INFLUENCE OF ANTHROPOGENIC FACTORS ON CLOUD FIELD

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We analyze a series of daily 8-term observations of the total cloudiness cover index n over St. Petersburg and over a small village Belogorka (countryside). The distribution function of the difference Δn between of the cloud cover index values in St. Petersburg and Belogorka is constructed for two seasons (summer and winter). The maximum of Δn occurrence is at $\Delta n = 0$ being equal to 68% in winter and 40% in summer. The occurrence of both synchronous and time-separated Δn values has been calculated. The probability that the cloud cover index remains the same or changes from one cloud gradation to another one is studied. From analysis of diurnal and monthly mean Δn values, we conclude that: (1) the cloud cover index of low-level clouds under urban conditions is a few tenths larger than under the rural ones; (2) dynamic factors are major contributors to the cloud formation process; and (3) thermal factors contribute no more than 10–20%.

Cloud formation and evolution are closely related to air temperature and humidity fields. Therefore, one can not exclude that thermal and moisture regimes in the air over a big city may influence the cloud field.

The first half of the paper presents 5-year (from 1975 to 1979) daily 8-term observations of the total cloud cover index (CCI) for St. Petersburg (P) and Belogorka (B), a small village 80 km to the south of P, as well as the observations in Sosnovo, a village 80 km to the north of P, carried out in some years.

In the second half of the paper, we analyze monthly mean CCI of low-level clouds at these same locations (P and B) for a 20-year period (from 1975 to 1994).

As in the case with other meteorological parameters, for CCI we have also analyzed the difference $\Delta n = n_P - n_B$ between P (n_P) and B (n_B) values.

Table I presents the distribution function F of the difference Δn. As is seen from the Table, the CCI values, n, in P and B may substantially differ. Moreover, it happened so that in 4% of winter and 2% of summer days clear skies were observed at one location while having overcast at the other one. The difference in cloud cover index, n, for P and B up to 5 units occurred in over than 13% of cases in winter and summer. The occurrence (in %) of P–B difference in a number of Δn gradation is as follows:

	-10 – -6	-5 – -3	-2 – -1	0	1–2	3–5	6–10
Winter	5	4	5	68	6	5	8
Summer	5	8	14	40	14	12	7

In winter season, when stratiform clouds are prevail, the same CCI ($\Delta n = 0$) is most frequently observed (in 68% of cases) at the two locations. Vigorous summertime convection leads to a much less frequent occurrence of zero difference Δn, that is being only 40%. However, in all seasons, the occurrence of positive Δn values is only few percent, 4% in winter and 6% in summer, larger than that of the negative Δn values.

In addition, we will compare the Δn occurrence (in %) separately for day-time (d) and night-time (n) observations:

		CCI difference Δn						
		-10 – -6	-5 – -3	-2 – -1	0	1–2	3–5	6–10
Winter	n	6	4	4	70	4	3	9
	d	4	5	6	65	8	6	6
Summer	n	6	9	12	41	12	11	9
	d	4	8	15	38	17	13	5

In winter, the occurrence of $\Delta n > 0$ is more frequent than that of $\Delta n < 0$ by 4% at night and by 5% during day-time; in summer, the figures are 5 and 8%, respectively. Also, $\Delta n = 0$ values are nearly equally frequent during the day- and night-time.

In addition to the difference Δn between the cloud cover indices measured synchronously, we have also tried to study the difference $\Delta n = n(0) - n(\tau)$ between the n values separated by a time lag, τ. We relate this difference to the wind direction by hypothesizing that, with south winds, the clouds first observed in B are then to be observed in P, τ hours later. In terms of the cloud cover index, the difference $n_B(0) - n_P(\tau)$ between B and P observations at times 0 and τ, respectively, should be less than that between synchronous observations, or when the same difference is taken for any other wind direction.

We have compiled such samples for south and north (± 22.5°) wind directions. Geographically, the observation sites chosen here (B, P, and S) are all located approximately at the same longitude (30°E), B to the south and S to the north of P.

