Investigation of eddy and advective heat fluxes in the southeastern part of Western Siberia

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Abstract. Estimates of seasonally averaged advective and eddy heat fluxes and relative vorticity at the earth’s surface are obtained for the southeastern part of Western Siberia and, in particular, for the Tomsk region (55°-62°N, 74°-90°E) based on daily ERA-Interim reanalysis data with a high spatial resolution. It has been found that, in general, in the early 21st century in the whole region a decrease in advective air transfer is observed in autumn and winter, and an increase in spring and summer. At the same time, the heat fluxes coming to the region from the southern border play a significant role in regulating these changes. For the eddy heat fluxes, the situation is quite similar, in general. In the past few years, there has been a decrease in cyclonic activity and an increase in anticyclonic circulation. Besides, there was a great fluctuation in relative vorticity at the beginning of the 21st century. However, in general, a tendency towards negative values is observed.

1. Introduction
During the last decades the climate change has led to increase in the number of unfavorable and dangerous hydrometeorological events [1]. Thus, in Russia the number of dangerous phenomena is growing annually by 6.3–7% [2]. The greatest number of dangerous events in Russia in the recent years has been observed in Western Siberia [3]. Moreover, the most frequently occurring dangerous phenomena are associated with strong winds (24.5%), as well as heavy precipitation (15.3%) [4]. The most frequent and long-lasting strong winds are in the valley of the river Ob and in the southern parts of Tomsk region. These events have a convective origin. Their frequency of formation and intensity describe the variability of atmospheric circulation processes.

One of the reasons of such changes could be the variability in advective and eddy heat and moisture fluxes coming to the territory, due to changes in the large-scale atmospheric circulation over the recent decades. Experiments with the ocean general circulation model using variations in the atmospheric influence [5] indicate that meridional heat transfer has increased during the recent decades.

The main goal of this study is to estimate the dynamics of advective and eddy heat fluxes in Tomsk region at the end of the 20th and at the beginning of the 21st centuries

2. Materials and Methods
The study of heat transfer in Tomsk region (55°-62°N, 74°-90°E) in 1979–2018 is based on the daily ERA-Interim reanalysis data with a spatial resolution of 1.25° × 1.25° for calculating advective heat fluxes and 0.125° × 0.125° for the analysis of relative vorticity.

The calculation method of advective heat fluxes was described in more detail in [6], and that of eddy fluxes, in [7]. The temporal variability of heat fluxes was obtained directly for the whole territory of Tomsk region and separately for its borders (northern, southern, western, and eastern ones). This approach made it possible to identify and estimate the dominant direction of heat transfer to the
territory in each season. Analysis of advective and eddy heat transfer was carried out in the layer of 1000 - 850 hPa.

Therefore, to estimate the eddy activity in the region, the relative vorticity was also calculated at the levels of 1000 hPa and 850 hPa.

To reveal the tendencies and to reduce the signal noise in time series of climatic parameters, low-pass filtering (LPF) was applied [8]. The LPF characteristics were derived using the Fourier spectrum of a time series of climatic values with a 10-year window width. The method of fluctuation calculation was described in [7].

The error of the calculations was determined through the standard deviation. Verification of the null hypothesis when estimating the linear trend coefficients was performed for $\alpha = 0.05$ [9].

3. Results and Discussion

The interannual variability of seasonal values of the total advective heat fluxes coming to Tomsk region in 1979 – 2018 is presented in Figure 1. The dotted line shows the variability of fluxes smoothed by the low-pass filter. The total heat flux represents the sum of all incoming and outcoming heat fluxes across the borders of the region. At the beginning of the 21st century over the whole region a decrease in the advective flux was observed in autumn and in winter, and an increase in spring and in summer (Figure 1). In addition, the maximum value of the incoming advective heat flux for 1979 – 2018 was observed in the winter season ($5.52*10^{12}$ W), and the minimum one in the summer season ($1.65*10^{12}$ W).

![Figure 1. Temporal variability of the total advective heat flux coming to Tomsk region.](image)
As for the eddy heat fluxes, the temporal tendencies are quite similar to those described above, but there are differences in some seasons. Thus, in winter while the advective heat transfer decreased, the magnitude of the eddy heat flux did not change. Significant fluctuations of the eddy heat flux were not observed in spring but, at the same time, the advective flux coming from Tomsk region increased. In contrast to the advective fluxes, the maximum of the eddy ones was revealed in spring months.

The value of the advective flux exceeds the corresponding total value of the eddy flux 3 - 5 times. However, they have the same order, except for the fluxes coming from the territory in summer and in autumn (here the advective flux value is much higher).

