Statistics of clouds over Tomsk: data of ground-based observations for 1993–2004 period

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We present data of ground-based observations of total (N_{tot}) and low-level (N_{low}) cloud amount over Tomsk in 1993–2004. Interannual variations of N_{tot} and N_{low}, as well as averaged over 11 years monthly and seasonal values of cloud amount are considered. The obtained results are compared with data of many-year ground-based observations in Tomsk for 1936–1965 and satellite data for 2001–2004. The statistics of cloud amount is analyzed using the synoptic information and data on sunshine duration in Tomsk.

Clouds are one of the main sources of uncertainty in weather and climate prediction. Their influence on radiation balance depends primarily on the cloud amount, cloud top height, and cloud liquid (ice) water, as well as particle shapes and sizes (see, e.g., Ref. 1). The theoretical studies have shown that a high reflectivity of low-level clouds leads to the atmosphere cooling.[2,3] This conclusion is supported by observation results: for instance, the combined analysis of Earth Radiation Budget Experiment (ERBE) and International Satellite Cloud Climatology Project (ISCCP) data have shown that cloud-induced atmospheric cooling is –27 W/m^2, approximately 60% of which is due to low-level clouds.[4] High clouds play just the opposite role, and the greenhouse effect induced by them, on the whole, favors the atmosphere warming.[4,5] At the same time, regularities relating to the entire globe (or hemisphere), may not work in individual regions. For instance, the simulation results[6] suggest that at high latitudes (in contrast to midlatitudes) the low-level clouds, on the average throughout the year, favor the heating of the underlying surface.

Despite the important role played by clouds in transformation of solar and thermal radiation in the atmosphere, modern models of the weather and climate prediction use cloud parameterizations, which are still far from perfect. Source of data required for improvement of the cloud representation in the models are the results of satellite and ground-based observations. The cloud monitoring based on satellite data for the last decades provides the information on cloud characteristics (in particular, the total and high-level cloud amounts) on the scale of the globe as a whole. The role of ground-based observations is that they help to validate satellite data and more adequately describe the features of the regional cloud distribution.

This paper presents the data of ground-based observations of the cloud state (total N_{tot} and low-level N_{low} cloud amounts) over Tomsk, obtained at the Siberian Climatic and Ecological Observatory (SCEO) of the Institute of Monitoring of Climatic and Ecological Systems (IMCES) SB RAS in 1994–2004. The ground-based observations of clouds have been conducted at SCEO IMCES (56°30′N, 84°55′E) from September 1994 to the present. Until 1996 the observations were conducted in main synoptic terms, eight times a day; since 1997, only daytime observations (at 03:00, 06:00, 09:00, and 12:00 GMT) are conducted. To store and use the accumulated data, the database produced at the Institute of Atmospheric Optics (IAO) SB RAS is employed. It contains the information on cloud types, N_{tot}, N_{low}, sunshine duration, etc. The information on the cloud amount for 1993 and January–August 1994, as well as on synoptic situation in Tomsk throughout the considered period, is obtained using the daily synoptic maps.

We consider the variations of average N_{tot} and N_{low} values for different (monthly, seasonal, and yearly) timescales, and compare our results with data of many-year ground-based observations in Tomsk in 1936–1965 and the satellite data for 2001–2004. In analysis of results we use the information on synoptic processes, observed in the Tomsk region in the same period.

1. Characterization of the observation period

Temperature and precipitation

The considered time interval 1993–2004 falls within the period of global warming (the second half of the twentieth century), characterized by the growth of the air temperature in lower atmospheric layers, both throughout the globe and the Northern Hemisphere (http://www.cru.uea.ac.uk). In most regions of the Russian Federation, including West Siberia, the recent warming began in early 1970s

(Ref. 7; http://climate.mecom.ru). The time series of averaged anomalies in the annually mean temperature (deviations from the standard base period 1961–1990) for West Siberia and Tomsk are presented in Fig. 1 (data on the near-ground temperature in Tomsk are taken from Ref. 8).

