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The Relationship of Total Atmospheric Ozone to the Sunspot Cycle

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Abstract. For the 27-year period 1933–1959 inclusive, highly significant negative correlation is found between the relative sunspot number and the worldwide average of total atmospheric ozone. Peak correlation with respect to the present-day 10-year sunspot cycle is found at a lag of 1½ to 2 years of the sunspots relative to ozone. The peak correlation of total atmospheric ozone with the mean latitudinal distance from the solar equator of the total area of sunspots is almost identical in magnitude to that with sunspot number. However, the peak correlation with sunspot latitude is found at a lag of less than 6 months of the ozone relative to sunspot latitude, in the opposite direction to that with sunspot number. This phase difference of the negative correlation suggests that atmospheric ozone is much more sensitive to sunspot latitude than to sunspot number.

INTRODUCTORY REMARKS

The author's longtime interest in atmospheric ozone as a possible link between solar activity and climate was increased by the implications of a recent paper by *Kraus* [1961]. He concludes that of the five possible factors of climatic control which he considers, ozone, volcanic dust, solar constant, solar corpuscular radiation, and CO_2, the probable effects of increased atmospheric ozone appear to fit best the general pattern of climatic change in high and low latitudes during recent decades. Subsequent discussion with Professor C. E. Palmer and with Dr. S. P. Venkiteshwaran at U.C.L.A. served to further this interest and to indicate the probable adequacy of present ozone data for a preliminary statistical check of any possible solar-ozone relationship. Apparently no previous effort has been made to check this possibility on a large scale.

A remark by Dr. Hans Dütsch at Boulder in April 1961 directed the author's attention to a compilation of all available northern hemispheric ozone data currently under preparation by Dr. J. London for Air Force Cambridge Research Laboratories. Dr. London was most obliging in supplying a complete tabulation of available data, in the form of monthly means of total ozone, for all observing stations of the northern hemisphere from the first observations at Oxford in 1925, up to and including 1959. Corresponding data from the southern hemisphere for Wellington, New Zealand, were kindly supplied by M. A. F. Barnett, Director of the New Zealand Meteorological Service, and for Aspendale (Melbourne), Brisbane, and Macquarie Island by C. H. B. Priestley, Chief of the Division of Meteorological Physics of the Scientific and Industrial Research Organization of the Commonwealth of Australia. All the ozone values, from all three sources, are based on the absorption coefficients found by Vigroux, and are expressed in the standard unit, milli-atmo-centimeters; hence they should be strictly comparable.

PROCEDURAL TREATMENT OF THE DATA

Nature of the data and averaging procedures. All the data used in this study were supplied in the form of monthly averages of individual station measurements of total ozone. In every case the number of individual daily observations that went into the station monthly mean was listed along with the mean value as tabulated. The great majority of station monthly mean values represent from 20 to 31 individual daily values, a substantial number of them contain between 10 and 20 daily values, and a small scattering contain less than 10 daily values. However, in averaging monthly mean station values to obtain either an annual mean value for a single station or a calendar monthly average value for a number of stations, in no case were the individual station monthly mean values weighted by the number of daily observations. This procedure was followed because the sampling in-

