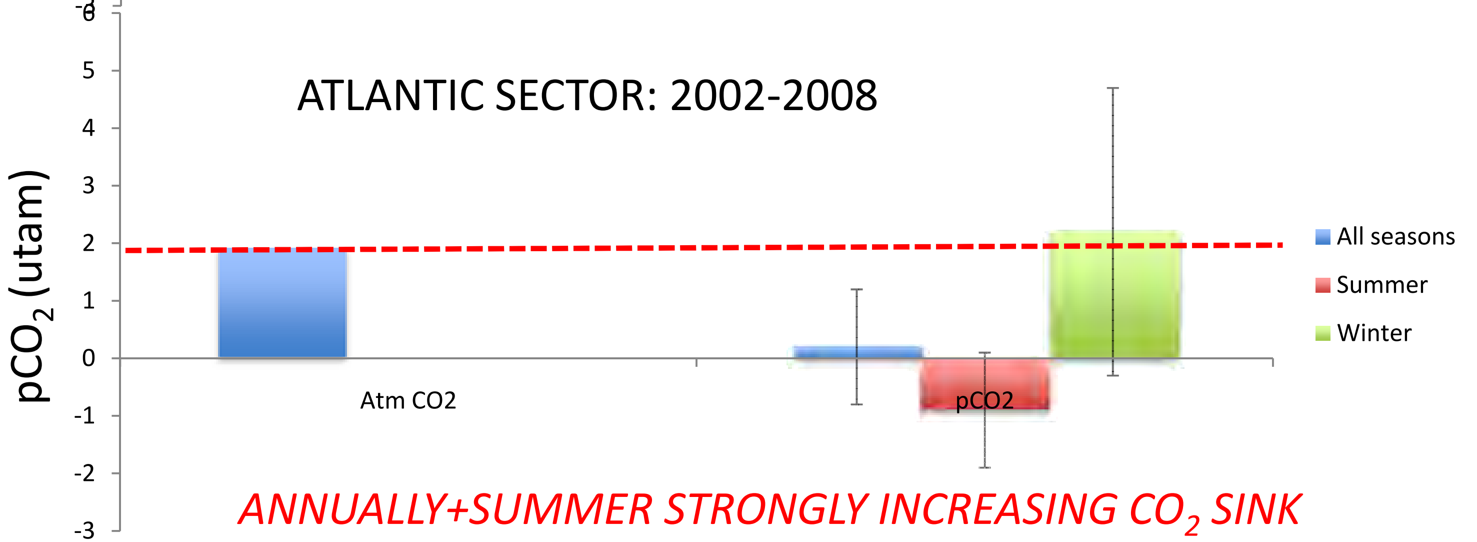
- Seasonal Ocean and Atmospheric CO2 growth rates



