

## **Investigating the Southern Ocean's role in the uptake of atmospheric CO<sub>2</sub> along glacial-interglacial timescales**

### **Abstract**

The Southern Ocean has been implicated as a major role-player in the modulation of global atmospheric circulation along glacial-interglacial timescales. Climate dynamics and ocean circulation poleward of 40° S set the stage for the Southern Ocean to be a site sensitive to C uptake. A number of models have been used to explain the 80-100 ppmv change in atmospheric CO<sub>2</sub> that have occurred between glacial and interglacial times during the last 420,000 years. These models or mechanisms invoke changes in CO<sub>2</sub> solubility, biological mechanisms, or physical oceanic conditions. With the exception of physical oceanographic models, invoking solubility or biological mechanisms alone cannot account for the magnitude of change observed in ice cores or fail to agree with geologic data. More successful models, such as the stratification hypothesis, tend to incorporate a synthesis of mechanisms, which produce results consistent with reconstructed values of atmospheric CO<sub>2</sub> and oceanographic data.

### *Introduction*

Gasses trapped in air bubbles found in continuous ice cores that span long intervals of geologic time have provided a wealth of information on the fluctuations in atmospheric CO<sub>2</sub> over glacial-interglacial timescales (Petit et al., 1999). These records reveal that CO<sub>2</sub> and temperature changes covary and appear to be modulated by changes in Earth's orbital geometry. Furthermore, the CO<sub>2</sub> changes in the Vostok ice core record show that these fluctuations are similar in structure and varied by consistent amplitudes of 80-100 ppmv during the last 420,000 years, leading investigators to hypothesize that there must be a single mechanism or an ordered set of mechanisms controlling the concentration of CO<sub>2</sub> in the atmosphere (Figure 1). Using the modern C cycle as starting point, scientists realized the importance of the deep ocean as a C reservoir and began to look for mechanisms to sequester and release significant amounts of C that could explain the observations in the ice core data (Broecker, 1982).

The Southern Ocean has been implicated as a major role-player in the modulation of atmospheric CO<sub>2</sub> over glacial-interglacial timescales due to two important modern observations: 1) surface nutrients are high indicating an incomplete utilization by biologic components (Sigman and Boyle, 2000) and 2) deep water with long residence times outcrop in the Southern Ocean due to global thermohaline circulation patterns (Figure 3 and 4). These two observations formed an important basis for mechanisms invoking changes in physical and chemical oceanographic processes and biologic production to explain

global CO<sub>2</sub> variations. However, a majority of the models that utilize these processes (biology, ocean chemistry, or ocean physics) either fail to produce the magnitude of the atmospheric CO<sub>2</sub> variations or do not agree with geologic data. Here I will review a number of mechanisms or models that utilize the Southern Ocean's unique oceanographic and biologic conditions and have been used to account for the glacial-interglacial changes in CO<sub>2</sub> and demonstrate that models that incorporate ocean physics tend to be most successful in terms of agreeing with geologic data and producing the necessary magnitude of change.

### *Southern Ocean Climatology and Physical Oceanography*

The unique climatology and physical oceanography of the Southern Ocean sets the stage for its role in C uptake over glacial-interglacial timescales. One of the most important climatic features of the Antarctic is the Southern Hemisphere westerly wind field (Figure 5). The westerlies have a large impact on Southern Ocean hydrography, as well as exert a great influence on sea ice distribution and biologic productivity, which in turn will play a role in modulating atmospheric CO<sub>2</sub> concentrations (Sigman and Boyle, 2000). The westerlies, which are largely constrained between ~40° and ~65° S, drive surface currents eastward and initiate a northward Ekman drift component that is critical to the formation of Antarctic intermediate water (AAIW). The strength and the latitudinal positions of the westerlies are largely controlled by the pressure gradient between Antarctic low pressure systems and subtropical high pressure cells centered in the Atlantic and Pacific Oceans (Kreutz et al., 1997; Pendall et al., 2001). An important low pressure cell in the Southern Ocean is the Amundsen Sea Low (ASL), which is a deep low pressure cell that is sensitive to atmospheric-ocean interactions in the tropics (Cullather et al., 1996). During a strong El Niño year the ASL experiences positive pressure anomalies, which in turn modulate the strength and latitudinal position of the westerlies (Figure 6). The fact that the ASL can be influenced by atmospheric dynamics in the tropics, such as the El Niño-Southern oscillation, argues that perhaps the westerlies can be a mechanism upon which to transport tropical climate changes to high southern latitudes.

The Southern Ocean is *the* major hub of global thermohaline circulation (Figure 3). North Atlantic deep water (NADW) flows southward toward the Antarctic continental margin and mixes to become Antarctic circumpolar water (ACW), which upwells at the location of Antarctic divergence centered at  $\sim 60^\circ$  S (Figure 4). The outcropping of deep waters is a major way that deep waters with significant  $\text{CO}_2$  concentrations can ventilate into the atmosphere. Part of this upwelled water is advected southward where it becomes dense and sinks as Antarctic bottom water (AABW) and flows equatorward, while a larger portion of the water is influenced by Ekman flow initiated by the westerlies and is carried northward. The northward flowing waters sink to intermediate depths at the Antarctic polar front zone and become Antarctic intermediate water (AAIW), which re-enters the global thermohaline circuit (Figure 4). By these physical oceanographic processes, it can be seen that waters can both be ventilated and thereby potentially increasing the flux of  $\text{CO}_2$  into the atmosphere, or by sequestering  $\text{CO}_2$  through the production of AABW or AAIW. These general observations are supported by observations and model results which show that although not much anthropogenic  $\text{CO}_2$  is stored in the Southern Ocean, it is one of the few areas on the earth where there is a net  $\text{CO}_2$  flux into the ocean (Caldiera and Duffy, 2000).

