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ISOTOPE TRACERS IN GLOBAL WATER AND CLIMATE STUDIES OF THE PAST AND PRESENT

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Abstract

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To date the global distribution of isotopes in modern precipitation has been characterized almost exclusively from the IAEA/WMO GNIP database, although patchiness of GNIP station records in both time and space has limited the potential of isotope hydrology and climate applications in some areas. Herein, we discuss the prospect of utilizing GCMs for simulating global isotope distributions as a supplementary tool for modern and paleoclimate isotope studies to bridge this gap. Such models currently generate reliable zonal isotope fields, and it is anticipated that future enhancements in fine-scale resolution of GCMs, and incorporation of land-surface feedbacks and topography will allow for future development of a global reanalysis data set ground-truthed by GNIP. Compilation of time-slice maps of past isotope distribution in precipitation from archival records of meteoric waters also offers significant potential for ground-truthing paleoclimate simulations extending back tens to hundreds of thousands of years.

1. INTRODUCTION

Water isotope data provide key information about past and present global climate and the global water cycle. The oxygen-isotope records obtained from carbonates in sediment cores from the world oceans, for example, yielded the first indisputable evidence of repeated Quaternary glacial-interglacial cycling, as well as shorter-term climate variability, as expressed by the interplay between the changing isotopic composition of ocean water and its temperature. Even more compelling quantitative evidence for past changes in global water balance and climate at temporal scales relevant to humanity is found in the stable isotope chronologies preserved in non-marine archives, ranging from detailed time-series of paleo-precipitation stored in glaciers, to the variably-resolved records of meteoric waters preserved in ground water, speleothems, lake sediments, tree rings and other materials.

Crucial isotopic records of very recent and ongoing hydrologic and climatic change also exist in the form of contemporary observational data, derived from sampling and isotopic analysis of meteoric waters over the past few decades. These data provide fundamental information about the global water budget that is not directly accessible or testable using other means. Foremost among such observational records, and a primary international resource, is the data base of the Global Network for Isotopes in Precipitation (GNIP), a long-running joint venture of the International Atomic Energy Agency and the World Meteorological Organization, dedicated to the documentation of the distribution of isotopes in global precipitation (e.g., see

[1]). The GNIP database has long been used for calibrating isotopic indicators of paleoclimate from various natural archives. Moreover, and perhaps more importantly, it constitutes the only comprehensive source of data for evaluating the modern global isotope field generated by atmospheric general circulation models (GCMs) equipped with water isotope diagnostics. Although simulations of the distribution of global precipitation and bulk water fluxes can be readily evaluated using more conventional data, the incorporation of isotope tracers provides an inherently more critical evaluation of a GCM's water cycle because of the need to account for the differing behaviours and abundances of three water isotopomers ($^1H^1H^{16}O$, $^1H^2H^{16}O$, $^1H^1H^{18}O$), that is, to balance simultaneously both mass and isotopes.

Prompted by the growing ability and potential of isotopic GCMs and the increasing availability of data, studies of isotopes in the hydrologic cycle are turning increasingly from identification of classical isotope effects and climatological norms to mapping and modelling of actual isotope climate (and paleoclimate). This shift in focus reflects growing appreciation of the unique information that water isotope data contribute to the analysis and understanding of global climate dynamics.

This article briefly reviews some of the key issues relevant to the evolving field of isotope climatology, focussing on consideration of the fidelity with which isotopic GCMs can simulate the global isotope field, the current state of observational data with which to evaluate such simulations of contemporary global isotope climate, and the opportunities for using paleo isotope data to assess simulations of the global isotope field under differing climates of the past.

2. MODELLING GLOBAL ISOTOPE CLIMATE

Isotopic GCMs first appeared in the 1980s as coarsely-resolved versions of the Laboratoire de Météorologie Dynamique and the Goddard Institute for Space Sciences models [2,3]. Subsequent developments have included sensitivity studies and simulations using the LMD and GISS models at finer spatial resolutions, as well as the introduction of isotope diagnostics into the ECHAM (Max-Planck Institute, Hamburg) atmospheric GCM in various simulations of present global isotope climate [4-13].