- Binned 3 monthly consistent with basin-scale sampling studies

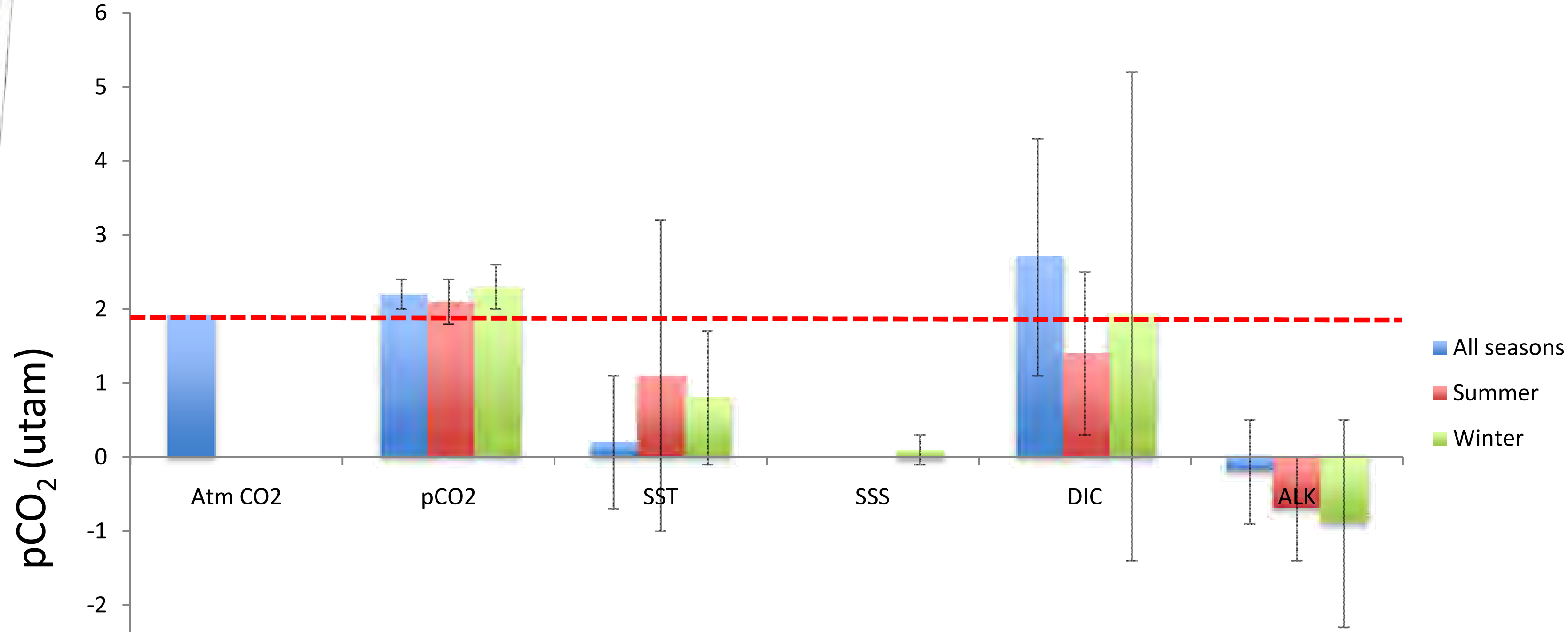
pCO_2 Trends Southern Ocean





WINTER IS CONSISTENT WITH OBSERVED CHANGES IN BOTH SECTORS

Trends and Attribution:
Indian-Pacific Sectors 1996-2008 (uatm)



All seasons, summer and winter : DIC changes are the largest – with almost balancing contribution from SST and ALK increases driving the trend in pCO_2

This response is consistent with a strengthening SAM of enhanced ventilation of carbon rich water. i.e. reduces carbon uptake relative to non-SAM.