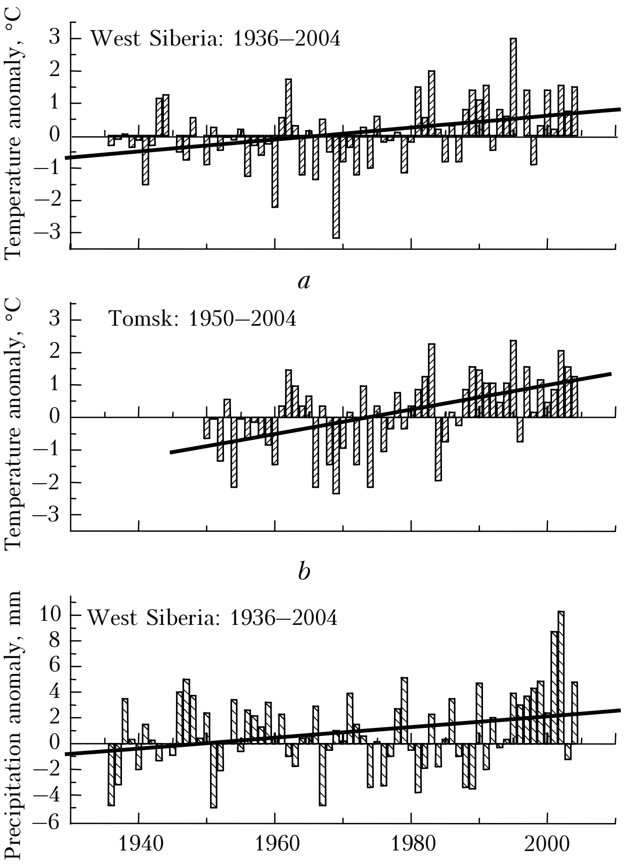

Fig. 1. Anomalies of the annually mean air temperature and precipitation (deviations from base period 1961–1990) and their linear trends: http://climate.mecom.ru (*a*, *c*) and Ref. 8 (*b*).

In the last 50 years, there is a tendency toward a decrease in annual and seasonal precipitation totals for Russia as a whole and its eastern regions.[7] At the same time, the period 1951–2004 at the territory of West Siberia is characterized by the growing precipitation anomaly (Fig. 1*c*), predominately in winter and spring; the precipitation excess in this region is observed every year for the last 10 years excluding 2003 (http://climate.mecom.ru). The results presented in Ref. 8 suggest that the precipitation amount in Tomsk, like at the territory of West Siberia, also increases.

Synoptic regime

The second half of the twentieth century (especially starting from 1980s) is characterized by intensification of cyclogenesis over Arctic (see, e.g., Ref. 9). Following to Ref. 9, a probable consequence of this fact, at a stable anticyclogenesis over continents, is the increase in the near-ground air temperature in the Northern Hemisphere, especially in the winter period. The change in atmospheric phenomena in the Arctic basin leads to considerable variations in the regional climate in the Siberian sector (60°–119°E), which is located at the interface between the northern and southern processes.

As the characteristics of the synoptic situation we considered the number of observation periods during which the territory of Tomsk was affected by fronts or their zones $N(F)$, cyclones $N(Zn)$, and anticyclones $N(Az)$. The specificity of the chosen period is that, as the data of Ref. 10 suggest, during 1993–2004 the number of $N(F)$ increased, the number of $N(Zn)$ decreased by about a factor of two, while $N(Az)$ remained almost unchanged.

Clouds and radiation

Monthly averaged ISCCP data show that, during the last twenty years, N_{tot} on the global scale varied according to the sinusoidal law: from 1985 to 2000 it decreased by ~4–5%, and in the subsequent years (between 2000 and 2004) it increased by 2–3% (Ref. 11). At the same time, N_{low} continued to decrease after 2000, whereas the middle- and high-level cloud amount $N_{mid-high}$ increased. The difference between N_{low} and $N_{mid-high}$, averaged over five years, was at a 7–8% level in 1985–1999, and almost doubled (13%) for the last 5 years. On the whole, the increase of the cloud amount was accompanied by the increase of the fraction of reflected solar radiation and, hence, the decrease of the solar energy reaching the Earth. However, the expected decrease in the Earth surface temperature has not occurred: in the opinion of authors of Ref. 11, this is due to redistribution of clouds over atmospheric levels, observed during last 5 years.