#### *Modulation of atmospheric $\text{CO}_2$ concentrations on glacial-interglacial timescales*

There are three important models or mechanisms used to account for the 80-100 ppmv variations seen between glacial-interglacial timescales during the Quaternary: solubility of  $\text{CO}_2$ , biologic pump, and physical models. The solubility of  $\text{CO}_2$  is an earlier and relatively simple model to explain the reduction of  $\text{CO}_2$  in the atmosphere during glacial periods. Because  $\text{CO}_2$  is more soluble in cold water, reducing surface temperatures (due to changes in the distribution and seasonality of insolation caused by changes in Earth's orbital geometry) will result in a decrease in atmospheric  $\text{CO}_2$  and initiate a positive feedback (i.e. colder temperatures). Models that have invoked only this mechanism have achieved reductions in atmospheric  $\text{CO}_2$  of  $\sim 30$  ppmv (Keir, 1988). However, there are other oceanic and terrestrial processes that will contribute to increasing  $\text{CO}_2$  levels. One of these is the fact that many areas of the earth were covered by ice and thus rather being a sink of  $\text{CO}_2$  they became a source of  $\text{CO}_2$  to the oceans (Sigman and Boyle, 2000). Furthermore, because sea level was lowered by  $\sim 100$  meters, salinity in the oceans

decreased in the ocean by 3%. The increase in salinity reduces the solubility of  $\text{CO}_2$  in the oceans, which in turn increases the amount of  $\text{CO}_2$  in the atmosphere. Combining the terrestrial source of C, the sequestering of C due to changes in temperature, and the release of C from the Oceans due to an increase in salinity, causes a net reduction of  $\sim 8.5$  ppmv. As can be seen, the small reduction in  $\text{CO}_2$  invoking solubility and a terrestrial source of C is not close to the 80-100 ppmv decrease in  $\text{CO}_2$  seen in the ice core record (Sigman and Boyle, 2000).

Global cycling of alkalinity and changes in the dissolved inorganic carbon (DIC) content of the oceans along glacial-interglacial timescales play a role in modulating atmospheric  $\text{CO}_2$  concentrations. Alkalinity, the acid-titrating capacity of sea water, is the total equivalence of ions that must be protonated in order to lower the pH of sea water to the  $\text{pK}_a$  of carbonic acid (Sigman and Boyle, 2000). Alkalinity is added to the oceans by carbonate weathering on land and removed through biogenic precipitation and burial in coral reefs and deep sea sediments (Millman, 1974). The depth of the lysocline in the oceans controls how much carbonate is buried or dissolved in the deep oceans, and provides a good measure of past changes in ocean alkalinity. Figure 8 illustrates the relationship between DIC, alkalinity, and  $\text{pCO}_2$  of the surface ocean. Increasing carbonate weathering on land and reducing the amount of carbonate that is buried in coral reefs due to a drop in sea level (a scenario reflecting glacial conditions) results in a decrease in atmospheric  $\text{pCO}_2$ . This process will also increase the carbonate ion concentration in the deep ocean and thereby lower the depth of the lysocline. To explain the 80-100 ppmv decrease in the atmosphere, the lysocline would have to deepen by over 2 km, which has not been seen in the geologic record (Catubig, 1998).

The biologic pump is another means by which atmospheric  $\text{CO}_2$  concentrations can be lowered through increased biologic production. Researchers have observed the high concentration of under-utilized nutrients in the Southern Ocean (Figure 2) and have hypothesized that these nutrients were utilized due to the increased flux of Fe (an essential but limiting nutrient) derived from dust (Kumar et al., 1995). Numerous productivity reconstructions have been performed in the Southern Ocean, but researchers have yet to reach a consensus on how productivity varies on glacial-interglacial timescales,

nor have they found a paleoproductivity proxy that can be applied to all areas of the Southern Ocean. Authors have argued for increases (Kumar et al., 1995), decreases (Charles et al., 1991), or changes depending on the location of the core site relative to the Antarctic polar front (Mortlock et al., 1991) in productivity during the LGM. During the Holocene, a high resolution sediment record from the Palmer Deep provides evidence for significant changes in productivity during the late Holocene, which the authors suggest is due to changes in atmospheric variability in the Southern Ocean (Shevenell and Kennett, 2002). Proxies that have been used to reconstruct productivity during the LGM include organic carbon, biogenic silica,  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  utilization, Cd/Ca, Pa/Th, Be/Th, biogenic Ba, and authigenic U. Organic C is subject to remineralization in the water column and is thought to be a better proxy for preservation efficiency rather than export production (Hartnett et al., 1998). Biogenic silica, although replete in the Southern Ocean, is subject to variable dissolution and is only an indicator of diatom productivity (Mortlock et al., 1991). Studies utilizing  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  utilization, Cd/Ca as tracers for nutrient concentrations have yielded inconsistent results with regard to productivity during the LGM (Chase et al., 2001). It has also been found that  $^{231}\text{Pa}/^{230}\text{Th}$  ratios are ineffective south of the polar front due to the fact that higher concentrations of opal cause an increase in the relative scavenging efficiency of  $^{231}\text{Pa}$  relative to  $^{230}\text{Th}$  (Walter et al., 1997).

Sigman and Boyle (2000) combine physical oceanographic processes, as well as the biologic pump, to explain the atmospheric  $\text{CO}_2$  variations in the ice core record. Figure 9 displays a schematic of their hypothesis for the structure of the Southern Ocean during present and glacial conditions. The modern regime is similar to what is displayed in Figure 4. During glacial periods, important changes in the physical oceanography of the Southern Ocean occur. The most important change is a hypothesized northward displacement of the westerly wind field that cause a reduction in upwelling of ACW (Sigman and Boyle, 2000). The northward displacement of the westerlies is reconstructed from lacustrine palynologic records along the western Andean front in Chile (McCulloch et al., 2000). Because upwelling of sequestered  $\text{CO}_2$  is still occurring the model, the authors cite increased biologic productivity in areas north of the present day polar front zone (Sigman and Boyle, 2000). In their model, the authors

also cite increases in sea ice extent, which cause increased stratification in Antarctic surface waters. The increased stratification also contributes to the reduction in upwelling in areas south of the polar front zone. Sigman and Boyle (2000) are able to arrive at reduction of atmospheric CO<sub>2</sub> concentrations that are on the same order of magnitude as those observed in the ice core records, and they are also able to reconcile nutrient utilization data that imply increased production in the Southern Ocean north of the polar front zone during the LGM (Francois et al., 1997; Sigman et al., 1999).

The Sigman and Boyle (2000) hypothesis is relatively controversial. Some potential problems in their study is the role of the westerlies—whether they are driven by local or more regional temperature gradients—and the role of stratification on upwelling—some argue that a stratified glacial ocean implies weakened eddy transport and therefore increased upwelling (Stephens and Keeling, 2000). Stephens and Keeling (2000) put forth an additional stratification hypothesis, one that only involves stratification (only ocean physics) due to increased sea ice extent. The authors argue that perennial sea ice cover around the southern ocean inhibited sea-air gas exchange that reduced the flux of sequestered CO<sub>2</sub> into the atmosphere (Stephens and Keeling, 2000). Furthermore, even if sea ice was not persistent during the entire year, stratification still existed because of a meltwater layer at the surface of the ocean. Using their model, Stephens and Keeling (2000) demonstrate the effect of sea ice cover on global atmospheric CO<sub>2</sub> concentrations (Figure 10) and arrive at a reduction of ~65 ppmv using only ocean physics, which is roughly on par for variations seen in the Vostok record.

