Isotopic composition of winter precipitation in Altai foothills

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Abstract. In recent years, some general circulation models have been improved by using stable water isotopologues, such as HDO (δD) and H$_2^{18}$O (δ$^{18}$O). In this paper, the results of a study of the isotopic composition of precipitation sampled in the winter seasons of 2014-2015 and 2015-2016 in Altai foothills are presented. The isotopic composition varied greatly: from -17.4 ‰ to -30.63 ‰ for δ$^{18}$O and from -132.1 ‰ to -235.0 ‰ for δD in 2014-2015; from -15.9 ‰ to -26.8 ‰ for δ$^{18}$O and from -118.5 ‰ to -207.7 ‰ for δD in 2015-2016. The weighted average values of δ$^{18}$O and δD for both seasons were close to each other (-21.2 ‰ and -160.1 ‰ for the first season and -20.4 ‰ and -157.5 ‰ for the second season), while the values of d$_{exc}$ differed significantly. A trajectory analysis (by the Hybrid Single Particle Lagrangian Integrated Trajectory – (HYSPLIT) model) has shown that the difference in the isotopic composition of the precipitation is largely associated with the change of the main source regions of atmospheric moisture, namely, the change of the North Atlantic waters (the 2014-2015 winter season) for the inland waters (the 2015-2016 winter season). A comparison of the results of an isotopic analysis has shown good agreement with data of the Global Network of Isotopes in Precipitation (GNIP) interpolated for 1960-2010. Thus, with a proper interpretation the data of the isotopic composition of the winter precipitation in Altai foothills can be used for this territory as an alternative source of the GNIP network data.

1. Introduction

Several general circulation models (GCMs) of the ocean and atmosphere have been improved by a possibility to explicitly simulate the hydrological cycle of two stable water isotopologues (hereafter called “water isotopes”), namely, HDO and H$_2^{18}$O [1-3]. Global modeling of the isotopic water composition can, therefore, help in interpreting the observed isotopic changes in various archives [4]. A number of studies have already clearly demonstrated this possibility to improve the interpretation of the detected water isotope variability in terms of climatic and environmental changes by using appropriate GCM simulations [1]. At present, there exist about a dozen of GCMs with explicit isotope diagnostics [5]. An example is ECHAM5-wiso; its simulation results on a global scale are in good agreement with the available observations of the isotopic composition [1-2]. However, when modeling on a regional scale, ECHAM5-wiso slightly underestimates the temperature over Europe (the mean difference: ~ 0.4 °C) and overestimates the modeled precipitation up to 30 mm/month in the central part of Western Europe [6].

With GCMs taking into account the isotopic composition of precipitation, the Global Network of Isotopes in Precipitation (GNIP) data are used first [7]. The GNIP has been monitoring the stable isotopes in precipitation since 1961. In the Russian Federation (USSR), there have been no more than 40 stations sampling precipitation for longer than a year [7]. Since early 2000s, no continuous
monitoring of the isotopic composition of precipitation according to the GNIP recommendations has been conducted. The research results mostly cover plain lands of the country [8-9].

The proportion of stable water isotopes in precipitation is determined by an empirical formula called the global meteoric water line (GMWL) [10-11]:

$$\delta D = 8 \times \delta^{18}O + 10\%,$$ (1)

Using the deviation of the isotopic ratios between $\delta^{18}O$ and $\delta D$ from the GMWL data, we can estimate the isotopic fractionation in the region under study, which is described by their local meteoric water line (LMWL), i.e. by the regional ratio between $\delta^{18}O$ and $\delta D$ in atmospheric precipitation. The deuterium excess ($d_{exc}$)

$$d_{exc} = \delta D - \delta^{18}O \times 8,$$ (2)

proposed by W. Dansgaard [11] on the basis of the GMWL-dependence to characterize the regional peculiarities of atmospheric water vapor or precipitation has been successfully used to identify their sources [12-13]. Thus, the changes in the isotopic composition of atmospheric precipitation in Russia, especially in piedmont and mountainous areas with adverse climatic and orographic conditions, are of utmost importance. Our aim is to study the formation of the isotopic composition of winter precipitation in the Altai foothills.

2. Materials and Methods

2.1. Study area

The Altai foothills are located between the Ob plateau, Prealtai plain, Biya-Chumysh upland, and Salair ridge. This area is of scientific interest, since it is in front of the Altai major orographic barriers and serves as a point of convergence of the oceanic and continental air masses responsible for wide variations in the isotopic composition of precipitation.

