Variations of oxygen-18 in West Siberian precipitation during the last 50 years

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Abstract

Global warming is associated with large increases in surface air temperature and precipitation in Siberia. Here, we apply the isotope-enhanced atmospheric general circulation model ECHAM5-wiso to explore the potential of water isotope measurements at a recently opened monitoring station in Kourovka (57.04°N, 59.55°E) to successfully trace climate change in Western Siberia. Our model is constrained to atmospheric reanalysis fields for 1957 – 2013 to facilitate the comparison with observations of δD in total column water vapour from the GOSAT satellite, and with precipitation $\delta^{18}O$ measurements from 15 Russian stations of the Global Network of Isotopes in Precipitation. The model captures the observed Russian climate within reasonable error margins, and displays the observed isotopic gradients associated with increasing continentality and decreasing meridional temperatures. The model also reproduces the observed seasonal cycle of $\delta^{18}O$, which parallels the seasonal cycle of temperature and ranges from -25‰ in winter to -5‰ in summer. Investigating West Siberian climate and precipitation $\delta^{18}O$ variability during the last fifty years, we find long-term increasing trends in temperature and $\delta^{18}O$, while precipitation trends are uncertain. During the last 50 years, winter temperatures have increased by 1.7°C. The simulated long-term increase of precipitation $\delta^{18}O$ is at the detection limit (< 1‰ per 50 years) but significant. West Siberian climate is characterized by strong interannual variability, which in winter is strongly related to the North Atlantic Oscillation. In winter, regional temperature is the predominant factor controlling $\delta^{18}O$ variations on interannual to decadal time scales with a slope of about 0.5‰/°C. In summer, the interannual variability of $\delta^{18}O$ can be attributed to short-term, regional-scale processes such as evaporation and convective precipitation. This finding suggests that precipitation $\delta^{18}O$ has the potential to reveal hydrometeorological regime shifts in Western Siberia which are otherwise difficult to identify. Focusing on Kourovka, the simulated evolution of temperature, $\delta^{18}O$ and, to a smaller extent, precipitation during the last fifty years is synchronous with model results averaged over entire Western Siberia, suggesting that this site will be representative to monitor future isotopic changes in this region.

1 Introduction

For the last several decades, an unequivocal warming of the climate system has been reported, evident from observations of increasing global average air and ocean temperatures, widespread melting of snow and ice and rising global-mean sea level (IPCC, 2013). However, while the rate of global warming averaged over the last 50 years amounts to about 0.1°C per decade, high-latitude regions of the Northern Hemisphere, such as Siberia, have been warming at considerably higher rates (e.g., Tingley and Huybers, 2013, and references therein). Among others, positive feedbacks associated with snow and sea-ice albedo, water vapour and clouds, greenhouse effect, and moisture transport as well as complex land surface – atmosphere interactions have been discussed as the possible reason for the observed Arctic amplification (for an overview see Masson-Delmotte et al., 2013, and references therein). While most studies so far have been focussed on the observed present and projected future temperature increase, it is uncertain how much other components of the Arctic climate system like the hydrological cycle will change as a consequence of the temperature rise. Bengtsson et al. (2011) have estimated that the strength of the Arctic water cycle, in terms of annual precipitation, may increase by some 25% by the end of the 21st century.

Since the pioneering work of Dansgaard (1953; 1964), Craig (1961), Merlivat et al. (1973), Sonntag et al. (1976), and others, it is well known that changes in climate and the atmospheric water cycle leave an imprint in the isotopic composition of different water reservoirs on Earth. For meteoric water, Dansgaard (1964) explained successfully through the atmospheric distillation process the linear relation between the isotopic composition of precipitation and the local temperature at the precipitation site (the so-called “temperature effect”) observed in many mid- to high latitude regions on Earth. Given the magnitude of Arctic warming over the past decades, climate change should be recorded in the isotopic composition of meteoric waters (or natural archives) in boreal regions of the Northern Hemisphere. The magnitude of this isotopic response is of interest when it comes to reconstruct past regional climate changes by isotope data retrieved from various palaeoclimate archives (e.g., Sidorova et al., 2010).

Unfortunately, isotope records of present-day boreal precipitation are sparse and discontinuous. For Russia, Kurita et al. (2004) have reviewed the modern isotope climatology. Data from 13 Russian monitoring sites sampled during the period 1996 – 2000 depict eastward isotopic depletion over Russia, which is explained by the gradual rain-out of moist, oceanic air masses, which are transported towards and over Russia by westerly winds. This continental effect has been known for some time (e.g. Araguas-Araguas et al., 2000, and further references therein). This isotopic gradient is weaker in summer, due to continental moisture recycling. Altogether, Kurita et al. (2004) estimate that 55% of the summertime isotopic variability in Russian precipitation are linked to temperature changes and variations of the recycling ratio of continental water sources, the latter effect accounting for about 20% of the signal. Combining simulation results of the isotope-enabled atmospheric general circulation model (AGCM) LMDZiso with satellite-based estimates of the isotopic composition of water vapour, Risi et al. (2013) also found that variations in continental recycling are minor contributions to the variability of isotope variations in high latitude precipitation.

To study the impact of climate change in Western Siberia, the Russian "mega-grant" research project "Impact of climate change on water and carbon cycles of Western Siberia" (WSibIso, http://wsibiso.ru) has recently started monitoring the isotopic composition of water vapour and precipitation at two high-latitude sites in Western Siberia. At Kourovka Observatory (57.04°N, 59.55°E), located approx. 80km west of Yekaterinburg, isotope monitoring has started in 2012 (Gribanov et al., 2013), while regular isotope measurements at Labytnangi (66.65°N, 66.40°E) have started in summer 2013.

Within the WSibIso Project, the understanding of the signals recorded at Kourovka and Labytnangi is supported by state-of-the-art climate simulations with two AGCMs equipped with explicit stable water isotope diagnostics, ECHAM5-wiso (Werner et al., 2011) and LMDZiso (Risi et al., 2010a). Such isotope-enabled AGCMs provide a mechanistic understanding of the atmospheric processes influencing the isotopic composition of meteoric water. Since the pioneering work of Joussaume et al. (1984), Jouzel et al. (1987), Hoffmann et al. (1998) and others, about a dozen different state-of-the-art GCMs have been equipped with explicit isotope diagnostics (see Sturm et al., 2010, for a detailed model overview). A number of studies have clearly demonstrated their usefulness for an improved climatic interpretation of present and past water isotope variability (e.g., Jouzel et al., 2000; Mathieu et al., 2002; Noone and Simmonds, 2002; Werner and Heimann, 2002; Vuille and Werner, 2005; Lee and Fung, 2008; Tindall et al., 2009; Risi et al., 2010b). A comparison of different models allows evaluating the robust features, and to scrutinize each model's parametrisations.