### *Conclusions*

The Southern Ocean's climatology and physical oceanographic setting is a unique oceanic environment that has great potential to modulate global CO<sub>2</sub> concentrations on glacial-interglacial timescales. Although a number of mechanisms have been proposed to explain the large changes in CO<sub>2</sub> during the Quaternary, the models that seem to work best (by achieving the same magnitude of change as seen in the ice record and corroborate other oceanographic data) incorporate both biology and physics. These studies are important both for understanding how the earth's climate system has varied in the past as well as helping provide a better understanding of the Southern Ocean's role in future climate change.

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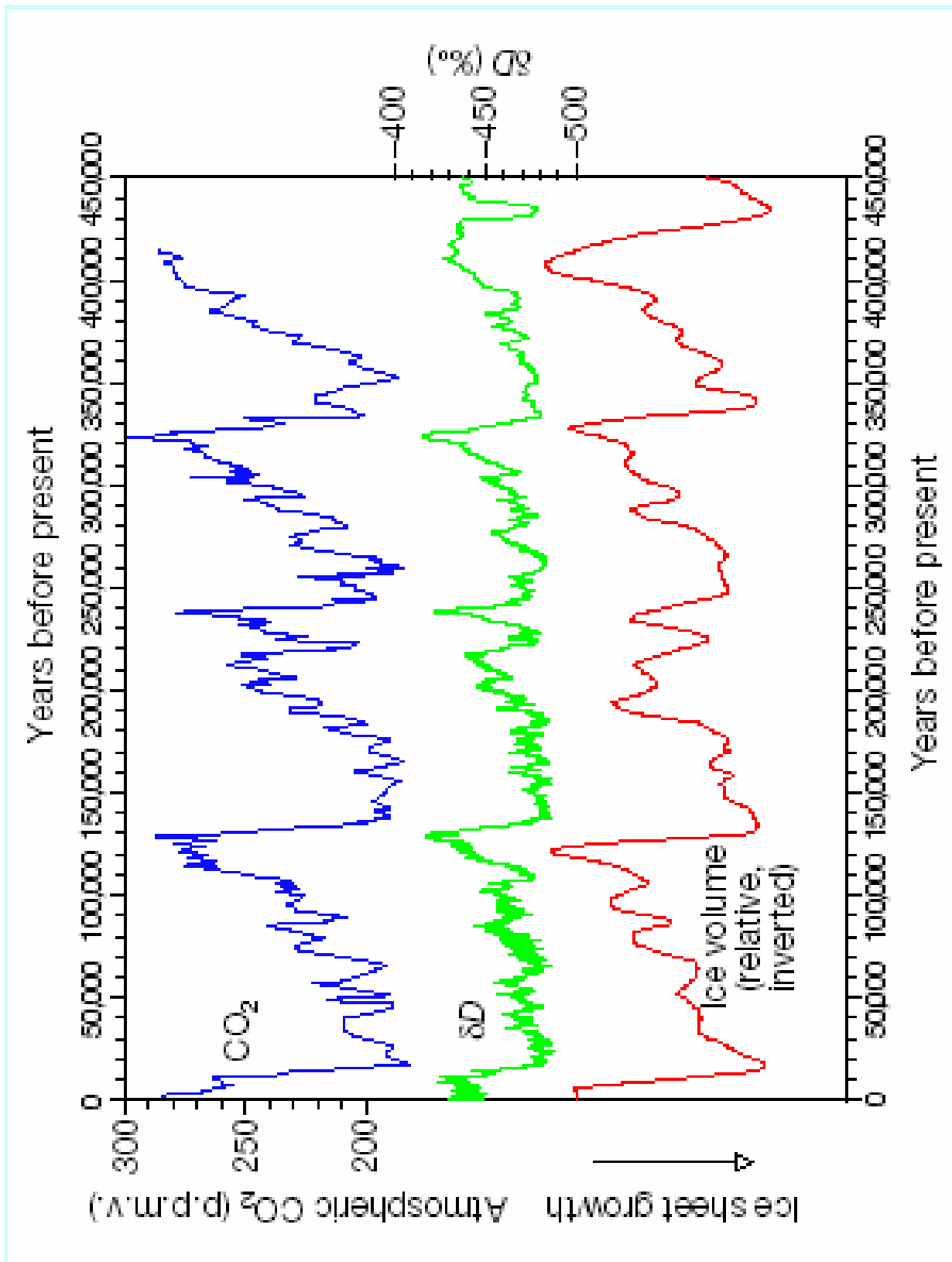


Figure 1. Variations in atmospheric CO<sub>2</sub>, δD, and reconstructed ice volume from Antarctic ice cores during the last 450,000 years. The relatively constant amplitude fluctuations in CO<sub>2</sub> (80-100 ppmv) over the length of the time series has led researchers to search for an “ordered” set of mechanisms that can explain the variability.

