On diurnal cloud variations and factors of cloud formation

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Using eight-term observational data for cloud amounts in Saint Petersburg, Belogorka, and Sosnovo, we have analyzed diurnal cloud variations and estimated the role of radiative–thermal and dynamical factors in the cloud formation. We found that the main role in formation of all cloud types is played by dynamical factors, such as synoptic-scale vertical motions, height variations of their velocity, and associated temporal increase of the vertical temperature gradient. The contribution of the radiative–thermal factor does not exceed 30% in most cases.

Multiform cloud systems belong to the most important natural phenomena among key factors determining the weather and climate on the Earth. Clouds influence the radiative budget of the atmosphere and surface, favor self-purification of the atmosphere, play an important role in natural water cycle, etc.

Therefore, the clouds were the topic of great recent concern (see, e.g., the reviewing works in Refs. 1–4). Most full information on clouds, including their geometric, physical, and structural characteristics, spatiotemporal variations, etc. are presented in Ref. 5. However, even this full publication contains no information on their diurnal variations. At the same time, the diurnal cloud variations are known to play a significant role in the process of the cloud–radiation interaction.

As it is well known, the clouds are formed under influence of several factors: vertical motions, as well as advective, turbulent, and radiation influxes of heat. At the same time, as argued in Ref. 6, a key role in formation of the stratiform (frontal) clouds is played by vertical synoptic-scale processes, as well as vertical and horizontal turbulent exchange.

As to another cloud type, cumuliform (convective) clouds, it is commonly believed that they are formed most frequently under influence of solar radiation influxes and appearing dry unstable thermal stratification. This factor is termed by us radiative thermal. It operates only during the day.

On the other hand, References 7 and 8 demonstrate that the moist unstable stratification arises due to dynamical factor, i.e., synoptic-scale vertical motions favoring a decrease of temperature and increase of its vertical gradient γ. If by the time of reaching saturation (at the condensation level), in the lifting air mass γ turns to be larger than the moist adiabatic gradient ($\gamma_{\rm ma}$), then a convective cloud develops. In the opposite case ($\gamma < \gamma_{\rm ma}$), a stratiform cloud is formed.

Taking this into account, we presents a quantitative estimate of diurnal cloud variations and contribution of these factors to cloud formation. To this end, we have analyzed distributions of cloud amount n for day and night, based on the data of 8-term observations in Saint Petersburg (SPb) and two villages: Belogorka (Bel) and Sosnovo (Sos), located 80 km to the south and to the north of the city. The observations at 09:00, 12:00, 15:00, and 18:00 were classified as day-time, and those at 21:00, 24:00, 03:00, and 06:00 as night-time. All times are either Moscow Standard Time (MST) or, for observations in Saint Petersburg, the Saint Petersburg Local Time (LT), calculated as MST minus 1h, because the temperature and other meteorological variables reach maximum 2–3 h later than the local noon.

We analyzed data samples for four summer months (June of 1977, July of 1977, July of 1979, and August of 1979) with a total of 492 (either day- or night-time) observations for each observation site.

As is well known, under impact of the dynamic factor, closely related to synoptic-scale vortices (primarily cyclones and troughs), the day and night intensities of cloud formation are equal, because the probability of vortex formation does not depend on the time of the day. Therefore, the difference between day ($N_{\rm d}$) and night ($N_{\rm n}$) numbers of clouds divided by the number of clouds for the whole day $N = N_{\rm d} + N_{\rm n}$

$$p = (N_{\rm d} - N_{\rm n})/N$$

characterizes the contribution of the radiative-thermal factor to cloud formation.

Tables 1 and 2 present information on daytime (d) and nighttime (n) frequencies of occurrence of particular cloud amounts and their groups (1–3, 4–6, 7–9, and 10), calculated from observations at Saint Petersburg, Belogorka, and Sosnovo in summer months. The volume of each (nighttime and daytime) sample, used for calculations, is 1476 observations in Table 1 and 492 observations in Table 2.

