Isotope Climatology and the Global Network for Isotopes in Precipitation: Directions for the Future

Discussion Document

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1. Introduction

The IAEA/WMO Global Network for Isotopes in Precipitation (GNIP) is an international observational research network dedicated to documentation and understanding of the shifting distribution of water isotope tracers in global atmospheric moisture. The GNIP originated in the early 1960s out of the need to track the dispersal of radioactive ^{3}H produced by atmospheric testing of nuclear weapons, but attention over the succeeding decades turned increasingly to monitoring and analysis of the systematic temporal and spatial variability of the naturally-occurring stable water isotopes ^{2}H and ^{18}O in precipitation. In addition to the original desire to develop annual hydrologic input functions for water resource studies, these investigations soon led to the recognition of water isotope tracers as highly sensitive climatological parameters and monitors of ongoing global climate change.

The GNIP database is an essential resource for calibrating isotopic indicators of paleoclimate from various natural archives. Perhaps even more importantly, it constitutes the only comprehensive source of data for evaluating simulations of the modern global isotope field generated by atmospheric general circulation models (GCMs) equipped with water isotope diagnostics.

Indeed, the growing ability of isotopic GCMs has been a major factor in the emerging science of isotope climatology, since the distribution of isotopes in precipitation provides fundamental information about the partitioning of the global atmospheric water budget that is not directly accessible or testable using other means. This has increased manyfold the value of the existing GNIP database and the ongoing GNIP program, as well as firmly establishing the importance of accurate mapping and modelling of global isotope climate. The use of water isotope tracers also provides unifying physical and conceptual links between the sometimes-disparate disciplines of climatology and hydrology.

Following in the tradition of conventional descriptive climatology, as well as simply to compensate for the patchiness of the GNIP database in time and space, considerable effort has been directed toward characterization of isotope climate "norms". However, growing awareness of the dynamic nature of climate and undeniable evidence for ongoing global climate change have recently fueled much more critical re-assessment of GNIP data, which has revealed systematic isotope climate variability at annual to decadal time-scales analogous to that discernible from other meteorological parameters. These observations present exciting new challenges and opportunities to more fully explore evolving isotope climate as captured in existing and future GNIP data.

This document provides a brief overview of current issues in isotope climatology and the central role played by the GNIP program in this emerging science. Recommendations are also made regarding the future of the GNIP and how it can continue to serve in the best interests of the international scientific community. Although it hardly needs pointing out, the seeds planted some 40 years ago in the early days of the IAEA/WMO GNIP initiative have borne remarkable fruit, and overwhelming justification exists for continuing and enhancing this joint activity as a unique contribution to international climate research.

2. Past and Present

Isotope climatology is founded on the meticulous descriptive analysis of the distribution of isotopes in contemporary global precipitation. This task has been spearheaded strongly by scientists affiliated with the IAEA/WMO GNIP program (*e.g.*, Yurtsever 1975; Yurtsever and Gat 1981; Rozanski *et al.* 1992, 1993; Araguás-Araguás *et al.* 2000; Gonfiantini *et al.* 2001). Major benchmarks in the understanding and modelling of water isotope partitioning in the hydrologic cycle also include the seminal studies of Craig (1961), Dansgaard (1964), Friedman *et al.* (1964), Craig and Gordon (1965) and others, as well as numerous more recent discussions of isotopic labelling during formation of precipitation (*e.g.,* Jouzel and Merlivat 1984; Ciais and Jouzel 1994), modern isotope-climate relations (*e.g.*, Rozanski *et al.* 1982, 1992; Merlivat and Jouzel 1979; Rindsberger and Magaritz 1983), and analyses of global and regional atmospheric water balance (*e.g.*, Gat 1980, 1996, 2000; Salati *et al.* 1979; Gat and Matsui 1981; Koster *et al.* 1993; Gat *et al.* 1994; Krishnamurthy and Bhattacharya 1991).

2.1 Global isotope climate modelling

Incorporation of water isotope diagnostics into atmospheric GCMs was pioneered in the 1980s using coarse-resolution configurations of the Laboratoire de Météorologie Dynamique (Joussaume *et al.* 1984) and the Goddard Institute for Space Sciences (Jouzel *et al.* 1987) models. These experiments represented a fundamentally new approach to the critical assessment of the ability of GCMs to simulate the global water cycle, introducing the need to conserve both mass and isotopes by accounting for the slight differences in the behaviour of the major water isotopomers during phase changes. Subsequent developments included sensitivity studies and simulations using the LMD and GISS models at finer spatial resolution, and also more recently the ECHAM (Max-Planck Institute, Hamburg) and GENESIS (National Center for Atmospheric Research) atmospheric GCMs, in various simulations of present global isotope climate (*e.g.*, Jouzel *et al.* 1991, 1996, 1997a, 2000; Cole *et al.* 1993, 1999; Hoffmann and Heimann 1993; Charles *et al.* 1995; Hoffmann *et al.* 1998, 2000; Mathieu *et al.* 2002), including examination of regional climatic features like the Southeast Asian monsoon cycle (Hoffmann and Heimann 1997). Differing global isotope climates have also been simulated, commonly focusing on the last glacial maximum (LGM; *e.g.*, Joussaume and Jouzel 1993; Charles *et al.* 1994; Jouzel *et al.* 1994, 2000; Juillet-Leclerc *et al.* 1997), but also including consideration of more subtle differences represented by warm and cool ENSO phases (Cole *et al.* 1993), warmer-than-present global climate during both the mid-Holocene and possible future states forced by elevated atmospheric CO_2 concentration (Jouzel *et al.* 1998, 2000; Hoffmann *et al.* 2000) and cold episodes induced by meltwater events in the North Atlantic (Werner *et al.* 2000b).

Prominent among emerging themes in the application of isotopic GCMs to address questions in global climate and paleoclimate research is the investigation of the isotopic expression of decadal-scale modes of climate variability like the El Niño–Southern Oscillation (*e.g.* see Cole *et al.* 1993, 1999) and critical assessment of the isotopic composition of past precipitation as a paleothermometer (*e.g.,* see Jouzel *et al.* 1997, 1998, 2000; Hendricks *et al.* 2000; Werner *et al.* 2000a). The latter has been driven strongly by growing confidence in non-isotopic methods for reconstructing or constraining paleotemperatures for comparison with simulated paleo-isotope data, notably including inverse modelling of ice borehole temperature profiles, which revealed striking deviations from the δ-T relations previously used to estimate glacial-interglacial temperature changes from Greenland ice cores (*e.g.,* Cuffey *et al.* 1994, 1995;

Johnsen *et al.* 1995), as well as measurement of noble gas ratios in ground water (*e.g.,* Stute *et al.* 1992, 1995a,b) and use of paleoecological data to estimate paleotemperature (*e.g.*, Edwards *et al.* 1996; Hammarlund *et al.* 2002).

2.1.1 Steady-state isotope climate modelling

Isotopic GCMs are commonly run to simulate average "equilibrium" or "steady state" global isotope climate, characterized by essentially stationary annual cycles in each grid cell that can be compared directly with GNIP-type average monthly-composite data at individual stations (where appropriately located) or with interpolated grid values. The notion of generating equilibrium isotope climate is a logical extension of the traditional characterization of conventional climate parameters in terms of climatological norms, and provides a powerful first-order test of a GCM's basic ability to partition the atmospheric moisture budget. Further testing of the level of skill in simulating the major features of equilibrium global isotope climate can be undertaken by consideration of derived relations between isotope abundances and climate, such as the classic "effects" (temperature, continental, altitude, precipitation amount), as well as between the oxygen and hydrogen isotopes themselves (the *d*-excess parameter).

