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Correction to "Antarctic sea ice and the control of Pleistocene climate instability" by Ralph F. Keeling and Britton B. Stephens

In the paper "Antarctic sea ice and the control of Pleistocene climate instability" by Ralph F. Keeling and Britton B. Stephens (*Paleoceanography, 16* (1), 112–131, 2001), approximately 10 paragraphs from section 5 and Appendix A were inadvertently omitted. The end of the paper from section 5 through the references, including Appendix A and Figure A1, appear below.

5. Concluding Remarks

We have outlined a hypothesis for the origin of Pleistocene climate instability that builds on the work of *Stommel* [1961] showing that feedbacks involving salinity can potentially lead to multiple states of thermohaline overturning, and draws on work of *Toggweiler and Samuels* [1993a, 1993b,1995, 1998] showing that a "reconfigured conveyor" overturning pattern can be sustained by the action of the winds in the Antarctic Circumpolar Current. The hypothesis assumes that the stability of the reconfigured conveyor is linked to freshwater forcing at high southern latitudes. This allows a transition to be made from stabilizing to destabilizing feedbacks as climate cools and as the freshwater budget of high southern latitudes becomes increasingly dominated by the effects of sea ice. A key threshold in the system is crossed at the point at which the heat reserve of the deep ocean is effectively exhausted, which allows Antarctic sea ice to form without a stabilizing halocline all the way north to the latitudes of AAIW formation. This allows the formation of relatively salty AAIW, which in turn destabilizes the reconfigured conveyor.

The hypothesis accounts for the progression from a stable "on" mode during interglacial periods, to variable "on/off" modes during states of intermediate cooling, and to a stable "off" mode during full glacial conditions. The progression results from shifts in stability limits of stable steady state overturning modes. The hypothesis was shown to be consistent with reconstructions of water masses in the glacial ocean, with the estimates of glacial deepwater temperatures, with estimates of glacial Antarctic sea ice limits, and with the observed link between climate instability and the thresholds in the oxygen isotopic composition of foramnifera. The hypothesis also provides a framework for explaining the stability of the Atlantic thermohaline circulation with respect to ice discharges in the Holocene as well as the instability with respect to changes in Antarctic climate and ice discharges in the Pleistocene.

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The hypothesis leads to two suggestions for the origin of D/O events: (1) that changes in the freshwater budget of high southern latitudes may provide the link between Antarctic warming and sudden Greenland climate changes associated with long-lived D/O events and (2) that the evaporation needed to regrow wasted ice sheets may provide the link between ice discharges and sudden Greenland climate changes associated with short-lived D/O events. Although not the only explanation for interstadial events and related oceanographic and paleoclimatic changes, [*MacAyeal*, 1993, *Birchfield and Broecker*, 1990; *Sakai and Peltier*, 1997] the hypothesis nevertheless provides a unified perspective on several disparate features of the paleorecord., e.g., the timing of the D/O events in relation to Antarctic warming and northern ice discharges, the relationship between global cooling and the onset of instability, changes in deep ocean structure, and links to Antarctic climate. Also, a similar oceanographic framework involving sea ice has been shown elsewhere [*Stephens and Keeling*, 2000] to provide a context for explaining why atmospheric CO_2 concentrations were lower during glacial periods, a long-standing puzzle.

Key aspects of our framework would be testable through improved reconstructions of past salinity distributions. A promising approach may be to directly observe salinity (or chlorinity) of sediment pore water, which can preserve remnants from the Last Glacial Maximum [*Schrag et al.*, 1996]. Our framework predicts that the salinity differences between waters originating in high and low latitudes should not be strongly tied to the oxygen isotopic composition, owing to the weak isotopic fractionation involved in freezing and melting of sea ice. A sensitive test would be showing that glacial Atlantic surface waters were fresher than expected from the global ocean salinity change and from the local changes in oxygen isotopic composition. Deepwater salinity changes are probably not a very sensitive test because the large volume occupied by the deep ocean precludes large changes. Another key test would be demonstrating that interstadial events are associated with episodic intrusions of NADW into high southern latitudes.

The framework motivates several directions for future modeling studies. An obvious goal is simulating the hypothesized overturning states (Figure 2) in an ocean general circulation model. Doing this may require careful attention to processes governing isopycnal and diapycnal mixing within the main pycnocline, the deep oceans, and the ACC. Another obvious direction is exploring the processes governing transitions between the postulated glacial and interglacial conditions. The framework suggests the importance of three positive feedback mechanisms in addition to salinity feedbacks: (1) ice-albedo feedback between growth of Antarctic sea ice and Southern Hemisphere cooling, (2) thermal feedback between deepwater upwelling and the heat budget of high southern latitudes, including effects on sea ice [e.g., *Gordon*, 1981], and (3) feedback between Antarctic sea ice and the CO_2 greenhouse effect, e.g., via the mechanism of *Stephens and Keeling* [2000]. It is possible these feedbacks may allow the nonlinear response of global climate to orbital eccentricity variations to be understood based on variations in southern insolation, consistent with the timing of the penultimate deglaciation [*Henderson and Slowey*, 2000], rather than based on variations in northern insolation, as generally assumed [e.g., *Imbrie et al.*, 1993].