TABLE 1. Monthly and Annual Means of Total Atmospheric Ozone, 1925–1959

Month			1925	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	All Years§
Jan.	Val.	*			360	328	285			298	344	332	320	303	312	318	327	352	348	368	339	275	300	268	270	334	314	310	332	366	316	328	298	314	304	312	335	318–319
	No.	†			2	2	4			2	2	2	3	3	4	3	3	3	3	4	6	3	3	4	4	3	4	2	7	10	10	13	22	21	15	37	32	240
	Lat.	‡		52	45	45	30			39																												
Feb.	Val.	*	424	333	370	346	305			332	354	342	370	335	352	325	327	383	399	406	355	371	362	318	366	314	330	342	380	367	355	369	343	335	338	353	342	349–350
	No.	†	1	1	2	2	3			2	2	2	3	3	4	3	2	4	6	5	5	3	3	4	4	4	3	2	7	11	12	16	23	22	18	37	31	256
	Lat.	‡	52	52	45	45	29			39																												
Mar.	Val.	*	382	347	400	367	302			356	370	370	355	387	353	332	362	394	416	397	376	380	371	355	372	339	344	346	410	424	371	379	346	340	328	366	356	362–363
	No.	†	1	1	4	3	4			2	2	2	3	3	4	4	3	5	6	6	6	4	3	4	4	4	4	2	8	12	11	18	24	22	17	40	32	271
	Lat.	‡	52	52	51	47	30			39																												
Apr.	Val.	*	424	358	402	379	319			358	356	342	362	385	337	365	357	404	407	398	381	378	396	351	382	378	368	367	388	406	388	400	341	352	340	371	364	370–370
	No.	†	1	1	7	3	4			2	2	2	2	3	4	4	3	5	6	7	5	4	3	4	3	3	4	1	8	14	14	19	25	23	18	44	31	282
	Lat.	‡	52	52	53	47	30			39																												
May	Val.	*	403	375	395	378	301			338	360	344	358	365	320	344	363	374	396	382	369	362	382	308	362	358	363	360	385	398	379	281	346	333	343	355	345	357–352
	No.	†	1	1	7	3	4			2	2	2	2	3	4	4	3	6	5	6	6	4	3	4	3	4	3	1	9	14	13	20	24	22	18	44	31	280
	Lat.	‡	52	52	53	47	30			39																												
June	Val.	*	373	344	356	342	291			330	356	334	320	322	305	316	335	346	358	350	337	341	346	314	339	333	358	341	340	371	357	355	333	327	322	337	335	338–338
	No.	†	1	2	7	3	3			2	2	2	2	3	4	4	3	6	5	7	5	4	3	4	3	4	2	1	10	13	12	19	23	20	18	44	32	276
	Lat.	‡	52	52	53	47	30			39																												
July	Val.	*	364	314	338	314	268			314	319	317	314	316	285	298	314	326	331	332	360	318	308	295	322	310	310	311	328	341	337	341	316	307	319	321	318	318–322
	No.	†	1	5	7	3	4			2	2	2	3	3	4	4	3	6	5	6	5	4	3	4	3	4	2	1	11	14	13	21	27	20	34	47	33	309
	Lat.	‡	52	56	53	47	38			39																												
Aug.	Val.	*	356	310	324	288	278	286	301	300	316	308	292	305	281	291	291	309	325	308	298	301	303	278	298	307	300	308	314	323	313	322	302	312	311	303	308	306–308
	No.	†	1	4	7	3	4	1	1	2	2	2	3	3	4	4	3	5	6	6	5	4	3	4	3	4	2	2	10	14	13	20	26	19	35	45	33	304
	Lat.	‡	52	53	53	41	38	47	47	39																												
Sept.	Val.	*	336	283	307	273	277		324	300	306	286	285	289	281	280	292	301	297	289	275	298	291	264	290	284	276	274	281	309	285	301	285	301	301	295	297	293–293
	No.	†	1	5	7	6	1		1	2	2	2	3	3	4	4	4	5	5	6	5	3	2	4	3	4	2	2	11	12	12	21	26	17	34	44	34	299
	Lat.	‡	52	53	53	36	30		47	39																												
Oct.	Val.	*	305	278	298	269	257		273	296	295	286	264	282	278	277	298	283	298	294	299	284	271	254	282	268	256	281	272	295	280	285	277	286	287	293	287	284–285
	No.	†	1	4	5	6	1		1	2	2	2	3	4	4	3	4	4	6	5	5	4	3	4	3	4	2	2	10	12	12	22	24	17	35	44	33	295
	Lat.	‡	52	51	51	36	30		47	39																												
Nov.	Val.	*	295	286	274	266			277	292	290	275	277	271	262	288	290	283	291	290	281	283	248	248	251	252	278	298	273	280	265	283	274	276	288	296	296	281–284
	No.	†	1	1	2	5			1	2	2	2	3	3	4	2	4	5	6	4	5	4	4	4	3	4	2	5	10	11	10	18	22	18	38	43	31	285
	Lat.	‡	52	47	45	34			47	39																												
Dec.	Val.	*		313	310	282			291	285	320	273	288	284	296	288	276	297	305	275	280	276	256	281	262	309	294	316	323	322	299	290	286	283	286	313	315	293–298
	No.	†		1	2	5			1	2	2	3	3	3	4	1	4	4	5	4	4	4	4	3	3	3	2	6	10	11	8	17	20	16	34	40	31	262
	Lat.	‡		47	45	34			47	39																												
Average	Val.	*	366	322	344	319	288	286	293	317	332	317	317	320	305	310	319	338	348	341	329	322	320	294	316	316	316	321	336	350	329	328	312	314	314	326	325	
	No	†	10	26	59	44	32	1	5	24	24	25	33	37	48	40	39	58	64	66	62	45	37	47	39	49	32	27	111	148	140	224	286	237	314	509	384	
	Lat.	‡	52	52	50	42	31	47	47	39																												

* Monthly or annual ozone value.