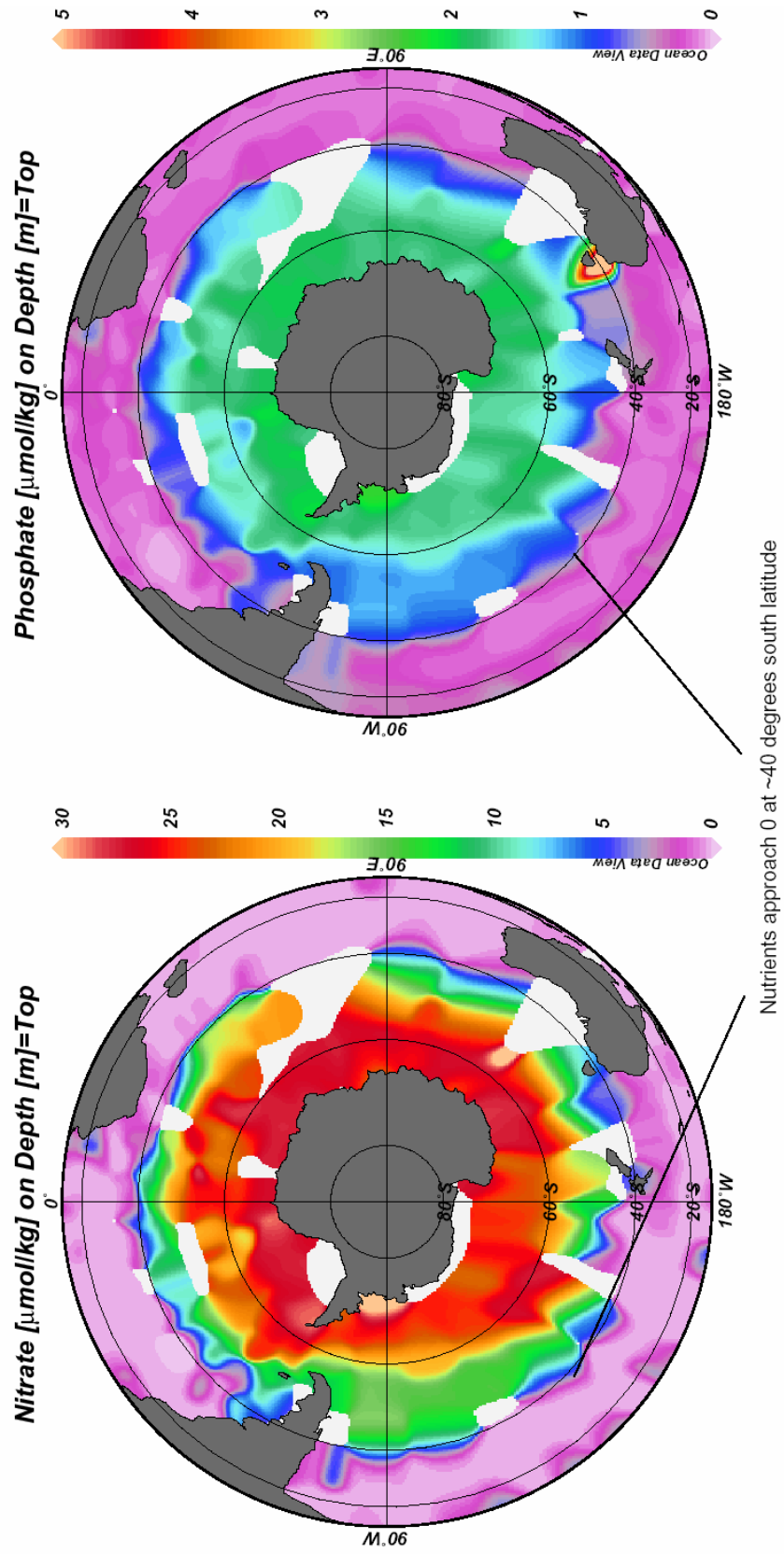


Figure 2. Sea surface concentrations in Nitrate and Phosphate. Note how values approach 0 towards the Sub-Antarctic front.

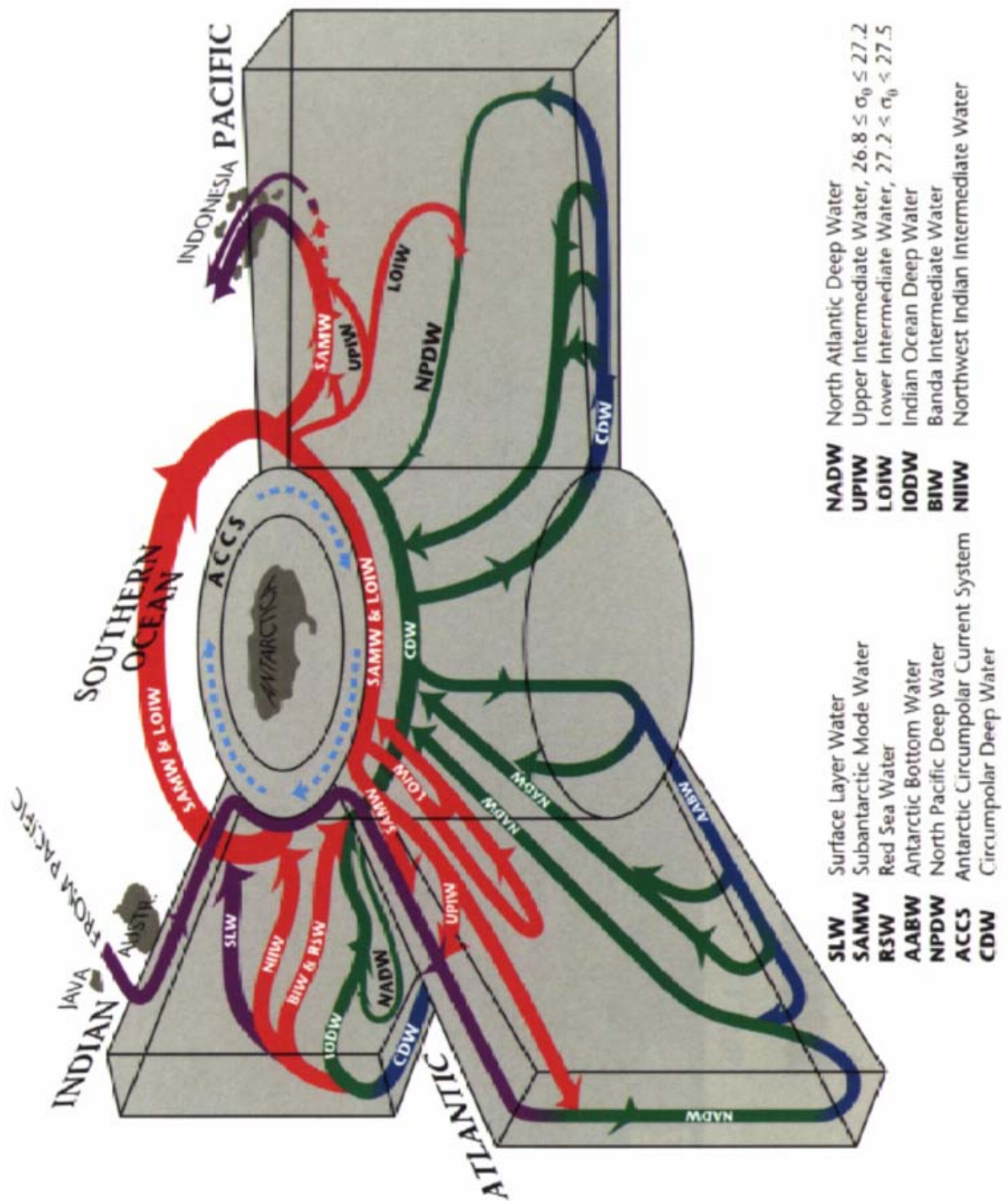


Figure 3. Schematic of global ocean circulation. The Southern Ocean plays a key role in the mixing of waters from different high-latitude and tropical locations.