Perhaps the most important point illustrated by our framework is the possibility that changes in Antarctic freshwater balance driven by cooling might cause the thermohaline circulation to transition from having a single steady state to multiple steady states. This behavior may provide a general context for explaining the instability of Greenland climate during the late Pleistocene, when Antarctica was very cold, as compared to the stability during the Holocene period, when Antarctica has remained relatively warmer. An important additional suggestion that requires further research is that the freshwater influence on thermohaline instability, which is critical to simulations of permanent NADW slowdown from global warming [*Manabe and Stouffer*, 1993; *Stocker and Schmittner*, 1997], may not be accurately represented in many coarse-resolution models.

Appendix A

Here we sketch a scenario for the formation of relatively salty AAIW in the absence of perennial sea ice extending to the APF. Briefly, the scenario assumes that upwelling south of the APF feeds the formation of AAIW only in the winter. In the summer, the upwelling is entrained into an Ekman layer that crosses the APF without sinking. The formation of salty AAIW is allowed as long as the combined influences of winter ice transport and summer Ekman drift are sufficient to counteract the annual input of freshwater from precipitation south of the APF.

To explore this scenario in more quantitative terms, suppose initially that winter sea ice forms without a stabilizing halocline, as allowed by the cooling of the full water column to the freezing point, thereby allowing the formation of salty AAIW (Figure A1a). Suppose next that springtime melting completely eliminates the ice cover (Figure A1b), contributing a freshwater excess to the surface mixed layer. After the melting, the freshwater excess E (measured in meters of freshwater equivalent) will change at a rate $dE/dt = F - M_{up} E/D_m$, where F is the precipitation rate, M_{up} is the upwelling rate, and D_m is the summer mixed layer depth, assumed here for simplicity to be constant with time. The freshwater excess thus approaches an equilibrium excess $E_{eq} = (F D_m)/M_{up}$ with a time constant of $\tau = D_m/M_{up}$. If the initial freshwater excess E_0 generated by spring melting exceeds E_{eq}, then the excess will decrease through the course of the summer in spite of net precipitation. The net freshwater loss over an ice-free season of duration Δt is given by $(E_0-E_{eq})(1-e^{-\Delta t/\tau})$.

Taking rough estimates for a hypothetical glacial ocean of $M_{up} = 35$ m yr^{-1}, $F = 0.3$ m yr^{-1}, $D_m = 40$ m, $E_0 = 1.5$ m, and $\Delta t = 0.3$ years, yields a net freshwater loss over the ice-free season of 0.27 m of freshwater equivalent. The figures for M_{up}, F, and D_m are based on estimates for the modern ocean [*Trenberth et al*, 1990; *da Silva and Levitus*, 1994; *Sverdrup et al.*, 1942, p. 609], with slight adjustments recognizing that under colder climate conditions, upwelling will be larger due to stronger winds, precipitation will be smaller due to reduced atmospheric moisture, and the mixed layer depth may be reduced due to stronger summer stratification associated with melting thicker sea ice layers. If we suppose that the initial freshwater excess of 1.5 m was comprised of 1.3 m from melting sea ice and 0.2 m from melting overlying winter snow, then the freshwater loss of 0.27 m will more than counteract the influence of the previous winter's precipitation (0.27 > 0.20). Additional reduction in the freshwater excess of the upper water column can continue via upwelling and surface divergence in the fall season, when the surface is again ice covered but while the surface freshwater layer remains, as shown in Figure A1c. Even without the additional freshwater losses in the fall, the circumstances ensure that regrowth of 1.3 m (freshwater equivalent) of sea ice during the subsequent winter will completely eliminate the surface freshwater excess, thereby returning the upper ocean to the same status as the previous winter and reestablishing the conditions needed for forming salty AAIW.

Although the above calculation should be viewed only as a rough scale analysis, it nevertheless clarifies that salty AAIW can form without year-round ice coverage near the APF and, indeed, almost certainly will form under a cooling climate before cooling has proceeded to this extent. Summer ice limits are therefore not a sensitive test of our hypothesis. With the seasonal perspective given in Figure A1, only the winter sea ice limits are critical.

The seasonal perspective shown in Figure A1 raises a significant new issue, however. The summer upwelling and northward surface drift results in a net conversion of deep water into lower latitude surface waters. To sustain a steady state, a compensating pathway for converting lower latitude surface waters into deep waters is required.