To investigate the distribution of heat fluxes in Tomsk region in more detail, analyses of the fluxes incoming and outgoing through each border of the region were carried out. Table 1 shows the percentage of advective heat flux in Tomsk region across its different borders for 1979 – 2018. The advective flux values that exceeded 40% are in bold. As a result, it was shown that in winter and autumn the heat flux coming to the region from the southern border dominated (up to 80 %). In spring, the value reduced down to 50 % due to the growth of the heat flux coming from the northern border. In summer, the opposite situation was observed: the heat incoming from the northern border was 50%; and the heat incoming from the southern border was 30 %. The outgoing advective heat flux had maximal values for the northern border in winter (61%) and for the southern one in summer (57%).

Table 1. Percentage of advective heat flux in Tomsk region for its different borders over 1979 – 2018.

| Flux  | Season | Total flux, 10^12 W | West, % | East, % | North, % | South, % |
|-------|--------|---------------------|---------|---------|----------|----------|
|       | Winter | 5.52                | 18      | 0       | 2        | 80       |
|       | Spring | 3.60                | 19      | 0       | 31       | 50       |
|       | Summer | 1.65                | 15      | 2       | 50       | 33       |
|       | Autumn | 3.80                | 18      | 0       | 5        | 77       |
|       | Winter | 4.23                | 0       | 37      | 61       | 1        |
|       | Spring | 2.43                | 0       | 28      | 54       | 17       |
|       | Summer | 1.50                | 3       | 18      | 22       | 57       |
|       | Autumn | 2.37                | 0       | 35      | 60       | 5        |

An analysis of the interannual variability of the heat fluxes incoming to and outgoing from the dominant directions to Tomsk region was carried out (Figure 2). The dotted line shows the variability of fluxes smoothed by a low-pass filter. It can be noted that there was a significant decrease in the heat fluxes coming to the region from south (Figure 2a).

![Figure 2. Temporal variability of the advective heat flux in winter: a) coming to Tomsk region from south; b) coming from Tomsk region from north.](image-url)
It was established that, in general, at the beginning of the 21st century a decrease in the outcoming advective heat flux through the northern border (Figure 2b) was observed over the whole region. However, during the last years the value of the advective flux on these borders had increased significantly (≈2 times). It is expressed mainly in the winter season. In spring, the situation was reversed: the incoming heat flux to the region from south and the outcoming one from north increased. In autumn, the incoming advective heat flux to the territory from the northern border increased, and the outcoming one through the eastern border decreased. In summer, the heat flux comes from Tomsk region through almost all borders, while cold air comes from the eastern border, and warm air comes from north. The incoming heat in summer to the territory was observed from both south and west.

In general, the advective heat flux incoming through the western border decreased, which confirms the conclusions on the strengthening of the meridional type of circulation [5, 6].

The distribution of the eddy heat fluxes at the borders of Tomsk region is similar to that of the advective heat fluxes. Table 2 shows the percentage of eddy heat flux in Tomsk region across its different borders for 1979 – 2018. It was shown that in winter and autumn the heat flux coming to the region from the southern border dominated (up to 73 %). The outcoming advective heat flux was maximal for the northern border in winter (52 %) and for the southern border in summer (48 %). However, unlike the advective flux, the maximum eddy heat flux for 1979 – 2018 was observed in spring (1.12*10^{12} W).

**Table 2.** Percentage of eddy heat flux in Tomsk region for its different borders over 1979 – 2018.

| Flux     | Season | Total flux, \(10^{12}\) W | West, % | East, % | North, % | South, % |
|----------|--------|---------------------------|---------|---------|----------|----------|
| Incoming | Winter | 0.74                       | 17      | 2       | 8        | 73       |
|          | Spring | 1.12                       | 15      | 0       | 34       | 51       |
|          | Summer | 0.67                       | 15      | 5       | 57       | 23       |
|          | Autumn | 0.81                       | 14      | 1       | 13       | 72       |
| Outcoming| Winter | 0.79                       | 1       | 42      | 52       | 5        |
|          | Spring | 1.05                       | 0       | 26      | 44       | 30       |
|          | Summer | 0.58                       | 5       | 15      | 34       | 46       |
|          | Autumn | 0.73                       | 1       | 41      | 48       | 10       |

The temporal variability of the eddy flux from season to season was similar to the variability of the advective heat flux (Figure 3). However, their tendency did not always match. For example, in autumn against the background of advective flux decrease, the eddy heat flux coming from the southern border practically did not change. The eddy flux was associated with the growth of the incoming heat from the northern border of Tomsk region in winter, and from the southern one in spring and summer. Also, the eddy flux was related to the decrease of the outcoming heat from the eastern border in winter and summer.