As with depiction of many other climatological processes, however, accurate simulation of isotopically-important mechanisms like rain-out and moisture recycling is highly dependent on the degree of detail with which the earth's surface can be represented, which is mainly constrained by computational limits on grid resolution. The simulated isotopic evolution (distillation) of a vapour parcel traversing a mountain range and its isotopic footprint in precipitation downwind, for example, will obviously be highly sensitive to the altitude and placement of that topographic barrier, as will other important features of regional air mass circulation. Similarly, differentiation between major land surface types, such as forests and lakes, can be expected to have a strong impact on the isotopic expression of moisture recycling in some regions via transpiration and evaporation.

Such limitations necessitate substantial expert judgement and reasoned latitude when comparing observational data with global equilibrium isotope climate simulations, since even the best simulations to date only approximate the observed spatial heterogeneity of the average distribution of water isotopes in global precipitation. An impression of the difficulty involved in evaluating isotopic GCM simulations can be gained from examination of Fig. 1, showing representations of the contemporary precipitation δ^{18}O field generated by two different models at differing grid resolutions. General patterns are certainly well-represented and similar in the two simulations, including 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), but the models are significantly restricted in their ability to reproduce the finer structure of the global isotope field. A somewhat fairer test of the ability of isotopic GCMs to capture the main features of global isotope climate, acknowledging the computational limits of current models, is provided by consideration of zonal means, which yields compelling evidence that poleward transport and distillation of atmospheric moisture (and hence energy) is being simulated realistically (Fig. 2).

In spite of their potential shortcomings, such simulations can serve as highly useful thinking tools, creating the need to critically address and explain deviations from observational data in control simulations, as a basic test of a model's ability and the utility of further experiments to hindcast or forecast isotope climate under different boundary conditions.

2.1.2 Transient-state isotope climate modelling

The skill of isotopic GCMs can also be probed using transient-state simulations, providing additional insight into how realistically a model's water cycle performs when forced by changing boundary conditions, such as the use of observed sea surface temperatures over a given period, rather than fixed average "climatological" SSTs. Transient simulations afford the opportunity to assess the magnitude and nature of the subsequent temporal variability in the simulated distribution of isotopes in atmospheric moisture and precipitation, as well as variability in the relations among isotopic and non-isotopic climate parameters. Direct comparison with observational data is limited by the restricted availability of continuous long time-series; nevertheless, promising representations of variability at time scales from interannual to daily offer further confirmation that isotopic GCMs can realistically mimic important aspects of the water cycle (*e.g.*, Cole *et al.* 1993, 1999; Hoffmann *et al.* 1998). Potential to evaluate model-simulated annual to decadal time-scale variability in the past also exists, given the ability to obtain paleo-isotope data from ice cores, tree ring sequences and other finely resolved archives.

2.3 Continental isotope paleoclimatology

Starting well in advance of the first attempts to incorporate water isotope tracers in GCMs, and continuing in parallel with both descriptive and model-based isotope climatology, has been the wide application of isotope data as indicators of continental paleoclimate. These range from estimation of paleotemperature based on the use of empirical spatial isotope-temperature relations as transfer functions, to inferences of water balance or other environmental factors without explicitly attempting to deconvolute the isotopic composition of paleoprecipitation. This extensive literature details the generation of isotopic time-series from various continental archives, with the main ones being polar and non-polar ice cores (*e.g.,* Aristarain *et al.* 1986; Johnsen *et al.* 1995; Fisher *et al.* 1995; Stuiver *et al.* 1995; Thompson *et al.* 1989, 1993, 1995, 2000), groundwaters and cave deposits (*e.g.,* Rozanski 1985; Winograd *et al.* 1992; Stute *et al.* 1992, 1995a, 1995b; Stute and Talma 1998), lake sediments (*e.g.,* Edwards and McAndrews 1989; von Grafenstein *et al.* 1992, 1999; Hammarlund *et al.* 2002), and terrestrial plant matter (*e.g.,* Edwards and Fritz 1986; Becker *et al.* 1991; Buhay and Edwards 1995; Pendall *et al.* 1999; Feng *et al.* 1999; Anderson *et al.* 2001; see also review by Rozanski *et al.* 1997).

Highlights of these studies include testing of the validity of empirical δ-T relations as temperature transfer functions from comparison of recent isotopic and instrumental temperature time-series, which indicates remarkable stability of this basic isotope-climate relation in some regions over particular time-scales, in spite of climate change (*e.g.,* Johnsen 1977; von Grafenstein *et al.* 1996), as well as identification of significant variation in δ-T relations at certain times in some locations as a prominent feature of climate change (*e.g.,* Edwards *et al.* 1996; Stute and Talma 1998; Hammarlund *et al.* 2002). Success has also been achieved in efforts to tease out the isotopic expression of past climate episodes like the Little Ice Age (*e.g.*, Hoffmann *et al.* 2001), characteristic modes of climate variability in isotope paleo-records, such as the El Niño–Southern Oscillation (*e.g.*, Cole and Fairbanks 1990; Thompson 1993) and the North Atlantic Oscillation (*e.g.,* Barlow *et al.* 1993; Appenzeller *et al.* 1998), as well as in preliminary attempts to map variations in the spatial distribution of isotopes in precipitation at times in the past (*e.g.,* Edwards *et al.* 1996; Wolfe *et al.* 2000).

Relatively little data-model comparison has been undertaken to evaluate isotopic GCM paleoscenarios, which have mainly targeted the LGM because of the strong contrast to present conditions and the availability of a paleo-SST (sea surface temperature) field to establish lower boundary conditions (CLIMAP Project Members 1981). Although considerable continental paleo-isotope data exist for the LGM, especially at polar latitudes, the best-constrained records at mid- and low latitudes primarily originate from glaciers at elevations that are too high to be adequately represented by GCMs. More definitive comparison should be possible with simulations of other climates, such as the mid-Holocene warm period (*c.* 6000 yr BP), for which considerable low-elevation paleo-isotope data exist (especially from lake sediments), but efforts to model this time-slice have been hampered by the lack of an appropriate SST field (Jouzel *et al*. 2000; Hoffmann *et al.* 2000).

Knowledge of the distribution of isotopes in past global precipitation is urgently needed by paleoclimate researchers, in addition to climate modellers. This ranges from workers seeking to use paleoprecipitation isotope data as a temperature proxy (*e.g*., see Cuffey and Marshall 2000), to those wishing to separate important environmental signals like changing lake water evaporative enrichment or other factors from the signal of changes in the isotopic composition of local paleoprecipitation (*e.g*., see Wolfe *et al.* 2000). Highly detailed isotope paleodata are available in polar regions because of the concentration of international effort to obtain long glacier ice records, but the task of compiling and mapping the shifting distribution of isotopes in paleoprecipitation in other regions, based on diverse investigations in various archives, is less advanced. The latter need has been recognized and is now being addressed within the International Geosphere-Biosphere Programme - Past Global Changes Project through ISOMAP (Isotope Calibration and Mapping Study). The ISOMAP database will extend the range of observational records into the past and provide consistent time-slices and time-series of the changing distribution of isotopes in paleoprecipitation, ultimately serving as a paleo-counterpart to the GNIP (Edwards and von Grafenstein 1995; Edwards 1998).

