THE DEVELOPMENT AND MOVEMENT OF WARM SEASON HAZE OVER THE CENTRAL AND EASTERN UNITED STATES

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Abstract

The origin and nature of warm season haze over the central and eastern United States is discussed. Summarizing the results of various studies dating back to the mid 1970s, the microphysical basis of haze is described, with emphasis on the fact that haze appears to be largely anthropogenic (man-made). The synoptic meteorology of haze in the United States is then presented. It is shown that haze forms primarily in modified polar air, not tropical air, as is commonly believed, and that its movement may be estimated by trajectories at the 850-mb level. A brief discussion of haze-free tropical surges along the East Coast follows, using synoptic charts to illustrate some recent surge events.

1. Introduction

During summer, the central and eastern United States may remain covered by a murky veil of haze that lasts for days. The haze robs color from the sky and dims the evening sun, sometimes making it fade altogether long before the day is really done. Haze is so common in some areas that it is assumed to be natural and is accepted as a fact of life.

Most of the haze blanketing the eastern United States each summer is not natural and its presence is worthy of attention for a number of reasons. First, and perhaps most importantly, haze affects human health. For example, researchers at the New York University Medical Center recently concluded that the acid droplets found in haze pose a serious hazard to exposed tissues of the lungs and breathing passages (Pendick 1993). They also determined that when haze occurs in association with smog (the brownish, local form of air pollution derived from automobile exhausts) the destructive nature of the smog is significantly enhanced.

Haze also affects aviation. It shrouds visual cues important to pilots and can significantly reduce visual range over thousands of square miles. When oriented in patches or bands, haze alters patterns of differential heating, encouraging convective development in some areas while suppressing it in others (Lyons 1980).

Haze, however, does more than just limit visibility and impair respiratory health. Because some of the same airborne compounds which constitute haze are also responsible for acid rain (Urone and Schroeder 1978; Husar 1990), haze is necessarily linked to the destruction of vast stands of Douglas fir trees by acid precipitation over the eastern United States in recent years (Mitchell 1994), as well as to the accelerated crumbling of concrete, mortar and statuary in cities. It is also worth noting that clouds in hazy air tend to produce less rainfall than those which form in less contaminated environments (Monastersky 1992). Thus, the presence of haze can influence regional patterns of precipitation.

Evidence is also mounting that haze plays a significant role in determining the global energy balance, since it not only diminishes the amount of solar energy reaching the surface but also reduces the rate at which the atmosphere radiates longwave energy to space (Ball and Robinson 1982; Penner et al. 1994). One study even concluded that because of haze, some parts of the eastern United States experience an annual solar radiation deficit of about 7.5% (Ball and Robinson 1982).

Another reason haze is of significance is that it profoundly affects the clarity with which we view the natural environment. Haze not only obscures the daytime sky and clouds, but also stars, the Milky Way and other features of the nighttime sky. Rainbows, haloes, and vivid sunset colors all disappear when haze shrouds the view. Haze robs the landscape of contrast and hue. A hillside that glows with color under a bright blue sky on a fall afternoon in New England will appear noticeably subdued on a day with haze. While it might be argued that haze adds a sense of depth to mountain scenery, ordinary scattering by air molecules and dust yields the same result without the loss of coloration and visual range associated with haze.

The reduction in visual quality caused by haze is, however, more than cosmetic. Campbell (1983), Evans and Cohen (1987) and Zeidner and Shechter (1988) indicate that poor visual air quality causes heightened levels of anxiety, tension and depression in humans. In a similar study, Jones and Bogat (1978) linked increased interpersonal aggression and hostility to reductions in visual air quality.

In summary, the impact of haze, though sometimes subtle, is seen to be quite significant. Yet for many in the operational community, haze remains poorly understood despite its importance and frequent occurrence. This paper addresses development and movement of summertime haze in the eastern United States, with emphasis on its largely anthropogenic (man-made) origin. Much of the material has been presented elsewhere, but generally not from an operational meteorologist's point of view.

The chemistry and microphysics of haze are discussed in Section 2 and a climatological overview of haze in the United States is given in Section 3. Section 4 discusses haze forecasting using several case study examples, while Section 5 presents the synoptic meteorology of haze-free tropical surge events over the eastern United States. A brief conclusion follows in Section 6.

2. What Haze Is

a. Haze as pollution

As was already noted, haze over the eastern United States is often assumed to be natural. Evapotranspirative products from trees are probably the most often-cited source. Haze is also sometimes attributed to the minute particles of salt that are released by breaking ocean waves. Popular meteorological

works (e.g., Ludlum 1991) which use the term "haze" to refer to strictly natural obstructions to vision perpetuate this view.

