Origin of water vapor in arid Asia simulated by regional climate model with simplified isotope process

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1. Introduction

Annual precipitation in Northeast Asian arid region is only several ten millimeter to few hundred millimeter per year. Most part of the annual precipitation, which has the large interannual variation, falls in the warm season. In order to study the features of the interannual variation of rainfall, results from water budget analysis can be a proxy to describe a hydrological cycle in this region.

Sources of the precipitated water and water vapor existing over arid/semi-arid area in Northeast Asia have been discussed in previous studies. There are two major routes of moisture transport that relates precipitation in Mongolia. The first route is along the Eurasian continent originated in the Atlantic Ocean, in which the moisture is transported by eastward-moving synoptic-scale disturbances and middle-latitude westerly wind. The second route is from the low-latitude regions in relation to the southwesterly flow due to the Asian summer monsoon. The local evapotranspiration from the grassland may be an additional contributor for the warm season precipitation. However, the sources of the atmospheric water vapor have not physically been investigated so far. Recently, land degradation is one of the concerns in this area. Xue (1998) revealed, from GCM experiments, that the warm season precipitation may decrease after the desertification occurs in Northeast Asia. The reduction of local evapotranspiration may induce the change of hydrological cycle in Mongolia.

The stable isotopes in precipitation or in vapor give us valuable information on the water cycle. During the intensive observation period of RAISE project (Sugita et al, 2006), water samples in precipitation and in the free atmosphere were collected at eastern Mongolia. Once the model, which can simulate isotope composition and atmospheric processes, is developed, we are able to study more details of the spatial and temporal variations of stable isotopes. Additionally, such information from isotope variations can be useful to examine the climate change which may be accelerated by the global warming or land use change.

In this study, we develop a stable isotope transport model driven by the regional climate model. The simulated isotope variations in precipitation and water vapor are compared to the observed values during the RAISE. The sources of water vapor and precipitation in arid Asia are also discussed using this modeling framework.

2. Model description

A Single-layer isotope transport model was developed and added into the Terrestrial Environmental Research Center - Regional Atmospheric Modeling System (TERC-RAMS; Sato and Kimura, 2005). Configurations of the model and detail settings for the calculation of the atmospheric variables are described in Sato et al. (2006). Horizontal resolution for isotope transport is 150 km in order to cover as large area as possible which may relate to the hydrological cycle in Mongolia. Although the resolution is not high, nested simulation with 30 km resolution around the Mongolia conducts very similar results to those presented here.

Oxygen stable isotope transport process is basically the same with that shown by Yoshimura et al. (2003), which uses vertical integration of the water vapor transport for simplification. In each time step, water budget and isotope budget are firstly computed using the hourly output of regional climate model before considering the precipitation. The Rayleigh-type isotopic fractionation is applied using the amount of precipitation in each grid box. The no-gradient condition of the oxygen stable isotope in the vapor is assumed at the lateral boundary of the model. The δ-values in the evapotranspired water and in the initial atmosphere are defined as a function of the latitude and altitude based on the estimation of Bowen and Wilkinson (2002). Temperature at 700 hPa level is used to determine the equilibrium fractionation factor. Simulation for the isotopic variation is carried out from 28th May to the end of August 2003 corresponding to the RAISE intensive observation period.

In order to estimate the origin of the moisture, the model was modified in which the tracers are emitted from each defined regions. In this study, the results from the multi-tracer model are briefly addressed in section 3.2.

3. Model description

3.1. $\delta^{18}O$ variation

Time series of the $\delta^{18}O$ in precipitation and water vapor over east Mongolia is shown in Fig. 1. Observed $\delta^{18}O$ exhibits large intraseasonal variability. The isotope transport model well reproduces the temporal variation of $\delta^{18}O$ in precipitation. The temporal variation indicates that it is strongly controlled by the synoptic

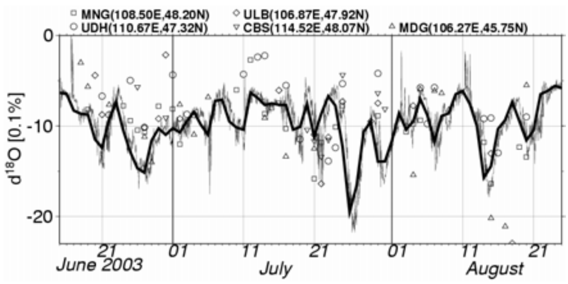

Figure 1: Temporal variations of $\delta^{18}O$ in precipitation. Dots represent the observed values at five sites while line indicates the simulated one as averaged over 105-115°E, 45-50°N.