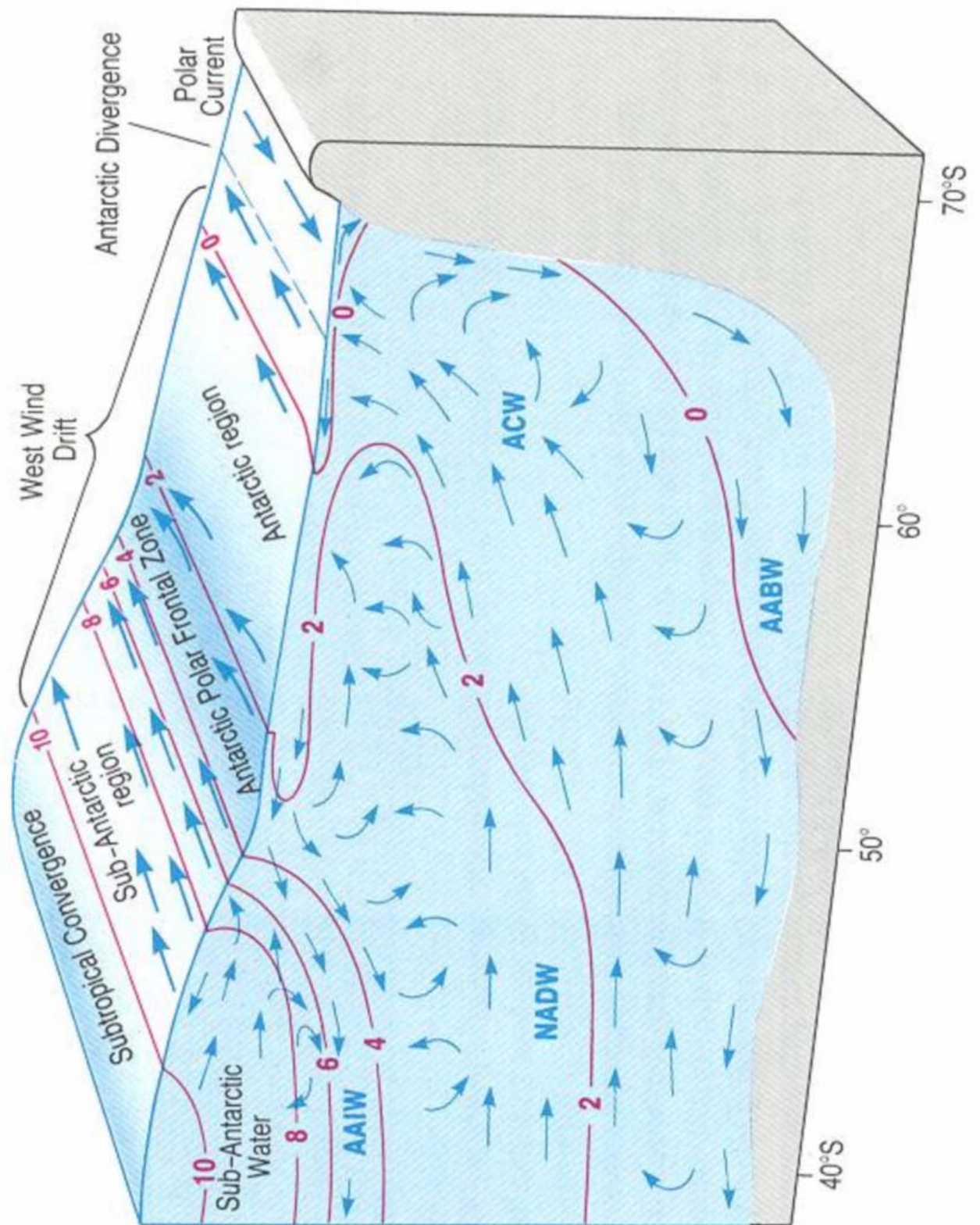


Figure 4. Schematic of circulation patterns and water masses surrounding the Antarctic margin poleward of ~40°S. One of the most prominent features is the transition of NADW into ACW and upwelling at the site of Antarctic divergence, followed by northward Ekman transport and subduction as AAIW.

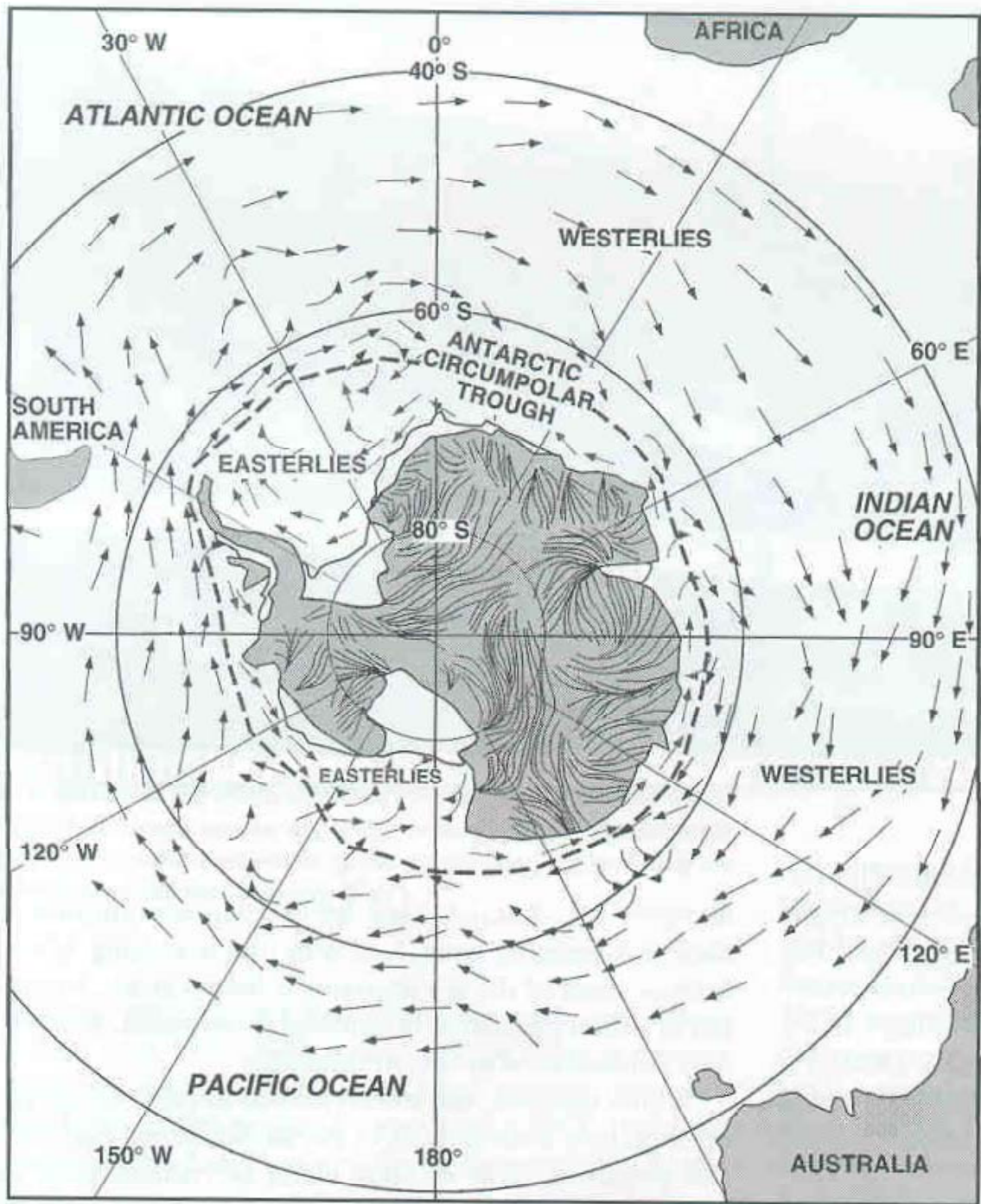


Figure 5. Overview of atmospheric circulation patterns in the Antarctic. One of the most prominent features is the Southern Hemisphere westerly winds, which play a large role in Southern Ocean hydrography and has been implicated as a major role-player in modulating glacial-interglacial changes in CO<sub>2</sub>.

