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OBSERVATIONS OF SMOKE PARTICLES AND CONDENSATION NUCLEI AT KEW OBSERVATORY

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I. INTRODUCTION

For some time now the attention of meteorologists has been directed towards a study of the nature and distribution of the particles which are found in suspension in the lower strata of the atmosphere. These particles may be divided into three distinct groups : (1) finely divided matter, such as soot, smoke, dust, pollen grains, crystals, etc. ; (2) nuclei of condensation ; (3) small electrified particles.

§ 1—SMOKE PARTICLES

The particles in the first group are responsible for what is commonly called atmospheric pollution. It is convenient to call these particles collectively " smoke particles " as in most places the latter form a large majority. Instruments for detecting smoke particles and measuring their concentration have been devised by Dr. J. S. Owens. Two such instruments, in use at Kew, are the automatic air filter[1], which gives a continuous record of the weight of suspended matter, and the jet dust counter[2], which is used to find the number of particles in suspension at a certain instant.

The automatic air filter consists essentially of a syphoning arrangement whereby air is aspirated through a disc of filter paper, depositing its pollution on the paper. The disc is rotated by a clock, but, while aspiration is in progress, the disc is retained in position by suction. After aspiration the disc is released, moves forward to a position determined by the clock, and is thus correctly set for the next aspiration. It is arranged that the pollution is deposited near the circumference of the filter paper, and the record consists of a series of small circular stains, usually three or four to the hour, around the edge of the disc of filter paper. Measurement is made by comparing the tint of the stain with a calibrated series of tints.

In the jet dust counter, air is aspirated through a moistened tunnel by means of a pump. It passes through a fine slit and impinges on a glass slide to which the moistened particles adhere. The slide is then removed, and the particles on it may be counted under a microscope. The efficiency of the dust counter has been tested quantitatively by Owens[3] and the results showed that very high efficiency is given.

Smoke particles are plentiful in cities, as many as 53,000 per cm.^{3} having been found in London during a dense fog[4]. At sea they are few and sometimes completely absent[4].

Measurements made by G. M. Watson[4] of the diameters of the largest particles visible under the microscope were found to range from 3×10^{-5} cm. to $7{\cdot}5\times10^{-5}$ cm. on days of no fog. During fog the maximum diameters were larger, varying from 12×10^{-5} to 20×10^{-5} cm., and extending on one occasion to 30×10^{-5} cm.

[1] *London Meteorological Office, Advisory Committee on Atmospheric Pollution. Report for the year ending March*, 1918, p. 20.
[2] *ibid.* 1922. p. 34.
[3] *ibid.* 1923. p. 33.
[4] *ibid.* 1923. pp. 36–38.

§ 2—CONDENSATION NUCLEI

Observations of condensation nuclei were first made in 1879 by Aitken. A simple instrument designed by Aitken[5] for their detection persists to this day. In this instrument a known volume of air is admitted into a moistened chamber which may be rendered air-tight. By means of a pump, the air inside the chamber may be expanded causing moisture to condense round the nuclei which are then precipitated on to a counting stage in the form of liquid drops.

The concentration of nuclei is very great, although there is considerable variation with locality, and, at individual stations, with meteorological conditions. In unpopulated regions there are fewer than in cities, and on clear days, generally speaking, there are fewer than during fogs. On a clear day at the summit of the Rigi, over Lake Lucerne, Aitken[6] found as few as 434 nuclei per $cm.^3$ Five hours later a haze had formed and there were then 2,050 per $cm.^3$ In Paris, air in the garden of the Meteorological Office was found to contain 210,000 per $cm.^3$ Nowhere has air been found completely free from nuclei.

As to the constitution of these nuclei little is known with certainty. It is thought that they are aggregates of water formed round a hygroscopic centre. It is known that they are produced by combustion; air collected from a Bunsen flame was found[7] to contain 30,000,000 nuclei per $cm.^3$ Aitken[8] found evidences of their production on the foreshores of the west coast of Scotland on sunny days. It is possible that in a number of cases the hygroscopic centre is a particle of sea salt produced by sea spray and diffused by convection and turbulence over the earth.

It has been shown by Nolan[9] and his collaborators that approximately 60 per cent of the condensation nuclei carry electric charges, positive and negative in about equal proportions. The charged nuclei are identical with the Langevin, or large, ions, and are formed by the adhesion of small ions and the resulting electrical reactions.

Experiments by Wigand[10] and by Boylan[11] have shown that dust particles do not act as nuclei of condensation even in spaces containing no natural nuclei. Boylan found that when dust particles were seen to fall on the glass scale of an Aitken instrument there was nothing to suggest that they had taken part in cloud formation. His experiments illustrated in a striking way how suspended dust would reduce the number of nuclei. "Shaking a quantity of fine dust through air enclosed in a bottle is probably very nearly the same thing as passing the air through a plug of cotton wool, and it is not therefore surprising that complete removal of nuclei is produced. The effect of dust in reducing the concentration of condensation nuclei, and hence of large ions, is probably of considerable importance in the air of large cities."

The radius of the large ion may be calculated by a method due to Cunningham, from considerations of the motion of an electrified sphere through a viscous gas. The value found[12] for the radius is approximately $4{\cdot}5 \times 10^{-6}$ cm. Thus the radius of a smoke particle is about ten times as large as that of a nucleus of condensation and hence its volume is of the order of 1,000 times as great.

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[5] J. Aitken: Collected Scientific Papers, Camb. Univ. Press, 1923, p. 236.
[6] *ibid.* p. 230.
[7] *ibid.* p. 204.
[8] *ibid.* p. 497.
[9] J. J. Nolan, R. K. Boylan and G.P. de Sachy: *Dublin, Proc. R. Irish Acad.* **37** (A), 1926, No. 1.
[10] A. Wigand: *Meteor. Zs. Braunschweig*, **30**, 1913, p. 10, and *Sci. Abstr.. London*, 1913. No. 773.
[11] R. K. Boylan: *Dublin, Proc. R. Irish Acad.* **37** (A) 1926. No. 6.
[12] Sir J. J. Thomson and G. P. Thomson: Conduction of Electricity through Gases, Camb. Univ. Press, 1928, pp. 187–9.

3—OBSERVATIONS AT KEW OBSERVATORY

Observations of the concentration of smoke particles and of condensation nuclei have been made at Kew Observatory since the beginning of 1928. The hour of observation is 15h. The continuity of observations of smoke particles was interrupted from September to December, 1928, when the jet counter was lent to another station. A further interruption occurred in May, 1930, when the objective of the microscope was being repaired. The nucleus counter was sent away on loan in April 1929. It was found subsequently that the pump was no longer cylindrical and spurious results were being obtained. It is probable that the damage dates from the time when the counter was sent away, and the observations from April 1929 onwards have therefore been rejected. A new instrument was supplied in March 1930, when observations were resumed.

In the following analysis of the observations, medians are used throughout instead of means. This is to avoid giving undue weight to isolated high values of the concentration of smoke particles which occurred under very special conditions. Generally, the mean was found to be higher than the median in the case of smoke particles; in the case of condensation nuclei the two values were approximately equal.

II. SMOKE PARTICLES

§ 4—ANNUAL VARIATION

The annual variation of the concentration of smoke particles is shown in the following table, the number of observations in each month being given in brackets. The average annual variation for the three years as a whole, which is also shown graphically in Fig. 1, has been found by grouping together the observations in one specific month, without regard to the year, and deriving the median.

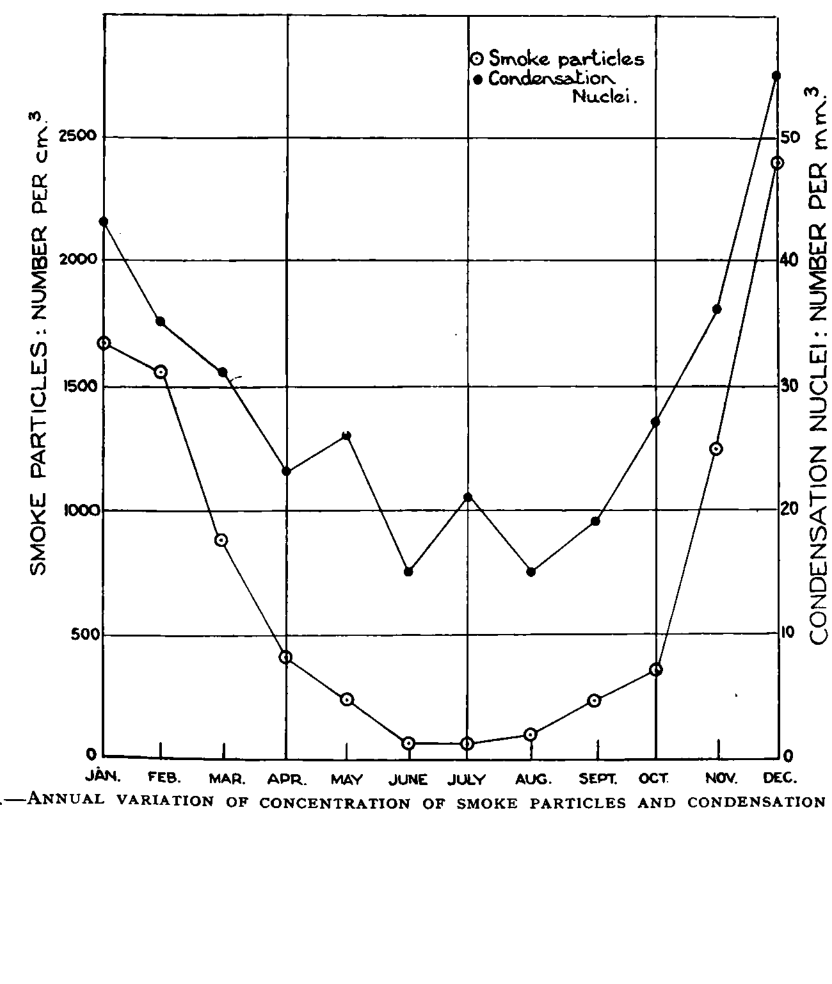

FIG. 1.—ANNUAL VARIATION OF CONCENTRATION OF SMOKE PARTICLES AND CONDENSATION NUCLEI.