† Number of stations included in monthly or annual value.

‡ Average latitude of all stations contributing to average value.

§ See explanation in text.

completeness is essentially random, at least with respect to the totality of stations, even if not with respect to the weather at a single station. Since consistent large variations of total ozone occur at every station with season of the year, and between all stations with latitude, it was felt that errors introduced by random incompleteness of the monthly observations would be much less than those that would be introduced by weighting individual station calendar monthly means by the number of daily observations represented.

Organization of the complete data for the study of the long-term fluctuation of ozone. In view of the impossibility of evaluating objectively the relative reliability of the ozone measurements at individual stations, it was decided to base this study on the entire body of ozone data. For this purpose every single recorded station value of monthly mean total ozone was included, even for stations that had only a few months' total record of observation. Obviously it is impossible under these circumstances to deal with station departures from normal, because many of the individual stations had records of very short duration and for many different time periods. All monthly mean station values were simply lumped together and averaged for each month from January 1925 through December 1959. The monthly average ozone values obtained in this manner obviously reflect variations of average latitude and longitude of the stations reporting for each month, and the annual average ozone values reflect also any monthly grouping of the reports. Nevertheless, in view of the lack of basis for any selective procedure, it appeared desirable to consider in this manner the entire body of data to make the sample as large as possible.

The total list of stations contributing data include 68 from the northern hemisphere, of which 26 are within ±15° of the Greenwich meridian, and 4 from the southern hemisphere, none of which report data taken before 1954.

Table 1 contains by months, and at the bottom by years, the average of the mean total ozone values, in milli-atmo-centimeters, of all of the 72 stations reporting, for each month, and for each year from 1925 to 1959. The number listed below each monthly or annual average ozone value is the total number of station monthly means included in that particular monthly or annual average value. Note that the annual average ozone value listed at the bottom of each annual column is the average of all monthly average values listed in the column, *not* weighted by the number of station values in each. For the first eight years, 1925–1932 inclusive, with each monthly average ozone value is listed also the average latitude of all of the stations contributing to that monthly average, and for each annual average value the average of the latitudes for all of the contributing calendar months, again *not* weighted by the number of station values included in each monthly average. The last column to the right in Table 1 contains three figures for each calendar month. The figure at the upper left is the simple average of all of the average monthly mean ozone values for that calendar month as listed in the corresponding line of the table. The upper figure at the right is the same average when the monthly average for each year *is* weighted by the number of stations contributing. The lower figure is the total number of station monthly means included in each monthly average in the entire period of years, i.e., the simple sum of the individual monthly station numbers in the line.

The results presented in Table 1 are discussed briefly in the next section.

TABLE 2. Departures of Average Total Ozone for Extreme Years from All Years

	1933	1937	1941	1946	1952	1955	Average All Years
Jan.	+26	−6	+30	−50	+48	−20	318
Feb.	+5	+3*	+50	−31	+18	−6	349
Mar.	+8	−9	+54	−7	+62	−16	362
Apr.	−14*	−33	+37	−19	+36	−29	370
May	+3	−37	+39	−49	+39	−11	357
June	+18	−33	+20	−24	+33	−5	338
July	+1	−33	+13	−23	+23	−2	318
Aug.	+10	−25	+19	−28	+17	−4	306
Sept.	+13	−12	+4	−29	+14	−8	293
Oct.	+11	−6	+14	−30	+11	−7	284
Nov.	+9	−19	+10	−33	−1*	−7	281
Dec.	+27	+3*	+12	−12	+29	−7	293
Year	+10	−17	+26	−28	+28	−10	322

* Months for which the sign of the departure is opposite to that for the year.

Presentation of Results

In Table 1, which contains the worldwide averages of total ozone for all available stations for each calendar month and year from January 1925 through December 1959, we may note particularly the following facts:

1. Throughout the 27-year period 1933–1959 inclusive, during which no annual average contained less than 24 station monthly means, a pronounced cyclical variation of over-all average total ozone is clearly evident, peak values being reached in 1933, 1941, and 1952, minimum values in 1937, 1946, and 1955.