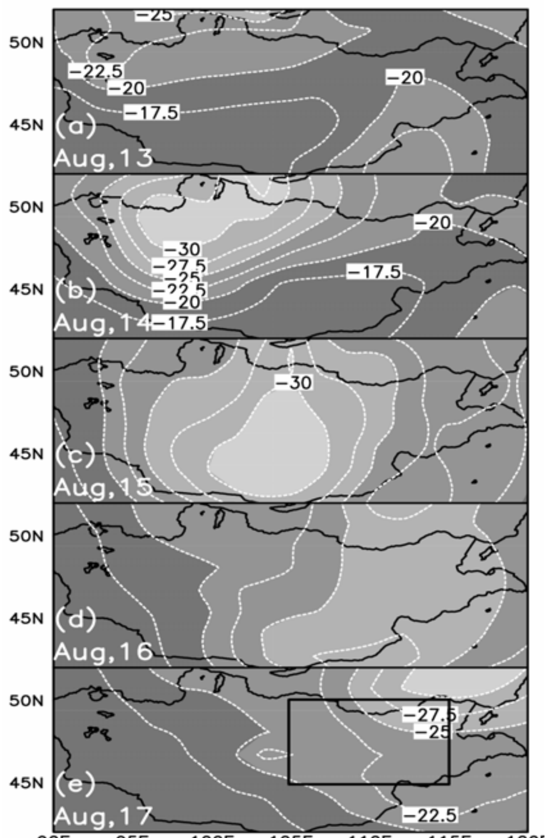

Figure 2: Animation of the $\delta^{18}O$ in water vapor simulated by the model. Light shade indicates the low δ-value. Box represents the area used for drawing the line in Fig. 1.

scale disturbances since it oscillates with approximately 3-5 day periods. Additionally, the δ-value tends to rapidly decrease together with precipitable water vapor and temperature, which again indicates that the cyclones or front systems affect the isotope variation in this area. The isotope transport model can well simulate the events of such rapid $\delta^{18}O$ decrease (Fig. 1).

Figure 2 represents the spatial distributions of $\delta^{18}O$ in the vapor during 13th through 17th August when the rapid decrease of $\delta^{18}O$ in precipitation was observed. Convective precipitation occurred near the Sayan Mountain, which results in forming the airmass composed of the light vapor after the Rayleigh process. The air mass proceeded eastward accompanying precipitation. Therefore, the δ-value remains lower around the precipitation system than that surrounding atmosphere during the eastward propagation, and finally reached at the observation site in 15th August. The intraseasonal variation of $\delta^{18}O$ due to the synoptic disturbances is dominant in Mongolia.

Result from the isotope budget analysis, the rapid decrease of the δ-value can be explained by the two mechanisms, the advection and the Rayleigh process. In the August case, as shown in Fig. 2, advection of the light vapor, which is generated around the mountain due to the Rayleigh process, mostly contributes to the drastic decrease of $\delta^{18}O$ at the observation site. This is because the $\delta^{18}O$ variation is precisely simulated even without precipitation around the observation site in the model. On the other hand, in the late June case (no figure), decrease of $\delta^{18}O$ can be further subdivided into two stages. During the first stage from 24th to 25th June, the advection of the light vapor tends to decrease the δ-value above the observation site. However, in the second stage from 26th to 28th June, advection term tends to increase the δ-value. At the same time, the Rayleigh process tends to decrease the column averaged $\delta^{18}O$. The decrease due to the precipitation overcomes the increase due to advection process in the second stage; thus, the $\delta^{18}O$ continuously decreases during these two stages.

3.2. Origin of water vapor

The isotope transfer model is modified to study the sources of water vapor in arid/semi-arid Asia. Twelve regions, West Siberia, East Siberia, Central Asia, Mongolia, Northeast Asia, Tibet, East China, Southeast Asia, India and Indian Ocean, South Pacific Ocean, and North Pacific Ocean are defined in the regional climate model domain. The evaporated water from each region is assumed to have its own tracers which make it possible to identify the origin of water vapor at a certain place in the model domain. Water vapor penetrating through the lateral boundary of the model is also considered by assigning tracers for the four (EWSN) boundaries. It is assumed that there is no fractionation during the condensation and precipitation process in the multi-tracer model.

Figure 3 shows the temporal variation of the vapor origins in the eastern Mongolia. Colors indicate the region where water vapor was finally evaporated. The

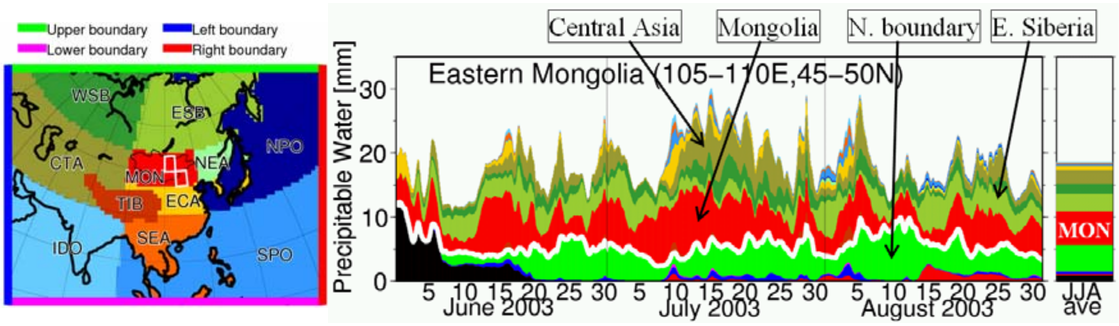

Figure 3: Time series of total precipitable water in eastern Mongolia and estimated sources of the water vapor. Colored area indicated the contribution ratio of evaporation from each region. Colors below white line are transported through the lateral boundary of the model. Black area indicates the water vapor initially existed in the model domain. Right panel shows the June-July-August averaged water vapor sources.

