NOAA Technical Memorandum ERL ARL-89

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ABSTRACT

The origin of the electrical conductivity of the atmosphere and the inverse correlation between the conductivity and the atmospheric burden of suspended particulates is discussed. A 13-year decline in the conductivity monitored in rural Boulder County, Colorado, is presented as evidence of a secular increase in particulate pollution since 1967 and a degradation of the regional air quality.

1. INTRODUCTION

The past few decades have seen a large population increase along the front range of the Colorado Rocky Mountains. The requirements of an expanding population, particularly energy and transportation needs which require the burning of fossil fuels, have led to an increase in atmospheric pollution of all kinds. Much of this pollution is smoke and dust particles of such a size that they fall out or are washed out of the atmosphere by rain within a day or so. Part of the pollution, on the other hand, is composed of particles so fine that gravity does not transport them to the ground with sufficient speed to clear the air. These particles, with diameters generally less than 1 μm are usually called "Aitken" or "condensation" nuclei. They largely comprise the fine particle pollution of the air and are the particles of principal interest in this report. These particles are particularly prevalent near cities and near the Earth's surface, and as a rule of thumb, one anticipates finding about 500,000 of them per cubic centimeter in a large city; about 10,000/cm^3 in the country; and less than 1000/cm^3 over the oceans. Another important class of suspended particles are known as "light," or "small," ions and they are produced in the air by cosmic rays and other radioactive sources.

A close correlation exists between the level of suspended particulates and the electrical state of the environment. Understanding this correlation logically follows an explanation of how the ionization and conductivity of the atmosphere is produced and maintained in the first place.

2. THE CONDUCTIVITY OF THE AIR

The air about us is one of the best insulating substances known. It is, however, slightly conducting; a fact easily demonstrated by observing that an electrically charged and highly insulated conductor, such as a metal ball suspended by a non-conducting thread, will systematically lose its charge to the surrounding air. Such conductivity as does exist near the Earth's surface, is due to the presence of the small ions mentioned above. These ions are initially created in oppositely charged pairs with each positive and negative ion carrying one elementary unit of charge. The ion pairs are formed when some external force removes an electron from a molecule of one of the atmospheric gasses. The ejected electron and the positively charged residue of the molecule both become attached to neutral air molecules, thus creating a positive and negative ion pair. The external force, mentioned above as capable of knocking an electron from a gas molecule, is generally a highly energetic cosmic ray particle or an x-ray particle emanating from some radioactive soil substance. The sea level concentration of small ions can range from 100 to 1500 ions per cm^3 and are produced near the Earth's surface at a rate which varies from 2 ion pairs cm^{-3} sec^{-1}, where ions are produced only by cosmic rays, to as much as 40 ion pairs cm^{-3} sec^{-1}, where there is considerable radioactive soil exhalation (Chalmers, 1967).

The conductivity of the atmosphere, made so by the continuous production of small ions, is largely controlled by the suspended Aitken particles, discussed earlier, which occupy the same environment. The major role of

suspended particulates, with respect to the electrical state of the atmosphere, is that of providing relatively stationary surfaces which the smaller and much more mobile small ions easily strike and become attached to. Particulates which acquire a net charge due to one or more collisions with small ions are called "large ions." Large ions are thus nothing more than charged nuclei and because of their relatively low mobility, they do not contribute to the conductivity of the air. In fact, they reduce the conductivity by capturing small ions which make the air conducting in the first place. The atmosphere thus contains a mixture of large and small ions and uncharged nuclei which interact to maintain a slightly conducting environment with the conductivity largely controlled by the nature of the ambient aerosol.

Although small ions are continuously being produced, a balanced small ion concentration is maintained at any particular location in the atmosphere since the ions are being removed at the same rate that they are being formed. The small ions are removed by recombination with oppositely charged small ions, thus neutralizing the charge, and by attachment to large ions and uncharged nuclei.

The following well known equation describes the change of small ion density with time, in terms of the production and disappearance of small ions in the atmosphere. Thus, considering the positive small ions,

$$\frac{dn_1}{dt} = q - \alpha\, n_1 n_2 - \eta_{12}\, n_1 N_2 - \eta_{10}\, n_1 N_0, \qquad (1)$$

where n is the small ion density, N is the large ion density, and the subscripts $_1$, $_2$, and $_0$ refer to ions or nuclei which are charged positively, negatively, or uncharged, respectively. The small ion pair production rate is q; α, η_{12} and η_{10} are the respective coefficients of recombination between oppositely charged small ions; between positive small ions and negative large ions; and between positive small ions, and uncharged nuclei. An equivalent expression exists for negative small ions.

The important thing to note in equation (1) is that the last three terms are small ion removal processes and that the relative significance of these "recombination" terms depends largely on the nuclei content of the air. In exceptionally clean air, such as that found at the NOAA baseline stations at Mauna Loa, Hawaii or at the South Pole, there are relatively few nuclei, thus the production of small ions is largely offset by recombination between oppositely charged small ions and the last two terms of equation (1) become insignificant. In air having a large number of nuclei such as might be found in a large city, on the other hand, the last two terms of equation (1) become predominate and small ion losses due to recombination with charged and uncharged nuclei will increase greatly. The extent to which suspended particulates reduce the conductivity depends on both the size and number of the particles since a few large nuclei will present as much surface area for impaction by small ions as a greater number of smaller sized nuclei.

The conductivity is traditionally the electrical parameter most often used in air pollution studies and although equation (1) does not pertain to the conductivity, a straightforward relationship between the conductivity and

small ion density may be expressed as follows:

$$\lambda_1 = n_1 e k_1 \quad , \tag{2}$$

where λ_1 is the positive conductivity; n_1 is the positive small ion density; k_1 is positive small ion mobility; and e, the elementary electronic charge per ion. An expression equivalent to equation (2) exists for the negative conductivity.

It should be pointed out that the relationship between conductivity and ion density in equation (2) is not unique since the mobility, k, is only relatively constant. This mobility, k, represents the average mobility of a small-ion size spectrum and as particulate pollution increases, the more mobile small ions will become attached to suspended particulates at a faster rate than those small ions with somewhat less mobility. This selective process of small ion removal according to mobility, results in a mobility factor in equation (2) which decreases as the particulate level increases and vice versa. Since the conductivity (Eq. 2), varies as the product of the ion density and mobility, both of which generally increase or decrease simultaneously, it becomes the most sensitive electrical parameter to use in air pollution detection.

The conductivity of the atmosphere has long been used in air pollution studies, particularly by scientists of the Carnegie Institute of Washington (Wait, 1927, 1933, 1946; Johnson and Wait, 1931). In more recent years this investigator and others have used long term conductivity measurements to establish atmospheric benchmark observations where the monitored conductivity can be used to detect secular changes in the global level of suspended particulates (Cobb and Phillips, 1962; Cobb and Wells, 1970).