For Kourovka Observatory, the observed variations of the surface vapour isotopic composition are very similar to the results of the ECHAM5-wiso simulation covering the period April to September 2012 (Gribanov et al., 2013). Both exhibit short-term fluctuations on time scales from a few hours to a few days. These variations can be attributed to the passage of synoptic-scale weather systems, advecting air from different source regions with different isotopic signatures to Kourovka (Gribanov et al., 2013). A detailed comparison of the Kourovka data with LMDZiso model results will be presented in an accompanying paper (Gryazin et al., 2014).

Here, we extend the isotope analyses from the year 2012 to the last 50 years. As there are no Russian water vapour isotope measurements prior to 2012, the extended time frame implies that we focus on the isotopic composition of precipitation. Our key questions are (1) How much has the isotopic composition of precipitation varied in Western Siberia over the last five decades? (2) What are the main mechanisms and processes causing the variations? (3) How well can large-scale West Siberian climate and water cycle variations be observed in the isotopic composition of precipitation at Kourovka Observatory, one of the key monitoring sites within the WSibIso project? Our analysis is based on a so-called "nudged" ECHAM5-wiso climate simulation performed for 1957 – 2013, covering the entire period of available ECMWF reanalysis data (Uppala et al., 2005; Berrisford et al., 2009; Dee et al., 2011).

The paper is organised as follows: After a description of the model setup we test the model performance with respect to various observational data sets. In particular, we present a thorough comparison of simulated and observed precipitation $\delta^{18}O$ in Russia, going beyond the previous global model assessment by Werner et al. (2011). This validation is a prerequisite for the following discussion of isotopic interannual variability and mechanisms. We finish with conclusions regarding the potential of isotope measurements at Kourovka to trace future climate changes in Western Siberia.

2 Methods

2.1 Model description

Atmospheric simulations were carried out using ECHAM5-wiso (Werner et al., 2011), which is the isotope-enhanced version of the atmospheric general circulation model ECHAM5 (Roeckner et al., 2003; Hagemann et al., 2006; Roeckner et al., 2006). The model considers both stable water isotopes $H_2^{18}O$ and HDO, which have been explicitly implemented into its hydrological cycle, analogous to the isotope modelling approach used in the previous model versions ECHAM3 (Hoffmann et al., 1998) and ECHAM4 (e.g. Werner et al., 2001). For each phase of "normal" water (vapour, cloud liquid, cloud ice) being transported independently in ECHAM5, a corresponding isotopic counterpart is implemented in the model code. Isotopes and "normal" water are described identically in the AGCM as long as no phase transitions are concerned. Therefore, the transport scheme for all water-related variables is the flux-form semi-Lagrangian transport scheme for positive definite variables implemented in ECHAM5 (Lin and Rood, 1996).

Additional fractionation processes are defined for the water isotope variables whenever a phase change of the "normal" water occurs in ECHAM5, considering equilibrium and non-equilibrium fractionation processes. Equilibrium fractionation takes place if the corresponding phase change is slow enough to allow full isotopic equilibrium (Merlivat and Jouzel, 1979). On the other hand, non-equilibrium processes depend even on the velocity of the phase change, and therefore on the molecular diffusivity of the water isotopes (Jouzel and Merlivat, 1984). Processes involving isotopic fractionation include the evaporation from the ocean, condensation either to liquid or to ice, as well as re-evaporation of liquid precipitation within the atmosphere. For evapotranspiration from land surfaces, possible isotopic fractionation is neglected (see Hoffmann et al., 1998, and Haese et al, 2013, for a detailed discussion of this issue).

ECHAM5-wiso has been evaluated against observations of isotope concentrations in precipitation and water vapour, both on a global and on a European scale (Langebroek et al., 2011; Werner et al., 2011). On both scales, annual and seasonal ECHAM-5-wiso simulation results are in good agreement with available observations from the Global Network of Isotopes in Precipitation, GNIP (IAEA/WMO, 2013).

Werner et al. (2011) have shown that the simulation of water isotopes in precipitation clearly improves with increased horizontal and vertical model resolution. Thus, for this study, we choose a horizontal model resolution of T63 in spectral space (horizontal grid size of approx. 1.9° × 1.9°), and a vertical resolution of 31 levels on hybrid sigma-pressure coordinates. Local ECHAM5-wiso results for GNIP stations (discussed further below) were obtained by bilinear interpolation to the station coordinates. To ensure a most realistic simulation of present-day climate variability, the model is forced with prescribed yearly values of present-day insolation and greenhouse gas concentrations (IPCC, 2000), as well as with monthly varying fields of sea-surface temperatures and sea-ice concentrations according to ERA-40 and ERA-Interim reanalysis data (Uppala et al., 2005; Berrisford et al., 2009; Dee et al., 2011). Furthermore, the dynamic-thermodynamic state of the ECHAM model is constrained to reanalysis data by an implicit nudging technique (Krishamurti et al., 1991; the implementation in ECHAM is described by Rast et al., 2013), i.e. modelled fields of surface pressure, temperature, divergence and vorticity are relaxed to the corresponding ERA-40 and ERA-Interim reanalysis fields (Uppala et al., 2005; Berrisford et al., 2009; Dee et al., 2011). The nudging interval is 6 hours, ensuring that the simulated large-scale atmospheric flow is modelled in agreement with the ECWMF reanalysis data on all analysed time scales. In contrast to the atmospheric flow, the hydrological cycle and its isotopic variations is still fully prognostic and not nudged to any reanalysis data. Vegetation in the model is prescribed by a time-invariant set of land surface data (vegetation ratio, leaf area index, forest ratio, background albedo; Hagemann, 2002).

The performed simulation covers the period 1 September 1957 until July 2013. Here we regard the first 28 months as model spin-up and analyse the 51-years period between 1960 and 2010. If not stated otherwise, we focus on monthly averaged model results of the isotopic composition of precipitation (typically expressed in a delta-notation as $\delta^{18}O$ or δD), covering the full period of available stable water isotope measurements in Russia.