The eddy activity in Tomsk region can be described by using the relative vorticity parameter. This parameter can characterize both the cyclonic (positive values) and anticyclonic (negative values) types of circulation. Thus, the study of this parameter allows one to better understand and describe the dynamics of individual elements of the regional climatic system, in particular, the features of the atmospheric circulation processes. The interannual variability of the relative vorticity at the levels of 1000 hPa and 850 hPa for winter and summer in Tomsk region is shown in Figure 4. It was found that over the last decades a significant decrease in the relative vorticity was observed, which is well pronounced in the winter season. This was typical for the levels of 1000 hPa and 500 hPa.

It was established that, in general, in Tomsk region the vorticity values in the troposphere were 2 times higher than that at the surface. There was a great fluctuation in this parameter at the beginning of the 21st century. However, a tendency towards the appearance of negative values was observed. This
indicates a decrease in the cyclonic activity and an increase in the anticyclonic circulation type. It was noted that the tendency of the relative vorticity was similar to that in Western Siberia [10].

**Figure 3.** Temporal variability of eddy heat flux in winter: a) coming to Tomsk region from south; b) coming from north.

**Figure 4.** Temporal variability of relative vorticity (*10^{-6}/s) in Tomsk region: a) 1000 hPa; b) 500 hPa.

Since the above-mentioned changes are associated with the atmospheric circulation variability, the fluctuation values in the processes of synoptic scale (2-7 days) were calculated for the air temperature (t), air humidity (q), the zonal (u), meridional (v), and vertical (w) components of wind speed in Tomsk region at the level of 850 hPa over two time intervals: 1979-1998 and 1999-2018. The derived estimates revealed areas with significant fluctuations of the temperature, humidity, and meridional component of wind speed in the winter season at the beginning of the 21st century. However, in the presence of nonlinearity in climatic systems many signals cannot be analyzed adequately by second-order statistical methods. For this reason, higher order statistical methods have been used [11]. Thus, the values of these parameters were calculated based on cumulants $K_{14}$ (Table 3). For this relationship, maximal estimates of the 5th-order cumulant were derived.
Maximal values of the cumulants correspond to the maximal contribution to the estimation of the probability of extreme events. As for Tomsk region, in the winter season maximal values for a combination of the two parameters were obtained for the air temperature and air humidity.

**Table 3.** Cumulant values of air temperature (t), air humidity (q), meridional component of wind speed (v) in Tomsk region. Statistically significant values (α=0.05) are in bold.

| Time interval | 1979 – 1988 | 1999 – 2018 |
|---------------|------------|------------|
|               | t – q      | v – q      | v – t      | t – q      | v – q      | v – t      |
| Winter        | 0.76       | 0.37       | 0.38       | 0.47       | -0.02      | -0.10      |
| Spring        | -0.29      | -0.18      | -0.18      | 0.14       | 0.00       | -0.04      |
| Summer        | 0.11       | -0.10      | 0.20       | 0.20       | 0.09       | 0.08       |
| Autumn        | -0.51      | -0.13      | 0.23       | 0.21       | -0.03      | 0.09       |

It should be noted that these values decreased at the beginning of the 21st century, but the values remained statistically significant. The approach being used specified the sources of nonlinear relationships and their significance for prognostic models.

4. Conclusions

Thus, estimates of seasonally averaged advective and eddy heat fluxes and relative vorticity at the earth's surface were obtained for the southeastern part of Western Siberia and, in particular, for the Tomsk region based on daily ERA-Interim reanalysis data with a high spatial resolution.

It was found that, in general, in the early 21st century in the whole region a decrease in advective flux was observed in autumn and winter, and an increase in spring and summer. At the same time, the heat fluxes coming to the region from the southern border play a significant role in regulating these changes. For example, in winter and autumn the heat flux coming to the region from the southern border was dominant (up to 80%). As for the outcoming advective heat flux, the maximal values were observed at the northern border also in the winter season (61%).

For the eddy heat fluxes, in general, the situation is quite similar. In the past few years there was a decrease in cyclonic activity and an increase in anticyclonic circulation. Also, it was established that, in general, in the Tomsk region the vorticity value in the troposphere was 2 times higher than that at the surface. There was a great fluctuation in this parameter at the beginning of the 21st century.

It was assumed that, to describe the changes in the meteorological parameters and in the atmospheric circulation processes, nonlinear statistical methods could be applied. As for the Tomsk region, in winter the maximal values of the two parameters were obtained for air temperature and air humidity.

Thus, during these periods the weather and climatic conditions were formed not only by the processes of large-scale atmospheric circulation. Probably, the influence of some local factors prevailed: some local forms of the circulation (cyclones and anticyclones) can contribute to the intensification of convective processes and, as a result, to the associated weather conditions. Therefore, when investigating regional climatic changes it is very important to take into account the local scale circulation processes.

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