It is generally not possible to determine the absolute particulate concentration from the conductivity alone. Attempts to do so (Cobb, 1974; Manes, 1977) show the general inverse relationship between conductivity and particulates, but with considerable scatter The scatter is quite obviously due to the fact that the recombination coefficients, α and η, in equation (1) are not constant and can vary with the size spectrum of the suspended particulates (Mohnen, 1977). The ion production rate, q, may also not be constant. While the ion production from extraterrestrial cosmic rays is relatively constant for a given location, ions produced from radioactive soil exhalation can vary considerably for soil that is dry, moist, frozen, or snow covered. The variability of these so-called "constants," is a fact to be recognized, however, it does not mask the overall inverse relationship between conductivity and suspended particulates. The monitoring of the conductivity during periods of variable atmospheric clarity, leaves no doubt in the observer's mind that the conductivity is a very sensitive indicator of the level of suspended particulates. On a day, for example, when meteorological conditions are favorable for the formation of this region's infamous "brown cloud," the conductivity will decrease by as much as 80 percent. A frontal passage, on the other hand, followed by a fresh new air mass and downslope winds from the Rocky Mountains, invariably results in increasing conductivity, often by several orders of magnitude.

The interesting correlation between atmospheric electricity and aerosol pollution is well documented in the scientific literature and the seriously

interested reader may wish to look into the research cited below in addition to that already referenced: Morita et al., 1973; Mani and Huddar, 1972; Ruhnke, 1966; Misaki et al., 1972; Sagalyn and Faucher, 1956; Cobb, 1972; and Wait and Parkinson, 1953.

3. COLORADO MEASUREMENTS

Since 1967, conductivity measurements have been made in a rural farming area known as Gunbarrel Hill, located 10 km northeast of the city of Boulder, Colorado. The site is typical of the environment occupied by much of the population along the front range and eastern slope of the Rocky Mountains. The western two-thirds of Boulder County is a lightly populated region of high mountains and foothills and most of the 200,000 population, more than doubled since 1967, reside in the eastern third of the county. The Gunbarrel Hill Field Site, a semi-arid wheat farming area, is typical of many areas in the region where agricultural land is gradually being converted to housing subdivisions, shopping centers and the accompanying sources of anthropogenic airborne particulates. Perhaps the factor with the greatest impact has been an increase in the number of motor vehicles registered in Boulder County which, during the measurement period, has increased by about 10,000 vehicles annually.

4. INSTRUMENTATION AND OBSERVATIONAL PROCEDURES

The bi-polar conductivity measurement system installed at Gunbarrel Hill is based on the method devised by Gerdien (1905) and substantiated by Swann (1914). While the primitive electrometers used to detect the low level ionic currents have steadily improved through the years, the basic sensor remains essentially unchanged and makes the comparison of data through the years more reliable than would otherwise be the case. The sensors are described in an earlier report by Cobb and Phillips (1962) and for a complete description of the Gerdien method, the serious investigator is referred to a report by Tammet (1970). In brief, the Gerdien method consists of a cylindrical condenser with an inner charged and highly insulated electrode. As air is drawn through the condenser, the electrode will attract oppositely charged ions and the collected ionic current can be continuously measured and recorded. The conductivity is easily derived from the electrometer measured current and two instruments are necessary to separately measure and record both the positive and negative conductivities.

The conductivity data on which this report is based, was obtained on "fair-weather" days. Precipitation, thunderstorms, fog, blowing snow, and dust from local farming operations, produce large fluctuations in the conductivity which are not considered typical of the region as a whole and these periods are not included in the data analysis. Although both the positive and negative conductivities were recorded, only the positive conductivity has been used in this report. Many years of records have shown that the negative conductivity very closely follows the positive but with an absolute value 10 to 20 percent smaller. This reduced negative conductivity is due to the fact that negative ions have an inherently higher mobility and thus more rapidly become attached to aerosol particulates. The negative

conductivity may be important for some applications, however, for this analysis only the positive conductivity has been considered and further references in this report are to the positive conductivity only.

5. RESULTS AND DISCUSSION

The results of this report are largely summarized in the first figure showing a decline in the electrical conductivity of the rural Boulder County environment; a decline attributed to a gradual increase in the level of suspended particulates since 1967. The annual conductivity value for each year is the average of all the hourly positive conductivity values during each year for all days having 24 hours of "fair-weather."

It is important to note that conductivity changes from year-to-year, as shown in Fig. 1, may not always be due to changes in particulates. An abnormally cold winter, for example, with extended periods of snow cover and frozen top soil, will suppress the conductivity, as explained earlier, by inhibiting the ionization from radioactive soil substances. A year with excessive rainfall, on the other hand, may result in high conductivity since rainfall is nature's most efficient way of removing aerosol particles and maintaining a cleaner atmosphere. Weather patterns may occasionally produce an annual conductivity value that does not follow a secular trend. Over 13 years such factors tend to equalize, however, and it is not possible, for example, that the downward trend in conductivity can be attributed to a gradually increasing annual snowfall. The secular decline in the conductivity since 1967 can only be attributed to an increased particulate loading; an increase due to either, or both, an increase in the size, or in the concentration of airborne particulates. The "+" marks in Fig. 1 are conductivity values made at Mauna Loa Observatory at seven year intervals since 1961 (Cobb, 1978). It is interesting to note that the conductivity at the mountain observatory has remained essentially unchanged since 1961 while the conductivity in Boulder County, Colorado has decreased, at least since these measurements were started in 1967.

It is highly unlikely that natural causes are responsible for any significant change in the suspended particulate burden since 1967. Thus, the deterioration in Boulder County's air quality, as documented in Fig. 1, can be attributed to a variety of anthropogenic pollution sources, most notably the automobile (Draftz and Durham, 1974), which result from a large population increase.

It should be noted that the Boulder County environment is still remarkably clean by any comparative standards. In spite of the increase in particulates indicated in Fig. 1., Pike's Peak, 140 km distant, is visible on most days from the Gunbarrel Hill field site.