Analysis of maximum possible daily sums of the total solar radiation for two periods (1964–1979 and 1981–1994), presented in Ref. 12, shows a decrease of the fraction of the radiant solar energy reaching the Earth's surface. The largest decrease (4–10%, depending on the season) was observed over the territory of Northern Hemisphere, largely in winter months. The statistically significant decrease of solar radiation between 1960 and 1987 was also recorded at 160 actinometric NIS stations.[13] Our data suggest that there are negative trends in the annual sums of the total (94% of cases) and direct (97% of cases) radiation, as well as the increase of the fraction of the scattered radiation in 60% of cases.

2. Interannual variations of cloud amount

Consider interannual variations of total and low-level cloud amounts and their root-mean-square deviation $\sigma_{N_{tot}}$ over Tomsk. In the period of observations, the minimal value of the annually mean N_{tot} (7.4) was observed in 1996–1997, and maximal one (8.6) in 2002 (Fig. 2). The $\sigma_{N\text{tot}}$ was quite stable and varied in the cloud amount range 2.9–3.5. The minimum of annually mean N_{low} (cloud amount of 2.8) was observed in 1994, while the maximum (4.3) was recorded in 2002 and 2004. Variations of the low-level cloud amount were stronger than those of N_{tot} and reached 3.2–4.1, depending on the year. Note that in 2002, when the total and low cloud amounts were maximal, the largest precipitation anomaly for almost 60-year period of observations was recorded in West Siberia (see Fig. 1*c*). During 1993–2004, a weak positive N_{tot} trend and a more considerable N_{low} increase were observed; the average total and low-level cloud amounts over 11-year period were 8 and 3.7, respectively.

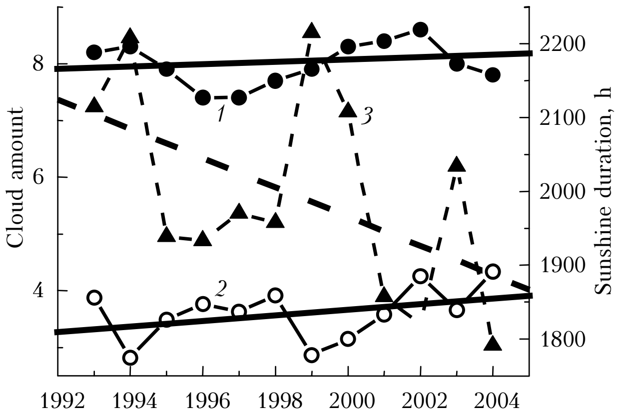

Fig. 2. Interannual variations of total and low-level cloud amounts (daytime observations) and the sunshine duration (SSD) over Tomsk according to the data of SCEO IMCES SB RAS: N_{tot} (*1*), N_{low} (*2*), and SSD (*3*).

The tendency towards the increase of the cloud amount also takes place in other regions of Russia (the data presented below refer to somewhat other observation periods than ours). The data of Meteorological Observatory of the Moscow State University (55°42′N, 37°31′E), located almost at the same latitude as Tomsk, suggest that, between 1958 and 1997, the annually mean N_{tot} value increased approximately by 0.7, while N_{low} increased by 1.1. (Ref. 14). As one of the possible causes of the cloud amount increase, Abakumova (Ref. 14) considers the growth of the repetition frequency of cyclonic types of circulation (as was noted above, in Tomsk, on the contrary, a decrease of the repetition frequency of cyclones was observed in period 1993–2004). Over the period 1967–1990, the increase of N_{tot} and N_{low} was also recorded at the territory of the European part of the former USSR, West Siberia, and Far East.[15] When the entire territory of the former USSR is considered, somewhat different situation takes place. The data of ground-based observations, presented by Zherebtsov and colleagues,[16] as well as data taken from Ref. 17, suggest that in period 1936–1990, the total and high-level cloud amount increased, whereas the low-level cloud amount decreased.

