PALAEOCLIMATE

Southern westerlies and CO_2

The Southern Hemisphere westerly winds affect the exchange of carbon dioxide between the ocean and atmosphere. Climate reconstructions from the southern mid-latitudes may reveal variability in the strength and position of the wind belt since the Last Glacial Maximum.

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The Southern Hemisphere westerly winds are the strongest time-averaged oceanic winds in the world, and have a strong influence on the circulation of the Southern Ocean. In particular, the winds modify the upwelling of carbon-rich deep water. This process, together with ocean biogeochemistry, influences the balance of carbon dioxide between the ocean and atmosphere[1]. Thus any change in the strength or position of the westerlies, such as the recently observed intensification of the winds, could influence whether the Southern Ocean acts as a net source or sink of atmospheric carbon dioxide[2]. Three recent studies published in *Nature Geoscience*[3–5] provide valuable new information about changes over the past 18,000 years.

The period since the Last Glacial Maximum encompasses the most recent transition from glacial to interglacial conditions between about 18,000 and 12,000 years ago. During this deglaciation, shifts in oceanic and atmospheric circulation patterns coincided with a rise in atmospheric CO_2 levels of approximately 50%. Most of this CO_2 was derived from the deep ocean.

One simplified study with a general circulation model[6] suggests that the belt of the Southern Hemisphere westerly winds may move northward towards the Equator during cold periods. When shifted, the core of the westerlies may no longer be positioned over the Antarctic Circumpolar Current that flows from west to east around Antarctica. This could exert a strong control on Southern Ocean upwelling. Thus, discussions of the mechanisms by which carbon dioxide was released during the most recent transition from glacial to interglacial conditions have centred on the westerly winds[6–8] and their role in the upwelling of CO_2-rich deep water in the Southern Ocean.

Three studies in *Nature Geoscience*[3–5] provide potentially important evidence for changes in the atmospheric circulation of the Southern Hemisphere following the Last Glacial Maximum. Records of the expansion of glaciers in New Zealand[3], of changing land surface temperatures farther south on sub-Antarctic Campbell Island[4], and of precipitation changes over South America[5] (Fig. 1) all bear witness to a reorganization of the Southern Hemisphere atmospheric circulation.

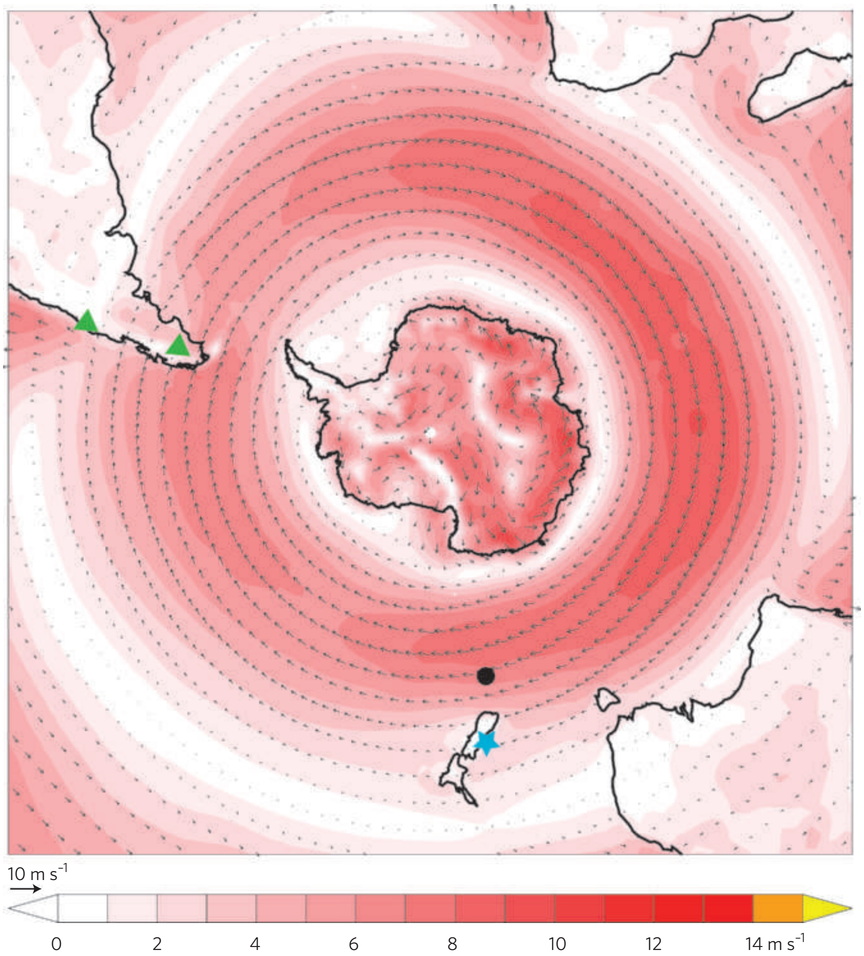

Figure 1 | The Southern Hemisphere westerly winds. The sites used by Putnam *et al.*[3] (star), McGlone *et al.*[4] (circle) and Lamy *et al.*[5] (triangles) are well suited to capture changes in the position and intensity of the westerlies. This plot shows annual mean wind at 10 m above the surface for the period 1979 to 1999, created with data from the European Centre for Medium-Range Weather Forecasts, using ERA-40 reanalysis data. Figure courtesy of T. Bracegirdle, British Antarctic Survey.

