# Radiative regime near Tomsk in 1995–2005

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We present some results of monitoring of total solar radiation performed at the TOR station of IAO SB RAS, Tomsk, in 1995–2005. It is found that, for the considered period, the radiative regime near Tomsk was quite stable with maximum annual total solar radiation in 2003. The magnitude and variability of monthly total radiation changed from season to season. In spring–summer period, the coefficient of variation of monthly total radiation was within 15–16%, and in winter it increased up to 20%. The interannual variation of the monthly total radiation for each month had positive trend except in March, July, and September. We studied the amount of total incoming radiation as a function of the type of air mass and synoptic conditions. The total incoming radiation during a year is found to depend, in a complicated way, on the type of air mass and this dependence reflects specific features of the atmospheric general circulation over the region. The daily total radiation is on the average 1.6 times larger during anticyclone than during cyclone throughout the year. The maximum daily total incoming radiation is observed in the northeast part of a cyclone, and for south and southwest part in an anticyclone.

## Introduction

The problem of long-term environmental and climate change is among most urgent problems nowadays. In the second half of the twentieth century, the global warming and general temperature increase over the entire globe, and in particular over the Northern Hemisphere, was observed. On the territory of Western Siberia, the warming is observed from the beginning of 1970s (http://www.cru.uea.ac.uk). It also should be noted that for the past 50 years, the tendency toward a decrease of the annual and seasonal precipitation was observed in Russia as a whole. Western Siberia is characterized by weak growth of precipitation predominately in winter and spring; however, during the past 10 years, excluding the year 2003 (http://climate.mecom.ru), there took place annual excess of precipitation in this region. During the past 20 years, the amount of clouds over the entire globe varied following the sinusoidal law: from 1985 to 2000 it decreased by ~4–5%, and from 2000 to 2004 it increased by about 2–3%.[1] This is reflected in variation of the components of the radiation balance (and in particular, solar radiation) and in their time behavior. Analysis of multiyear variations of incoming solar radiation incident on the Earth's surface on the territory of Russia and, in particular, in Western Siberia, according to data of the USSR actinometric network until 1990, made in Refs. 2 and 3, has shown that, on the whole, a decrease of the annual total and direct radiation and an increase of the annual total of scattered radiation was characteristic for the territory of Western Siberia. The same conclusion was drawn in Ref. 4 based on analysis of the components of radiation balance of the atmosphere at the stations of Baikal region in Eastern Siberia over the past 50 years. The authors note that on the most of the territory a statistically significant reduction was observed of the direct and total solar radiation, reaching 6.3%, on the average and 2.5% for 10 years. At the same time, there is a seasonal dependence of long-term variations of the total radiation. In the last quarter of the twentieth century, many continental actinometric stations in Russia, that are far from the ocean,[5] reported on a statistically significant positive trend in the total radiation in summer months and negative trend in winter. In addition to the general regularities of the long-term variation of the radiation balance components on the territory of Russia at a number of actinometric stations nearest to Tomsk, some individual seasonal features[6] caused by the local conditions were observed.

On the territory of Tomsk Region, there were two actinometric stations, "Aleksandrovskoe" and "Kolpashevo," which performed the observations of solar radiation since 1959 and 1955, respectively. At present, the actinometric observations are performed only at "Aleksandrovskoe" station. In Tomsk, regular or network measurements of the characteristics of solar radiation were not performed. Therefore, on the base of automatic post (TOR station), put into operation in 1992 at IAO SB RAS, and intended for monitoring of gas and aerosol composition of the air, meteorological parameters, and other geophysical variables,[7] the work on arranging the block of radiation measurements was initiated in 1995. Since April 1995, systematic measurements of total solar radiation $Q$ are being performed there. The measurements use standard M-115M pyranometer (the spectral range from 0.4 to 2.3 μm), which is periodically tested at the test office of West-Siberian Administration of the Russian Hydrometeorological Agency.