One of the characteristics, frequently used in analysis of cloud amount variations, is the sunshine duration (SSD). Data of observations[8,18] suggest that since 1958 the SSD over Tomsk increases, whereas the considered period 1993–2004 is characterized by its considerable decrease (Fig. 3).

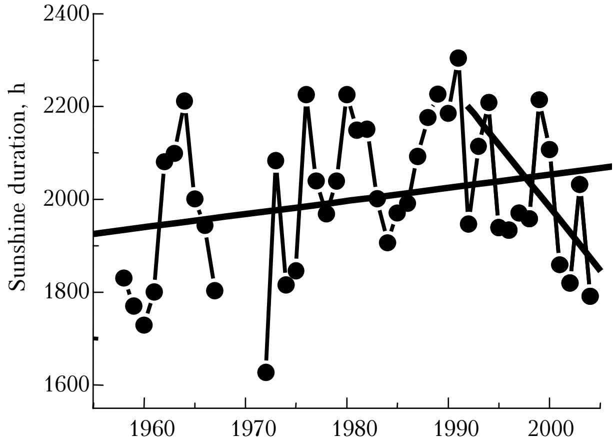

Fig. 3. Sunshine duration over Tomsk in 1958–2004 (according to data of Ref. 18 and SCEO IMCES SB RAS).

The observed negative SSD trend is consistent with the cloudiness increase over Tomsk; of note is a significant anticorrelation dependence between SSD and the low-level cloud amount (see Fig. 2). Note that the SSD decrease at the positive cloud amount trend is also observed in other regions of the globe (Ireland,[19] USA[20]). The correlations between the cloud amount and the sunshine duration in more detail can be analyzed using the information on the cloud distribution over atmospheric levels.

3. Monthly mean cloud amount according to data of many-year observations

The 1993–2004 data suggest that the largest cloud amount was observed in fall–winter months with maximum (8.7) in November (Fig. 4). In the annual N_{tot} behavior there are two minima (7.3), in March and July. The local maxima of the low-level cloud amount N_{low} are recorded in June (4) and October (5.1); minimal value of the low-level cloud amount (2.4) was observed in March. As to the N_{low} and N_{tot} minima in March, it should be noted that this month was unusually dry: data of Ref. 8 suggest that for period 1950–1998 no cases of the excessive humidity were recorded.

The root-mean-square deviation of total $\sigma_{N\text{tot}}$ and low-level $\sigma_{N\text{low}}$ cloud amounts varied from 2.9 to 4.0 and from 3.4 to 4.5, respectively. Values of the cloud amount were most stable in summer. In September–October, $\sigma_{N\text{tot}}$ reached the minimum (2.9), while $\sigma_{N\text{low}}$ was maximal (4.5). Noteworthy, $\sigma_{N\text{tot}}$ had the largest variability range (3.4–4.0) in spring with minimum in March, while $\sigma_{N\text{low}}$ varied most strongly in winter (3.4–4.3) with minimum in January.

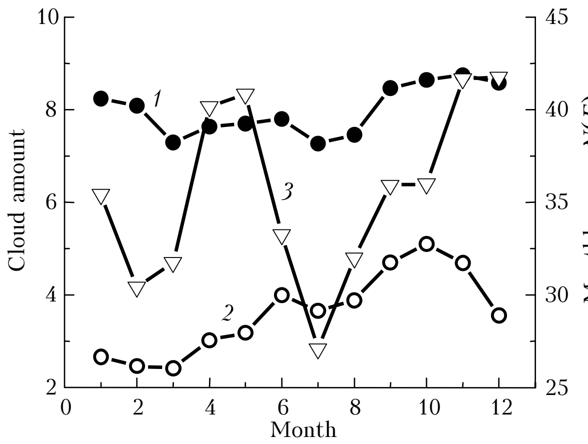

Fig. 4. Monthly mean values of the cloud amount and planetary frontal zones $N(F)$, based on the data of many-year observations in 1993–2004: N_{tot} (*1*), N_{low} (*2*), $N(F)$ (*3*).

