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Downward transport of ice-forming aerosols from the stratosphere

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ABSTRACT. The possibility of association of the observed increases at the ground in the concentration of the ice-forming aerosols with the phenomenon of the stratospheric mass transport downwards has been investigated. The study, which is qualitative in nature, has indicated that transport downwards from the stratosphere of ice-forming aerosols is a strong possibility. It also suggested, by implication, that the stratosphere could be rich in ice nuclei.

1. Introduction

The sources of origin considered of the natural ice-forming aerosols are many and diverse, *e.g.*, land (Price and Pales 1964), sea (Battan and Riley, 1960), stratosphere (Bigg and Miles 1963) and extra-terrestrial (Maruyama and Kitagawa 1967). The influence of land and of ocean on the ice-forming aerosols, as suggested by measurements of the aerosols at a few places in India, has been discussed (Kapoor *et al.* 1969). Analysis of measurements, made at Delhi (Lat. 28° 35'N, Long. 77° 12', 216 m a.s.l.) during 1962-63, has pointed out that part of the ice-forming aerosols measured in the region could sometimes be also of stratospheric origin (Ramana Murty *et al.* 1967), but the feature indicated has not been examined in detail due to paucity of data. As measurements for a further period of one year have since become available for Delhi, it is now proposed to examine more fully, with all the available data, whether there could have occurred in the region downward mass transport from the stratosphere (Reed and Danielsen 1959 and Staley 1962) on those occasions when anomalies had been noticed in the concentration of the ice-forming aerosols measured at the ground. The analysis made and the results obtained are presented and discussed.

2. Data

Daily concentration of ice-forming nuclei (aerosols), active at —15°C, as obtained, in the afternoon hours (around 1430 IST), by the millipore technique of measurement, is available for Delhi from March 1962 to May 1963 and from October 1964 to March 1966. Considering that the effect of nuclei transport from the stratosphere, if any, will be reflected in the measurements made on occasions of ice nuclei burst (days of unusually large ice nuclei concentration in the air), such occasions as have been indicated by the ice nuclei data, according to the criterion laid down, have been taken into account. Also, keeping in view that occasions associated with significant increases in the total amount of atmospheric ozone are representative of the stratospheric-tropospheric interaction in the region (according to Reed 1950, about one-third of the change noticed in the total ozone was due to vertical transport in the middle latitudes of the northern hemisphere and according to Kulkarni 1963, it was between one-third and one-half of the total change in the middle latitudes of the southern hemisphere), and also like-wise, that occasions associated with increases in radioactive fallout are an indication of the downward mass transport from the stratosphere (Libby and Palmer 1960), the data for Delhi of total ozone and of airborne fallout beta-activity as available from published measurements by the India Meteorological Department and by the Atomic Energy Establishment, Trombay, respectively have been considered. The fallout data used have not been time-corrected. Further, as it is known that direct exchange of air between the stratosphere and troposphere could take place on occasions when the tropopause becomes difficult to be located (Kroening and Ney 1962), the tropopause data for Delhi as obtained from published reports of the India Meteorological Department for the 0530 IST have been taken into account for the purpose of classifying the tropopause in

TABLE 1

Catalogue of the dates of occurrence of ice nuclei burst and of the nearest day of occurrence of non-strong tropical/ extra-tropical tropopause