In October 2002, the TOR station was additionally equipped with ultraviolet pyranometer UVB-1 (Yankee Environmental Systems, Inc., USA),

0235-6880/07/01 54-06 $02.00 

that measures integrated intensity of UV-B radiation in the wavelength range from 280 to 320 nm. Operation of both pyranometers is controlled with a computer using special converters. The measurements are conducted all day hourly. The measurement cycle itself lasts for 10 min, during which the reading of the parameters with the frequency of 1 Hz is performed. The result, recorded by the computer, is obtained by averaging 600 single values and by calculating the root-mean-square deviation from these for each of the measured quantities. The measured result on the intensity of total solar radiation and UV-B radiation is recorded on a hard disk and stored in the corresponding database. Since September 2003, the radiation complex is extended to include Brewer spectrophotometer, allowing measurement of UV radiation in the spectral range from 290 to 325 nm with the step 0.5 nm. Simultaneously, the results of processing daily synoptic maps, with the same frequency, are used to create database, containing information on synoptic situation characteristic of Tomsk, as well as on the type and amount of total and low-level clouds.

This paper provides an estimate of the amount of incoming total solar radiation and its variations over 11-year period of measurements (1995–2005).

## Synoptic situation

The amount of solar radiation, incident on the underlying surface at midlatitudes, depends not only on season and time of the day, but also on the cloud amount and type, which, in their turn, are influenced by the synoptic conditions of the region. We have made such an analysis of the synoptic situation in the region of Tomsk over the past 15 years in Ref. 8. In this paper we formulate the main features of the considered period. Analysis of synoptic maps for the studied period has shown that the average frequency of occurrence was 18.8 and 25.9% for cyclones and anticyclones, respectively, 11.7% in the contrast zone, 12.7 and 8.4% within trough and ridge, respectively, 14.1% for a low-gradient field, and 5.8% for a valley.

The frequency of occurrence $P$ (%) of cyclones and anticyclones is not constant and varies within wide limits from year to year. For instance, $P$ of cyclones varied from 28% in 1994 to the minimum value 3.8% in 2003. Interannual variations in the occurrence of anticyclones was much lower: from 30.9% in 1997 to 17.6% in 2004.

The frequency of occurrence of anticyclones has annual behavior with minimum in summer, while for cyclones the annual behavior is poorly pronounced, though the primary minimum also takes place in summer (July). This is because the planetary temperature contrasts move to the north and the altitudinal-frontal zones are more often observed northward of Tomsk.

In addition, analysis of occurrence of geographic types of air masses has shown that on the average there was insignificantly more frequent occurrence of air mass from midlatitudes than from Arctic. Analysis of its annual behavior, revealed a very interesting situation. From January to July, the midlatitude air mass has more frequent occurrence than all others, and starting from August the situation changes: there is increase of occurrence of arctic air mass while the midlatitude air mass starts playing a secondary role. From analysis of the distribution of occurrence of air from south latitudes, it is seen that it is more frequently observed in the region of Tomsk in winter and in the transition periods, whereas in summer, when the intensity of the processes decreases and arrival of the south cyclones becomes rare, the frequency of occurrence is minimum. The maximum frequency of occurrence of subtropical and tropical air is observed in May.

One of the characteristics of the solar activity is the Wolf sunspot numbers. The main part of the considered period falls within the phase of high Wolf numbers of the 11-year solar cycle (Fig. 1$a$).