Atmospheric precipitation (snow) samples were collected in the Altai foothills (Figure 1) immediately after their formation in the periods from December to February of 2014-2015 and 2015-2016.

![Figure 1. Altai foothills (black asterisk: precipitation sampling point).](image)

2.2. Isotope analysis

An isotope analysis of water samples was performed at the Chemical-Analytical Centre of the Institute for Water and Environmental Problems of the Siberian Branch of the Russian Academy of Sciences with IR-laser absorption spectroscopy on a device Picarro L2130-i equipped with a WS-CRDS system (Wavelength-Scanned Cavity Ring Down Spectroscopy). The use of the WS-CRDS system made it possible to eliminate the spectral overlay [14] and achieve high accuracy and reproducibility in estimating $\delta^{18}O$ and $\delta D$ in the analysed samples. The detection limit was 0.4 ‰ and 0.1 ‰ for $\delta D$ and $\delta^{18}O$.
δ¹⁸O, respectively. The analysis was performed according to the V-SMOW-2 (Vienna Standard Mean Ocean Water 2) standard.

2.3. Synoptic analysis
The synoptic situation in the precipitation period was analyzed on the basis of meteorological observations at the precipitation sampling point and using data of the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) [15] and the National Oceanic and Atmospheric Administration (NOAA) [16]. Besides, we used NCEP CFSR data [17] on the wind direction and speed at 10 meters.

2.4. Trajectory analysis
The moisture transport history of the precipitation in the observation period was traced by using a HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model developed at the National Oceanic and Atmospheric Administration Air Resources Laboratory (NOAA ARL) [18]. We used Global Data Assimilation System (GDAS) data of 1 degree, global, from 2006 to the present time. The backward trajectories were calculated for each precipitation day. The backward trajectories started at the beginning of precipitation from the sampling point in the Altai foothills. Each backward trajectory covered a 240-hour interval. All the backward trajectories data were combined into a single directory based on the Google Earth. Then, using a program called ArcGIS (ESRI, USA) we completed the conversion of the data in a map data model. Cartographic visualization allowed us to analyse the time and space changes in the parameters under study, namely, to trace the paths of backward trajectories of the air masses.

3. Results and Discussion
3.1. Synoptic situation
The total precipitation amounts for the two winter seasons being analyzed differed significantly from each other. In the winter of 2015-2016 precipitation was 30% less than that in the 2014-2015 season (Figures 2a and 2b). The monthly distributions of precipitation were also different. In the winter of 2014-2015, there was more precipitation in late January and early February, while the 2015-2016 precipitation was mostly in December. The temperature conditions of precipitation were different as well. On average, the precipitation temperature during 2015-2016 was two times higher than the average one for the 2014-2015 winter season. At the same time, in 2015-2016 (in contrast to the 2014-2015 season) snow was observed even at positive temperatures (above 0°). An analysis of maps of average wind speed and direction at 10 m (the data are from NCEP CFSR) showed no significant differences between the data of the winter seasons (Figure 2).
3.2. Isotopic composition of precipitation

The isotopic composition of precipitation in the winter of 2014-2015 ranged from 17.4 ‰ to -30.63 ‰ for δ¹⁸O, and from -132.1 ‰ to -235.0 ‰ for δD. The deuterium excess for this winter season ranged from 0.1 ‰ to 16.3 ‰. The isotopic composition in the winter of 2015-2016 varied in a smaller range both for δ¹⁸O (from -15.9 ‰ to -26.8 ‰) and δD (from -118.5 ‰ to -207.7 ‰); d<sub>exc</sub> showed both negative and positive values (from -5.3 ‰ to +11.9 ‰).

The weighted average isotopic composition of precipitation in the 2014-2015 winter season reached -21.2 ‰ for δ¹⁸O and -160.1 ‰ for δD, and d<sub>exc</sub> was 9.4 ‰. In the winter of 2015-2016, the weighted averages for δ¹⁸O and δD were close to those of the previous season with -20.4 ‰ and -157.5 ‰, respectively, while d<sub>exc</sub> being equal to 5.7 ‰, decreased by almost 4 ‰. This allows us to assume greater isotopic fractionation of precipitation in the winter of 2015-2016 as compared to 2014-2015 and/or a change in the precipitation sources from season to season.