We see large uncertainties – limit of detection

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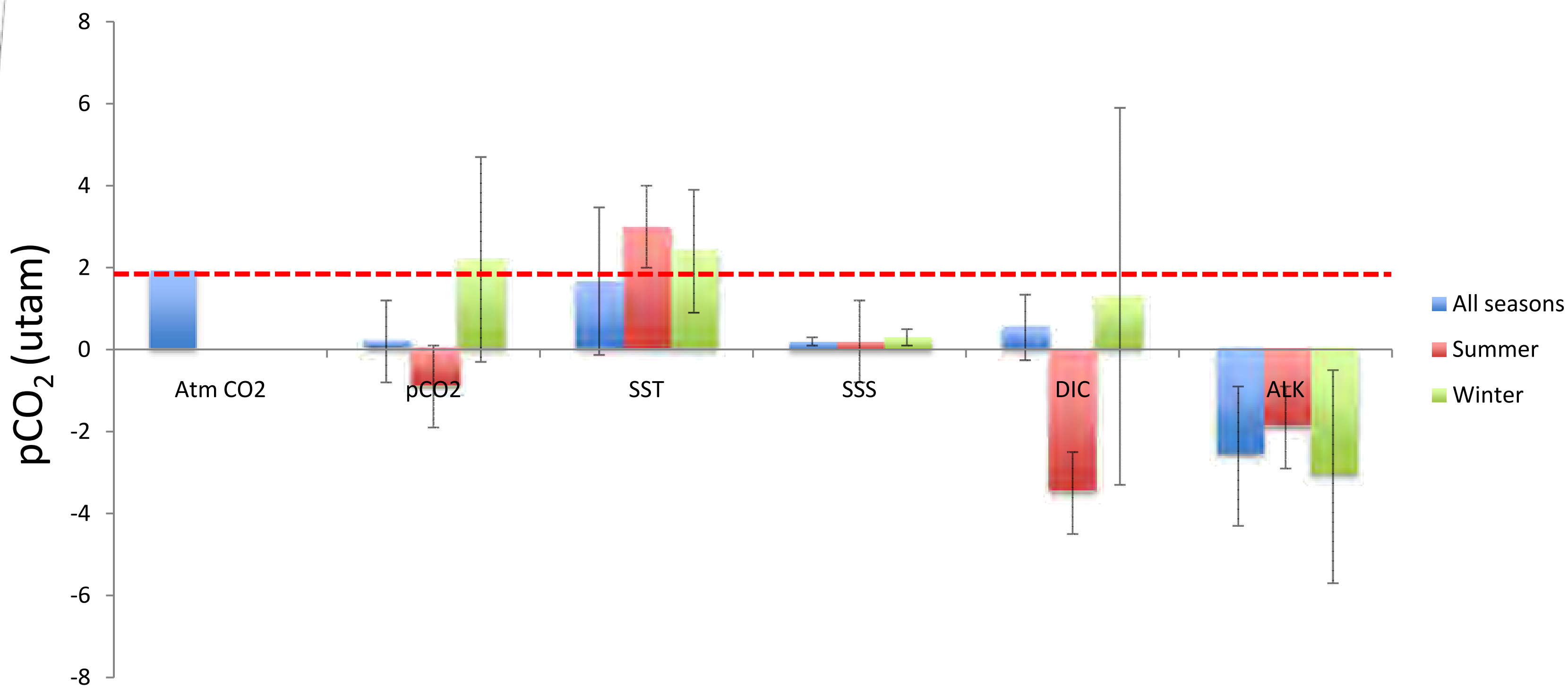
Trends and Attribution: Atlantic Sector 2002-2008