S No.	Date of ice nuclei burst for which tropopause data commencing from the very day of the burst backwards, are available	Concentration of ice nuclei (number per 1,000 litres of air, active at —15°C)	Nearest day of occurrence, within the preceding five days of		Whether wind with minimum speed of 6 kt has been reported on the day of tropopause gap and if so maximum wind in kt and its height of occurrence in km, reported		
			non-strong tropopause	tropopause gap	Yes/No	kt	km
1	27 Apr 1962	490	3				
2	8 May 1962	127	1	2	Yes	85	13·5
3	15 May 1962	219	1	5	No	—	—
4	31 May 1962	896	2				
5	26 Jun 1962	113	Not occurred, observations available are few				
6	20 Jul 1962	685	4				
7	12 Oct 1962	146	1				
8	17 Oct 1962	119	4				
9	1 Nov 1962	600	Not occurred, observations available are few				
10	18 Dec 1962	130	2				
11	18 Jan 1963	110	1	1	Yes	130	14·0
12	21 Jan 1963	500	1	2	Yes	115	11·5
13	23 Nov 1964	110	2	2	Yes	70	10·9
14	11 Dec 1964	880	2	2	Yes	100	10·9
15	14 Dec 1964	3330	2	1	Yes	90	7·0
16	1 Jan 1965	120	3				
17	10 Mar 1965	275	1				
18	12 Mar 1965	338	3	1	Yes	85	11·2
19	15 Apr 1965	113	1	1	Yes	115	14·4
20	20 Apr 1965	429	1	1	Yes	95	13·4
21	23 Apr 1965	158	1	1	Yes	120	12·5
22	27 Apr 1965	117	4	5	Yes	120	12·5
23	7 May 1965	121	3	4	Yes	100	12·6
24	17 May 1965	117	1	5	Yes	70	11·6
25	27 Sep 1965	104	5				
26	12 Nov 1965	177	4				
27	10 Dec 1965	154	1	5	Yes	90	10·5
28	20 Dec 1965	163	2	5	Yes	95	12·1
29	22 Dec 1965	563	1				
30	27 Jan 1966	100	2	1	Yes	90	11·8
31	3 Feb 1966	233	2	1	Yes	70	10·0
32	7 Feb 1966	179	2	1	Yes	80	10·3
33	19 Feb 1966	396	2				

the region on any day into one of the two broad categories, namely, 'strong' which is considered not favourable for the occurrence of downward stratospheric transport and 'non-strong' which is considered favourable for such occurrence. The data have also been taken into account for the purpose of reckoning whether there is extra-tropical tropopause present in addition to the usual tropical tropopause, giving rise to the presence of the so called tropopause gap. The extra-tropical tropopause, whenever it occurs in the Indian region, is characterized by its lower height (mean value 11·5 km) in contrast with the height of the tropical tropopause which is about 16·5 km (Sivaramakrishnan *et al.* 1970). The development, in the region, of tropopause gap when the presence of jet stream also has been indicated in the vicinity has been considered favourable for downward stratospheric mass transport, just in the same manner as it has been shown to be so in the case of extra-tropical regions by many investigators, *e.g.*, Reed and Danielson (1959) and Reiter (1963). The occurrence of wind having a minimum speed of 60 kt has been arbitrarily considered, for the present purpose, as an indication of the presence of jet stream in the vicinity, and this aspect has been examined from the daily Vertical Time Section Charts as available in the Office of the Deputy Director General (Forecasting) of the India Meteorological Department. The word 'tropopause' wherever occurs in the present study, unless otherwise stated, refers only to tropical tropopause.

3. Suppositions involved in and criteria considered for analysis

The mechanism of ice-nuclei transport from stratosphere and of the possible association of ice nuclei burst with total ozone increase and with beta fall-out increase is considered to be as follows. Stratospheric air, containing ice nuclei, may penetrate into the upper troposphere by subsidence or intensified mixing, whenever the interface, which is the tropopause, is not strong or when there appears tropopause gap and presence of jet stream in the vicinity is indicated as stated earlier. Then, the process of vertical mixing brings the air into lower levels causing increased ice nuclei concentration at the ground. Some of the ice nuclei bursts observed at the station could, therefore, have been caused in this manner by the nuclei entering the troposphere in regions upstream. Droessler's (1964) study has clearly demonstrated that the ice nucleus storm observed by him did occur under nearly similar synoptic conditions as stated above. As it is known that stratospheric air is rich in ozone and also that stratosphere is the reservoir for the old radioactive debris, it is anticipated that occasions marking ice nuclei burst at the ground, due to transport of ice nuclei from the stratosphere, will more often be associated with increase of total ozone and of beta fallout.