As shown in Fig. 1, control simulations of the "equilibrium" mean annual global $\delta^{18}O$ field produced by the GISS and ECHAM models both capture the expected major features of the contemporary global precipitation $\delta^{18}O$ field, notably the progressive depletion in heavy-isotope content inland and poleward (*i.e.*, classical continental and latitudinal or temperature effects) and in the subtropics (amount effects). Convincing evidence that these two models can realistically simulate the poleward transport and distillation of moisture at global scale is also provided by comparison of zonally averaged means in comparison with GNIP-derived data (Fig. 2), although acceptance of these promising results must be tempered by recognition of the limitations in the actual coverage provided by observational data (see below).

Closer examination of the maps shown in Fig. 1 reveals significant differences in the models' abilities to reproduce the finer-scale structure of the isotope field. This is especially obvious, for example, in the greater skill of the ECHAM model to resolve the anticipated altitude

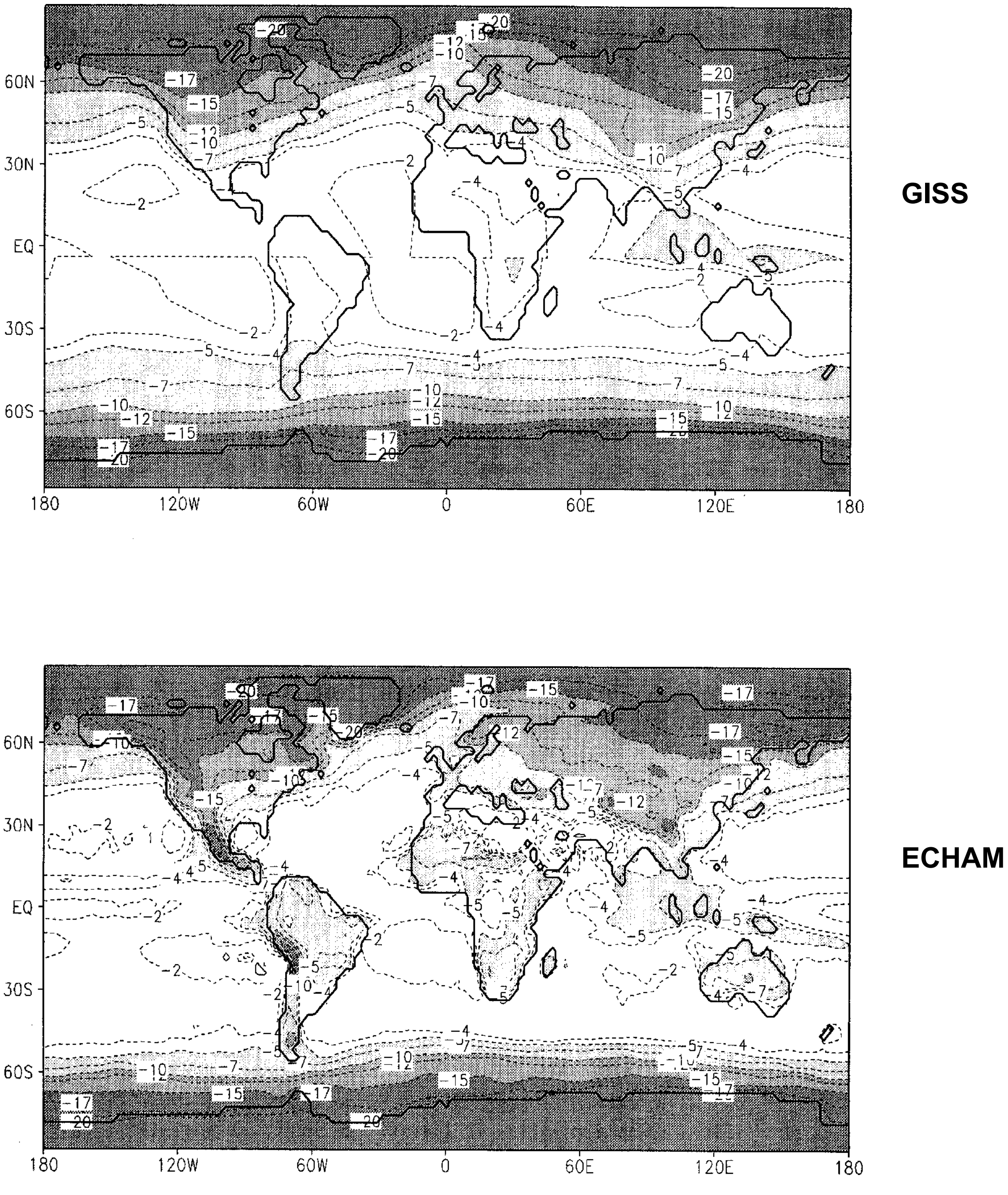


FIG. 1. *Comparison of the long-term average global weighted mean annual precipitation* $\delta^{18}O$ *field as derived from "equilibrium" simulations using the GISS and ECHAM isotopic GCMs (after [13; Fig. 2]). The GISS map is contoured from 8° latitude* x *10° longitude gridded output, whereas the ECHAM map is based on a 2.8°* x *2.8° grid. Note the significantly better representation of altitude and continental effects in the ECHAM simulation, especially at low to mid latitudes, in part attributable to more realistic representation of orography permitted by the finer spatial resolution.*

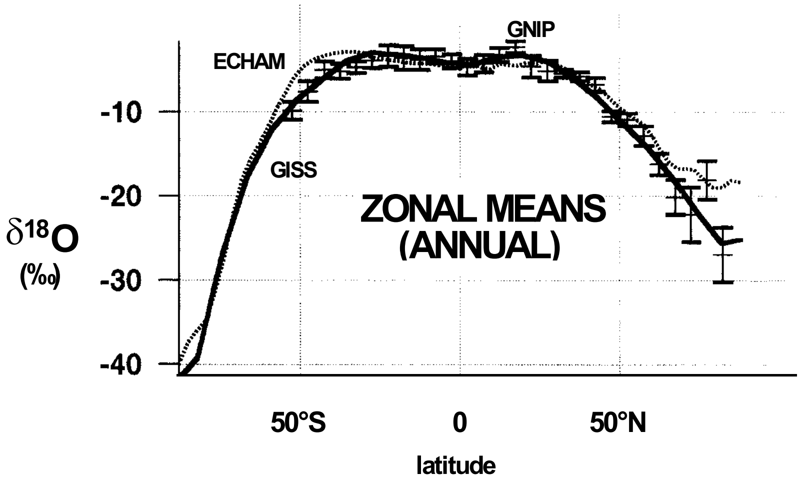


FIG. 2. *Zonally averaged $\delta^{18}O$ of weighted mean annual precipitation, as depicted in the GISS and ECHAM simulations shown in Fig. 1, compared to zonal means over 5° latitudinal intervals based on GNIP data (after [13; Fig. 3]). Both isotopic GCM simulations provide a remarkably good fit, including the steeper latitudinal gradients in the southern high latitudes versus the more shallow gradients observed in the northern hemisphere.*