Increases in SST and SAL

All seasons: DIC and SST are balanced by ALK -> *NET INCREASE*

Summer: Decreases in DIC and ALK and larger than SST -> *NET INCREASE*

Winter: DIC and SST increases balanced by ALK -> *NO CHANGE*

SHORT TIME SERIES AT THE LIMITS OF DETECTION

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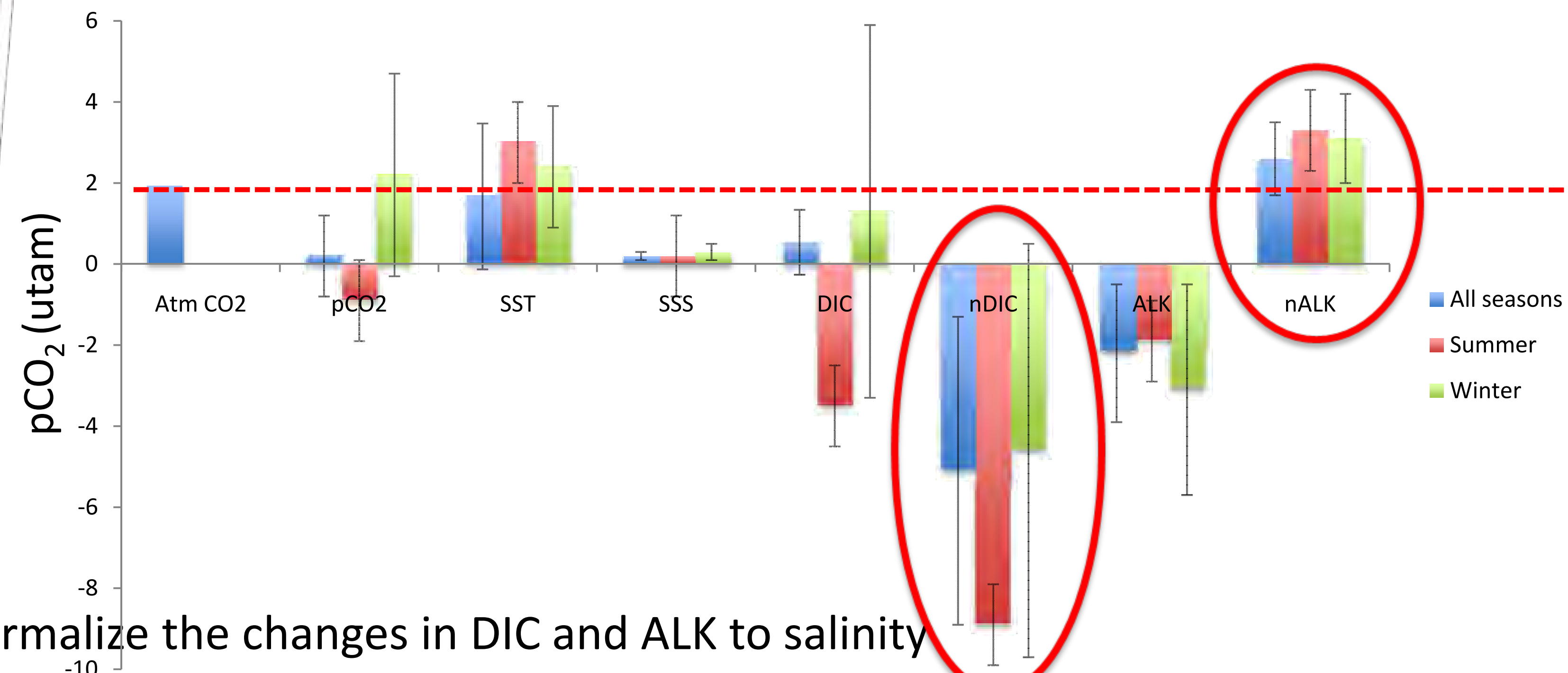
Trends and Attribution: Atlantic Sector 2002-2008