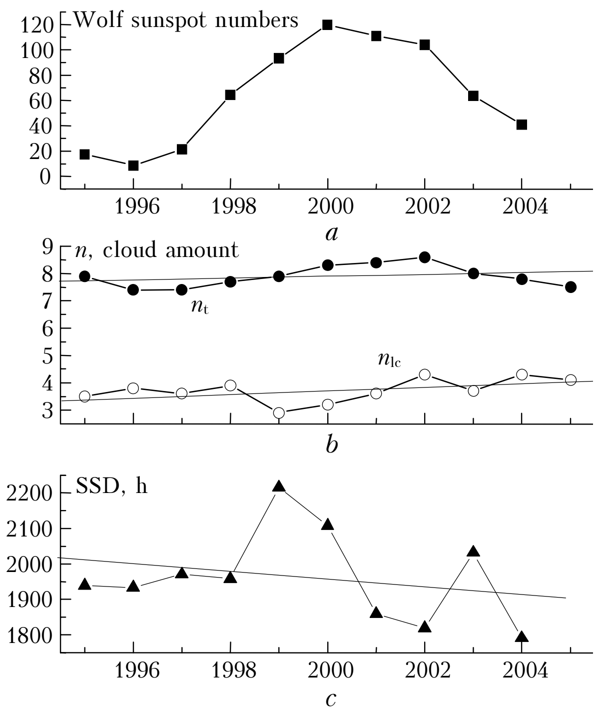


**Fig. 1.** Variation of the Wolf numbers ($a$), average annual amount of total and low-level clouds ($b$), and annual total of sunshine duration for 1995–2004 ($c$).

The analysis of data from the Siberian Climatic and Ecological Observatory at the Institute of Monitoring of Climatic and Ecological Systems SB RAS (daytime observations) from 1994 to 2005 has shown that there was a weak positive trend in the annual mean amount of the total clouds ($n_t$) and stronger trend of the low-level ($n_{lc}$) clouds. The amount of the cloud amount of total clouds increased by 0.2, and the amount of the low-level clouds increased by 0.6 (Fig. 1$b$). Because of the increase of the cloud amount, the annual total of sunshine duration (SSD) decreased (Fig. 1$c$) and the relative magnitude of the trend was 5.5%. Note that there is a significant anticorrelation between the SSD and cloud amount of the low clouds.

## Total radiation

For analysis of variations of the total solar radiation for the measurement period from 1995 to 2005 we calculated the daily sums, as well as the monthly and annual income of $Q$. Preliminarily, we considered the initial data array and the gaps in the measurements, caused by failures of the instrumentation, were filled through approximation of the values in the preceding and succeeding periods.

To estimate the trends of monthly sums of the total radiation, their time series were approximated by the linear functions:

$$x = \alpha_0 + \alpha_1 t;\ \beta_x = \frac{10\alpha_1}{\bar{x}} \cdot 100\%,$$

where $x$ is the current value of the component of the series; $\alpha_0$ and $\alpha_1$ are the coefficients calculated by the least squares method, $t$ is order number of the year, $\beta_x$ is the relative intensity of the trend, in percent, characterizing the rate of its change for a 10-year period.

### Annual behavior

The obtained data suggest that the annually averaged amount of incoming solar radiation for 11-year period was 4280.43 MJ/m$^2$, and the root-mean-square deviation was 250.15 MJ/m$^2$. The radiative regime in the region of Tomsk over the considered period was quite stable. The annual sum of $Q$ practically did not change from year to year with the exception of 2003, when maximum annual sum was recorded (Fig. 2).

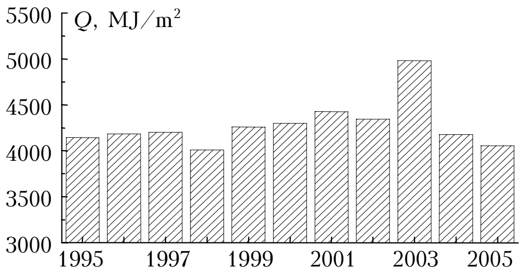


**Fig. 2.** Annual amount of incoming solar radiation in the region of Tomsk.

It should be noted that the specific feature of 2003 is that the cyclones in the region of Tomsk were only in November and, in addition, the southern and southwestern parts of the cyclones were observed. This means that southern cyclones invaded had centers to the west of Tomsk. The coefficient of variation of annual sums of the total radiation $V$ was 5.8% that agrees with the data for Western Siberia (4–5%) by Pivovarova.[9]

According to data from Ref. 10, the annual amount of total incoming radiation for 1965–1970 in Tomsk, calculated using data of Kolpashevo station, was 3884 MJ/m$^2$ under cloudy conditions and 5627 MJ/m$^2$ under clear sky conditions. Unfortunately, we have no other estimates of the amount of incoming solar radiation in Tomsk for a longer time period. Therefore, we will compare our results with data of multiyear observations at Aleksandrovskoe and Ogurtsovo sites for the period from 1959 to 1994. No significant trends of the total radiation[6] were revealed at these sites for the 36-year period of observations and annually mean amount of incoming radiation $Q$ was 3491.39 and 4041.08 MJ/m$^2$, respectively. The obtained results are comparable with multiyear observations at Ogurtsovo site located 150 km to the southwest of Tomsk.