2.4 Isotope hydroclimatology

Water isotope tracers also play a growing role in hydroclimatologic investigations, ranging from studies of catchment-scale water balance and runoff generation to basin-scale evaporation-transpiration partitioning. Investigations directly relevant to the spatial and temporal resolution of both GNIP data and isotopic GCMs include a pioneering use of water isotope data to obtain a "snapshot" of the water balance of the Mackenzie River Basin (Hitchon and Krouse 1972; see also Gibson *et al.* 1994; Gibson 2001), assessment of long time-series of stable and radioactive water isotope data from the Danube River (Rank *et al.* 1998), and ongoing efforts to use isotopic data to constrain predictions of the hydrologic and climatic impacts of Amazonian deforestation (Henderson-Sellers *et al.* 2001). Preliminary analysis of short-term records of stable water isotope tracers and other indicators has also been undertaken recently in the St. Lawrence (Yang *et al.* 1996) and Ottawa (Telmer and Veizer 2000) river systems. As emphasized by Hoffmann *et al.* (2000), such investigations can provide highly valuable data to aid in the evaluation of isotopic GCM scenarios because of the integration provided by runoff generation over large basins, which helps to compensate naturally for the mismatch between station-based observational data and gridded model output. As well, studies like that of Telmer and Veizer (2000) reflect increasing realization of the potential to use information inherent in the distribution of water isotopes in the hydrosphere to link water and energy cycles. Both viewpoints strongly underscore the value of incorporating water isotopes into regular monitoring of the discharge and chemistry of major rivers of the world and especially within targeted field programs like the continental-scale studies of the Global Water and Energy Cycle Experiment (*e.g.*, see Edwards and Gibson 1995).

3. Directions for the Future

As the preceding discussions outline, the historical GNIP database and the ongoing GNIP program clearly have important roles to play in global climate and water research. Though noted above only briefly, it is important to keep in mind that the GNIP continues to be a source of valuable information for local hydrological studies, especially in regions where conventional meteorologic, hydrometric and hydrogeologic data are sparse, and where difficulties in managing water resources (and the human need) are often particularly acute. This would provide ample justification for maintaining the GNIP program in (at least) its current state, even in the absence of concerns about climate change and the need for better knowledge of the water cycle.

3.1 Mapping isotope climate

The increasing use and sophistication of isotopic GCMs has helped to fuel demand for more comprehensive global observational data, which are needed for improved documentation of the average distribution of isotopes in annual and monthly global precipitation, as well as for much better characterization of transient-state isotope climate at various time-scales. A significant challenge exists to provide global precipitation isotope data in a form that allows more effective comparison with isotopic GCM output, compensating for both the patchiness of GNIP data in time and space and the inherent mismatch between data from fixed stations on a complex surface and uniformly gridded GCM output on a highly simplified surface. Station data can be contoured and integrated over a grid cell for comparison with a corresponding model-generated grid value, but this can obviously engender large discrepancies in areas of high relief or highly variable surface characteristics. On the other hand, future-generation isotopic GCMs will certainly be able to simulate much finer spatial resolution and more realistic representation of Earth's surface, as can already be done with finer-resolution regional climate models nested within GCMs. As illustrated in Fig. 3, mapping of the average (steady-state) global isotope field appears to have progressed substantially from the early 1970s to 1990s, although a certain amount of this apparent progress simply reflects a substantially greater amount of interpolation, rather than a real increase in data coverage, driven by the desire for maps that could be visually comparable to isotopic GCM output. A more realistic impression of the current state of documentation of the annual and monthly average global isotope fields as contained in the GNIP data base (and the potential for better representation of such data) can be gained from examination of the series of maps in Figs. 4 and 5.

One possible strategy to bridge the gap between isotopic mapping and modelling could be to actively use isotopic GCMs as tools for interpolating and contouring GNIP station data, rather than simply comparing patterns and trends and isotope-climate effects. This could ultimately lead to the creation of a real-time global isotope re-analysis dataset (GIRAD) comprising best-approximation time-slice maps of the distribution of isotopes in global precipitation over actual months and years. Although founded on real and unchanging GNIP data, the GIRAD dataset would evolve in concert with the evolution of isotopic GCMs, providing the basis for much more detailed and effective data-model (and model-model) comparison for evaluation of equilibrium and/or transient isotopic GCM simulations. Ideally, GIRAD would incorporate all available GNIP data, weighted for reliability and with flexible, realistic error estimations reflecting the varying confidence to be placed in any given set of gridded values for $\delta^{18}O$, $\delta^{2}H$ and d-excess. This database itself could also be directly updated, tested and corrected through ongoing monthly GNIP sampling, as well as through targeted sampling campaigns such as those of the ISOHYC (Isotopes in the Hydrological Cycle) initiative or GEWEX.

4. Key points and recommendations

- GNIP data, both "historical" from the past four decades, and "contemporary" from ongoing sampling and analysis, are seeing widening use in global climate and water studies, far beyond that originally envisioned.
- The GNIP database constitutes an extremely valuable resource, recording actual time-slices and time-series of the distribution of isotopes in precipitation in different regions and different times that can be linked directly with conventional meteorologic and hydrometric observations. This potential for development of "real-time" isotope climatology represents a fundamentally new way of analysing GNIP-style data, which has traditionally been heavily smoothed and averaged in both time and space in the interests of defining artificial norms and stationary cycles. Although this traditional approach initially met the demand for depictions of steady-state isotope fields for comparison with isotopic GCM simulations, this strategy has probably impeded the development of more sophisticated understanding of global isotope climate and, arguably, has significantly undermined the justification for continuing the GNIP program and its affiliated national networks, by seeming to suggest that the major benefits of the program have already been realized.
- Maintenance of the GNIP station network world-wide at some minimum density remains essential, in order to ensure that real-time data continue to be collected. Determination of what that minimum density should be and which stations need to be re-activated or added poses crucial questions, yet the knowledge to properly inform such an evaluation does not currently exist. To a large extent, this is simply because sufficiently sophisticated analysis of existing and accumulating GNIP data remains to be undertaken. Efforts to motivate both producers (mappers) and users (modellers) of isotope climate data to undertake this challenge should be a high priority.
- One approach could be to directly couple isotope climate mapping and modelling, with the aim of producing an evolving, global isotope re-analysis dataset ("GIRAD") comprising "soft" model-interpolated gridded data fields founded on "hard" GNIP station data. Such a dataset would provide a valuable common baseline description of real-time global isotope climate for more effective testing and comparison of isotopic GCMs, as well as a much more sophisticated basis for other uses of precipitation isotope data, ranging from better definition of hydrologic input functions and their variability to the calibration of isotopic paleo-indicators, and the opportunity to incorporate additional layers of data (*e.g.*, isotopic characterization of atmospheric water vapour and surface waters).
- Although GNIP data availability has been greatly improved with the advent of electronic, web-based publication, the lack of readily interpretable and usable global and regional "isomaps" has almost certainly contributed to under-utilization of the GNIP database, simply because of the difficulty in visualizing dynamic variability in seemingly static data. Presentation of existing data in various mapped forms, beginning with traditional "steady-state" views and leading ultimately to real-time "GIRAD" maps, should also be a priority of the GNIP program.