Putnam *et al.*[3] report exposure ages of glacial moraines on the South Island of New Zealand which show a regionally coherent expansion of glaciers on both sides of the Southern Alps 13,000 years ago. This glacier expansion coincides with a period of abrupt cooling in Antarctica between 14,540 and 12,760 years ago, known as the Antarctic Cold Reversal[9]. Putnam *et al.* therefore conclude that the geographic footprint of this cold event extended into the southwest Pacific region, as far north as 44° S. Glaciers at higher latitudes in some parts of Patagonia also advanced at this time[10,11].

This coherent expansion suggests that glaciers throughout the mid-latitudes of the Southern Hemisphere may have been affected by a hemispheric-scale climate change during the Antarctic Cold Reversal. In addition, cooling of the surface ocean during this time has been documented at similar latitudes south of Australia[12], in the southeastern Pacific Ocean[13] and the south Atlantic Ocean[14], indicative of changes in atmosphere and ocean circulation as far north as 36° S. If these events can be attributed to a shift in the position of the westerlies towards the Equator, as Putnam *et al.* suggest, the resultant decline in upwelling could explain why a pause in the rise of global atmospheric CO_2 levels was observed at this time[15].

McGlone *et al.*[4] provide a temperature reconstruction that seems to show a similar atmospheric cooling during the Antarctic Cold Reversal. They compare pollen-based temperature reconstructions from peat bogs on Campbell Island, located south of New Zealand, with sea surface temperature proxies in a marine sediment core off the east coast of New Zealand over the past 18,000 years. Both records show that during deglaciation, atmospheric temperature on the island generally varied in concert with Southern Ocean sea surface temperatures.

However, after the Antarctic temperature maximum between 12,000 and 9,000 years ago[9], the land-based temperature trends began to diverge from those of the ocean. At this time Campbell Island warmed while sea surface temperatures, inferred from the nearest marine sediment core some 980 km away, seem to have cooled. Although this divergence is less marked when the Campbell Island record is compared with some other Southern Ocean temperature records[12], McGlone *et al.*[4] attribute it to a discrepancy between terrestrial and marine proxies. Temperature proxies derived from high-altitude and mid-latitude vegetation reflect atmospheric temperatures during the relatively short summer growing season, whereas oceanic temperature proxies more closely reflect annual mean sea surface temperatures. McGlone and colleagues therefore suggest that, beginning 9,000 years ago, terrestrial summers warmed while mean annual sea surface temperatures fell. They attribute this pattern to changes in the Southern Hemisphere westerly winds.

In this scenario, the agreement between the temperature records before 9,000 years ago reflects a more poleward position of the westerlies, relative to the late Holocene. They infer that the westerlies were situated at about 50° S before 9,000 years ago, positioned over the Antarctic Circumpolar Current and to the south of Campbell Island. During the cooling that marked the end of the Antarctic temperature maximum after 9,000 years ago, they suggest that the westerlies moved north to a position over Campbell Island, and intensified. This resulted in sea surface temperature cooling while increasing the airflow towards the pole, bringing more atmospheric heat southwards and warming the land.

Finally, Lamy *et al.*[5] suggest a different scenario: just shifting the belt of the Southern Hemisphere westerly winds north or south cannot explain the climate changes they observe in the mid-latitudes of South America. Instead, they suggest that an expansion and contraction of the belt, in particular at its northern edge, can best explain the precipitation variability found in records from coastal shelves, lake sediments and peat bogs. These records show wetter conditions in central Chile at the same time as the climate became drier and less windy over the southern Chilean fjords, a pattern that cannot be explained by a simple north–south shift of the winds. Instead, they suggest that past variability in the wind intensity may resemble the changes in the configuration of the Southern Hemisphere westerly winds observed during the present-day seasonal cycle.

Today, during the Southern Hemisphere winter, the northern margin of the belt expands towards the Equator, whereas during the summer, it contracts. Lamy *et al.* suggest that during the peak warmth in Antarctica 12,000 to 9,000 years ago, the latitudinal extent of the belt was relatively small, analogous to its present-day summer configuration. Conversely, beginning 5,500 years ago, there was a latitudinal expansion of the belt of the Southern Hemisphere westerly winds, similar to the present-day winter configuration.

The three studies all highlight the potential importance of understanding the changes in atmosphere and ocean circulation during the transition from glacial to interglacial climate. However, they also reveal uncertainty regarding the behaviour of the Southern Hemisphere westerly winds during deglaciation. McGlone *et al.* and Putnam *et al.* both suggest that north–south shifts in the position of the belt and the intensity of the winds may be at least partly responsible for the observed changes on land and in the ocean during the last glacial termination and, in the case of McGlone *et al.*, the Holocene. In contrast, Lamy *et al.* propose that the observed changes, at least in southern South America, can be accounted for only by a latitudinal expansion and contraction. However, much of the evidence in all three studies is indirect and is largely drawn from land-based proxies. Glacial moraine, peat bog pollen and lacustrine proxies all tend to represent moisture changes. Thus, although the studies present strong evidence for hemispheric-scale changes in atmospheric moisture delivery, it is less clear at this stage whether the observed variability reflects shifts or expansions of the Southern Hemisphere westerly winds.

Observational studies of Southern Hemisphere circulation changes like the ones by Putnam, McGlone, Lamy and their colleagues[3–5] are critical to deciphering the role of the Southern Ocean as a source and sink of CO_2, and to assessing its contribution to the deglacial rise in global atmospheric CO_2. The remaining difficulties in interpreting these indirect observations may in future be resolved through an examination of the relationship between changes in the position and intensity of the westerly winds, and changes in moisture delivery. A better understanding of the links between CO_2 and the Southern Hemisphere atmospheric circulation during deglaciations may then help us infer the consequences of the recent changes in the winds on future atmospheric CO_2[2,7]. ❐

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