### Interannual variability

Let us consider in a more detail the interannual variability of $Q$ since the year-to-year variability of the monthly amount of incoming radiation is higher than that of the annual amount. As is seen from Fig. 3 the magnitude and range of variations of the monthly sums depend on season.

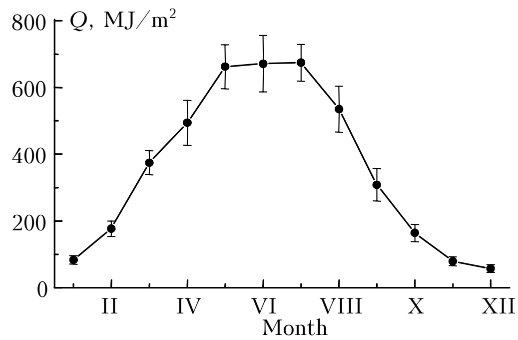


**Fig. 3.** Annual behavior of total solar radiation in the region of Tomsk.

In the spring–summer period, the coefficient of variation $V$ of the monthly sums varied in the range from 10 to 13%, while during the fall it was 15–16%, that well agrees with data by Pivovarova and Stadnik.[9]

The instability of circulation processes in winter has manifested itself in an increase of the coefficient of variation of monthly sums $Q$ up to 20%. In spring–summer period, the distinctly unstable monthly sums are characteristic of April and June ($V = 13\%$), and quite stable sums for July (8%). As is seen from the annual behavior, the main contribution (67%) to the annual sum of the total radiation came during warm period (May–September), with the maximum of monthly sums observed in July. At the same time, it should be noted that this maximum is not well pronounced and its value only insignificantly exceeds the average sums $Q$ in May–June. For the considered period, the largest monthly sums were recorded in May (804.71 MJ/m$^2$) and in June (831.62 MJ/m$^2$)

2003 because of the predominating anticyclones with the highly transparent atmosphere.

Let us analyze now how the amount of incoming solar radiation changed from year to year for different seasons. In the fall–winter period, the average amount $Q$ practically did not change (Fig. 4).

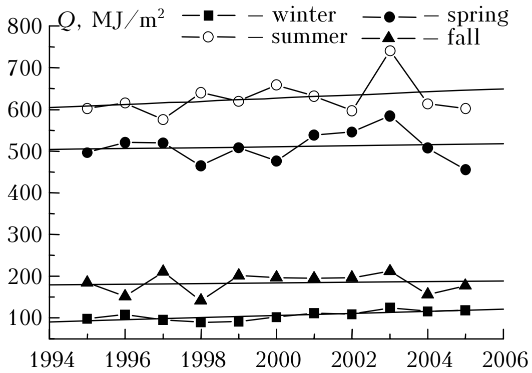

**Fig. 4.** Interannual variations of the amount of total incoming solar radiation as a function of season.

In summer period, the minimum amount of total incoming radiation was recorded in 1997, and maximum in 2003. In spring, there were two maxima: in 1996–1997 and 2003. Overall, during 1995–2005 a weak positive trend in $Q$ was observed in fall–winter period and a more significant increase of $Q$ in spring and summer. The pattern observed within a season is somewhat different. From Table 1 it is seen that the interannual variations of monthly sums of $Q$ for each month have a positive trend with the exception of three months (March, July, and September).