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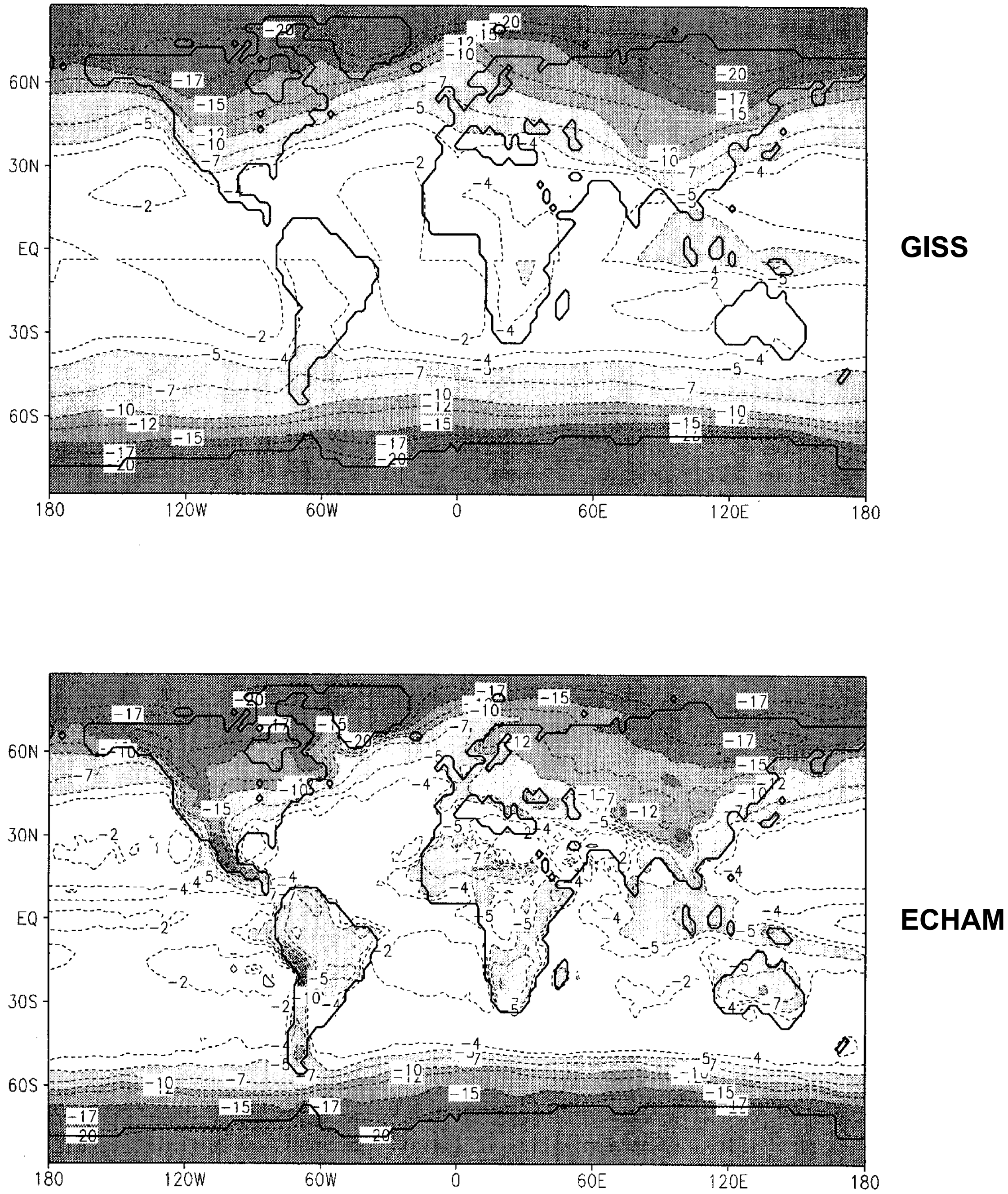


Fig. 1. Comparison of the long-term average global weighted mean annual precipitation $\delta^{18}O$ field as derived from "equilibrium" simulations using the GISS and ECHAM isotopic GCMs (after Hoffmann *et al.* 2000; Fig. 2). The GISS map is contoured from 8° latitude x 10° longitude gridded output, 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, mainly resulting from more realistic representation of orography permitted by the finer spatial resolution.

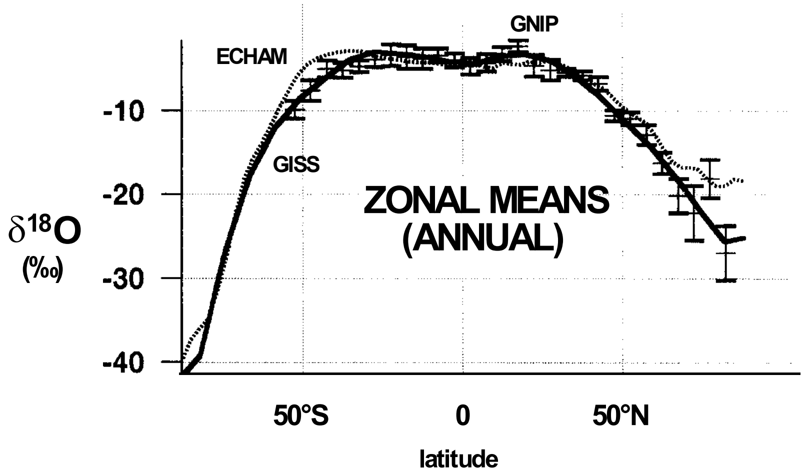


Fig. 2. Zonally averaged $\delta^{18}O$ of weighted mean annual precipitation, as depicted in the GISS and ECHAM simulations shown in Fig. 1, compared to zonal means over 5° latitudinal intervals based on GNIP data (after Hoffmann *et al.* 2000; Fig. 3). Both isotopic GCM simulations provide a remarkably good fit, including the steeper latitudinal gradients in the southern high latitudes versus the more shallow gradients observed in the northern hemisphere.