The total cloud amount is known to depend ambiguously on the type of synoptic systems, because under different circulation conditions inside atmospheric system there are both regions with low cloudiness, and regions with heavy cloudiness. In cyclones, the cloudy weather is observed most often in their central part and in zones of atmospheric fronts; in anticyclones, the presence of clouds is most probable in peripheral regions.

Analysis of synoptic situation over the territory of Tomsk has shown[10] that the annual behavior of the occurrence of cyclones is poorly expressed and has three local minima (the strongest one in July). The occurrence of anticyclones from month to month has a higher significance (with minimum in summer period). The quite well expressed annual behavior of cloudiness best agrees with a seasonal change of the position of planetary frontal zones (PFZs) (see Fig. 4). At midlatitudes, PFZs in summer period migrate in the northern direction, decreasing in intensity; as a consequence, in the warm period the cloudiness is formed, which is not continuous in most cases.[21]

4. Comparison with data of many-year ground-based observations

Reference 22 presents data on the occurrences of clear (N_{tot} = 0–2), half-clear (N_{tot} = 3–7), and cloudy (N_{tot} = 8–10) weather in Tomsk, based on results of diurnal observations in 1936–1965. The climatically significant 30-year period of observations was in the time interval of a comparatively small cooling between two periods of warming (1910–1940 and from 1970 to the present). The period was characterized by the following features (Fig. 5):

– cloudy weather was most probable (over 50% in all months); clear weather was observed in more than 20–25% of cases (except in October, with 15% cases); cloudiness with N_{tot} = 3–7 was the least probable;

– the probability of the cloudy sky was minimal in July (51%) and maximal in October (76%); clear sky was most probable in February (35%) and the least probable in October (14%);

– the occurrence of half-clear days increased between January (7–8%) and July (23%), followed by a symmetric decrease until December (7%).

Is it possible to estimate the occurrences of the clear, half-clear, and cloudy weather for the considered time period based on the available information? The problem is that the data on diurnal cloud variations cover only a four-year period of observations (1993–1996).

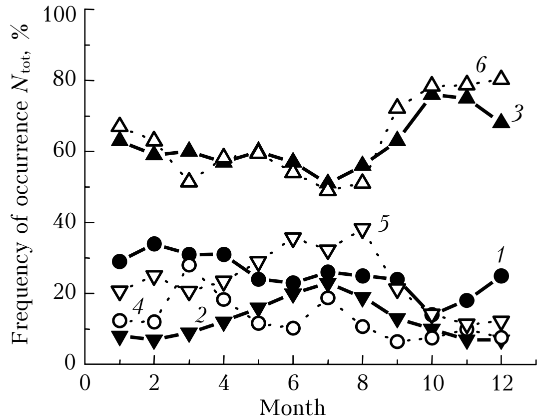

Fig. 5. Comparison of occurrences of clear, half-clear, and cloudy weather, inferred from diurnal observations in 1936–1965 at N_{tot} = 0–2 (*1*), 3–7 (*2*), and 8–10 (*3*); and in 1993–1996 at N_{tot} = 0–2 (*4*), 3–7 (*5*), and 8–10 (*6*).

It follows from the Table that the data of daytime observations of the total cloud amount in 1993–1996 and 1993–2004 practically coincide, both for individual seasons and the periods on the whole. Therefore, it can be supposed that the results of N_{tot} diurnal observations for 1993–1996, are also more or less characteristic of the entire 11-year period of observations. Let us use the results of diurnal observations in 1993–1996 for comparison with the data of many-year 1936–1965 observations of the occurrences of the clear, half-clear, and cloudy weather.