effects (*i.e.*, δ^{18}O lows) associated with the Rockies and Andes mountain chains. Some of this apparent superiority would certainly disappear if both maps shared the coarser spatial resolution of the GISS simulation, yet this difference also reflects more fundamental limitations on the accurate portrayal of orographic effects, imposed by grid-based representation of Earth's surface. As illustrated in Fig. 3 and 4, the simulated distillation of moisture traversing a topographic barrier is strongly influenced by the fidelity with which that barrier can be represented, and the results naturally propogate downstream and hence, to some extent, throughout the simulated global isotope field. Improvement in coupling of GCMs and land surface schemes to account for moisture recycling is also expected to enhance the reality of the model simulations.

The skill of isotopic GCMs can also be probed using transient-state simulations, providing additional insight into how well a model's water cycle performs when forced by changing boundary conditions, such as the use of observed sea surface temperatures (SST) over a given period, rather than fixed average climatological SST fields. Although only sparse observational time-series exist for direct comparison, promising representations of variability at daily to interannual time-scales have been generated (*e.g.*, [8,9,12].

3. PRESENT GLOBAL ISOTOPE CLIMATE AND DATA-MODEL COMPARISON

As noted above, knowledge about the actual distribution of isotopes in contemporary global precipitation derives almost exclusively from the IAEA/WMO GNIP database. In spite of the patchiness of GNIP station records in both time and space, they provide the fundamental observational data for evaluating isotope-climate linkages and, ultimately, the only set of convincing benchmarks for ground-truthing isotopic GCM simulations. Consideration of the

