Global Simulation of Stable Water Isotope Circulation Using Iso-GSM and Spectrum Nudging

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INTRODUCTION

Stable oxygen and hydrogen isotopes in water ($H_2^{18}O$ and HDO) are useful natural tracers for the hydrologic cycles. Because their concentration is very sensitive to phase changes of water during its circulation, geographical and temporal variations of isotopic ratios emerge in the land surface reservoirs such as rivers and ground water. In order to understand, explain and apply observed variations in the reservoirs, the relation between atmospheric processes and isotopic information in water vapor and precipitation has been intensively studied (e.g., Gedzelman and Arnold, 1994; Webster and Heymsfield, 2003).

There is a dynamical method that utilizes isotope-incorporated AGCMs to understand the process (Joussaume et al., 1984, Jouzel et al., 1987; Hoffmann et al., 1998; Mathieu et al., 2002; Noone and Simmonds, 2002; Schmidt, et al., 2005). These methods try to simulate three-dimensional structure of vapor isotope distribution with explicit consideration of complex phase changes of water associated with atmospheric circulation. These simulations showed good agreement with climatological distribution of isotopes, but their variations were not correctly corresponded with those of the observations (Hoffmann et al., 2000). The reason for this poor simulation is partly due to the poor representation of atmospheric circulation by the AGCM's, which is forced only by the observed sea surface temperature. In fact, Yoshimura et al. (2003; 2004) successfully reproduced the daily to interannual variations of precipitation isotopes over the globe by a simpler model using the observed circulation from reanalysis and concluded that the isotopic AGCMs would be capable to simulate day-to-day isotopic variations in precipitation more accurately if the large scale circulation fields are accurately simulated.

Recently, Yoshimura and Kanamitsu (2008) developed a global application of the spectral nudging technique for the purpose of downscaling reanalysis over the globe. The technique is an economical alternative to very expensive high-resolution data assimilation and enables us to downscale global coarse resolution reanalysis, keeping the large scale features unaltered but without distorting the small scales.

In this study we apply this global spectral nudging technique to an isotopic AGCM, but without increasing the horizontal resolution of the model. This method is considered as simplified isotope data assimilation without using isotope observation, and produces multi-decadal and three dimensional isotopic gridded data. We used Iso-GSM, which was newly developed from up-to-date version of the Scripps ECPC (Experimental Climate Prediction Center) GSM (global spectral model; Kanamitsu et al., 2005) as a GCM, and NCEP/DOE Reanalysis 2 (Kanamitsu et al., 2002) as an observed large scale circulation.

METHOD

(a) Model description

Scripps ECPC GSM, which was based on the medium range forecast model used at NCEP for making operational analysis and predictions, was applied in this study. Physics and dynamics in the model are mostly the same as those in Reanalysis 2, except that RAS (Relaxed Arakawa-Shubert) deep convection and NOAH land surface are used in this study. For more detail of the GSM, refer to Kanamitsu et al. (2005).

Gaseous forms of isotopic species (HDO and $H_2{}^{18}O$) were incorporated into the GSM as prognostic variables in addition to water vapor. The isotopic tracers are independently advected by the dynamical processes whereas they are differently treated as water vapor in the physical processes, due to the small but significant isotopic fractionation associated with phase transitions as explained in the next section. Such physical processes in the GSM include precipitation processes (convective precipitation and large scale condensation) and surface and boundary layer processes.

The equilibrium fractionation factors were taken from Majoube (1971a and 1971b). Most fractionation at a phase transition occurs at thermal equilibrium except for three particular cases; surface evaporation from open water (Merlivat and Jouzel, 1979); condensation from vapor to ice in super-saturation condition (Jouzel and Merlivat, 1984); and evaporation from liquid raindrop into unsaturated air (Stewart, 1975). These are called kinetic fractionation, in which the difference of molecular diffusivities (Merlivat, 1978) plays a key role. For the equilibrium fractionation, the Rayleigh distillation theory is applied for vapor condensation and evaporation during all precipitation processes. These isotopic parameterizations are commonly used among the previous isotopic AGCMs (e.g., Brown et al., 2006). Iso-GSM assumes no fractionation when water evapotranspirates over land, even though there can place significant influence on the global isotopic cycle (e.g., Yoshimura et al., 2006). Every precipitation is fully mixed into simple bucket-type storage and isotope ratio of evapotranspiration is assumed to be the same as stored values. These parameterizations are summarized in Table 1.