Diurnal and daytime values of total N_{tot} and low-level N_{low} cloud amount in Tomsk

Season	1993–1996				1993–2004	
	Diurnal		Daytime		Daytime	
	N_{tot}	N_{low}	N_{tot}	N_{low}	N_{tot}	N_{low}
Winter	8	2.5	8.3	2.6	8.3	2.9
Spring	6.9	2.3	7.4	2.7	7.5	2.9
Summer	6.9	2.7	7.3	3.5	7.5	3.9
Fall	8.5	4.7	8.8	5	8.6	4.9
Entire period	7.6	3.1	8	3.5	8	3.7

The analysis of the results shows (see Fig. 5) that the probability of occurrence of the cloudy weather remained the largest, whereas the number of clear days decreased, especially in winter months (approximately by 20%). The occurrence of half-clear days ($N_{tot} = 3–7$) increased, while the annual behavior (with the maximum in summer months) remained unchanged.

Emphasize that the 4-year averaging period hardly can be considered sufficient to conduct a valuable analysis; nonetheless we used these data for lack of other, more representative ones. Moreover, the difference between the 4-year average diurnal and daytime N_{tot} values does not exceed the cloud amount equal to 1 (see the Table) and, seemingly, cannot change significantly the conclusions.

5. Comparison of ground-based and satellite data

Compare monthly mean values of total cloud amount based on ground observations of N_{tot} and values retrieved from satellite measurements $N_{tot}(0)$ (Modis/Terra Atmosphere Monthly Global Product) for 2001–2004 (the used $N_{tot}(0)$ values correspond to the spatial resolution 1°×1° for grid cell containing coordinates of Tomsk (56–57°N, 84–85°E).

It should be expected that N_{tot}, determined by an observer from the Earth's surface, will exceed $N_{tot}(0)$ since the observer's field of view may be shaded by cloud lateral sides. In the period under analysis, the inequality $N_{tot}(0) \le N_{tot}$ held almost always (Fig. 6).

However, a high reflectivity of snow cover decreases the accuracy of $N_{tot}(0)$ retrieval algorithm, and in some winter months of 2001–2004 a reverse inequality took place (see, e.g., Fig. 6*d*). Comparing N_{tot} and $N_{tot}(0)$, we should also keep in mind that the accuracy of ground observations of the cloud amount depends on the observer's qualification and can influence to some degree the quality of observations. Our data suggest that the maximal difference between N_{tot} and $N_{tot}(0)$ was observed at the end of spring and in summer months: for instance, in May–June 2003 the difference reached 3.

To bring the data of ground-based and satellite observations into closer correspondence, i.e., to mitigate as much as possible the effects caused by the cloud lateral sides, different empirical formulas are used. For instance, Ref. 23 presents the following formulas relating N_{tot} and $N_{tot}(0)$:

$$N_{tot}^{(1)} = N_{tot}(0) + 0.5N_{tot}(0)\left[10 - N_{tot}(0)\right] \quad (1)$$

and

$$N_{tot}^{(2)} = N_{tot}(0) + 0.8\left[10 - N_{tot}(0)\right]\left[N_{tot}(0)\right]^{0.8}. \quad (2)$$

When the cloud amount is low, formula (2), as authors of Ref. 23 think, is more exact; however, it gives overestimated values at $3 < N_{tot}(0) < 8$.

Let us compare data of ground-based observations and cloud amount calculations by formula (1). For 2001, 2002, and 2004, the N_{tot} and $N_{tot}^{(1)}$ values reasonably well agree with each other: the $|N_{tot} - N_{tot}^{(1)}|$ value does not exceed 1, except for some winter months, possibly, due to inaccuracy of $N_{tot}(0)$ determination above snow cover. Large differences between N_{tot} and $N_{tot}^{(1)}$ were observed in 2003, when $|N_{tot} - N_{tot}^{(1)}|$ exceeded 1.5 in May–June.

Simultaneous analysis of N_{tot} and $N_{tot}^{(2)}$ has shown that the use of formula (2), on the average, leads to more significant differences between the ground-based and satellite data.