TABLE I—AVERAGE MONTHLY CONCENTRATION OF SMOKE PARTICLES AT 15h.
(Number per cm.^{3})

	1928	1929	1930	1928–30
January	1460 (9)	3520 (7)	1350 (15)	1670 (31)
February	640 (10)	1410 (7)	2197 (14)	1560 (31)
March	715 (15)	1810 (11)	1020 (7)	880 (33)
April	455 (12)	414 (5)	555 (8)	414 (25)
May	210 (10)	222 (4)	221 (14)	231 (28)
June	80 (9)	52 (12)	—	60 (21)
July	55 (10)	60 (13)	—	60 (23)
August	80 (7)	81 (16)	131 (9)	86 (32)
September	90 (3)	190 (17)	281 (10)	226 (30)
October	—	255 (19)	420 (13)	345 (32)
November	—	1253 (8)	1140 (11)	1245 (19)
December	1420 (9)	1095 (9)	3735 (9)	2400 (27)

(The number of observations in each month is shown by the figures in brackets.)

The diminution in the number of smoke particles as summer approaches is very marked. This must be due largely to the discontinuance of fires for heating purposes.

The combustion of fuel is devoted to two principal uses, firstly to provide heat, and secondly to provide energy for manufacturing and kindred purposes. The pollution in the summer, when the domestic fire is dispensed with and artificial heating is unnecessary, must be almost entirely due to furnaces maintained to drive machinery. There are, it is true, a certain number of fires for cooking and for producing hot water, but cooking in a London suburb is mostly by gas. If the furnaces, etc., may be regarded as consuming an amount of fuel which is practically constant throughout the year, a measure of the pollution traceable to this source is given by the number of particles found in the summer. A large proportion of the increase in the number of particles found at Kew in winter must therefore be due to fires used solely for heating purposes, but as the rate at which smoke is dispersed should be taken into account as well as the rate of generation, the figures must be used with caution.

The number of particles which has thus been attributed to furnaces used in the industry is small chiefly because Kew Observatory is some distance from the manufacturing areas of London. Conditions closer at hand are no doubt greatly different.

Comparing individual years with the average, it may be seen from the table that the mean monthly concentration of smoke particles was below the average for the whole of 1928, except for April; in 1929 the monthly concentration was below the average except in January, March and November. In 1930 pollution was above the average for seven months out of the ten for which figures are available. The mean of the last column in the table, which may be taken to represent the annual average, is 765 particles per cm.^{3} The mean for the summer months, April to September, is 180, while that for the winter months, October to March, is 1,367. From the point of view of pollution October appears to be more nearly a summer month than a winter month. This is perhaps on account of a tendency to postpone the regular domestic fire until as late in the year as possible.

The greatest number of particles per cubic centimetre found in the period under review was 16,600 on January 21, 1929. This was a foggy day, with a light easterly wind. The least number was 20 on June 6, July 5, and August 14, 1928. On the last two days fresh south-westerly breezes were blowing; on the first day light or gentle south by westerly breezes. On all three days the sky was three quarters covered by clouds of the cumulus type.

It may be mentioned that owing to the time of observation these numbers may be expected to represent approximately the minimum for the day. The mean hourly values of atmospheric pollution as recorded by the automatic air filter are published for each month in the *Observatories' Year Book*. The diurnal variation averaged for the year is shown in the following table, from values given in the *Year Books*.

TABLE II—DIURNAL VARIATION OF ATMOSPHERIC POLLUTION AT KEW OBSERVATORY (mg./m³.)

Hour G.M.T.	1	2	3	4	5	6	7	8	9	10	11	Noon
1928	·12	·12	·11	·11	·12	·13	·17	·22	·23	·21	·17	·13
1929	·16	·14	·12	·12	·12	·12	·15	·22	·25	·25	·22	·19
1930	·09	·08	·08	·08	·09	·10	·13	·18	·19	·17	·16	·15
Hour G.M.T.	13	14	15	16	17	18	19	20	21	22	23	Midt.
1928	·10	·09	·10	·13	·14	·18	·20	·21	·21	·20	·16	·14
1929	·17	·15	·14	·16	·19	·20	·21	·23	·23	·22	·20	·18
1930	·13	·13	·13	·14	·16	·18	·19	·20	·18	·17	·14	·11

It will be seen that the value at 15h. is not very different from the minimum except in 1930. It may be added that to convert these figures into numbers representing the concentration of smoke particles per cm.³, multiplication by a factor of the order of 10,000 is necessary.

§ 5—VARIATION WITH WIND DIRECTION

The nature of the smoke particles found at Kew Observatory suggests that they are conveyed by wind from the industrial and residential areas surrounding the Observatory. It may be anticipated that their concentration depends to a great extent upon the direction of the wind. An analysis of the variation with wind direction has been made by segregating into one group the observations on days when the wind was in a specific direction, and deriving the median number for this group. To diminish the effect of annual variation the two seasons of summer (April to September) and winter (October to March) were dealt with separately. Even so, a certain amount of scatter in each group remains, part of which is traceable to annual variation. The results are given in Table III and are shown graphically in Fig. 2.

TABLE III—THE VARIATION OF SMOKE PARTICLES WITH WIND DIRECTION

Wind direction		N.	NNE.	NE.	ENE.	E.	ESE.	SE.	SSE.
Particles per cm.³	Winter	1000 (4)	1420 (5)	1560 (11)	2420 (8)	3735 (13)	1250 (5)	1140 (9)	690 (4)
	Summer	210 (6)	160 (4)	141 (10)	218 (4)	390 (12)	180 (3)	165 (2)	313 (4)
% of mean	Winter	77	110	121	187	289	97	88	53
	Summer	118	90	79	123	220	100	93	176
		S.	SSW.	SW.	WSW.	W.	WNW.	NW.	NNW.
Particles per cm.³	Winter	820 (15)	460 (18)	839 (20)	1005 (17)	1135 (14)	645 (4)	675 (3)	1876 (6)
	Summer	93 (11)	83 (22)	69 (18)	117 (14)	225 (14)	80 (8)	75 (10)	337 (7)
% of mean	Winter	63	36	65	78	88	50	52	145
	Summer	52	47	39	66	126	45	42	189

(The number of observations in each month is shown by the figures in brackets.)

The contrast between the order of the concentration of smoke particles in winter and summer is very marked. Both curves agree in exhibiting an excess of smoke particles when the wind is from E., W., and NNW. The excess in the summer curve at SSE. is probably spurious. There are only four observations for this direction and three of these occur in April when the number of particles is normally higher than the summer average. To the west and north-north-west of the Observatory isolated factories from which pollution may be derived by suitable winds can be located with precision, and the agreement in direction is perfect. In the eastern quadrant is an agglomeration of factories and, further distant, central London, all of which may subscribe to the sum of pollution brought to Kew by winds from this direction.

A more precise description of the possible sources of atmospheric pollution in the neighbourhood of Kew Observatory may usefully be added. The most conspicuous source is in the Flour Mills at Isleworth, 700 yards west. Further distant in nearly the same direction (bearing 285° at 1 mile) is the Pears Soap factory. Another large factory is that of the Firestone Tyre Co., 1½ miles away, bearing 330°. Brentford Gas Works are also at 1½ miles (bearing 10°). There are several other factories at Brentford. In the north-east sector there are large works at Chiswick, Acton and Willesden, as well as sewage works and a dust destructor between Kew and Mortlake, the brewery at Mortlake and electric light works and dust destructor at Barnes. London is continuous in this sector, say between 20° and 105°, almost the whole area between 1-mile and 18-mile circles being occupied by houses. Richmond, lying between ½ mile and 1½ miles, has bearings 90° to 155°, but has the unoccupied area of Richmond Park lying beyond it. In the south-east sector Isleworth and Twickenham make a continuous belt of houses (mostly small) a mile or so in width.

It is noteworthy that the isolated industrial districts to the west and north-north-west can contribute an amount of pollution which, though not so great, is comparable with that produced by the entire area of central London. This must be because the concentration of pollution is directly proportional to the intensity of the source and inversely proportional to the distance from the source: Brentford and Isleworth represent small but proximate sources, while London represents a powerful but distant source.

