Influence of Thunderstorms on Environmental Ozone

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THUNDERSTORMS exert considerable influence upon the environment of many locales. The unique destructive offspring of the thunderstorm which includes lightning, hail, and tornadoes make these storms great destroyers of life and property. Even the rain associated with the thunderstorm often becomes more destructive than beneficial, creating floods which take life and destroy property. These more destructive agents of the thunderstorm have been well publicized, making it unnecessary to do more than mention them. Less known is the fact that there is an indirect, and less dramatic aspect of the thunderstorm which may also have harmful environmental effects. This aspect is the thunderstorm's role as a causal agent in increases of ozone, one of the trace gasses of the atmosphere, in the environment. Thunderstorm induced increases of ozone in the low levels of the atmosphere occasionally are high enough to be harmful to plants and perhaps to animal life.

This paper summarizes some of the observed influences of the thunderstorm upon ozone concentration. It also describes the way in which observations indicate that the thunderstorm is able to produce increases of this gas in the environment.

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INSTRUMENTATION AND METHODS

The National Weather Service Office for Agriculture, located at the University of Florida Research and Education Center at Quincy has monitored low-level tropospheric ozone for the past 10 years. Mast Ozone Meters, Model 724–2,[1] are operated continuously throughout the year. These instruments use an electrochemical detector to coulometrically measure the oxidation of a buffered potassium iodide solution. Concentrations of ozone are given in parts per hundred million (pphm) by volume and are continuously recorded on strip charts.

In addition to ozone, observations included precipitation, profile soil and air temperatures, evaporation, humidity, wind direction and velocity including gusts, solar radiation, and sferics (thunderstorm static electricity). The time and type of fronts passing the station as well as airmass type, thunderstorm activity, the occurrence of squall lines and thunderstorm severity, the occurrence of hail, and any other weather information of significance are recorded daily for correlation with ozone concentrations and fluctuations. The observational record through February, 1973, included approximately 2700 days.

The records during thunderstorms were critically examined. When ozone rises were noted, the time of the increases were related to the lightning activity, the beginning of the downdraft winds of the storm, radar reports of storm tops, the height of the tropopause, and any other parameters deemed significant.

OZONE

Ozone, also referred to as tri-atomic oxygen, is a nearly colorless gaseous form of oxygen. Ozone has a characteristic odor resembling weak chlorine. It is occasionally possible to detect this odor during or following thunderstorms in which there has been a sharp increase in the ambient ozone levels. The normal concentration of this gas is only 1 to 3 pphm by volume in the lower levels of the atmosphere.

[1] Mention of trade name and/or manufacturer is for identification only and does not imply endorsement by the Department of Commerce, NOAA, or the National Weather Service.

The greatest amount of atmospheric ozone is found above the tropopause in the stratosphere at levels normally above 30,000 feet (Brewer, 1960). Here it is photochemically produced by ultraviolet and near-ultraviolet solar radiation interacting with the oxygen atoms and molecules in the rarified atmosphere. In addition to stratospheric ozone, some ozone is also photochemically produced near the surface of the earth in the lowest layers of the atmosphere. Sunlight interacting with hydrocarbons, nitrogen oxides, sulfur dioxide, and other pollutants is an oxidant producer which includes ozone (Haagen-Smit, 1952, 1958, Went, 1960a, 1960b).

Ozone is a strong oxidant in contact with organic matter and is destroyed rapidly in the oxidation process. Ozone is damaging to both herbaceous and woody plants in relatively small concentrations (Daines et al. Rich, 1964, Davis and Dean, 1966). Damage occurs at even lower concentrations when soil moisture is high (Dean and Davis, 1967). Commercially important forest tree species may experience needle or leaf damage in concentrations as low as 6.5 pphm (Berry and Ripperton, 1963). Davis and Dean (1972) made a comprehensive review of ozone records in north Florida and related observed values associated with the various weather parameters with the reported damaging threshold concentrations for tree species.

The literature has little information on the ozone threshold concentrations for damage to insects and other animal life. It is known, however, that ozone is harmful in high concentrations which may reach levels which are lethal even to man. Ten pphm has been established as the maximum concentration in which human beings should work and 8 hours is the recommended maximum for one to remain where ozone is this high.

