Wind driven upwelling in the Southern Ocean and its impact on CO_2

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With contributions from

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And funding from NOAA and NSF

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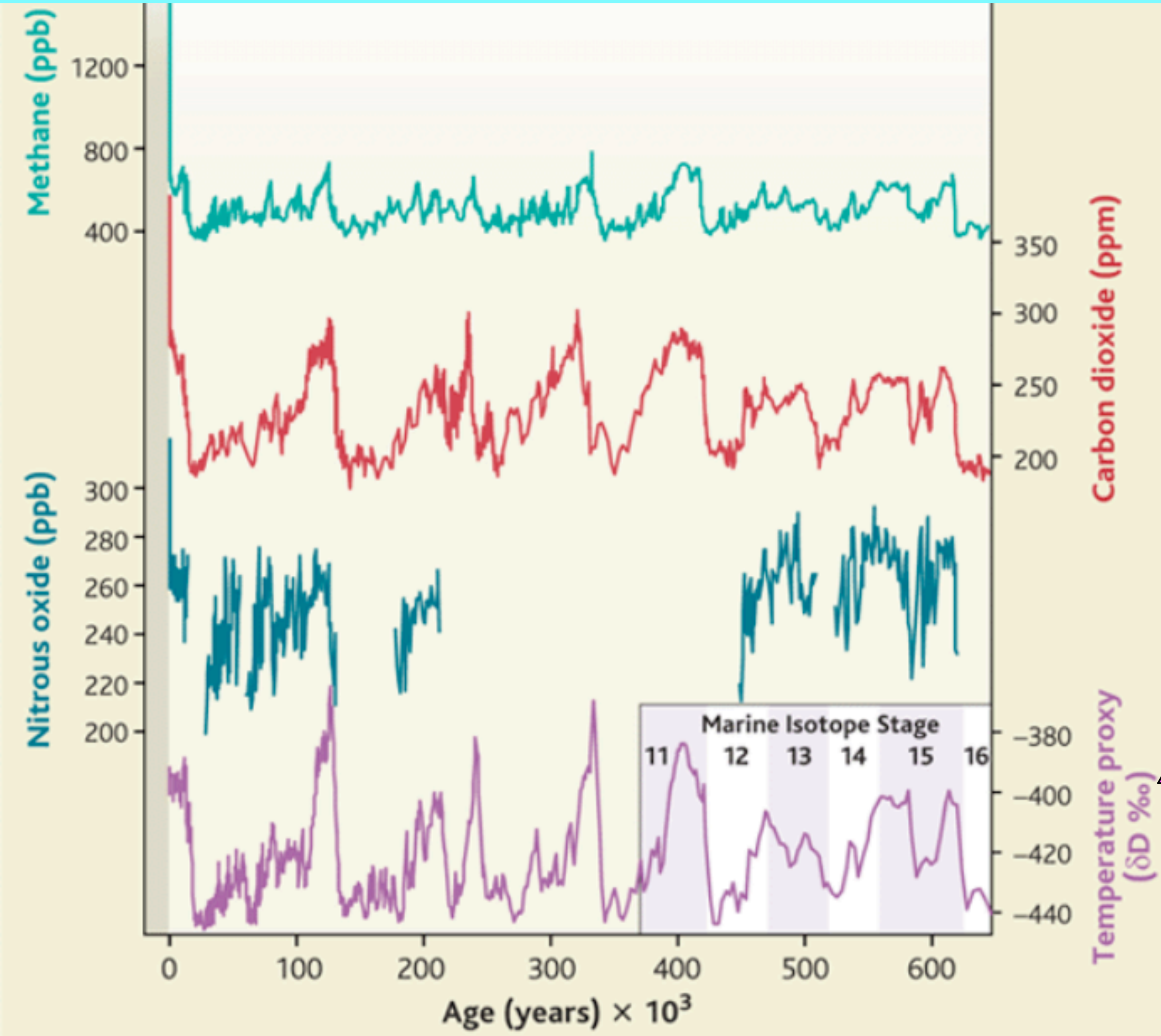
THE EARTH INSTITUTE AT COLUMBIA UNIVERSITY

Ice core records show tight coupling between CO_2 and climate



From Brook, 2005 Comment on Siegenthaler et al., 2005

CO_2

Warmer

Climate

Ice core records show tight coupling between CO_2 and climate

Ocean control is required

Suite of possible control mechanisms proposed by Broecker 1982

No single process can regulate observed variability

Multiple synergistic processes required

Ice core records show tight coupling between CO_2 and climate

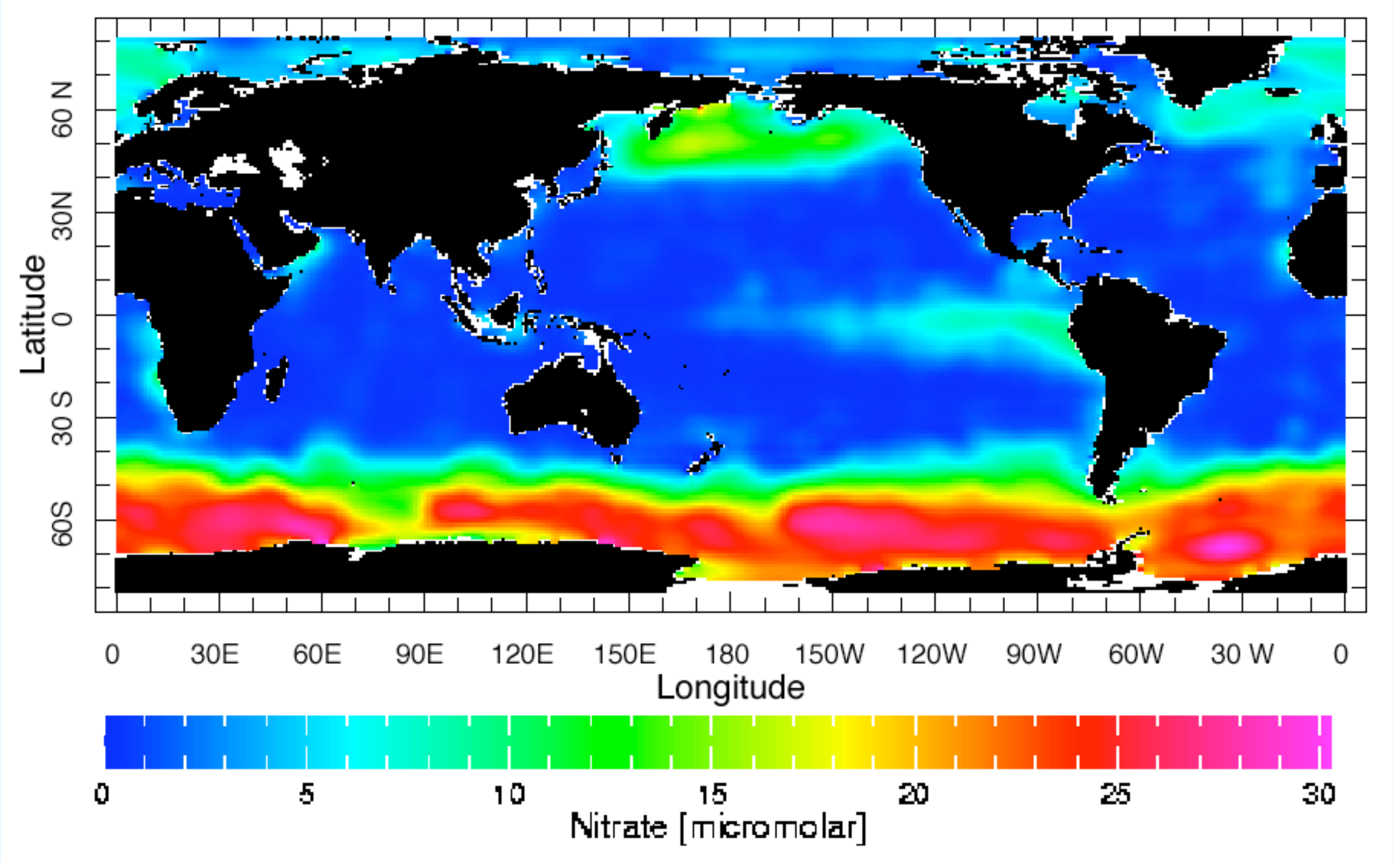
Previous studies invoked control by varying rates of upwelling in the Southern Ocean

Deep water masses are ventilated primarily in the Southern Ocean

But: No direct evidence until now to support this hypothesis!

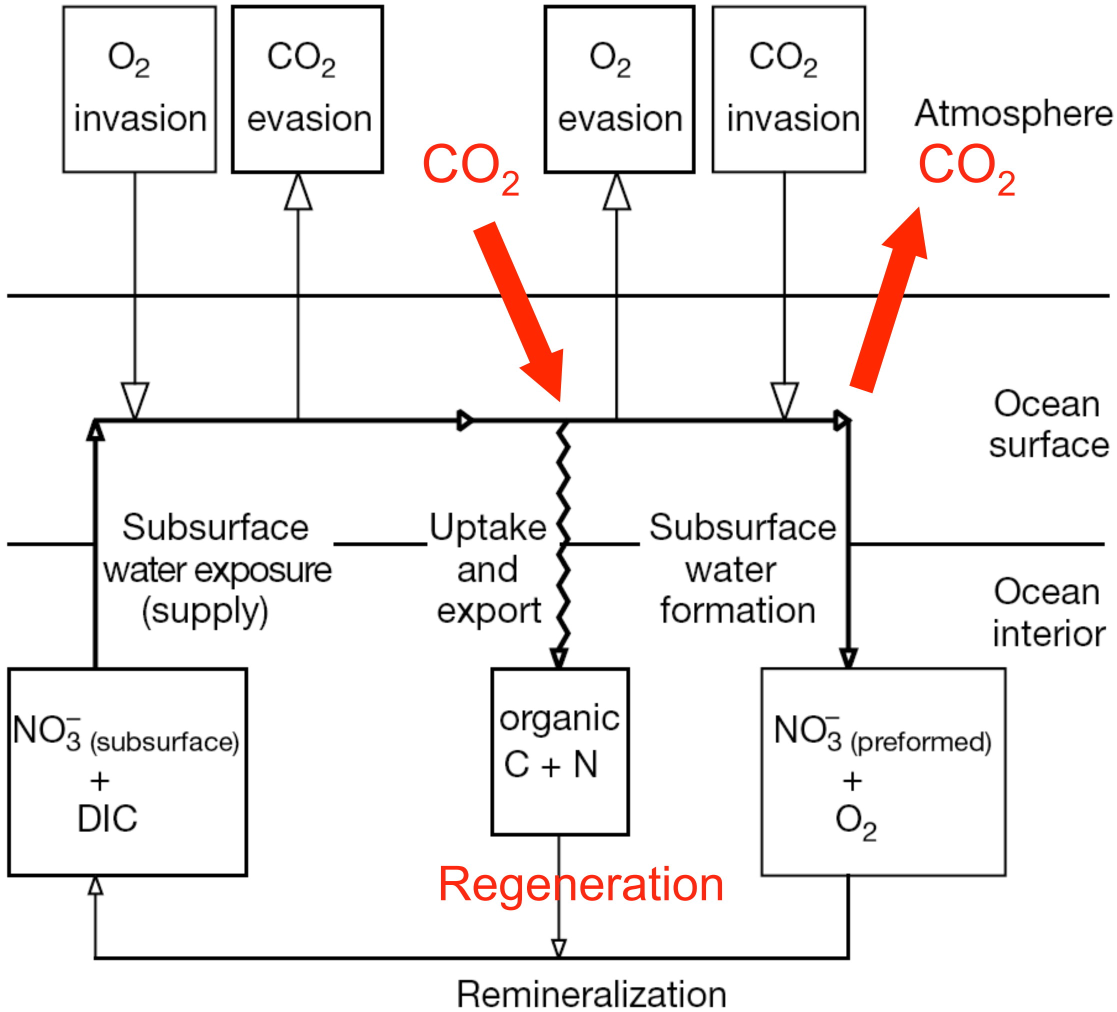
Why Upwelling?

Upwelling is tied to efficiency of the ocean's "biological pump"



Surface nitrate illustrates high efficiency of the biological pump over most of the ocean. Principal exception is the Southern Ocean.

