Continental water recycling and H 2 18 O concentrations

Randal D Koster, D. Perry de Valpine, Jean Jouzel

► To cite this version:

Randal D Koster, D. Perry de Valpine, Jean Jouzel. Continental water recycling and H 2 18 O concentrations. Geophysical Research Letters, 1993, 20 (20), pp.2215-2218. 10.1029/93GL01781 . hal-03340136

HAL Id: hal-03340136

<https://hal.science/hal-03340136>

Submitted on 10 Sep 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

CONTINENTAL WATER RECYCLING AND H_2^{18}O CONCENTRATIONSRandal D. Koster¹, D. Perry de Valpine², and Jean Jouzel³

Abstract. Using a GCM fitted with tracer diagnostics, we examine how continental moisture recycling affects the stable water isotope content of precipitation, focusing on its contribution to the "noise" in the well-established relationship between temperature and $\delta^{18}\text{O}$. On a global basis, for temperatures between -30° and 15°C , continental recycling explains more than a third of the variability in annual $\delta^{18}\text{O}$ that is not explained by temperature. Recycling appears almost as important as temperature in defining $\delta^{18}\text{O}$ distributions during northern hemisphere summer.

Introduction

The concentration of the water isotope H_2^{18}O in precipitation varies strongly with temperature. Figure 1 shows H_2^{18}O concentrations (expressed as $\delta^{18}\text{O}$, i.e., in permil units relative to standard seawater) plotted against annual surface temperature for a number of measurement sites around the globe. (Nonpolar data were obtained from the IAEA/WMO network [IAEA, 1981a]; polar data were compiled from Dansgaard *et al.* [1973], Lorius and Merlivat [1977], Morgan [1982], and Lorius [1983].) The roughly linear relationship below 15°C can be explained [Dansgaard, 1964] with a Rayleigh distillation model, in which an idealized air parcel is slowly cooled and condensate is removed from the parcel as soon as it is formed. Because the vapor pressure of H_2^{18}O is lower than that of regular water (H_2^{16}O), the $\delta^{18}\text{O}$ in the parcel vapor is reduced with each condensation event and thus with temperature.

An important application of this relationship is the inference of paleotemperatures from isotope concentrations in ancient precipitation (e.g., Jouzel *et al.*, 1987a). The success of this inference, however, may be complicated by the response of H_2^{18}O to additional climate variables. The extent of continental water recycling, i.e., the return of land surface evaporation water to the land surface as precipitation, is one potentially important variable.

The main effect of evaporating H_2^{18}O from the land surface is a replenishment of the atmosphere's H_2^{18}O content; plant transpiration in particular is non-fractionating [Zimmerman, 1967]. Due to recycling, the ocean/continent

Fig. 1. Observed $\delta^{18}\text{O}$ versus observed T (annual mean). The annual means for the IAEA [1981a] sites are computed from monthly means through precipitation weighting.

spatial gradient of heavy isotope concentration is generally (except in polar regions) much less intense than that implied by Rayleigh distillation [Gat, 1980]. This consequence of recycling has been verified in the Amazon [Salati *et al.*, 1979; Gat and Matsui, 1991] and in Europe [Rosanski *et al.*, 1982] through detailed studies of the regional hydrological cycle and associated isotope concentrations.

For non-fractionating evaporation, this effect of recycling does not change the predictions of a Rayleigh distillation model as long as the model considers only the net loss of moisture from the air parcel. A secondary effect, however, can lead to reduced $\delta^{18}\text{O}$ values. Because $\delta^{18}\text{O}$ values in precipitation tend to be smaller over continents than over oceans [e.g., Dansgaard, 1964], the water evaporating from continents in mid- to high latitudes tends to be isotopically lighter than the corresponding oceanic evaporation water, even though the latter is subject to fractionation. Thus, given two regions that are otherwise climatically equivalent, precipitation in the region with the higher recycling ratio R (defined here as the fraction of a region's precipitation water that had previously evaporated from non-ocean sources) should be characterized by lower $\delta^{18}\text{O}$ values [Dansgaard, 1964; Joussaume and Jouzel, 1993]. Note that the temperatures of land and ocean evaporation sources may be similar—although lower continental $\delta^{18}\text{O}$ values imply lower precipitation temperatures, evaporation will occur during warmer periods as allowed by diurnal and day-to-day atmospheric variability.