Certainly natural forms of haze do exist, but as the following pages show, the "haze" commonly seen over the eastern half of the United States in summer is not predominantly natural. It is in fact a vast blanket of man-made pollution. More specifically, haze is a form of "wet" air pollution—a veil of tiny droplets (aerosols) of condensed pollutants.[1] The adjective "wet" is used to distinguish eastern U.S. haze from the dry forms of haze which consist of fine dust particles and are more commonly observed elsewhere in the world (e.g., the Harmattan haze of west Africa, or the shamal wind haze of the Persian Gulf).

Numerous studies since the mid 1970s (e.g., Ferman et al. 1981; Wolff et al. 1982; Malm 1992; Husar and Wilson 1993) have consistently shown that warm-season haze over the eastern United States is composed primarily of sulfates (i.e., of sulfate aerosols). To understand the formation of sulfate aerosols, then, is to understand the formation of warm-season haze.

b. *The chemistry of haze*

1) SO_2 and sulfates

Sulfates are sulfur-based compounds which contain sulfate ions (ions of the form SO_4^{2-}). The sulfates which comprise haze aerosols are derived mainly from the oxidation of sulfur dioxide (SO_2) and may exist in solid or liquid form. Airborne sulfates also originate from bursting air bubbles in ocean waves and, over arid regions, from wind abrasion of sulfate-bearing soils (Wallace and Hobbs 1977). These two sources produce comparatively large particles (>2.0 μm in diameter) which, like salt particles from ocean waves, settle out fairly rapidly and, therefore, are not a major component of regional-scale haze.

Since haze-producing sulfates originate from SO_2, a few words are in order regarding the origin and nature of atmospheric SO_2. Sulfur dioxide is a colorless gas that has the odor of burning sulfur. It may be both natural or man-made (anthropogenic) in origin. Most natural SO_2 is produced from the oxidation of hydrogen sulfide gas (H_2S), a by-product of vegetative decay. Volcanoes are another significant natural source of SO_2 (de Pena 1982).

Anthropogenic SO_2 is produced in great quantity during the large-scale combustion of sulfur-bearing fossil fuels in power plants, oil refineries and steel mills. Lesser amounts are produced during the manufacture of pulp and paper. In this country, SO_2 emissions are concentrated along the "industrial crescent" extending from the mid Mississippi Valley east into the lower Great Lakes and mid-Atlantic States (Fig. 1). A separate SO_2 source region is associated with oil production along the upper Texas and Louisiana Gulf Coasts.

Nearly 2.7×10^7 metric tons of SO_2 are produced in the United States each year, about one fourth of the world's total output (Brueske 1990). Coal-burning power plants in the Ohio Valley alone annually contribute 3 million tons (Malm 1992). Worldwide, man-made SO_2 emissions increased nearly 30-fold between the mid 1800s and the mid 1900s as a result of industrial development (Heicklen 1976).

Even in highly polluted environments, the concentration of SO_2 in the atmosphere rarely exceeds 1 part per million; over rural areas average concentrations are on the order of one part per billion. More than half, however, of the SO_2 over continental areas is thought to be anthropogenic, compared to about one third for the atmosphere as a whole (de Pena 1982). This is especially true over the northern hemisphere, where more than 90% of the total man-made output is produced (Heicklen 1976). A more precise estimate of the total anthropogenic component of SO_2 over a given area is difficult to ascertain because of lingering unknowns in the many sulfur budget equations involved.

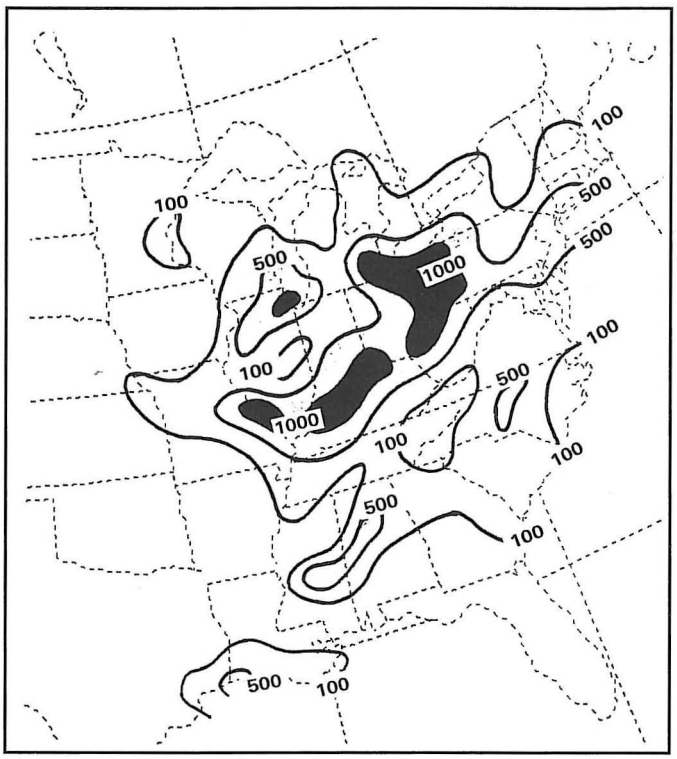


Fig. 1. Distribution of SO_2 emissions during the summer over the eastern United States in metric tons per day (After Brueske 1990).