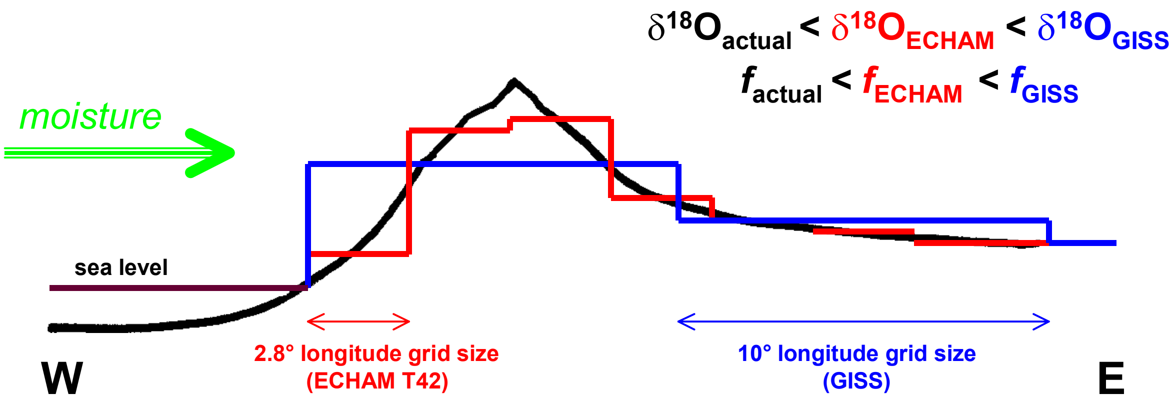


FIG. 3. *Schematic representation of variations in the distillation of atmospheric moisture crossing a topographic barrier as simulated for differing GCM grid sizes. The progressive smoothing and lowering of the topography with increasing GCM grid size leads to increased heavy-isotope and mass transfer downstream, as shown also in Fig. 4.*

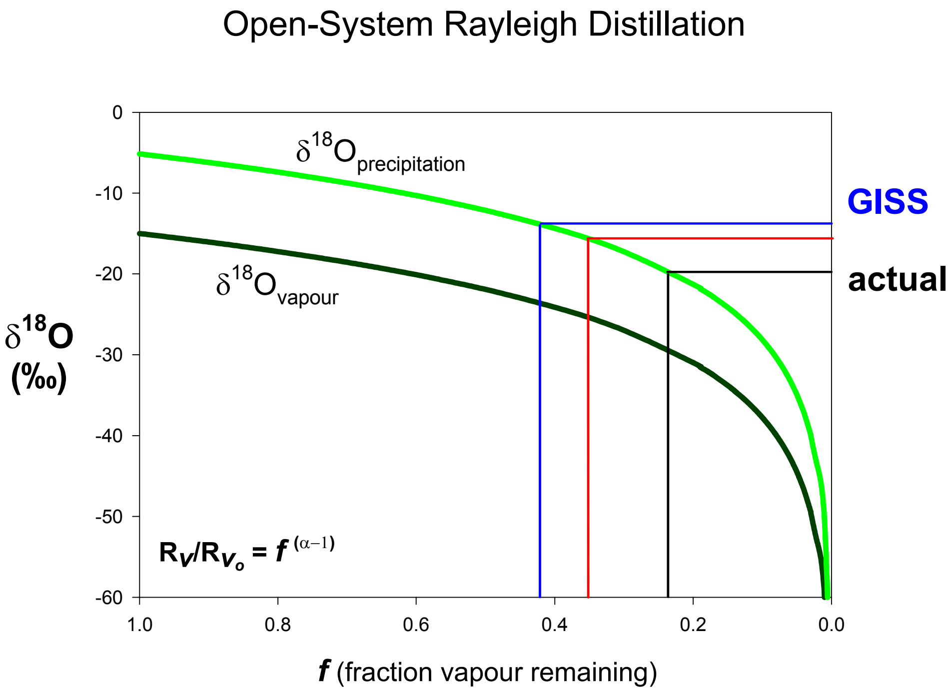


FIG. 4. *Variations in Rayleigh-type distillation of atmospheric moisture corresponding to the situations depicted in Fig. 3. Increasingly coarse GCM grid size has the effect of suppressing both heavy-isotope and mass losses downstream, leading to reductions in both isotope- and rain-shadow effects.*