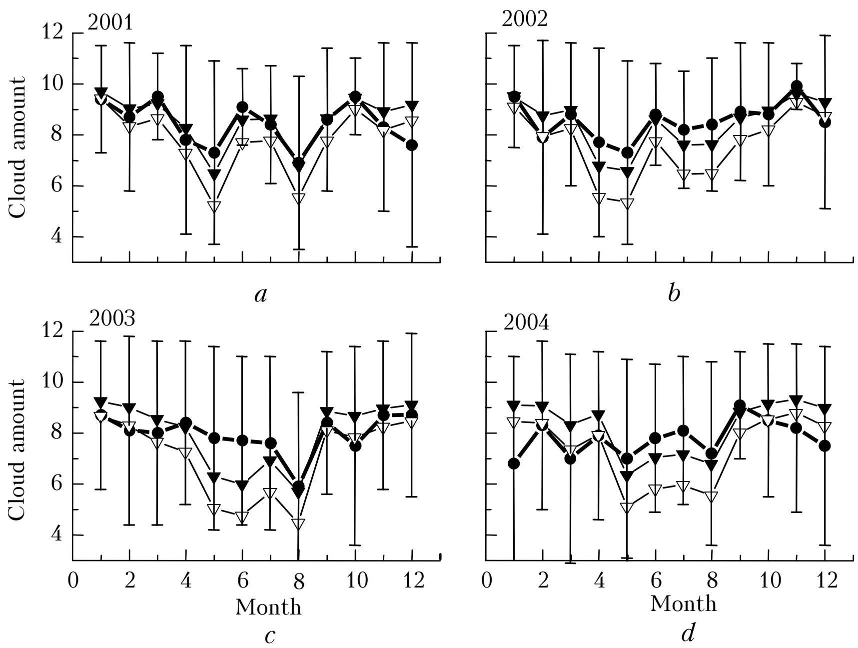

Fig. 6. Total cloud amount over Tomsk, based on data of ground-based and satellite observations in 2001–2004: (–●–) ground-based observations; (–▽–) satellite data; (–▼–) calculations by formula (1).

Conclusion

Analysis of variations of total and low cloud amounts over Tomsk, observed during 1993–2004, has shown the identity of the main climatic parameters, namely many-year interannual behavior of anomalies of the annually mean temperature and precipitation in Tomsk and West Siberia (typical region of the boreal forest zones) as a whole. This indicates that the results obtained by us are not exclusive and reflect to some degree the tendencies characteristic of the entire region.

The obtained conclusions are as follows:

1. The cloud amount over Tomsk was estimated on the basis of regular ground-based full-day observations (1993–1996) and at daylight observations (from 1997 to the present). The results of daytime observations have shown a positive trend of the total and low-level cloud amounts, with a more significant increase (≈ 0.7) for the low-level cloud amount as compared to the total one. Against the background of many-year observations in 1936–1965, there is a tendency toward reduction of days with little cloudiness and increase of the number of days with cloud amount of 3–7 .

2. Simultaneous analysis of the total cloud amount and synoptic information has shown that the annual N_{tot} behavior most closely correlates with seasonal variations of the planetary frontal zone locations and is weakly related to the passage of cyclones and anticyclones over the territory of Tomsk.

3. In period 2001–2004, the ground-based observations of N_{tot} satisfactorily (predominately in the limits of 0–1) agree with monthly mean values of the cloud amount inferred from data of satellite measurements (Modis/Terra Atmosphere Monthly Global Product).

4. The sunshine duration observed in Tomsk since 1958 increased, whereas in 1993–2004 the SSD was characterized by a negative trend and pronounced anticorrelation dependence on the low-level cloud amount.

Since the considered time series 1993–2004 is short as compared to the scales of climate changes, the obtained results correspond only to the given period of observations. The persistence of the revealed tendencies in cloud variations in the future is still early to discuss.

Undoubtedly, the obtained results will be helpful in analysis of available data of radiation measurements and the projected experiments (in particular, those based on the instrumentation available at the IAO SB RAS).

Acknowledgments

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