Table 1. Total (over three sites) frequency of occurrence (%) of each cloud amount for day and night. Summer

Time of day	Cloud amount 0	1	2	3	4	5	6	7	8	9	10
Low clouds											
Day	19	4	6	8	8	7	10	5	5	3	25
Night	35	4	5	4	5	3	4	2	2	1	35
P, %	−30	−1	14	38	22	38	42	50	36	42	−16
Total clouds											
Day	6	2	3	5	6	4	7	5	8	8	46
Night	14	4	5	5	6	2	4	3	4	4	49
P, %	−43	−27	−22	1	1	41	23	21	33	36	−4

Table 2. Frequency of occurrence (%) of different groups of cloud amounts in Saint Petersburg (SPb), Belogorka (Bel), and Sosnovo (Sos) at day (d) and night (n). Summer

Site	Groups of cloud amounts														
	0			1–3			4–6			7–9			10		
	d	n	P, %	d	n	P, %	d	n	P, %	d	n	P, %	d	n	P, %
Low clouds															
SPb	20	38	−32	15	9	27	21	11	32	18	7	44	26	35	−16
Bel	15	28	−27	16	13	10	24	11	38	18	8	42	27	40	−20
Sos	21	37	−28	22	14	20	30	15	33	4	3	19	23	31	−13
Total clouds															
SPb	8	17	−41	7	11	−18	11	12	−4	29	15	33	45	45	0
Bel	3	15	−64	10	13	−10	20	10	31	21	15	29	40	47	−7
Sos.	7	11	−24	15	18	−8	19	12	23	6	3	37	53	56	−3

It follows from analysis of Tables 1 and 2 that:

– the obtained distribution of cloud amount well agrees with the well-known regularity (Ref. 4): ground observations for cloud amount at a fixed site (generally, with a small viewing area) indicate that the frequency of occurrence, independent of time of the day, is maximum for 0 (clear sky) and 10 (overcast) cloud amounts. For instance, the frequency of occurrence is 19% during the day and 35% during the night for clear sky (low clouds), and 25% during the day and 35% during the night for overcast; whereas the frequency of occurrence for all other cloud amounts is quite small and, for each cloud amount, does not exceed 8–10% during the day and 4–5% during the night;

– in contrast to the distribution of individual cloud amounts, for groups of cloud amounts the maxima of frequency of occurrence for 0 and 10 cloud amounts are found only at night, because in the daytime, only for Saint Petersburg and Belogorka just the maximum of occurrence of overcast is observed;

– the probability of occurrence of clear sky or overcast is much higher during the night than during the day (for other cloud amounts, this is not the case). Indeed, it is clearly seen from Table 1 that the frequency of occurrence of 0 and 10 low cloud amounts is by 35% at night and much less (19% and 25%) during the day.

The same is true for distribution of groups of cloud amount.

We also estimated the frequency of occurrence of similar, synchronous (with respect to cloud amount) atmospheric states at two and three sites, i.e., the ratio of these states to the total number of observations, equaling 248 for both day and night. These frequencies of occurrence are presented in Table 3, from which it is clearly seen that they are almost independent of the time of the day.

Table 3. Ratio of synchronous atmospheric states at different sites to the total number of observations (%). Summer

Clouds		SPb–Bel	SPb–Sos	Three sites	
Total	Daytime	41	41	29	25
	Nighttime	42	40	36	25
Low	Daytime	39	37	25	25
	Nighttime	47	41	36	27

Though the total occurrence of similar states is not very rare (about 40% at two sites), the majority of these states are observed for overcast and clear sky (Table 4). Total percentage of 0 and 10 cloud amounts lies between 81 and 90% at two sites and between 95 and 97% at three sites for total clouds, and between 73 and 95% at two sites and between 90 and 99% at three sites for low clouds.