This implies a negative correlation between $\delta^{18}\text{O}$ and R . In a general circulation model (GCM) study focusing on interannual isotope variability, Cole *et al.* (1993) find evidence of a negative correlation in tropical South America. The GCM analysis below quantifies the isotope/recycling relationship in the temperature range $-30^\circ\text{C} < T < 15^\circ\text{C}$ through multiple regression on global fields.

¹Hydrological Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD.

²Yale University; now at Sierra Club Legal Defense Fund, San Francisco, CA.

³Laboratoire de Modelisation du Climat et de l'Environnement, CEA Saclay, France; also at Laboratoire de Glaciologie et de Geophysique de l'Environnement, CNRS, Grenoble, France.

GCM Experiment

GCMs solve the fundamental equations of motion over a discretized representation of the atmosphere, under diurnal and seasonal radiation forcing, to produce a series of global weather patterns that can be averaged over time. The simulated model climate is determined in part by the imposed parameterizations of precipitation, land surface physics, and other subgrid processes.

This study employs the $8^\circ \times 10^\circ$ NASA/GISS Model II GCM [Hansen *et al.*, 1983] with prescribed sea surface temperatures and fitted with special tracer diagnostics [Koster *et al.*, 1988]. The model computes the evaporation of a water tracer (e.g., H_2^{16}O or H_2^{18}O) from the Earth's surface and then follows the tracer through the atmosphere. Every GCM process that transports water between grid boxes (e.g., advection, precipitation, re-evaporation of raindrops) also transports the tracer. Isotope concentrations are prescribed in ocean water but predicted in land and ice. This modeling environment can produce global fields of temperature, recycling ratio, and $\delta^{18}\text{O}$ in precipitation over any time period of interest. (In contrast, recycling ratios in the real world can only be estimated indirectly, if at all.) Although GCM climate does differ in many respects from that of the real world, the simulated fields are fully consistent between themselves.

Jouzel *et al.* [1987b] performed a 3-year simulation with this isotope tracer model and compared the simulated global distributions of $\delta^{18}\text{O}$ in precipitation, which depend only on the model's climate and on the applied isotope fractionation physics, to observed distributions [IAEA, 1981a]. The model successfully captures the main features of the observed fields. The model does fail, however, to reproduce a few observed features, most notably the seasonal cycle of $\delta^{18}\text{O}$ over Greenland. Sensitivity tests [Jouzel *et al.*, 1991] demonstrate that the model is robust.

To determine GCM recycling ratios, the model was reconfigured to follow two H_2^{16}O tracers, one representing (i.e., consisting of) the water evaporating from the land fractions of all grid squares, and the other representing the complementary oceanic evaporation water. Every water mass evaporating from land was followed through the atmosphere until it returned to the Earth's surface; the travels of ocean evaporation water were similarly monitored. The recorded tracer precipitation fields (after "spin-up") allowed us to separate a given region's total precipitation into "land source" water and "ocean source" water, leading to an estimate for the region's recycling ratio. The modeling approach, including the treatment of coastal grid squares, is equivalent to that used by Koster *et al.* [1992].

For the present study, the 3-year simulation of Jouzel *et al.* [1987b] was extended two additional years. The final four years of this 5-year simulation provided monthly mean surface temperatures and $\delta^{18}\text{O}$ values in precipitation at every grid square. GCM recycling ratios were obtained in a separate 25-month simulation. The two GCM simulations use the same boundary conditions but represent different simulation years. Although the 2- and 4-year averages may reflect some interannual variability, they should be sufficient for the first-order analysis below.

Fig. 2. Simulated $\delta^{18}\text{O}$ versus simulated T (annual mean). The annual means for the different grid squares are computed from monthly means through precipitation weighting.

Simulation Results

The simulated relationship between annual temperature and $\delta^{18}\text{O}$, shown as a scatter plot in Figure 2, is very similar to the observed relationship (Figure 1). The correlation coefficient r , for the temperature range $-30^\circ\text{C} < T < 15^\circ\text{C}$, is 0.964. (The $\delta^{18}\text{O}/T$ relationship for both model results and observations breaks down at temperatures greater than 15°C , for which $\delta^{18}\text{O}$ is more highly correlated with precipitation amount [Dansgaard, 1964]. Also, Antarctic squares with temperatures below -30°C have anomalous $\delta^{18}\text{O}$ values that are probably unrelated to recycling. This paper focuses on the effects of recycling in regions with less extreme temperatures, in the range $-30^\circ\text{C} < T < 15^\circ\text{C}$.)