In the table, the results are also expressed in percentages of the mean. These bring out more clearly the comparability of the variation in winter and summer. The summer percentage is notably higher than the winter percentage with winds from SSE., W., NNW. and N. The excess with SSE. winds in summer has been referred to above and set aside as being spuriously high. The remaining directions are those associated with the local industrial areas. It has already been suggested that in summer pollution is mainly due to factory smoke owing to the discontinuance of the domestic fire; the fact that the percentage increase in summer is higher than the percentage increase in winter seems to bear out this suggestion. From NE. to E. the situation is reversed, a lower percentage occurring in the summer than in the winter. Presumably pollution from this quarter arises less from the factories and works than from the domestic fires in London and its suburbs.

It is evident that wind direction is a highly active factor in determining the number of smoke particles in a particular locality. On the average, an easterly wind at Kew produces about two and a half times the mean concentration; south-south-westerly winds in winter and south-westerly winds in summer produce about one-third of the mean concentration.

§ 6—VARIATION WITH WIND VELOCITY

To investigate the effect of the speed of the wind upon the concentration of smoke particles, the observations were allocated into groups corresponding to wind speeds of 0 to 1, 1 to 2 . . . 7 to 8, 8 to 10 m./sec., and the median number of each group was formed. As above, the two seasons of summer and winter were dealt with separately. The results are summarised in Table IV. A large amount of the irregularity in the run of the numbers is no doubt due both to annual variation within each group and also to variation with wind direction. In spite of this irregularity certain features are well marked.

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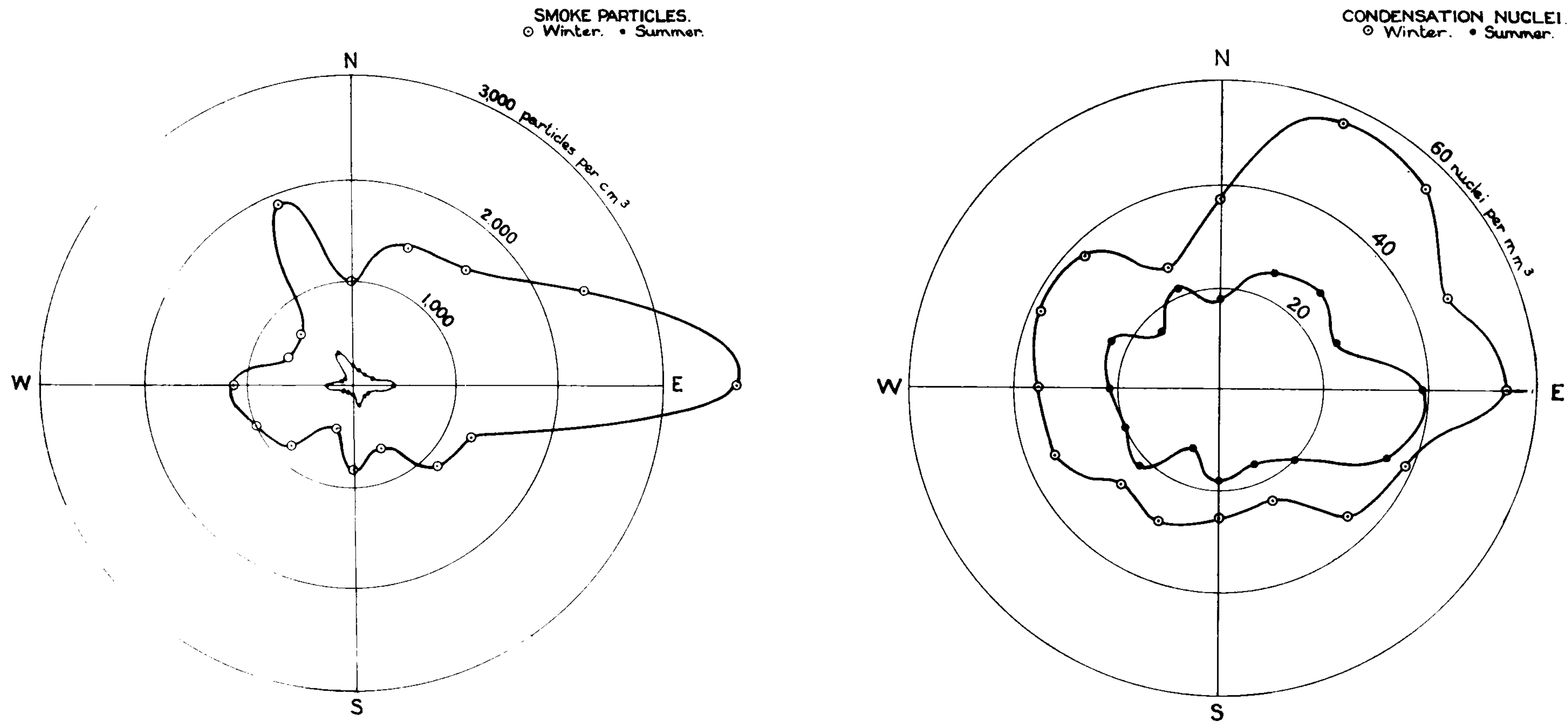

Fig. 2. VARIATION OF SMOKE PARTICLES AND CONDENSATION NUCLEI WITH WIND DIRECTION

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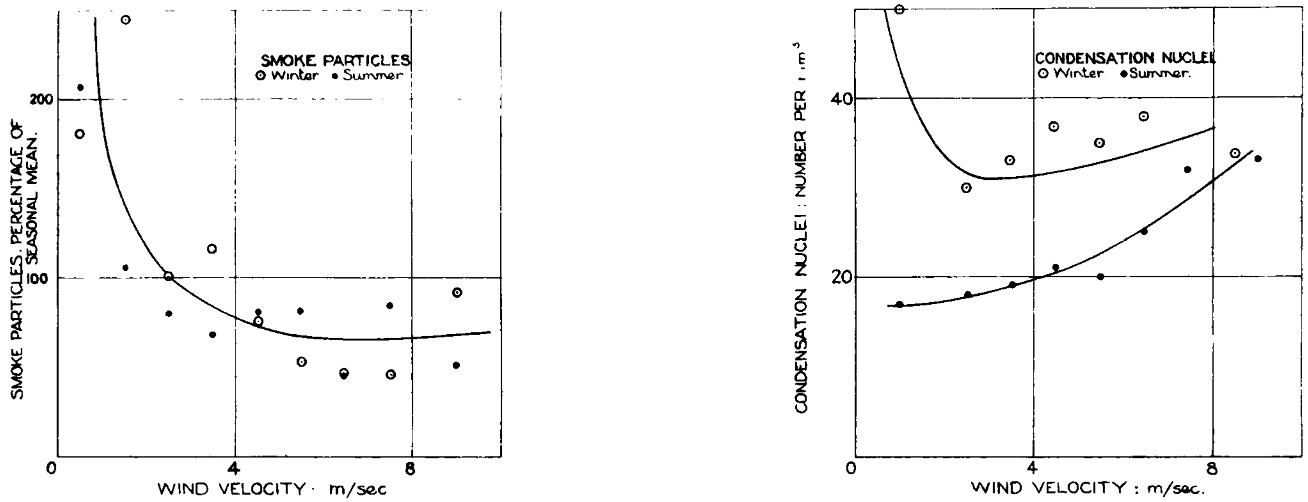

Fig. 3. VARIATION OF SMOKE PARTICLES AND CONDENSATION NUCLEI WITH WIND VELOCITY.