2) Formation of sulfate aerosols

The oxidation of SO_2 in the atmosphere can occur in a number of different ways. Some of the chemical paths involve only gas-phase reactions, while others are exclusively liquid-phase processes or some combination of the two. Those paths which result in the formation of sulfate aerosols are good examples of what is known as "gas-to-particle conversion" since they involve the formation of liquid or solid aerosols from a gas.

For example, one gas-phase SO_2 oxidation path involves oxidation of the SO_2 to form gaseous sulfuric acid (H_2SO_4). The latter gas is then converted to a liquid sulfate aerosol either by contact with existing aerosols or by serving as a nuclei for the condensation of water vapor (Rogers and Yau 1989). In contrast, liquid-phase oxidation of SO_2 occurs inside cloud droplets after the gas has become dissolved in them.

Because gas-to-particle conversion typically requires the presence of secondary pollutants such as ozone (O_3), conversion reactions are usually enhanced by sunlight. Reaction rates also vary with relative humidity. For example, the oxidation rate of SO_2 to sulfate increases by a factor of eight when the relative humidity increases from 70 to 80% (Wallace and Hobbs 1977).

The particular type of sulfate which forms during the oxidation of SO_2 is dependent not only on whether the reaction

[1]Technically speaking, the term "aerosol" refers to a *system* consisting of particles suspended in a gas. Here, however, aerosol will be used in its more popular sense to refer to the particles themselves.

occurs in the gaseous or liquid phase, but also on the degree of neutralization which occurs during the oxidation process. Neutralization, in turn, is governed by the number and type of cations (positive ions) present during the reaction. Ammonium, calcium, sodium and magnesium are the most common neutralization ions. For example, complete neutralization by ammonium produces ammonium sulfate ($(NH_4)_2SO_4$), whereas partial neutralization results in the formation of ammonium bisulfate ($(NH_4)HSO_4$). The production of sulfuric acid (H_2SO_4), meanwhile, represents a complete absence of neutralization.

Even with some neutralization, the sulfates found over the eastern United States tend to be very acidic. These particles generally exist as aqueous nitric and sulfuric acid, the result of gas-phase reactions during which the gaseous acids are converted to liquid form by the addition of water vapor. It is the downstream transport of these aerosols, and their eventual elimination from the atmosphere in the form of acid rain and snow, that results in the low pH (high hydrogen ion concentration) characteristic of precipitation over the Appalachians and much of the remainder of the eastern United States.[2]

3) Growth of sulfate aerosols and their appearance as haze

All sulfate aerosols, depending upon their degree of neutralization, are at least somewhat hygroscopic. This means that they adsorb water molecules from the environment, even when the relative humidity is below 100 percent. As a result, sulfates are excellent condensation nuclei. The aerosols grow (deliquesce) as water vapor condenses on them, and they continue to grow until they reach a size at which they are in equilibrium with their environment.[3]

If the environment is supersaturated with respect to water, sulfate droplets eventually reach such a size that they become visible as a cloud. If, however, the humidity in their vicinity is somewhat lower, say around 85 percent, the droplets might grow to only about .5 μm in diameter. This is about one tenth the size of most cloud droplets but perhaps twice the diameter of the aerosols before they were "wetted." Aerosols of this size are within the range (.1 μm to 1 μm) over which scattering efficiency per unit particle mass reaches a maximum (National Research Council 1990); in fact, such particles scatter visible sunlight a million times more effectively than air molecules. Figure 2 illustrates graphically the relationship between scattering by aqueous sulfate aerosols and increasing relative humidity.

The scattering of sunlight by gas molecules in the atmosphere is a form of Rayleigh scattering. Rayleigh scattering is a general term for scattering produced by particles that are very small compared to the wavelength of the incident light. The degree of scattering which occurs is inversely proportional to the fourth power of the wavelength involved. Thus, since blue light is of a shorter wavelength than red (.39 vs. .76 μm), a sky dominated by Rayleigh scattering appears blue.[4]