**Table 1. Characteristics of the linear trend of monthly and annual mean values of the total radiation in Tomsk in 1995–2005**

| Month | $Q$, MJ/m$^2$ | $\sigma_Q$, MJ/m$^2$ | $\alpha_1$ | $\beta_Q$,% |
|---|---|---|---|---|
| I | 83.23 | 12.97 | 2.1549 | 25.89 |
| II | 176.61 | 23.01 | 3.7464 | 21.21 |
| III | 374.90 | 36.19 | −5.0468 | −13.46 |
| IV | 494.12 | 67.15 | 2.2284 | 4.51 |
| V | 662.24 | 65.80 | 6.2492 | 9.43 |
| VI | 671.30 | 54.30 | 14.1701 | 21.11 |
| VII | 674.07 | 54.86 | −5.6619 | −8.40 |
| VIII | 534.88 | 69.14 | 2.8053 | 5.24 |
| IX | 308.37 | 48.63 | −1.3322 | −4.32 |
| X | 164.16 | 25.87 | 2.5772 | 15.70 |
| XI | 79.12 | 13.32 | 1.1828 | 14.95 |
| XII | 57.44 | 11.41 | 2.1360 | 37.18 |
| Year | 4280.43 | 250.15 | 23.7662 | 5.55 |

Note. $Q$ is the 11-year average, $\sigma_Q$ is the root-mean-square deviation, and $\beta_Q$ is the relative intensity of the trend.

Increase of the total and especially low clouds in March, July, and September has led to a decrease of the monthly sums of the total radiation and thus to the negative trend. The coefficient of correlation $r$ between monthly sums of the total radiation and the average cloud amount of the total and low clouds was $r(Q, n_t) = -0.70$ and $r(Q, n_{lc}) = -0.61$ in March, −0.70 and −0.81 in July, and −0.64 and −0.83 in September, respectively with the confidence probability $q = 0.975$.

## Variations of the daily sums

It is interesting to consider the variations of the daily sums because the variations of the daily sums incorporate the within month variations of the radiation of each year, caused by change of synoptic processes, as well as the year-to-year variations associated with the change of dominating types of the general circulation in separate years. Table 2 gives the daily mean sums of the total radiation $Q_{day}$, as well as their minimum and maximum values recorded at the TOR station.

**Table 2. Daily mean sums of the total radiation (MJ/m$^2$) at the TOR station for the period from 1995 to 2005**

| Month | Average | min | max | $V$ |
|---|---|---|---|---|
| I | 2.71 | 0.49 | 7.22 | 0.494 |
| II | 6.28 | 1.21 | 13.55 | 0.435 |
| III | 11.86 | 2.37 | 21.77 | 0.343 |
| IV | 16.52 | 3.09 | 29.33 | 0.375 |
| V | 21.41 | 3.93 | 36.00 | 0.339 |
| VI | 22.22 | 5.02 | 35.89 | 0.351 |
| VII | 21.79 | 3.55 | 35.08 | 0.319 |
| VIII | 17.36 | 2.95 | 30.71 | 0.365 |
| IX | 10.35 | 1.18 | 22.12 | 0.485 |
| X | 5.27 | 0.49 | 14.11 | 0.612 |
| XI | 2.63 | 0.34 | 9.39 | 0.612 |
| XII | 1.78 | 0.32 | 5.21 | 0.539 |

As to the interdiurnal variations, one should notice quite a stable radiative regime in spring–summer period and two times larger variations in October and November. At the same time, no quick variations of the daily mean sums of $Q$ was recorded. In Ref. 11 we extensively considered how the daily sums of $Q$ varied within a month as a function of the season in years from 1995 to 1998. In the period from 1995 to 2005, no significant variations of the distribution of the frequency of occurrence of the daily sums of the total radiation as a function of the season was revealed. The curves of the distribution of the daily sums also have asymmetry: negative in spring–summer period and positive in winter and fall months.