2.2 Observations of isotopes in Russian precipitation

In Western Siberia (here defined as the region ranging from 55°E-90°E and 55°N-70°N), monthly precipitation $\delta^{18}O$ data are available from 9 GNIP stations operating for different time periods between 1973 and 2000. Individual records range from a few months to up to ten years. Given the sparseness of these observations, we also include in this study data from 12 other GNIP stations in Russia for an improved model evaluation. Except for Cherskiy (68.76°N, 161.34°E) there are no published stable water isotope data for more recent times than year 2000 (S. Terzer, IAEA, Isotope Hydrology Section, personal communication, 2014).

To this set of 21 GNIP stations, we applied the following data selection: (a) We considered only stations where the sampling period of isotopes in precipitation was at least five years; (b) Unrealistic delta values of approx. +50‰ for both HDO and $H_2^{18}O$ isotopes from Amderma are excluded; (c) Five outliers with anomalous positive delta values from Barabinsk and Yaktutsk stations are excluded; (d) We excluded six stations (Kandalaksa, Khanty-Mansiysk, Kursk, Olenek, Salekhard, and Terney) where reported monthly mean temperatures are clearly unrealistic (i.e. reporting winter values for summer months or vice versa) and systematically disagree from WMO measurements and/or ECWMF reanalysis data, indicating issues with data quality control within the GNIP database.

After data filtering, our database consists in results from 15 GNIP stations (comprising 1161 monthly observations of $\delta^{18}O$ between 1970 and 2009; Table 1) used hereafter for further analyses.

2.3 Satellite observations of isotopes in water vapour

Although precipitation and water vapour have a different isotopic composition due to fractionation processes, a comparison of ECHAM5-wiso results for isotopes in water vapour with available data from satellite and ground-based remote sensing techniques is valuable. It will reveal some first-order information if the model correctly simulates the spatial gradients of the isotopic signal in atmospheric water vapour (and thus consistently also in precipitation) over Russia. Ground-based remote sensing of $\delta^{18}O$ in water vapour has been realised recently (Rokotyan et. al., 2014) but so far, only few point measurements have been carried out. For this reason we consider global observations of deuterium (δD) in total column water vapour retrieved from the GOSAT satellite (Boesch et al., 2013; Frankenberg et al., 2013) for the period April 2009 to June 2011. We select only measurements that pass a series of quality criteria involving the absence of clouds and the retrieval precision for different species (Frankenberg et al. 2013, Risi et al. 2013).

To rigorously compare ECHAM5-wiso with GOSAT, the model output needs to be processed in two ways. First, we need to take into account the spatio-temporal sampling. GOSAT makes measurements only along its orbit, and not all measurements pass our quality selection. Therefore, we select only the locations and days for which GOSAT has made valid measurements. Such a selection makes sense because ECHAM5-wiso is nudged toward reanalysis, so that the atmospheric properties simulated by ECHAM5-wiso and observed by GOSAT can be compared at the daily scale.

Second, we need to take into account the instrument sensitivity. The column-integrated δD value retrieved by GOSAT is not exactly the column-integrated δD value that actually occurred. This is because retrievals are affected by atmospheric conditions such as the temperature and water vapour vertical profiles or the presence of clouds. The "averaging kernels" describe how a given vertical profile in δD, for given atmospheric conditions, translate into the GOSAT column-integrated δD retrieval values (Rodgers and Connors, 2003). An averaging kernel is produced for each GOSAT measurement. Therefore, for each GOSAT measurement, we apply the corresponding averaging kernel to the model outputs. This allows us to compute the column-integrated δD values that GOSAT would retrieve if it was flying in ECHAM5-wiso's simulated atmosphere (Risi et al., 2012a).

3 Results and discussion

3.1 Present-day mean climate

Gribanov et al. (2013) showed that the ECHAM5-wiso simulation results agree well with observations from Kourovka Observatory and the surrounding area for the year 2012. As we are going to analyse model results for 1960 – 2010, the period of model validation with meteorological observations has been extended accordingly. This section summarises the results of the updated validation. Surface temperatures and precipitation rates in Yekaterinburg (56.80°N, 60.60°E; WMO data for station Sverdlovsk retrieved from the KNMI Climate Explorer, http://climexp.knmi.nl/) were compared to the ECHAM5-wiso model values (calculated as the mean over the period 1960 – 2010). Simulated surface temperatures show a small cold bias of less than 1°C in the annual mean, with larger deviations (of up to -3°C) in winter. Precipitation rates simulated by ECHAM are slightly above observed values in winter (by 5 – 10 mm/month between November and March), but up to -18 mm/month lower between July and September.

Fig. 1 shows annual-mean patterns of simulated surface temperature (T), total precipitation amount (P), and oxygen-18 content of precipitation ($\delta^{18}O$) for the region 0–160°E, 40–80°N, covering Central and Eastern Europe, Russia and parts of Asia.

Surface temperatures (Fig 1a) decrease from southwest to northeast. Comparing model temperatures averaged over 1960 – 2010 with the CRU temperature reconstruction for the same period (University of East Anglia Climatic Research Unit (CRU), Jones and Harris, 2013), we find slightly colder values in the simulations than observed (in the range -0.5 – -1.5°C) in Eurasia and Western Siberia. Conversely, simulated temperatures in Central and Eastern Siberia are higher by ~0.5 – 1.5°C than the CRU data, with maximum differences of up to 5°C found for the Verkhoyansk Range.

Precipitation fields (Fig 1b) are zonally aligned in the simulated annual mean pattern. Total precipitation decreases from 60 – 80 mm/month at the East European Plain eastwards and arrives at minimum values of 20 – 30 mm/month in a zone ranging from the southern part of the West Siberian Plain to Northeast Siberia. Precipitation values peak in the Russian Far East in the Stanovoy Range. Compared to the CRU precipitation reconstruction (University of East Anglia Climatic Research Unit (CRU), Jones and Harris, 2013), simulated precipitation is higher by 10 – 20 mm/month north of 60°N, and by up to about 30 mm/month in the Russian Far East mountain areas. In the southern part of the West Siberian Plain, ECHAM produces slightly less precipitation than observed. The precipitation deficit increases with increasing continentality.

The simulated annual mean $\delta^{18}O$ values of precipitation over Russia are plotted in Fig. 1c. Within Russia, $\delta^{18}O$ values decrease from southwest to northeast. In contrast to temperature and precipitation, no global dataset of observed $\delta^{18}O$ in precipitation exists for comparison, yet. Figure 1c illustrates the large observational gaps in Russia. A more rigorous model – data comparison of $\delta^{18}O$ will be presented further below.