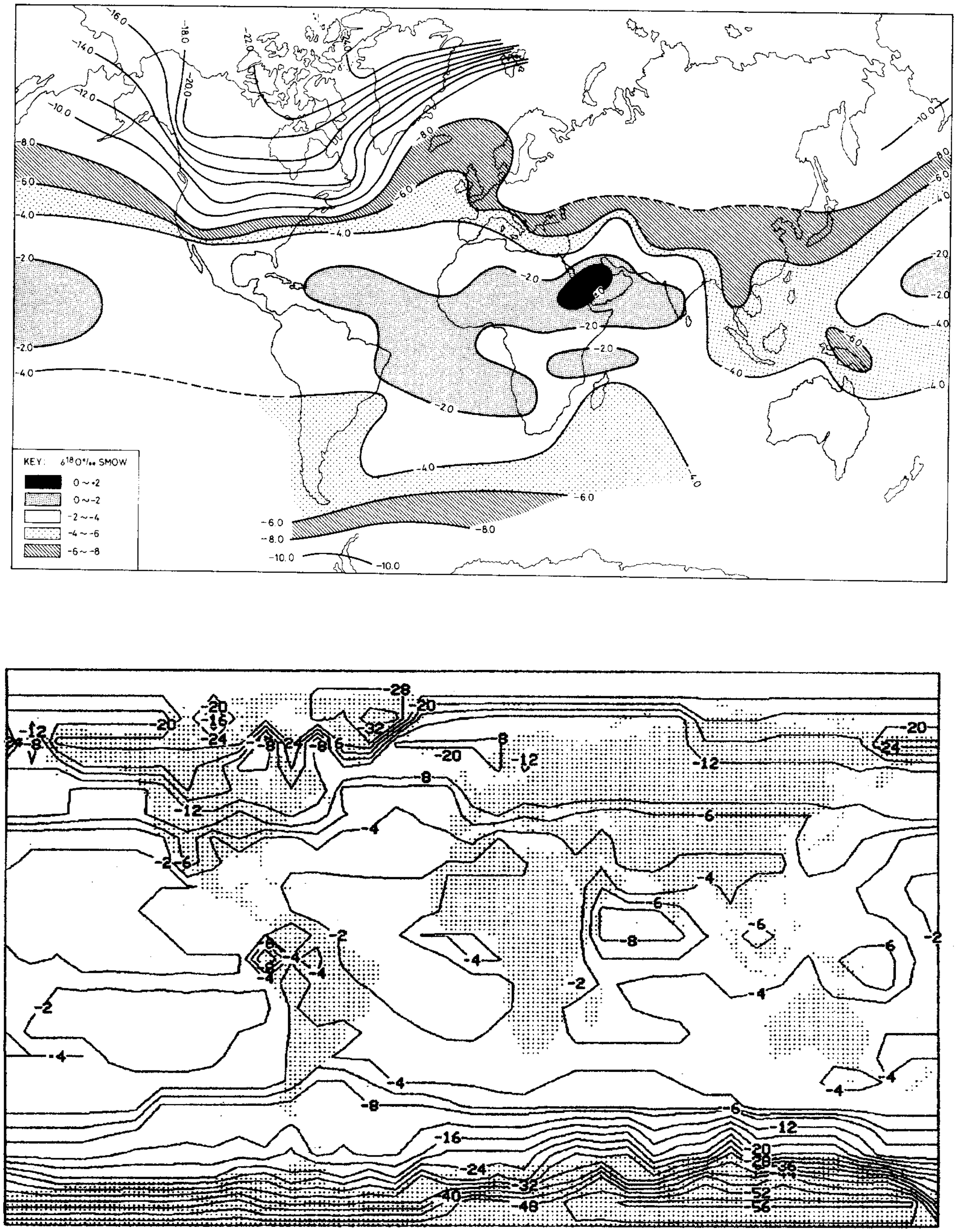
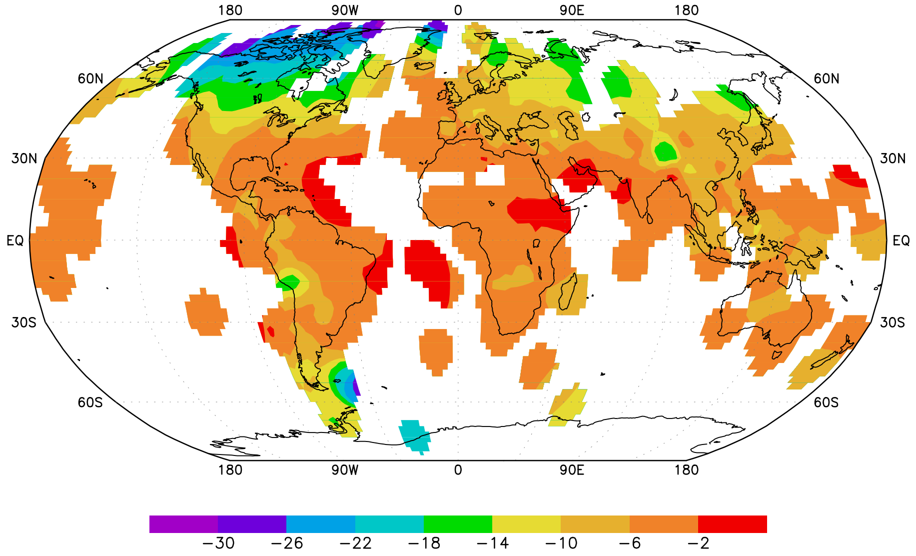


Fig. 3. Two views of the contemporary global weighted mean annual precipitation $\delta^{18}O$ field, based on observational data; (top) contoured from GNIP data for stations having at least 24 months of record as of June 1972 (after Yurtsever 1975), and (bottom) contoured from interpolated gridded data at 8° latitude x 10° longitude using GNIP station data up to 1992 supplemented by additional data from Greenland and Antarctica (adapted from Jouzel *et al.* 1998; Fig. 3).

Fig. 4. (page 20) Contour maps of the weighted mean annual precipitation $\delta^{18}O$, $\delta^{2}H$ and *d*-excess fields based on GNIP data up to 1997 (S.J. Birks, PhD thesis, University of Waterloo, in preparation). Large areas of the world oceans and continents (*e.g.*, NE Eurasia, Saharan Africa) have insufficient data to support contour mapping without excessive interpolation. Note also that significant differences exist between the depiction of the $\delta^{18}O$ field shown here and that used for comparison with the GISS model output shown in Fig. 3.

Fig. 5. (pages 21-24) Time-series of contour maps showing weighted mean monthly precipitation $\delta^{18}O$ fields generated from GNIP data up to 1997 (S.J. Birks, PhD thesis, University of Waterloo, in preparation). Consideration of the maps in sequence clearly reveals the dynamic annual cycling of the global isotope field, even in this artificial steady-state depiction. Sufficient data exist over some time periods and places to produce actual monthly time-series, which could be used to map the progress of real-time isotope climate, for example during significant climatic fluctuations like El Niño - Southern Oscillation.



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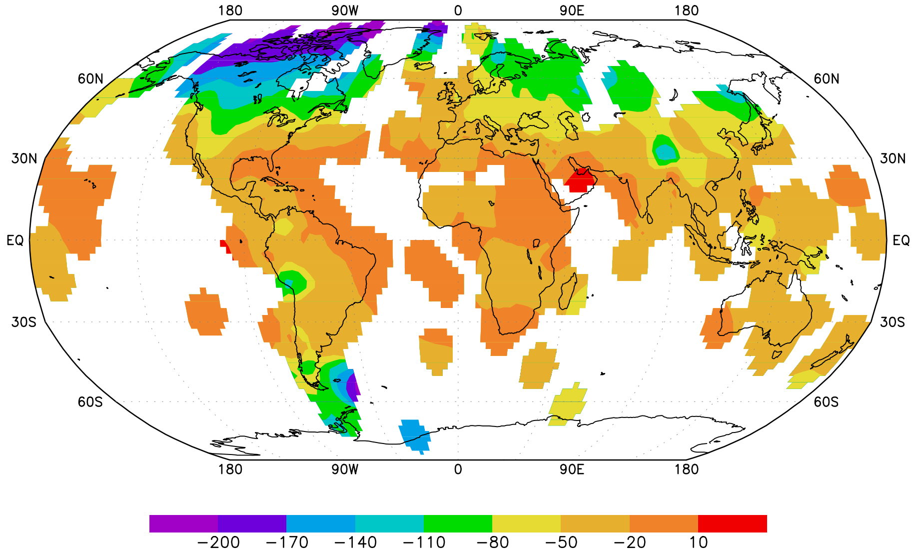