It is well known that the diurnal amount of solar radiation incident on the earth's surface is determined not only by the astronomic factors and clouds, but to a certain degree by the atmospheric transparency and reflection properties of the underlying surface. Based on the data of multiyear observations (1964–1994) at the world radiometric network, the authors of Ref. 12 analyzed maximum possible daily sums of the total solar radiation for different latitudes and all months of the year. By the maximum possible total the authors mean daily sum of solar radiation incident on the surface under combination of conditions, most favorable for arrival of the solar radiation, namely, atmospheric transparency, state of the sun disk, and surface albedo. Comparison of the daily $Q$ sums, measured at the TOR station, with the maximum possible sums for 56°N, published by Morozova and Myasnikov,[12] has shown that, in fact, for one day the earth surface in Tomsk receives 35 to 65% of the possible incident radiation. The percentage of the possible total radiation was maximum in July (65) and minimum in November (33).

It is also of interest the dependence of variations of diurnal totals on the type of pressure system and the type of air mass. For this, from the entire data array we have separated out the days with a certain dominating pressure system (cyclone/anticyclone) or type of the air mass (Arctic, midlatitude, or subtropical).

Since 1995 until 2005, Tomsk was influenced, during 429 days, by cyclones, and during 740 days by anticyclones. From the diurnal behavior of the daily sums of the total radiation under cyclone and anticyclone conditions, it is seen (Fig. 5*a*) that during the anticyclone the diurnal amount of total incoming radiation is larger all over the year. At the same time, the absolute difference between $Q$ sums under anticyclone and cyclone conditions grows as season progresses from winter to summer.

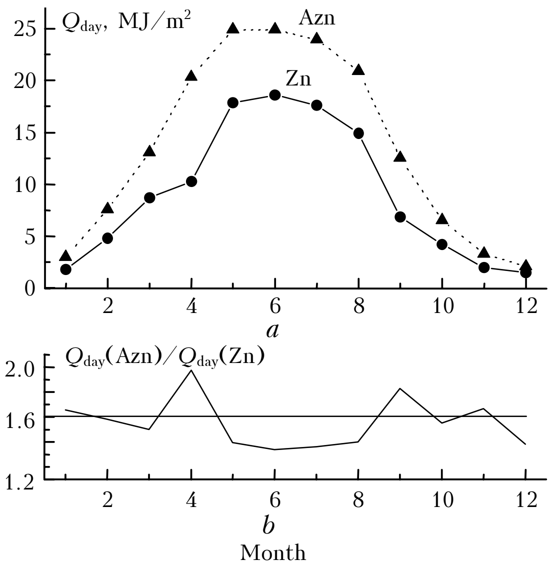


**Fig. 5.** The dependence of daily sums of the total solar radiation on the pressure system; here Zn is cyclone and Azn is anticyclone.

Obviously, the absolute value of the difference is caused by the increase of the sunshine duration at summertime. In fact, the differences in the amount of incoming solar radiation under cyclone and anticyclone conditions exist during whole year. This can be seen from Fig. 5*b*, which shows the ratio of daily sums under cyclone and anticyclone conditions. On the average, this ratio equals 1.6 and ranges from 1.4 to 2.0. We have considered in detail how the total radiation is distributed within cyclone and anticyclone. For this we normalized, to eliminate the seasonal variation, the daily sums for each month by the monthly mean daily sum for the corresponding month. From Fig. 6 it is seen that the largest amount of the total radiation is observed in the northeastern part of cyclone, while in the anticyclone the maximum is observed when south and southwestern parts dominate. For the total clouds in these parts of the system, the situation is opposite that does not contradict the current conceptions.