Total column water vapour values of δD according to ECHAM5-wiso and to GOSAT satellite retrievals are shown in Fig. 2. As there is no absolute calibration for column-integrated δD of GOSAT (Risi et al., 2013), we subtract the global average of δD for both GOSAT and ECHAM to enable an improved comparison focussing on the spatial distributions. The model captures the pattern of total column water vapour δD variations over Russia well (Fig. 2a and Fig. 2b). Even some details such as the regional δD gradient southwest of Kourovka Observatory are resolved. Regarding the meridional δD gradient along the longitude zone including Kourovka, ECHAM5-wiso captures the northward depletion retrieved by GOSAT (Fig. 2c). Considering the zonal δD variation along the latitude zone including Kourovka (Fig. 2d), we find that ECHAM5-wiso tends to underestimate the eastward depletion associated with the continental effect. From 20°E to 120°E, δD decreases by about 80‰ in GOSAT observations and by only about 40‰ in ECHAM5-wiso.

For more quantitative analyses, we compare the climatology from our ECHAM5-wiso simulation results to available GNIP measurements. For each GNIP location, we restrict the data-model comparison to those months within period 1960 – 2010, when measurements have been reported (see Table 1 for details). Thus, mean values of T, P and $\delta^{18}O$ are calculated over different periods for each GNIP station and from ECHAM5-wiso. The results of this comparison are shown in Figure 3. The uncertainty range indicated by the error bars is ±2 standard errors of the estimated mean values. In the following, uncertainty ranges always refer to the 95% confidence interval.

As expected from our nudging strategy, Figure 3a shows a good agreement between modelled surface temperatures and GNIP observations. The root mean square (RMS) difference between modelled and observed mean temperatures is 1.13°C. Model results and observations are highly correlated ($r^2 \sim 0.95$) and lie close to a line with slope 1. A linear fit, applying an algorithm which accounts for the uncertainties in both coordinates (Krystek and Anton, 2007), yields an optimum slope of 1.05±0.23 and an optimum intercept of (-0.75±1.45)°C. This may suggest that the model tends to underestimate the observed temperatures. Regarding individual stations, the largest difference is found for Perm, where the model is too cold by 2.9°C. However, given the uncertainty range of the fit, the conclusion of an overall cold bias of ECHAM5-wiso is not robust. The average variability of modelled and observed temperatures (i.e. the average length of the error bars) is virtually the same (±2.83°C vs. ±2.88°C). This indicates that ECHAM5-wiso captures the temporal variability of observed surface temperatures in Russia (note that the range of model values only reflects temporal variability while the observational range may also include measurement errors).

For precipitation the scatter of model results is larger (Fig. 3b), resulting in a correlation which is weaker than for temperature ($r^2 \sim 0.73$). The RMS difference between simulations and observations is about 10.5 mm/month, with the largest deviations for Murmansk (+24 mm/month) and for Rostov (-19 mm/month). The model results for these stations are clearly beyond the uncertainty range of a linear fit (slope = 1.25±0.16 and intercept = (-6.68±5.78) mm/month). Ten out of 15 model mean values lie above the line with slope 1, which points to a moist bias of ECHAM5-wiso. On the other hand, the model slightly underestimates the variability of observed precipitation rates (±6.55 mm/month vs. ±6.99 mm/month).

Fig. 3c indicates that ECHAM5-wiso captures annual mean $\delta^{18}O$ records in Russia reasonably well. Model results and GNIP data are highly correlated ($r^2 \sim 0.96$) and coalesce along a line with a slope close to 1 (0.97±0.11; intercept: (1.15±1.37)‰). The RMS difference amounts 1.05‰. Maximum differences of up to +4‰ are found for two stations in Eastern Siberia (Cherskiy and Yakutsk) where ECHAM5-wiso does not simulate sufficient depletion. Uncertainty ranges of the simulated and observed means are rather the same (±1.17‰

simulated vs. ±1.16‰ observed). The model slightly underestimates the spatial gradients of $\delta^{18}O$ observed in Russia. The meridional isotope gradient (observed slope: -4.2‰ per 10° latitude, simulated slope: -3.6‰ per 10° latitude), reflecting the meridional temperature gradient, is by about a factor of four to five larger than the zonal isotope variation (observed slope: -0.9‰ per 10° longitude, simulated slope: -0.8‰ per 10° longitude) associated with increasing continentality (not shown).

Studying anomalies of $\delta^{18}O$ ($\Delta\delta^{18}O$) and surface temperatures (ΔT), we find a linear relationship for all seasons with a typical slope of 0.5‰/°C (Fig. 4). The correlation between GNIP ΔT and $\Delta\delta^{18}O$ is most pronounced in autumn (SON, $r^2 = 0.69$) and winter (DJF, $r^2 = 0.61$). In spring (MAM, $r^2 = 0.50$) and summer (JJA, $r^2 = 0.40$) the correlation is weaker, but still significant ($p \ll 0.05$ applying a t-test). The weaker coupling indicates that the $\delta^{18}O$ signal during the warm season is significantly affected by other processes such as moisture recycling. ECHAM5-wiso simulates a similar seasonal relationship but the correlation between $\Delta\delta^{18}O$ and ΔT is higher than for the observations ($r^2 = 0.50 – 0.79$). The model overestimates the coupling between $\Delta\delta^{18}O$ and ΔT especially in spring ($r^2 = 0.79$).

We now compare the simulated and observed seasonal cycle of precipitation $\delta^{18}O$ in Western Siberia (Fig. 5). The data exhibit seasonal variations ranging from -25‰ in winter to -5‰ in summer, closely following the seasonal cycle of temperature. Peak values of up to -1‰ were observed in Perm during the second half of the 1980s. Despite the reported small annual-mean temperature biases, ECHAM5-wiso correctly simulates the timing and magnitude of the seasonal variations of both temperature and $\delta^{18}O$ (Fig. 5) in Western Siberia. Observations and simulations from Pechora and Perm also show interannual variations, which will be discussed in the next section.