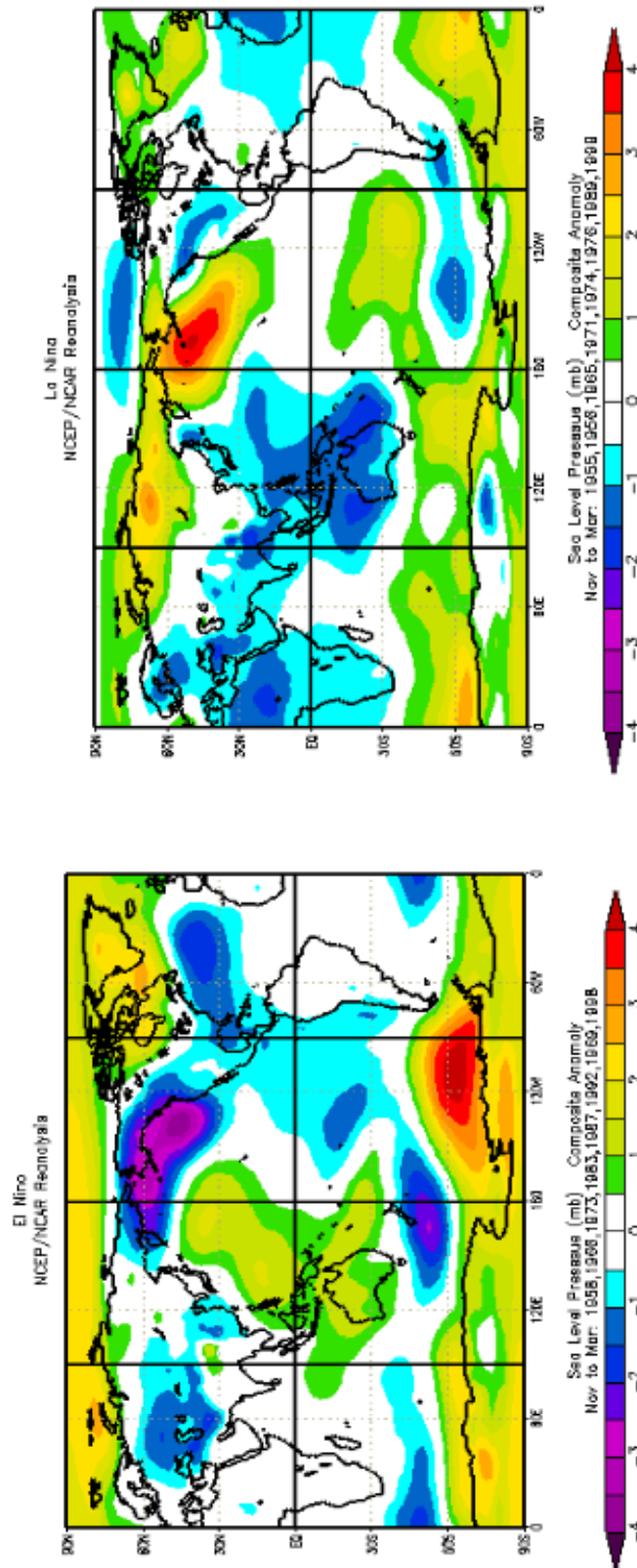


Figure 6. Sea level pressure anomalies in the Southern Ocean associated with the El Niño-Southern Oscillation (ENSO). The large anomalies in the Amundsen Sea region are quite responsive to changes in ENSO.