The decreasing conductivity trend is apparent in both winter and summer as shown in Fig. 2, however, the wintertime decrease is considerably more pronounced. Wintertime periods of exceptionally low conductivity have gradually become more frequent and longer lasting at the field site. These periods of very low conductivity are usually indicative of air pollution "episodes" which often accompany cold stagnant air masses, strong temperature inversions, and reports of less than acceptable air quality from Front Range cities. Figures 1 and 2 both indicate that the natural processes of aerosol

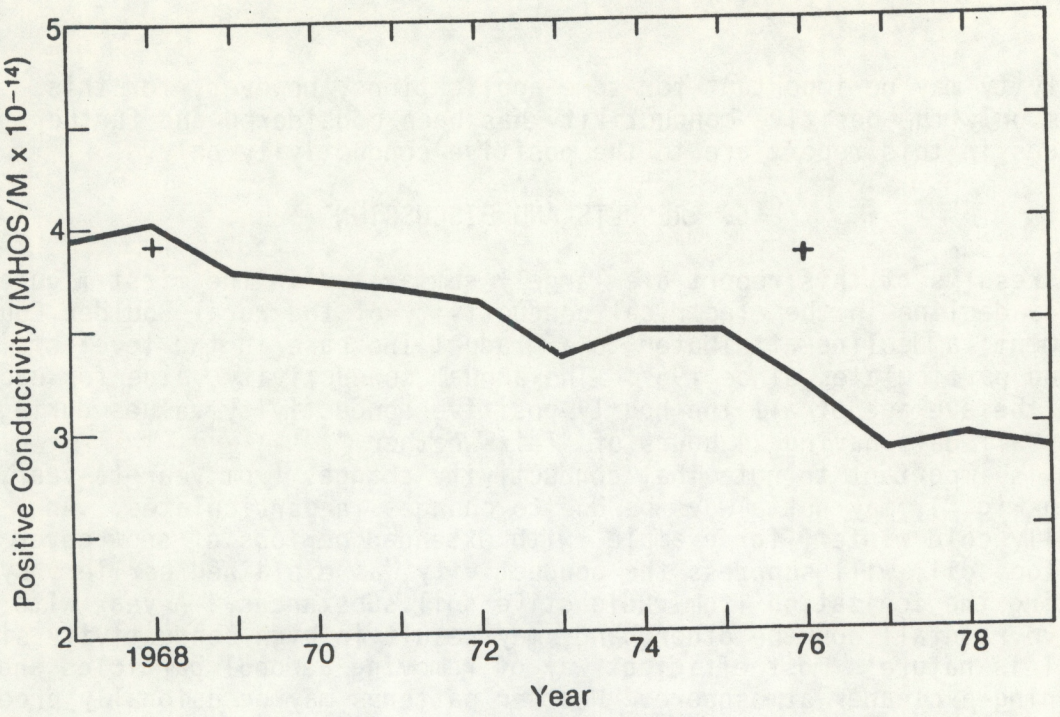

Figure 1. *A secular decline in the electrical conductivity of the rural Boulder County, Colorado environment is attributed to an increase in the level of suspended particulates. The "+" marks are conductivity values from Mauna Loa Observatory, Hawaii, a global background station where the conductivity has not changed significantly since 1961.*

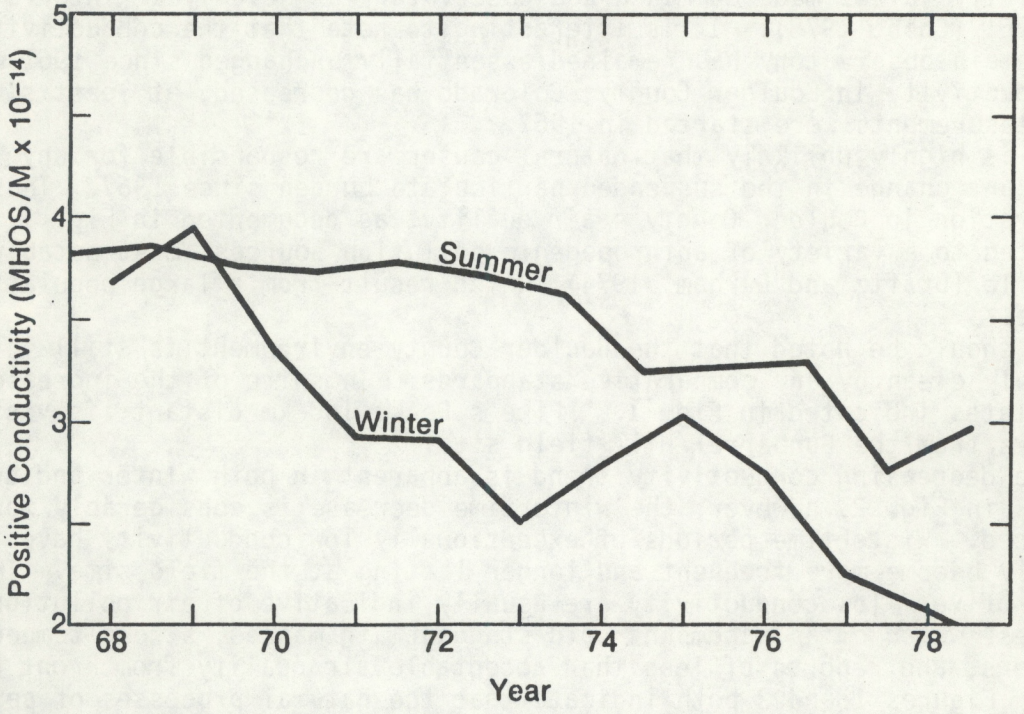

Figure 2. *The secular decline in conductivity since 1967 shows a larger decrease occurring in the winter months resulting from the increased particulate loading in the winter.*

removal have not kept pace with the increased production of airborne particulates in the region, particularly in the winter months.

Fig. 3 shows the mean annual variation in conductivity for the 1967-1979 period. The curve indicates "clean air" peaks in the spring and fall and the greatest particulate pollution occurring in December and January. It should be noted that the winter decrease in conductivity is not entirely due to an increase in particulates since that portion of the conductivity due to ionizing radiation from the soil will be reduced when the surface is frozen or snow covered. The fall and spring peaks in conductivity and corresponding air cleanliness occur during periods of relatively frequent fresh air mass intrusions and when solar insolation inhibits the strong temperature inversions associated with mid-winter pollution episodes. Periods of exceptionally high conductivity and extreme atmospheric clarity have been observed in all seasons but more frequently in the spring and fall and almost always with westerly downslope winds.

The mean diurnal variation in conductivity over a one year period, March 1978-March 1979, is shown in Fig. 4, where the daily values are obtained from the average of 24 hourly, fair-weather values. As would be expected, the conductivity curve indicates the cleanest air at the field site occurring before sunrise and the most particle laden air occurring in the afternoon. The rapid morning decline in the conductivity is attributed to an increase in particulates following the daily onset of human activities and also to the increasing efficiency with which gaseous pollutants are converted to particles by sunlight. Fig. 4 indicates that, on the average, the eight hours from 0500 to 1300 is a period of increasing particulate concentration while the subsequent 16 hours is the "clean up" time required to restore the local environment to its pre-dawn cleanliness.