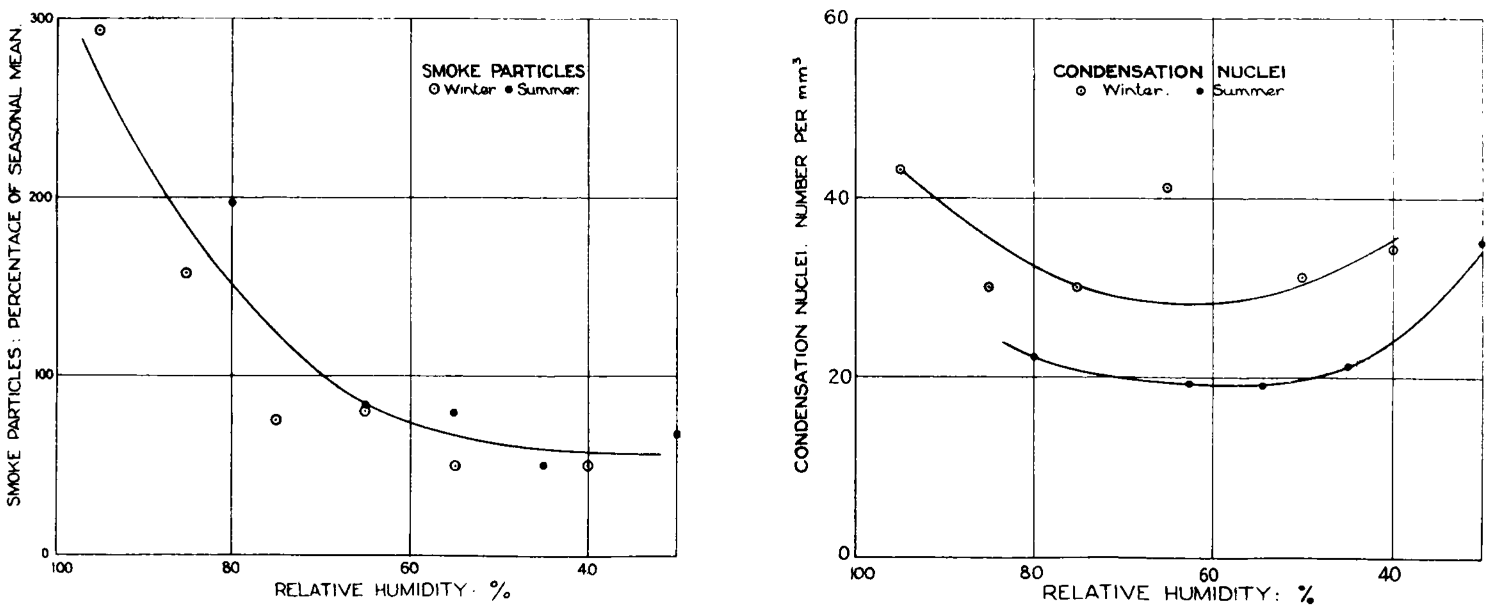

Fig. 4. VARIATION OF SMOKE PARTICLES AND CONDENSATION NUCLEI WITH RELATIVE HUMIDITY.

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TABLE IV—THE VARIATION OF SMOKE PARTICLES WITH WIND VELOCITY

Wind velocity m./sec.		0·0–0·9	1·0–1·9	2·0–2·9	3·0–3·9	4·0–4·9	5·0–5·9	6·0–6·9	7·0–7·9	8·0–10·0
Particles per cm.^{3}	Winter	2460 (11)	3330 (22)	1365 (26)	1569 (25)	997 (34)	713 (23)	617 (14)	600 (12)	1483 (6)
	Summer	370 (3)	188 (14)	141 (24)	120 (29)	140 (23)	140 (30)	80 (13)	150 (9)	89 (14)
% of mean	Winter	180	244	100	115	73	52	45	44	92
	Summer	205	104	78	67	78	78	44	83	49

(The number of observations in each group is shown by the figures in brackets.)

An excess of particles in light winds is definitely shown, both in summer and in winter. This may be because the absence of turbulence in light winds tends to prevent the dispersion of particles to greater heights and the concentration near the ground is thereby increased. In winter the diminution in the concentration of particles with increasing wind strength is more gradual than in summer. In fact the variation in summer for wind speeds greater than 2 m./sec. is indeterminate. If the winter numbers are divided by the winter mean (1,367 particles per cm^3.) and the summer numbers by the summer mean (180), the similarity of the variation in the two seasons is more clearly shown, though considerable scatter remains. Percentages of the seasonal means are included in Table IV and are illustrated graphically in Fig. 3.

In winter the excess shown with the strongest winds may be due to associated causes ; the six occasions occur in the months of December, January and February, and these are months in which pollution is higher than the winter average. Moreover, on five of the six occasions the wind was from between E. and NE., a quarter of considerable pollution. It is likely that the excess in summer with winds of velocity between 7·0 and 7·9 m./sec. may be similarly explained. On six of the nine occasions the wind was between NE. and SSE. and the pollution associated with winds from this quarter is relatively high even in summer. On eight of thirteen occasions when the strength of the wind was 8·0 m./sec. or more, the direction was SSW. ; the pollution associated with this direction is about one half of the average. Probably the figure for wind speeds of 7·0 to 7·9 m./sec. in summer is unduly high while that for wind speeds of 8·0 to 10·0 m./sec. is unduly low.

The curve in Fig. 3 is similar to the one which was obtained by Owens [13] from records given by the automatic air filter. Owens's diagram is far smoother than that illustrating the Kew results, but the observations which Owens analysed were taken in the heart of London, where variation with wind direction would be practically negligible, and were also confined to winter days so that annual variation would be eliminated.

§ 7—VARIATION WITH RELATIVE HUMIDITY

The observations of smoke particles on occasions when the relative humidity was within specified limits have been grouped together, and the median numbers for each group determined. The latter are shown in Table V. Winter and summer were dealt with separately, as in the preceding work. On account of the rarity of extreme values of the relative humidity certain groups have been taken together as indicated on the table. Percentages of the seasonal means are included in the table and are represented graphically in Fig. 4.

TABLE V—THE VARIATION OF SMOKE PARTICLES WITH RELATIVE HUMIDITY

Relative humidity (%)		90–100	80–89	70–79	60–69	50–59	40–49	30–39	20–29
Particles per cm.^{3}	Winter	4007 (18)	2147 (32)	1010 (50)	1095 (39)	675 (21)	675 (13) (40–39)		—
	Summer	—	355 (18) (90–79)		146 (31)	143 (50)	87 (42)	120 (18) (30–29)	
% of mean	Winter	294	157	74	80	49	49 (40–39)		—
	Summer	—	197 (80–79)		81	79	48	67 (30–29)	

(The number of observations in each group is shown by the figures in brackets.)

[13] *London, Meteor. Off. Adv. Com. Atmos. Poll.* 1925, p. 42.

An excess of smoke particles is found with relative humidity above about 80 per cent ; for lower values of the relative humidity the variation is not on the whole very great. Since smoke and dust particles do not act as centres of condensation, the excess of particles with high humidity cannot denote a physical relation. In fact this excess may be adduced as confirmatory evidence that smoke particles are not centres of condensation, for if they were they would to a certain extent abstract moisture from the air and so reduce the relative humidity. It is probable that the excessive concentration of particles with high relative humidity is explained by the association of high relative humidity with stable air, which is conducive to smoke particles remaining in the lower strata.

§ 8—VARIATION WITH CLOUD AMOUNT

The variation of smoke particles with cloud amount has been derived by similar grouping of the observations. The average concentration of smoke particles associated with specified cloud amounts is shown in Table VI. In the table the results are also expressed in percentages of the seasonal mean to illustrate the similarity of the variation in winter and summer. The percentages are represented graphically in Fig. 5.

TABLE VI—THE VARIATION OF SMOKE PARTICLES WITH CLOUD AMOUNT

Cloud amount (tenths of sky)		0	1, 2, 3	4	5	6	7	8	9	10
Particles per cm.^{3}	Winter	3900 (15)	1350 (15)	831 (10)	655 (12)	990 (10)	537 (10)	877 (16)	1270 (32)	1505 (51)
	Summer	173 (10)	150 (18)	98 (14)		89 (16)	150 (16)	85 (23)	143 (31)	233 (27)
% of mean	Winter	285	99	61	48	72	39	64	93	110
	Summer	96	83	54		49	83	47	79	129

(The number of observations in each group is shown by the figures in brackets.)

The variation of smoke particles with cloud amount is on the whole slight. For cloud amounts 4 to 8 the concentration is generally low both in winter and summer. This may be ascribed to the extraction of particles from the lowermost layers of air by convection currents, with which broken skies are normally associated.

The excessive concentration for cloudless days in winter may be due to associated conditions ; of the fifteen days from which the median number is derived, there are seven occasions of easterly winds and two of calms. Both these associations are known to result in a high concentration of smoke particles. If these occasions are excluded, the median number for this group is reduced to 1,210, which is approximately equal to the average for winter and is, if anything, below it.

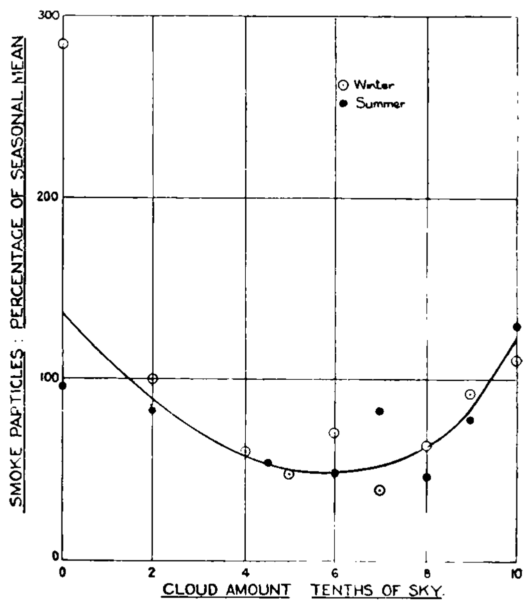

Fig. 5.—Variation of smoke particles with cloud amount.

For overcast skies the number of smoke particles in both winter and summer is above normal. This is perhaps due to the inversion at the height of the cloud layer acting as a barrier to the dispersion of particles by turbulence to greater heights.

§ 9—COMPARISON OF THE JET COUNTER WITH THE AUTOMATIC AIR FILTER

The record given by the air filter is measured by comparing the stain on the filter paper with a calibrated series of shades to which numbers 1, 2, 3 . . . are assigned, so arranged that shade number is proportional to the weight of pollution. In the normal way multiplication by the factor 0·32 transforms shade units into milligrams per cubic metre.