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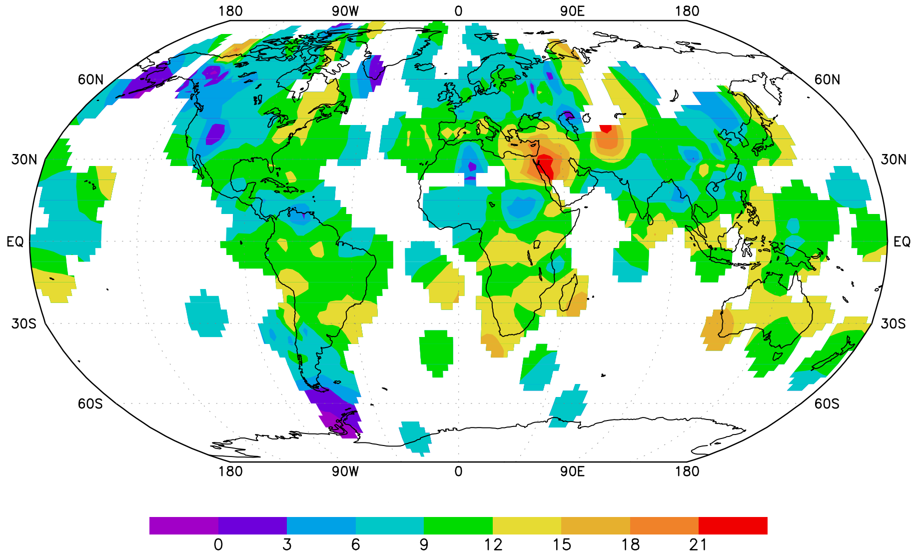