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TABLE I. Distribution function F (%) of the difference $\Delta n = n_{\rm P} - n_{\rm B}$ of the total cloud cover indices, N is the sample size.

Season	$\Delta n \le$, CCI difference													N
	−10	−8	−6	−4	−2	−1	0	1	2	4	6	8	10	
Winter	2	3	5	8	12	14	82	84	88	91	94	97	100	3608
Summer	1	2	5	9	19	27	67	75	81	91	96	99	100	3680

The calculated occurrence of Δn is presented in Table II for several gradations around $\Delta n = 0$. Entries in the left-hand half must, as the hypothesis dictates, depend on direction of cloud motion, and those in the right-hand half must not.

TABLE II. Occurrence (in %) of the difference between cover indices in P ($n_{\rm P}$), Sosnovo ($n_{\rm S}$) and Belogorka ($n_{\rm B}$) for the summer of 1979.

τ, h	CCI difference Δn,				CCI difference Δn,				N
	0	-1–1	-2–2	-3–3	0	-1–1	-2–2	-3–3	
North wind									
	$n_{\rm S}(0) - n_{\rm P}(\tau)$				$n_{\rm P}(0) - n_{\rm S}(\tau)$				94
0	47	52	63	72	47	52	63	72	
3	43	51	58	67	42	50	57	64	
6	28	32	40	47	33	37	42	49	
	$n_{\rm P}(0) - n_{\rm B}(\tau)$				$n_{\rm B}(0) - n_{\rm P}(\tau)$				94
0	46	56	65	73	46	56	65	73	
3	40	49	58	64	43	54	64	75	
6	36	42	51	61	46	53	58	68	
	$n_{\rm S}(0) - n_{\rm B}(\tau)$				$n_{\rm B}(0) - n_{\rm S}(\tau)$				94
0	46	55	66	73	46	55	66	73	
3	43	51	59	70	44	50	60	70	
6	48	57	63	69	42	45	52	57	
South wind									
	$n_{\rm P}(0) - n_{\rm S}(\tau)$				$n_{\rm S}(0) - n_{\rm P}(\tau)$				50
0	26	38	50	58	26	38	50	58	
3	15	25	37	42	12	26	40	49	
6	10	20	26	42	26	32	45	48	
	$n_{\rm B}(0) - n_{\rm P}(\tau)$				$n_{\rm P}(0) - n_{\rm B}(\tau)$				50
0	40	48	64	78	40	48	64	78	
3	29	36	53	65	22	34	51	55	
6	25	28	37	46	23	32	48	48	
	$n_{\rm S}(0) - n_{\rm P}(\tau)$				$n_{\rm P}(0) - n_{\rm S}(\tau)$				50
0	30	40	48	60	30	40	48	60	
3	24	44	49	54	29	41	48	57	
6	13	25	31	37	25	37	46	49	

As is easily seen, the results in Table II do not support the hypothesis that CCI difference depends on the direction of cloud motion. Really, all the frequency values at τ equal to 3 and 6 h are to be less than those for $\tau = 0$ provided that the effect of cloud motion is essential. In reality we have quite opposite situation (except for only 3 cases of 48). At the same time, the occurrence values shown in the right-hand and left-hand parts of the Table practically do not differ.

In this regard, the following remark is in order. Cloud fields are known to be transported by air flows. Therefore, the transport characteristics are an important meteorological predictor of cloudiness and precipitation. However, these processes are characteristic of large-scale cloud fields (frontal clouds, entire cyclones) and, most frequently, of the overcast fields.

In our case, we consider mesoscale cloud fields (with the horizontal size of several tens of kilometers). Moreover, we estimate the influence of cloud motions on each CCI value. Quite naturally, on these spatial scales, clouds, aside from being formed, may transform into other types while moving.

The significance of this process is illustrated by Table III; which gives the probability that the initial cloud cover index n_0 changes to another gradation $n(t)$ or remains unchanged in a time period t.

