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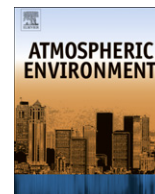
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New Directions: Restoring the westerly winds in the Southern Hemisphere: Climate's lever

In recent years, the idea of managing Earth's radiation budget as a "quick fix" for mitigating some of the effects of climate change has garnered much attention in both the peer-reviewed and popular media. While we recognize that such geoengineering solutions, even if successful, can only delay global warming, we present here some new ideas that we hope will stimulate future research. These ideas are based on findings and techniques described elsewhere, but we combine them in a novel way so as to present scenarios for further exploration.

The westerly winds in the Southern Hemisphere are an important force contributing to climate modulation (Toggweiler and Russell, 2008; Anderson et al., 2009). Global warming, combined with loss of Antarctic ozone have increased the temperature difference (ΔT) between the southern mid- and high-latitudes (Shindell and Schmidt, 2004), causing strengthening of the westerly wind velocities and also shifting them $\sim 3\text{--}4^\circ$ southward (Fig. 1; Sen Gupta et al., 2009). Continued climate change is expected to intensify these winds (Yin, 2005). The alignment of the westerlies with the wind-driven Antarctic Circumpolar Current is key to the amount of ocean meridional overturning circulation and in determining the Earth's climate mode, i.e. glacial versus interglacial (Toggweiler and Russell, 2008; Anderson et al., 2009). Today, $\sim 70\%$ of the global wind energy used in ocean overturning circulation goes into the Antarctic Circumpolar Current (Wunsch, 1998) and upwelling of warm, salty Circumpolar Deep Water (CDW) is the chief process for venting deep water.

During glacial periods, ΔT is at a minimum and the westerlies are closer to the equator having less overlap with the Antarctic Circumpolar Current. This results in decreased Ekman pumping of CDW, which further reduces the flux of CO_2 to the atmosphere, cooling the Earth (Toggweiler and Russell, 2008; Anderson et al., 2009). During these periods, Antarctic sea ice extends much farther north resulting in greater albedo and even less coupling between the westerlies and the Antarctic Circumpolar Current (Sen Gupta et al., 2009). Conversely, slight warming, such as that caused in the past by changes in the Earth's orbit, can activate the poleward shift of the westerlies. The greater wind stress acting on the Antarctic Circumpolar Current moves more water northward via Ekman transport. This in turn pulls more CDW to the surface, releasing CO_2 into the atmosphere and prompting further warming and upwelling (Toggweiler and Russell, 2008; Anderson et al., 2009).

Presently, a portion of this wind-driven upwelling is transported north, where it combines with surface water and sinks below the ocean mixed layer, sequestering considerable amounts of anthropogenic CO_2 (Sabine et al., 2004). However, levels of CO_2 in the southwest Indian Ocean and portions of the Southern Ocean are increasing faster than they are in the atmosphere, indicating

a reduced ocean CO_2 sink that appears to be caused by enhanced CDW upwelling (Metzl, 2009; Takahashi et al., 2009). The portion of upwelled CDW that moves southward supplies heat to Antarctic sea ice, ice shelves, and ice sheets, causing them to melt, potentially accelerating sea level rise (Walker et al., 2007). During this century it is estimated that 25–30% of sea ice volume may be lost due to changes to the westerly winds (Sen Gupta et al., 2009).

In order to address some of the negative consequences of climate warming outlined above we propose applying two cloud-brightening methods in two separate regions. Limited iron fertilization (LIF; Wingenter et al., 2007; 2008) would be used for the purpose of cooling the region south of the westerlies to decrease the net flux of CO_2 out of the Southern Ocean and to protect the ice. Cloud brightening just in this region would exacerbate ΔT and the overlap between the westerlies and the Antarctic Circumpolar Current. To overcome this and restore atmospheric and ocean circulation, greater cooling north of the westerlies by cloud brightening would be needed. This can be achieved by injecting sea salt particles into the lower troposphere (Salter et al., 2008; Rasch et al., 2009). Cooling in this region would also result in greater flux of CO_2 into the ocean.

The natural sulfur cycle can be enhanced by LIF. In many areas, iron is the key nutrient to ocean productivity (Martin et al., 1990). Iron fertilization experiments in the equatorial Pacific (Turner et al., 1996) and Southern Ocean (Turner et al., 2004; Wingenter et al., 2004) have shown that trace amounts of iron promote phytoplankton growth producing large amounts of dimethyl sulfide (DMS). Isoprene production was also greatly enhanced during the Southern Ocean Iron Enrichment Experiments (SOFEX; Wingenter et al., 2004). In the troposphere, DMS and isoprene oxidation products can add to, or produce, new aerosol particles which can grow to cloud condensation nuclei (CCN), increasing cloud reflectivity and cooling the region (O'Dowd and De Leeuw, 2007; Wingenter et al., 2007, 2008). Cloud brightening and significant cooling could also hypothetically be achieved by a second method; injecting micron-size sea salt aerosols from ships such as those described by Latham and coworkers (Salter et al., 2008).