In the present analysis the following criteria have been considered for classifying the tropopause and for defining ice nuclei burst, total ozone increase and beta fallout increase. Tropopause has been considered non-strong when the temperature lapse rate, $-(\partial T/\partial Z)$, indicated above the the tropopause is greater than zero. An event of ice nuclei burst is considered to have taken place on any day whenever the nuclei concentration given for that day is 100 or more per 1,000 litres of air and is also atleast twice the value of that of the nearest previous day for which measurement is available (the day-to-day ice nuclei concentration varied from as low a value as zero to a few hundred per 1,000 litres of air). An ozone increase is said to have taken place if an increase of atleast 20 units (milli atmo cm) has been noticed in the value of total ozone either on the day of ice nuclei burst or on any day within the preceding five-day period as compared to the value on the corresponding previous day. It is also said to have taken place if the value of ozone has been steadily increasing for any length of period within the preceding five days and the total increase noticed during that period has been atleast 20 units. Increase in beta fallout has been considered to have occurred if the value given of the beta-activity on the very day of the ice nuclei burst is higher than the value on the previous day by atleast 10%.

4. Analysis and results

(*i*) *Ice nuclei burst and tropopause character*

Information relating to the nature of the tropopause noticed, namely, whether it is strong or non-strong according to the criterion laid down and stated above and also whether there is present tropopause gap on the 33 instances of the ice nuclei burst for which tropopause data, commencing from the very day of the burst backwards, are available is given in Table 1. Also given in the table is the information whether wind having a minimum speed of 60 kt has been reported on each of the 'tropopause gap' instances and if so, the maximum speed of the wind and its height of occurrence on those instances. It is seen from the table that, concurrently with the occurrence of the ice nuclei burst, non-strong tropopause was present on 8 instances, tropopause gap on 5 instances and both on 4 instances. The presence of jet stream in the vicinity has been indicated on all the 9 'tropopause gap' instances noticed.

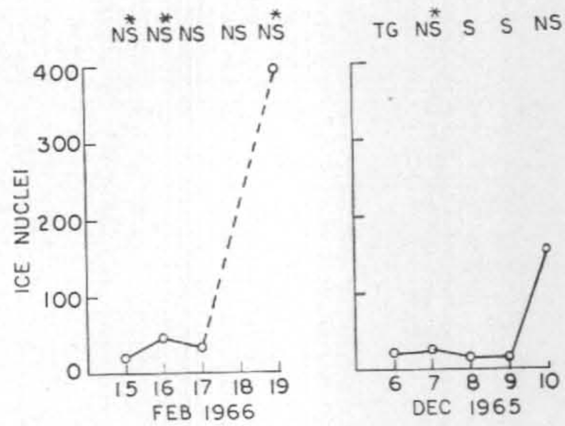

Fig. 1

Daily concentration of ice nuclei (number per 1,000 litres of air, active at—15°C) within the preceding five days of occurrence of the ice nuclei burst and tropopause character (S — strong, N.S. — non-strong and TG— tropopause gap) on the corresponding days. On days when data of tropical tropopause are not available, the character found of the extra-tropical tropopause, if present, has been given. Such instances have been indicated by the additional symbol, *

If it is considered that particles would appear at the station within a day of their entry into the troposphere in regions upstream (in the case of radioactive particles it has been estimated to take about 11 hours to reach the surface of the earth from the tropopause, according to the model developed by Kao 1966), the findings suggest that 50% of the total number of occasions of ice nuclei burst considered (17 out of 33) have been favourable for downward stratospheric mass transport to occur. However, keeping in view the possibility that the ice nuclei which enter through the tropopause take more time than a day to reach the ground and that the time taken will depend upon the prevailing conditions in the troposphere (according to Mahlman 1969, relatively large percentage of fallout increases have occurred at the ground within five days of the cyclone index decrease noticed at the tropopause level suggesting that it could be anywhere upto five days in the case of beta-fallout) examination has been made of the character of the daily-tropopause indicated on the five successive days preceding each of the ice nuclei burst occasions. Also, the occurrence or otherwise of wind with a minimum speed of 60 kt has been examined, as before, on all the days when 'tropopause gap' was noticed. For the purpose of counting the five successive days, the day of occurrence of the ice nuclei burst has been considered as the first day in the series. The analysis made (Table 1) revealed that of the 33 ice nuclei burst occasions considered as many as 31 have been associated, within the preceding five days' period of each such occasion, with favourable tropopause conditions, *i.e.*, occurrence of either non-strong tropopause alone or of tropopause gap together with indication of presence of jet stream in the vicinity, for downward mass transport to take place from the stratosphere. In almost all of the 'tropopause gap' occasions noticed the presence of jet stream has been indicated. The maximum winds reported on those occasions varied from 70 to 130 kt and their heights of occurrence varied from 7·0 to 14·4 km.