The mean daily conductivities are compared for the months of July and December, 1978, in Fig. 5. The figure illustrates a relatively stable air quality, with respect to particulates for July, and quite the opposite for December. As a frame of reference, a mean 24-hour conductivity value of 1 x 10^{-14} mhos m^{-1} is indicative of a relatively high level of particulate loading for the Gunbarrel Hill environment; most likely a day with a stagnant air mass over the region, a light easterly wind component at the surface, and a persistent temperature inversion a few hundred meters aloft. Conversely, a mean daily conductivity of 3 x 10^{-14} mhos m^{-1}, at the field site is typical of a very clear day, with a deep blue sky, a relatively low particulate level and visibility in excess of 140 km.

The December 1978 conductivity record (Fig. 5) is typical of winter months in recent years and is notable for the number and duration of pollution episodes, marked with arrows, and the frequent purging of atmospheric particulates by downslope winds (W), or frontal passages (FP).

6. SUMMARY

The origin of the electrical conductivity of the atmosphere and the correlation between the conductivity and the level of suspended particulates is discussed. A 13-year record of decreasing conductivity in rural Boulder County, Colorado is presented as evidence of an increase in suspended particulates and a gradual deterioration in the regional air quality. It is

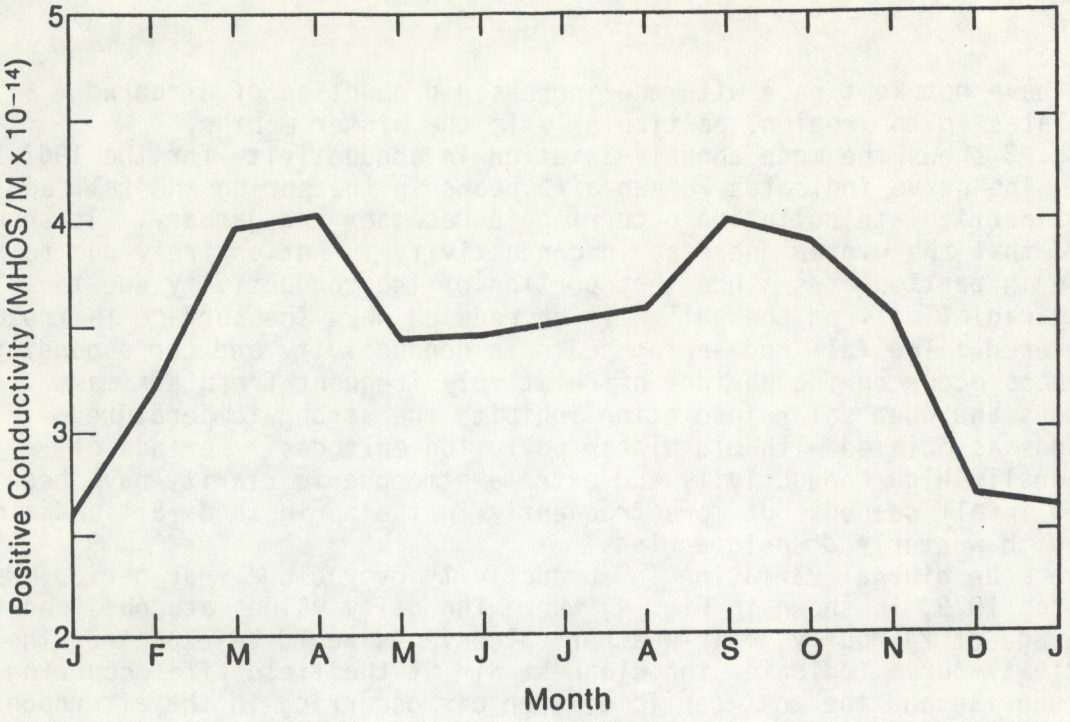

Figure 3. *Mean annual variation in conductivity for the period 1967-1979. The curve indicates "clean air" peaks in the spring and fall and the greatest particulate pollution occurring in December and January.*

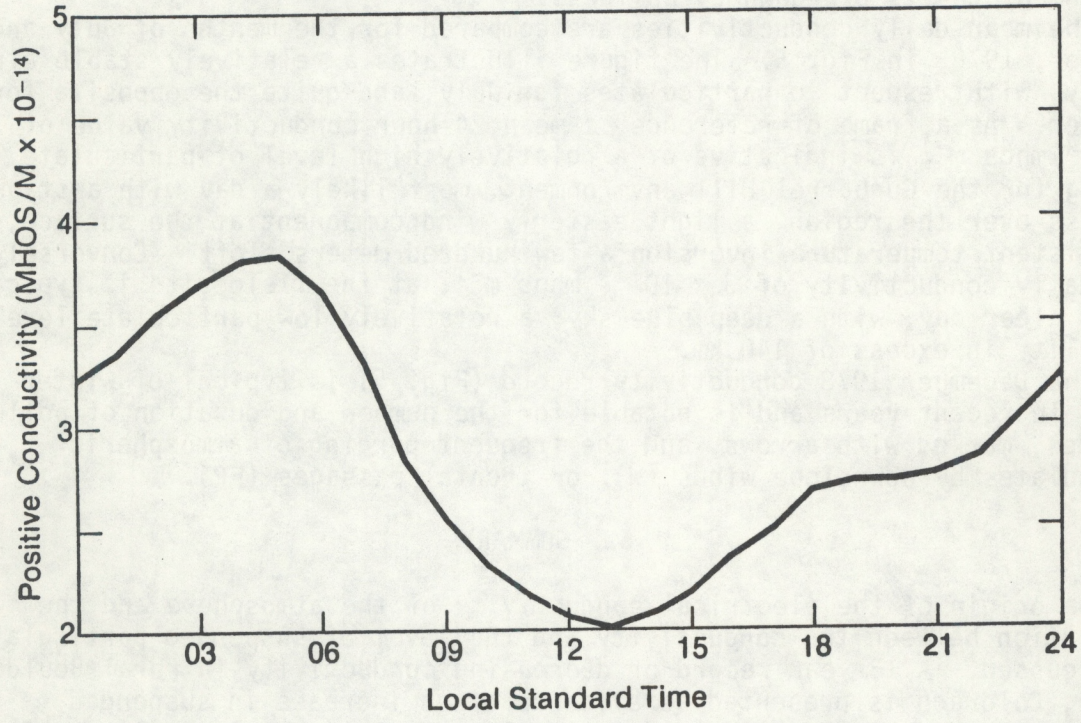

Figure 4. *Diurnal variation in the conductivity for the year ending April 1979 indicates the cleanest air occurring before sunrise and the dirtiest in the afternoon.*