2. The years of excessive or deficient average total ozone are surprisingly consistent throughout the 12 calendar months. This consistency is shown in Table 2, which lists the departure of the average of the total ozone for each of the 72 calendar months during the above six maximum and minimum years from the 1925–1959 calendar monthly averages. Of these 72 calendar months only four show departures of the opposite sign to that prevailing for the year, and of these four deviations, three occurred during the first five years of the 27-year period when the data presumably were more heterogeneous.

3. The three years of maximum total ozone occur from zero to three years before the minimum sunspot years of 1933, 1944, and 1954, and the three years of minimum total ozone occur from zero to two years before the sunspot maximum years of 1937, 1947, and 1957.

TABLE 3. Lag Correlations of Worldwide Average Total Ozone and Sunspots
(Based on annual ozone values, 1933–1959.)

Lag, yrs.	r	Probable Error	Lag, yrs.	r	Probable Error
−16	+0.26	±0.12	−3	+0.66	±0.07
−15	+0.63	±0 07	−2	+0.34	±0.12
−14	+0 76	±0.06	−1	−0.02	±0.13
−13	+0.60	±0 08	0	−0.40	±0.11
−12	+0.27	±0.12	+1	−0.68	±0.07
−11	−0.10	±0.13	+2	−0.67	±0.07
−10	−0 45	±0.11	+3	−0.43	±0.11
−9	−0.68	±0.07	+4	+0.11	±0.14
−8	−0.65	±0.07	+5	+0.58	±0.09
−7	−0.33	±0.12	+6	+0.80	±0.05
−6	+0.10	±0.13	+7	+0.70	±0.07
−5	+0.56	±0.09	+8	+0.35	±0.13
−4	+0.74	±0.06			

4. In the eight years previous to 1933 this relation between total ozone and sunspots breaks badly. The three very low years of 1929–1931 come shortly before the sunspot minimum of 1933, and the high values of 1925–1927 lead up to the sunspot maximum of 1927.

However, these early years are extremely heterogeneous as to the number and to both the geographical and seasonal distribution of the reporting stations. The confirmation of the geographical heterogeneity of the reporting stations was the purpose of the computation and the listing of the average latitude of the stations contributing to each monthly and annual average ozone value in the first eight columns of Table 1, for the years 1925–1932. Note in particular the following:

1. The low annual value for 1931 is made up of five monthly values for a single station (Arosa) for those five months of the year (August-December) when normal ozone is at a pronounced seasonal minimum.

2. The low annual value for 1930 represents a single station monthly mean (Arosa) for the month of August for which the ozone value normally lies much closer to the autumn minimum than to the spring maximum.

3. The low value for 1929 contains 32 station monthly means, but it happens that the average latitude of the contributing stations for this single year falls far into the lower latitudes (31°) where ozone values, particularly during the peak spring season, are normally far below those in higher latitudes.

4. The high values during 1925–1927 are contributed by stations (predominantly in the British Isles, average latitude 52°N) in a region where particularly the late winter and spring peak values run extremely high. The especially inconveniently high value of 366 in 1925 was contributed by ten monthly values from a single station (Oxford, England) from which the relatively ozone-poor months of December-January (average 19 points below the annual mean) were missing, whereas the ozone-rich months February-May (average 40 points above the annual mean) were all included.

For these reasons it is quite evident that the total ozone values of Table 1 for the period 1925–1932 must be considered completely nonrepresentative of worldwide total ozone. Conse-