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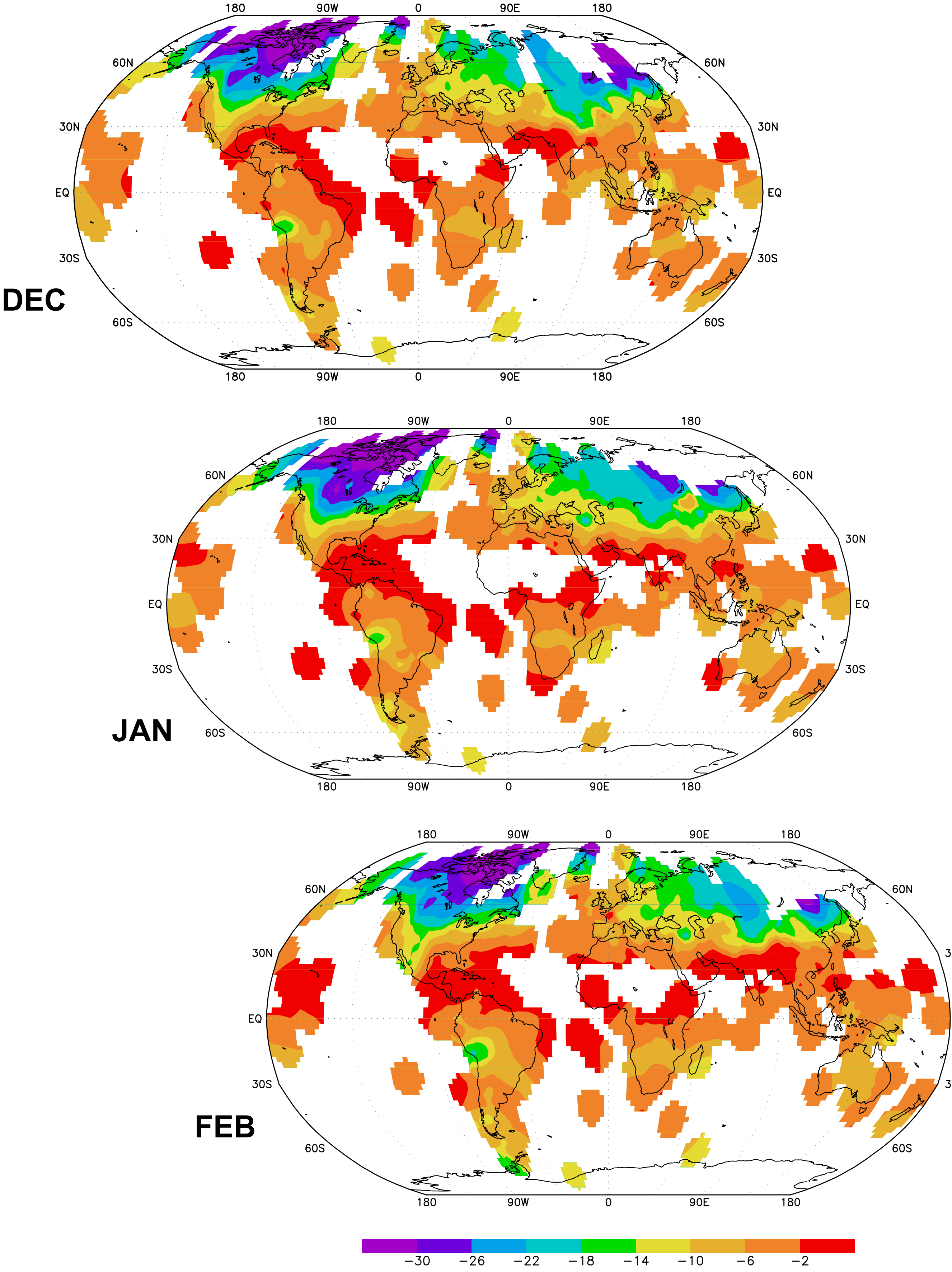
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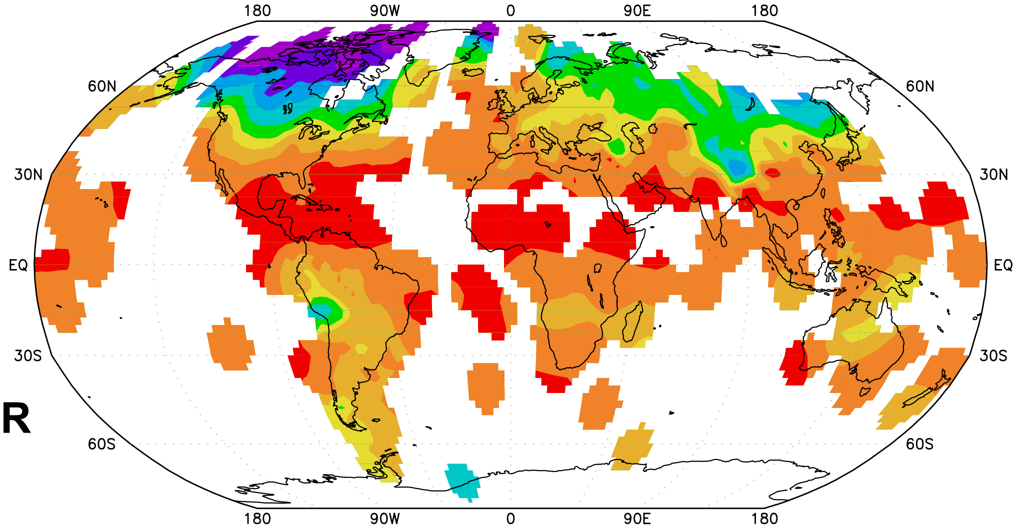
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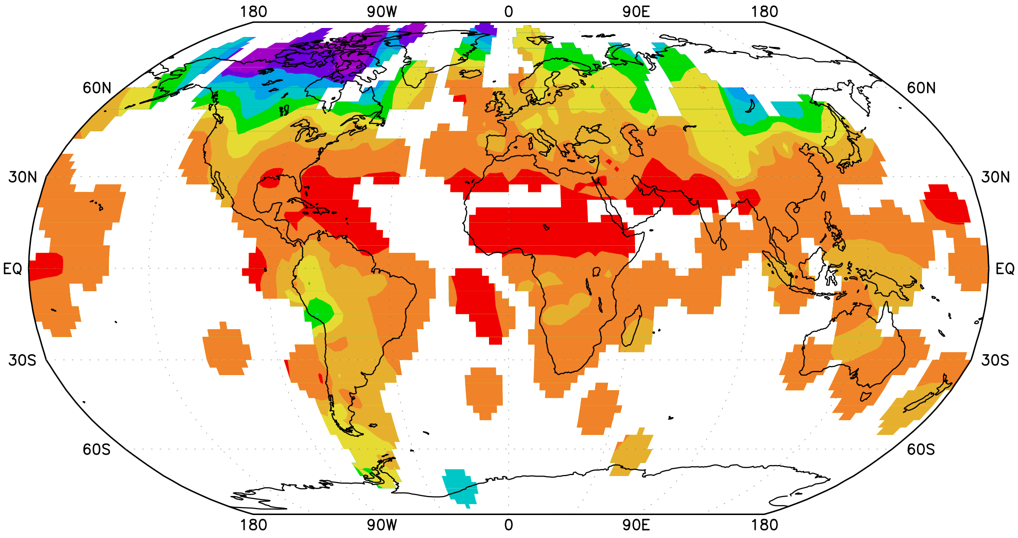
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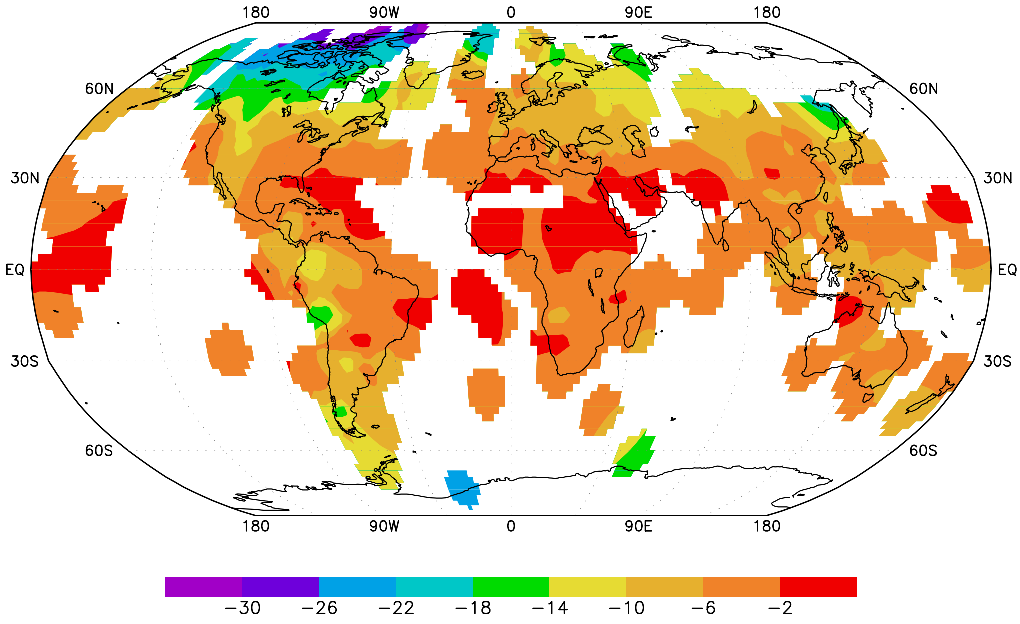
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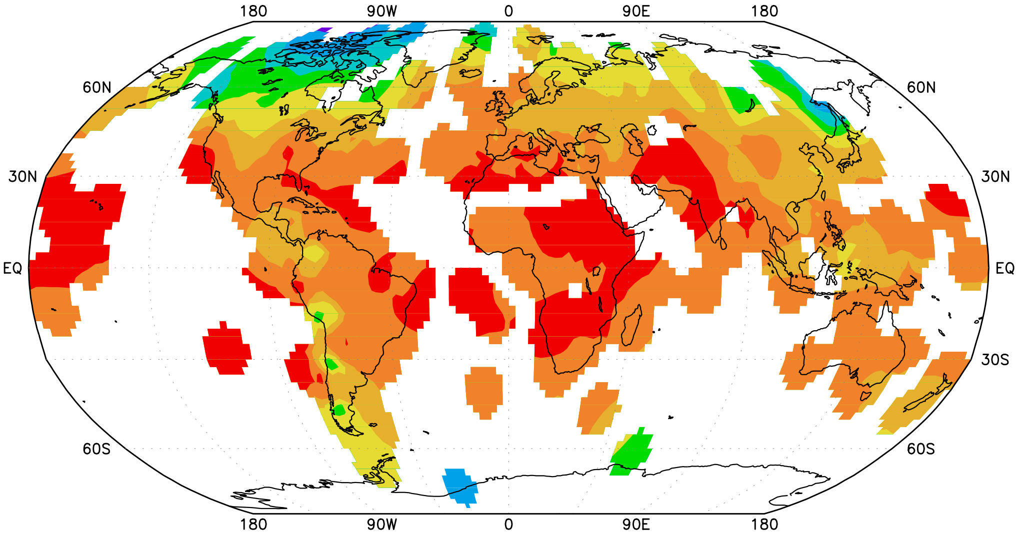