Records show a diurnal, day-to-day, seasonal, and annual variation in the amount of ozone in the troposphere (Davis, 1968, Dean and Davis, 1972). The day-to-day variations are associated with changing weather patterns and phenomena. The thunderstorm, either singularly, in association with cold fronts, as elements of squall lines ahead of cold fronts or thunderstorm conglomerates, is one meteorological phenomena responsible for some of the increases of ozone in the environment.

THUNDERSTORMS

The increases of ozone in association with thunderstorms has most frequently been attributed to local production by the lightning stroke. There are two ways in which ozone production by the lightning stroke may take place. First, the interaction of the ultraviolet and near-ultraviolet rays of the lightning stroke with oxygen atoms and molecules produces ozone in the same manner as that photochemically produced above the tropopause. The second involves the photochemical action of the light of the lightning stroke with nitrogen dioxides. Nitrogen oxides, part of which are dioxides, are produced when the lightning discharge causes nitrogen of the atmosphere to unite with oxygen. Haagen-Smit (1952, 1956, 1958) has established that nitrogen dioxide, as well as hydrocarbons, in the presence of ultraviolet light is a producer of ozone. Therefore, the nitrogen dioxide resulting from one lightning stroke becomes the source of ozone production when exposed to the ultraviolet light component of subsequent lightning strokes. The amount of ozone produced by the lightning stroke is questionable. The observations indicate that it must be rather insignificant. If the lightning stroke were the primary source, or the sole source, of ozone associated with thunderstorms as most literature implies, significant increases of ozone should occur with all thunderstorms having heavy lightning activity and sufficient downdraft to transport the ozone to the surface, regardless of the location or the time of year.

Hundreds of thunderstorms occurred within 20 miles of the observation station during the past 10 years. No increase, or a decrease, in ambient ozone occurred in many instances regardless of the amount and intensity of lightning. An example was on June 23, 1967, when thunderstorms began near 1:00 PM. Prior to the start of the thunderstorm activity, the ozone meter had been recording from 2 to 2.2 pphm for 2½ hours. At the beginning of the first thunderstorm, the concentration dropped 10–20 percent. Thunderstorms continued for 4 hours during which time the sferics counters indicated better than 4,700 lightning strokes. One thousand and six hundred were recorded in 1 hour. Concentrations never reached levels above 2 pphm during the remainder of the day. It occurs to the author that there should have been some increase if the lightning produced ozone were significant.

Examination of records showed that concentrations frequently increased 1 to 4 pphm with thunderstorms during the late winter, spring, and early summer months. Occasionally the increase was in excess of 4 pphm. Except for a very few instances, concentrations changed little, if at all, during thunderstorms of late summer and early fall, irrespective of the lightning activity of the storm. The question then arises as to why there are ozone increases with some storms and not with others. To resolve the question it is necessary to first consider the likely source of the ozone. Secondly, it will be necessary to review the aspects of the thunderstorm which might transport ozone into the environment of the lower atmosphere.

It was previously noted that most ozone is located above the tropopause. The height of the tropopause varies through the year. It is normally lowest in the late winter, spring, and early summer. This is the time of year that the total amount of ozone in the northern hemisphere is the greatest (Brewer, 1960). There is normally little transport of matter, including ozone, across the tropopause. With some of the extratropical disturbances including thunderstorms, however, stratospheric matter is able to move into the troposphere (Staley, 1960, Danielsen, 1964). It is well known today that thunderstorms penetrate the tropopause. Long (1966), in a 4 year study of thunderstorms, found a large number of cumulonimbus clouds with tops of 60,000 feet, or higher, from the Gulf of Mexico northward. Along the northern Gulf coast the maximum number of penetrations of the tropopause occurred in the spring. The National Weather Service radar located at Apalachicola, Florida, often spots thunderstorms over north Florida with tops well above the tropopause. This is, in fact, one of the criteria used by the National Weather Service to identify storms with sufficient development to be severe with hail, high winds, and tornadoes. The records indicate that whether or not a significant ozone increase takes place is dependent upon whether or not the system is able to penetrate the tropopause reaching the ozone-rich air in the stratosphere. Since the tropopause is normally lower in the late winter to early summer, the thunderstorms during this period of the year have a better chance of developing to a height sufficient to reach the ozone source. This is believed by the author to be the primary reason that thunderstorms in the late winter, spring, and early summer are more apt to give ozone increases than thunderstorms in the late summer and fall months when the tropopause is high. The coefficient of correlation of tropopause height with the daily maximum ozone concentration for 765 days when tropopause height data were available was -.9155. This is significant at the 1 percent level. For 484 days when total ozone data were available, measured at Florida State University 18 miles southeast of the observation point, the coefficient of correlation of maximum low-level ozone with total ozone was .7091, also significant.