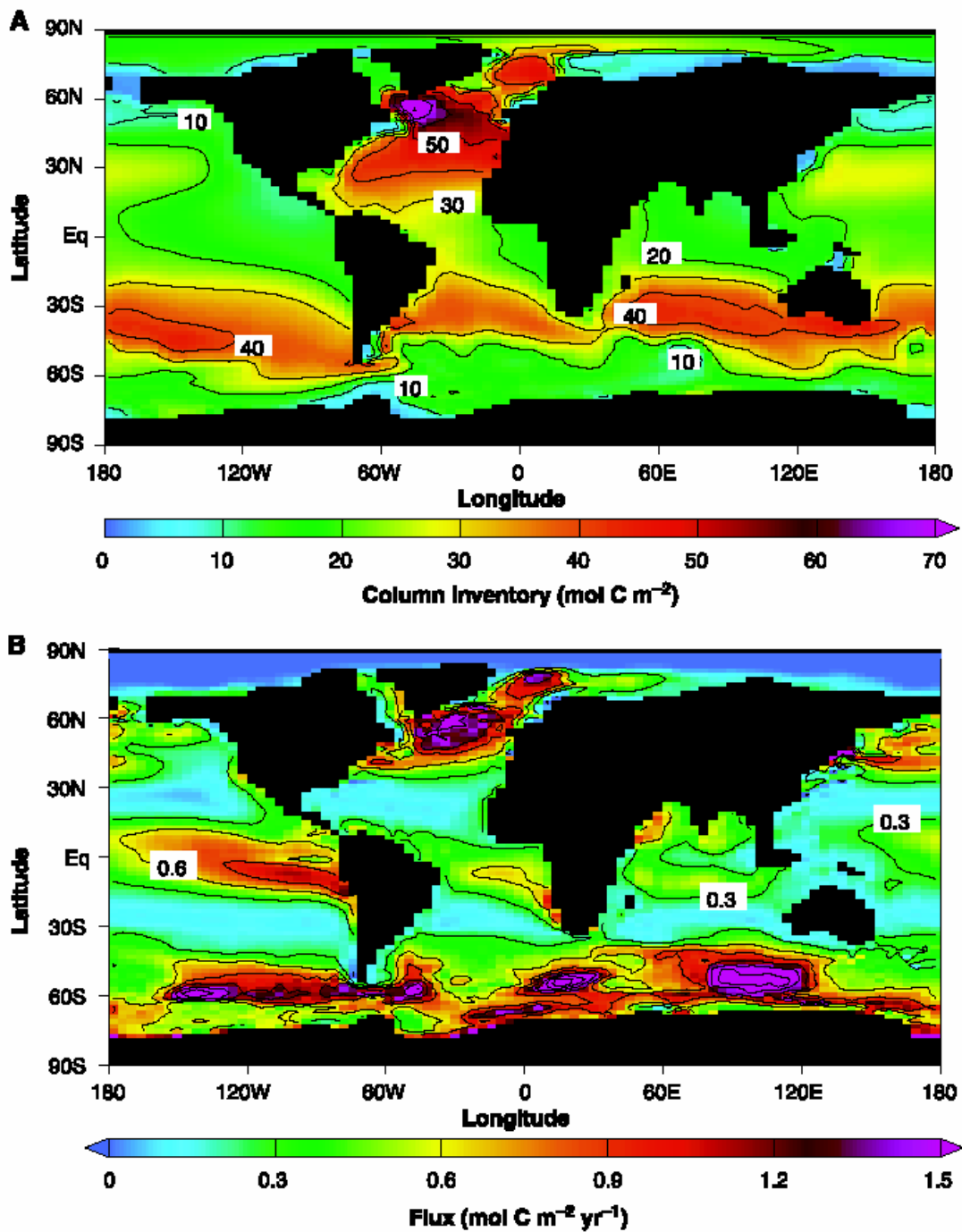


Figure 7. Concentration (panel A) and flux of anthropogenic  $\text{CO}_2$  into the global oceans. Through physical processes alone, the Caldera and Duffy (2000) model is able to show the high flux of  $\text{CO}_2$  into the Southern Ocean. Most of the  $\text{CO}_2$ , however, is stored at lower latitudes.

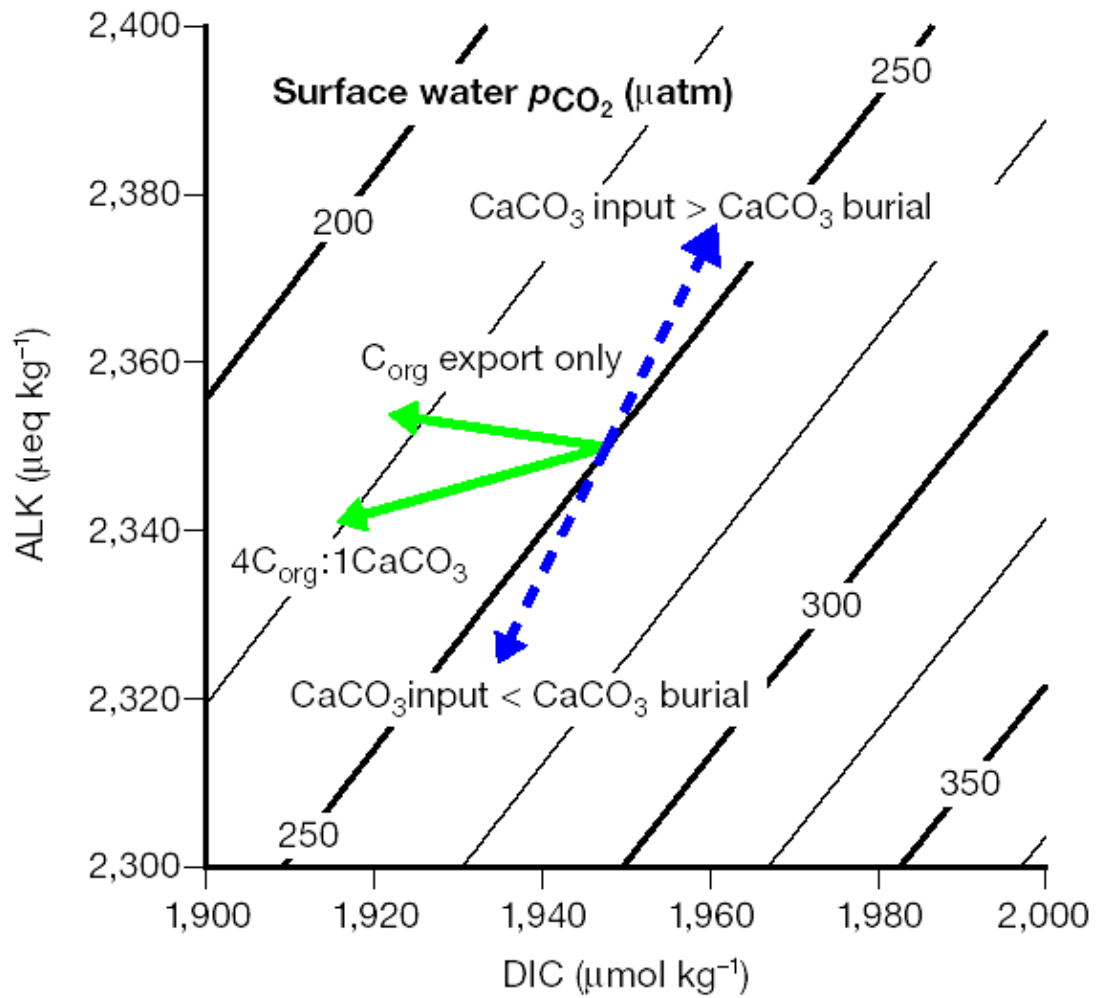


Figure 8. Relationship between DIC, alkalinity and surface water  $p\text{CO}_2$  in the global ocean. During the LGM,  $\text{CaCO}_3$  input is hypothesized to have been larger than removal from carbonate reef building or burial of carbonate sediments. This relationship would drive surface  $p\text{CO}_2$  to lower values.