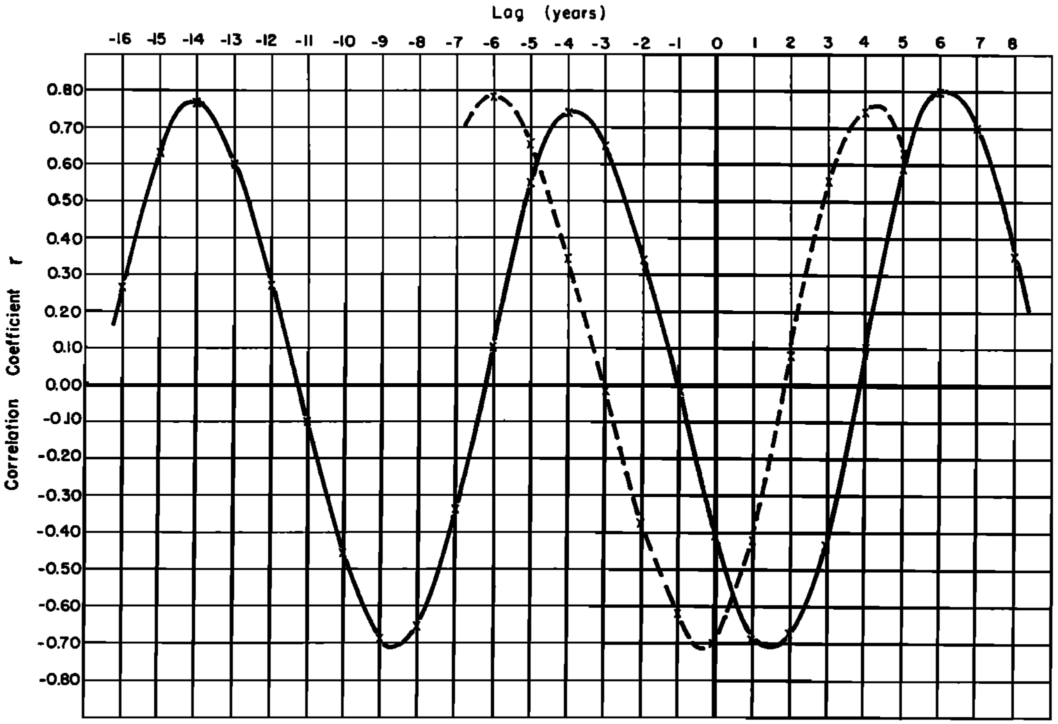

Fig. 1. Correlation of average total ozone with number of sunspots (solid curve). Mean absolute latitude of area of sunspots (dashed curve).

quently it was decided to restrict the correlation of worldwide average total ozone values with annual sunspot numbers to the period 1933–1959 inclusive. Linear correlation coefficients were computed between the Zurich annual relative sunspot number and the average total ozone values as listed in Table 1 for the years 1933–1959. No smoothing either of sunspot or of ozone values was performed. The only manipulation of the data was to extrapolate the sunspot numbers through 1961 and 1962, with values of 60 and 40, respectively. These assumed values are extremely unlikely to be in error by more than ±20, and the correlation coefficients would be most insensitive ($< \pm 0.02$) to deviations of that amount. This addition of two annual sunspot numbers to the series was made to maintain the number of pairs (n) at positive lag at as high a level as possible. The number n remains at 27 for all lags computed from -16 through $+3$, falling to 22 at lag $+8$. Positive lag is chosen in these correlations to mean that sunspots are lagged after ozone values, i.e., taken the indicated lag number of years after ozone, or before if the lag is negative.

Table 3 contains the correlation coefficients, together with the corresponding probable errors, for lags from -16 to $+8$. The magnitude and significance of these correlations is really surprising. It must be recognized that the high degree of serial correlation which exists in both the sunspot data and the ozone data drastically reduces the statistical significance of the probable errors computed for n ranging from 22 to 27. The autocorrelation at one year's lag for the 27-year series is $+0.80$ for sunspots but only $+0.54$ for ozone. It cannot be stated just how much this serial correlation effectively reduces the degrees of freedom of the data, but probably it is by somewhat more than 50 per cent. Even so, the correlation remains highly significant.

The variation of the ozone-sunspot correlation with lag is represented by the solid line graph (Fig. 1). The evidence of this graph is even more striking than is that of Table 3. Note not only the exact replica of the 10-year period of

TABLE 4. Contribution by Stations to Annual Average Total Ozone Values, 1925–1959