The simulated distribution of recycling ratio, for annual precipitation, is shown in Figure 3. The dimensionless R can be large even where the precipitation is small; thus, although the volume of recycled water in the Amazon is considerable, the recycling ratio there is still smaller than that in central Asia. The annual distribution masks the strong seasonality of R , which increases during summer.

We quantify the effect of recycling on the distribution of $\delta^{18}\text{O}$ through multiple regression. We first determine, on a monthly and annual basis, which grid squares fall into the temperature range $-30^\circ\text{C} < T < 15^\circ\text{C}$. We then regress the $\delta^{18}\text{O}$ values at those squares against the corresponding temperatures T and recycling ratios R to determine the

Fig. 3. Distribution of simulated annual recycling ratios.

Table 1. Statistics From Monthly Regression Analysis.

	no. of squares	$r_{\delta^{18}\text{O}/T}$	$r_{\delta^{18}\text{O}/R}$	$r_{T/R}$	a	b	c	$r_{\delta^{18}\text{O}/T,R}$
Jan	397	0.935	-0.518	-0.372	-10.42	0.530	-12.343	0.953
Feb	371	0.952	-0.358	-0.337	-11.70	0.547	-2.392	0.953
Mar	383	0.968	-0.279	-0.252	-11.92	0.555	-1.498	0.969
Apr	409	0.938	-0.341	-0.158	-11.63	0.599	-6.364	0.958
May	401	0.815	-0.379	0.064	-10.97	0.586	-10.130	0.923
Jun	376	0.692	-0.455	0.193	-10.66	0.494	-11.985	0.916
Jul	347	0.636	-0.570	0.125	-10.83	0.479	-12.566	0.913
Aug	361	0.688	-0.491	0.153	-10.61	0.514	-13.350	0.916
Sep	395	0.838	-0.407	0.026	-10.72	0.526	-13.211	0.942
Oct	417	0.950	-0.348	-0.181	-11.37	0.545	-8.237	0.967
Nov	414	0.943	-0.364	-0.265	-11.24	0.546	-7.858	0.950
Dec	407	0.923	-0.501	-0.312	-10.37	0.542	-15.193	0.950
Annual	408	0.964	-0.439	-0.300	-11.58	0.541	-5.029	0.977

optimal coefficients a , b , and c for the equation

$$\delta^{18}\text{O} = a + bT + cR. \quad (1)$$

The extent to which the correlation coefficient $r_{\delta^{18}\text{O}/T,R}$ for the multiple regression is higher than that for the $\delta^{18}\text{O}/T$ regression alone will indicate the importance of recycling on the global scale—it will establish, for the GCM climate, how much of the $\delta^{18}\text{O}$ variability not explained by temperature is explained by recycling. In addition, the derived c value will indicate how a given region's $\delta^{18}\text{O}$ might change with recycling ratio. (In a similar analysis, IAEA (1981b) regressed measured $\delta^{18}\text{O}$ against measured temperature, precipitation, latitude, and altitude; they found the latter three variables to be relatively unimportant.)

Results for each month are presented in Table 1. The correlation coefficient $r_{\delta^{18}\text{O}/T}$ between $\delta^{18}\text{O}$ and temperature alone is generally high, though it does decrease significantly (to 0.636) in the northern hemisphere summer, when continental recycling is strongest. As expected, the correlation coefficient between $\delta^{18}\text{O}$ and R is negative every month. The relatively small correlation coefficient $r_{T/R}$ between T and R suggests that these two variables are somewhat independent and that recycling ratio calculations (especially in northern hemisphere summer) are not biased toward warmer temperatures.

The correlation coefficients for the multiple regression are shown in the final column. For each month $r_{\delta^{18}\text{O}/T,R}$ is at least 0.91. Continental recycling clearly explains much of the $\delta^{18}\text{O}$ variability during northern hemisphere summer—*e.g.*, in July, r increases from 0.636 for the $\delta^{18}\text{O}/T$ regression to 0.913 for the multiple regression. Comparison of $r_{\delta^{18}\text{O}/T}$ and $r_{\delta^{18}\text{O}/R}$ suggests that during this season, recycling is almost as important as temperature in defining the global distribution of $\delta^{18}\text{O}$.

Results for the full year are listed in the final row. Recycling explains over a third of the scatter in Figure 2 for $-30^\circ\text{C} < T < 15^\circ\text{C}$. ($r_{\delta^{18}\text{O}/T}=0.964$ implies 7.07% unexplained variance, whereas $r_{\delta^{18}\text{O}/T,R}=0.977$ implies 4.55% unexplained variance.) The decrease in unexplained variance is based on an analysis of 408 grid squares and is statistically significant at the 0.1% level or better.