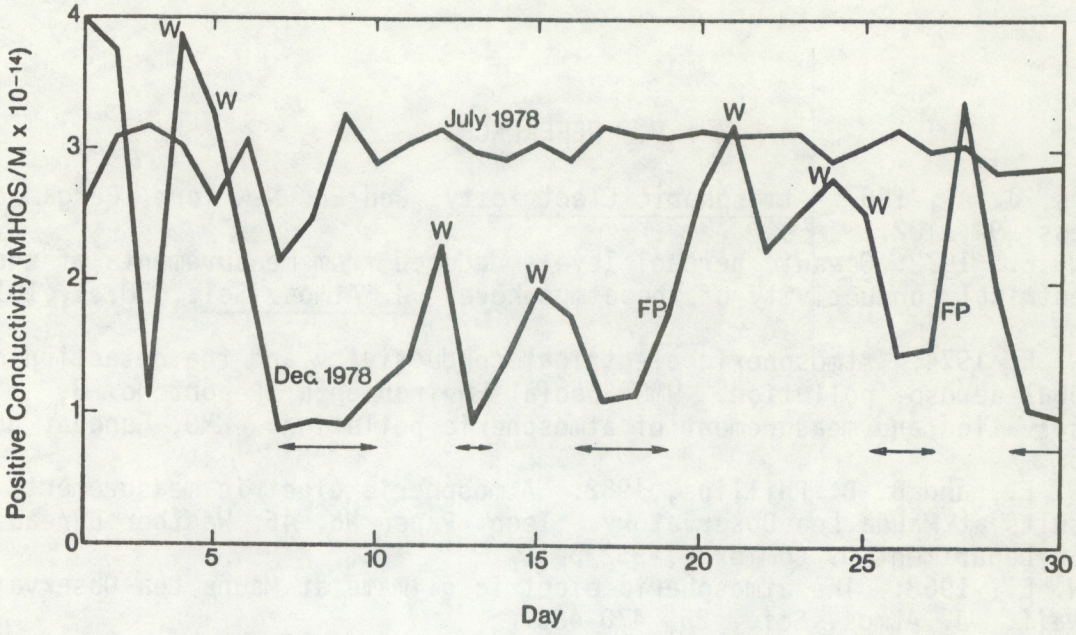

Figure 5. *The mean daily conductivities compared for July and December, 1978. Days with downslope winds are marked with "W"; "FP" for frontal passage, and the arrows indicate pollution episodes.*

concluded that, while it is possible that climatic variability may cause changes in the mean conductivity from season to season or from one year to the next, there is little doubt that the 13-year downward trend in conductivity is due to a gradually increased particulate level.

Conductivity measurements from the Gunbarrel Hill Field Site indicate that there are many days when the environment is extremely clean, probably as pollution free as in the centuries before there was any human impact in the region. These periods of high conductivity and low particulate levels have become less frequent and of shorter duration over the past 13 years, however, while particulate pollution episodes have become more frequent and persistent over the period.

Motor vehicles are generally deemed responsible for the largest share of the man-made fine particle pollution, particularly at Colorado's higher elevation where internal combustion engines become less efficient. The established decrease in conductivity since 1967 and the trend to be determined in coming years should be helpful in determining the effectiveness of mandatory emission control devices now required by state and federal regulations.

7. FUTURE OBSERVATIONS

This report is largely based on the long term measurement of a single parameter, the electrical conductivity. The results have provided the stimulus to more fully investigate the nature of the ambient aerosol at the location now known as the Gunbarrel Hill Air Quality Research Site. Sensors have been installed to measure particle concentration and size distribution in the sub-micrometer size range as well as several meteorological parameters. The results of this investigation will be published later.

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9. Table 1.--Daily mean values of the positive conductivity for days with 24 hours of fair weather for the years 1967 through 1979.

Gunbarrel Hill Field Site, Boulder County, Colorado

Data: Positive Conductivity, daily mean values

Units: Mhos m^{-1} X 10^{16}

Year: 1967

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	462	377	525	478	344	378	361	401	302	473	488	
2		384	537	473	366		365	409	456	491		290
3	418	391	537	489	244	354		441	456	539	290	307
4	395	435		565	322	366	285	441	478	326	290	307
5	331			561			361	438	405	295	329	290
6		412	530	482	288		398	401	473	279	434	473
7	285	389		553	486	328		406	473	491	415	268
8	285	379	538	572	366	400	372		399	504	418	186
9	312	438	453		325		381		388	458	431	268
10	310		472	484	470	411	372	325	440	445	509	303
11	296	192	525	478			345	425	538	459	509	455
12	340	404	539	248			342	436	473	507	431	
13	398	384	384			372	381	447	545	463	363	303
14			355	400			406	438	399		403	245
15	274	221	351	393	442			401	492		431	253
16		417	381	400	380		363	441	473	445	488	230
17	182			446	362	300	371	432	456	458	415	438
18	159	413	433	495		356		432	438	463	403	312
19	248		454	495		354	367	468		539	483	308
20	324	162	531	487			358	435	421	396	429	321
21	369	387	531	482	341	380	363	392	489	396		432
22	345	381	495	418	378	364	402	405	456	471	436	432
23	178	352	524		365		361	446	431	523	418	395
24	150	353	525	293	365	300	367	472	431	458	483	312
25		376				312	328	443	465	408	429	303
26	165	385	539	488		372	282	443		411	382	
27	199	380	524	503		388	321	428	503	459	404	330
28	278	429	457	482	395	350	385	445	492	470	316	286
29	314		527	491		366	350	435	437		283	258
30	386		527			389	372		448	473	403	
31	345						365	431		459		190
Ave	298	367	469	464	367	360	360	427	452	449	411	315

Gunbarrel Hill Fields Site, Boulder, Colorado

Data: Positive Conductivity, daily mean values

Units: Mhos m^{-1} X 10^{16}

Year 1968

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	229	490	512	472	316	339	352	305	392	568	277	412
2	253	384		484	325	326	340	420	408	465	382	429
3	253	481	558		329	343	337	420		444	413	536
4	351	450	512	502	329	358	352	420	408	568	413	495
5	335	390	491	281	361	474		363	384	465	405	437
6	363	422	491	510	470	358	282	410	389	444	416	429
7	264	413	558	564	314		364	394	392	400	277	394
8	229	417		460	301	378	323	387	408		294	508
9	245	398		460	325	358	366		527	396	346	394
10	218	404		580	316	330	352		411	396	388	416
11	229	370	230	484	332	381	388	319	495	400	479	402
12	348		398	489	482	384	448	394	514	444	490	394
13	278	254	354	322	430	474	327	415	417	454	389	380
14	350	246	570	553	461	343	356		429	468		295
15	356	275	567	580	415	309	419	488	427	454	285	295
16	232	246	409			358	448	427			393	388
17	294	372	376	482	288	397	356	430	495	473	416	
18	382	244	570	334		384	378	427	427	439	419	393
19	334	405	500	325	300	360	348	490	411	439	405	403
20	466			459	315	360	352	454	484	473	301	400
21	332	250	432		329	381	324	411	484	441	429	
22		269	428	489	288	457	383	438		568	429	393
23	327	469	406	472	309	344	349	488	514	468	479	295
24	323	481	546	501				459	427	468	482	336
25	400	384	427	420	341	339	346	415	408	468	382	348
26	355		498		321	375	362	426	530	574	388	377
27	356		546		292	465	371	411	538	441	405	412
28	347	381	504	448	353	368	337		440	560		418
29	360	387	432	470	335	465	354	419	323	454	410	393
30	372		538	484	357	368		437	315	474	413	
31	356		488		286		354	446				288
Ave	318	372	475	465	344	378	360	419	437	468	393	395