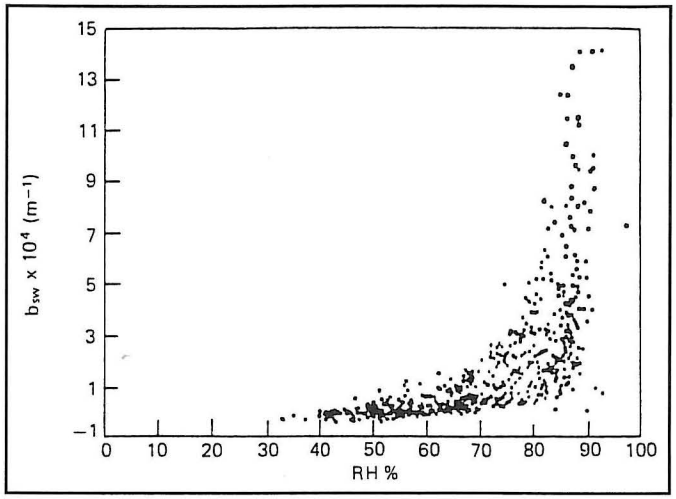


Fig. 2. Effect of relative humidity on the scattering of visible light by liquid sulfate aerosols, as measured by extinction coefficient, b_{ext}. Extinction coefficient is a measure of the attenuation of a beam of light as a result of scattering (as in this case) or absorption in a medium. (After Ferman et al. 1981).

In contrast to the scattering of sunlight by air molecules, the scattering produced by hygroscopic sulfate aerosols is not strongly wavelength-dependent. Because such particles are comparable in size to the wavelength of light, the scattering they produce is a complex function of particle size and wavelength. If the aerosols are all of the same size, the sky might take on a faint red or blue hue depending upon the size of the aerosols and whether the part of the sky being viewed is seen by scattered or transmitted light. But if a range of aerosol sizes exists, as is most often the case, no particular color is favored and the sky appears white. In addition, since the aerosols represent a net increase in the number of particles normally present in the atmosphere, the tendency for whitening is further increased. These extra particles also enhance the atmospheric absorption of sunlight—and, therefore, reduce the amount of light that reaches the ground.

4) The natural component

Because haze is such a familiar sight in the eastern U.S. and has no obvious source, casual observers find it difficult to believe that it is not natural in origin. Some note that the Blue Ridge and Smoky Mountains were named long before the widespread industrial use of fossil fuels. Indeed, a small percentage of the particles found in haze are derived from volatile hydrocarbons such as terpenes, that are released by certain trees (Chang 1990). In addition, atmospheric sulfates are not entirely anthropogenic.

Studies using data dating back to 1940, however, show an incontrovertible link between industrial sulfur emissions and the degree of haziness over the eastern U.S., as shown, for example, in Fig. 3 (Husar 1990; Malm 1992).[5] Sulfate haze is also on the increase in the Arctic (Shaw 1995). Research conducted in the Blue Ridge mountains has shown that naturally-occurring aerosols are responsible for no more than 20% of

[2]It should be noted that sulfate aerosols and gases also exit the atmosphere via *dry deposition,* the deposit of airborne particles and gases on the earth in the absence of precipitation.

[3]Aerosol growth can also occur via *coagulation,* the process whereby droplets which bump together adhere to each other and then merge into one (Malm 1992).

[4]Theoretically, Rayleigh scattering should produce a violet sky since that color has the shortest wavelength in the visible spectrum. Since human eyes are most sensitive to the middle part of the spectrum, a clear sky appears blue.

[5]Similar regional trends have been observed elsewhere in the world (e.g., western Europe and China).

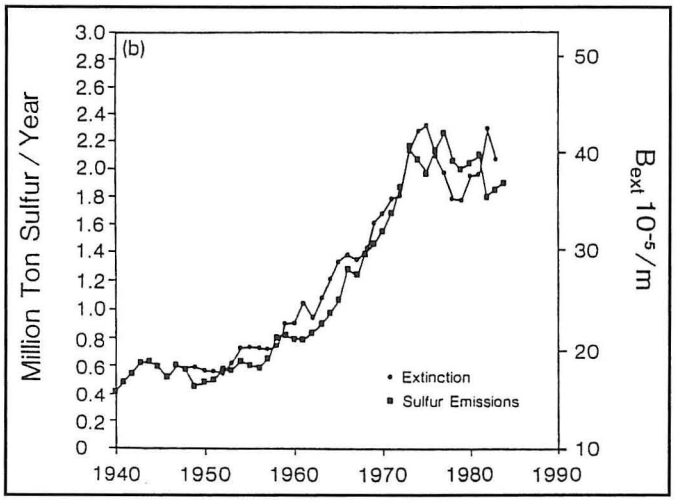


Fig. 3. Comparison of long-term sulfur emissions and degree of summertime haziness (as measured by extinction coefficient) over the southeastern United States. (From Malm 1992).

the total light extinction due to haze (Ferman et al. 1981). The primary reason for this is that most organic aerosols (such as those from trees) are relatively hydrophobic and, therefore, do not grow to such a size that they become visible as haze.

The Ferman study estimated that if all natural sources of pollution in the eastern U.S. were taken together, surface visibility would still exceed 25 miles—well above the 4 to 6 mile visual range characteristic of summer afternoons over the region today. If any haze were visible at all, it would be of the thin, "blue" variety first noted by the Cherokees in the early 1700s (Powell 1968)—not the murky pall that frequently obscures the Blue Ridge mountains today. Accounting for the mean warm-season airflow over the eastern U.S. in summer, the study concluded that "observed airflow patterns are consistent with previous findings that Midwestern [sulfate] source areas are a major cause of widespread summertime haze in the eastern U.S."