Observational Data

An analysis of observations tends to support the GCM results. Here we estimate the extent to which the consideration of recycling reduces the scatter in the observed $\delta^{18}\text{O}/T$ relationship (Figure 1)—*i.e.*, the extent to which recycling explains the $\delta^{18}\text{O}$ variability not explained by temperature.

Observed annual T and $\delta^{18}\text{O}$ values are available for a number of sites across the globe (IAEA, 1981a; Jouzel *et al.*, 1987b). No recycling estimates are available at most sites, however, so we are forced to use as surrogates the simulated R values in the corresponding GCM grid squares. Multiple regression on the combined observational and GCM data produces a “best fit” line of $\delta^{18}\text{O} = -9.701 + 0.628T - 12.78R$.

These coefficients differ from those in Table 1. Some disagreement is expected given the inherent difficulties of merging observations with GCM data. Problems likely arise, for example, from the assignment of grid-square-average recycling ratios to specific sites along coastlines, where the R gradient is very high. Also, the modeled and observed R , T , and $\delta^{18}\text{O}$ fields likely have inconsistencies. Still, the coefficients are of the same order as those in Table 1, suggesting that the $\delta^{18}\text{O}/\text{recycling}$ relationship in nature is at least similar to that predicted by the GCM.

Also telling is the fact that the correlation coefficient for the $\delta^{18}\text{O}/T$ regression in Figure 1, for the temperature range $-30^\circ\text{C} < T < 15^\circ\text{C}$, is 0.918, whereas that for this multiple regression is 0.946. The GCM's recycling ratios explain over 30% of the unexplained variance in the observed $\delta^{18}\text{O}/T$ relationship.

Discussion

Our results are limited by inaccuracies in the GCM's simulation of climate. GCMs are notoriously poor at reproducing certain features of the Earth's climate, such as precipitation fields. The “bucket model” surface hydrology and simplicities in the model's moist convection algorithm may very well lead to excessive recycling ratios. Still, the GCM fields are fully consistent between themselves, so that the statistical analysis may “cancel” (at least partially) the effects of these errors.

Given this caveat, the results of the study can be summarized as follows. Multiple regression of $\delta^{18}\text{O}$ against temperature T and recycling ratio R over grid squares for which $-30^\circ\text{C} < T < 15^\circ\text{C}$ produces significantly higher correlation coefficients than a regression of $\delta^{18}\text{O}$ against T alone, especially in northern hemisphere summer, when continental recycling is highest. Differences in recycling ratio explain over $\frac{1}{4}$ of the variability in annual $\delta^{18}\text{O}$ that is not explained by temperature. A supplementary analysis, in which observed T and $\delta^{18}\text{O}$ values are combined with GCM recycling ratios, suggests similar isotope behavior.

The GCM results reflect an assumption of negligible isotope fractionation during continental evaporation. If this fractionation were included in the model (to reflect evaporation from bare soil or fresh water lakes), the continental evaporation would be even more depleted in H_2^{18}O , and recycling would presumably increase in importance. Non-fractionating transpiration, however, is typically assumed (e.g., Rozanski et al., 1982) to dominate continental evaporation. GCM sensitivity tests [Jouzel et al., 1991] help justify the non-fractionation assumption.

Our results suggest that some knowledge or inference of a region's recycling ratio may improve the estimation of temperature from measured isotope concentrations. The derived multiple regression coefficients provide a first-order estimate of how to account for recycling.

Acknowledgments. Much of this work was performed while one of the authors (PdV) attended NASA/GSFC's 1992 Summer Institute on Atmospheric and Hydrospheric Sciences. Sylvie Joussaume, Julia Cole, Thomas Bell and two anonymous reviewers provided useful advice on the research and manuscript. We are grateful to GISS for the use of the GCM and to Reto Ruedy and Alex Armengaud for technical assistance. Climate modeling at GISS is supported by the NASA Climate Program.