3.2 Interannual to decadal variations over the last five decades

The sampling period of precipitation $\delta^{18}O$ in Russia is too short for a thorough investigation of the long-term variability seen in the West Siberian isotope and climate records shown in Fig. 5. To overcome this problem, we extend the time frame by considering model results for the period 1960 – 2010. Therefore, the following analysis of interannual to decadal variations of T, P and $\delta^{18}O$ over Russia during the last decades is entirely based on model outcomes. If not stated otherwise, the model results are presented as anomalies from their long-term climatological mean (1961 – 1990). A zero-phase bidirectional low-pass filter with a length of

24 equally weighted months is employed on the ECHAM5-wiso results to highlight long-term variability. To explore the potential influence of global warming during the period 1960-2010, we apply a t-test comparing the reference period with the period 1981 – 2010 (significance level is 5%). In addition, we investigate linear long-term trends derived from a regression of annual-mean model results. The numerical results of this trend analysis are listed in Table 2.

At the global scale, (Fig. 6a, blue line), surface warming has been accompanied by increasing atmospheric moisture content (not shown) while modelled precipitation over land has slightly decreased (Fig. 6b). In parallel, global water vapour and precipitation have become progressively enriched with heavy water isotopes (Fig. 6c). The simulated increase of land surface temperatures is statistically significant. The trend analysis indicates a long-term increase of annual-mean global land surface temperatures by (1.27±0.01)°C per 50 years which is in the range of trend estimates based on observations (for a compilation of climatological observations see Hartmann et al., 2013, and references therein). Simulated anomalies of global land precipitation peaked in the mid-1970s which is also seen in global precipitation data sets. For more recent periods, the simulation does not reproduce the observed amplitude of interannual precipitation variability. However, the changes are statistically significant, and the modelled long-term decrease of global land precipitation by (2.18±0.49) mm/month per 50 years is in line with observations (Hartmann et al., 2013; note that global precipitation trends there relate to the different period 1951 – 2008).

Long-term trends in T, P, and $\delta^{18}O$ are also found in Western Siberia (averaged over the area 55°E – 90°E, 55°N – 70°N) as well as at Kourovka (Fig. 6, red and green lines). Regional and local warming is statistically significant and occurred at higher rates than global ((1.19±0.18)°C per 50 years averaged over Western Siberia and (1.08±0.15)°C per 50 years in Kourovka). The long-term warming is particularly pronounced in winter (DJF), especially in Western Siberia and Kourovka, where DJF warming rates are in the range 1.5 – 1.7°C per 50 years. Our model also suggests a positive long-term trend of annual precipitation. For both Western Siberia and Kourovka, annual-mean precipitations rates have been increasing by 2 – 3 mm/month during the last 50 years, with a tendency towards enhanced DJF precipitation at the expense of JJA rainfall. However, except for winter precipitation in Western Siberia, the changes are statistically insignificant, and the uncertainty range of the regional and local precipitation trends is high, exceeding the projected average long-term anomaly. Long-term trends of precipitation $\delta^{18}O$ are also positive. The changes are small and at the detection limit

(< 1‰ per 50 years) but everywhere statistically significant at the annual time scale. For Western Siberia we find that the long-term changes of $\delta^{18}O$ are more pronounced during JJA than during DJF, which is opposite to the simulated seasonal temperature trends. The reason for this decoupling is that moisture import to Western Siberia intensifies more in summer than in winter (not shown), while the opposite is simulated for precipitation. As a consequence, the isotopic signature of moisture available for precipitation is less affected by continental depletion during recent summer seasons than during recent winters.

At the regional and local scale the long-term trends are superimposed by strong interannual variability reaching values of up to ±1.5°C, ±10 mm/year, and ±1‰, respectively. Temperature anomalies simulated for Western Siberia and Kourovka covary since the late 1960s. During most of the simulation period, temperature differences between Western Siberia and Kourovka are less than about ±0.5°C, with Kourovka showing larger fluctuations than Western Siberia. Simulated precipitation anomalies for Western Siberia and Kourovka appear to be less synchronous than it is the case for temperature, in particular between 1995 and 2000 when the precipitation curves are out of phase. Moreover, in Kourovka the precipitation variability is considerably larger (by up to 10 mm/month) than its average for Western Siberia. The larger deviation between the mean precipitation amount in West Siberia and the values in Kourovka as compared to the surface temperatures is not surprising, as precipitation is known to strongly vary at short spatial and temporal scales. Consistent with the temperature patterns, anomalies of $\delta^{18}O$ in Western Siberia and Kourovka are most of the time in phase and differ within ±0.5‰ with the larger variability being simulated for Kourovka. In our simulation, $\delta^{18}O$ and surface temperature mostly covary, which is not the case for precipitation amount. However, $\delta^{18}O$ and temperature are not rigidly coupled. This is indicated by our model results for the years around 1990, when temperatures in Kourovka were below the Western Siberian average while the opposite is obtained for $\delta^{18}O$. The overall good agreement between mean temperature and $\delta^{18}O$ changes in West Siberia and Kourovka is a key finding with respect to the objectives of the WSibIso Project. It indicates that Kourovka Observatory is a well-representative site to monitor climate change in Western Siberia.

While we find that annual and seasonal-mean values of T, P and $\delta^{18}O$ have been slowly changing during the last decades (at least at the global scale), we do not arrive at a significant conclusion regarding potential changes in their interannual variance. Compared with the interannual variance between 1961 and 1990 (estimated from the standard deviation of detrended model results), the last decade (2001 – 2010) is characterized by increased variability of winter temperatures (0.4°C) and winter precipitation (2 mm/month) in Western Siberia, and by increased variance of winter and summer precipitation rates (3 mm/month) in Kourovka. The last decade does not exhibit substantial changes in $\delta^{18}O$ variability.

Further analyses of the temporal correlation between simulated values $\delta^{18}O$ in precipitation and surface temperatures (Fig. 7) reveal that the correlation of annual-mean values seen in Fig. 7a is mainly controlled by a strong linkage between surface temperature and $\delta^{18}O$ in precipitation in Western Siberia during winter (DJF). While the correlation coefficient between winter T and $\delta^{18}O$ can reach maximum values of up to 0.9 (Fig. 7b), the correlation between both climate variables is substantially weaker for summer (Fig. 7c). In the WSibIso target area, only one quarter of the observed interannual $\delta^{18}O$ variability can be explained by a linear relationship with local surface air temperature changes.