More recent studies have continued to support these ideas, attributing more than three quarters of summertime light extinction in the central Appalachians to sulfates (Malm 1992; Sisler et al. 1993). This is perhaps not too surprising considering Malm's observation that the *average* sulfate concentration over the eastern states is some 5 to 10 times greater than the estimated natural background value of approximately .8 $\mu g\ m^{-3}$ (Ferman 1981; Trijonis et al. 1991).

3. The Climatology of Haze

a. A summer phenomenon

Sulfate aerosols are both small and chemically stable. As a result, they settle out only very slowly and can remain airborne for days (Wolff et al. 1981). Most are eventually washed from the atmosphere in the form of acid rain. Although sulfate aerosols are formed wherever the precursor gas-to-particle conversion reactions occur, it is synoptic-and regional-scale weather conditions that govern their overall concentration and thus the occurrence and persistence of haze.

Because large scale atmospheric transport reaches a minimum during summer and boundary layer relative humidity tends to be high, sulfate haze is primarily a warm season phenomenon. As Fig. 4 shows, haze in the United States is most common east of the Mississippi River. Note that haze is less frequently observed over south Florida and northern New England—areas farther removed from major SO_2 source regions and areas more likely to experience air of a less contaminated origin. The data also show an overall trend for increased haziness in recent years, especially over the Southeast. This reflects the increased summertime use of coal for electrical purposes such as air conditioning (Husar and Patterson 1980).

b. Why the eastern U.S. is hazy

Proximity to the semi-permanent Bermuda anticyclone makes the eastern third of the United States especially prone to prolonged episodes of synoptic-scale sulfate haze in summer. Large scale transport over the eastern States reaches a minimum during July and August. Moist air parcels originating over the lower Mississippi Valley may take 3 or 4 days to reach the

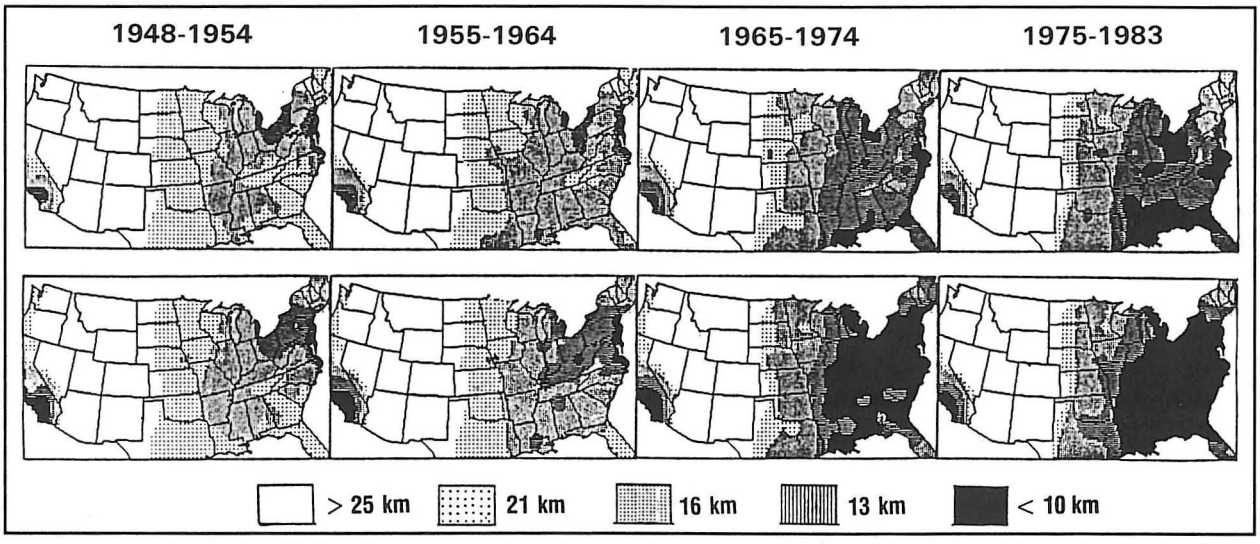


Fig. 4. Long-term spatial distribution of haze (expressed as average visibility in km) over the United States. Top row: spring (April–June); bottom row, summer (July–September). (From Husar 1990).

eastern Great Lakes or mid-Atlantic States. Vertical mixing is also often quite limited, especially east of the Appalachians where subsidence is enhanced closer to the mean position of the anticyclone. This increases the atmosphere's loading of both SO_2 and its sulfate oxidation products. In addition, since summer days are long and large-scale cloudiness is at a minimum, photo-enhanced gas-to-particle conversion can proceed at a maximum rate.