Gunbarrel Hill Field Site, Boulder, Colorado

Data: Positive Conductivity, daily mean values

Units: Mhos m^{-1} X 10^{16}

Year: 1969

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1						358	370	362	357	477		465
2						352	362	316	288	539		471
3						345	383	370	310		378	380
4						455		408	313		375	356
5						364	441	415	313	460	381	
6						371	328	395	307	468	401	349
7						328	388	391	330	463	484	346
8							370	402	372	468	378	253
9							370	384		444	342	329
10						333	355	382	348		330	335
11							350	390	310		330	372
12						379	346	427	363		327	380
13						379	364	402	351	531	342	372
14						356		478	388	345	509	364
15						254	378	422	404	339	354	265
16							370		414	356	342	329
17							364	384	401	345		336
18						352	270	378	325	359	375	354
19						356	346	395	348	318	351	270
20						364		398		561	362	263
21						455	269	402	337	443	351	462
22						387	401	412	357	338	342	347
23						349	388	427	360	340	384	361
24						363	376	378	373	322	396	
25						385	404	304	448	465	362	357
26						371	472	416	421	459	396	370
27						332	418	465	409	452	478	
28						339	435	395	464	334	375	
29						355	369		396		378	380
30						355	353		385		378	364
31							376	390		443		364
Ave						361	372	396	364	420	378	355

Gunbarrel Hill Field Site, Boulder County, Colorado

Data: Positive Conductivity, daily mean values

Units: Mhos m^{-1} X 10^{16}

Year: 1970

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	280		460		395	424	370	365	412	414		
2	311	299	428	396	374	416	356	469	425	285		
3	311	351	444		362		370		402	448		
4	383	336	534	479	329		424	327	402	313		
5		255	447	393	401		378	358	378	411		
6	240	342	447	296	377		385	358	396	215		
7	234	351	458	378	356		370	404	424			
8	185	358	432	355	356			371	412	209		
9	224	360	435	318	374		323	380	396	313		
10	380	374		304	392			474	518			
11	317	325			404		267	470	520	455		
12	326	351	343	396	330		331	365	300	332		
13	282	342	349	347			474	380	307	220		
14	285	339	392	360			350	371	419			
15	298	356		487	486	352	385	274	425	402		
16	194	360		400	356	360	380	378	405	358		
17		452			480	371	362	378	444	394		
18	202	448		502	388	371	356	340	381	349		
19	291	450	404	487	392	333	374		495	317		
20	164	317	383	469	377	328	367		431	317		
21	298	335	428	343	319	328	299	271		300		
22	392	294	491	370	250	345		347		298		
23	373	278	548	434	382	352	382	469	401	324		
24	384	239		487	376	352	411	400		389		
25	384	450	504	451	390	360	370	371				
26	286	461	441	400	384	374	374	371	532	372		
27	414	342		326	474	399	414	365	419	380		
28	283	339	432	330	486	399	469	326	425	314		
29	369			396	412	419	400	348	378	317		
30	292			340	378	379	367	368	425	380		
31	288						364	374		215		
Ave	299	352	440	394	385	370	374	374	417	335		

Gunbarrel Hill Field Site, Boulder County, Colorado

Data: Positive Conductivity, daily man values

Units: Mhos m^{-1} X 10^{16}

Year: 1971

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	132	248	471	409	386	325	305	355	384	385	521	
2		255	424	412	386	344	382	359	442	385	509	175
3			433		365	378	398	375		392	485	169
4			315	388	292	325	324	412	449	398	414	259
5	201		356	314	289	360	469	359	540	336	414	259
6	212			502		367	460	300	442	400	405	244
7	300		359	450	292		460	333		427	414	
8	204	314	424	412	383		452	368	437	400	378	
9	218	314		437			382	402	574	329	369	171
10	192	449		562			477	390	465	355	422	359
11		248		314			469	364	436	385	412	240
12		386	475	325	350		423	364	436	404	400	240
13	184	460	452	444	402		405	383	445	400	494	178
14	190	372	439	459	386			355	481	392	389	254
15	123	347	439	465	391		316	364	413	351	380	362
16	165	444	455	367	376		371	347		444		355
17	233	379		418			405	340				254
18		205		398			451	340		373	447	267
19	140	340	527		496			364	442	403	422	236
20	338		439		386		411	355	429	392	412	340
21	335		402		365		400	306		389	405	265
22	329	337	334		292	385	419	361	440	389	300	337
23	304	257	356	409	289	402	386	323	393	335	262	344
24	278	355	330	307	295	396	455	395	465	329	378	259
25	231	361	384	310	383	339	451	344	382	352	512	250
26	235	439	441		391	360	324	359	402	490	405	193
27	235	449	502	533	412	371	325	364	537	484	382	193
28	281	349	391	430	299	407	422	359	393		397	200
29	293		460	377	350	401		362	391		399	337
30	268		568	398	506	404	400	362	392	312		325
31	253		474		384		398	361		490		186
Ave	235	348	426	410	366	371	405	359	442	390	412	259

Gunbarrel Hill Field Site, Boulder County, Colorado

Data: Positive Conductivity, daily man values

Units: Mhos m^{-1} X 10^{16}

Year: 1972

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	267	244	333	350			287	355	385	386		360
2	171		426	350			285	355	411	459	386	274
3		347	444	474				261	408	459	389	
4		300		481			326	363	496	386	380	
5	360	338	430	481			368	372	384	312	414	
6	368	312	429	468			386	385	384	318	411	356
7	357	300	338	471			386	379			405	155
8	255	300	417	436			368	372	427	459		258
9	360		422	436	379		386	290	411	467		
10	164		338	432	384		407	316	385	436	300	248
11	348	319	324	427	392		431	385	390	459	354	244
12		444	350	399	400		456	411	374	421		208
13	164	327	350	385	400		482	431		412		263
14		362	208	436	384		434	458	418	395	268	263
15	159	438	338	459	360		400	411	358	386	295	274
16	262	455	439	439	326		386	385	500	459	420	356
17	287	249	371	445	445				492	324	491	290
18	209	362	318	454	379		355	342	385	318		165
19	325	451	335	442	368		368	333	420	400	405	258
20	242	347	196	456	371		355	359	374	300		244
21	242	251	442		478		412	361	385			281
22	165	377	338		403		426	375	402		378	349
23	264	444	239		341		417		397	472	525	277
24	251	400	420		330		382		301	530	328	200
25	254		245		336		386	367	385	431	446	244
26		334	178		368		350	342	406	441		240
27		315			390		409	320	389			265
28	250	438			384		382	331	402		328	219
29	365	296	242		392		378	331	397		491	
30	258		242		392		393	370	390		487	
31	254				384		367	292				208
Ave	264	350	339	436	382		385	359	402	410	395	260