Evidently a weight of impurity of less than 0·3 mg./m.³ will produce a stain lighter than shade number 1, with the result that all such occasions would be classed together as giving less than 0·3 mg./m.³ In practice, however, a distinction may be made between such stains according to whether they appear to be nearer 1 or 0. The former is denoted by 1—, and the latter by 0+. Since 1— days are classed with 1 days, we may say that shade 0 means less than 0·2 mg./m.³

On June 26, 1928, an auxiliary reservoir was fitted to the instrument in use at Kew, whereby about three times the volume of air was aspirated through the filter, and from this date onwards the factor transforming shade units into milligrams per cubic metre was 0·1. This modification of the apparatus enabled small quantities of suspended matter to be measured with greater precision.

Owing to exposure, the shades on the calibrated scale tend to fade as times goes on. If the fading process is allowed to continue for too long serious error may be introduced into the numbers assigned to the stain on the filter paper. A new scale (K.O.3) was brought into use at Kew on August 1, 1930. By this time the previous scale (K.O.2) was reading about ½ unit too low. The discrepancy is not large enough to affect seriously the comparison which follows, but it emphasises the necessity for frequent standardisation of the calibrated scales.

A comparison between the jet counter and the air filter has been made by grouping together all observations with the jet counter on days when, at the time of observation, the weight of pollution determined by the air filter was a specified amount. The two seasons of summer and winter were taken separately, and the median number of each group was then determined. Table VII summarises the results of the analysis. The last group in the table, >0·9, is the aggregate of ten isolated groups varying from 1·0 to 2, 6 mg./m.³, the median of the ten being 1·3 mg./m.³

TABLE VII—COMPARISON BETWEEN THE JET COUNTER AND THE AIR FILTER

Atmospheric pollution : mg./m.³			<0·1	0·1	0·2	0·3	0·4	0·5	0·6	>0·9
Smoke particles per cm.³	Winter	Jan.–Mar. 1928	535 (18)		1600 (16)			—	—	—
		Oct. 1928–Dec. 1930	116 (10)	675 (57)	1550 (30)	2400 (21)	3700 (5)	—	5220 (4)	10000 (10)
	Summer	Apr.–June 1928	150 (27)		920 (5)			—	—	—
	Winter	June 1928–Sept. 1930	85 (82)	265 (41)	391 (1)	—	—	—	—	—
Winter Oct. 1928–Dec. 1930	Pollution : mg./m.³ / Particles : no./cm.³	10⁻⁴ ×	—	1·5	1·3	1·3	1·1	—	1·1	1·3

(The number of observations in each group is shown by the figures in brackets.)

On account of the rarity of mist and fog at 15h. in summer the filter paper is rarely stained beyond the degree of shade 1. It may be noted however that for a specified stain on the filter paper the concentration of particles is invariably less in summer than in winter. Thus the particles present in the air in summer are more effective in staining the filter paper than are those found in winter. This would mean that smoke particles are blacker, larger or heavier in summer than in winter. Possibly it is a combination of all three characteristics which produce the observed effect. It has been suggested above that smoke pollution at Kew in summer may be due less to the domestic fire than to the industrial furnace. Perhaps factory smoke contains larger and heavier particles than that originating from dwelling houses, or more precisely particles which are more effective in staining the filter paper.

The results for winter prior and subsequent to the change in the apparatus are in good agreement. The latter which form the more extended and reliable series show a direct proportionality between the number of smoke particles and their weight. This is clearly seen from the lowermost row of the table in which are given the quotients of the first and third rows. This direct proportionality indicates a tendency to uniform grading by weight, whether pollution is slight, moderate, or dense.

The mean of the quotients in the lowermost row is 1·3, and thus the weight of an average smoke particle (in winter) is $1{\cdot}3 \times 10^{-13}$ gm. A similar result has been obtained by Owens from a more extended set of observations. Two separate sets gave an equivalence of 1·0 and 0·8 mg./m.^{3} for 10,000 particles per cm.^{3}

It is to be remembered that the Kew observations refer consistently to 15h.; those analysed by Owens are presumably taken in London at different times of the day. The higher value at Kew may represent a distinction due to locality or one due to the time of day.

In London the sources of pollution are more concentrated than those at Kew. As smoke travels out from a source the heavier particles no doubt settle out, and so it may be expected that particles from a nearby source are on the whole heavier than those from a distant source. Thus it might have been anticipated that particles found in London, originating from nearby sources, would be heavier than those found at Kew, originating from more distant sources. Actually the reverse is the case, particles at Kew being on the average slightly heavier than those in London.

It seems possible that the distinction may be due to the time of the day. The motion of a smoke particle in a vertical plane must be largely governed by convection. The tendency to uniform grading by weight and the settling out of heavier particles does however suggest that gravity may be active as well. If this is the case it may be supposed that the particles which are less heavy are more readily dispersed by convection, and hence at 15h., which is approximately the time of maximum convection, all but the heaviest particles will have been swept upwards. Thus the average weight of a particle may be expected to be slightly greater at 15h. than at other times of the day.

The same argument, it may be noted, would explain why the average weight of a smoke particle is greater in summer, when convection is considerable, than in winter, when convection is slight.

From the value which has been found for the average weight of a smoke particle we may deduce approximately the radius. If it is assumed that the particles are spherical the radius r is given by

$$\frac{4}{3} \pi r^3 \rho = 1{\cdot}3 \times 10^{-13}$$

where ρ is the density. Hence

$$r = 3{\cdot}1 \times 10^{-5} \rho^{-\frac{1}{3}} \text{ cm.}$$

If ρ lies between ·4 and 1·7, r lies between 3×10^{-5} and 4×10^{-5} cm.

These figures agree with the measurements, quoted above, of the diameters of the largest particles visible under the microscope.

III. CONDENSATION NUCLEI

The observations of condensation nuclei have been analysed by methods similar to those adopted in the case of smoke particles. For the sake of uniformity the use of medians instead of means has been continued, though in practice there is little difference between the mean of a group of nucleus observations and the median of the group.

On account of the great number of nuclei present in the air at Kew, it is convenient to take as units the number per cubic millimetre instead of, as in the case of smoke particles, the number per cubic centimetre.

§ 10—ANNUAL VARIATION

In Table VIII is given the median number of condensation nuclei for each month; in Fig. 1 the results for the three years taken together are illustrated graphically.

TABLE VIII—AVERAGE MONTHLY CONCENTRATION OF CONDENSATION NUCLEI AT 15h. (number per mm.^{3})

	1928	1929	1930	1928–30
January	42 (10)	46 (10)	—	43 (20)
February	28 (7)	43 (7)	—	35 (14)
March	28 (19)	33 (15)	47 (4)	31 (38)
April	23 (14)	21 (7)	39 (9)	23 (30)
May	30 (13)	—	27 (15)	26 (28)
June	14 (10)	—	19 (11)	15 (21)
July	21 (15)	—	21 (13)	21 (28)
August	15 (14)	—	15 (16)	15 (30)
September	17 (13)	—	24 (15)	19 (28)
October	20 (9)	—	29 (16)	27 (25)
November	33 (11)	—	42 (12)	36 (23)
December	43 (11)	—	69 (9)	55 (20)

(The number of observations in each month is indicated by the figures in brackets.)

A definite annual variation in the concentration of condensation nuclei is shown, but the range, relatively to the mean, is small compared with that which was found for smoke particles. The mean of the last column in the table, which may be taken to represent the average concentration, is 29 nuclei per mm.^{3}; the mean for the winter months, October to March, is 38, while that for the summer months, April to September, is 20.

Comparing individual years with the average, it may be seen that in 1928 the mean monthly concentration of nuclei was equal to or below the average except in May. In 1930 the monthly concentration was equal to or above the average in every one of the ten months for which observations are available. It may be remembered that, in the main, similar results were found in the case of smoke particles.

The greatest number of nuclei found at Kew was 215 per mm.^{3}, on January 17, 1929. This concentraction occurred with a light south-westerly breeze, and there was a slight mist at the time but no fog.

It will appear subsequently that this number should be regarded with some reserve, as it is thought that the nuclei on this day may have been produced by some adventitious cause, *e.g.*, a fire in the grounds of the Observatory. The next highest concentration of nuclei found in the period under review was 108 per mm.^{3} on December 22, 1930. This was a day of dense fog; at the time of observation a light wind was blowing from SSE., and the relative humidity was 96 per cent. A concentration of 106 per mm.^{3} occurred on March 12, 1929, an occasion of moderate fog and a gentle easterly breeze; the relative humidity was 67 per cent.

The least number of nuclei found was 4 per mm.^{3} on August 18, 1928. On this day a light south-south-westerly breeze was blowing, and at the time of observation the relative humidity was 46 per cent. The sky was one quarter covered with cumulus cloud. Visibility was very good all day.

It should be remembered that these numbers refer to observations at 15h. and it may be expected that they represent approximately the minimum for the day. Mention may be made of a few observations made on three days in the morning. These observations, which show how the concentration of nuclei decreased as afternoon approached, are given in Table IX.