Two typical instances, one each depicting association of non-strong tropical tropopause and of tropopause gap, within the preceding five days of occurrence of ice nuclei burst, are shown in Fig. 1.

(*ii*) *Ice-nuclei and total ozone*

It is known that, photochemically, ozone is in equilibrium above about 35 km and that the amount of ozone present in the troposphere is small. Any phenomenon associated with the variations noticed in total ozone refers, therefore, essentially to that of the lower stratosphere. Also, it has been demonstrated by Danielsen (1968) that ozone is a good tracer of stratospheric air. Monthly mean values of the total ozone content and the monthly mean concentration of ice nuclei, for the period for which ice nuclei data are available, are shown in Fig. 2. Though there is no single specific trend of variation noticed between ozone and ice nuclei over the entire period considered, the figure revealed an interesting feature and, that is, the two parameters varied nearly alike over one portion of the period, namely, September 1962 to March 1963 and also nearly in opposite direction over another portion of the period, namely, August 1965 to March 1966. If a sizable fraction of the change noticed in the total ozone is due to the phenomenon of vertical transport (Reed 1950 and Kulkarni 1963) the feature

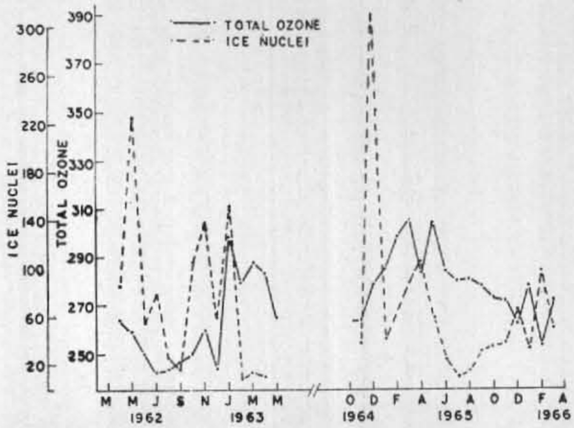

Fig. 2

Monthly mean concentration of ice nuclei (number per 1,000 litres of air, active at — 15°C) and total ozone (milli-atmo-cm)

noticed as above, while suggesting that stratospheric-tropospheric transport processes could play a role in influencing the ice nuclei concentration at the ground, points out that the air being transported downwards from the stratospheric exit regions could sometimes be rich and also sometimes be deficient in ice nuclei. The findings which are contradictory to each other appear to be consistent, for it is known that the stratosphere, on the time scale of months or a year, is not a well stirred region and, therefore, large gradients could exist inside the stratosphere in the vertical and horizontal, as has been pointed out to be the case with radio-active debris (Machta 1961). Measurements reported by Bigg and Miles (1964) have also revealed both high and low values of ice nuclei concentration in the stratosphere.

(iii) Ice-nuclei burst and total ozone increase

The daily values of total ozone content, as noticed on the day of ice nuclei burst as well as on the preceding four days and on the following day, have been examined in the case of each of the 41 out of the 43 occasions of the ice nuclei burst for which ozone data are available. The analysis (Table 2) showed that ozone increase occurred, within the preceding five days' period of the burst occasion, only on 11 occasions. The findings point out that downward mass transport from the stratosphere, of the magnitude required for detection by a well defined ozone increase, has taken place only on a small fraction of the ice nuclei burst occasions considered, *i.e.*, 11 out of 41. No ozone increase of the magnitude considered, *i.e.*, of 20 units, has been noticed on any occasion on the same day as of the ice nuclei burst.