We now explore the relationship between West Siberian climate and precipitation isotopic composition, and large-scale atmospheric circulation. Previous studies have revealed a strong linkage between surface temperatures, $\delta^{18}O$ in precipitation and the North Atlantic Oscillation (NAO) for major parts of Europe (e.g., Baldini et al., 2008; Field, 2010; Langebroek et al., 2011; Casado, et al, 2013). It is also known that the influence of the NAO on the large-scale atmospheric circulation is not bound to Europe but extends further east towards Russia (e.g. Halpert and Bell, 1997). Correlating simulated $\delta^{18}O$ values in Kourovka with the simulated global sea level pressure field, we find for winter a pattern which is characteristic for the NAO (Fig. 8; cf. Hurrell and Deser, 2009). Thus, as a next step we investigate the influence of NAO variations on temperature and $\delta^{18}O$ variability over Russia.

Fig. 9 shows the observed and simulated station-based NAO seasonal winter (DJF) index for the period 1960 – 2010. ECHAM5-wiso model faithfully captures the observed NAO index (Hurrell et al., 2013) consistent with the reanalysis pressure fields used for nudging. Minor deviations between the observed station-based index and the modelled values can be attributed to the chosen model resolution T63, which can result in a slightly different average surface pressure of a relatively large grid cell as compared to a point-like station location. A correlation analyses of this simulated station-based NAO seasonal winter (DJF) index with modelled values of T, P, and $\delta^{18}O$ reveals that the NAO influence on surface temperature, precipitation amount and $\delta^{18}O$ in precipitation extends in a broad band from Europe until

Northern Siberia (Fig. 10). To a large extent, the covariation between winter NAO and $\delta^{18}O$ (Fig. 10a) is controlled by air temperature. Winters are mild in years when the NAO is strong, which is indicated by the positive correlation between NAO index and DJF surface temperatures shown in Fig. 10b. Winter precipitation in Northern Russia also increases when the NAO is strong (Fig. 10c). Further analyses reveal that the correlation between NAO and winter precipitation is also associated with enhanced moisture transport from the subtropical North Atlantic, (Fig. 11a). Conversely, when the NAO is weak, the origin of atmospheric moisture import shifts towards the Arctic Ocean (Fig. 11b).

In a recent modelling study assessing the effect of precipitation intermittency on the temporal correlation between seasonal temperatures and the NAO, Casado et al. (2013) found that precipitation weighting of temperatures reduces the correlation strength in Eastern Siberia during winter. While our results are based on unweighted monthly temperatures, we additionally assessed the effect of precipitation weighting for the winter season. We find that the correlation decreases in Northern Siberia from $r \sim 0.6$ to values less than about 0.4 (not shown) which partly supports the findings by Casado et al. (2013). However, the effect is probably overestimated as our calculation employs monthly values, while Casado et al (2013) showed that precipitation weighting should be carried out for daily or even shorter time intervals. Regarding the results for unweighted temperatures as well as for $\delta^{18}O$ which Casado et al. (2013) obtained using the LMDZiso model, LMDZiso shows a weaker response to the winter NAO than ECHAM5-wiso. This is probably due to the different nudging strategies, as the LMDZiso model is only nudged to the wind field while ECHAM5-wiso is also nudged to temperatures.

Our analyses shown in Fig. 10 reveal that in wintertime the NAO-associated atmospheric circulation changes have a slightly weaker impact on precipitation $\delta^{18}O$ ($r \sim 0.6$) over West Siberia than on the surface temperatures in this region ($r \sim 0.7$). On the contrary, $\delta^{18}O$ in precipitation is much more strongly correlated to the NAO than the precipitation amount itself ($r \sim 0.3$). This exposes the potential of reconstructing past changes of the NAO strength from various $\delta^{18}O$ records, e.g. retrieved from lake sediments, speleothems, or tree-rings (e.g., Sidorova et al., 2010) from this region. The ECHAM5-wiso results indicate that archives storing the $\delta^{18}O$ signal of winter precipitation should be suitable for such a NAO reconstruction.

While the interannual variability of $\delta^{18}O$ in winter precipitation can be largely attributed to temperature variations in Western Siberia associated with the NAO, we do not find such a teleconnection for the summer. Previous studies have shown that evapotranspiration fluxes significantly contribute to summer precipitation in Russia, and estimated that the regional moisture recycling rates can exceed 80% (e.g., Koster et al., 1993; Numaguti, 1999; Risi et al., 2013). Accordingly, Kurita et al. (2003; 2004) have suggested that snow melt and subsequent evaporation of soil moisture carrying the isotopic imprint of winter precipitation could significantly influence the isotopic composition of regional precipitation, counterbalancing the positive coupling between temperature and $\delta^{18}O$. Studying one-point correlation maps for JJA, we find that $\delta^{18}O$ at Kourovka is negatively correlated with the regional soil moisture reservoir (Fig. 12a) and local evaporation (see Table 3) which supports this hypothesis. Moreover, we identify a negative correlation between $\delta^{18}O$ and total precipitation (Fig. 12b), which is mainly due to the variability of convective precipitation (Fig. 12c, see also Table 3). If we consider only years in which convective precipitation is below the arithmetic long-term average, the correlation between $\delta^{18}O$ and local surface temperature raises from $r \sim 0.4$ to $r \sim 0.6$ (i.e. comparable to winter values, cf. Table 3). In the opposite case (convective precipitation above the long-term average) the correlation between $\delta^{18}O$ and surface temperature decreases to $r \sim 0.3$. This suggests that the isotope signal in West Siberian summer precipitation is rather controlled by the temperature variability at the level of condensation than by temperatures at ground. In principle, a correlation of $\delta^{18}O$ with vertical temperatures should permit to identify the altitude range of precipitation formation. However, correlating monthly-mean values we did not arrive at conclusive results.

Figure 12 clearly reveals that the summer $\delta^{18}O$ signal at Kourovka reflects hydrometeorological changes at the regional scale. Regarding precipitation and the seasonal-mean moisture flow, the correlation pattern is asymmetric. Areas in which the correlations are statistically significant are rather small upwind of Kourovka but more extended downwind. Downwind areas may contribute to the isotopic signal at Kourova through mixing, i.e. in situations of transient perturbations of the mean atmospheric flow. In fact, according to Fukutomi et al. (2004), Kourovka lies in the Siberian summer storm-track zone with high synoptic-scale eddy activity. This is reflected in our model results by greater monthly variability of atmospheric moisture transport towards Kourovka during summer than during winter. In summer, monthly moisture fluxes vary within ~ ±35% in magnitude and within ~ ±25° in flow direction, while in winter monthly-mean fluxes vary within ~ ±10% in magnitude and ~ ±15° in flow direction, respectively. These findings as well as the results of our correlation analyses are probably overly smoothed to fully resolve effects of moisture recycling, atmospheric convection, and transient perturbations, as the effective timescales of these processes can be considerably shorter than a month.