From: iridl.ldeo.columbia.edu/SOURCES/.LEVITUS94

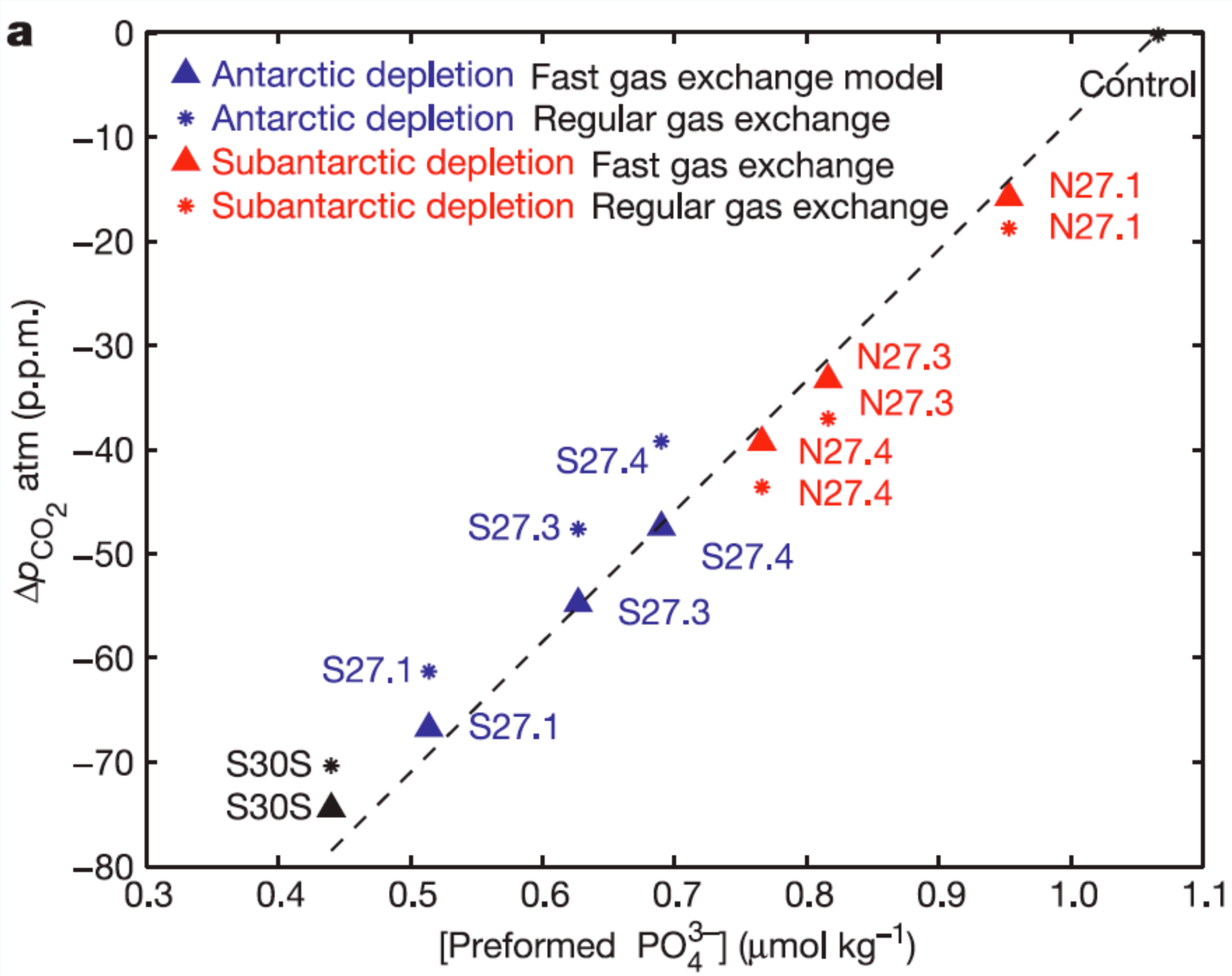


$$\text{Nutrient utilization} \equiv \frac{\text{Uptake}}{\text{Supply}} = 1 - \frac{[NO_3^-]_{\text{preformed}}}{[NO_3^-]_{\text{subsurface}}} \propto \frac{CO_2 \text{ invasion}}{CO_2 \text{ evasion}}$$

Efficiency of the biological pump is measured in terms of nutrient utilization and "preformed nutrients"

From: Sigman and Boyle, 2000

CO_2 sensitivity to preformed nutrients



Princeton Ocean GCM runs with different So. Ocean nutrient utilization scenarios.

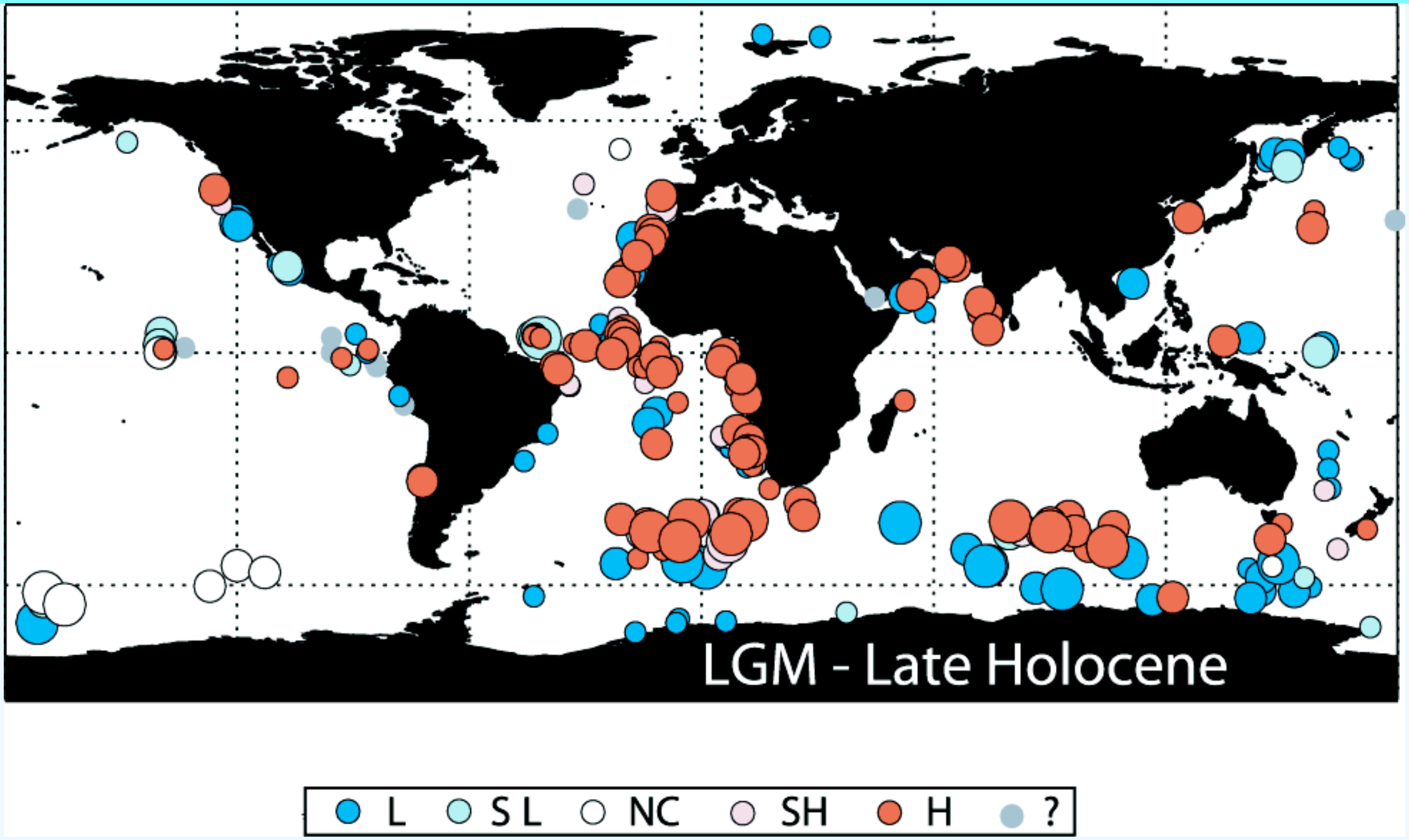
Constant ocean nutrient inventory.

From: Marinov et al., 2006

Mechanisms to increase nutrient utilization efficiency

1) Increase nutrient utilization (e.g., John Martin's "Iron Hypothesis")
2) Reduce nutrient supply (e.g., glacial stratification hypothesis)

Iron fertilization was not pervasive in the glacial Southern Ocean



Reconstructed change in export production (Glacial - Holocene):
Blue = lower during glacial; Red = higher during glacial

Kohfeld et al., Science, 2005

Ice core records show tight coupling between CO_2 and climate

If not iron fertilization, then what about control by varying rates of upwelling in the Southern Ocean?

Proposed more than 10 years ago.

But: No direct evidence until now to support this hypothesis!

Upwelling occurs South of the Zero in Wind Stress Curl

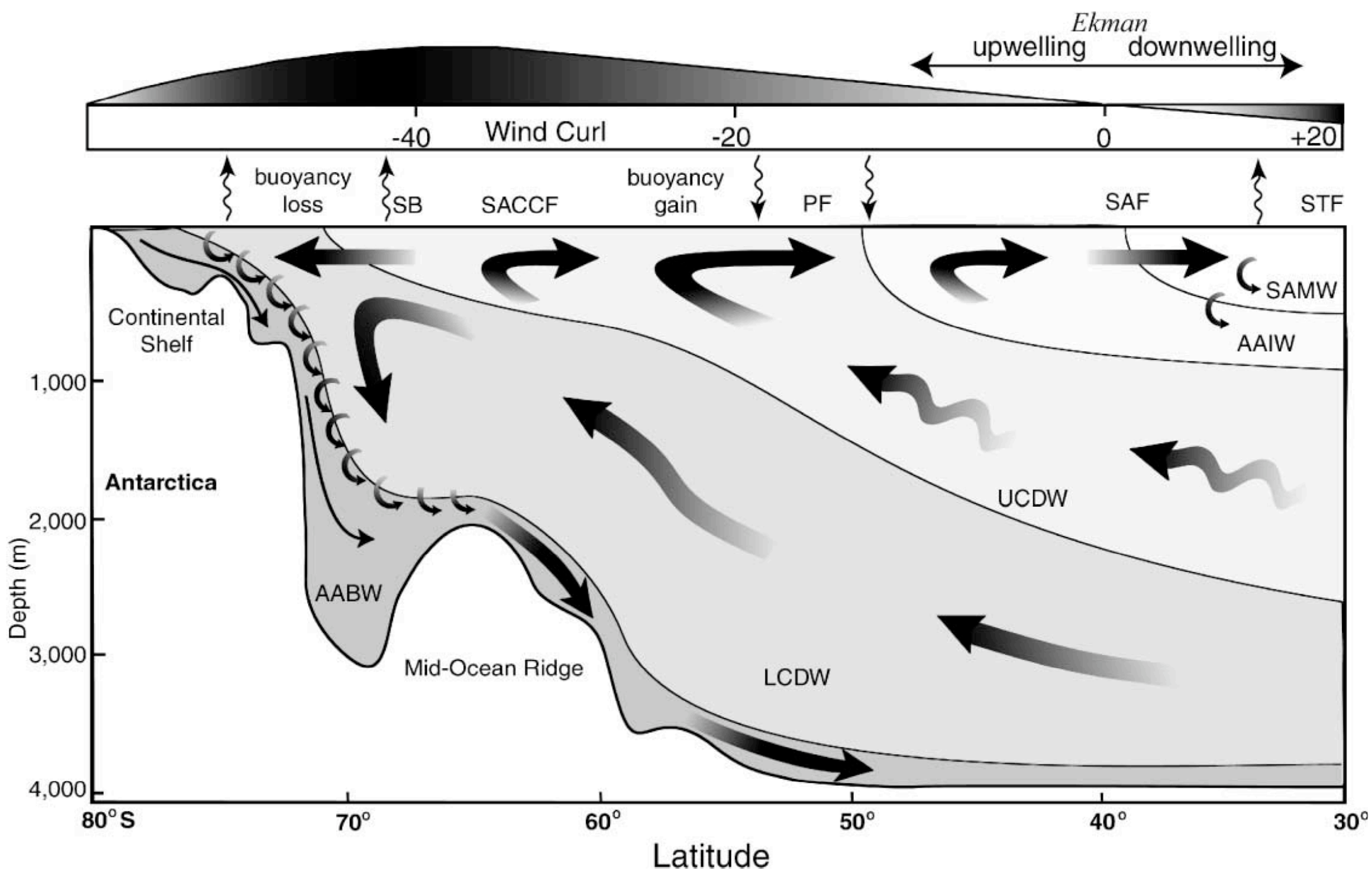
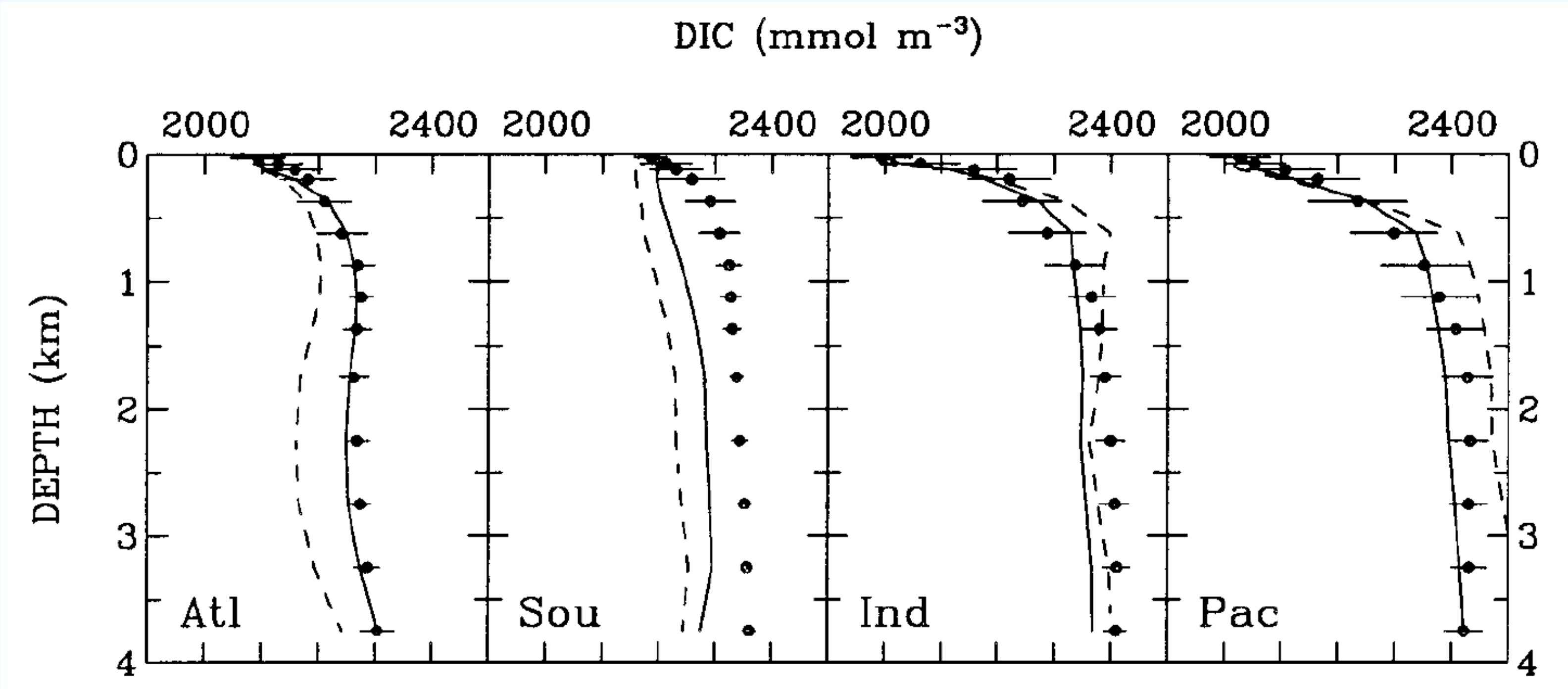