TABLE III. The probability (in %) that CCI, n, changes to another gradation or remains unchanged. Here N is the sample size. The data represent observations in Sosnovo village, and Leningrad region, in summer of 1979.

Initial	$n(t)$	t, h					N
CCI n_0		−12	3	6	12	24	
0	0	45	65	56	44	49	268
	1–3	19	13	16	17	15	
	4–6	19	10	12	20	19	
	7–9	1	1	2	2	1	
	10	16	11	14	17	16	
1–3	0	35	30	34	38	31	137
	1–3	17	33	25	18	24	
	4–6	24	23	23	21	20	
	7–9	1	0	1	1	2	
	10	23	14	17	22	23	
4–6	0	34	20	25	31	23	157
	1–3	18	18	19	22	24	
	4–6	21	40	33	21	27	
	7–9	3	3	1	0	3	
	10	24	19	22	26	23	
7–9	0	42	25	18	25	36	12
	1–3	8	25	9	8	0	
	4–6	0	25	18	42	36	
	7–9	8	8	18	8	0	
	10	42	17	36	17	28	
10	0	27	12	19	28	29	162
	1–3	18	14	16	20	16	
	4–6	26	20	25	25	22	
	7–9	1	2	1	3	2	
	10	28	52	39	24	31	

It is seen, that CCI noticeably changes in as short time as 3 h. Only under clear sky conditions, $n_0 = 0$, and the overcast, $n_0 = 10$, the CCI values remain unchanged in 3 h with the probability of about 50%, however substantially decreasing afterward (especially in the $n_0 = 10$ case).

Intermediate CCI gradations(1–3 and 4–6) remain constant with the probability of only 20 to 30%. Also, CCI may change from n_0 to any other gradation, and with time (24 h later) all gradations become nearly equally probable. For instance, in 24 h CCI transitions from $n_0 = 0$ to the gradations of 1–3, 4–6, and 10 occur with the probabilities of 14, 19, and 16%, respectively; from $n_0 = 4–6$ to 0, 1–3, and 10 with the probabilities 23, 24, and 23%; and from $n_0 = 10$ to 0, 1–3, and 4–6 with the probabilities of 16, 22, and 31%.

Below we present the frequencies of occurrence (%) for different n_0 gradations for three seasons in 1979.

	0	1–3	4–6	7–9	10
Spring (N = 736)	45	11	6	2	36
Summer (N = 736)	36	19	2	2	22
Fall (N = 736)	20	8	10	1	61

In warm seasons (spring and summer), the clear skies are more frequent than the overcast while in cold seasons (fall and winter) the opposite situation occurs. It is characteristic of this sample, that clear skies are most frequent in May and June with the frequency of occurrence being 53% and 49%. The frequency of the overcast ($n = 10$) in these months was 21% and 13%, respectively.

Since only ground-based observations have been used in this analysis the distributions of cloud cover index obtained have U-shapes what is characteristic of small areas observed[1]. For this reason the distribution maxima are at CCI value. The other n values are much less frequent than clear skies and the overcast. For making a comparison of the 1–3, and 4–6 gradation occurrence with the occurrence of 0 and 10 gradations the former one must be divided by 3. The least frequent occurrence, 0.3–0.6% as small, is found for the cloud cover indices in the 7–9 gradation interval.

Note, in this regard, that the occurrence of the 8–10 gradations, often presented in the literature, closely coincides with the observed occurrence of the gradation 10. The U-shaped CCI distribution is typical not only for the initial values (n_0), but also for those samples that are formed in different time intervals, given fixed n_0 value (Table III). As in the above discussion, a common feature here is a higher occurrence of clear skies ($n = 0$) than of the overcast in summer season. This is not surprising regarding the clouds that appear after the clear-sky conditions: for all t, the occurrence of $n(t) = 0$ is several times (about 2.5 to 6 times) more frequent than that of $n(t) = 10$. This is a consequence of the cloud-formation process inertia. It is interesting, that the inertia effects on the CCI distribution, $n(t)$, during some 3–6 h in the case of cloud evolution starting with the overcast ($n_0 = 10$). Thus the $n(t) = 10$ cases are factors of 4 and 2 more frequent than the cases of $n_0 = 0$ in $t = 3$ and 6 h, respectively. This occurrence disparity between clear skies and the overcast practically disappears at time separations of 12–24 h. The same is also valid for $n(t)$ samples referenced back to the n_0 gradations 1–3 and 4–6.