Table 1: Summary of the isotopic parameterizations and the spectral nudging technique

Isotopic parameterizations	
Equilibrium fractionation	Majoube (1971a, 1971b)
Molecular diffusivity	Merlivat (1978)
Ice crystal formation	Jouzel and Merlivat (1984)
Open water evaporation	Merlivat and Jouzel (1979)
Raindrop evaporation	Stewart (1975)
Surface isotopic reservoir	No fractionation, 50 mm bucket
Sea water	Constant ($\delta^{18}O=\delta D=0‰$)
Forcings and nudging technique	
SST and sea ice	NCEP analysis
Circulation field forcing	Reanalysis 2 (Kanamitsu et al., 2002)
Nudging technique	Yoshimura and Kanamitsu (2007)
Nudging variables	U, V, and T
Nudging coefficient	0.9
Nudging scale	1000 km

(b) Global spectral nudging technique

This study adopts the spectral nudging technique for a global simulation (Yoshimura and Kanamitsu, 2008); Fourier series coefficients of zonal waves whose physical scale is larger than 1000 km for temperature and zonal and meridonal wind components are nudged towards 6-hourly Reanalysis 2 (R2) data (Kanamitsu et al., 2002) at all 28 sigma-levels. The nudging constant of 0.9 is used. Water vapor and the isotope species were not nudged, so that they were passively predicted under the conservation law.

A root mean square difference of 500 hPa geopotential height is one of the good indicators to measure the fitness of the thermo-dynamical field of the Isotope Reanalysis to the NCEP/DOE Reanalysis. The average RMSD at 500Z is about 4-7 m for all period in all the 6-hourly steps, indicating that the simulation keeps the large scale thermo-dynamical field of R2.

(c) Simulation period and specification

We chose T62 horizontal resolution (about 200 km) and 28 vertical sigma levels for isotope analysis, same as R2 resolution. After a spin-up period of about 10 years, the simulation was run for 1979 to 2006, the period for which R2 data is available. The NCEP analyses of sea surface temperature and ice distribution were used. The monthly averaged precipitation isotope distributions are compared with GNIP (Global Network of Isotopes in Precipitation) observations (IAEA, 2001). Daily observation data over Thailand are taken from Yoshimura et al. (2003).

RESULTS

(a) Long term trend of isotopes in global precipitation

Figure 1 presents 20-year (1980-1999) time series and climatology of global monthly mean precipitation total, δ^{18}O, and d-excess. Ranges of three iso-AGCM results (SWING, 2007) are also shown. First, a trend in global precipitation is detectable in the Isotope Reanalysis, especially the latter half of the period. This is due to the fact that the Isotope Reanalysis inherited the positive precipitation trend of R2. The latest reanalysis product by ECMWF, ERA40, also showed strong positive trend (Chen and Bosilovich, 2007). Although we do not have any good evidence to believe in this trend, it is important to find that our product's well capturing the feature of the reanalysis data. The precipitation amount is somewhat comparable to other models. There is no significant trend in δ^{18}O but there is for d-excess. This difference in trend may present a new interpretation of d-excess signal, but further investigation is left for future studies.

Despite of model differences, both δ^{18}O and d-excess of the Iso-GSM are in the upper range of SWING (stable water isotopes intercomparison group) member. Monthly climatology of δ^{18}O and d-excess in global precipitation ranges from -7.0 to -6.5 ‰ and 8 to 10 ‰, respectively, in Iso-GSM. Seasonality of δ^{18}O and d-excess resembles the pattern as that of precipitation indicating the seasonality is strongly influenced by precipitation total. However, there is some difference in the phase, i.e., δ^{18}O's higher peak is a couple of months earlier than that of precipitation, whereas d-excess's opposite pattern hits its lower peak a couple of months later.

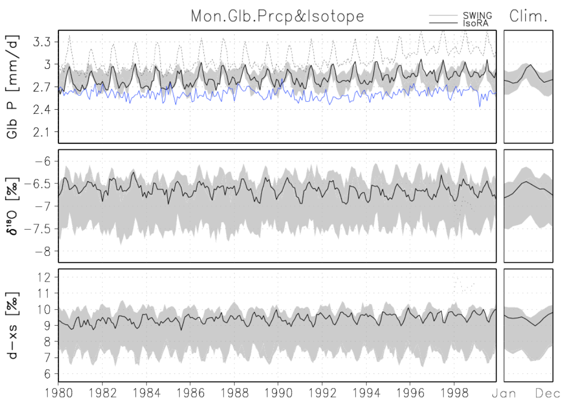

Figure 1: Monthly variation and climatology of global mean precipitation, δ^{18}O, and d-excess. Shades indicate ranges of three simulations by SWING member. Blue, dashed, and black solid line show GPCP, R2, and Iso-GSM, respectively.