Figure of K Speer redrawn by T Trull

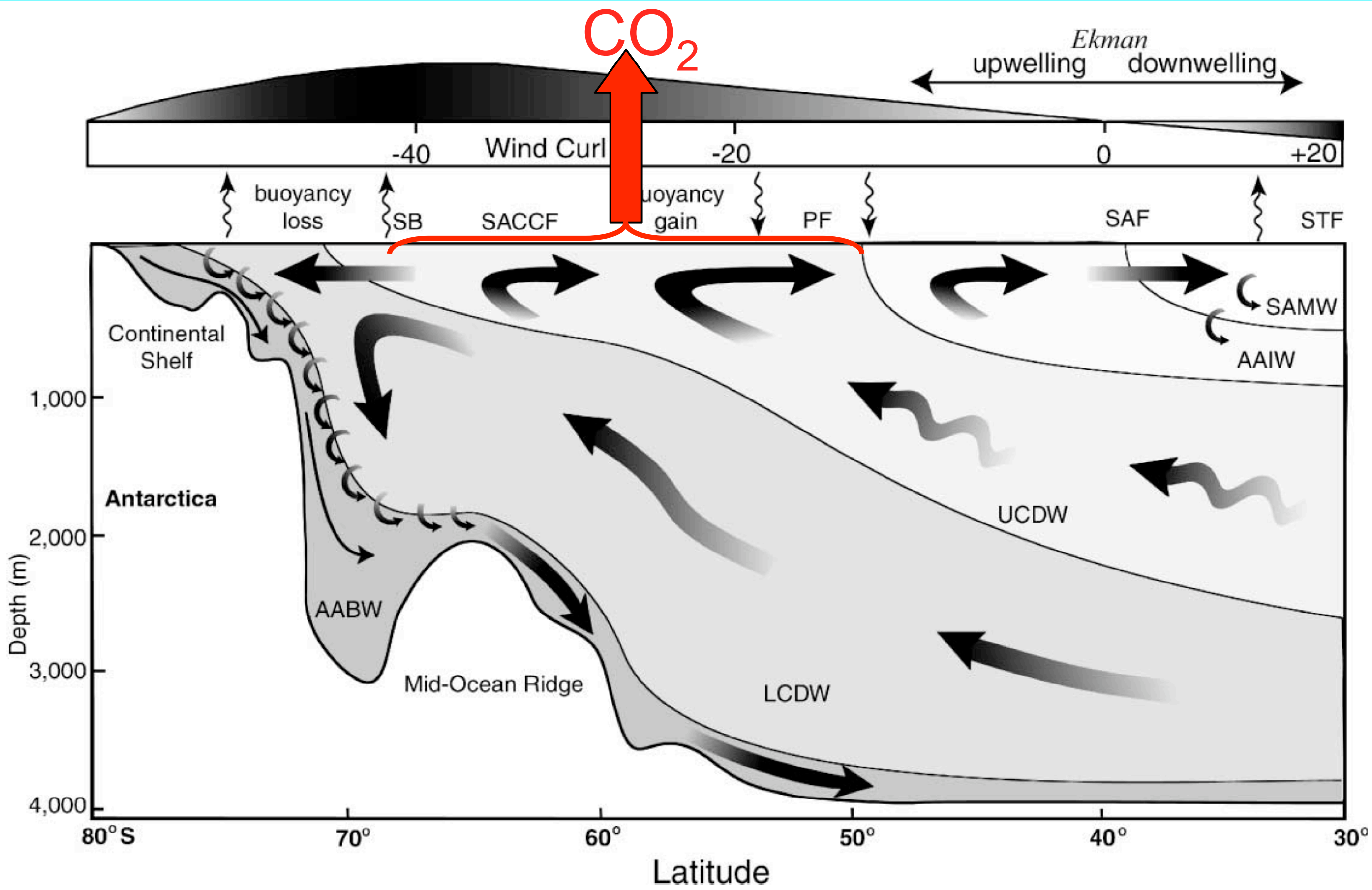
Deep waters are enriched in CO_2



Biomass formed in the surface ocean sinks after organisms die. Decay of organic matter in the deep ocean enriches water in CO_2

Figure of Marchal et al., 1998

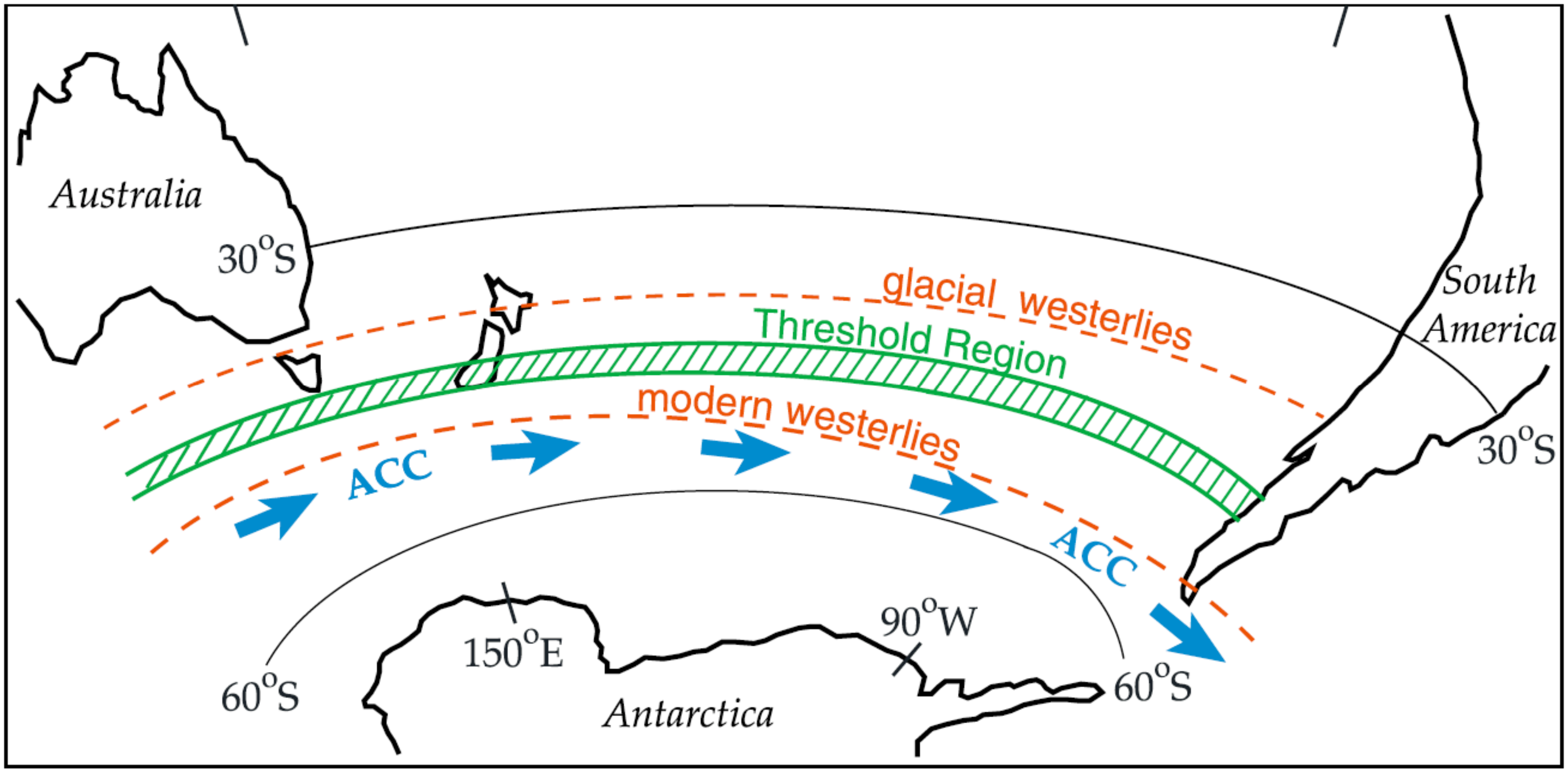
Upwelling occurs South of the Zero in Wind Stress Curl



Upwelling ventilates CO_2-rich deep water masses S of the APF

Figure of K Speer redrawn by T Trull

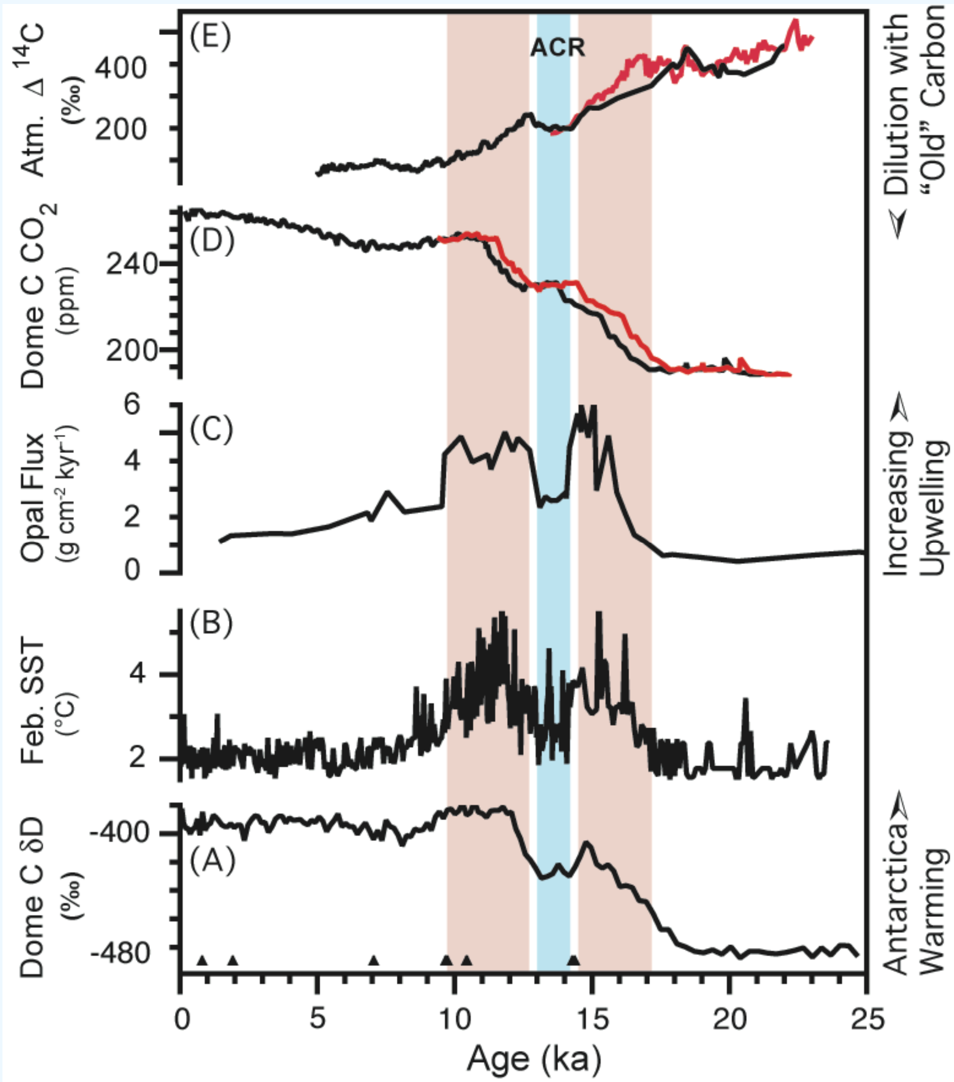
Ventilation and CO_2 exchange controlled by SH Westerlies?