The source region of the air commonly present over the Midwest and eastern U.S. in summer is another factor which fosters the development of haze. While the Gulf of Mexico is typically blamed for the region's oppressive summertime combination of heat, haze and humidity (''The Three Hs''), careful examination of surface trajectories reveals that *in most cases such air does not originate over the Gulf, but is rather continental polar in origin.* Typically this air has undergone strong modification in the lowest layers and is returning poleward after having overspread the eastern states two or three days before.

Since these air masses have had a recent history of subsidence, an inversion is typically present around 850 or 900 mb. Because of the inversion, moisture added by evapotranspiration—and haze aerosols—remain trapped in a shallow layer near the ground, while cleaner, drier conditions persist aloft. The low ''lid'' placed on top of the haze layer enhances its negative impact on visibility and encourages additional aerosol growth. True Gulf air, in contrast, typically lacks a low-level subsidence inversion and is characterized by thermodynamic instability through a comparatively deep layer. Any haze that may be present mixes through that deeper layer and, therefore, appears much less dense.

The top of a haze layer in a modified polar air mass is often quite distinct, and the resulting haze horizon is a familiar sight to airline passengers flying over the eastern United States in summer. The ''horizon,'' of course, marks the top of the atmosphere's well-mixed boundary layer. Because relative humidity reaches a local maximum at the top of the boundary layer, haze is usually densest at an altitude just below that of the ''horizon.''[6]

c. Haze in the western U.S.

The western United States is largely free of sulfate haze since SO_2 emissions are comparatively low and the climate is dry. In addition, since the air is often of recent oceanic origin, it tends to be cleaner (i.e., contains fewer background particles) than that found over the eastern United States. As Fig. 4 shows, however, other forms of haze do occur in parts of the western U.S.. In particular, ozone smog and nitrate-based haze plague much of southern California in and around the Los Angeles basin. These forms of pollution are derived primarily from motor vehicle emissions (Sisler 1993).

4. Haze Forecasting

a. Introduction

The National Weather Service forecast discussions and the WX-TALK (Weather-Talk) on-line bulletin board postings shown in Fig. 5 illustrate that the forecasting of haze continues to pose problems for operational meteorologists. Although a number of studies dating back to the mid 1970s have documented the growth and movement of sulfate haze ''blobs'' over the eastern United States (see, for example, Hall et al. 1973; Gillani and Husar 1976; Lyons et al. 1978; Husar et al. 1981; Wolff et al. 1981; or Wolff et al. 1982), little of this material was written for or has found its way into the operational environment. What follows is a distillation of some of the information presented in those papers, along with a few additional notes

(A) State Forecast Discussion
National Weather Service Birmingham, AL
402 AM CDT Sunday 21 July 1991

Upper high will drift west across Tennessee Valley this afternoon and models show it still building. Temperatures expected to climb a couple more degrees today and could see 100 at Muscle Shoals. Gulf flow at low levels expected to get cut off...at least over northern and central Alabama as low-level winds shift to w and then nw with time. Curious pattern continues...with weather systems moving from east to west. Are we in Cuba?

Inclusion of "haze" in yesterday's forecast for today was embarrassing...have never seen such a beautiful blue sky in Birmingham in July. Suspect haze will return...especially over northern Alabama today or tomorrow...but want to see it first.

(B) Forecast Discussion for Southern New England
National Weather Service Taunton, MA
330 PM EDT Thursday 21 July 1994

Big picture remains the same...ridge over the western Atlantic and trough over the western Great Lakes. Remnants of tropical system...now a shortwave...progged over central Pennsylvania by 00z.

Ridge over western Atlantic blocks Great Lakes shortwave which will finally move east as second more powerful feature pushes system east. Hazy...hot and humid weather will likely continue into Sunday...with only possible relief in the form of clouds and showers as midwest front moves slowly east.

Forecast Discussion for Southern New England
National Weather Service Taunton, MA
940 PM EDT Thursday 21 July 1994

Skies cleared out nicely late this afternoon. Apparently some sort of boundary passed through region because winds kicked up out of the southwest and the haze cleared. Feel that we must have broken into the pure tropical air. Temperatures look good from previous forecast.

(C) WX-TALK Computer Bulletin Board
Date: 14 August 1994
From: (A NOAA/NESDIS research meteorologist)
Subject: Comments about haze

I'd just like to challenge anyone to be able to make a 24 hour forecast of haze in the eastern half of the United States. Certainly no one is doing it in an official manner today.

I make that comment because of the conditions I've seen in the last several days here in the D.C. area. Starting with Thursday we had haze thick enough to obscure most of the sky. On Friday, the haze continued until an outflow boundary passed from south to north. Visibility increased after passage to 50 miles or more (I could see Cbs that far away). On Saturday, the haze increased and visibilities were back down to a few miles. On Sunday, strong southwest winds and humid conditions were the rule, but no haze. Why?