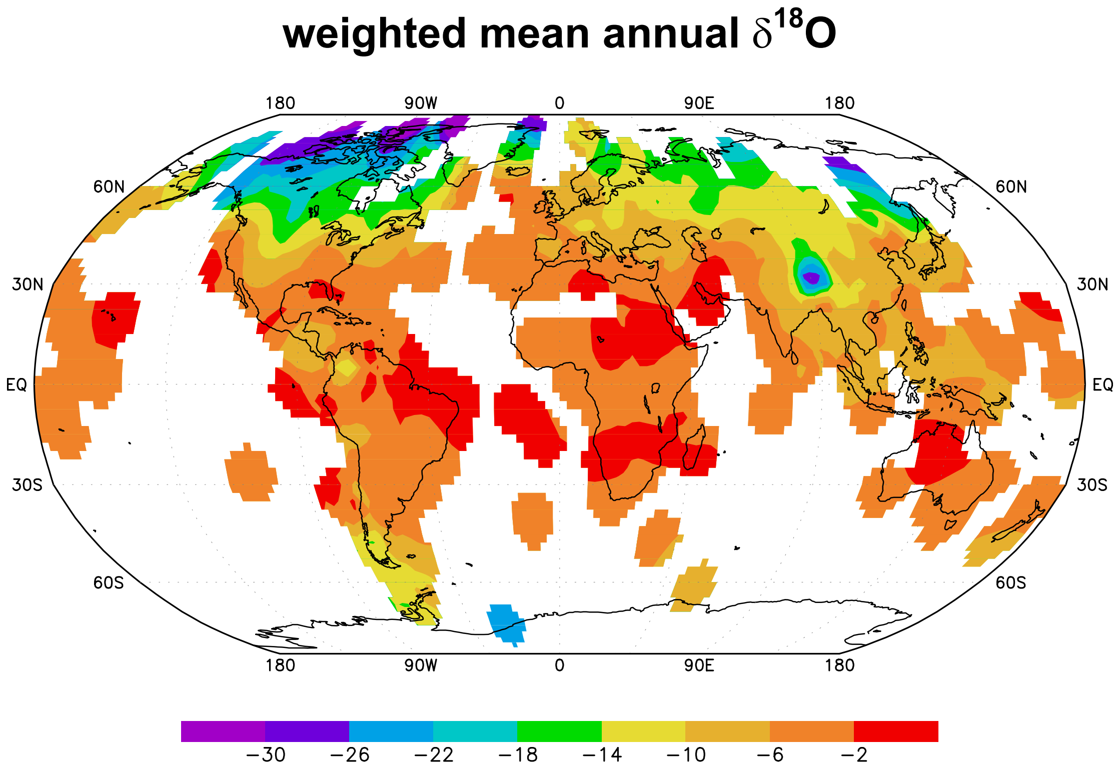


FIG. 5 *Contour map of amount-weighted mean annual* $\delta^{18}O$ *in precipitation derived from the GNIP database, for stations reporting as of 1997 (see [1]).*

global δ^{18}O field as mapped from GNIP data (Fig. 5) in relation to the two aforementioned GCM control simulations (Fig. 1), however, provides a strikingly less favourable impression of the potential for direct data-model comparison than that suggested by zonally averaged results (Fig. 2). A predominant feature of the observational data field is the presence of significant gaps over the oceans, as well as some continental areas, such as northeastern Eurasia (due to lack of stations) and northern Africa (due to lack of precipitation). Although data do exist to fill in some areas (like the polar ice caps), much of this could only be filled by unreasonably extreme interpolation between existing GNIP station data. Recognizing the practical impossibility of fully mapping the entire global isotope field in sufficient detail, this comparison clearly suggests that direct ground-truthing of isotopic GCM output through point-for-point data-model comparison is not a realistic goal.