The calculated LMWLs for the winter seasons of 2014-2015 and 2015-2016 are described by the following regression equations (Figure 3):

\[
\delta D = 8.2 \times \delta^{18}O + 13.4\text{‰}, \quad (R^2 = 0.99), \quad (3)
\]

\[
\delta D = 7.8 \times \delta^{18}O + 2.6\text{‰}, \quad (R^2 = 0.97), \quad (4)
\]

The deviation to the right of the LMWL for the 2015-2016 winter season from the GMWL is due to the influence of evaporative fractionation on the formation of the isotopic composition of precipitation.
Figure 3. GMWL (black line) and LMWL of precipitation in December-February of 2014-2015 (blue line) and 2015-2016 (turquoise line).

The weighted average isotopic composition of precipitation was compared with the GNIP interpolated data for the period of 1960-2010 (Table 1) obtained for the Altai foothills with the help of an online calculator [7].

Table 1. Weighted average isotopic composition of precipitation in Altai foothills (December-February) according to GNIP interpolated data (1960-2010) and observational data of 2014-2015 and 2015-2016.

|              | GNIP   | 2014-2015 | 2015-2016 |
|--------------|--------|-----------|-----------|
| $\delta^{18}$O (%) |        |           |           |
| $\delta D$ (%)  | -22.5  | -21.2     | -20.4     |
| $d_{exc}$ (%)   |       | 3.9       | 9.4       |

The isotopic compositions of winter precipitation in the Altai foothills are in good agreement with the results of the GNIP. The difference for $\delta^{18}$O is ~2‰, and for $\delta D$, ~19‰. The values of $d_{exc}$ for the winter precipitation in 2014-2015 and 2015-2016 differed significantly from the GNIP interpolated data. The differences may be due to a change in the atmospheric precipitation sources from season to season and the fact that different time series are analyzed (some seasons and averages are for 1960-2010).

3.3. Precipitation sources

Using the HYSPLIT model, we calculated backward trajectories of air masses for each of the precipitation times to assess the change in their sources. An analysis of the backward trajectories (the 2014-2015 winter season) showed that the air masses responsible for precipitation were transported mainly from northwest (Figure 4a), in particular, from the North Atlantic Ocean. This is confirmed by the weighted averages of $d_{exc}$ (9.4 ‰) for precipitation, which is not significantly different from the $d_{exc}$ value for the North Atlantic Ocean [19]. In the 2015-2016 winter season the trajectories of air masses responsible for precipitation were mostly of south-western and western directions (Figure 4b). These air masses passed over some inland water bodies (such as the Caspian Sea), whose evaporating moisture could change the isotopic composition of water in the air masses responsible for precipitation in the Altai foothills. This is confirmed by the fact that the weighted average of $d_{exc}$ decreased in the 2015-2016 winter season.
Figure 4. Backward trajectories at 500 m (red lines), 1500 m (blue lines), and 3000 m (green lines) for air masses which determined precipitation in December-February 2014-2015 (a) and 2015-2016 (b) in the Altai foothills.

Thus, the trajectory analysis of air masses for the 2014-2015 and 2015-2016 winter seasons allowed us to identify the main source regions of precipitation whose change led to isotopic fractionation of precipitation, exhibited by variations in $d_{exc}$ (of about 4 ‰) between the two winter seasons.

4. Conclusions
The isotopic composition of precipitation sampled in the Altai foothills in the winter seasons of 2014-2015 and 2015-2016 varied over a wide range. The maximum values were ~15 ‰, ~117 ‰, and ~22 ‰ for $\delta^{18}O$, $\delta D$, and $d_{exc}$, respectively. The weighted averages of $\delta^{18}O$ and $\delta D$ for the two seasons were close to each other (-21.2 ‰ and -160.1 ‰ for the first season and -20.4 ‰ and -157.5 ‰ for the second season), while $d_{exc}$ varied significantly. The results of an isotopic analysis showed good agreement with the GNIP interpolated data for 1960-2010, however, $d_{exc}$ only for the second winter season was close to the GNIP interpolated data. A trajectory analysis (with the HYSPLIT model) showed that the differences in the isotopic composition between the seasons were largely due to a change in the main source regions of atmospheric moisture, namely, the replacement of North Atlantic waters (in the winter of 2014-2015) with inland waters (in the winter of 2015-2016). Thus, the data on the isotopic composition of precipitation in the Altai foothills with a correct interpretation of the results can be used as an alternative source of information for the GNIP data.

Acknowledgements
This work was supported by the Russian Foundation for Basic Research (project no. 16-35-00188 mol_a), government order on project VIII.77.1.5 “Climatic and Ecological Changes in Siberia according to Data of Glacio-Chemical, Diatomic, and Pollen Analysis of Glacier Core Samples” (no. 0383-2014-00052013).

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