Gunbarrel Hill Field Site, Boulder County, Colorado

Data: Positive Conductivity. daily mean values

Units: Mhos m^{-1} X 10^{16}

Year: 1973

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	205	281	386	264		362	450	367	377	363		197
2	136	284	412		346	464	374	367	294	485		
3		377			354	458	336	367	472	420		
4		374	509	440	444		355	390	398	409		301
5	108	198	312	440		433	352	404	424	390	252	298
6	316		420			365	332	358	431	390	248	190
7			409		250	329	355		431	387	337	309
8		222	424	271	452	333	387	336		472	252	295
9		265	387	274	452	329	400	342		263	235	244
10	110	256	414	259	271	342	379	367	278	291	326	226
11	127	259	420	299	242	345	348	390			418	174
12	308	277		303	238	326	332	454	387	477	368	181
13	341			307	250	370	461	467	387	490	384	188
14	303	185	395	362	333	342	403	400	385	344	326	234
15	205	374	414		329	381	396	364		352	409	284
16	194	239	431	462	354	458	380	361	288	365	319	295
17	233	324	450	455	360	458	355	355	396	390	337	135
18	315			311	439	440		372	398	412	319	
19	222	240			346	365	257	375	420	387		096
20		300	434	448	444	251	257	268	472	472	418	102
21	205	256	324	404		320	260	361	432	435	406	135
22	201	369	453	462		438	301	344	418	412	409	147
23	249	386	350	351	378	381	304	339	485	335	408	
24	225	246	451			392	298	339	488	490	301	
25	182	246			341	353	326	366	398	305	242	147
26		235	447		302	345	352	372		274		104
27		374		318	312	321	352	349	315	326	400	278
28	150	247		450	427	301	447	349		355	384	180
29	150			362	312	304	363	450		277	271	114
30	144					298	363	384	334	466	271	
31	156		455		282		374	319		466		096
Ave	208	284	414	362	344	365	355	369	396	390	335	198

Gunbarrel Hill Field Site, Boulder County, Colorado

Data: Positive Conductivity, daily mean values

Units: Mhos m^{-1} X 10^{16}

Year: 1974

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	206	330		511	394	303	318	290	411	405		252
2	300	425			205	347	325	332		480		168
3	230	419			205	330	357	228	405	495		158
4	191	342		410	216	323	412	290	416	402		245
5				464	287		419	367	480	302		
6	202	219		495	313		426	379	422	286		
7	296	222		499	317		412	332	416	430		
8	218	333		377	220		307	345	477	430		285
9		404	301	359	216	225	304	345	398	430	360	354
10	224	405		381	268	324	325	367	382	360	454	300
11	188	405	422		398	231	260	445			377	224
12	379	342	425	310	329	424	257	409			470	369
13	411	330	436		299	342	318	290	286	286		296
14	411	401	395	422	313	368	220	325	325		268	202
15	403	365	320	416	310	411	325	300	325	411	275	239
16	355	306	413	410	271	430	314	316	382	422	348	245
17	284		497	410	275	424	338	344	398	431	360	245
18				416	330	310	223	349	509	498	470	236
19	256	290		488	342	344	290	329	416	480	449	354
20	218	178	362	495	414	327	290	329	291	480	399	348
21		274	362	307	389	308		316	330	495	405	348
22	379	398		393	294	231	301	325	347	312	399	185
23	270	333		399	216	222	316	366	365	279		
24	202		296	418	205	285	325	360	379	384	384	261
25	251		443	401	201	285	366	290	398		461	345
26	289		443	401	299	308	340	240	398		280	234
27	384		427	310	408	319	333	240			360	217
28	397		497		405	323	290	298	495			149
29	403		505		302	327	278	325	422		302	261
30	403		459	387	344	327	344	379	480		305	250
31	403				305		357	379				250
Ave	302	336	412	412	300	323	323	330	398	405	375	260

Gunbarrel Hill Field Site, Boulder County, Colorado

Data: Positive Conductivity, daily mean values

Units: Mhos m^{-1} X 10^{16}

Year: 1975

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	312	301	319	288	425				416	383	300	379
2	296	347	260	285	409				433	410	332	276
3	385	336	260	285	340				403	383	300	284
4	385	260	443	288	312				412	475	337	302
5	379	260	344	291	326				418	331	337	276
6	376	432	337	467	416				403	328	418	177
7	379	400		490					300	402	306	255
8	302	254		490					325	469		282
9	158	357		388					484	483		365
10	312	429							469	470	322	379
11	162	432								402	435	188
12	305	360		301					374	355	435	175
13	379	364	308	297					287	177	426	
14	327		337	376	250				396	469	419	
15	200	247	362	312	250				477	355	306	368
16	200	222	331	475	250				479	396	299	
17	385	236	435		250				433	402	278	
18	341	347	429		326				312	416		276
19	376	328	345	411	318				312	400		244
20	405	418	345	468	222				316	457	284	266
21		405	226	425	331				325	383	284	276
22	297	412	398	475					505	378	340	270
23	297	312	425	478	340				448		357	270
24	297	435	425	380	419				460		426	270
25	330	320	377	380	356				477	369		215
26	398	320		405	326				495	373	293	283
27	162	425			323				425	196	273	381
28	264	412	313	457					388	291	190	
29	222		345	485					312	450		254
30	215		446	355	331					480	415	254
31	212									222		
Ave	302	347	355	390	326				403	383	338	279