(b) Climatology of global distribution of isotopes

Figure 2 shows annual climatology and seasonal departure (DFJ-JJA) of δ^{18}O in precipitation for observation (GNIP) and the simulation (Iso-GSM). The simulation agrees well with the observation for both annual and seasonal climatology. For annual climatology, lower δ^{18}O values in high latitudinal regions ("latitude effect"), in high elevation regions ("altitude effect"; over Andes, Sierras, and Tibet, etc.) and in inland region ("continent effect"; e.g., over Siberia) are clearly reproduced. Small hotspots with especially high δ^{18}O values over southern Atlantic and Pacific indicate large influence of re-evaporation from droplets that causes removal of normal water preferably and enrichment of droplets (so-called "post condensation process").

Precipitation $\delta^{18}O$ in DJF are smaller over northern high latitude and moist regions in the southern tropics, and they are higher over southern high latitude The mechanism of these similar seasonal departures are different; in the northern high latitude, low air temperature and corresponding fewer moisture content plays significant role ("temperature effect"), but strong monsoonal variations that give large precipitation in DJF deplete precipitation $\delta^{18}O$ over tropics ("amount effect").

In Figure 3, similar figures as Fig.2 but for deuterium excess (d-excess; defined as $\delta D - 8 * \delta^{18}O$) are shown. The d-excess is particularly sensitive to kinetic processes in water surface and post condensation processes, and it has more complex geographical distribution. The lowest values appear over the southernmost tip of South America and Antarctic Peninsula. Iso-GSM shows that such low values are parts of the zonal band in 70 to 50 degree south in the Antarctic Ocean. In other oceanic areas, d-excess ranges from 6 through 10 ‰, where observation and simulation agree well. Comparing with oceanic precipitation, they both show slightly larger d-excess over most of the lands, such as over South Africa, South America, parts of Europe, northeastern part of North America, and Australia. The highest values over Middle East Asia are reasonably well simulated although with somewhat overestimation.

Larger d-excess values in JJA in southern hemisphere are reasonably reproduced by the model, *i.e.*, over South America, Australia, Africa, and southern oceanic regions. Those JJA peaks also appear in Bamako (Mali), Hetian (China/Xinjiang), the Maritime continents, east Europe and Russia, and those features were captured in the model, especially the Bamako's bull eye. On the other hand, most of other areas in the northern hemisphere show larger d-excess in DJF such as over North America, East Asia including Japan, Middle East Asia and Mediterranean regions. Model captured most of them, except the opposite seasonality in the northern North America.

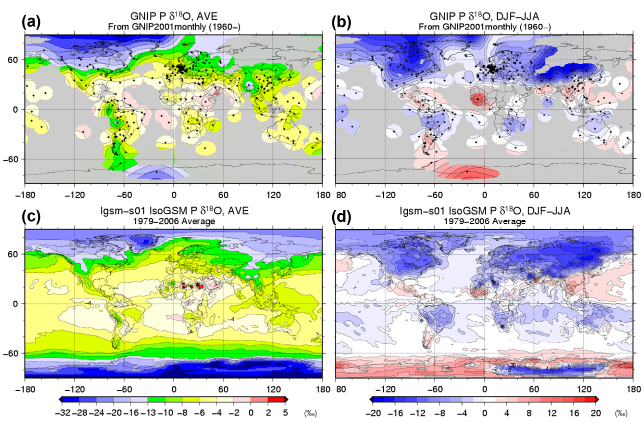

Figure 2: Annual average (a and c) and seasonal difference (b and d) of precipitation isotope ratio ($\delta^{18}O$) by GNIP observations (a and b) and Iso-GSM simulation (c and d)

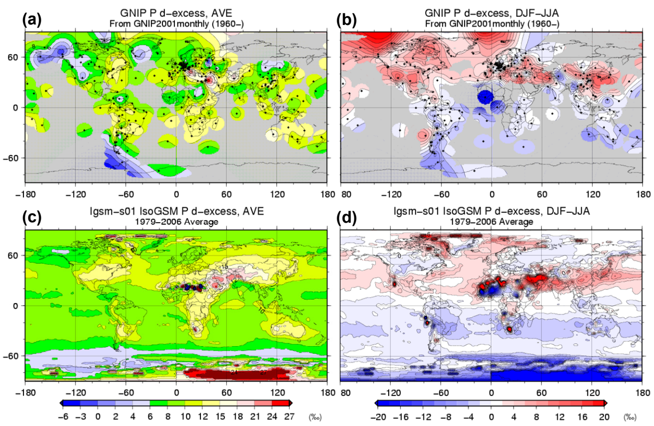

Figure 3: Same as Figure 2, but for d-excess

(c) Daily to interannual variations over specific locations

One of the biggest advantages of the study is that the analysis provides wide ranges of time scales, and allows us to compare daily through inter-annual variations. Figure 4 compares daily precipitation isotopic ratio at three sites over Thailand. The diurnal variation was well captured in this analysis. This analysis confirmed the results of Yoshimura et al. (2003; hereafter Y03), that large scale moisture transport is the main control of the daily isotopic variations. The correlation coefficients of isotopic ratio between analysis and observation were 0.33 to 0.66, which were not as good as Y03, *i.e.*, 0.48 to 0.77. There seem to be two main reasons for this inferior performance; (1) errors in detail isotopic processes, and/or (2) accuracy of model produced precipitation (Y03 used observed GPCP precipitation). These problems may be solved by more detailed in-situ observations and high-resolution regional simulations, which are left for future studies.

