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Interactive Comment

Interactive comment on “Synchronization of ice core records via atmospheric gases” *by* T. Blunier et al.

Anonymous Referee #2

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This paper provides an important piece of the puzzle on the topic of why Earth’s climate varies rapidly on millennial time-scales. Orbital-scale variations of climate are understood to result ultimately from changes in the distribution of sunlight in time and space over the Earth’s surface, due to cyclical changes in the Earth’s orbit around the sun at the well-known 20- and 40- kyr periods. Millennial-scale variations remain much less well understood, and apparently lack any known external (to the Earth system) forcing. Strong internal dynamics of the Earth system are therefore implicated in most or all of the millennial-scale climate variations. This is a much harder problem than the orbital one, because cause and effect are entangled in the coupled ocean-atmosphere-land system to a high degree. The internal dynamics of coupled systems are notoriously hard to understand from observations of their behaviour, without the luxury of exper-

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imental perturbation. Observations of past behaviour through paleo archives are the best we can do. Thus exceptional efforts on the part of Earth scientists are called for in this case, if understanding is to be achieved.

One clue about the internal dynamics of these millennial events may come from the observation, well-documented now from several ice cores at both poles, that Antarctic and Greenland temperatures vary in anti-phase or at least asynchronously, during one part of these events. This behaviour fits one hypothesis for the events, namely that the Atlantic ocean meridional overturning circulation lies at the heart of the events. This circulation robs heat from the southern hemisphere and deposits it in the north, partially explaining why Greenland is warmer than Antarctica today. Past cessation of this circulation would in theory have opposite effects in the two hemispheres, a pattern borne out by models. One remaining problem, however, is that the relative timing of events in two hemispheres is not as precisely determined as one would like, in order to test further hypotheses for the millennial-scale events. For example, certain hypotheses could be rejected if relative timing were known to the decade.

The significance of this paper is that it provides a step forward in reducing the uncertainty of the relative dating of an Antarctic climate record, the recently drilled and analysed EPICA Dronning Maud Land ice core. This climate record has special significance because it is the first one from the Atlantic sector of Antarctica, and shows a stronger signal of millennial changes than other Antarctic cores. Synchronization between the hemispheres is attained with atmospheric methane variations, measured in cores from both hemispheres, taking advantage of the fact that long-lived atmospheric gas concentrations are nearly the same everywhere due to the well-mixed nature of the atmosphere. Prior efforts on other cores have also used methane; one novel aspect of the present paper is that a more quantitative and objective assessment of the uncertainty is done using Monte Carlo simulation and other inverse methods. The authors have taken great pains to remove subjective decision-making from the process of matching methane records, and seem to have found a technique that should be independently reproducible by other investigators, which is the gold standard for scientific research.

Overall, this is an important contribution on a highly topical subject, and after some improvements should be published.

More specific comments on the paper include the observation that the major remaining source of uncertainty appears to come from the estimate of the EPICA DML gas age-ice age difference. Perhaps this uncertainty could be reduced if the authors pursued high-precision and high-resolution d15N of N2 measurements in the core, which might reveal signals of local temperature change in the gas phase as has been done in Greenland. Clearly, this will be much more difficult in Antarctica than in Greenland due to the much smaller magnitudes of temperature change. However, it seems to me that it is not hopeless. If successful, the d15N signals could be directly compared with the methane variations, thus comparing two gases from the same core with each other. This would eliminate the gas age-ice age difference model calculation uncertainty at least at some discrete points. The authors probably would need to have a d15N measurement every 50 years or less, with a precision of 0.002 per mil or better. This is difficult but not impossible given current laboratory methods.

Further to this line of reasoning, the authors make a strong statement that the models work, and emphasize that conditions in the past at DML were always within the range of modern calibration sites. However, the authors did not mention the fact that the models have some error when predicting Dage at modern sites that have been removed temporarily from the “training set” used in calibration. Also, even when modern sites are not removed from the training set, there is some error. It would be helpful if the authors mentioned the magnitude of this error, in years.

The physical basis for this error may be that density variations within the firn column on a scale of tens of cm or so cause substantial variations in the effective bulk density at which gases become occluded, due to the existence of sealed impermeable horizon-

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tal high-density layers in firn that has a bulk density lower than the expected (model) bubble close-off density. Some sites have these layers, while others do not. The cause of these layers may be seasonal solar-driven sublimation, wind-packing, depth hoar, radiation crusts, or other complicated processes. This so-called nondiffusive zone or lock-in zone can easily change the Dage by several hundred years. Therefore the models have neglected an important physical variable, and the complexity of this variable makes it unlikely that it will be successfully incorporated in the models anytime soon. More to the point, there is no reason to believe that these layers are present in all climate regimes. They could be present today at DML, but absent during the last glacial, for example, leading to a Dage estimate for the last glacial that is too small by several hundred years.

The authors have one very important check on the model Dage, which is the Be-10 spike at 41 ka, which provides an independent estimate of Dage at one point. But this occurs at a time that is substantially warmer than the last glacial maximum, and therefore a change in the degree of firn layering between 20 ka and 41 ka cannot be ruled out.

If the authors could produce even one tie point during the last glacial maximum using d15N-based Dage, it would greatly strengthen the paper. There is a small methane variation at 24 ka, due to Interstadial 2, and there is a corresponding Antarctic Isotope Maximum (AIM) just before it. Perhaps a d15N signal of AIM 2 could be found in EDML.

Minor comments:

The authors say that the d18Oatm decreases from 28 ka to 15 ka. I think this should be “increases” - it just happens to be plotted upside down.

The English needs some work. The paper is readable but sentence structure is often awkward and punctuation needs improvement.

The mention in the introductory paragraph about O2/N2 is potentially confusing, since

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the meat of the paper has nothing to do with this, and indeed, the gas age-ice age difference does matter for the paper. So the statement that the O_2/N_2 method avoids use of gas age-ice age differences is potentially confusing to the reader. Perhaps this sentence could be simplified, so it is more in the format of background information about previous dating methods. In particular, the statement that the O_2/N_2 method avoids gas age-ice age differences could be cut.

Interactive comment on Clim. Past Discuss., 3, 365, 2007.