Gunbarrel Hill Field Site, Boulder County, Colorado

Data: Positive Conductivity, daily mean values

Units: Mhos m^{-1} X 10^{16}

Year: 1976

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	185	371	300	365	353				384	371	303	215
2	260	177		341	367				431	360	295	307
3	159	223		377	353			438	385	475	284	212
4	248			362	450			342	381	368	267	212
5	260		340	337	256			339	377	276	308	122
6	263		340	335				342	390		314	219
7		371	340	362	344			339		376	303	320
8	147	358	254	365	331			384	283	468	454	179
9	239	347	378	458	370			330	377	481	329	174
10	248	276	251	261	374			324	355	465	205	
11	263	374	201	362	457			451	486	271		310
12	245	220		348	353			390	450	274		179
13	362	255	325	365	347			265	295	404	284	182
14	355	230	227	386	344			339	362	395	292	182
15	355	276	198	368				327	405	283	292	196
16	234	252	372	350	370			339	384	472	340	212
17	225	347	404		356			274	250	277	303	329
18		339	375	350	353			365	328	328	299	320
19	263	277	369	334	448			336		376	270	238
20	269		346	365	445			336	381	460	248	226
21	347	283	347	377				325	411	353	198	304
22	312	350	265	331				350	390	353	202	176
23	355	234	412	254	239				377	479	248	187
24		236	248	331	375			347	418	475	402	
25		248	201	362	357			339		379		296
26	212	277	189	461	256			336			398	296
27	212	256	265		339			277		270	251	304
28	245	277			450			269	428	339	416	299
29	320	271			279			285	423	339	405	293
30	239		273		311			455	423	353	245	
31	251		280		307			277		325		320
Ave	262	285	300	356	355			340	383	374	302	243

Gunbarrel Hill Field Site, Boulder County, Colorado

Data: Positive Conductivity, daily mean values

Units: Mhos m^{-1} X 10^{16}

Year: 1977

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	240	227	440	335	389	288	281	279	360	320	251	277
2	187	130			303	267	276	289	401	340	254	314
3	184	194	229	395	303	279	271	282	382	338	258	174
4	106	231	207	364	300	279	250	233	269	327	265	277
5	126	231	330	430	303	250		168	391	232	240	
6	181	231	330	395	281		288	254	414	218		085
7	214	216	348	342	288	299	276	279	475	421	218	137
8		237	437	364	319	380	320	311	369	430		
9	219	227	352	326	300	376	303	305	382	366	355	
10	177	127		288	307	284	327	179	382	242	312	141
11	288	245	251		351	267	378	279	269	421	254	126
12	200	328	348	342	299	242	371	182	272	373	258	255
13	143	130	426	388	337	235	281	263	353	344	227	168
14	143			401	281	279	253	241	326	240	352	262
15		202	248		328	336	273	294	319	311	355	182
16	177	266	426	326	403	243	239	303	353	444	348	252
17	282	331	237	448	303	177	262	179	379	430	153	280
18	269	290	345		395	190	276	332	380	300	160	143
19	115	234	429		294	184	270	303	411	325		085
20	156	328	244		328	249		388	455	317	149	277
21	145	242	411	319	392	235	204	311	405	229	234	119
22	103	225	440	264	296	312	159	239	456	342	254	129
23		325	320	358	300	305	378	239	453	418	309	266
24	105	328	312	441	309	274	294	266	405	356	337	271
25	252		415	364	353	248		279	450	321	313	137
26	282	111	329	380	300	376	175	391	391	433	355	091
27	288	340	337	448	395	300	281	289	333	427	240	097
28	108	230	452	358		274	262	266	344	337	240	134
29	177		428	333	258	398	245	266	382	278	348	150
30	184		286	351	201	265	245	282	439	266	142	168
31	268		415		385		262	286				099
Ave	190	239	349	365	320	279	275	273	380	338	266	182

Gunbarrel Hill Field Site, Boulder County, Colorado

Data: Positive Conductivity, daily mean values

Units: Mhos m^{-1} X 10^{16}

Year: 1978

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	234	336					257	328	359	332	212	325
2	240	412					305	378	340	348	238	
3	237	287					338	361	354	342	302	105
4	222	244					302	301	351	295	297	284
5	240	218					285	228	389	364	405	410
6	363	192					310	253	418	301	310	200
7	342	135					236	266	366	275	235	137
8	116	176					278	282	344	341	325	086
9	215	204					363	293	375	364	364	089
10	222	201					263	267	343	301	462	120
11	259						306	296	359	366	355	117
12	325						325	316	314	336	256	231
13	120						315	335	353	384	338	115
14	198	162	412		260		287	257	290	259	285	098
15		148	404		282	309	291	284	291	213	235	179
16	204	240	322		304	284	325	250	314	331	193	217
17	215	321	420		257	278	300	274	400	291	194	102
18	103	221	418			292	332	294	355	428	208	127
19		390	363		206	291	318		334	269	248	124
20	108	244	445		306	340	337		296	355	228	266
21	108	284	434		299	259	314		239	411	170	299
22	106	363	609			304	252		252		225	231
23		397	412	380		295	339		272		370	316
24	103	335	262	363	298	303	277		384		317	220
25	240	192	246	358	298	309	294		358		308	315
26	222	158	337	373	299	304	327		415		337	154
27	126	201	364	375		314	316		403	172	216	114
28	130	189		473		296	294		363	247	270	322
29	116				405	347	302		346	264	397	244
30	106				316	285	177		313	315	273	114
31	108						267	313		317		083
Ave	190	250	389	387	294	301	298	293	343	316	286	191

Gunbarrel Hill Field Site, Boulder County, Colorado

Data: Positive Conductivity, daily mean values

Units: Mhos m^{-1} X 10^{16}

Year: 1979

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	139	060	209		298		422	344	365	423	281	136
2	153	085	267			270	390	404	345	365	239	112
3	130	140				296	372	386	374	425	248	318
4	164	084	188			348	404	362	345	308	272	290
5	101	095	176	358		292	370	338	324	322		300
6	099	155	301	255	302	412		374	345	347		204
7	133	227	265	252	424	302	376	390	367	355	155	220
8	093	234		292	212		344	420	307	411	213	138
9	138	156		217	286	340	384		351	561	357	128
10	156	215		368		196	344		404	256	186	294
11	132	264	197		228	224	356	411		427	219	
12	172	239	224		316	286	366	340	328	384		116
13	224	188	314	278	312	284	330	466	378	460	107	174
14	122	316	182	253		370	406		326	386	116	216
15	238	295	217	178	298	370	384		241	502	186	388
16	304	213	211	240	350	364	390		252	429	163	340
17	241	215	315	278	352	392	524	266	307	446	153	224
18	160	273		300	364	252	490	310	409	369	296	340
19	144	242	160	322	370	440	384	246	376	479	278	296
20	198	323	159	342		422	386		392	466		188
21	322	246	157	292	278	348	352	262				194
22	382	278	354	314	270	348	398	260	388	262		
23	197	216	130	308	256	380	380	318	442		160	
24	126	205	197	360	264	296	362	423			186	144
25	198	204	300	360	274	350	436	386	433	300	238	202
26	119	166		298	346	376	444	431	433	266	160	196
27	067		157	428	286	358		324	423	341	120	
28	072		327			372		388	400	285	096	
29	093		275	350		364		357	357	493	110	082
30	106		315	362		336		361	448	501	136	092
31	067						482	411		369		130
Ave	161	205	233	305	304	335	395	359	365	391	195	210