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SIO 102

Factors Controlling Carbon Fluxes in the Southern Ocean

Intro

The ocean is a major carbon reservoir on Earth. Compared to terrestrial reservoirs, it interacts with the atmosphere on rapid timescales, exerting controls over global climate. The Southern Ocean region is particularly critical for these processes: the ocean South of 35° S is responsible for about 40% of global oceanic uptake of carbon dioxide (Landschützer et al., 2015) because it is a site of major downwelling that sequesters carbon from the atmosphere to the deep oceans (figure 1). Understanding the forces driving Southern Ocean carbon dynamics is critical to anticipating changes in the Earth's climate, as well as understanding past climate fluctuations.

Several factors are known to control the rate, and direction, of carbon dioxide fluxes in the Southern Ocean. Sea ice plays a major role by 'capping' outgassing in the winter, presenting a physical barrier to air-sea transfer. Meanwhile, phytoplankton species sequester carbon through photosynthesis in a process known as the 'biological pump,' and dominant winds control upwelling and downwelling patterns. Furthermore, increases in atmospheric carbon alter the equilibrium state of the ocean-air system and force changes in the observed carbon fluxes of the past. Because the Southern Ocean plays such a key role in Earth's climate, it is now an active area of research, aided by additional observational capacity from float-based sensors providing new access to a traditionally forbidding region.

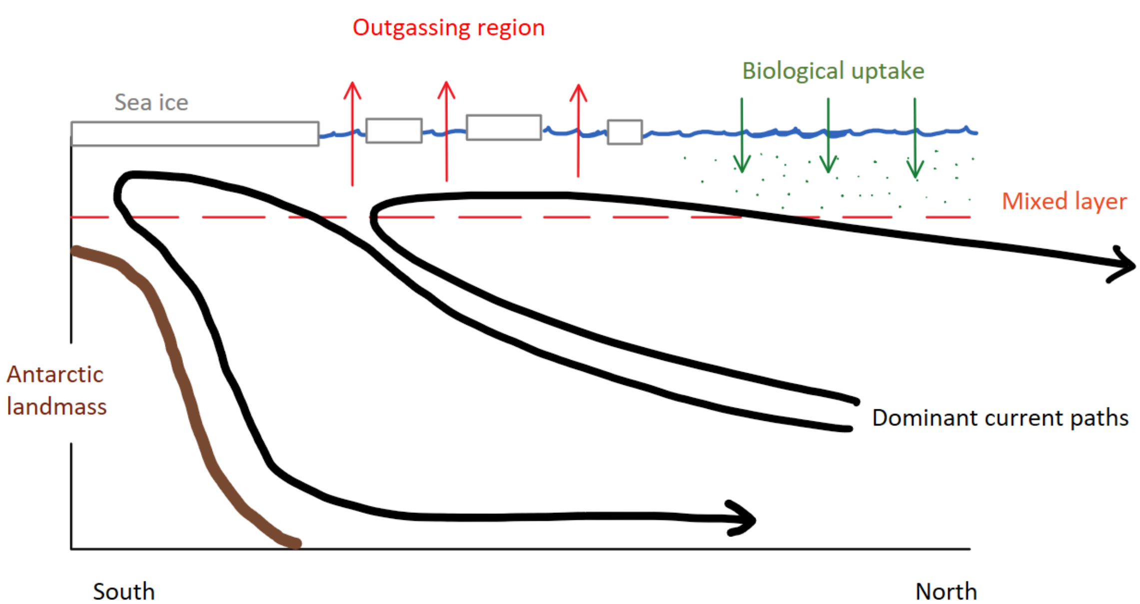

Figure 1: A simplified model of Southern Ocean downwelling dynamics. Bottom and intermediate waters rise upwards to the surface, exchanging gases before subducting once more, sequestering carbon to the deep ocean. (Modeled after Gupta et al., 2020.)

Body

Sea ice is known to affect carbon fluxes in the polar oceans, because its presence effectively places a lid on air-sea gas transfer. This effect is described by Stephens & Keeling (2000), who hypothesized that sea ice coverage was responsible for observed carbon dioxide minima during glacial periods compared to interglacial periods. Based on evidence that low-latitude upwelling and gas transfer appeared to be overstated by contemporary general circulation models, their simplified box model confined deep-water upwelling to the south of 55° S and found that increasing sea ice coverage reproduced 67 ppm of the observed ~80 ppm CO_2 decrease during glacial periods. Thus, sea ice could be one mechanism explaining the majority of CO_2 variation in long term climate, based on the assumptions that most Southern Hemisphere upwelling occurs in the Southern Ocean and that phytoplankton can continue to sequester carbon during the winter, not due to increased productivity but from prevention of outgassing.

Other modeling approaches present a different expected outcome of sea ice cover. By identifying the competing effects of sea ice capping and light attenuation, Gupta et al. (2020) suggest that an expansion of sea ice may actually increase atmospheric CO_2. They argue that sea ice blocks enough light to the ocean surface to significantly weaken the biological pump, while only a near complete sea ice coverage can effectively block air-sea interaction. With both effects combined, model results suggest that expanding sea ice will result in a net increase of carbon flux to the atmosphere. Expanding sea ice also results in cooling of seawater, increasing solubility of carbon dioxide enough to have a significant effect but not reversing the direction of exchange. Disagreement between sea ice models could be assessed with year-long in-situ measurements from a project similar to the MOSAiC expedition in the polar North.