Normalize the changes in DIC and ALK to salinity

SAL increases: drive the net increase in ALK

: reduce the magnitude of the change in DIC

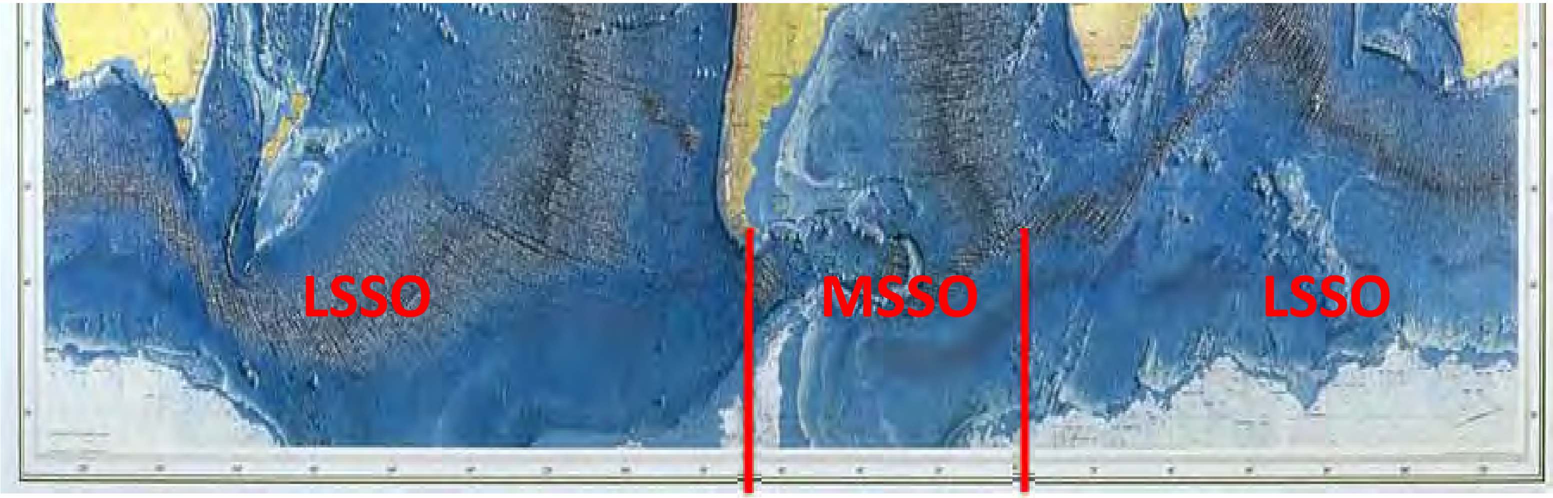
The increases in SAL act to reduce the strength of the sink

The strong decrease suggests reduced upwelling and enhanced PP.

hypothesized by Bopp et al (2001) to respond to changes in stratification

Stratification: 1996-2009

- Dong et al (2008) based on ARGO
  - More stratified Southern Ocean (MSSO: 65W:0)
    Atlantic Sector
  - Less stratified Southern Ocean   (LSSO: 0:65W)
    Indian & Pacific Sectors