References

- Cole, J. E., D. Rind, and R. G. Fairbanks, Isotopic responses to interannual climate variability simulated by the GISS GCM, *Quaternary Science Reviews*, in press.
- Dansgaard, W., Stable isotopes in precipitation, *Tellus*, 16, 436-468, 1964.
- Dansgaard, W., S. Johnsen, H. Clausen, and N. Gundestrup, Stable isotope glaciology, *Medd. Groenl.*, 197, 1-53, 1973.
- Gat, J. R., The isotopes of hydrogen and oxygen in precipitation, in *Handbook of Environmental Isotope Geochemistry*, 1, *The Terrestrial Environment*, ed. P. Fritz and J. Fontes, pp. 21-47, Elsevier, Amsterdam, 1980.
- Gat, J. R. and E. Matsui, Atmospheric water balance in the Amazon Basin: An isotopic evapotranspiration model, *J. Geophys. Res.*, 96, 13179-13188, 1991.
- Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy, and L. Travis, Efficient three-dimensional global models for climate studies: Models I and II, *Mon. Weather Rev.*, 111, 609-662, 1983.
- International Atomic Energy Agency (IAEA), Statistical treatment of environmental isotope data in precipitation, *Tech. Rep. Ser. I.A.E.A.*, 206, 1-256, 1981a.
- International Atomic Energy Agency (IAEA), Stable isotope hydrology; deuterium and oxygen-18 in the water cycle, *Tech. Rep. Ser. I.A.E.A.*, 210, 1981b.
- Joussaume, S. and J. Jouzel, Paleoclimatic tracers: An investigation using an atmospheric general circulation model under ice age conditions, 2, Water isotopes *J. Geophys. Res.*, 98, 2807-2830, 1993.
- Jouzel, J., C. Lorius, J. Petit, C. Genthon, N. Barkov, V. Kotlyakov, and V. Petrov, Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years), *Nature*, 329, 403-408, 1987a.
- Jouzel, J., G. Russell, R. Suozzo, R. Koster, J. White, and W. Broecker, Simulations of the HDO and H_2^{18}O atmospheric cycles using the NASA GISS general circulation model: The seasonal cycle for present-day conditions, *J. Geophys. Res.*, 92, 14,739-14,760, 1987b.
- Jouzel, J., R. Koster, R. Suozzo, G. Russell, J. White, and W. Broecker, Simulations of the HDO and H_2^{18}O atmospheric cycles using the NASA GISS general circulation model: Sensitivity experiments for present-day conditions, *J. Geophys. Res.*, 96, 7495-7507, 1991.
- Koster, R. D., P. S. Eagleson, and W. S. Broecker, Tracer water transport and subgrid precipitation variation within atmospheric general circulation models, *Tech. Report 317*, 364 pp., Ralph M. Parsons Lab., Dept. of Civ. Eng., M.I.T., Cambridge, MA, 1988.
- Koster, R., J. Jouzel, R. Suozzo, and G. Russell, Origin of July Antarctic precipitation and its influence on deuterium content: a GCM analysis, *Climate Dynamics*, 7, 195-203, 1992.
- Lorius, C., Antarctica: Survey of near-surface mean isotopic values, in *The Climate Record of the Polar Ice Sheet*, edited by G. de Q. Robin, pp. 52-56, Cambridge University Press, New York, 1983.
- Lorius, C. and L. Merlivat, Distribution of mean surface stable isotope values in East Antarctica; Observed changes with depth in a coastal area, Isotopes and Impurities in Snow and Ice, *IAHS Publ.*, 118, 127-137, 1977.
- Morgan, V. I., Antarctic ice sheet surface oxygen isotope values, *J. Glaciol.*, 28, 315-323, 1982.
- Rozanski, K., C. Sonntag and K. Munnich, Factors controlling stable isotope composition of European precipitation, *Tellus*, 34, 142-150, 1982.
- Salati, E., A. Dall'Olio, E. Matsui, and J. Gat, Recycling of water in the Amazon Basin: An isotopic study, *Water Resour. Res.*, 15, 1250-1258, 1979.
- Zimmermann, U., D. Ehhalt, and K. Munnich, Soil-water movement and evapotranspiration, changes in the isotopic composition of the water, in *Isotopes in Hydrology*, pp. 567-585, International Atomic Energy Agency, Vienna, Austria, 1967.
- P. de Valpine, 309-D Steiner St., San Francisco, CA 94117.
- J. Jouzel, Laboratoire de Modelisation du Climat et de l'Environnement, Direction des Sciences de la Matiere, Batiment 709, Centre d'Etudes de Saclay, 91191 Gif sur Yvette, France.
- R. Koster, Code 974, NASA/Goddard Space Flight Center, Greenbelt, MD 20771.

Received: March 31, 1993

Accepted: June 29, 1993