(iv) Ice-nuclei burst and beta fallout increase

Considering the period for which daily data of beta-activity are available it is noticed that, of the 21 occasions of the ice nuclei burst observed during that period, as many as 16 have been associated with beta fallout increase (of magnitude 10% and more) as shown in Table 3. As radioactive dust is known to be stored for much longer periods in the tropical stratosphere — estimated mean residence time for tropical stratosphere is 5 years (Staley 1962) — the results of the analysis help confirm the possibility that prevailing stratospheric exchanges do influence the observed ice nuclei concentrations at the ground. The results also lend support to one of the assumptions involved in the study, namely, that the ice nuclei from the stratosphere and the beta fallout have similar life times in the troposphere.

(v) Ice nuclei burst, total ozone increase and the beta fallout increase

Of the 21 instances of the ice nuclei burst for which beta fallout and ozone data are both available, only 5 instances have been found to be common for all (Table 3). The finding suggests that there could be a common controlling source for the three parameters, *i.e.*, ice nuclei, ozone and beta fallout, atleast on those 5 occasions, which is definitely the stratosphere.

(vi) Correlation between ice nuclei and total ozone

The correlation coefficient between the daily values of ice-nuclei concentration and the corresponding total ozone content has been calculated for the one year period, March 1965 to February

TABLE 2

Catalogue of the dates of occurrence of ice nuclei burst and of the day of occurrence of total ozone increase

S. No.	Date of ice nuclei burst for which ozone data are available	Concentration of ice nuclei (number per 1,000 litres of air, active at —15°C)	Day of occurrence, if any, of total ozone increase of 20 or more units within the preceding five days
1	3 Mar 1962	500	4(27)
2	9 Mar 1962	2080	2(23)
3	27 Apr 1962	490	
4	8 May 1962	127	
5	15 May 1962	219	3(47)
6	26 May 1962	271	
7	31 May 1962	896	
8	26 Jun 1962	113	
9	20 Jul 1962	685	No earlier observation
10	1 Oct 1962	107	
11	12 Oct 1962	146	
12	17 Oct 1962	119	2(24)
13	1 Nov 1962	600	2(36)
14	16 Nov 1962	171	
15	14 Dec 1962	160	
16	18 Dec 1962	131	
17	31 Dec 1962	180	
18	9 Jan 1963	200	2(33)
19	18 Jan 1963	110	No earlier observation
20	21 Jan 1963	500	Do.
21	23 Nov 1964	110	
22	11 Dec 1964	880	
23	14 Dec 1964	3330	
24	1 Jan 1965	120	
25	10 Mar 1965	275	
26	12 Mar 1965	338	
27	15 Apr 1965	113	4(54)
28	20 Apr 1965	429	3(20)
29	23 Apr 1965	158	
30	27 Apr 1965	117	
31	7 May 1965	121	
32	17 May 1965	117	
33	27 Sep 1965	104	
34	12 Nov 1965	177	
35	10 Dec 1965	154	
36	20 Dec 1965	163	
37	22 Dec 1965	563	1(24)
38	27 Jan 1966	100	2(30)
39	3 Feb 1966	233	1(27)
40	7 Feb 1966	179	
41	19 Feb 1966	396	
42	24 Feb 1966	571	
43	5 May 1966	158	

NOTE—Figures in brackets under last column indicate actual increase noticed in ozone value in units of milli-atmo-cm

TABLE 3

Catalogue of the dates of occurrence of ice nuclei burst, beta fallout increase and total ozone increase

S. No.	Date of ice nuclei burst for which beta fallout data are available	Whether beta fallout increase occurred on the same day and if so percentage increase noticed over the previous day (given in brackets)	Whether ozone increase of 20 units or more observed within the preceding five days
1	3 Mar 1962	No	Yes
2	9 Mar 1962	Yes (25)	Yes
3	27 Apr 1962	No	
4	8 May 1962	Yes (10)	
5	15 May 1962	Yes (47)	Yes
6	26 May 1962	Yes (4)	
7	26 Jun 1962	Yes (12)	
8	20 Jul 1962	Yes (131)	
9	1 Oct 1962	Yes (84)	
10	12 Oct 1962	Yes (33)	
11	17 Oct 1962	Yes (297)	Yes
12	1 Nov 1962	Yes (15)	Yes
13	16 Nov 1962	Yes (41)	
14	14 Dec 1962	Yes (107)	
15	18 Dec 1962	Yes (13)	
16	31 Dec 1962	Yes (3)	
17	9 Jan 1963	Yes (14)	Yes
18	18 Jan 1963	Yes (81)	
19	21 Jan 1963	Yes (62)	
20	7 May 1965	No	
21	17 May 1965	Yes (86)	