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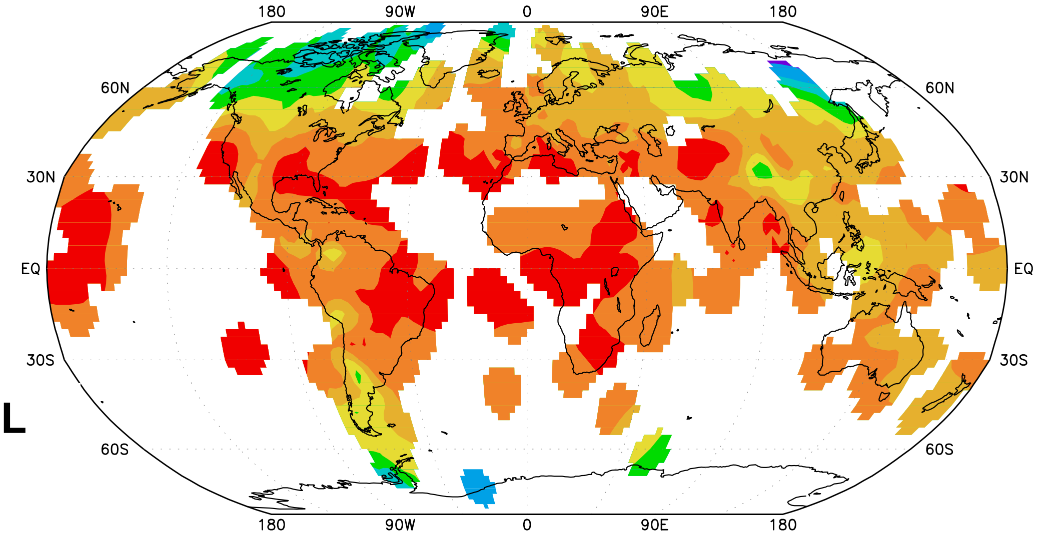
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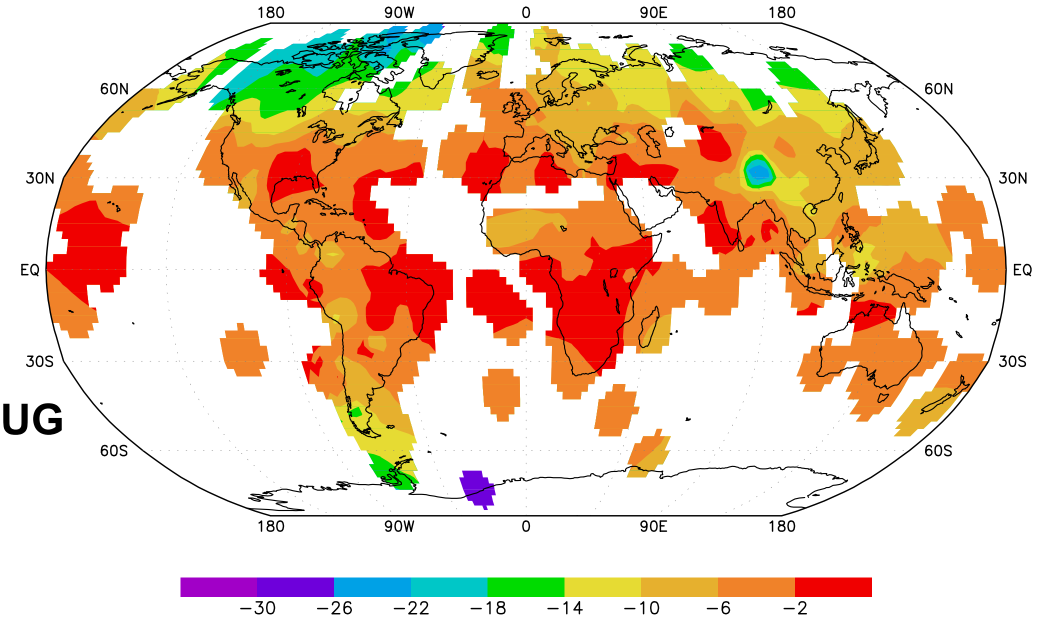
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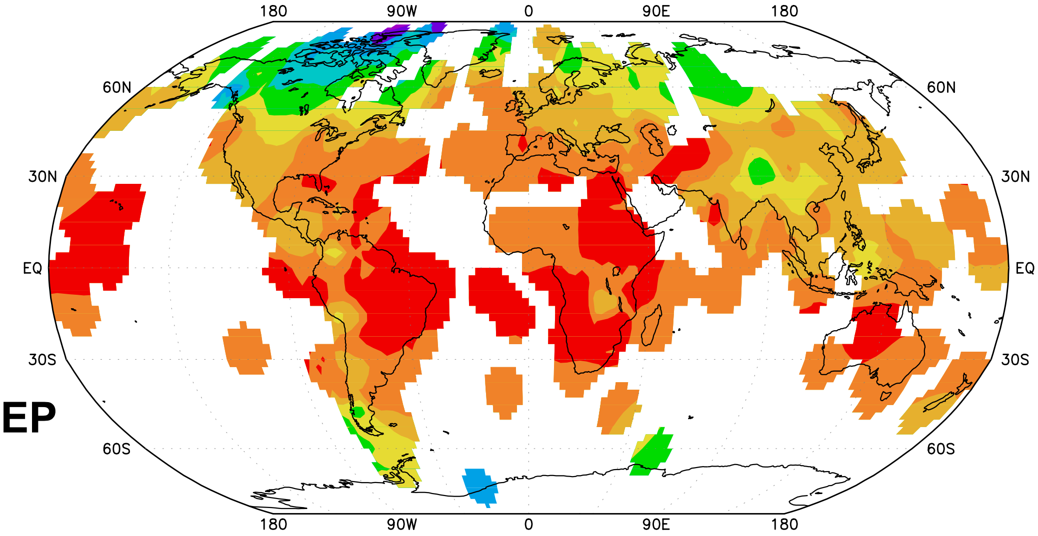
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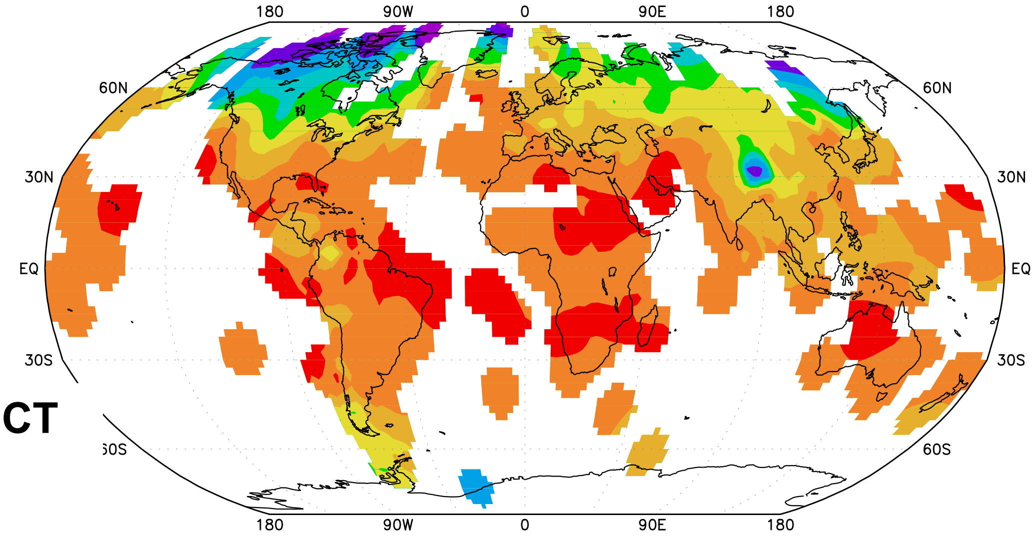
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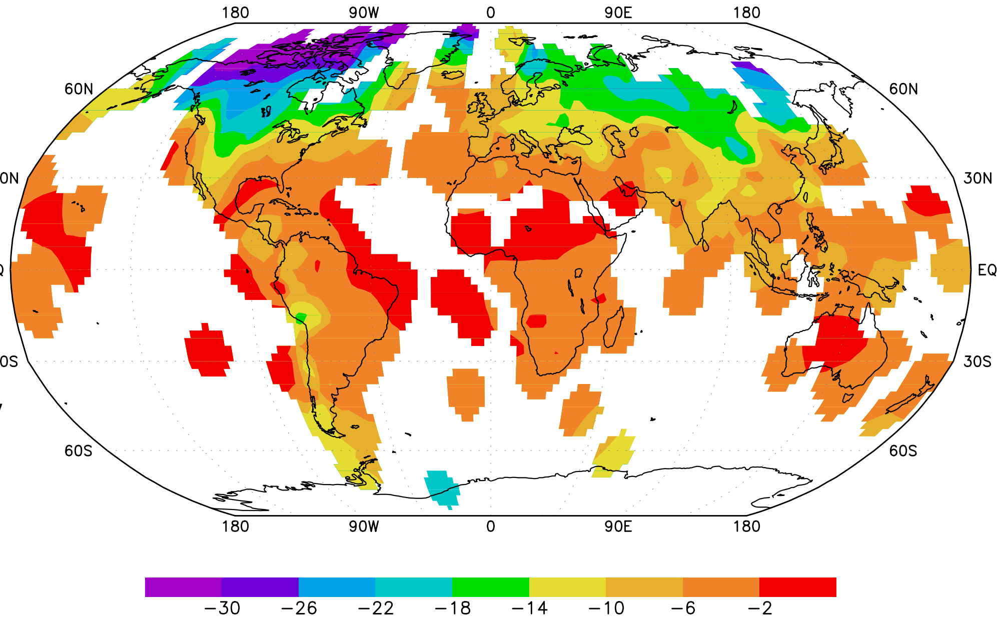
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