A review of the life-cycle of the thunderstorm reveals those features of the thunderstorm which apparently account for the transport of stratospheric ozone into the lower levels of the troposphere. Thunderstorm cells progress through three stages during their life-cycle. The cumulus, or first stage, is characterized by converging winds and an updraft which drives warm air up beyond condensation levels. Clouds begin to form at this level. Continued upward movement produces cumulus formations. The updraft develops in a region of gently converging winds where the atmospheric pressure is slightly lower than in the surrounding area. As the updraft continues, air flows through the cloud's sides in a process called entrainment. The entrained air mixes with, and feeds, the updraft.

Once the cloud has formed, the phase changes of water result in a release of heat energy which increases the momentum of the storm's vertical development. The rate at which this energy is released is directly related to the amount of gaseous water vapor converted to liquid water.

As water vapor in the billowing cloud is raised to saturation levels, the air is cooled sufficiently to liberate solid and liquid particles of water, and rain and snow begin to fall within the cloud. The cloud tower rises beyond the level where fibrous streamers of frozen precipitation elements appear. The formation and precipitation of particles large enough and in sufficient quantity to fall against the updraft marks the beginning of the second, or mature stage, of the thunderstorm cell. At this time the cell may be 50,000 feet, or more, in height. The top of the storm at this point may be located in the stratosphere, especially if it is occurring during that time of the year when the tropopause is lowest.

A thunderstorm's mature stage is marked by a transition in wind direction within the storm cell. The prevailing updraft which initiated the cloud's growth is joined by a downdraft generated by the falling precipitation. The downdraft is fed and strengthened, as the updraft was, by the addition of entrained air and by evaporational cooling caused by interactions of the entrained air and falling precipitation. Note that the entrained air may be entering in the upper parts of the cell as well as in the lower part. Entrained air at, or above the tropopause may be ozone-rich. Downdrafts will transport the ozone-rich air into the lower parts of the cell and subsequently into the atmospheric portion of the biosphere. The downdraft of the storm in the mature stage spreads out from the cloud in gusting divergent winds bringing a marked drop in the temperature. It is at this point in the storm's development that the storm has generally attained its maximum altitude which is frequently above 60,000 feet.

Ozone records show that if a significant ozone increase occurs, it most often starts at the time the cold downdraft is first noted. The increase is generally indicated on the strip chart as a sharp rise to an elevated value. The increased ozone normally will continue as long as the downdraft winds persist. The timing of the ozone rise with the downdraft is illustrated in Figure 1 which shows the recorded wind speeds, dry-bulb and dewpoint temperatures, and the ozone concentrations as the downdrafts of a thunderstorm started shortly after 1600 EST, April 29, 1971. It will be noted that the ozone rise started at about the exact time that the temperature drop and wind gusts began indicating the beginning of the downdraft. Radar observations at 1645 EST showed thunderstorms east and north of the observation point with tops from 50 to 56,000 feet. No lightning was observed and only one clap of thunder was heard.