1966. It has also been calculated for conditions of ice-nuclei concentration leading and lagging the total ozone content upto 11 days in steps of one day. The values obtained of the correlation coefficient, although very small, are found more significant only for lag or lead of 7 to 8 days (*vide* Table 4). The feature noticed points out that there is a weak but definite common periodicity in both the parameters which is perhaps due to the presence of a common controlling influence. As it has been established that variations which occur in the total ozone are largely due to the variations which take place in the ozone content in the lower stratosphere (*e.g.*, Dutsch 1966 and Kulkarni 1966), the inference as above suggests the possible existence of propagating wave disturbance at that level with a periodicity of around 15 days. It may be noted in his connection that observational

TABLE 4

Correlation coefficients between ice nuclei and total ozone (Data from March 1965 to March 1966)

	Lag in days											
	0	1	2	3	4	5	6	7	8	9	10	11
(A) Ozone lagging												
Correlation coefficient	+0·05	−0·04	−0·06	−0·01	+0·05	+0·01	+0·07	+0·12	+0·11	+0·03	−0·05	−0·07
Sample size	257	257	256	255	257	258	257	258	258	255	253	253
Significance level								10%	10%			
(B) Ice nuclei lagging												
Correlation coefficient	+0·05	+0·06	+0·04	+0·03	−0·02	−0·03	+0·02	+0·10	+0·15	+0·12	+0·11	+0·11
Sample size	257	254	256	256	257	259	258	261	257	260	259	255
Significance level								10%	5%	10%	10%	10%

TABLE 5

Auto-correlation coefficients of total ozone with given lags

Lag in days	Correlation coefficient	Sample size	Lag in days	Correlation coefficient	Sample size
0	1·00	356	9	0·48	320
1	0·84	342	10	0·44	321
2	0·71	339	11	0·40	321
3	0·63	336	12	0·43	320
4	0·60	331	13	0·42	319
5	0·58	328	14	0·44	318
6	0·57	326	15	0·44	316
7	0·55	324	16	0·43	314
8	0·53	322			

evidence has also been cited which strongly suggests that such wave disturbances are present in the tropical stratosphere (Wallace and Kousky 1968).

(*vii*) *Total ozone values and auto-correlation coefficients*

If a propagating wave disturbance is to be present at stratospheric levels with a periodicity of around 15 days as suggested above the daily ozone data, when subjected to auto-correlation analysis, should help reveal the existence of such feature. However, the auto-correlation coefficients found of the daily ozone data for the period March 1965 to February 1966 for time lags upto 15 days have not shown minimal values around the 7th day (*vide* Table 5), which is contrary to what has been anticipated. Perhaps, the study calls for further analysis and examination of data of ice nuclei and of total ozone over longer periods.

(*viii*) *Ice nuclei content at ground and cyclogenetic processes at tropopause level*

Mahlman (1969) has shown that short term surface radioactive fallout increases are statistically related to rapid decrease in the cyclone index which is indicative of cyclogenesis at tropopause level. Considering that ice nuclei from the stratosphere would be like radioactive fallout in their response to the cyclogenesis at the tropopause level, analysis has been made of the cyclone index variation at the 200-mb level for the period March to December 1965 with a view to examining the correspondence, if any, between the epochs of cyclone index variation and the epochs of the ice nuclei increases inclusive of the bursts. The cyclone index '*C*' according to Mahlman (1969) is given by —

$$C = 1 - \frac{(\overline{\gamma^2})^{\frac{1}{2}}}{90} \quad \text{where, } (\overline{}) \text{ operator}$$