Station	Lat.	Long.	1925	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
Aarhus	56N	11E																7	7	9	11								4	12	11	10	12	12	12	11	12
Abastumani	42N	43E																																	6	12	
Abisko	68N	19E		1	6							1	3																								
Ahmedabad	23N	73E																															4				
Albuquerque	35N	107W																														7					
Aldergrove	54N	6W																												12	12	12	12	10	4		
Alert	82N	62W																																	6	11	
Alma–Ata	43N	77E																																	2	12	
Arosa	46N	9E		6	12	12	6	2	5	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	12	12	12	12	12
Aspendale	38S	145E																															6	12	12	12	12
Bismarck	46N	100W																														12	12	11	6	12	12
Bombay	19N	73E												3	12	9																					
Brisbane	27S	153E																																3	11	12	12
Cagliari	39N	9E																														3	11	8	12	12	
Cambourne	50N	5W																										2	12	12	12	12	12	8	12	12	9
Caribou	46N	68W																																		9	12
College	64N	147W																												9	11	11					
Dikson	73N	80E																																	2	6	
Dombas	62N	9E																9	10	7	12	10	12	6													
Downham Market	52N	0E																										2	11								
Edmonton	53N	113W																										5	12	12					6	11	12
Elbrus	43N	42E																																	2	12	
Elmas	39N	9E																																	6	12	12
Eskdalemiur	55N	3W																																	7	12	11
Flagstaff	35N	111W																														4	12	12			
Fort Worth	32N	97W																														12	11				7
Green Bay	44N	88W																																		10	12
Gulmarg	34N	72E																															7	6			
Helwan	30N	31E				4	9																														
Hemsby	52N	1E																											2	10	12	12	9				
Kabul	34N	69E																											12								
Kagoshima	31N	130E																																		10	9
Kodaikanal	10N	77E				4	8																													12	12
Lerwick	60N	1W		3	8																								4	10	12	11	12	12	12	12	12

TABLE 4. *Cont.*

Station	Lat.	Long.	1925	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
Lindenberg	52N	14E		4	7																																
Macquarie Island	54S	159E																																	5	12	
Magny Les Hameaux	48N	2E																															12	12	12		
Marcus Island	24N	154E																																		12	12
Marseille	43N	5E			12	12																															
Mauna Loa	19N	155W																																	2	12	10
Messina	38N	15E																														6	12	12	12	12	12
Moosonee	51N	80W																																	6	12	12
Mount Abu	24N	72E																															12	11	11	12	10
Naples	40N	14E																																		6	12
New Delhi	28N	77E																					2	12	3								12	12	12	12	12
New York	40N	73W																	12	11	10	12															
Oslo	60N	10E																						6	12	12	4										
Oxford	51N	1W	10	9	8	7																						2	12	12	12	12	12	12	12	12	12
Paris–Montsouris	49N	2E																																	3	8	
Pasadena	34N	118W															4	6																			
Potsdam	52N	13E																		4	5																
Resolute	74N	95W																																	6	12	12
Reykjavik	64N	22W																												9	9	9	5		6	12	10
Rome	42N	12E																														9	12	12	12	12	12
Santa Maria	37N	25W																											2		12	12	12	7		1	
Sapporo	43N	141E																																		12	12
Shanghai	31N	121E								12	12	12	12	12	12	11	12	12	12	12																	
Silver Hill	38N	77W																																			6
Spitzbergen	78N	15E					2																					2	10	12	10	11	7	6	4	4	
Srinagar	34N	74E																																6	12	12	12
Table Mountain	34N	117W				5	8																														
Tateno	36N	140E																															6	11	11	12	12
Torishima	30N	140E																																	2	12	12
Tromso	69N	19E											6	10	12	8	10	12	12	12	12	12	12	11	12	11	4		10	12	7	9	9	5	6	12	9
Uccle	50N	4E																											4	8		10	10		8	9	
Uppsala	60N	17E																											4	10	12	11	12	12	12	12	
Valentia	52N	10W		2	8																																
Vigna di Valle	42N	12E																																	6	12	12
Vladivostok	43N	132E																																	4	9	
Voeikovo	60N	30E																																	5	10	
Washington	39N	77W																								11	12	3				12	12	9	6	12	3
Wellington	41S	175E																														12	11	6	11	12	12

the sunspot cycle (almost exactly 10 years from 1917 to 1957), but even more the symmetry of the correlation curve with respect to maximum and minimum points, in spite of the well-known asymmetry of the sunspot cycle (descending branch averages 50 per cent longer than the ascending branch). If we discount the significance of Figure 1 on the basis that less than three complete cycles of the 10-year period common to both the sunspot and the ozone data are included in the correlation sample, then we should offer some likely explanation other than sunspots for the predominant 10-year period in the ozone data. There is no obvious explanation other than the random combination in the annual total ozone averages of station monthly means that may be widely variable as to latitude and season. For those who may wish to check in any manner the actuality of such variability as it is reflected by any of the annual average ozone values of Table 1, the monthly contributions to each annual average are listed in that table. Table 4 is introduced to facilitate the computation of the latitudinal variability of the annual average ozone totals. This table lists the number of monthly mean values contributed by each station to each annual average ozone value.