For storms being accompanied by no increase, the ozone trace showed little change with the onset of the downdraft. Occasionally there was a decrease with the beginning of rain. This occurred ir-

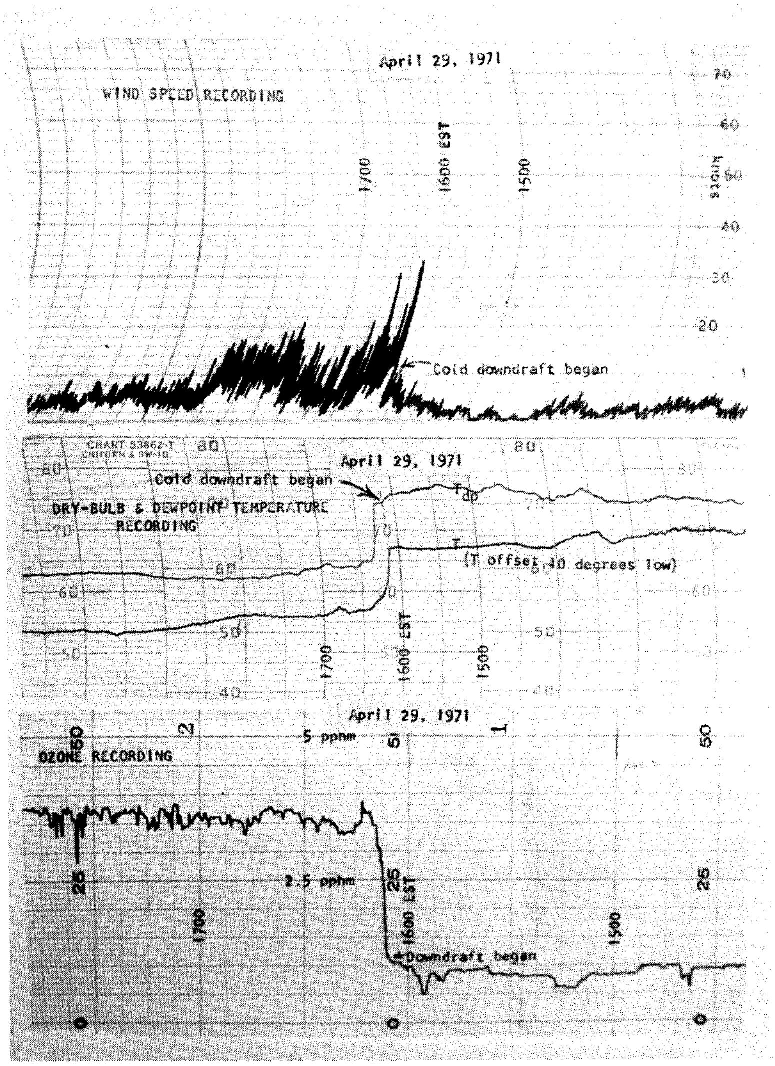

FIG. 1. Recorded wind speed, dry-bulb and dewpoint temperatures, and ozone concentrations as the downdraft of a thunderstorm began shortly after 1600 (4:00 PM) EST on April 29, 1971.

respective of the intensity and severity of the lightning activity as in the case on June 23, 1967, as previously discussed.

As the thunderstorm enters maturity, the storm has begun to die. The downdraft shares the circulation with the sustaining updraft, then strangles it. The storm loses its source of moisture and heat energy as the updraft is cut off from its converging low-level winds. Precipitation weakens, stops, the cold downdraft ceases, and the thunderstorm spreads out and dies. Ozone levels will remain elevated for some time after the storm has dissipated when there has been an increase. As the ozone sink of the earth takes over, recorders usually return to levels they were indicating prior to the storm.

The greatest increase in ozone of the 10-year record occurred on the early morning of March 3, 1964, as a squall line preceding a cold front moved through (Fig. 2.). As the squall line approached at 5:00 AM, the recorder trace rose vertically from 1 pphm, which it had been recording for several hours, to the top limit of the chart which was 10 pphm. The concentration was obviously much higher than the 10 pphm. It is unfortunate that the peak concentration was not recorded. Ozone levels did not return to normal until near noon. The massive outflow of ozone in connection with this squall line probably resulted from what Danielsen (1964) has described as a folded tropopause. With the folded tropopause, the tropopause is brought much closer to the earth's surface than normal allowing stratospheric matter to reach the lower levels of the troposphere.