Northward shift of winds reduced ventilation during glacials.
Evidence for wind shift from precipitation proxy records.

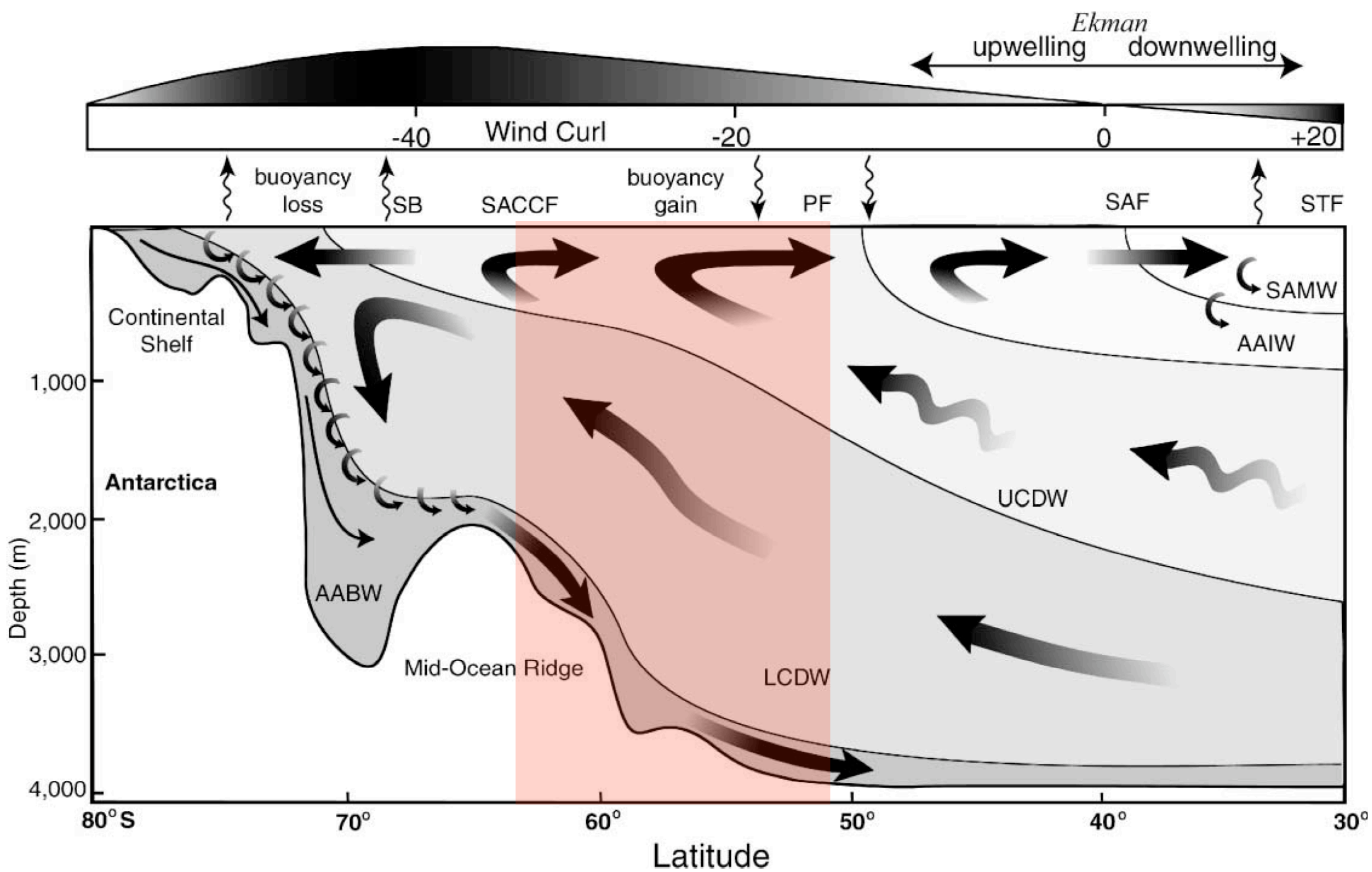
Toggweiler, 2006

Evidence for increased upwelling during deglaciations?



GOAL:
Demonstrate that opal flux in So. Ocean sediments is a proxy for upwelling, and that it is correlated with the deglacial rise in CO_2.

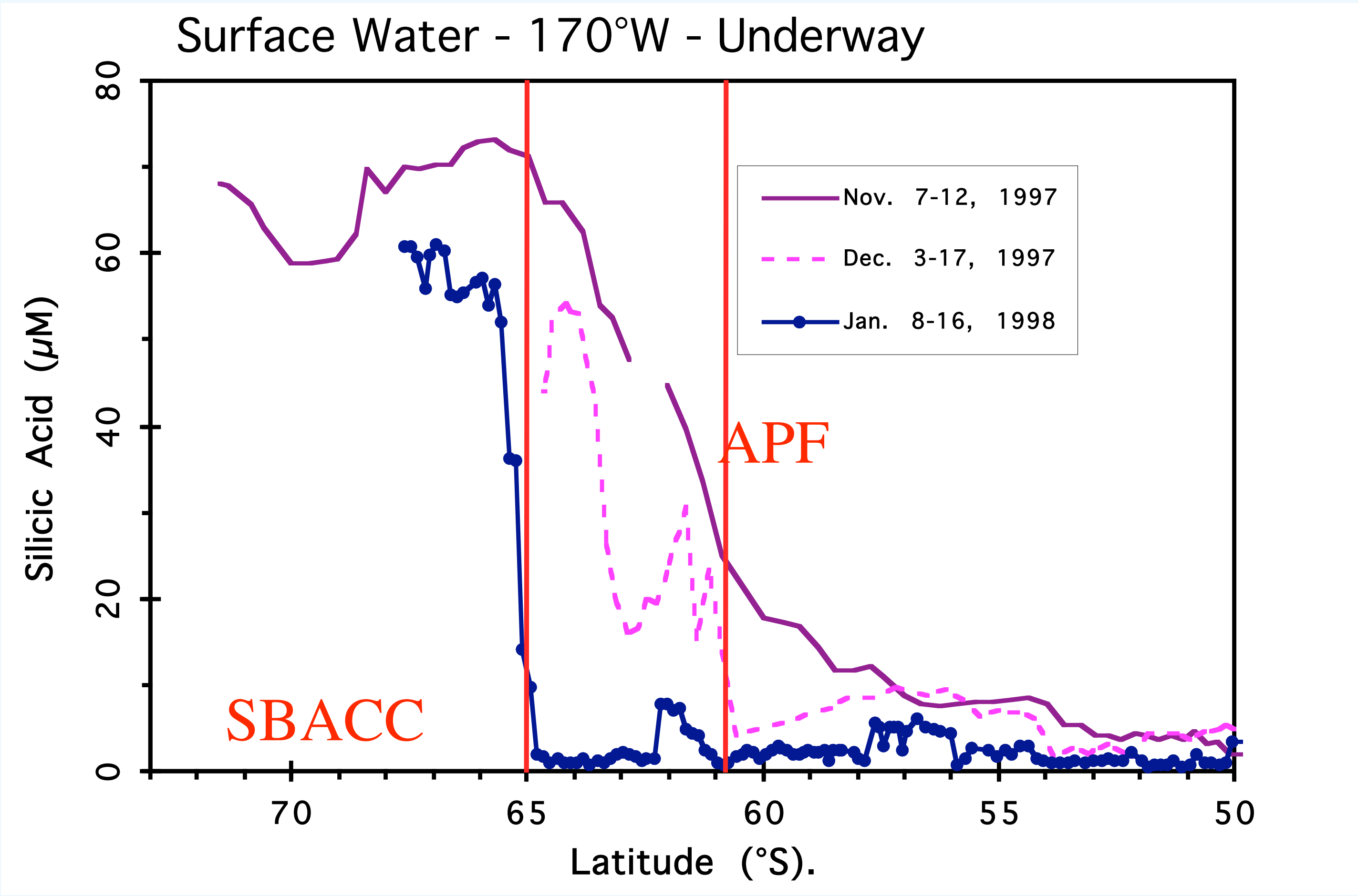
Principle: Upwelling brings nutrients (N, P, Si) as well as CO_2



Maximum nutrient supply is between the APF and the SACCF

Figure of K Speer redrawn by T Trull

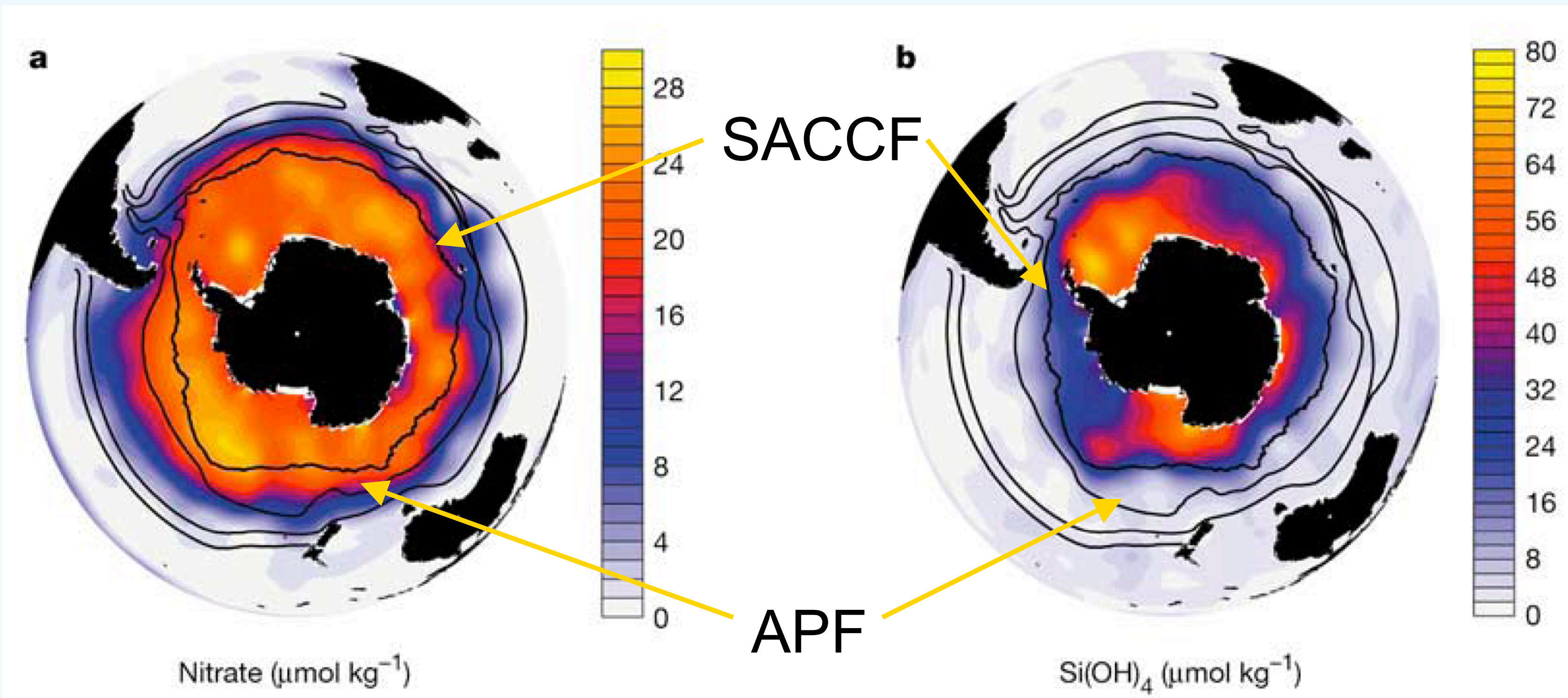
Principle: Between APF and SACCF Si is consumed by diatoms



Although N and P go largely unused, nearly all Si is consumed

Figure from US JGOFS/AESOPS

Principle: Between APF and SACCF Si is consumed by diatoms



Although N and P go largely unused, nearly all Si is consumed.
This is true throughout the Southern Ocean.