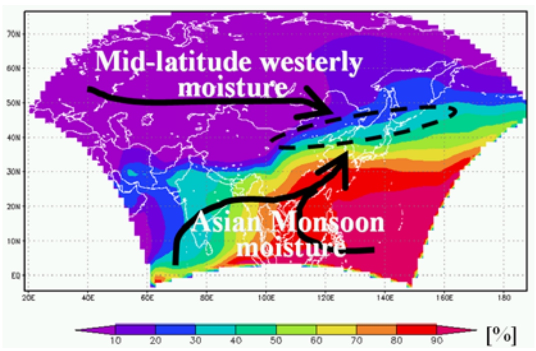

Figure 4: Contribution ratio of water vapor evaporated at low-latitude regions (Southeast Asia, India, and South Pacific Ocean). June-July-August average.

colored area means the contribution ratio of evapotranspired water from each region to the total precipitable water vapor. The precipitable water vapor varies significantly with the passage of synoptic disturbances. Contributions from Central Asia, Mongolia, and northern boundary are dominant in the warm season average. It is worth to note that the ratio of water vapor evaporated at the Central Asia tends to increase when total precipitable water vapor increases, which indicates that the large amount of moisture is transported by the extra-tropical cyclones. However, the moisture transport from low-latitude Asia does not prevail in eastern Mongolia although it has been widely believed to contribute warm season rainfall. In some cases, e.g. middle July and early August, the water vapor evaporated at Southeast Asia and South Pacific Ocean increases their ratios. However, the Mongolia and Central Asia regions also increase their contribution ratios at the same time.

On the other hand, around Inner Mongolia in China, the contribution from low-latitude Asia is not negligibly small. Additionally, the water vapor originated from low-latitude Asia increases when precipitable water vapor increases, which indicates the water vapor from low-latitude region are likely to be included into the precipitation in Inner Mongolia.

Figure 4 shows the June-July-August averaged contribution ratio of tropical (Southeast Asia, India, South Pacific) evaporation. In Mongolia, the contribution of tropical water vapor is less than 10 %. However, large gradient exists between Mongolia and Northeast China. Therefore, the contribution of tropical-originated water drastically increases to the southeastward. In Inner Mongolia, it reaches 20 – 40 %. As seen in Fig. 4, the eastern Mongolia and Northeast China is situated on the border area between westerly wind (middle-latitude synoptic cyclones) originated moisture and southerly wind (Asian summer monsoon) originated moisture regions.

Contribution ratio of local evapotranspiration to the total amount of water vapor in the atmospheric boundary layer can be estimated by the Keeling plot analysis. Tsujimura et al. (2006) found that the contribution ratio of local evapotranspiration could be 30-46 % at Forest site (108.65E, 48.35N, 1632m) on 23rd August and 25-44 % at KBU site on 21st August. Although the distinct separation between Forest and KBU site seems to be difficult with 150 km resolution, the multi-tracer model estimates approximately 25-40 % of the precipitable water vapor in eastern Mongolia as a local evapotranspiration during 21st to 23rd August (See Fig. 3). The modeling and observational approaches reveal that the evapotranspiration in Mongolia does not only primal contributor to the atmospheric water vapor in Mongolia.

4. Conclusion

The regional climate model, which can simulate the simplified oxygen stable isotope transport process, is developed to reproduce the observed $\delta^{18}O$ variation at eastern Mongolia. The model well replicates the intraseasonal variation of the $\delta^{18}O$ in precipitation and in vapor, especially when the δ-value showed a rapid decrease, although it tends to underestimate the $\delta^{18}O$ in the average state.

The simulated variations of the $\delta^{18}O$ and other meteorological variables revealed that the δ-value is strongly affected by the synoptic-scale disturbances. During the passage of cyclones or front systems, $\delta^{18}O$ in precipitation and water vapor undergoes rapid decrease by two processes. The advection of the light water vapor generated due to the former precipitation near the mountain area seems to be a primary process in the model, which influenced the $\delta^{18}O$ variation in late June and middle August cases. The Rayleigh process due to the precipitation near observation site also decreases the δ-value, which has the larger impact in the late June case.

The origin of the water vapor reached over arid/semi-arid region is also examined using regional climate model. The water vapor evaporated around Central Asia and Mongolia dominates in the atmosphere at eastern Mongolia while the contribution from low-latitude Asia is negligibly small. However, once we put our focus on the Inner Mongolia, China, which is located in the immediate southwest of the observation site, water vapor evaporated at low-latitude region consists 20-40 % of the total water vapor amount. These results indicate that the boundary between Atlantic origins, which relates to the synoptic-scale disturbances, and low-latitude origins, which relates to the Asian summer monsoon, exist near eastern Mongolia.

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