TABLE 5. Values of Total Ozone and of the Average Latitude of Solar Spottedness

Year	Average Total Ozone	Average Latitude Sunspot Areas
1927		14.9
1928		13.3
1929		10.5
1930		9.8
1931		9.0
1932		9.1
1933	332	8.2
1934	317	17.4
1935	317	23.4
1936	320	20.9
1937	305	16.8
1938	310	15.2
1939	319	13.2
1940	338	11.4
1941	348	10.2
1942	341	8.8
1943	329	10.2
1944	322	15.7
1945	320	20.4
1946	294	20.7
1947	316	16.7
1948	316	14.6
1949	316	13.2
1950	321	13.3
1951	336	11.1
1952	350	8.2
1953	329	9.5
1954	328	20.0
1955	312	25.7
1956	314	21.0*
1957	314	18.5*
1958	326	16.5*
1959	325	14.5*
1960		12.0*
1961		10.0*

* Extrapolated values.

It appears that total atmospheric ozone may be used with statistical plausibility to forecast sunspots 8 years in advance. The physical plausibility of such prognosis is much more difficult to justify. However, it is not entirely inconceivable that possible solar radiations affecting the ozone balance might be related to the cycle of solar activity in such a manner as to have almost any phase displacement relative to the sunspot number. Be that as it may, the comparative shape of the ozone curve at cyclical minima indicates a sunspot minimum extending from 1963–1965, a flat minimum with annual values probably remaining above 10. It is most probable, however, that as we approach a point of change from a short active (10-year) solar cycle to a long inactive (12-year) solar cycle, as may well be the case at the present moment, the pattern of the ozone-sunspot relationship must undergo a readjustment that will temporarily affect its prognostic applicability.

TENTATIVE COMMENTS ON THE RESULTS

It will require much more quantitative information than is now available about the higher atmosphere and the variable solar emissions incident thereon even to hypothesize a physical explanation of any fluctuation of total ozone with the cycle of solar activity. There are, however, several comments, primarily meteorological in their implications, which may be offered with reference to the ozone-sunspot relationship indicated above:

1. The explanation of any real correlation, such as that indicated between total ozone and sunspots, might lie primarily either in a direct insolational effect on the ozone balance in the ozonosphere, or the explanation might lie indirectly in a large-scale insolational effect on the over-all planetary circulation, particularly

TABLE 6. Lag Correlations of Worldwide Average Total Ozone and Mean Latitude of Total Sunspot Area

(Based on ozone values 1933–1959.)

Lag, yrs.	r	Probable Error	Lag, yrs.	r	Probable Error
−6	+78	±0.05	0	−69	±0.07
−5	+66	±0.07	+1	−42	±0.11
−4	+35	±0.12	+2	+08	±0.13
−3	−02	±0.13	+3	+56	±0.09
−2	−37	±0.12	+4	+74	±0.06
−1	−62	±0.08	+5	+63	±0.08

one that consistently alters circulatory or turbulent exchange between the ozonosphere and the lower stratosphere. However, in view of the marked consistency of the relationship on a worldwide basis and of the failure heretofore to find any correspondingly significant and consistent correlation between sunspots and atmospheric circulation, it appears highly probable that the primary explanation must be looked for in a direct insolation effect, presumably in the spectral distribution of insolational energy in the ultraviolet.

One further fact supports the argument that it is primarily the variable net insolational creation of ozone rather than the vertical transport of ozone by atmospheric circulation or turbulence that causes the fluctuation of total ozone with the sunspot cycle. *Chistyakov and Teifel* [1956] find some evidence from studies of noctilucent clouds that the effective height of the ozone layer (ozone shadow) in the atmosphere varies inversely with the sunspot number. This negative correlation between the effective height of the ozone layer and sunspot number requires an effective net increase of ozone production in the upper ozone levels at time of fewer sunspots. This would imply in the upper ozone levels a relative increase of solar ultraviolet in the shorter wavelengths ($<$ 2000 A) at sunspot minimum, and a relative increase in the longer wavelengths ($>$ 2400 A) at sunspot maximum. More measurements of the vertical distribution of ozone should finally resolve the question of the relative importance of direct insolational versus indirect circulatory factors in any ozone-sunspot relationship.