TABLE IX—CONCENTRATION OF NUCLEI IN MORNING AND AFTERNOON

Date	G.M.T.	No. of nuclei per mm.^{3}	Visibility
May 26, 1930	09.49–10.32	73	Mist
	11.40–11.57	49	Mist to slight mist
	13.05–13.12	12	Slight mist
	14.50–15.10	15	Slight mist
May 27, 1930	09.01–09.41	30	Slight mist
	11.01–11.17	21	Good visibility
	14.51–15.07	19	Very good visibility
Nov. 14, 1930	09.50–10.06	50	Fog
	10.12–10.26	46	Fog becoming thinner
	10.54–11.04	33	Mist
	11.31–11.33	30	Slight mist
	14.50–15.10	25	Slight mist

In passing it is interesting to note that during the foggy period of November 14, the number of condensation nuclei was quite moderate. The pollution record at the time showed 0·4 mg./m.^{3} This corresponds with about 3,000 particles per cm.^{3}, a rather high number. It seems legitimate to conclude that this was a smoke fog, although it is possible that with so large a concentration of smoke particles there was coagulation between particles and nuclei with the result that the number of " free " nuclei was reduced in accordance with Boylan's theory (See § 2).

§ 11—VARIATION WITH WIND DIRECTION

The variation of condensation nuclei with wind direction is given in Table X and is illustrated graphically in Fig. 2.

TABLE X—VARIATION OF CONDENSATION NUCLEI WITH WIND DIRECTION

Wind direction		N.	NNE.	NE.	ENE.	E.	ESE.	SE.	SSE.
Nuclei per mm.^{3}	Winter	37 (5)	57 (8)	55 (9)	47 (7)	55 (10)	39 (6)	35 (6)	25 (6)
	Summer	18 (6)	25 (8)	27 (5)	24 (2)	39 (14)	35 (1)	20 (5)	17 (6)
Wind direction		**S.**	**SSW.**	**SW.**	**WSW.**	**W.**	**WNW.**	**NW.**	**NNW.**
Nuclei per mm.^{3}	Winter	25 (10)	29 (14)	27 (15)	35 (14)	35 (10)	38 (5)	37 (4)	26 (5)
	Summer	18 (12)	13 (23)	21 (21)	20 (15)	21 (17)	23 (8)	16 (10)	21 (11)

(The number of observations in each group is shown by the figures in brackets.)

A definite excess of nuclei is shown with winds from between NNE. and ESE. Otherwise the concentration is fairly uniform.

The graph invites comparison with the corresponding diagram in the same figure showing the variation of smoke particles with wind direction. It will be noticed that the diagrams have one feature in common, an excess with easterly winds. Closer examination however reveals that in the case of NNE. winds the excess of nuclei is relatively greater than the excess of smoke particles. There are three outstanding features in opposition : (1) no excess of nuclei is shown with the W. and NNW. winds which bring an excess of smoke particles from, it is supposed, three isolated industrial areas ; (2) the distinction between the summer and winter curves is far less marked for nuclei than it is for smoke particles ; (3) more general uniformity with wind direction is shown to exist for nuclei than for smoke particles.

Consideration of the effect of gas cookers suggests itself; in practically all the houses surrounding Kew Observatory cooking is effected by gas and not by coal fires. These presumably produce very few, if any, smoke particles, but great numbers of nuclei (*cf.* Aitken's experiment with a Bunsen flame). Since Kew Observatory is almost entirely surrounded by dwelling houses, the general uniformity with wind direction may be satisfactorily accounted for by supposing a large proportion of nuclei to be produced by gas.

The slight distinction between the summer and winter curves of nuclei relatively to the considerable difference between the summer and winter curves of smoke particles would also be explained, for gas cookers are in use all the year round, whereas the domestic fire, producing smoke particles, is almost entirely dispensed with in summer.

With regard to the excess of nuclei found with NNE. winds, which is not reproduced in the diagram illustrating the variation of smoke particles with wind direction, it is perhaps significant that Brentford gas works bear north by east. It may also be noted in this connection that the excess of nuclei with NNE. winds in summer is not so great as the excess in winter: in summer less gas would require to be generated.

That sources of smoke are also sources of nuclei cannot however be disregarded. I was recently able to test air near a bonfire in the grounds of Eskdalemuir Observatory. In a part of the grounds distant from the fire, I found 7·2 nuclei per mm.^{3} Forty yards to leeward of the fire, in line with the wind, there were at least 63 per mm.^{3}, and possibly many more, as owing to the large number of nuclei counting was difficult (closer still there were far too many to count). Ten yards to windward there were 7·1 per mm.^{3} These are the means of about fifteen or twenty counts, each quite consistent.

At Kew it is possible that gas nuclei are produced in great numbers from all directions and these are augmented by nuclei from smoke sources, but it is difficult to formulate the relative proportion of each. Isolated smoke sources apparently contribute a very small proportion. It will be seen later that there are reasons for believing that about 18 nuclei per mm.^{3} are produced by gas, and that this number is approximately the same in winter as in summer. The additional 2 or 3 in summer, and 15 or so in winter, which are found with winds in the western semicircle, may be produced by the combustion of coal in the dwellings round about.

The possibility of the presence at Kew of nuclei formed from sea spray should not be overlooked. These would be fairly constant all the year round, and in an island such as Great Britain, it may be expected that little variation with wind direction would be shown. It will be seen later that there is some reason for believing that of the nuclei present in the air at Kew the number produced by gas is very much greater than the number formed from sea spray.

§ 12—VARIATION WITH WIND VELOCITY

As in the case of smoke particles, the observations of nuclei on days when the wind speed at the time of observation lay between specified limits have been grouped together and the median number of each group derived.

The results are shown in Table XI and are illustrated graphically in Fig. 3.

TABLE XI—THE VARIATION OF CONDENSATION NUCLEI WITH WIND VELOCITY

Wind velocity: m./sec.		0·0–1·9	2·0–2·9	3·0–3·9	4·0–4·9	5·0–5·9	6·0–6·9	7·0–7·9	8·0–10·0
Nuclei per mm.^{3}	Winter	50 (18)	30 (23)	33 (29)	37 (26)	35 (19)	38 (10)	34 (15)	
	Summer	17 (12)	18 (19)	19 (33)	21 (36)	20 (30)	25 (9)	32 (11)	33 (10)

(The number of observations in each group is shown by the figures in brackets.)

In winter an excess of nuclei is found with light winds, but this falls off very quickly until a wind speed of about 2 m./sec. is attained. Thereafter is shown a tendency to increased concentration of nuclei with increasing wind strength.

In summer the concentration of nuclei increases steadily with increasing wind strength.

It is curious to find this distinction in the shape of the curves for the two seasons. It was thought that the excess associated with light winds in winter might be due to (1) a prevalence of light winds from the N. or E. in winter, or (2) a prevalence of calms or light winds in December, the only month in which the average concentration of nuclei is well above the winter normal. To see how far the excess might be due to (1) observations when the wind was between N. and E. were excluded. The median number was however unaltered. With regard to (2), when six observations in December were rejected, the median number was reduced to 41. This is still considerably higher than the median for any other wind speed in winter, so that the excess with light winds in winter may hardly be regarded as fortuitous.

In summer the seasonal variation is so slight that it cannot be held to account for the increased concentration of nuclei with strong winds. To see whether this excess might be due to an accompanying effect of wind direction the observations associated with wind velocity of 6 m./sec. and over were regrouped and those on occasions when the wind was between NNE. and SE. were excluded. The median number of the remaining 21 observations was 25, a figure still considerably higher than those for lower wind speeds. Thus an increased concentration of nuclei with strong winds remains.

The behaviour of condensation nuclei with winds of varying strength appears to be quite different from that of smoke particles. The stronger the wind the higher the concentration of nuclei and the lower that of smoke particles. An exception to this statement has to be made in the case of calms or light airs in winter. Under these conditions the behaviour of both types of suspensoid is similar : both tend to increase.

It is not at all clear why the concentration of nuclei should increase with increasing wind strength. It is possibly due to the increased turbulence associated with strong winds, but it is not obvious why the mixing of air which is the consequence of turbulence should result in an increased concentration of nuclei. The seasonal distinction in calms is more easily accounted for : calms and light airs are associated with anticyclonic weather. In summer this is accompanied by clear skies, and the strong sunshine leads to convection currents which carry the nuclei upward ; the concentration near the ground is thus decreased. In winter, however, anticyclonic weather is most frequently accompanied by an extensive and uniform layer of strato-cumulus cloud ; this layer forms a "lid" preventing the dispersion of nuclei to greater heights. They are thus crowded into a relatively thin layer of air extending only to the height of the cloud, and an increased concentration is found.

§ 13—VARIATION WITH RELATIVE HUMIDITY

The observations of condensation nuclei in winter and in summer have been collected into groups according to the relative humidity at the time of observation, and the median number of each group found. The results are shown in Table XII and are illustrated graphically in Fig. 4.