Another large influence on Southern Ocean carbon fluxes is climate variability. In addition to ongoing global warming, the Southern Annular Mode (SAM) exerts significant control on upwelling patterns. The SAM is a climate oscillation characterized by the strength of the pressure gradient between a low-pressure system at high latitude and high pressure further North (Hauck et al., 2013). A positive SAM index is associated with strong westerly winds, which force increased upwelling and outgassing of carbon-rich deep waters. Thus the positive SAM phase observed in recent decades may decrease carbon uptake. Furthermore, the SAM itself is driven to positive phase by greenhouse gas emission (Thompson et al., 2011). Although greenhouse gas emission naturally drives air-sea interactions toward absorption due to higher concentration in the atmosphere (following LeChatelier's principle), a profound effect on SAM trends is expected to influence the effectiveness of the carbon sink in the future.

Another study conducted by Landschützer et al. (2015) found that high- and low-pressure systems had not weakened the carbon sink despite making its distribution more asymmetric (figure 2). In fact, their findings suggested that the Southern Ocean had regained its expected capacity over the period of 2002 – 2012, and was overall more sensitive to short-term climate and wind trends than previously considered. Pressure systems caused a dual effect of influencing water motion and solubility via surface temperature; tracking these systems, particularly their interaction with climate change, will also help discern the spatial and temporal variability in Southern Ocean carbon fluxes.

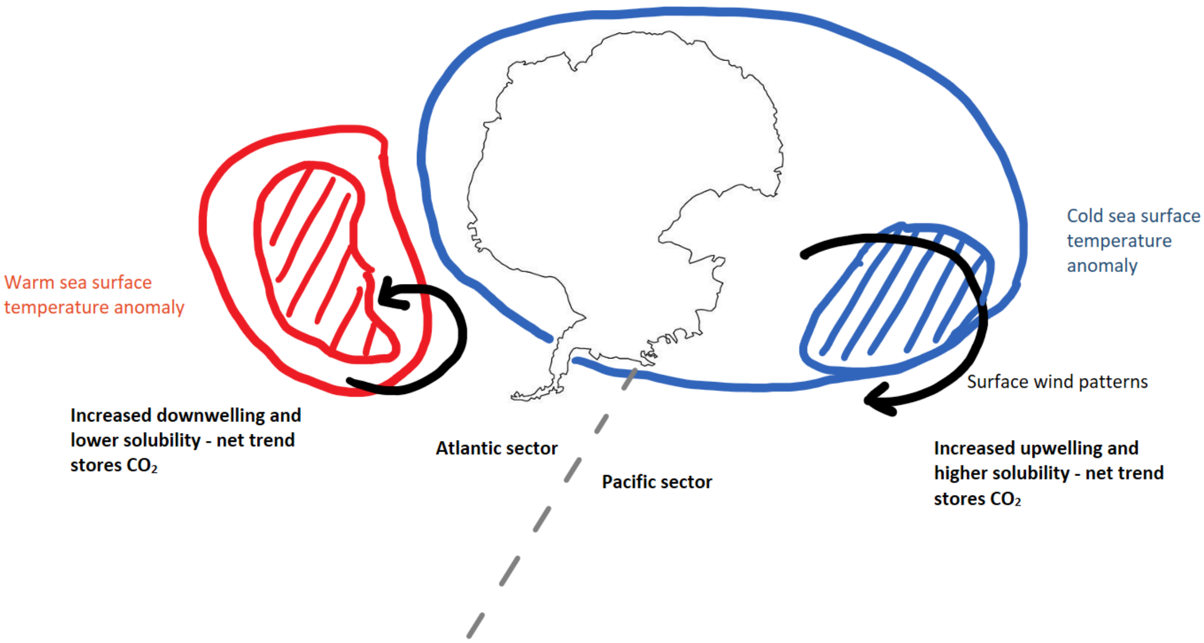

Figure 2: A high-pressure system in the Atlantic (left) and low-pressure system in the Pacific (right) that both contributed to a net carbon storage despite opposing physical changes. (Modeled after Landschützer et al., 2015.)

Wind patterns often drive carbon outgassing as well. Following the deployment of automated float profilers in the Southern Ocean from 2014 to 2017, wintertime outgassing was found to be much more significant than previously considered, likely owing to strong wind-induced upwelling during the sampling period (Gray et al., 2018). These findings prompted a reassessment of year-round carbon fluxes in the region, estimated by Bushinsky et al. (2019) to be -0.75 ± 0.22 Pg C/yr as opposed to previous ship-based estimates of -1.14 ± 0.19 Pg C/yr.

Conclusions

Various factors independently exert significant control on carbon fluxes in the Southern Ocean. Variable sea surface temperatures alter solubility and shift reactions towards absorption or outgassing, while sea ice blocks air-sea gas exchange and forces carbon removal from the atmosphere. However, sea ice also attenuates light for phytoplankton species which play their own key role of biological carbon uptake and sequestration in the deep ocean. Meanwhile, large-scale weather patterns force month-to-decade timescale variability. Global climate change is expected to alter the Southern Annular Mode toward its positive index, possibly reducing the efficacy of the carbon sink; nonetheless, current findings suggest that a reduction of sea ice due to warming could enhance the sink and act as a negative feedback, although seawater warming trends push chemical reactions toward outgassing. Each individual process is unique, but also connected to ongoing global warming, which is amplified in the polar regions. In the future, longer datasets incorporating shipboard and float measurements with higher spatiotemporal coverage will illuminate pathways for the Southern Ocean system, allowing for more developed predictions of its feedback effect for global warming.

Works Cited

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