ELSEVIER

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QSR

Context

Off the grid

Massive discharges of icebergs to the North Atlantic occurred seven times during the last glacial period and were associated with the coldest and harshest climates of the last 130,000 years in the Northern Hemisphere. That these so-called Heinrich Events (HEs) were accompanied by perturbations to ocean circulation and climate globally is becoming well established but their cause remains unknown (Hemming, 2004). Curiously, each HE was followed by rapid warming in Greenland and the North Atlantic region (by about half the magnitude of warming during the end of the last ice age).

Synchronization of ice core climate records from Greenland and Antarctica using atmospheric methane variations demonstrates that central Antarctica warmed substantially during at least four of the HEs (H4, H5, H5.2 (or H5a), and H6) that occurred 35,000 to 65,000 years ago (Blunier and Brook, 2001). Explaining the coincidence of anomalous warmth in Antarctica and extreme cold in northern high latitudes has been one of the 'holy grails' of paleoclimatology in recent years.

Any viable hypothesis must account for the different temporal evolution of the climate change in the north and south. Whereas northern high latitudes cooled abruptly at the start of HEs, then warmed rapidly at their terminus, Antarctica gradually warmed prior to HEs and gradually cooled after them. In this issue of *JQSR* Keeling and Visbeck (2005) present a novel hypothesis for the different behavior of northern and southern high latitudes during HEs.

Keeling and Visbeck hypothesize that increased eddy heat transport across the Antarctic circumpolar current (ACC) may have occurred in response to an amplified density gradient during periods of enhanced meltwater discharge in the North Atlantic during HEs. With reasonable fluxes (0.1 Sv) of meltwater to the North Atlantic their scale analysis and box model produce warm events in southern high latitudes that resemble the Antarctic warm events of the last glacial period in magnitude (2 °C) and shape (gradual warming followed by gradual cooling).

An analysis of the sensitivity of Antarctic warming in their model to changes in six mixing parameters leads them to conclude that only mixing across the ACC by eddies and the amount of overturning in the North Atlantic are important. Much attention has been given to the latter, with proxies of overturning circulation (McManus et al., 2004) and water mass geometry (Vidal et al., 1997) indicating that both deep water production and the deep overturning cell that exist in the modern North Atlantic were weak or non-existent during HEs. What is new here is consideration of the role that eddy heat transport may have played in warming Antarctica during HEs.

Keeling and Visbeck's eddy hypothesis differs from the 'bipolar seesaw' hypothesis (Broecker, 1998; Stocker, 1998), which calls upon the removal of heat from the entire Southern Hemisphere by the Atlantic Ocean's meridional overturning circulation, and its deposition in the North Atlantic (Crowley, 1992; Schiller et al., 1997), by providing for heating of high southern latitudes (>60°S). This is an important distinction because the only strong evidence for Southern Hemisphere warmth during HEs comes from central Antarctica. As far south as Chile and New Zealand (~40°S) there is evidence from mountain glacier advances for cooling during the time of HEs (Lowell et al., 1995). The eddy hypothesis also circumvents the challenge to the 'bipolar seesaw' hypothesis posed by models that produce cooling of high southern latitudes in response to a collapse of Atlantic meridional overturning circulation.

Like the skier's pole that knocks a gate down, eddies in the Southern Ocean act to flatten isopycnals. The wind counteracts the eddies, driving isopycnals vertical in the Southern Ocean. An increase in the density gradient across the ACC, caused by freshening to the north, would, like the westerly winds, increase the slope of isopycnal surfaces. Eddy transports would increase in response, the crux of Keeling and Visbeck's study.

Whether or not eddy transports across the ACC are sensitive to realistic fluxes of meltwater in the North Atlantic will require much more sophisticated dynamic models that can produce and propagate eddies. Unfortunately, the physics underlying the generation and maintenance of eddies, and their interaction with the mean flow, are not well understood. Confounding the

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situation is the sheer computing power necessary to handle such small-scale features (scale length ~100 km) in global general circulation models with a typical 'grid size' several times larger. Those models that 'permit' sub-grid-scale turbulent processes, such as eddies, generally contain eddy-mixing coefficients tuned to produce a realistic circulation pattern in lieu of a first-order treatment of the physics. Yet the importance of these mesoscale features of the ocean circulation cannot be underestimated. They account for a large fraction of all energy dissipation in the ocean (Wunsch and Ferrari, 2004).

In closing, the eddy–meltwater hypothesis may shed light on recently published reconstructions of subantarctic ocean productivity (Sachs and Anderson, 2005) and ventilation (Pahnke and Zahn, 2005) during HEs. Steepening of isopycnal surfaces across the ACC from freshening of surface waters to the north would be expected to ventilate intermediate depths of the subantarctic ocean, consistent with increases in the carbon isotope ratio of benthic foraminifera on the southern Chatham Rise east of New Zealand at the time of HEs (Pahnke and Zahn, 2005).

In addition, because eddies represent a two-way street—i.e., their transport of heat poleward is accompanied by an equatorward transport of chemicals from the Southern Ocean—they may have contributed to algal productivity maxima in the subantarctic ocean during HEs (Sachs and Anderson, 2005). Melting of sea ice south of the ACC would be expected in response to increased poleward eddy heat fluxes. Any iron-rich dust that had accumulated on the ice would be released to seawater. In addition, because most iron in Southern Ocean surface waters comes from upwelling, and the drawdown of that iron by phytoplankton and scavenging onto particles is likely diminished under sea ice, newly exposed surface waters might have been relatively enriched with iron. Keeling and Visbeck's eddies would have transported this iron equatorward across the ACC to fuel algal growth in the subantarctic ocean.

With all of their inherent simplifications, box models like the one employed by Keeling and Visbeck, remain powerful tools for testing the sensitivity of heat and chemical transport to eddy mixing. Until these sub-grid-scale processes are understood and properly represented in ocean circulation models they may be the best tool we have for understanding the cause and effect of HEs.

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