TABLE XII—THE VARIATION OF CONDENSATION NUCLEI WITH RELATIVE HUMIDITY

Relative humidity (%)		90–100	80–89	70–79	60–69	50–59	40–49	30–39	20–29
Nuclei per mm.^{3}	Winter	43 (12)	30 (15)	30 (24)	41 (21)	31 (16)	34 (15)		—
	Summer	—	22 (16)		19 (39)	19 (65)	21 (36)	35 (9)	

(The number of observations in each group is shown by the figures in brackets.)

In winter, the isolated high value of 41 nuclei per mm.[3] corresponding with relative humidity between 60 per cent and 69 per cent is largely due to the fact that on half of the occasions from which the figure is deduced winds from between NNE. and E. were blowing. If these occasions are excluded, the median number is reduced to 33, which, though still a trifle high, is practically in line with the others. The high value associated with relative humidity between 90 per cent and 100 per cent is not spuriously large on this account. If occasions of winds between NNE. and E. are excluded, the median is reduced to 39, and this is still greatly in excess of the number for lower humidities.

In summer, the excessive concentration of nuclei associated with relative humidity between 20 per cent and 39 per cent is reduced to 21 by the exclusion of three large values when the wind was between NNE. and ESE. The exclusion of all easterly winds would likewise reduce the other numbers in the table, and so the concentration with low humidity remains relatively large. Probably, however, the figure given in the table for this group is unduly high.

The general trend of the curves in both winter and summer suggests a somewhat curious association between relative humidity and the concentration of nuclei. For high concentrations of nuclei the relative humidity is either very high or very low; for low concentrations the relative humidity is of an average order.

It is not easy to see how the interaction occurs. Presumably, as in the case of smoke particles, the stable air with which high relative humidity is associated, is conducive to nuclei remaining in the lower strata. This implies that the two elements increase together when relative humidity is high.

On the other hand it is possible that nuclei abstract moisture from the air owing to their hygroscopic centre and thus their presence in large numbers tends to lower the relative humidity. This would imply an inverse proportionality.

The resultant of two such curves would be similar to the graphs in Fig. 4.

The latter consideration raises the interesting question of the reaction of relative humidity with the various forms of nuclei: sulphates, chlorides, etc. Perhaps certain types of nuclei abstract moisture from the air more readily than others. The point cannot, however, be usefully pursued until further knowledge of the constitution of nuclei becomes available.

§ 14—VARIATION WITH VAPOUR PRESSURE

The nucleus observations may be associated with vapour pressure in a similar manner. The average concentration of nuclei associated with vapour pressure within specified limits is shown in Table XIII and the results are illustrated graphically in Fig. 6.

The points in the diagram are distributed fairly closely about a straight line, the winter points being on the whole slightly above and the summer points slightly below. When nuclei are numerous the vapour pressure is low, and conversely. This may be interpreted as showing the drying effect of nuclei due to their hygroscopic centre.

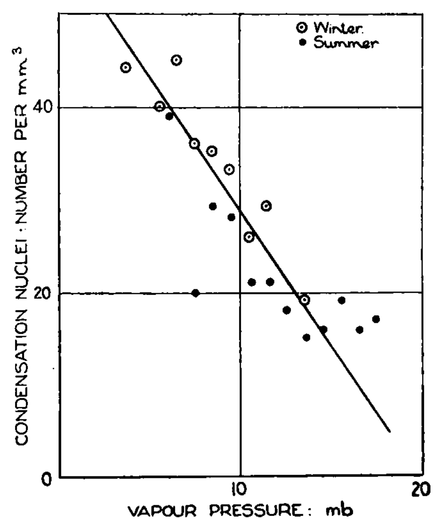

FIG. 6.—VARIATION OF CONDENSATION NUCLEI WITH VAPOUR PRESSURE.

This diagram is the only one of those which have been obtained in the present work in which the distribution of points is approximately the same in summer as in winter. Thus with a given vapour pressure there is associated a concentration of nuclei which is practically the same in winter as in summer. This suggests that their mutual association is not due to the reciprocity of the annual variation of each.

TABLE XIII—THE VARIATION OF CONDENSATION NUCLEI WITH VAPOUR PRESSURE

<table>
<tr><td colspan="2">Vapour pressure .. (mb.)</td><td>2·0–4·9</td><td>5·0–5·9</td><td>6·0–6·9</td><td>7·0–7·9</td><td>8·0–8·9</td><td>9·0–9·9</td><td>10·0–10·9</td></tr>
<tr><td rowspan="2">Nuclei per mm.³</td><td>Winter</td><td>44 (7)</td><td>40 (15)</td><td>45 (27)</td><td>36 (19)</td><td>35 (26)</td><td>33 (17)</td><td>26 (9)</td></tr>
<tr><td>Summer</td><td>—</td><td colspan="2">39 (4)</td><td>20 (8)</td><td>29 (18)</td><td>(28 12)</td><td>(21 21)</td></tr>
<tr><td colspan="2">Vapour pressure .. (mb.)</td><td>11·0–11·9</td><td>12·0–12·9</td><td>13·0–13·9</td><td>14·0–14·9</td><td>15·0–15·9</td><td>16·0–16·9</td><td>17·0–17·9</td></tr>
<tr><td rowspan="2">Nuclei per mm.³</td><td>Winter</td><td>27 (10)</td><td colspan="3">19 (8)</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>Summer</td><td>21 (19)</td><td>18 (24)</td><td>15 (21)</td><td>16 (9)</td><td>19 (10)</td><td>15 (7)</td><td>17 (5)</td></tr>
</table>

(The number of observations in each group is shown by the figures in brackets.)

It would seem that the amount of moisture in the air is in some way related to the concentration of nuclei. Consideration of the diurnal variation of each element shows however that the dependence is not likely to be so great as is suggested by the graph in Fig. 6. The diurnal variation of nucleation is considerable, while that of vapour pressure is slight; moreover the diurnal variation of vapour pressure is singly periodic while the diurnal variation of nucleation at Kew is probably similar to that of pollution which is doubly periodic.

§ 15—VARIATION WITH CLOUD AMOUNT

The median number of nuclei associated with specified cloud amounts is given in Table XIV.

TABLE XIV—THE VARIATION OF CONDENSATION NUCLEI WITH CLOUD AMOUNT

Cloud amount: 10ths of sky		0, 1	2, 3	4	5	6	7	8	9	10
Nuclei per mm.³	Winter	41 (21)	26 (7)	38 (9)	36 (7)	34 (6)	42 (10)	30 (13)	28 (21)	40 (44)
	Summer	33 (12)	15 (15)	21 (10)	19 (9)	20 (19)	19 (22)	24 (20)	21 (24)	22 (33)

(The number of observations in each group is shown by the figures in brackets.)

The variation is not very definite and may well be due to chance. In fact the effect of the state of sky upon the concentration of nuclei is overshadowed to a very great extent by other influences.

§ 16—CORRELATION COEFFICIENTS BETWEEN SMOKE PARTICLES AND CONDENSATION NUCLEI

The preceding work has shown that smoke particles and condensation nuclei have some features in common and others in opposition. Among those in common are (1) an annual variation similar in form, (2) a low average concentration of both for 1928 and a high average concentration of both for 1930, (3) an excess of both with easterly winds, (4) an excess of both with high relative humidity; while features in opposition are (1) a far greater distinction between winter and summer in the concentration of smoke particles than in that of nuclei, (2) the absence of an excess of nuclei associated with winds from W. and NNW. which produce a marked excess of smoke particles, (3) dissimilarity in the variation with wind speed, except perhaps in winter, (4) dissimilarity with low relative humidity.

These considerations suggest that it may be useful to have an index of the connection between the two such as is given by a correlation coefficient. A priori a positive correlation may be expected from the fact that the formation of smoke particles by combustion implies the formation of condensation nuclei as well (though with smokeless fuel nuclei may be formed without smoke particles), and that certain meteorological conditions, *e.g.*, stable air, are conducive to increased concentrations of both.

The observations at Kew from 1928 to 1930 may conveniently be divided into five groups, three winters and two summers. In the summer of 1929 only three pairs of observations are available owing to the rejection of the counts of nuclei for reasons noted above. The correlation coefficient has been worked out for each group separately in order to trace its consistency or otherwise in different years and seasons, and has then been worked out for certain groups taken together, and for the complete set of observations, with the exception of the three pairs in the summer of 1929.

In the course of the work it became apparent that the observation of nuclei on January 17, 1929 was definitely incongruous. This was the day, noted above, on which the exceptionally large number of 215 per mm.^{3} was found. It is not suggested that the observation is at fault, but the conditions prevailing at the time do not indicate that such an outstanding number is representative. It is possible that some local and adventitious cause such as a fire in the grounds of the Observatory may have given rise to this excessive concentration. It seems unfair to include this observation in a comparison of smoke particles and nuclei, and accordingly the observation was rejected at the outset.

The means, standard deviations, and correlation coefficients, are shown in Table XV.

TABLE XV—CORRELATION COEFFICIENTS BETWEEN SMOKE PARTICLES AND CONDENSATION NUCLEI

(The unit used for both elements is the number for cubic centimetre.)