Specifically, we propose to apply iron in narrow strips (a few km wide) orthogonal to the prevailing winds (Fig. 1) to 7% of the mixed layer of the Southern Ocean to the south of the westerlies between about 55 and 60°S (Fig. 1). Iron concentrations in the strips would be increased from ~ 0.2 nM (nanomolar; 10^{-9} M) to 1.2 nM, then allowed to dilute by a factor of 3, as occurred during SOFEX (Coale et al., 2004), to an area of $\sim 20\%$ of this 5° latitude band. Strip application should lead to a more even dispersion of DMS and isoprene and may yield greater particle production, compared to fertilizing one large area. We estimate that this iron application

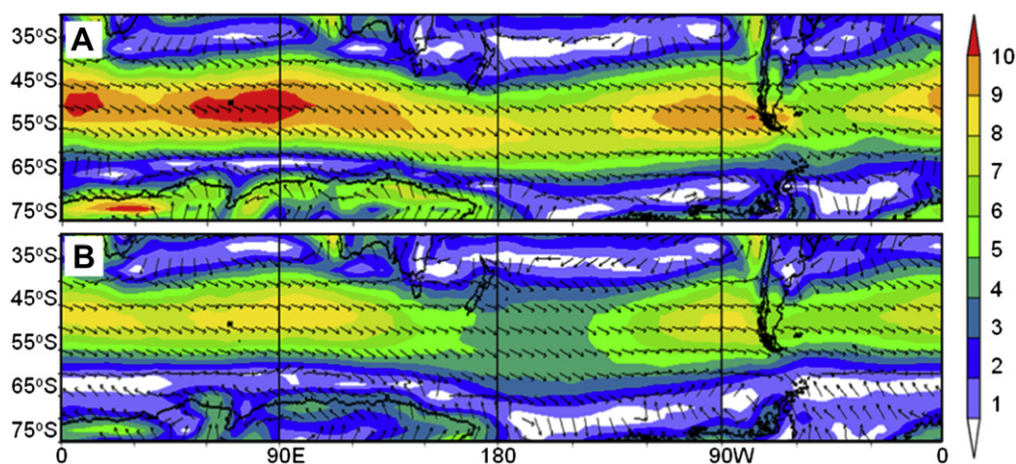


Fig. 1. November through March composites surface vector winds over the Southern Ocean. Contours indicate wind speed (ms^{-1}) and arrows direction. A) is averaged over 1999–2008 and B) 1949–1958. Data from NCEP NCAR Reanalysis (Kalnay et al., 1996). Application of a trace amount of iron in narrow strips between 55 and 60°S is proposed.

would increase the DMS flux by about 80% and would translate to an increase in CCN of about 40% if confined to this latitude band (Ayers et al., 1997; Vallina et al., 2007). Assuming uniform poleward dilution we estimate an average increase in CCN of 10%, resulting in increased cloud albedo (Seinfeld and Pandis, 2006). If the area were completely covered with low altitude clouds having no overlap with higher clouds, we would expect an increase in reflection of $\sim 2.2 \text{ Wm}^{-2}$ (assuming 300 Wm^{-2} of incoming solar radiation) for the area south of 55°S. Allowing for less than complete low cloud coverage and overlap reduces this estimate to about 1 Wm^{-2} , which would cool the Southern Ocean region south of the westerlies by $\sim 0.7 \text{ }^{\circ}\text{C}$. The low pressures south of the westerlies (Gillett and Thompson, 2003) and prevailing winds (Fig. 1) should help contain the CCN and precursors from advecting northwards. However, even in this case, weather systems will transport some of the additional DMS and particles away to the north, limiting cooling south of 55°S to about $0.5 \text{ }^{\circ}\text{C}$. Ship usage would cost about \$100–200 M for applications during late Spring, Summer and early Fall, with additional costs for *in situ* and satellite monitoring, modeling studies and scientific oversight.

North of the prevailing winds injection of sea salt may be able to cool the mid-latitude region by an additional $0.5 \text{ }^{\circ}\text{C}$, compared to the high-latitudes, in order to decrease ΔT and shift the westerlies northward. If control of new particle production via LIF proves to be insufficient at high latitude, then sea salt injections may be needed there as well. Using either method, the amount of cooling can be monitored from the surface and space. The extra production of CCN could be halted almost immediately if some unforeseen consequence should occur. The CCN concentrations would return to their previous value within about a month. Rewarming of the region would take longer.

The cloud brightening techniques described above could also be used with other geoengineering methods proposed to restore climate. For example, certain stratospheric solar radiation management proposals may aggravate the southward shift of the westerlies (Tilmes et al., 2008). Any such shift may be headed off by including cloud brightening as part of the overall strategy.

We have described new climate intervention ideas that could restore several aspects of climate by cooling the Southern Ocean region and decreasing the temperature difference between the southern mid- and high-latitudes. However, the risks and benefits cannot be adequately assessed until extensive research has been done. Further development of fully-coupled biogeochemical general circulation models are needed. If LIF were to be used, extensive field,

laboratory and modeling experiments would be required to determine its impact on ecosystems, trace gas production and gas-to-particle-albedo processes. Discussion of errors and unintended consequences associated with LIF can be found in previous work (Wingenter et al., 2007, 2008). Our treatment of aerosols, CCN and albedo does not include other potentially important effects such as changes in cloud lifetime and moisture. These impacts are discussed in Rasch et al. (2009) and references therein. However, these factors may be less important for LIF because it would require only a relatively modest 10% increase in CCN. Fully functional vehicles which can generate micron-sized sea salt aerosols need to be built and field tested under conditions expected in the Southern Ocean. The impact of full-scale iron fertilization for the purpose of CO_2 sequestration may, unintentionally, over-cool a region and could negatively disrupt ocean and atmospheric circulation. Geoengineering, if successful, can only delay global warming. Emissions of greenhouse gases must be controlled to avert catastrophic climate change.

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