Such a transformation of the $n(t)$ distribution is due to the temperature-field effect on the cloud field: in the warm seasons, because the temperature rise events dominate over the temperature drops; what favors dissipation and, consequently, transformation towards smaller cloud fractions.

One important conclusion more may also be drawn from Table III. For that one has to compare the distributions $n(t)$ for different initial values n_0 taken at $t = 12$ h and $t = 24$ h. It is seen that these distributions practically coincide, especially for $n_0 = 0$ and $n_0 = 10$. That means that the diurnal variations of temperature and thermal stability have little impact on the cloud field at a fixed point (domain).

Indeed, let us suppose (following a tradition) that the major part of convective clouds of 1–3 and 4–6 gradations is being formed during day-time, 12 h after night-time clear-sky conditions (from Table III, the fractions of such clouds are 17 and 20%). Then, during the next 12 hours these clouds would dissipate due to day-to-night change and 24 hours after the initial (night-time) clear-sky conditions, the occurrence of the 1–3 and 4–6 gradations would be nearly zero under the dominating influence of thermal stratification. However, between 12 and 24 hours after the initial conditions the occurrence of these gradations remains practically constant (at 15 and 19%, respectively).

This conclusion is also valid for other gradations of n_0, e.g., when initially cumulus clouds are prevail ($n_0 = 1–3$ or 4–6), the distribution $n(t)$ changes only a little with time. Thus the fraction of cumulus clouds (1–6 CCI), at the initial CCI of $n_0 = 1–3$, is 39% in 12 hours and 44%, while at the initial CCI of $n_0 = 4–6$, it is correspondingly 43% and 51%.

In the above discussion we have considered the data on total cloudiness and now we will focus on the low-level clouds. From the physical point of view, it is obvious that the low level clouds should be most sensitive to the effects from urban areas, if any. Table IV presents season mean n values for Petersburg, together with the difference $\Delta n = n_P - n_B$ between P and B seasonal values of n; it is seen that the season mean amount of the low-level clouds in P is lower than in B, $n_P < n_B$, almost in all cases (28 of 32). In 14 (of 32) cases, this difference is greater than 0.5 ($|\Delta n| \geq 0.5$), and it is especially large in last five years.

The data from Tables V and VI show that the amount of low clouds is lower over a large town than in a countryside.

TABLE IV. Season mean values of low cloud amount in Petersburg and the difference $\Delta n = n_P - n_B$.

Time of a day	n_P				$10\Delta n$			
	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
				1975–1979				
Day	4.7	5.0	6.9	6.2	−0.8	−4.4	1.0	−5.0
Night	4.6	4.9	6.2	6.3	5.6	−0.4	−0.8	−5.8
				1980–1984				
Day	4.4	5.2	7.2	7.0	−5.4	−4.0	−1.8	−3.4
Night	3.8	4.2	6.7	7.2	−4.0	0	−0.6	−4.6
				1985–1989				
Day	4.5	5.5	6.9	6.0	−6.4	−5.8	−1.4	−7.0
Night	4.1	4.3	6.3	6.1	−3.6	−2.2	0.8	−8.2
				1990–1994				
Day	4.7	4.6	6.7	6.9	−8.0	−12.8	−6.6	−8.4
Night	4.1	3.8	6.4	7.0	−11.0	−11.4	−5.2	−5.0

TABLE V. Distribution function (%) of the difference Δn between monthly mean CCI in Petersburg and Belogorka, n_P and n_B, for 1975–1994.