	Number of obs. N	Smoke particles		Condensation nuclei		Corr. coeff. r	Standard Error of r $\frac{1-r^2}{\sqrt{N}}$
		Mean	Standard deviation	Mean	Standard deviation		
Winter 1928	32	1,470	1,460	36,500	14,200	·58	·12
Winter 1929	22	3,610	3,750	43,700	23,300	·70	·11
Winter 1930	33	1,980	2,430	44,000	21,400	·81	·06
Summer 1928	46	227	286	22,700	13,800	·22	·14
Summer 1930	36	305	207	25,900	10,900	·27	·15
Winter 1928–1930	87	2,210	2,670	41,200	20,000	·71	·05
Summer 1928–1930	82	261	257	24,000	12,700	·25	·10
Year 1928	78	739	1,140	28,400	15,500	·54	·08
Year 1930	69	1,110	1,890	34,500	19,100	·77	·05
All observations ..	169	1,640	2,158	32,900	18,900	·69	·04

The correlation coefficient for the complete set of 169 observations is ·69 ± ·04, a figure of some significance. The correlation factor for all winter observations is ·71 ± ·05, and those for the individual winters are of the same order. The factor for all summer observations is ·25 ± ·10, and those for the individual summers are practically the same.

The insignificance of the summer factor shows that there is but slight connection between the concentration of the two suspensoids in summer. This no doubt is due to the decline in fuel consumption in the warmer weather. In winter, when fuel consumption is higher, the correlation factor increases.

Comparing the coefficients for the years 1928 and 1930, it will be seen that the coefficient for 1930 is of considerably greater significance. It may be recollected once again that, on the average at 15h., 1930 was a year of greater pollution than 1928; thus perhaps the proportion of nuclei formed by combustion was relatively larger in 1930 than in 1928, and this may be expected to lead to a higher correlation.

It may be noted that Boylan[14] has obtained a correlation factor of ·73 ±·056 from 70 observations in the city of Dublin.

The high correlation with high fuel consumption and the low correlation with low fuel consumption is in accordance with the suggestion, invoked to explain the distinction between the variation of particles and nuclei with wind direction, that the condensation nuclei found at Kew may be divided into two types, (1) those originating from the same sources as smoke particles, and (2) those originating from other sources, *e.g.*, smokeless fuel and sea spray.

Pursuing this suggestion it may be inquired what proportion of nuclei may be expected to belong to each type. As no apparatus exists which will differentiate between types of nuclei, any inquiry must be prosecuted by statistical methods. From considerations of the changes that are likely to occur in winter and summer, and by making various assumptions which do not seem unreasonable, it is possible to assign average values for the two seasons from the data for winter and summer contained in Table XV.

We set $$n = x + \alpha$$

where x is the number of nuclei originating from smoke sources, α is the number originating from other sources, and n is the total number. Let p denote the number of smoke particles; $\bar{p}$, $\bar{x}$, etc., denote mean values; σ_p, σ_x, etc., standard deviations; and r_{px}, r_{pn}, etc., correlation coefficients. Finally, let unaccented quantities refer to summer values, and accented quantities to winter values.

From first principles it may be expected that p and x are strongly correlated and that p and α and also x and α are but slightly correlated. Further it is not unreasonable to suppose that p and x are correlated as strongly in winter as in summer. We therefore make the following assumptions:

$$r_{pa} = r_{p'a'} = 0\,; \quad r_{xa} = r_{x'a'} = 0\,; \quad r_{px} = r_{p'x'}$$

It may then be shown that

$$r_{pn}\sigma_n = r_{px}\sigma_x\,; \quad r_{p'n'}\sigma_{n'} = r_{p'x'}\sigma_{x'} = r_{px}\sigma_{x'}\,;$$

$$\sigma_n^2 = \sigma_x^2 + \sigma_a^2\,; \quad \sigma_{n'}^2 = \sigma_{x'}^2 + \sigma_{a'}^2.$$

Since it may be surmised that α is the product of gas or sea spray, and both of these sources may be expected to produce on the average approximately the same number of nuclei in winter as in summer, it is further assumed that

$$\sigma_{a'} = \sigma_a \text{ and } \bar{\alpha}' = \bar{\alpha}.$$

Hence $$\left(\frac{r_{p'n'}\sigma_{n'}}{r_{pn}\sigma_n}\right)^2 = \frac{\sigma_{x'}^2}{\sigma_a^2} = \frac{\sigma_{n'}^2 - \sigma_a^2}{\sigma_n^2 - \sigma_a^2}.$$

From Table XV,

$$\sigma_{n'} = 20{,}000, \qquad \sigma_n = 12{,}700,$$

$$\frac{r_{p'n'}\sigma_{n'}}{r_{pn}\sigma_n} = \frac{\cdot 71 \times 20{,}000}{\cdot 25 \times 12{,}700} = 4{\cdot}5.$$

Hence $$\sigma_a = 12{,}200$$
$$\sigma_x = 3{,}550$$
$$\sigma_{x'} = 15{,}900$$

[14] *loc. cit.* footnote 11.

It now remains to obtain a value for the mean number of each type of nucleus. We have from Table XV

$$\bar{x}' + \bar{\alpha} = \bar{n}' = 41{,}200 \qquad (1)$$
$$\bar{x} + \bar{\alpha} = \bar{n} = 24{,}100 \qquad (2)$$

Let us assume that the means of each type are in the same proportion as their standard deviations.

Then
$$\frac{\bar{x}'}{\bar{\alpha}'} = \frac{\sigma_x'}{\sigma_a'} = \frac{15{,}900}{12{,}200} = 1{\cdot}30_3$$

and
$$\frac{\bar{x}}{\bar{\alpha}} = \frac{\sigma_x}{\sigma_a} = \frac{3{,}500}{12{,}200} = {\cdot}29$$

From equation (1)
$$\bar{\alpha} = 17{,}900$$

and from (2)
$$\bar{\alpha} = 18{,}700$$

The close agreement of the values of $\bar{\alpha}$ derived from the two equations affords a measure of justification for the assumption that the ratio of the means was equal to the ratio of the standard deviations*.

Adopting a mean value of $\bar{\alpha}$ equal to 18,300, it follows that

$$\bar{x}' = 22{,}900 \text{ and } \bar{x} = 5{,}800.$$

The large increase in winter of nuclei originating from smoke sources is noteworthy. The ratio of $\bar{x}'$ to $\bar{x}$ is 4·4. This does not however seem unduly high in view of the ratio of the average number of smoke particles in winter to the average in summer, which is 7·6.

It appears then that on the average about three-fifths of the nuclei at Kew in winter originate from smoke sources; in summer only one quarter are smoke produced. Such proportions would account for the correlation coefficient between the numbers of smoke particles and nuclei being high in winter and low in summer.

The number of nuclei which has been attributed to sources other than smoke is much higher than could be accounted for on the basis of sea-spray nuclei. Average values of the concentration of condensation nuclei over the oceans are shown in Table XVI reproduced from a recent paper by Wigand[15]. For a number as high as 18,000 we must look to some source other than sea spray. It seems probable that of the nuclei present at Kew which originate from sources other than smoke the vast majority are produced by gas.

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* In place of the assumption that $\sigma_a' = \sigma_a$ and $\bar{a}' = \bar{a}$ it might have been assumed earlier that the standard deviations were in the same ratio as their means. That is

$$\frac{\sigma_{x'}}{\sigma_x} = \frac{\bar{x}'}{\bar{x}} \equiv \xi ; \quad \frac{\sigma_a'}{\sigma_a} = \frac{\bar{a}'}{\bar{a}} \equiv \eta ; \quad \frac{\sigma_a}{\sigma_x} = \frac{\bar{a}}{\bar{x}}$$

If $\beta \equiv \frac{\sigma_{n'}}{\sigma_n}$, $\gamma \equiv \frac{\bar{n}'}{\bar{n}}$ we have

$$\frac{\sigma_a^2}{\beta^2 - \xi^2} = \frac{\sigma_x^2}{\eta^2 - \gamma^2} = \frac{\sigma_n^2}{\eta^2 - \xi^2} ; \quad \frac{\bar{a}}{\gamma - \xi} = \frac{\bar{x}}{\eta - \gamma} = \frac{\bar{n}}{\eta - \xi} ; \quad \xi = \frac{r_{p'n'}\sigma_{n'}}{r_{pn}\sigma_n}$$

$$\text{Thus} \quad \left(\frac{\eta - \gamma}{\gamma - \xi}\right)^2 = \frac{\eta^2 - \beta^2}{\beta^2 - \xi^2}$$

whence $\eta = {\cdot}84_3$. Hence $\bar{a} = 18{,}300$; $\bar{a}' = 15{,}400$

Thus either assumption leads to final mean values of $\bar{a}$ which are in close agreement.

[15] A. Wigand : *Ann. Hydr., Berlin*, **58**, 1930, pp. 212–6.

TABLE XVI—CONCENTRATION OF CONDENSATION NUCLEI AT SEA

Author	*Locality*	*Nuclei* no./cm.³
W. Knocke	Mid. and S. Atlantic	1130
Frank T. Davies ..	Caribbean	2000
	Pacific	4000–5000
Parkinson	Atlantic	870
G. R. Wait	Pacific	774
A. Wigand	N. Atlantic	649

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