Figure from Sarmiento et al., 2004

Review: Features of the region between the APF and SACCF

- Maximum upwelling and nutrient supply
- Nearly all Si used by diatoms
- Annual opal production is limited by Si

    i.e., by upwelling

    Not by light or by Fe

This does NOT mean that uptake of N, P and CO_2 would not be stimulated by increasing light or Fe.

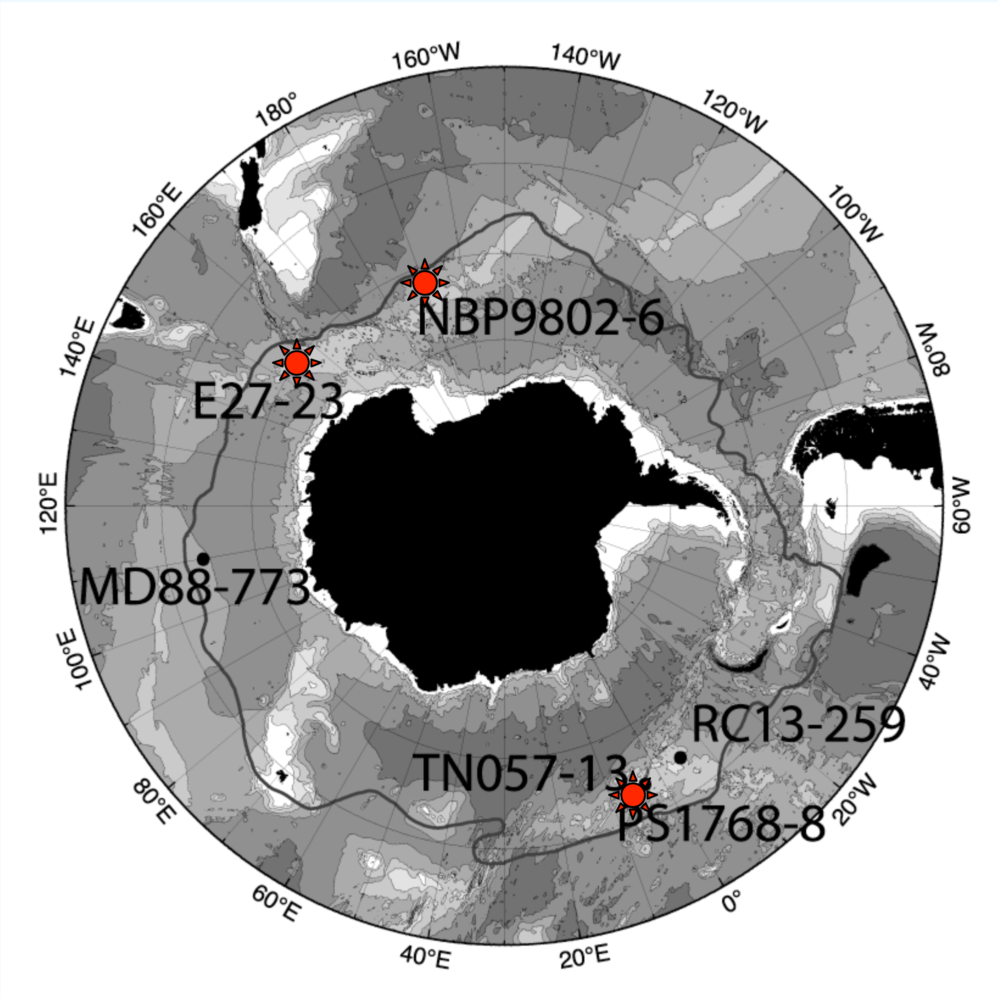
Si uptake by diatoms is decoupled from uptake of N and C!

Implication for the region between the APF and SACCF

Production of opal by diatoms in this region can exceed today's maximum values only by increasing the supply of dissolved Si…

…i.e. By increasing the rate of upwelling

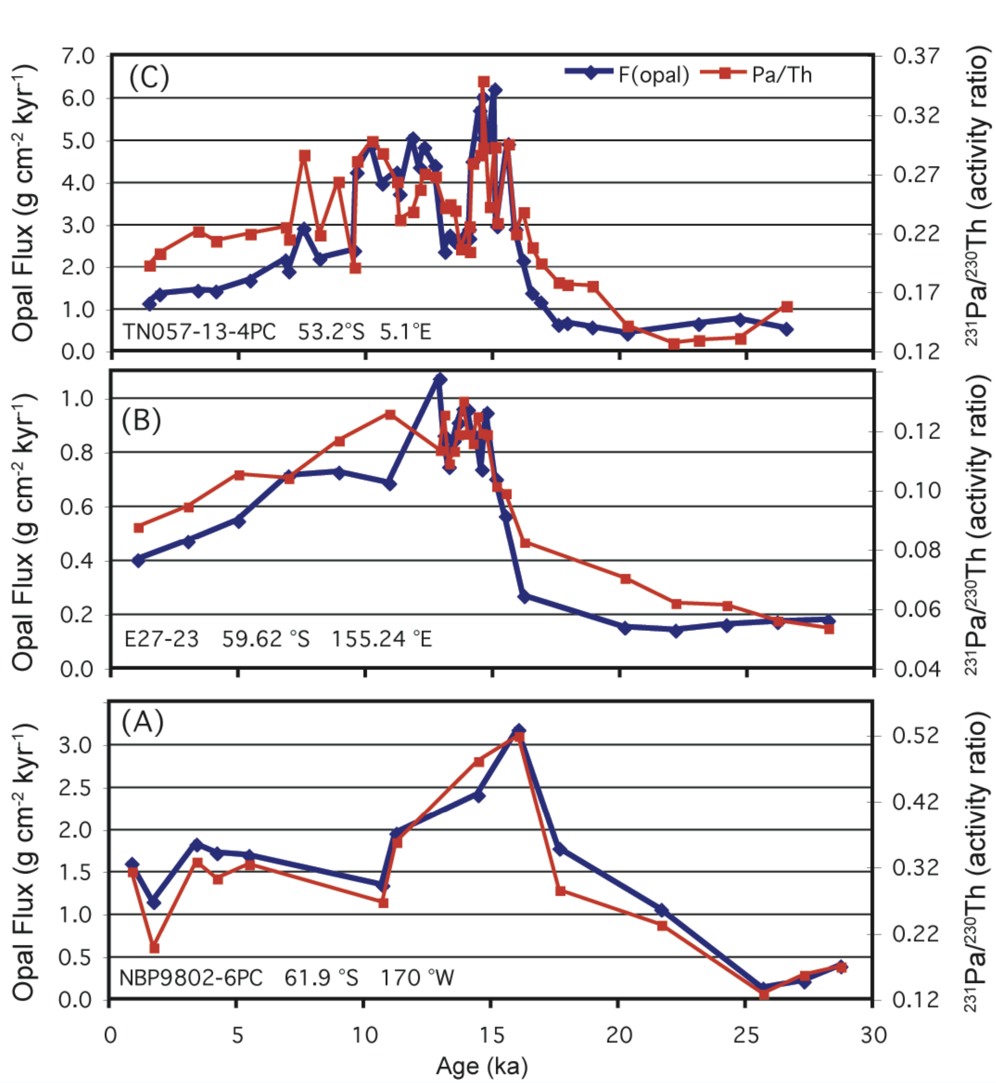
Sites where deglacial maxima in opal burial have been observed



Feature occurs:

- South of the APF
- In all sectors
- Results from selected sites

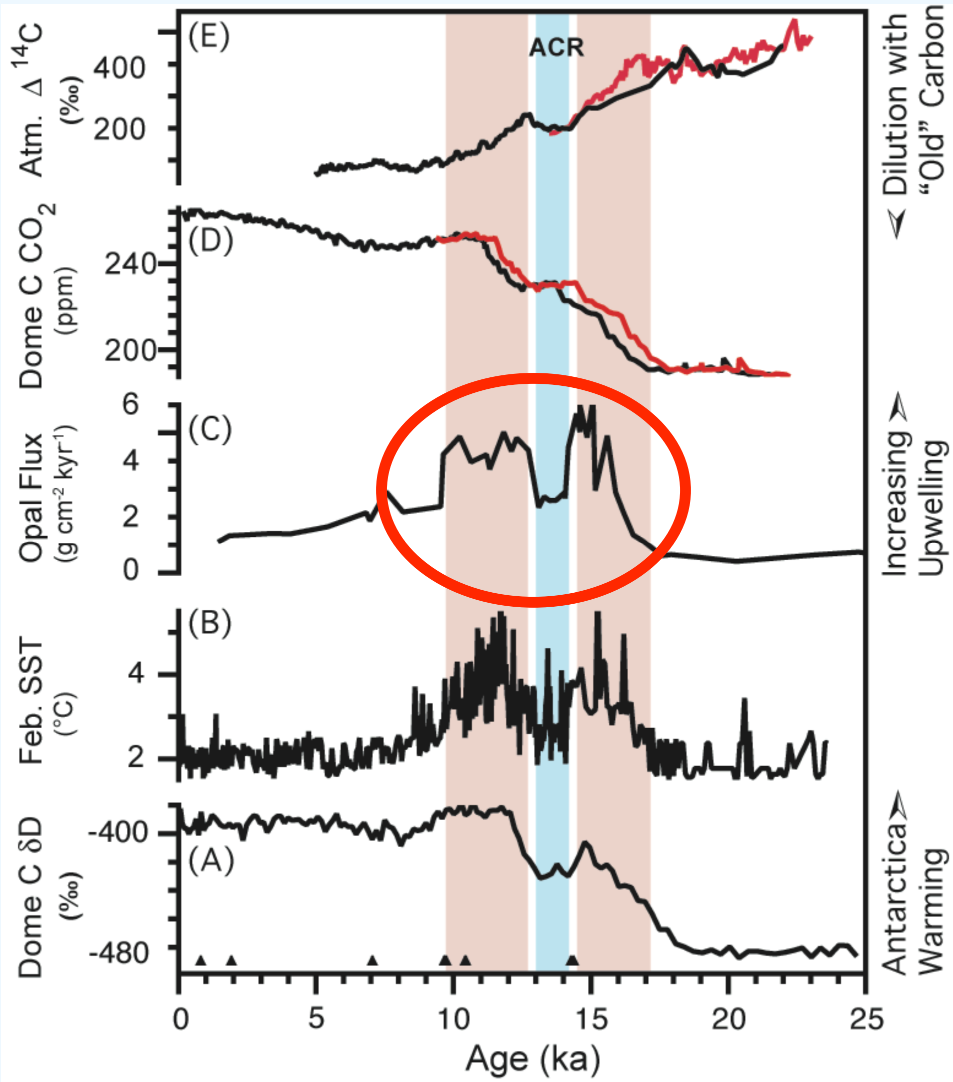
Sites where deglacial maxima in opal burial have been observed



Opal burial flux:

- Peaks during deglaciation
- Correlates with $^{231}Pa/^{230}Th$
- Flux reflects diatom production, not opal preservation