2. Walker's southern oscillation, statistically the most significant phenomenon of the general circulation, shows significant positive correlation with sunspots at about 2½ years' lag [*Willett*, 1950], as against a negative correlation of ozone with sunspots at about 1½ years' lag. The southern oscillation seems to reflect, at least in part, a change of continentality, or seasonal 'breathing' of the Asiatic continent. If changes of total atmospheric ozone of the amount observed can alter appreciably the 'Greenhouse effect' of the atmosphere, then a change of continentality might reasonably be associated with any sunspot-ozone cycle.

THE RELATIONSHIP OF TOTAL ATMOSPHERIC OZONE TO THE MEAN LATITUDE OF SOLAR SPOTTEDNESS

After the first submission of the preceding manuscript, Professor Starr at the Massachusetts Institute of Technology suggested that possibly the equatorward progression of solar spottedness in the course of the 11-year cycle is connected with the apparent phase relationship of total atmospheric ozone to sunspot number. It was decided to check this possibility statistically. Monthly and annual values of the average latitudinal distance from the solar equator of the total area of spottedness on the sun are available for the years 1873–1955 inclusive in the Greenwich Observatory publications, 'Sunspot and Geomagnetic Storm Data.'

Since this mean solar latitude of total spottedness runs in a cycle that is even more regular than that of the sunspot number, the annual values in this series were extrapolated for the years 1956–1961 inclusive, to facilitate the lag correlation of the 1933–1959 annual mean total ozone values with the average latitude of solar spottedness. Any likely errors in this extrapolated curve will have an extremely small effect on the correlation coefficients.

Table 5 contains the values of total ozone and of the average latitude of solar spottedness that were correlated.

The correlation coefficients that are obtained when sunspot latitude is lagged from −6 to +5 years relative to total ozone are contained in Table 6. Thus we note that the negative correlation of approximately −0.70 between the mean latitude of solar spottedness and total ozone is almost exactly equal in magnitude to that between total ozone and sunspot number. However, the phase lag shifts from approximately −18 months with sunspot number to approximately +4 months with the mean latitude of total sunspot area. This phase shift is immediately obvious from Figure 1, in which the dashed curve represents the time-lag graph of the ozone–sunspot latitude correlations, corresponding exactly to the solid line time-lag graph of the ozone–sunspot number correlations.

With respect to this phase shift it is interesting to note that for the 1933–1959 period the annual sunspot number correlates +0.19 contemporarily with the mean latitude of total sunspot area, +0.71 with mean latitude 1 year previously, and +0.92 with mean latitude 2 years previously. Total sunspot area correlates contemporarily +0.98 with sunspot number.

This phase relationship indicates clearly that, insofar as the variability of atmospheric ozone may be causally related to sunspot activity, it is the mean latitude of the solar spottedness rather than the number or total area of the spots that is significant. The same conclusion may be drawn with respect to the southern oscillation and other meteorological activity that tends to precede the sunspot cycle by approximately 2 years.

Since the range of position of the earth on the ecliptic lies between ±7° of the solar equator, the apparent effectiveness of sunspots in depressing total atmospheric ozone seems to be very sensitive to the degree to which the spottedness directly faces the earth. This result supports the very tentative hypothesis that some ozone-depressive radiation, presumably ultraviolet in the 2400- to 2900-A range, is largely beamed directly upward from its source in disturbed areas connected with sunspots on the sun's surface.

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REFERENCES

Chistyakov, V. F., and V. G. Teifel, Some questions on the nature of noctilucent clouds, *Vsesoyuz. Astron. Geodez. Obshchestvo Byull.*, no. 19(26), 17–30, 1956.

Kraus, E. B., Physical aspects of deduced and actual changes of climate, paper presented at the New York Academy of Sciences Symposium on Solar Variations and Climatic Change, January 1961, to be published in the Proceedings of the Symposium.

Willett, H. C., *Final Report of the Weather Bureau—M.I.T. Extended Forecasting Project for the Fiscal Year July 1, 1949—June 30, 1950,* pp. 32–37, dated September 1, 1950, unpublished.

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