Time of a day	$10\ \Delta n \le$														
	-20	-16	-12	-10	-8	-6	-4	-2	0	2	4	6	8	10	12
								Spring							
Day	3	7	18	28	42	45	65	78	83	92	97	98	100	–	–
Night	3	5	15	25	34	42	54	71	80	81	88	88	92	95	97
								Summer							
Day	3	10	25	32	35	47	60	77	83	92	98	100	–	–	–
Night	2	8	20	28	33	40	50	58	73	80	85	87	90	93	97
								Fall							
Day	5	8	8	17	27	42	58	70	80	88	88	88	98	98	98
Night	5	5	7	12	24	28	41	50	67	79	81	88	91	95	97
								Winter							
Day	2	3	10	25	42	53	70	78	90	98	100	–	–	–	–
Night	3	3	17	33	47	55	63	68	88	92	98	100	–	–	–

According to Table V, monthly mean values in P are lower than in B in 80–90% of cases in spring, summer, and winter seasons (in fall, the probability that $\Delta n < 0$ is close to 70%). In 25–30% of cases, the amount of low clouds is 1–2 larger in B than in P (in fall, the probability that $\Delta n < -1$ is near 15%). The number of Δn cases is distributed quite uniformly over the gradations listed in Table VI.

It can be assumed that the reduction of cloud amount, as well as fog and haze amount, in P is mainly due to the enhanced air temperature in the air over a city.

The data from Tables IV–VI can be used to estimate the contributions of different factors to the formation of a cloud field. It is worth noting that, the cloud amount at night is only slightly lower than during day-time.

Dynamic factors (advection, vertical motions) are the only contributors to cloud formation during night-time. Thus, it should be concluded that the dynamic processes and, primarily, the synoptic-scale vertical motions lead to the fact that amount of clouds formed during a day is identical to that observed at night.

TABLE VI. Occurrence (number of cases) of monthly mean values of CCI difference $\Delta n = n_P - n_B$ for 1975–1994.

Time of a day	$10\Delta n$					
	-12 – -10	-9 – -7	-6 – -4	-3 – -1	0 – 2	3 – 5
			Spring			
Day	7	9	13	9	7	4
Night	9	6	11	12	4	4
			Summer			
Day	4	6	11	12	7	5
Night	6	6	7	9	8	4
			Fall			
Day	5	4	7	8	6	5
Night	3	6	9	9	12	3
			Winter			
Day	12	17	10	8	9	1
Night	12	12	6	9	8	4

In its turn, thermal factor (change of thermal stability of the near-ground layer due to insolation) can only cause the difference between the day-time and night-time values of the cloud amount, n_d and n_n.

According to Table IV, the difference $n_d - n_n$ divided by nighttime CCI n_n (to yield relative contribution of a dynamic factor) averaged over 20 years is as follows (in per cent):

Site	Spring	Summer	Fall	Winter
Petersburg	10	18	8	−2
Belogorka	6	11	7	−2

As it could be expected, the relative contribution of thermal factor reaches maximum of only 18% in P and 11% in B during summer season, as compared to the dynamic factors. In spring and fall, the thermal factor contributes about 8–10% in P and 6–7% in B. In winter season, when the radiation budget is negative, the thermal factor can even lead to cloud dissipation.

From the data discussed above it follows that (a) the influence of anthropogenic factors on cloud fields, primarily the total cloud fields, is less significant than on fogs, hazes, and temperature and humidity fields; (b) under the influence of temperature field, the amount of low clouds is somewhat (1–2 CCI, for monthly mean values) lower under urban conditions than in the rural areas; (c) cloud amount substantially changes in as little as 3–24 h; (d) measurement data disagree with the commonly accepted fact that thermal factor influences considerably the cloud formation during day-time; and (e) the dominating contribution to the formation of cloud fields (including cumulus and cumulonimbus) comes from the dynamic factors, mainly synoptic-scale vertical motions.

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