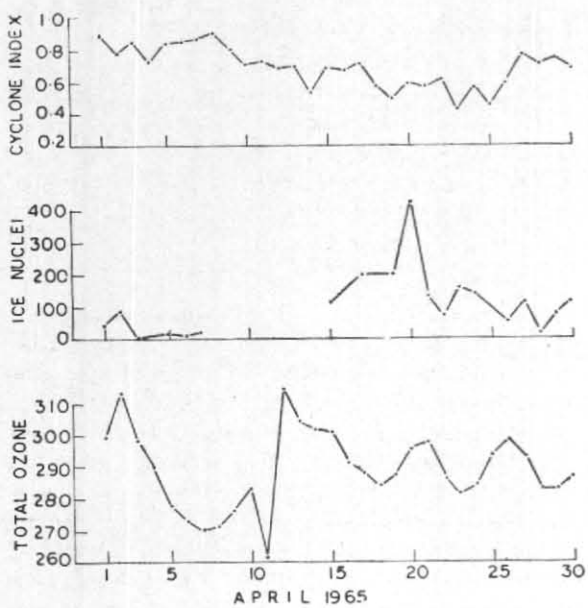

Fig. 3(a)

Daily variation of cyclone index, ice nuclei concentration (number per 1,000 litres of air, active at —15°C) and total ozone (milli-atmo-cm)

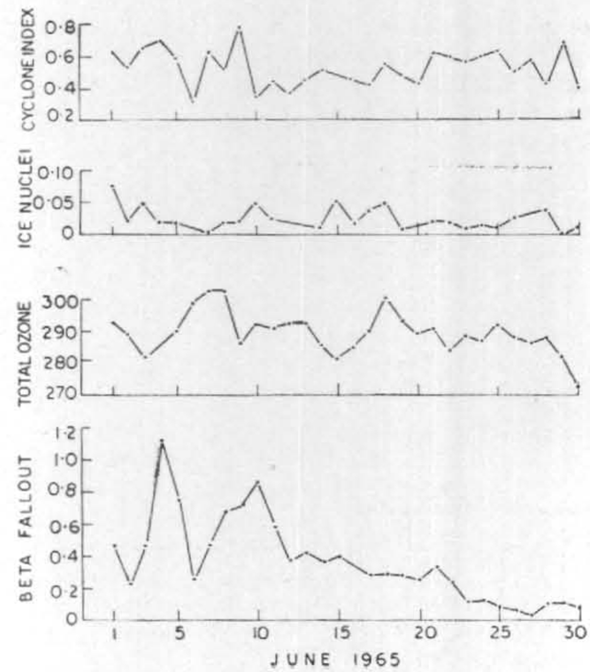

Fig. 3(b)

Daily variation of cyclone index, ice nuclei concentration (number per 1,000 litres of air, active at —15°C), total ozone (milli-atmo-cm) and beta fallout (micro micro curie per 1,000 litres of air)

is a zonal average and γ is defined as the deviation of the wind direction at a point from a zonal direction of 270°, *i.e.*, the acute angle between the wind direction and the east-west line. It has been calculated for the region around 28° 30′ N, covering from 22°N to 35° N, within the longitude interval 60°E to 95°E, by considering the data from all the available stations within this geographical boundary. The analysis made has, however, not shown consistent relation between the cyclone index variation noticed and the ice nuclei increases observed including the bursts. Values obtained for two representative months are shown in Figs. 3(a) and 3(b). The values of ozone and of beta fallout where available have also been shown, plotted in the figures.

5. Discussion

Examination, by different methods of approach, of the question of whether there could have occurred downward mass transport from stratosphere on the specific instances considered (ice nuclei burst occasions) has not revealed unique answer. The association noticed of the favourable stratospheric conditions for mass transport to occur from the lower stratosphere, with fifty per cent of the ice nuclei burst occasions (17 out of 33) on the same day of occurrence of the burst and with more than ninety per cent of the ice nuclei burst occasions (31 out of 33) within the preceding five days of occurrence of the burst, and the occurrence, on the same day, of beta fallout increase on more than seventy-five per cent of the ice nuclei burst occasions (16 out of 21) strongly suggest that stratospheric air would have intruded into the troposphere on the occasion of ice nuclei burst and that, as a result, the troposphere would have been enriched on such occasions with particulates of ice-nucleating capability. But, the other features noticed, namely, the small traction associated of the ice nuclei burst occasions with a well defined ozone increase (11 out of 41) and the lack of a single specific trend in the variation between the total ozone content and ice nuclei concentration do not fully support the above contentions. However, these features do not also lend support to the view that neither stratospheric air has intruded into the troposphere on any of the occasions of the ice nuclei burst nor that stratospheric air is always poor in ice-nuclei content. Keeping in view that there have been definitely occasions, although few in number, which have been common to ice nuclei burst, ozone increase and beta fallout increase the study points out that the source of origin of part of the ice nuclei noticed at the ground could sometimes be traced back to stratospheric levels. The study does not reveal and also is not aimed at to knowing the primary source of origin of the ice nuclei likely to be present in the stratospheric levels. Such nuclei may or may not have been originally generated in the stratosphere. The nuclei could have been there trapped in from above (from extra-terrestrial sources) and also from below (from ground sources by transport through cumulonimbus tops).