Fig. 5. Selected State forecast discussions mentioning haze from (a) NWSFO Birmingham, AL (0900 UTC 21 July 1991), and (b) NWSFO Taunton (Boston), MA (1930 UTC 21 July 1994 and 0140 UTC 22 July 1994); (c) excerpt from the WX-TALK computer on-line bulletin board (14 August 1994). The Boston discussions reflect forecast thinking prior to and just after passage of a typical tropical surge (Section 5).

[6]The ''haze horizon'' can sometimes be observed indirectly from the ground as a dark band on the flanks of cumulus towers which penetrate beyond the boundary layer. The dark band marks the angle of maximum light extinction due to haze between the observer and the cloud.

on the effect of different synoptic patterns on the development and movement of haze.

From what has already been presented, it is apparent that haze forms wherever the sources of atmospheric sulfates overwhelm the sinks. This is why haze is usually associated with regions of large-scale stagnation. With both vertical and horizontal mixing at a minimum, whatever aerosols are present accumulate at first locally and then regionally over the area experiencing minimal air flow and high relative humidity.

Favorable conditions for haze formation are realized on a regular basis each summer over the SO_2 source regions of the central and eastern United States, a day or so after a polar air mass has settled over the area and the surface winds have become light. Under sunny skies, evapotranspiration adds considerable moisture to the boundary layer in such situations, with dew points often rising into the upper 50s or low 60s by the end of the second day after cold frontal passage. Since conditions are favorable for rapid aerosol growth, and because the aerosol can readily accumulate in the statically stable environment of the modified polar air, haze typically becomes noticeable in such an air mass within about 48 hours of its having become stationary over the eastern United States.

b. A typical example

Because eastern haze is generally confined to the lowest 7 or 8 thousand feet above the surface, its movement over a period of days is generally well-correlated with the streamlines of flow at 850 mb (Wolff et al. 1981). Figure 6 shows the progress of a typical summertime haze event over the east-central United States, with the areas of haze plotted on the 850-mb charts. In this case, a mass of hazy air which formed over the Ohio Valley was first shunted south to the Gulf Coast states ahead of a weakening cold front.

Once over the Gulf Coast region, the air mass stalled and picked up an additional load of moisture and sulfates from the refineries of southeast Texas and Louisiana. The hazy air then made a return visit to its original home as it was drawn northward ahead of a new cold front approaching the Mississippi Valley. In this way, especially dense areas of haze may form as sulfate aerosols accumulate in a given mass of air that makes one or more return visits to an SO_2 source region.

As Fig. 6 shows, haze tends to concentrate in bands parallel to fronts. This might seem perplexing considering that the depth of the boundary layer tends to be greatest in the vicinity of fronts. But because large scale ascent and low-level convergence are maximized there as well, relative humidity is also at a maximum near fronts. Thus, sulfate production is enhanced and those aerosols which do form grow to a comparatively large size. Weak fronts are sometimes detectable in visible data satellite imagery when their associated haze bands appear as discontinuities in the brightness field.

The case shown in Fig. 6 also illustrates the importance of trajectory analysis to forecasting haze movement. Trajectory analysis is used to determine air parcel motions forward or backward in time from a specific point or region (Yarnal 1991). Since the formation of haze is not an instantaneous process, and since haze can be advected from one area to another, knowledge of an air mass' recent history is essential to making an accurate forecast of haze movement. For example, in this event, a forecaster in Peoria, knowing that haze was reported earlier in the week at Little Rock and Memphis, should not be surprised by the appearance of haze over northern Illinois on 18 August. Even though the 850-mb flow over Illinois on the 18th was rather strong and from the west—conditions not normally associated with haze in that part of the country—back trajectories reveal that the air mass entering the state was indeed