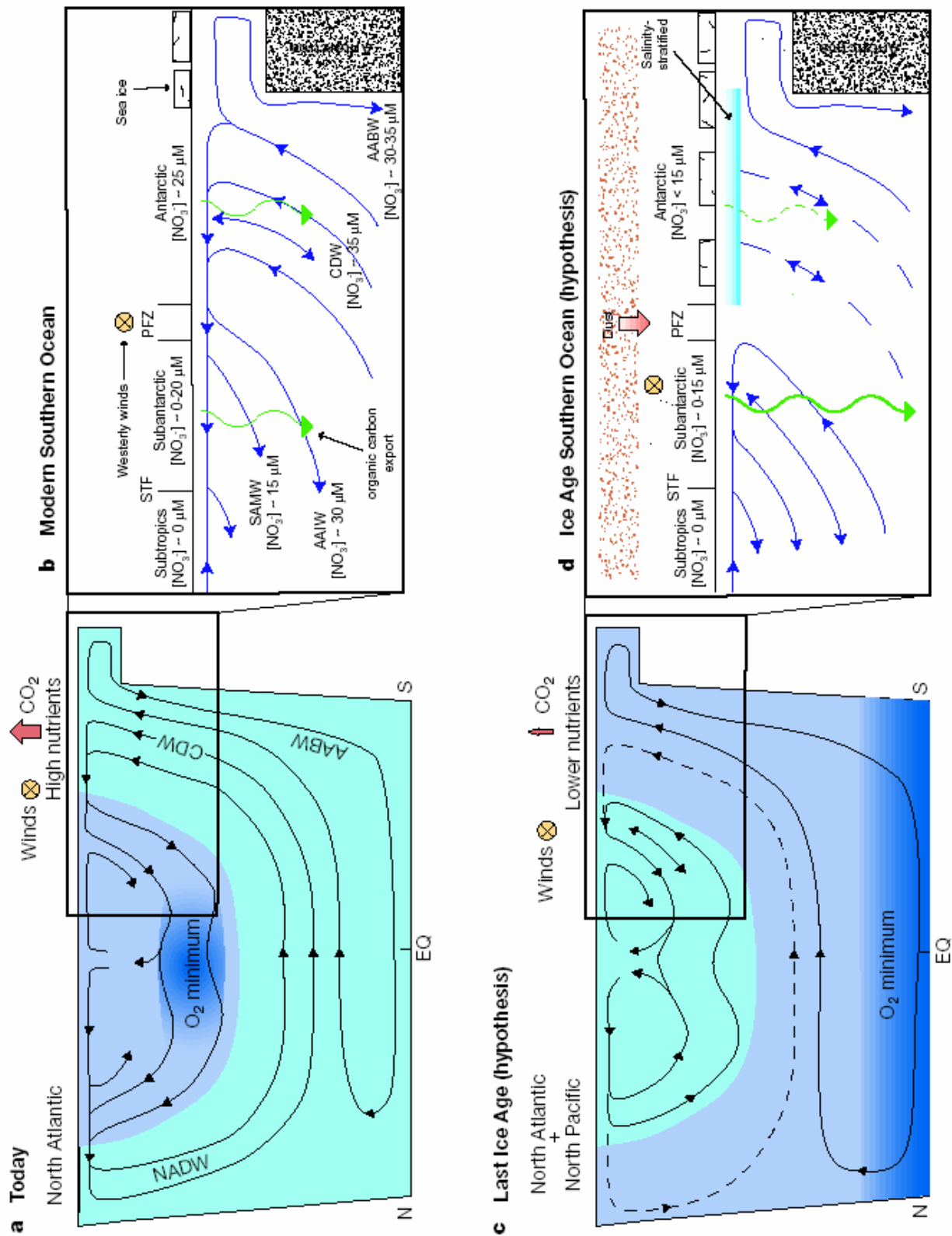
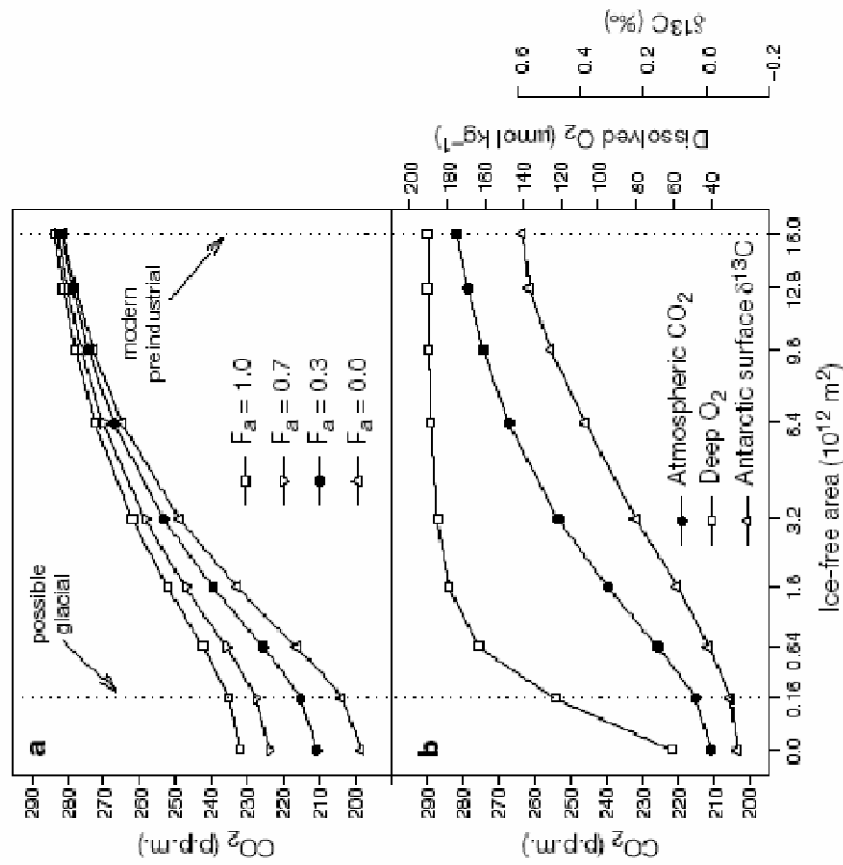
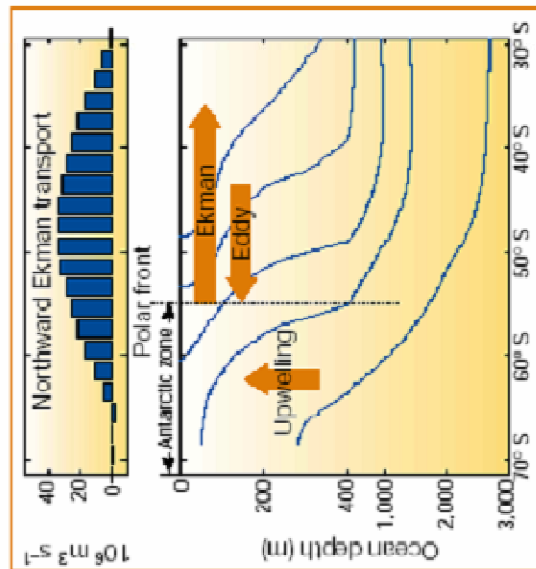


Figure 9. Schematic of modern and model of hypothesized LGM ocean circulation in the Southern Ocean. Prominent changes that occurred during the LGM include a northward migration of the westerlies and an increase in sea ice extent. Sigman and Boyle (2000)



Stephens and Keeling, 2000



Keeling and Vaisbeck, 2001

Figure 10. Schematic illustrating how sea ice extent alone can play a large role in stratifying the Southern Ocean and thereby reduce the flux of CO<sub>2</sub>.