The link between $\delta^{18}O$ and climate during the West Siberian summer deserves further investigations. The effects of atmospheric convection and transient perturbations could be investigated by analysing the evolution of $\delta^{18}O$ at the timescale of single meteorological events, which may also involve the use of second order isotopic data (d-excess or ^{17}O excess; e.g., Landais et al., 2010; Guan et al., 2013). Moisture recycling and the origin of advected moisture could be investigated by moisture tagging, i.e. by simulating the dispersal of numerical water tracers evaporating from different predefined source regions (e.g., Koster et al, 1986; Numaguti, 1999; Risi et al., 2013). Nonetheless, our findings for the summer are in line with previous studies arguing that variations of $\delta^{18}O$ in precipitation are rather a regionally integrated signal of several climate variables than a proxy for either local temperature or precipitation changes (e.g., on a global scale: Schmidt et al., 2005; for Western Europe: Langebroek et al., 2011).

4 Summary and Conclusions

Using the few available observations as well as a new simulation from the isotope-enhanced atmospheric general circulation model ECHAM5-wiso covering the period 1958 - 2013, we have investigated the spatiotemporal variations in the isotopic composition of precipitation in Russia during the last decades. In its nudged configuration, the model simulates temperature and precipitation fields over western Siberia within reasonable error margins, providing a realistic framework to investigate the model performance for $\delta^{18}O$. The model reproduces the spatial pattern of precipitation $\delta^{18}O$ when compared with averaged observations from 15 stations of the Global Network of Isotopes in Precipitation between 1970 and 2009. The model has difficulties to capture the amount of $\delta^{18}O$ depletion in Eastern Siberia while temperature and precipitation are correctly simulated.

According to our model results, temperature is the predominant factor controlling up to 80% of the variability of annual-mean and winter precipitation $\delta^{18}O$ in Russia on interannual to decadal time scales. Interannual variations in winter temperature and isotope signals show a strong imprint of the North Atlantic Oscillation. During summer, local temperature has only a minor impact (about 20%) on the isotopic composition of West Siberian precipitation. Instead, our analyses indicate that $\delta^{18}O$ integrates effects of regional hydrometeorological processes on time scales shorter than a month. The results support the hypothesis of moisture recycling, involving the delayed reevaporation of isotopically depleted winter precipitation retained in snow melt and soil water. In addition, the isotopic summer signal is significantly influenced by convective precipitation formation, which does not occur in this region in winter. We also find enhanced variability of moisture transports towards Western Siberia. The relative importance of these processes should be further investigated with higher temporal resolution, or by using second order isotopic data (e.g., deuterium excess) as well as numerical moisture tagging diagnostics. Our results indicate that $\delta^{18}O$ has the potential to reveal hydrometeorological regime shifts in future summers, which are otherwise difficult to identify.

Recent observations reveal significant isotopic variability on the diurnal and daily time scale (Gribanov et al., 2013). The impact of short-term variations on the isotopic signal seen in the monthly GNIP records cannot be analysed, but continuous monitoring of water vapour $\delta^{18}O$ and daily sampling of precipitation $\delta^{18}O$ will permit to study processes at the event scale. Regarding Kourovka Observatory, where such a monitoring programme has recently been established, we find that the simulated variability of temperature and $\delta^{18}O$ at this location is similar to model results averaged over the entire West Siberian region. Therefore, we conclude that that this location is highly suitable to monitor isotopic changes all over in Western Siberia.

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Table 1. GNIP $\delta^{18}O$ records from Russia considered in this study.

Name	Lat (°N)	Lon (°E)	Alt (m)	t_{obs} $\delta^{18}O$	N_{obs} $\delta^{18}O$
Arkhangelsk	64.58	40.50	13	1981-1990	78
Astrakhan	46.25	48.03	-18	1980-2000	168
Bagdarin	54.47	113.58	903	1996-2000	34
Barabinsk	**55.33**	**78.37**	**120**	**1996-2000**	**37**
Cherskiy	68.76	161.34	30	2001-2009	57
Kalinin	56.90	35.90	31	1980-1988	94
Kirov	58.65	49.62	164	1980-2000	102
Moscow	55.75	37.57	157	1970-1979	61
Murmansk	68.97	33.05	46	1980-1990	71
Pechora	**61.12**	**57.10**	**56**	**1980-1990**	**79**
Perm	**57.95**	**56.20**	**161**	**1980-1990**	**79**
Rostov	47.25	39.82	77	1980-1990	74
Saratov	51.57	46.03	166	1980-1990	74
St. Petersburg	59.97	30.30	4	1980-1990	107
Yakutsk	62.08	129.75	107	1978-2000	46

Stations located in Western Siberia are highlighted in bold. For each station, we report the latitude, longitude and altitude, as well as the sampling period (t_{obs}) and the number of available monthly measurements (N_{obs}).

Table 2. Linear trend estimates and 95% confidence intervals for annual and seasonal surface temperature, precipitation, and $\delta^{18}O$ in precipitation simulated for the period 1960 – 2010.

	Area	Annual mean	DJF	JJA
Temperature (°C per 50 years)	Global land	1.23±0.01	1.38±0.02	1.12±0.01
	W Siberia	1.19±0.18	1.72±1.37	{0.52±0.16}
	Kourovka	1.08±0.15	1.54±0.90	{0.91±0.27}
Precipitation (mm month^{-1} per 50 years)	Global land	-2.18±0.49	{-0.46±1.56}	-2.82±0.76
	W Siberia	{2.18±2.16}	3.10±3.75	{-0.38±12.0}
	Kourovka	{3.09±8.60}	{3.28±11.0}	{-11.9±63.0}
$\delta^{18}O$ (‰ per 50 years)	Global land	0.58±0.00	0.36±0.01	0.62±0.01
	W Siberia	0.48±0.05	{0.13±0.23}	0.55±0.03
	Kourovka±	0.47±0.08	{-0.24±0.41}	{0.58±0.11}

Values for Western Siberia are averaged over the area 55°E – 90°E, 55°N – 70°N. DJF = December – February, JJA = June – August. Curly brackets indicate that the underlying model anomalies for the period 1981 – 2010 are not significantly different to the reference period 1961 – 1990 (applying a t-test, significance level = 5%).