Suitable pathways are not hard to identify. In the glacial "on" state a possible pathway is the conversion of lower latitude surface waters to NADW, and the subsequent

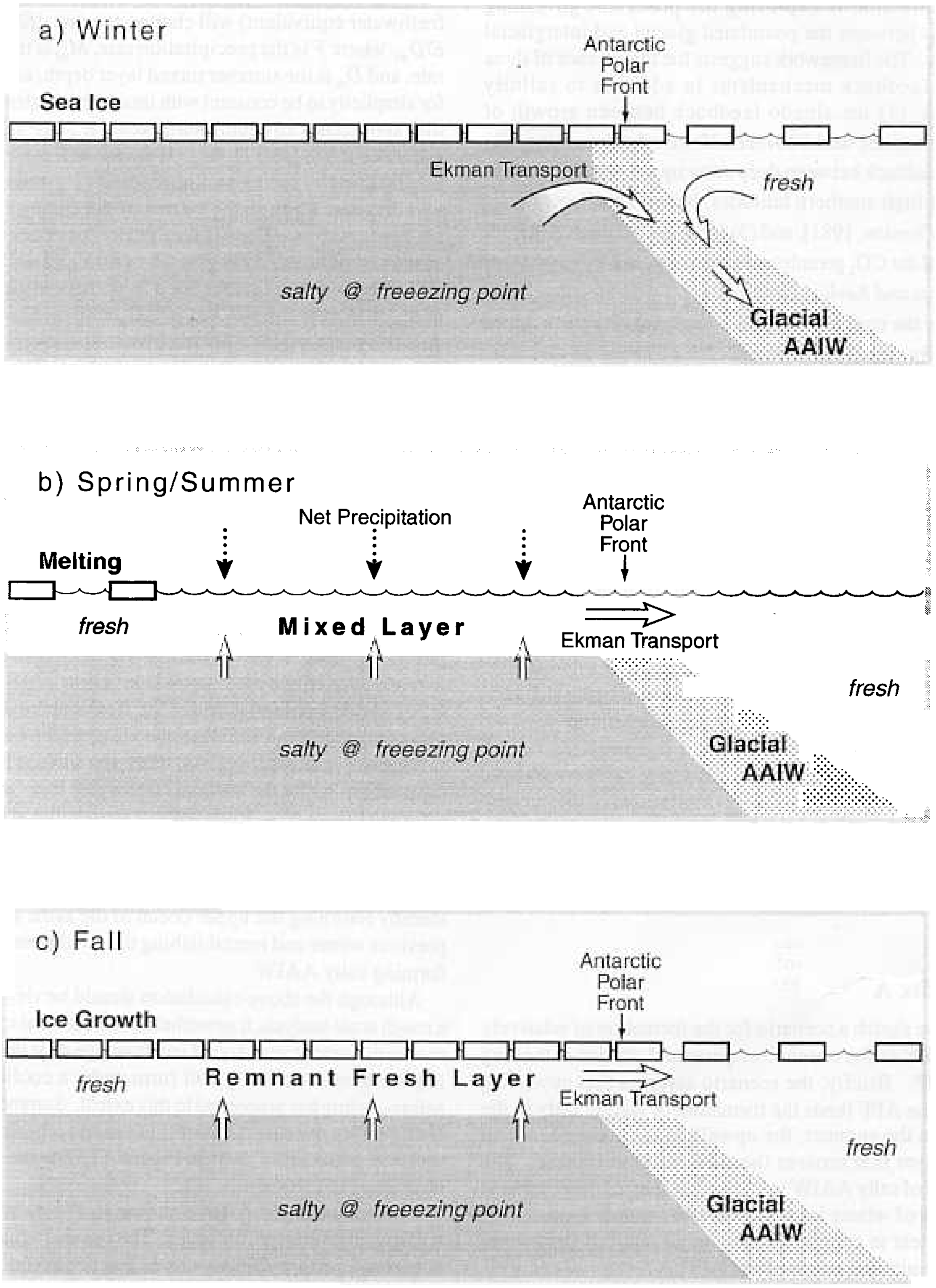

Figure A1. Seasonal controls on the freshwater excess of Antarctic surface waters. (a) Winter ice cover, which allows for formation of salty AAIW. (b) Spring/Summer melting of ice, which produces a freshwater excess in the surface mixed layer, and this excess evolves through the summer as determined by precipitation and entrainment of deeper waters balanced by northward Ekman drift. (c) Fall ice coverage, which shields water column from precipitation, while entrainment and surface Ekman drift continue.

penetration of NADW into abyssal layers. In the glacial "off" state a possible pathway is the entrainment of lower latitude surface waters into AAIW and the subsequent penetration of a portion of the AAIW into abyssal layers. The diapycnal mixing needed to support downward penetration of NADW or AAIW could occur via several possible mechanisms, such as via eddy mixing within the ACC or turbulence generated over rough topography in the oceans interior [Ledwell *et al.*, 2000]. The need for this compensating pathway clarifies that diapycnal mixing actually promotes our hypothesized glacial overturning patterns, provided the mixing is concentrated at high southern latitudes or at depths below ~2500 m but not within the main pycnocline.

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