Maximum So. Ocean upwelling coincided with deglacial rise in CO_2



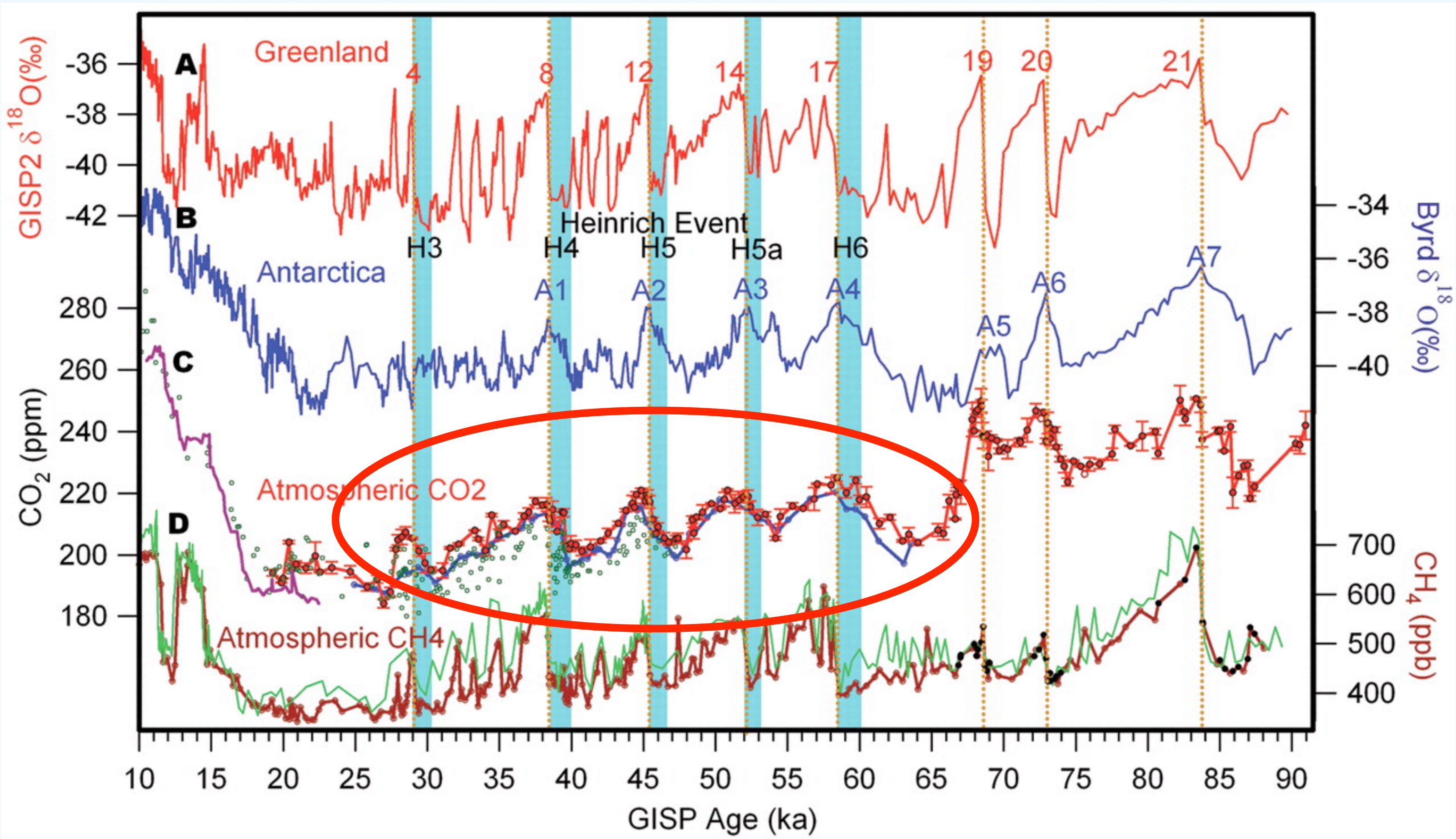
SUMMARY OF EVIDENCE:

Peak upwelling (opal flux) coincided with:

- warming in Antarctica,
- deglacial rise in CO_2
- deglacial drop in atm. $\Delta^{14}C$

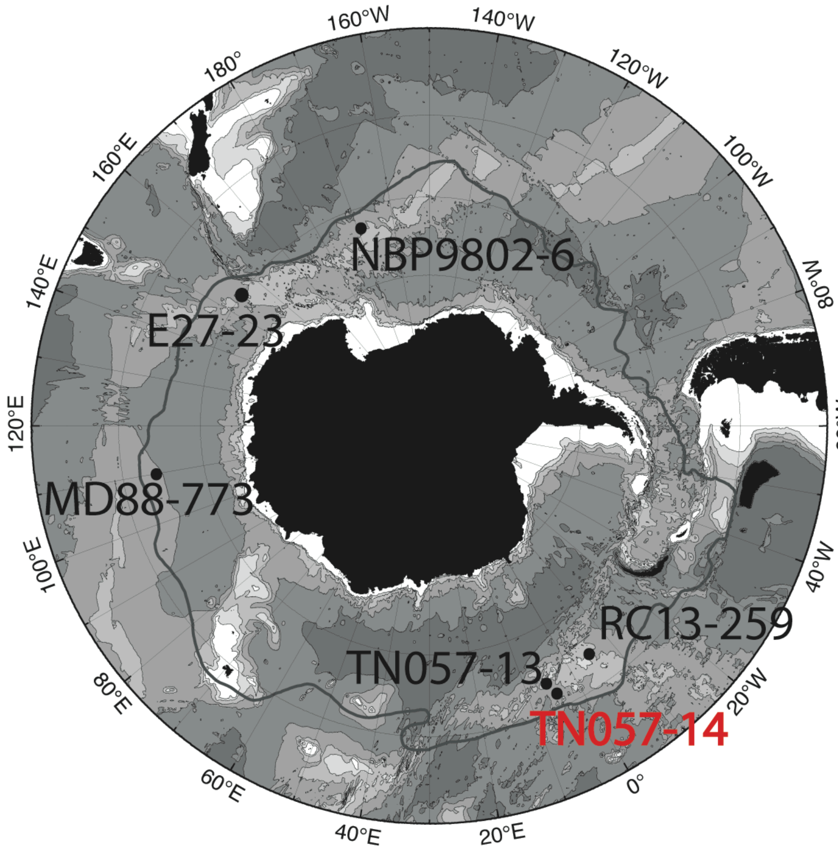
Including pause during ACR

Atm CO_2 increased during NH cold intervals surrounding <u>earlier</u> HEs



High resolution CO_2 record from Byrd ice core (red CO_2) extended through last glacial period (Ahn and Brook, 2008)

TN057-14: Opal flux upwelling proxy through last glacial period

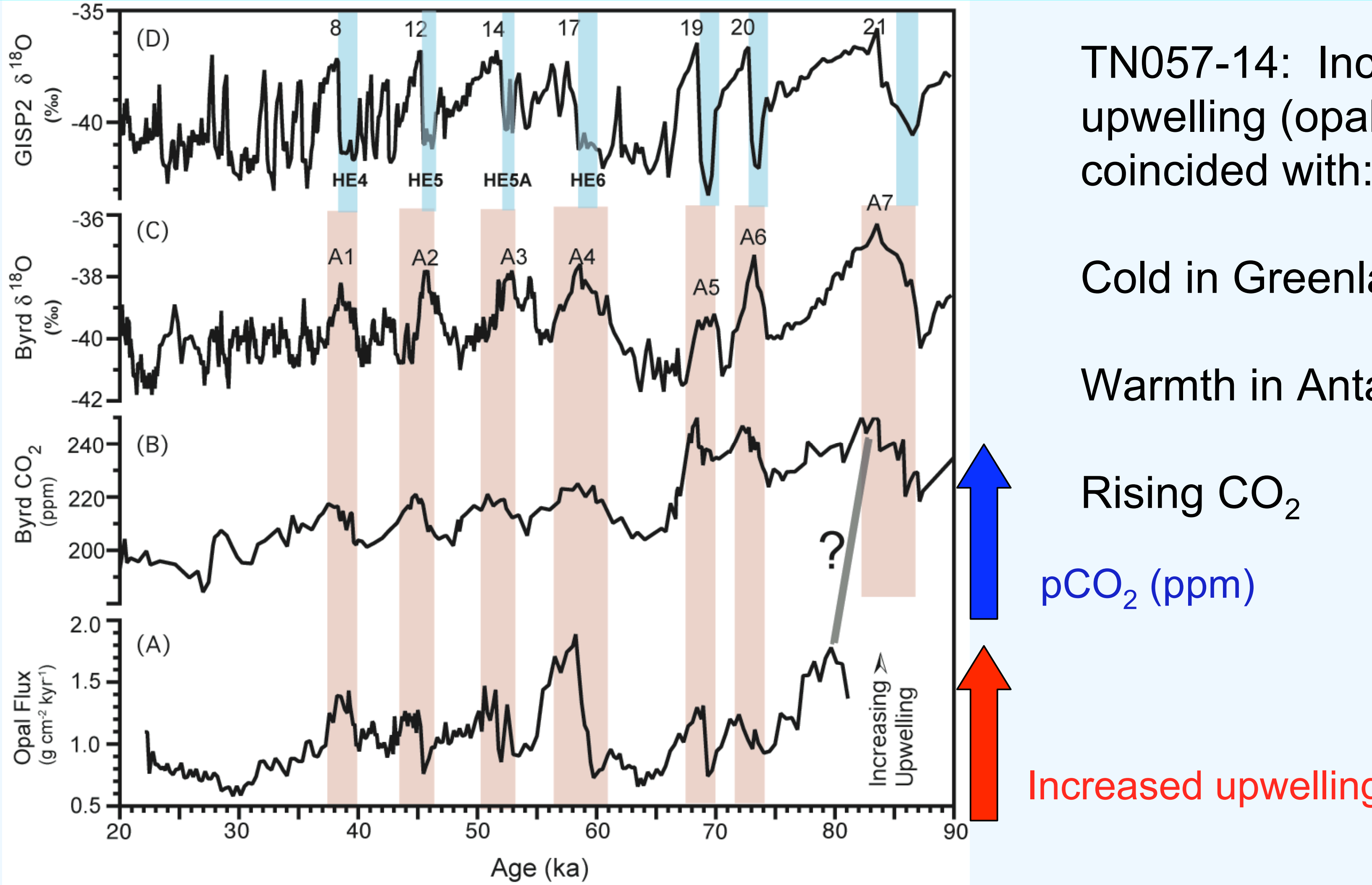


Sediment focusing changed with climate.

TN057-13 has an expanded deglacial section.

TN057-14 has an expanded section during the last glacial period.

Upwelling proxy correlates with pCO_2 throughout last glacial period



TN057-14: Increased upwelling (opal flux) coincided with:

Cold in Greenland

Warmth in Antarctica

Rising CO_2

Upwelling Summary

Deglacial Si supply to surface waters south of the APF exceeded supply before or after; increased upwelling is the only plausible cause.

Increased upwelling (opal burial) coincided with earlier periods of rising atmospheric CO_2.

Wind-driven upwelling in the Southern Ocean is a primary mechanism driving changes in atmospheric CO_2.

Proposed Trigger

Heinrich Events (and Younger Dryas)

- Extreme cold in N. Hemisphere
- N. Hemisphere iceberg discharge
- Increased sea ice covered N. Atlantic
- **Reorganization of wind systems**

Teleconnection via winds (global atmospheric circulation)

- **Change in N. Hemisphere Westerlies** during HE1 and YD recorded in Lake Lahontan level (Benson, 1995) and during YD recorded in German Lake sediments (Brauer et al., 2008)

- **Southward shift of ITCZ** and reorganization of monsoons during HEs (many references, land and ocean records)

- **Southward shift of S. Hemisphere westerlies**: SST records off S. Chile (Lamy et al., 2007) Coupled GCMs (Timmermann et al., 2007)

Wind stress at 60°S increases in response to waterhosing (~HEs)