Table 3. Correlation r of $\delta^{18}O$ in precipitation with meteorological variables at Kourovka according to model results for the period 1960 – 2010.

Variable	DJF	JJA
Surface temperature T_{surf}	0.62	0.43
Total precipitation P	{0.27}	-0.45
Large-scale precipitation	{0.27}	{-0.25}
Convective precipitation P_C	{0.15}	-0.44
Evaporation E	{-0.21}	-0.31
Soil wetness	{0.09}	-0.45
T_{surf} (seasons | $P < \langle P \rangle$)	0.68 (29 seasons)	0.46 (30 seasons)
T_{surf} (seasons | $P_C < \langle P_C \rangle$)	{*}	0.63 (23 seasons)
T_{surf} (seasons | $E < \langle E \rangle$)	0.62 (25 seasons)	0.55 (27 seasons)

DJF = December – February, JJA = June – August. Values in curly brackets are statistically insignificant ($p \geq 0.05$ applying a t-test). The lower three rows show the correlation with surface temperature if only seasons are considered in which total precipitation P, convective precipitation P_C or evaporation E are below their respective arithmetic long-term values $\langle P \rangle$, $\langle P_C \rangle$, and $\langle E \rangle$. *Convective precipitation at Kourovka is zero during DJF.

Figure captions

Fig. 1 Left column: Simulated mean annual values of (a) surface temperature, (b) precipitation, and (c) $\delta^{18}O$ in precipitation, averaged over the period 1960 – 2010. Right column: CRU data of (d) surface temperature, and (e) precipitation amount, averaged over the same period. The circles in Fig. 1c mark the position of the various GNIP stations used for analyses in this study.

Fig. 2: Distribution of annual-mean δD in total column water vapour, (a) as observed by the GOSAT satellite, (b) as simulated by ECHAM, after collocation with GOSAT observations and convolution with the corresponding averaging kernels. In (a) and (b) the global average of δD has been subtracted to highlight spatial patterns, and the black squares indicate the location of Kourovka Observatory; white squares are grid cells with low-quality observations. (c) Meridional transects of observed (black) and simulated (green) δD averaged over the longitude band 50°E – 70°E around Kourovka. The annual-mean δD value averaged over the area 30°N – 80°N, 50°E – 70°E has been subtracted to highlight the meridional variations. (d) Zonal transects of observed (black) and simulated (green) δD averaged over the latitude band 50°N – 64°N around Kourovka. The annual-mean δD value averaged over the area 50°N – 64°N, 20°E – 120°E has been subtracted to highlight the zonal variations.

Fig. 3: Comparison of mean values of (a) surface temperature, (b) precipitation amount, and (c) $\delta^{18}O$ in precipitation for a selection of 15 GNIP stations located in Russia and the related ECHAM5-wiso model results (see text for details on station selection and mean value calculation at each station). Length of the error bars is ±2 standard errors of the estimated means. Straight lines are obtained from a weighted total least-squares algorithm accounting for uncertainties in both observations and model results (Krystek and Anton, 2007), dashed lines are 95% confidence intervals for the fits.

Fig. 4: Relationship between $\delta^{18}O$ and surface temperature. Shown are monthly anomalies ($\Delta\delta^{18}O$ and ΔT) according to monthly observations from 15 GNIP stations in Russia (circles) and the related ECHAM5-wiso model results (crosses), (a) winter season, (b) summer season. Solid lines are obtained from a least-squares linear fit of observations and model results; dashed lines indicate 95% confidence intervals for the fits.

Fig. 5: Observed versus modelled monthly $\delta^{18}O$ values in precipitation for the period 1980 – 2000. Measurements of 3 GNIP stations located in Western Siberia are plotted as blue circles:

a) Pechora, b) Perm, c) Barabinsk. The red line shows ECHAM5-wiso results corresponding to the same locations. Also shown are observed (blue) and modelled (red) surface temperatures.

Fig. 6: Simulated time series of (a) surface temperature, (b) precipitation, and (c) $\delta^{18}O$ in precipitation for the period 1962 – 2008. Shown are anomalies from the climatological mean (reference period: 1961 – 1990). The ECHAM5-wiso results are averaged globally (blue line), for the region of Western Siberia (green line), and interpolated to the location of Kourovka Observatory (red line). A zero-phase bidirectional low-pass filter with a length of 24 equally weighted months has been applied to the simulated monthly mean values for filtering short-term fluctuations. Straight lines are trends obtained from least-square fits of annual-mean values for the period 1960 – 2010; dashed lines are 95% confidence intervals for the trends. See also Table 2 for a summary of numerical results.

Fig. 7: Temporal correlation between simulated values of $\delta^{18}O$ in precipitation and surface temperatures for the period 1960 – 2010. Correlation coefficients are calculated for (a) annual mean, (b) winter (DJF), and (c) summer (JJA) values of temperature and $\delta^{18}O$.

Fig. 8: One-point correlation map showing the correlation between $\delta^{18}O$ in precipitation at Kourovka and sea-level pressure during winter (DJF, correlation period is 1960 – 2010). Also shown is the average atmospheric moisture transport during DJF (vectors; only every second vector is drawn). The green box indicates Western Siberia, position of Kourovka is marked by a green cross.

Fig. 9: NAO winter (DJF) station index for the period 1960 – 2010, according to observations (blue line; Hurrell et al., 2013), and as simulated by the ECHAM5-wiso model (red line).

Fig. 10: Temporal correlation between station-based NAO winter (DJF) index and (a) $\delta^{18}O$ in precipitation, (b) surface temperature, and (c) total precipitation amount. Statistically insignificant areas (where $p \geq 0.05$ applying a t-test) are blanked.

Fig. 11: Simulated moisture transport (vectors; only every second vector is drawn) and anomalies of $\delta^{18}O$ in precipitation (colours) for (a) strong NAO+ (mean over all years with NAO index ≥ 2), and (b) weak NAO- conditions (mean over all years with NAO index ≤ -2).

Fig. 12: One-point correlation map showing the correlation between $\delta^{18}O$ in precipitation at Kourovka during summer (JJA) with (a) soil moisture, (b) total precipitation, and (c) convective precipitation. Also shown is the average atmospheric moisture transport during

JJA (vectors; only every second vector is drawn). The green box indicates Western Siberia, position of Kourovka is marked by a white cross. Correlation period is 1960 – 2010. Statistically insignificant areas (where $p \geq 0.05$ applying a t-test) are blanked. See also Table 3 for numbers.