Table 4. Ratio of the number of similar synchronous states to the total amount of states (%). Summer

Sites		Total cloud amount					Low cloud amount				
		0	1–3	4–6	7–9	10	0	1–3	4–6	7–9	10
SPb-Bel	Day	18	3	3	10	66	33	2	11	14	40
	Night	18	5	5	9	63	47	4	0	1	48
SPb–Sos	Day	8	5	3	3	81	45	6	13	1	35
	Night	12	3	6	1	78	60	3	6	1	30
Bel–SPb–Sos	Day	5	3	0	0	92	37	3	5	2	53
	Night	6	3	2	0	89	64	1	0	0	35

For comparison, in addition to summer months, we also have analyzed the day and night distribution of cloud amount, based on observations at the same sites (Saint Petersburg, Belogorka, and Sosnovo) in Marches of 1978–1980. Taking into account that the temperature maximum can be delayed by more than 2 h relative to the local noon, in addition to the above-mentioned division of the day into day and night parts (I), for comparison we have processed the data, attributing 12:00, 15:00, 18:00, and 21:00 LT to daytime hours, and 24:00, 03:00, 06:00, and 09:00 LT to nighttime hours (II). In this case, the volume of each (daytime and nighttime) sample ranged from 1109 to 1116 observations.

As in summer, in March the frequency of cloud occurrence, according to Table 5, is maximal for 0 and 10 cloud amounts having practically equal probabilities. However, the probability of clear sky and overcast occurrence at night and day is markedly higher in March than in summer. In addition, these probabilities, calculated for day and night periods, are nearly equal.

Table 5. Total (over three sites) frequency of occurrence (%) of low-level clouds. March

Time of the day		Cloud amount				
		0	1–3	4–6	7–9	10
I	Day	41	4	6	3	46
	Night	46	2	4	2	46
II	Day	43	4	6	3	44
	Night	44	3	3	2	48

Comparison of cloud distributions for I and II methods of day division (see Table 5) reveals no significant difference in cloud distributions: difference in cloud occurrences between the I and II day-division methods generally does not exceed 1–2%. At least, no regularity (e.g., of any specific sign) during transition from method I to method II is seen in Table 5 and data on the frequency of occurrence of low or total cloud amounts.

In addition to frequencies of occurrence, Tables 1 and 2 also give values of parameter P, characterizing the contribution of the radiative-thermal factor to the cloud formation. It follows from these tables that the radiative-thermal factor leads to cloud formation only in cases where (e.g., for low-level) the cloud amount equals 2–9. For 0 and 10 cloud amounts we have $P < 0$, suggesting that these cloud states occur more often at night than during the day, i.e., that the dynamic factor prevails.

Table 6 presents the weighted mean values of P for all cloud amounts.

Table 6. Weighted mean values of P (%) for all cloud amounts

Clouds	Summer				Spring			
	SPb	Bel	Sos	Three sites	SPb	Bel	Sos	Three sites
Total	5.5	6.3	2.2	4.7	19.3	5.5	10.0	10.7
Low	13.1	9.3	11.4	10.8	4.0	2.0	7.2	4.4

It follows from this table that the radiative effect on the average does not exceed 20%, and even 10% in most cases.

Table 7, in addition, presents the distribution density (%) of P at the three sites for low clouds. This table demonstrates quite high frequency of occurrence of the atmospheric states when cloud formation is more intense at night than during the day ($P < 0$); the distribution density of these states is 32% in summer and 7% in spring.

Table 7. Distribution density (%) of P at three sites for low clouds

Season	Values of P, %					
	< 0	0–10	10–20	20–30	30–40	> 40
Summer	32	9	7	14	25	13
Spring	7	25	23	11	9	25

Most positive values of P fall within the interval 0–40%; only in 13% of cases in summer and in 25% of cases in spring P exceeds 40%.

It was also found from the available data that in summer the radiation stronger affects the low-level clouds, for which P is larger than for the total clouds. However, the situation is reversed in March, when P values are smaller for low than for total clouds.

In the whole, the spring- and summertime data well agree. It follows from these data that the clouds are formed both at day and night; and that the key role in the cloud formation is played by the dynamic factor, i.e., by synoptic-scale vertical motions and turbulent exchange.

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