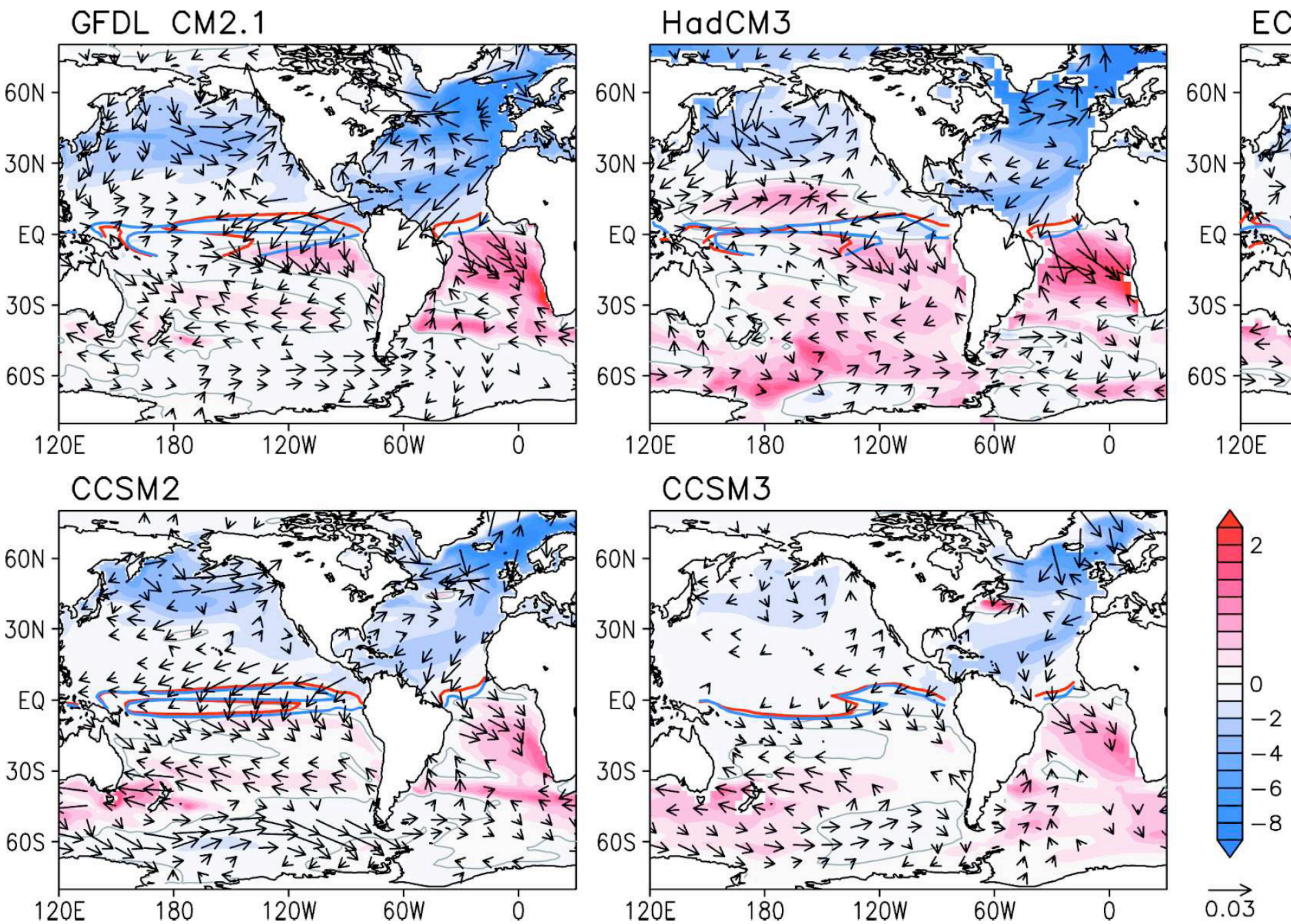
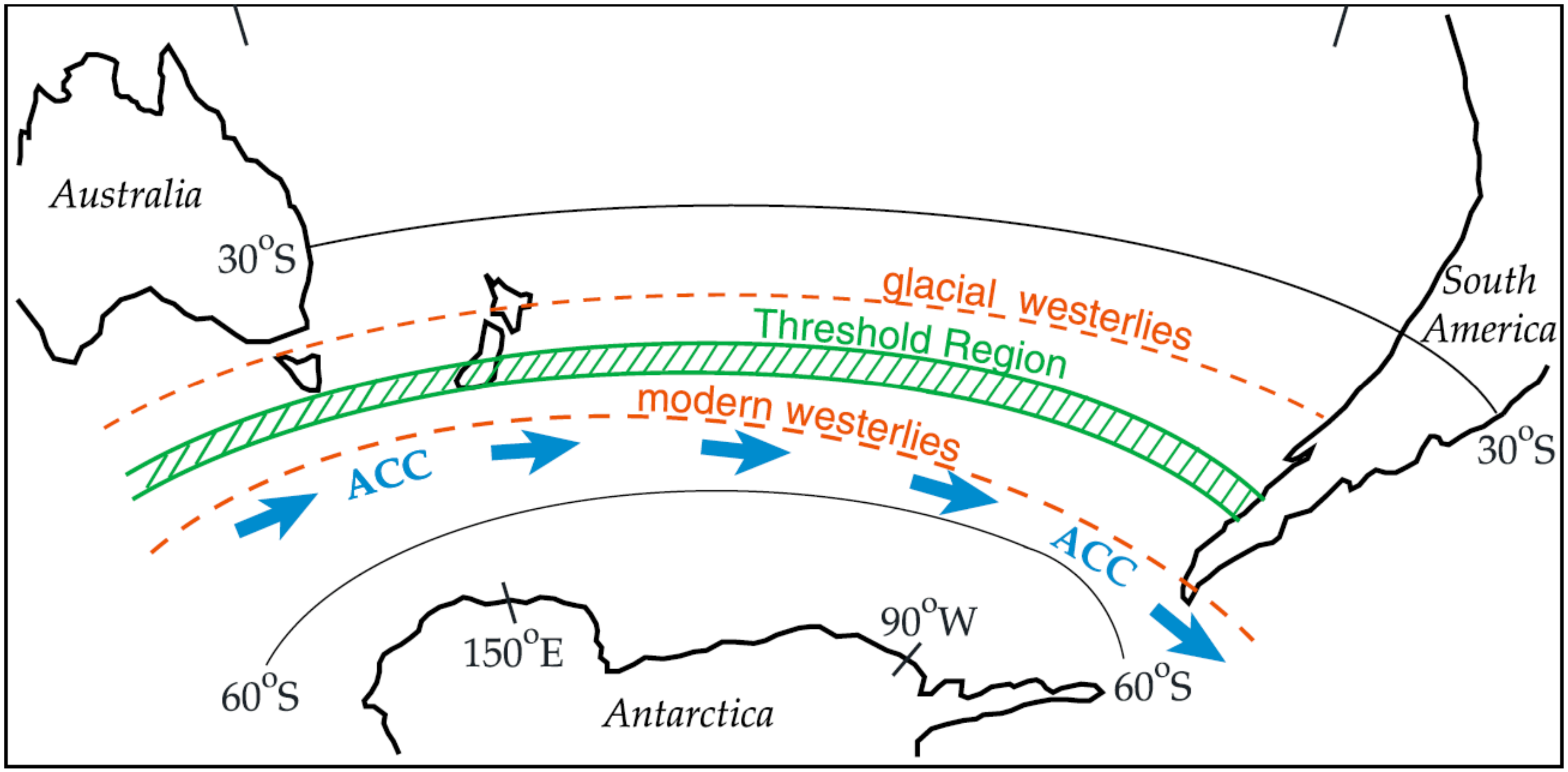


FIG. 4. SST anomaly (K) and wind stress anomaly ($N\,m^{-2}$) generated by the shutdown of the AMOC for the (top left) GFDL CM2.1, (top middle) HadCM3, (top right) MPIO-M1, (bottom left) CCSM2, and (bottom right) CCSM3. The red and blue lines represent the annual mean $\tau_y = 0$ lines in the control and waterhosing experiments, respectively. Note the asymmetric temperature scale.

Timmermann et al., 2007

Increased wind stress at 60°S drives upwelling in the So. Ocean



Maximum wind stress at the latitude of the Drake Passage favors upwelling of deep CO_2-rich water masses.

Toggweiler, 2006

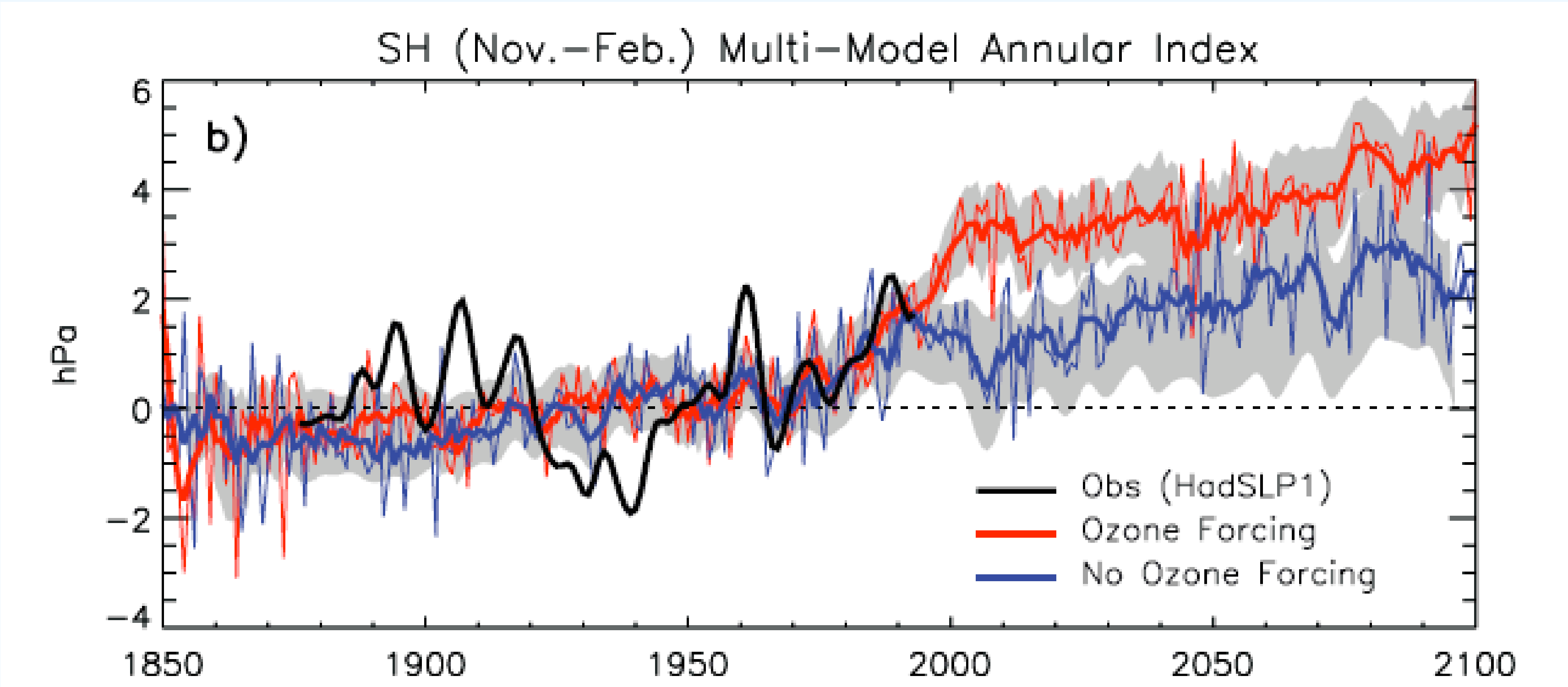
Summary of Winds and CO_2

Extreme N Hemisphere cold events (HEs) induced reorganization of global atmospheric circulation.

Southward shift of SH Westerlies during HEs forced increased upwelling in the Southern Ocean and release of CO_2 from deep waters.

Asymmetry of polar temperature changes caused the southward shift of SH Westerlies to be more extreme during HEs than during the Holocene or warm interstadials.

Implications and Challenges



Southern Annular Mode has intensified during the past half century and is projected to continue, creating upwelling-favorable conditions in the Southern Ocean.

IPCC AR4 Fig 10.17

Implications

Saturation of the Southern Ocean CO_2 Sink Due to Recent Climate Change

Corinne Le Quéré,[1,2,3]* Christian Rödenbeck,[1] Erik T. Buitenhuis,[1,2] Thomas J. Conway,[4] Ray Langenfelds,[5] Antony Gomez,[6] Casper Labuschagne,[7] Michel Ramonet,[8] Takakiyo Nakazawa,[9] Nicolas Metzl,[10] Nathan Gillett,[11] Martin Heimann[1]

Based on observed atmospheric carbon dioxide (CO_2) concentration and an inverse method, we estimate that the Southern Ocean sink of CO_2 has weakened between 1981 and 2004 by 0.08 petagrams of carbon per year per decade relative to the trend expected from the large increase in atmospheric CO_2. We attribute this weakening to the observed increase in Southern Ocean winds resulting from human activities, which is projected to continue in the future. Consequences include a reduction of the efficiency of the Southern Ocean sink of CO_2 in the short term (about 25 years) and possibly a higher level of stabilization of atmospheric CO_2 on a multicentury time scale.