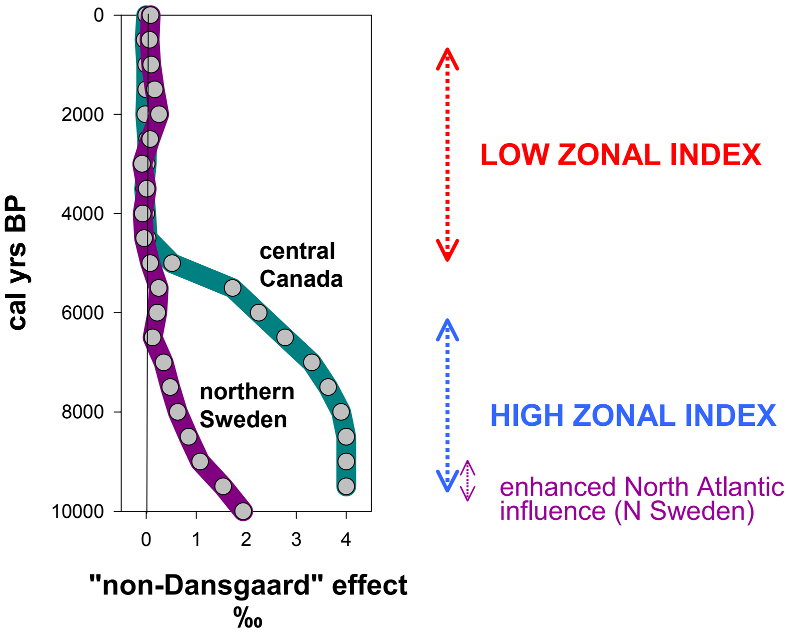
Nevertheless, more thoughtful consideration of the mapped and modelled results does lead to the alternative concept that models constrained by GNIP "benchmarks" and the prescribed need to conserve mass and isotopes, could be used to fill in the gaps in the observational data field. Informed interpolation of the global isotope field in this way could, in theory, lead to the creation of a harmonized reanalysis data set, including both annual and monthly means, as well as actual monthly time-series, analogous to those generated for various other climatological parameters. This would enhance the value of the GNIP data base significantly as a source of hydrologic input functions for water resource studies (one of its initial purposes) and as a primary training set for calibration of isotope indicators of paleoclimate, as well as providing new scope for testing and refinement of the isotopic GCM(s) used to undertake the reanalysis. Moreover, and perhaps even more importantly, the availability of a long time-series (potentially on the order of 40 years) of monthly maps of the global isotope field would offer tremendous opportunity for detailed synoptic analysis of isotope climate, including investigation of the expression of characteristic modes of climate variability on interannual to decadal time scales like the El Niño-Southern Oscillation and the North Atlantic Oscillation.

4. PAST GLOBAL ISOTOPE CLIMATE

Documentation of past global isotope climate is highly fragmentary and relatively little data-model comparison has been undertaken to evaluate isotopic GCM paleoscenarios, largely because of the paucity of well-constrained estimates of the isotopic composition of paleoprecipitation during appropriate time-slices. The Last Glacial Maximum (LGM) has been targeted frequently because of the pervasive difference from contemporary conditions, as well as the availability of a global paleo-SST field, but robust LGM paleo-isotope data are mainly limited to the polar ice caps and the best records at mid- and low latitudes originate primarily from glaciers at elevations too high to be adequately represented by GCMs. Conversely, efforts to simulate the mid-Holocene warm period (*c.* 6000 yr BP), for which more relevant paleo-isotope benchmarks exist, has been hindered by the lack of an appropriate SST field [7,13].

Although compilation of comprehensive global paleo-isotope maps remains a challenging long-term task (and a goal of the International Geosphere-Biosphere Programme, Past Global Changes project), significant opportunities already exist to selectively map smaller areas in greater detail. A prime example is the northern circumpolar region, where the highly detailed records from Greenland ice-cores can be used to anchor time-slices incorporating relatively abundant data from high-latitude glaciers, lake sediments and other archives from northern Eurasia and North America. Evidence for pronounced spatial and temporal fluctuations in apparent isotope-temperature relations (so-called “non-Dansgaard effects”) in some sectors during the Holocene, speculatively linked to changes in the prevailing strength of zonal atmospheric circulation, affords particularly intriguing potential for probing isotopic GCM ability (see Fig. 6).

FIG. 6. *Apparent deviations from present-day (i.e., “Dansgaard”) isotope-temperature relations for two areas in the northern circumpolar region, based on independent assessments of local mean annual precipitation* $\delta^{18}O$ *and temperature. The major “non-Dansgaard” signals in both areas are consistent with reduced distillation of atmospheric moisture under conditions of higher zonal index, conceptually analogous to the effect of lowering topography depicted in Fig. 3 and 4 (data from [14,15].*



5. CONCLUDING COMMENTS

The science of isotope climatology is developing rapidly, fueled in part by the accumulation and accessibility of global isotope data, especially as provided by the IAEA/WMO GNIP programme. The growing promise of isotopic GCMs is also a factor, fostering the need to critically assess and ultimately improve understanding of global climate dynamics. Particularly exciting potential exists to actively integrate mapping and modelling, with the aim of creating an actual time-series global isotope reanalysis data set. Isotope paleodata also have a role to play in these endeavours by offering access to global climate states lying well beyond the limited range captured by contemporary observations.

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