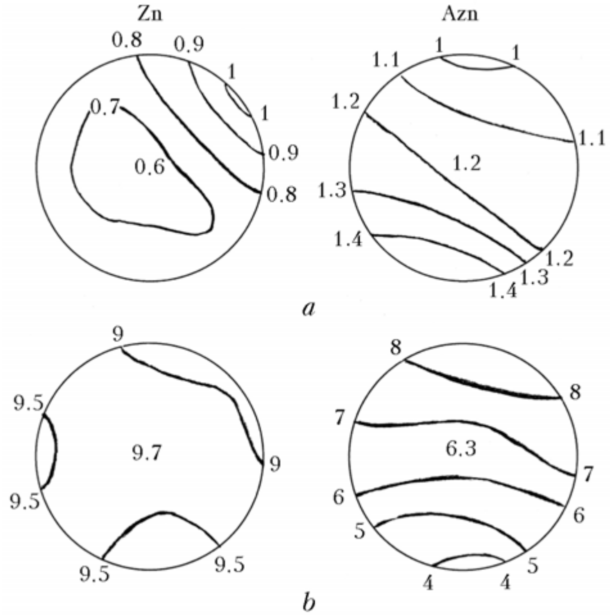


**Fig. 6.** Distribution of the normalized daily sums of total solar radiation (*a*) and total clouds (*b*) in cyclone (Zn) and anticyclone (Azn).

Under real conditions, the variations of radiative characteristics are influenced by the change of air masses. Tomsk Region is characterized by the dominance of arctic and midlatitude air masses. In the considered period, there were 993 days with arctic air mass (AAM), 968 days with midlatitude air mass (MAM), 242 days with subtropical air mass (SAM), and only 9 days with the tropical air mass. At the same time, we have to note that we excluded from the sample the days when change of air mass type occurred.

Over the year the influence of air mass on the amount of total incoming radiation differed. For instance, from October to May the daily sums of radiation in arctic and midlatitude air masses are close in value, in the summer periods $Q_d$ is larger in midlatitude air mass (Fig. 7).

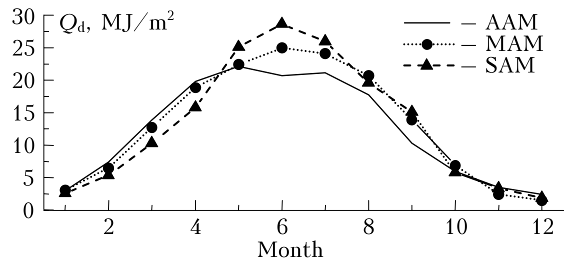


**Fig. 7.** Dependence of diurnal totals of total solar radiation on the type of air mass: arctic, moderate, and subtropical.

Seemingly, this is because in summer period, in cleaner, on the average, arctic air mass the attenuation of radiation by the total and low clouds is manifested. From July to September, in the arctic air mass the days with 8–10 total cloud amount and those with over 5 low cloud amount dominated more frequently than in the midlatitude air mass. This has led to almost 22% less diurnal totals than in midlatitude air mass. In the period from May to July, the daily sums of the total radiation are larger in subtropical air mass than in the arctic and midlatitude ones. In the cold period, the amount of total solar radiation is less in subtropical air mass than in cases with other types of air mass. This is primarily because the warm air, arriving at the cold underlying surface is rapidly saturated with water vapor, favoring more intense cloud formation. In the warm half year, the situation is opposite. Dry warm air arrives at the warm soil. At the same time, weather with little clouds is conserved, therefore the total radiation is larger in midlatitude and arctic air mass.

## Conclusion

Based on the analysis made we can conclude the following:

- Overall, for the considered period the radiative regime near Tomsk was quite stable and only insignificant positive trend of the total radiation was revealed despite the fact that, according to multiyear observations until 1994, on the territory of Western Siberia, the tendency was observed toward decrease of the annual mean of the total radiation.
- In 2003, because of the specific features of the circulation processes the annual amount of the total incoming radiation increased by 16% relative to the average over the considered period.
- The interannual variations of monthly sums of the total radiation for each month have a positive trend with the exception of March, July, and September.
- The dependence of the amount of total incoming radiation on the type of air mass occurred.
- The amount of daily sums of the total radiation in anticyclone is on the average 1.6 times larger than in cyclone, year round. The maximum diurnal amount of total incoming radiation is observed in the northeastern part of cyclones and in the south and southwestern parts of anticyclones.

The question is if this result characterizes only considered period or reflects multiyear regularities of $Q$ variations in Tomsk? Since we considered a short time series (1995–2005), the obtained results characterize only the considered period of observations.

### Acknowledgments

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