The conditions under which ice nuclei transport from the stratosphere is favoured most should be identical to those which have been found to be conducive for mass exchanges to occur from the stratosphere to the troposphere as by various investigators, *e.g.*, Reed and Sanders (1953), Reed and Danielsen (1959), Kroening and Ney(1962) and Reiter and Mahlman (1965). The association found of one or the other of the favourable conditions, namely, non-strong tropopause or presence of tropopause gap with indication of jet stream in the vicinity, with a very large percentage of the observed ice nuclei burst occasions within the stipulated five days' period preceding the burst occasions (31 out of 33 considered), confirm this view-point. Also, the possibility of propagating wave disturbance at stratospheric levels with a periodicity of around 15 days referred to earlier further increases prospects of stratospheric mass transport downwards when conditions are favourable.

Regarding the physical processes by which the stratospheric transports contemplated are effected, it is to be noted that according to Newell (1963 and 1964) eddy transport processes in the lower stratosphere are responsible for the annual variations noticed (Maximum in spring and in middle latitudes) in surface fallout and total ozone. Also, according to Mahlman (1969), shorter period fallout increases seem to be controlled by cyclogenetic processes at the tropopause level. The present study which has not indicated a definite spring maximum in the ice nuclei content (*vide* Fig. 2) and which also has not shown, as already pointed out, consistent association between the ice nuclei increase at the ground and the cyclone index decrease at the tropopause level does not help throw light on the processes by which those ice nuclei, suggested to come from the stratosphere. are transported downwards. It is true, however, that whereas in the case of total ozone and old beta fallout stratosphere happens to be the only, or atleast the major, source region, it is not so in the case of ice nuclei. It may be difficult, therefore, to visualise, by ice nuclei measurements alone, any of the possible physical processes which are responsible for the transport downwards of the ice nuclei from the stratosphere unless such nuclei, in course of the measurements, are distinguished from those being contributed by the remaining source regions and this, for the present, appears to be a remote possibility. However, observations made over longer time periods than considered here and also at different latitudes are of useful value in this regard.

6. Conclusion

The study has shown that downward ice nuclei transport from the stratosphere is a strong possibility and that, therefore, by implication, the stratosphere could be rich in ice nuclei. Also, it has suggested that there could be a propagating wave disturbance with periodicity of about 15 days at stratospheric levels. The inferences drawn have not been reflected equally strongly in the results obtained by all the methods of analysis considered. Further examination of data (ice nuclei, beta activity and ozone) concurrently collected over longer time periods becomes, therefore, necessary before definitive conclusions are possible.

The view that there could be linkage even between the gross atmospheric particulate content (ice forming aerosol does form a fraction of it, although extremely tiny) and the stratospheric global circulation is beginning to emerge; for recent measurements reported of atmospheric turbidity over the United States (Flowers *et al.* 1969) have revealed highest turbidity values over Boulder and Idaho Falls in the month of May which also happens to be the period for the occurrence of peak total ozone values in mid-latitude U.S. stations. As a multiple structure of tropopause is frequently observed at many latitudes (Flohn 1963) and also as occurrence of non-strong tropopause may not be limited to particular latitudes, the phenomenon of exchange of air between stratosphere and troposphere may have to be considered as global in extent. Such phenomenon, when becomes strong enough on critical occasions, may exercise large scale influence on weather on account of the prominent changes likely to be brought about on those occasions in the ice nuclei concentrations of the air in lower tropospheric levels.

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