Comment on "Greenland-Antarctic phase relations and millennial time-scale climate fluctuations in the Greenland ice-cores" by C. Wunsch ☆

Much attention has been paid recently to millennial-scale climate variability, and abrupt climate change in particular. We wish to clarify an issue that was raised in a recent publication (Wunsch, 2003), to minimize the level of confusion in this complex and rapidly evolving field. In his abstract, Wunsch (2003) states that "A serious question concerns the extent to which the Greenland cores reflect tracer concentration change without corresponding abrupt climate change. The large, abrupt shifts in ice $\delta^{18}O$ can be rationalized as owing to wind trajectory shifts, perhaps of rather modest size." For the record, we wish to point out that this hypothesis is no longer tenable in light of new data on the nitrogen and argon isotopic composition of gases trapped in the Greenland ice cores. This rapidly growing data set shows that all of the abrupt $\delta^{18}O$ shifts studied thus far (over 17 at this writing) are accompanied by gas isotope anomalies. The magnitudes of these anomalies demonstrate that the warmings and coolings were large, typically 10°C (Lang et al., 1999; Leuenberger et al., 1999; Severinghaus and Brook, 1999; Severinghaus et al., 2001, 2003; Goujon et al., 2003; Landais et al., submitted). The conventional interpretation of $\delta^{18}O$ of ice in fact *underestimates* the true magnitude of these temperature changes (Jouzel, 1999; Severinghaus et al., 2003).

Furthermore, abrupt shifts in atmospheric methane concentration are observed to occur at the same time (within ~30 yr) as the Greenland temperature shifts (Severinghaus et al., 1998; Severinghaus and Brook, 1999; Flückiger et al., 2004; Landais et al., submitted). This synchroneity demonstrates that the abrupt climate shifts in Greenland cannot have been just local phenomena, because methane sources are widely distributed over the globe (Chappellaz et al., 1993; Brook et al., 1996, 2000).

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Response to J.P. Severinghaus et al.☆,☆☆

I have no disagreement with the inference that some large isotopic changes in the Greenland cores correspond to major temperature changes—in Greenland, and for an uncertain distance surrounding it. Persistent wind direction shifts over and near Greenland would not only change tracer amounts deposited there, but would also be expected to shift local temperatures too—as any observer of local weather will recognize. Significant temperature shifts in Greenland would generally be expected to coincide with isotopic deposition shifts, except for those isotopic tracers that are globally, instantaneously, homogeneous. Determining the extent to which the observed shifts are a worldwide phenomenon requires a *quantitative* result. For example, although modern ENSO fluctuations can be detected on a global basis, few would argue that they are not primarily a tropical phenomenon generating sometimes measurable, but typically small, shifts elsewhere. Much of the accompanying globally observed atmospheric CO_2 disturbance apparently arises through tropical Pacific Ocean uptake changes alone. Earthquakes are globally detected, but have well-defined, highly local epicenters.

Climate proxies in ice and deepsea cores are tracers. As such, they can be transported and mixed over global distances by the atmosphere and ocean on a variety of time scales. Detection of a tracer deposition change cannot be used automatically to infer a local climate change. An increase in e.g., CH_4, from a large emission anywhere, would be detectable everywhere. The hard facts seem to be that there have major abrupt temperature changes over Greenland, with corresponding associatable alternations in global methane concentrations. The main issue is the extent to which an indirect signal (a tracer concentration change) can be said to demand major changes in the climate system. Severinghaus and Brook (1999) follow many other authors in invoking a massive, qualitative shift in the North Atlantic circulation to explain their observations. The question raised in my own paper (Wunsch, 2003), and the subject of the Severinghaus et al. (2004) comment, is whether such an exciting scenario is necessary to rationalize the data, or whether more modest changes in the system are not adequate? It is characteristic of tracer fields, because they integrate over atmospheric, riverine, or oceanic advective pathways, that small alterations in source or sink strength or pathway, can produce rapid, striking changes in deposition rates. Roe and Lindzen (2001), for example, show how changes in the continental ice sheets, which were present during all of the observed intervals of rapid tracer change, can lead to major shifts in the wind field.

Severinghaus et al. (1998) assert that the methane sources of the North Atlantic basin alone are insufficient to give rise to the observed methane changes of the Younger Dryas. Inference that the global methane concentration change corresponds to a global climate shift is built upon a chain of assumptions about methane source response to precipitation and temperature changes, atmospheric oxidizing capability, seasonality, and the interpretation of paleo data in terms of wetland coverage (Brook et al., 1996). Note however, that Chappellaz et al. (1993) summarize the situation as "For LGM, direct information on the extent and distribution of wetlands. The largest single CH_4 source,

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is sparse and generally not quantified…." They then go on to make a valiant attempt to estimate the source during the LGM, but end with a list of caveats. At this time, it is at least as attractive to assume that past methane emissions were sensitive to small atmospheric shifts, as it is to assume a massive change occurred in the oceanic general circulation, albeit the resulting story is much less interesting. The claim that major climate shifts near Greenland correspond to significant climate shifts in Antarctica (the focus of Wunsch, 2003) would be much more compelling if the $\delta^{18}O$ or δD proxies, most commonly believed to at least partly reflect *local* temperatures, were more obviously correlated between the two locations. On the time scales of the abrupt events in Greenland, such a correlation is nearly invisible. (To say this in more concrete terms: if temperature in Boston co-varies with that in Buenos Aires, one can conclude that their climates are linked; if CH_4 co-varies there, one can only conclude that they see the same globally-mixed gas.)

This subject has advanced to the stage where the most pressing need is for numbers describing relative importance. If rapid climate change events are *detectable* at locations remote from the North Atlantic sector, then the extent to which they can be said to be important in those remote locations has to be determined. At the present time, the inference that some abrupt changes seen in Greenland correspond to observable global-scale tracer changes seems clear; that they also correspond to truly global climate events is a reasonable, but undemonstrated, hypothesis.

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