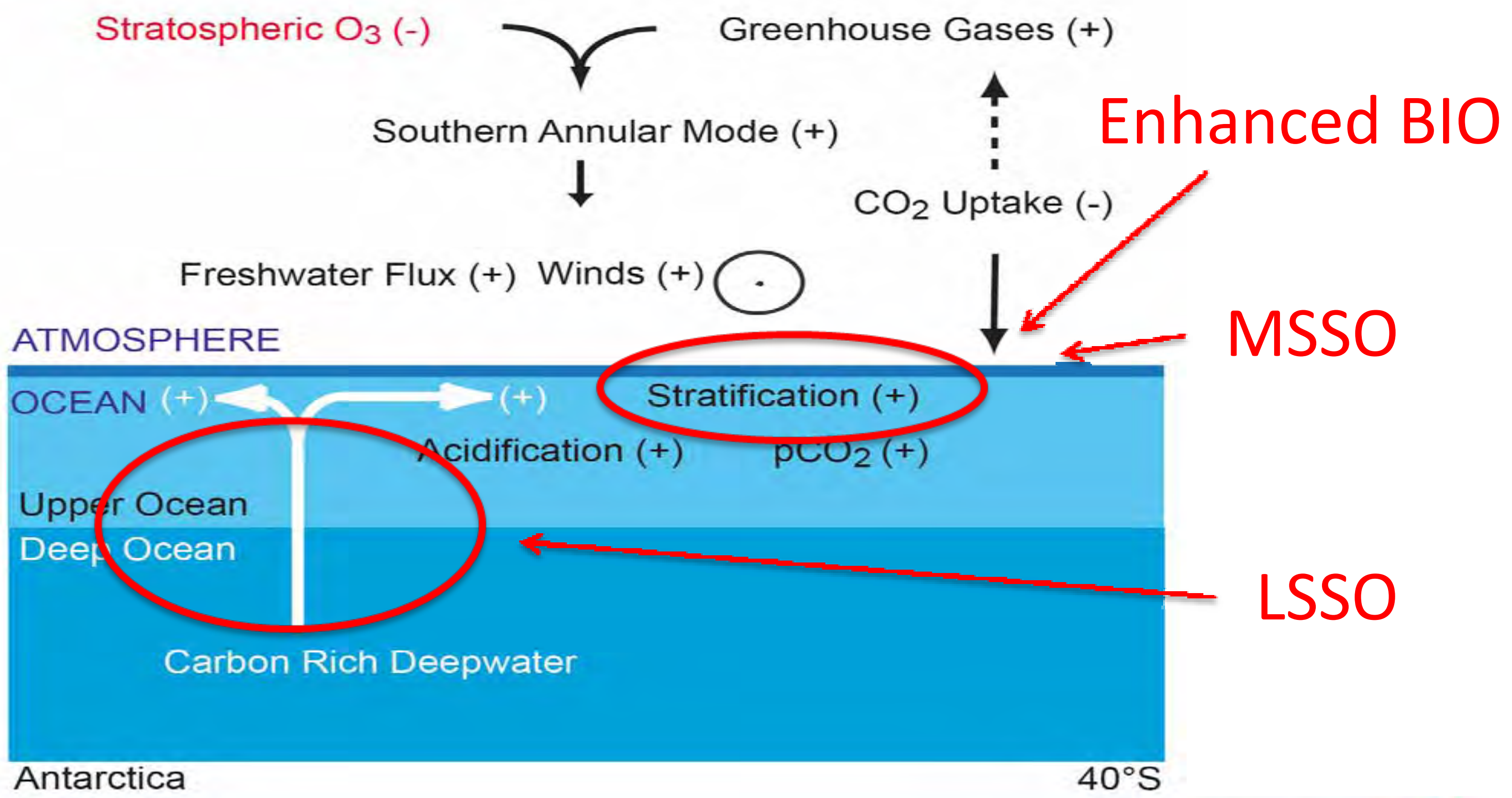


Is the Atlantic a Natural Lab for how the Southern Ocean carbon cycle may respond in the future? E.g. Sarmiento et al (2004)

Overview Southern Ocean : 1996-2009

SAM Response:

Competition between stratification and vertical supply



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Conclusion Southern Ocean I : 1996-2008:

We reconstruct the drivers of oceanic pCO2:DIC, Alkalinity, SST and Salinity

Despite ongoing efforts the periods over which robust trends can be calculated is short we at the limits of detection

The Southern Ocean separated into: LSSO (0:65W) and MSSO (65W:0) based on stratification

LSSO: Oceanic CO2 growth rate consistent with a SAM response close the atmosphere and slightly above in the winter

MSSO : increasing sink of atmospheric $CO_{2;}$ ventilation of carbon rich deep water appears retarded by the stratification and linked to increases biological production

Conclusion Southern Ocean:

While we see similar trends in winter they are controlled by different drivers

Impossible based on these short records to separate climate variability and change

Highlights the importance of collecting ongoing and continuous records of pCO2 as well as DIC and ALK to understand the drivers of oceanic pCO_2 and reduce uncertainty

Also highlights the importance of seasonal view as annual (all seasons) view can mask or compensate the seasonal