Ozone concentrations of 1 to 3 pphm are considered normal and do not constitute a threat to plant or animal life. Ozone rises where the concentration in the atmospheric portion of the biosphere reaches or exceeds 4 pphm may have ecological consequences. Such rises as described above with the March 3, 1964, storm in which concentrations exceeded 10 pphm for several hours can be severely damaging to commercial crops including forests. Losses were minimal in the 1964 storm since it occurred prior to the start of the crop season and while the trees were still dormant.

This conference has dealt in depth with the consequence of the lightning stroke as a source of forest fires. In this respect, it might be noted that excessive rises in low-level ozone, whether in association

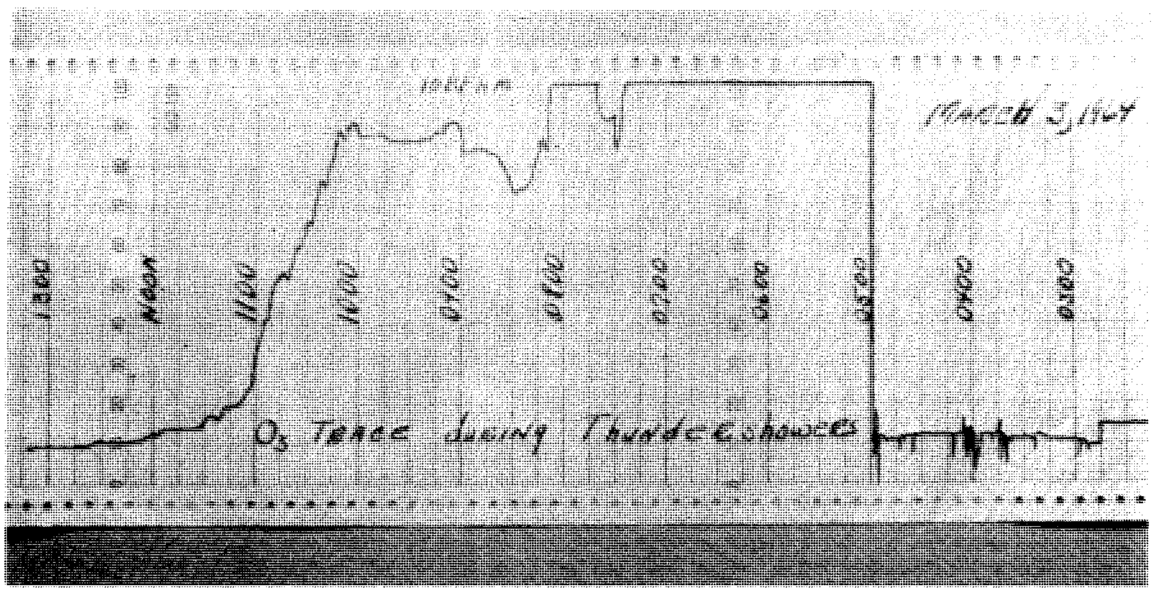

Fig. 2. Recorder trace of ozone concentrations during squall-line thunderstorms on morning of March 3, 1964. Concentrations exceeded 10 pphm, the limit of the chart for approximately 3 hours.

with thunderstorms, other weather phenomena, or atmospheric pollution may damage the needles of conifers (Barry and Ripperton, 1963). Premature needle drop as a result of the damage could make the forest more easily ignited in subsequent thunderstorms.

SUMMARY

Ozone observations in north Florida show that thunderstorms play a role in the daily amount of environmental ozone. Increases associated with thunderstorms occur more frequently in the late winter, spring, and early summer than in other months. The observations strongly suggest that ozone produced by the lightning stroke must be insignificant. Stratospheric ozone is indicated to be the principal source of ozone associated with thunderstorms. Stratospheric ozone is believed to be entrained into the thunderstorm at high levels, near or above the tropopause. It is transported into the low levels of the atmosphere by the storm's downdraft. Finally, observations show that increases of ozone associated with thunderstorms occasionally reach sufficient magnitudes in the atmospheric portion of the biosphere to have ecological consequences.

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