Le Quéré et al., 2007

Implications

Lovenduski et al., 2008

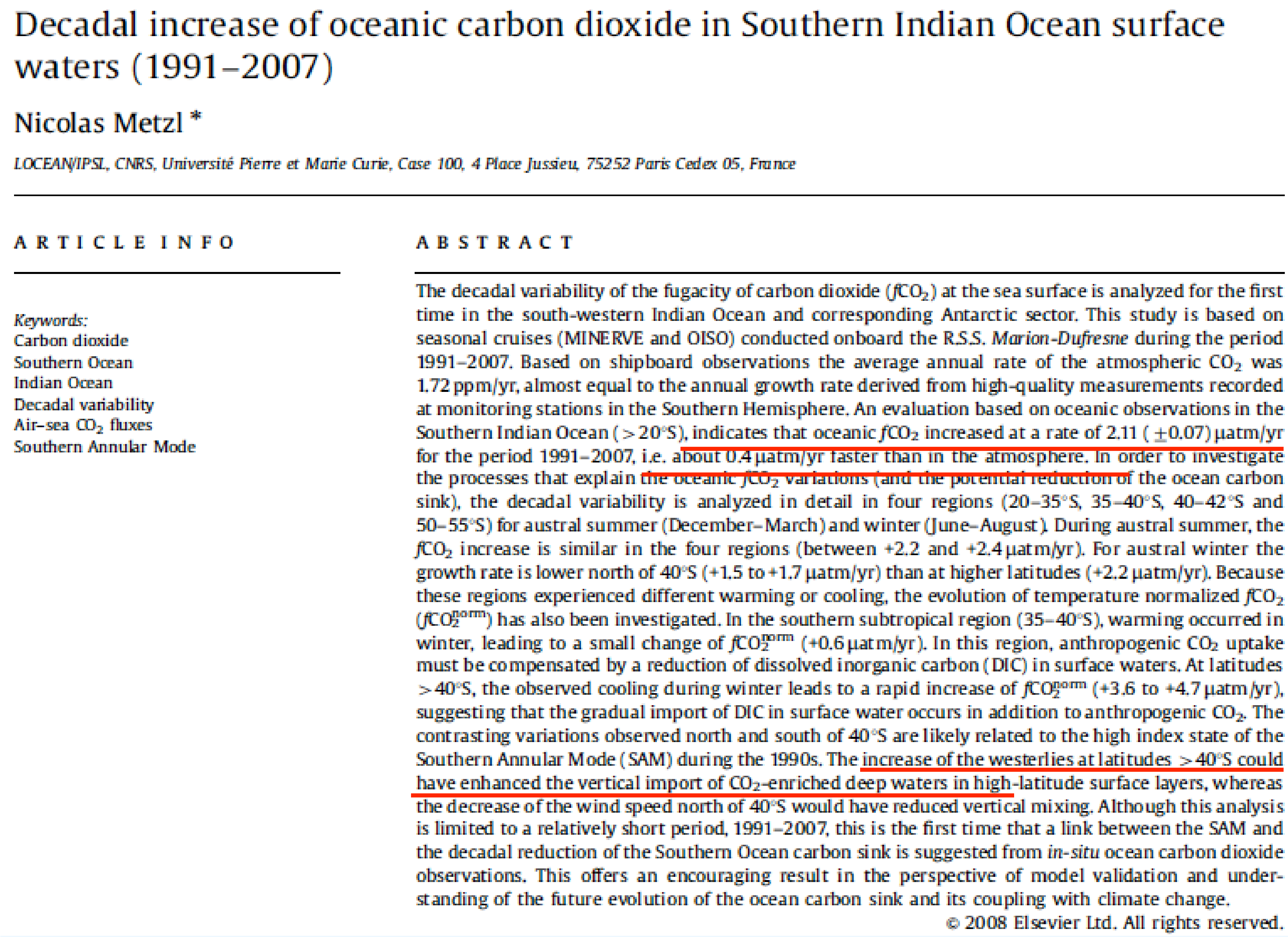
Toward a mechanistic understanding of the decadal trends in the Southern Ocean carbon sink

Nicole S. Lovenduski,[1] Nicolas Gruber,[2] and Scott C. Doney[3]

Received 8 November 2007; revised 4 May 2008; accepted 5 June 2008; published 16 August 2008.

[1] We investigate the multidecadal and decadal trends in the flux of CO_2 between the atmosphere and the Southern Ocean using output from hindcast simulations of an ocean circulation model with embedded biogeochemistry. The simulations are run with NCEP-1 forcing under both preindustrial and historical atmospheric CO_2 concentrations so that we can separately analyze trends in the natural and anthropogenic CO_2 fluxes. We find that the Southern Ocean (<35°S) CO_2 sink has weakened by 0.1 Pg C a^{-1} from 1979–2004, relative to the expected sink from rising atmospheric CO_2 and fixed physical climate. Although the magnitude of this trend is in agreement with prior studies (Le Quéré et al., 2007), its size may not be entirely robust because of uncertainties associated with the trend in the NCEP-1 atmospheric forcing. We attribute the weakening sink to an outgassing trend of natural CO_2, driven by enhanced upwelling and equatorward transport of carbon-rich water, which are caused by a trend toward stronger and southward shifted winds over the Southern Ocean (associated with the positive trend in the Southern Annular Mode (SAM)). In contrast,

Implications


Decadal increase of oceanic carbon dioxide in Southern Indian Ocean surface waters (1991–2007)

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ABSTRACT

The decadal variability of the fugacity of carbon dioxide (fCO_2) at the sea surface is analyzed for the first time in the south-western Indian Ocean and corresponding Antarctic sector. This study is based on seasonal cruises (MINERVE and OISO) conducted onboard the R.S.S. *Marion-Dufresne* during the period 1991–2007. Based on shipboard observations the average annual rate of the atmospheric CO_2 was 1.72 ppm/yr, almost equal to the annual growth rate derived from high-quality measurements recorded at monitoring stations in the Southern Hemisphere. An evaluation based on oceanic observations in the Southern Indian Ocean (>20°S), indicates that oceanic fCO_2 increased at a rate of 2.11 ($\pm$0.07) µatm/yr for the period 1991–2007, i.e. about 0.4 µatm/yr faster than in the atmosphere. In order to investigate the processes that explain the oceanic fCO_2 variations (and the potential reduction of the ocean carbon sink), the decadal variability is analyzed in detail in four regions (20–35°S, 35–40°S, 40–42°S and 50–55°S) for austral summer (December–March) and winter (June–August). During austral summer, the fCO_2 increase is similar in the four regions (between +2.2 and +2.4 µatm/yr). For austral winter the growth rate is lower north of 40°S (+1.5 to +1.7 µatm/yr) than at higher latitudes (+2.2 µatm/yr). Because these regions experienced different warming or cooling, the evolution of temperature normalized fCO_2 (fCO_2^{norm}) has also been investigated. In the southern subtropical region (35–40°S), warming occurred in winter, leading to a small change of fCO_2^{norm} (+0.6 µatm/yr). In this region, anthropogenic CO_2 uptake must be compensated by a reduction of dissolved inorganic carbon (DIC) in surface waters. At latitudes >40°S, the observed cooling during winter leads to a rapid increase of fCO_2^{norm} (+3.6 to +4.7 µatm/yr), suggesting that the gradual import of DIC in surface water occurs in addition to anthropogenic CO_2. The contrasting variations observed north and south of 40°S are likely related to the high index state of the Southern Annular Mode (SAM) during the 1990s. The increase of the westerlies at latitudes >40°S could have enhanced the vertical import of CO_2-enriched deep waters in high-latitude surface layers, whereas the decrease of the wind speed north of 40°S would have reduced vertical mixing. Although this analysis is limited to a relatively short period, 1991–2007, this is the first time that a link between the SAM and the decadal reduction of the Southern Ocean carbon sink is suggested from *in-situ* ocean carbon dioxide observations. This offers an encouraging result in the perspective of model validation and understanding of the future evolution of the ocean carbon sink and its coupling with climate change.

Metzl, DSR-II in press

Challenges

The response of the Antarctic Circumpolar Current to recent climate change

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Observations show a significant intensification of the Southern Hemisphere westerlies, the prevailing winds between the latitudes of 30° and 60° S, over the past decades. A continuation of this intensification trend is projected by climate scenarios for the twenty-first century. The response of the Antarctic Circumpolar Current and the carbon sink in the Southern Ocean to changes in wind stress and surface buoyancy fluxes is under debate. Here we analyse the Argo network of profiling floats and historical oceanographic data to detect coherent hemispheric-scale warming and freshening trends that extend to depths of more than 1,000 m. The warming and freshening is partly related to changes in the properties of the water masses that make up the Antarctic Circumpolar Current, which are consistent with the anthropogenic changes in heat and freshwater fluxes suggested by climate models. However, we detect no increase in the tilt of the surfaces of equal density across the Antarctic Circumpolar Current, in contrast to coarse-resolution model studies. Our results imply that the transport in the Antarctic Circumpolar Current and meridional overturning in the Southern Ocean are insensitive to decadal changes in wind stress.

Do eddies offset Ekman transport?

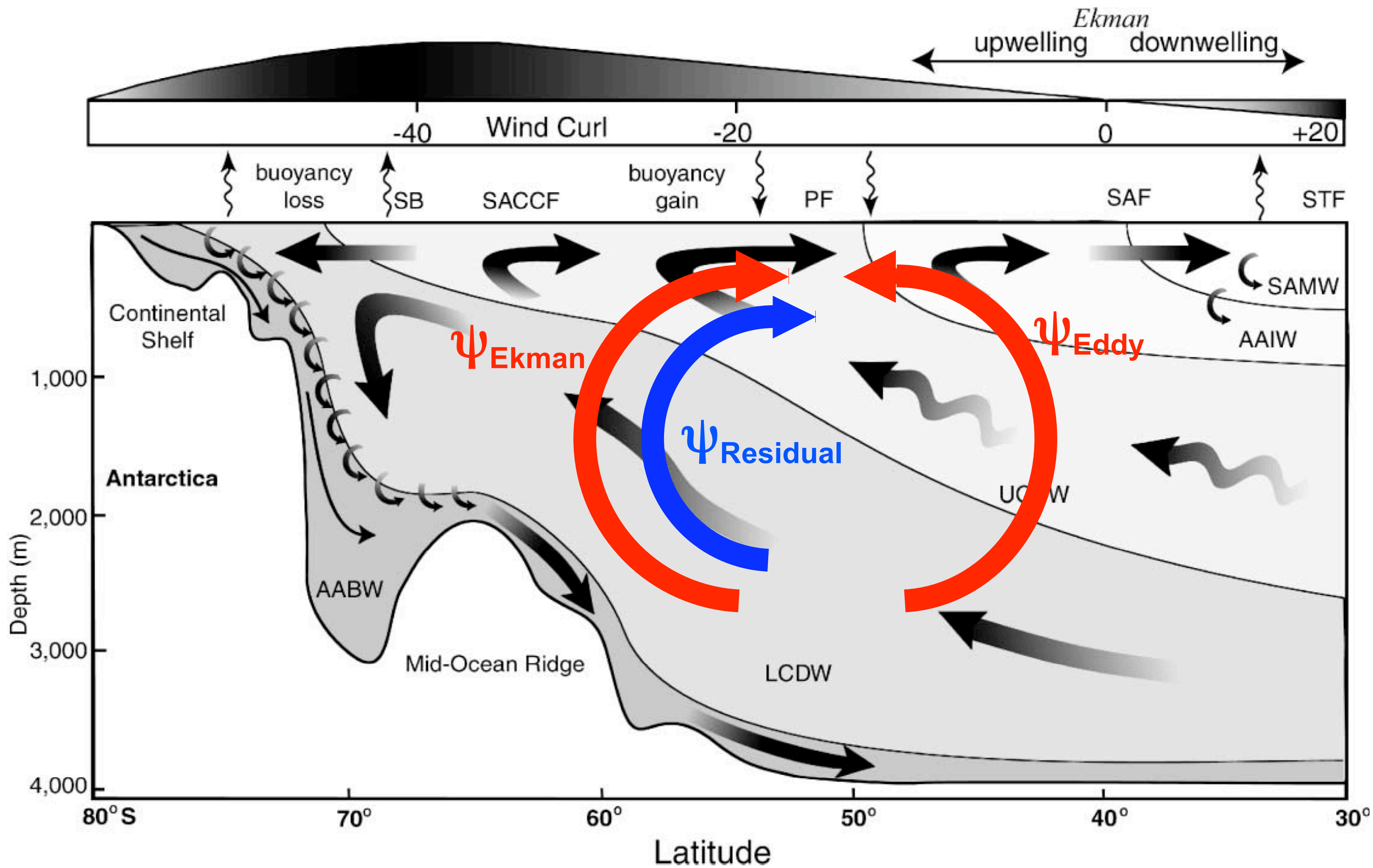

Illustration based on figure in Thompson (2008) modified by Khatiwala

Summary and Recommendations

Paleo data suggest intensification of SH winds induced increased ventilation of deep ocean waters and rising atmospheric CO_2.

Historical data and models suggest So. Ocean CO_2 sink is weakening due to intensifying SAM.

But: Theoretical arguments suggest wind forcing is ineffective in inducing So Ocean overturning.

Unanswered Questions

1) How does upwelling in the Southern Ocean respond to historical changes in the intensity and mean position of wind stress?

2) How does biological utilization of nutrients respond to changes in the physical environment associated with changes in the winds?

Strategy to Address Questions

1) **Observing system**(s) to monitor changes in:
   a) Physical parameters such as **upwelling**, mixed layer depth, etc. (ARGO?)
   b) Biogeochemical parameters related to **nutrient utilization**.

2) **Models** that:
   a) Resolve eddies and accurately simulate their impact on ACC transport.
   b) Accurately represent species composition and the sensitivity of nutrient utilization to changing physical and chemical environment.

3) **Experimental studies** to constrain (2a&b).