Overview Southern Ocean : 1996-2009

LSSO: Decreasing Sink of Atmospheric CO2

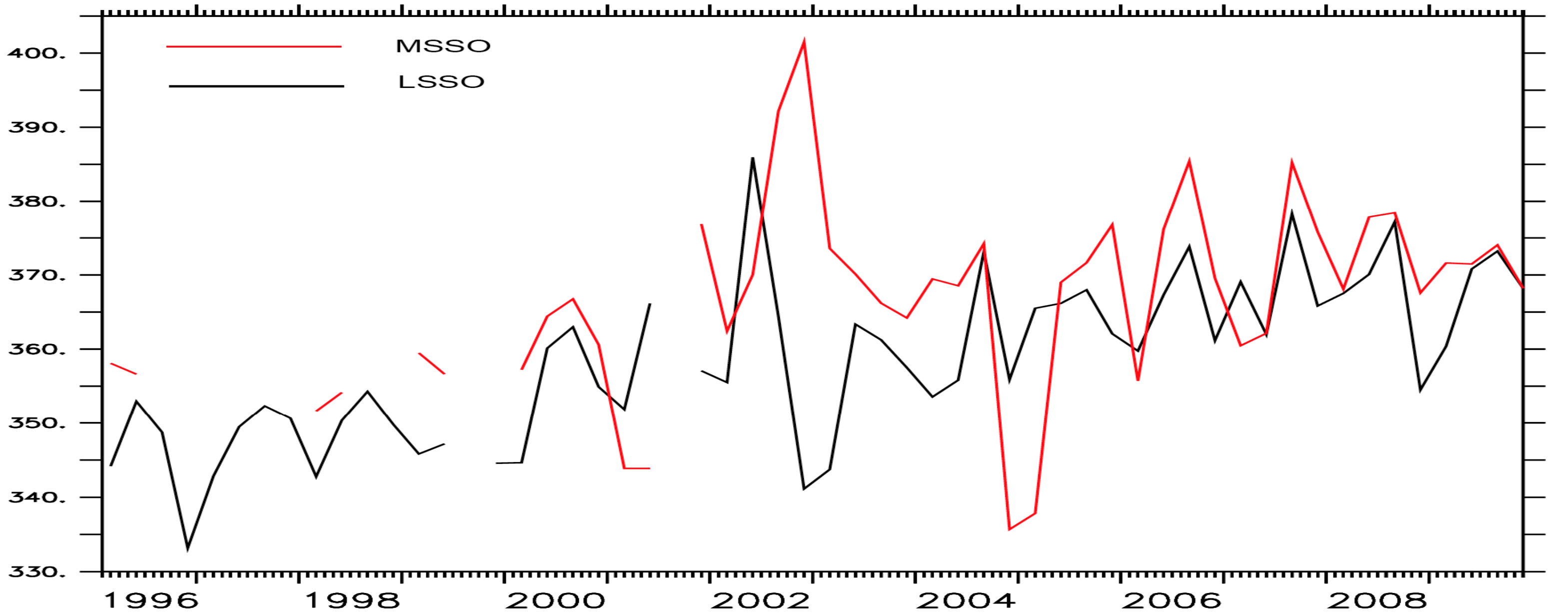
- pCO2 growth rates consistent growth in summer and winter
- Little trends in SST and SAL
- pCO2 growth rates similar suggest little change in biological production
- DIC key consistent with an SAM response

MSSO: Increasing sink of Atmospheric CO2

- pCO2 growth rates show a weak trend in the period 2002-2009
- Very short time series – significance?
- Strong summer decreases in DIC & ALK increased Biological Production?
- DIC and ALK winter trend driven by physical changes
- Response not by upwelling suggest that stratification retarding upwelling /vertical supply and hence natural carbon supply?

Basin Scale Response Southern Ocean : 1996-2009

1996-2008: Atmospheric Trends 1.9 uatm/yr



LSSO: 1996- 2009		MSSO: 2002-2009	
Annual	2.2±0.2 uatm/yr	Annual	0.2±1 uatm/yr
Summer	2.1±0.3 uatm/yr	Summer	-0.9±2.5 uatm/yr
Winter	2.3±0.2 uatm/yr	Winter	2.2 ± 1.1 uatm/yr