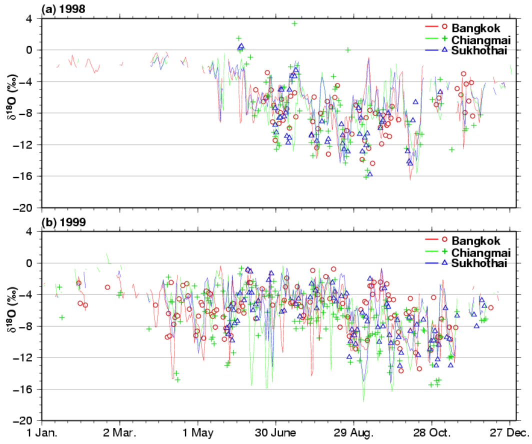

Figure 4: Daily variations of precipitation $d^{18}O$ in Thailand, 1998 (a) and 1999 (b). The symbols indicate observations at three sites and the lines indicate Iso-GSM simulations.

Figure 5 shows variations of monthly anomaly of $\delta^{18}O$ at Vienna and Bangkok. The climatology of precipitation isotopes are reasonably well-simulated by all isotopic AGCMs, therefore the additional value of the new dataset should exist in the reproduction of the interannual variations Evidently, both at Vienna and Bangkok, the interannual variations were reproduced only by the Iso-GSM. Table 2 is the simple average of correlation coefficients over all available GNIP observation sites (about 250). It clearly shows that the Iso-GSM had the best accuracy in the monthly variations as well as in the monthly anomaly variations of precipitation $d^{18}O$. This success is mostly due to the use of observed atmospheric circulation in Iso-GSM, while the other models are forced only by SST (and/or sea ice). It is cautioned that this result does not imply superiority of the isotopic parameterization nor other dynamical and physical processes in Iso-GSM, but it does imply the importance of the atmospheric circulation.

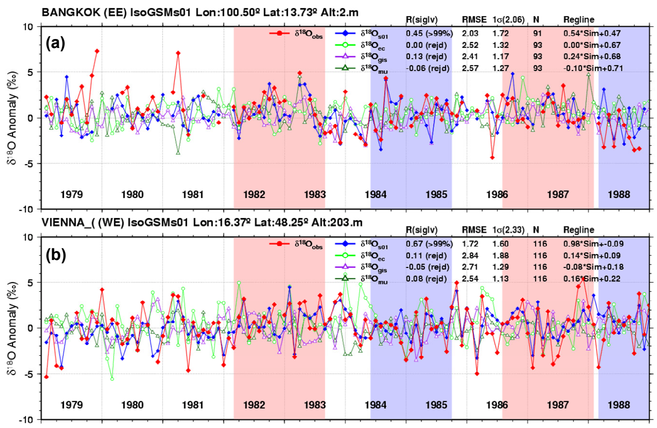

Table 2: Global average of the direct correlation and anomaly correlation coefficients between GNIP and simulated monthly precipitation $\delta^{18}O$

Comparison with GNIP for 1979-1988				
	ECHAM	GISS-E	MUGCM	Iso-GSM
Cor.	0.38	0.44	0.27	0.61
Anom.Cor.	-0.03	0.03	0.00	0.35

Figure 5: Monthly variation of precipitation $\delta^{18}O$ anomaly at Bangkok (a) and Vienna (b). Red lines are GNIP, blue lines are Iso-GSM, and other lines are from three SWING members.

SUMMARY AND CONCLUSIONS

In this study, we produced a multi decadal and global three-dimensional dataset of stable water isotopes. This was accomplished by introducing the isotope fractionation process into the NCEP/SIO global spectral model and applying spectral nudging using NCEP/DOE reanalysis. This procedure mimics the isotope data assimilation, but without utilizing isotope observation, and expected to produce better isotope analysis than the ones simulated by GCMs forced by observed SST. Another important advantage of this procedure is that the analysis provides isotope variation for a wide range of time scales from diurnal to inter-annual. Limited comparison with station observations showed that the Iso-GSM agreed well with observations in those time scales. The spatiotemporally interpolated isotope data which is consistent with Reanalysis meteorological variables are useful in at least two aspects; as boundary and initial conditions for isotopic regional model simulations, and for comparison and further analyses of in-situ and short term isotopic observations, which are not routinely conducted.

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