CLOSE the ATM

ENHANCED SINK

Controls on surface CO_2 variability: Synthesis from LDEO data

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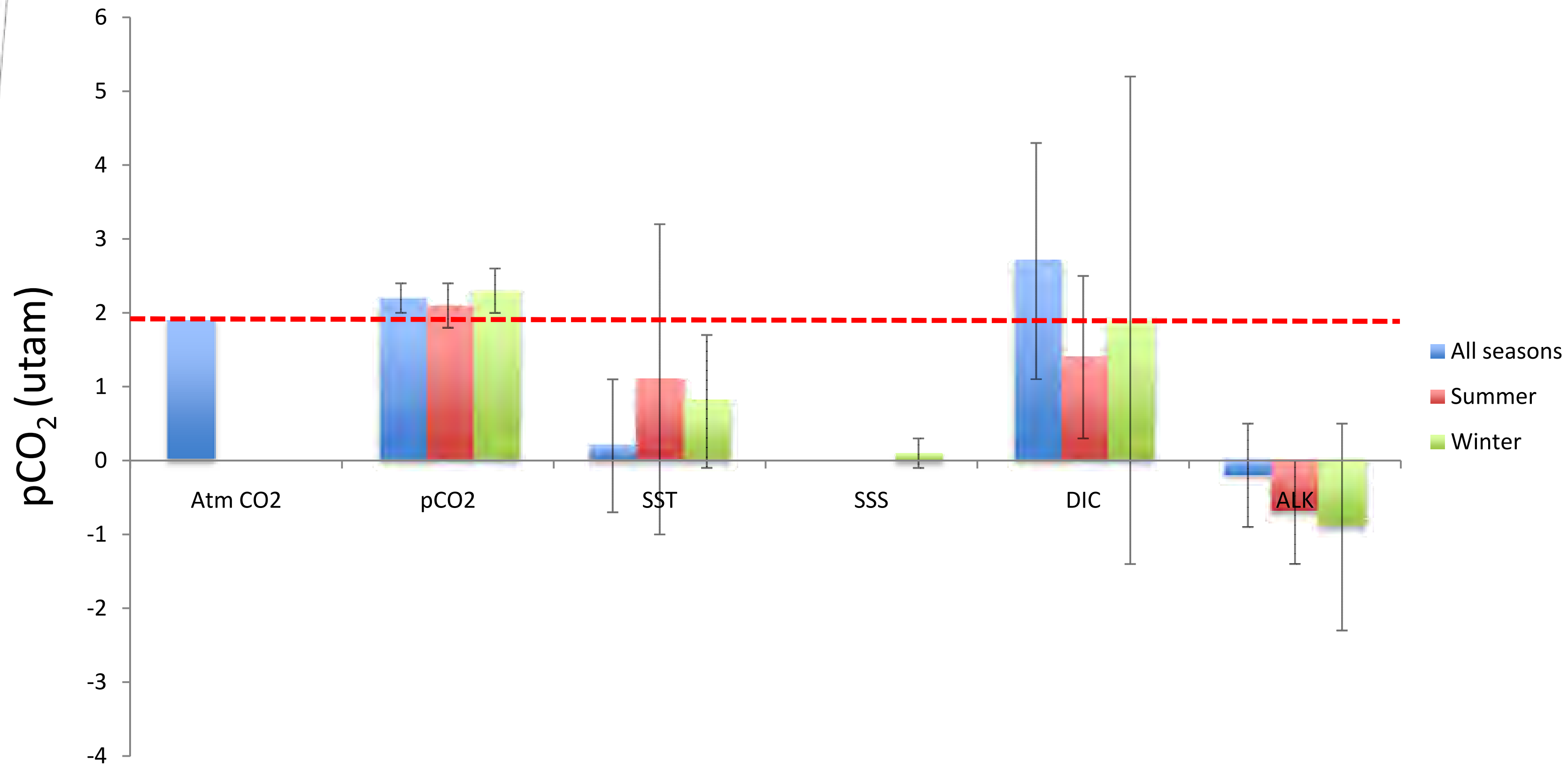
Trends and Attribution LSSO: Indian-Pacific Sectors



Controls on surface CO_2 variability: Synthesis from LDEO data

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Trends and Attribution MSSO: Atlantic Sector

pCO_2 (utam)

Oceanic pCO2 growth rate close to the atmospheric rate

Controls on surface CO_2 variability: Synthesis from LDEO data