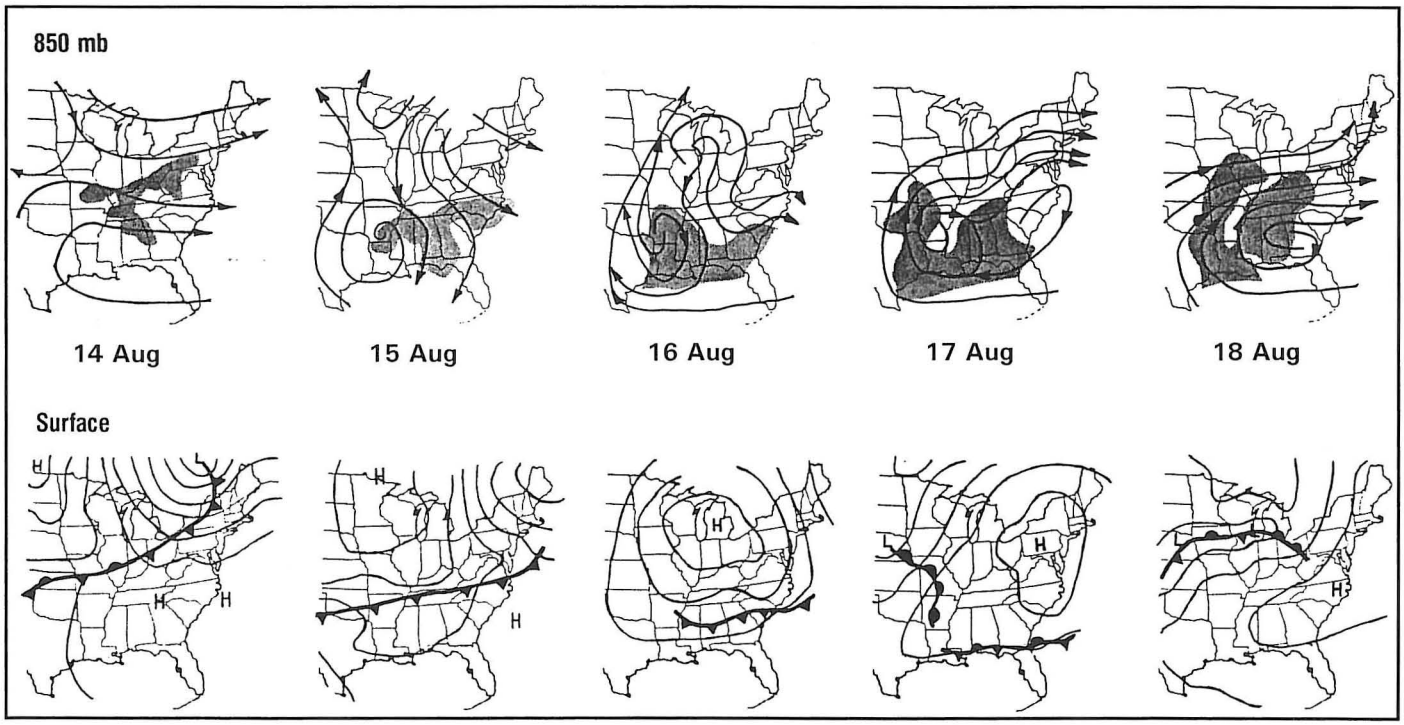


Fig. 6. A haze "blob" which twice affects the lower Ohio Valley in August 1979. Haze areas (visual range less than 10 km) shaded, with 850-mb streamlines and surface isobars. Map times: 1200 UTC (After Wolff et al. 1981).

the same one which had brought haze to Arkansas and Tennessee two days earlier.

In contrast to the mid Mississippi Valley, it is in fact *not* uncommon for brisk westerly winds to accompany haze over the eastern Great Lakes and New England. Indeed, some of the worst haze episodes in the Northeast occur in conjunction with mid-summer heatwaves and moderate to strong westerly flow on the northern fringe of an elongated Bermuda High. The enhanced westerly flow is frequently associated with the approach of a short-wave trough over the Saint Lawrence Valley. The winds, which are typically strongest in advance of an east-west cold front associated with the trough, tap dense haze areas that may have been developing under nearly perfect sulfate-forming conditions over the Ohio Valley for several days. When the ''blobs'' arrive in New York or New England, it is often just in time to produce a fall of acid rain as thunderstorms erupt along the front.

Once an area of haze has developed, it remains in existence until it is either advected to a new location or the aerosols are washed out by rain. Dry deposition of haze (see Footnote 2) is minimal. Recent evidence also suggests that boundary layer sulfates may be vented through the anvils of mesoscale convective systems (McNaughton et al. 1994). Qualitative evidence certainly indicates that surface visibilities increase in the wake of most mesoscale convective complexes and larger mesoscale convective systems. In contrast, although isolated thunderstorms may rid the boundary layer of local buildups of pollutants, visibility often is not improved because the increase in humidity in the vicinity of such storms enhances the growth of remaining aerosols.

c. Early season haze

Observations show that surface dew points in the 60s are most often associated with the onset of haze in summer, since lower dew points at that time of year are indicative of fresh outbreaks of polar air. However, haze can occur with lower dew points, especially during spring and fall. A classic example of ''low dew point haze'' is illustrated in Fig. 7. This event occurred in early April with surface dew points in the 40s and temperatures in the 60s. The haze was clearly not derived from natural sources such as trees since very little plant growth was in progress at the time due to unusually cold weather during the preceding weeks.

The main haze ''blob'' formed in a zone of persistent easterly flow north of an east/west stationary front, where vertical mixing was limited by presence of a strong frontal inversion (Fig. 8). The sulfates originated in the industrial area surrounding the lower Great Lakes and were carried west along the southern fringe of a large polar anticyclone which had invaded the area earlier in the week. Pollution from Chicago, Cleveland,

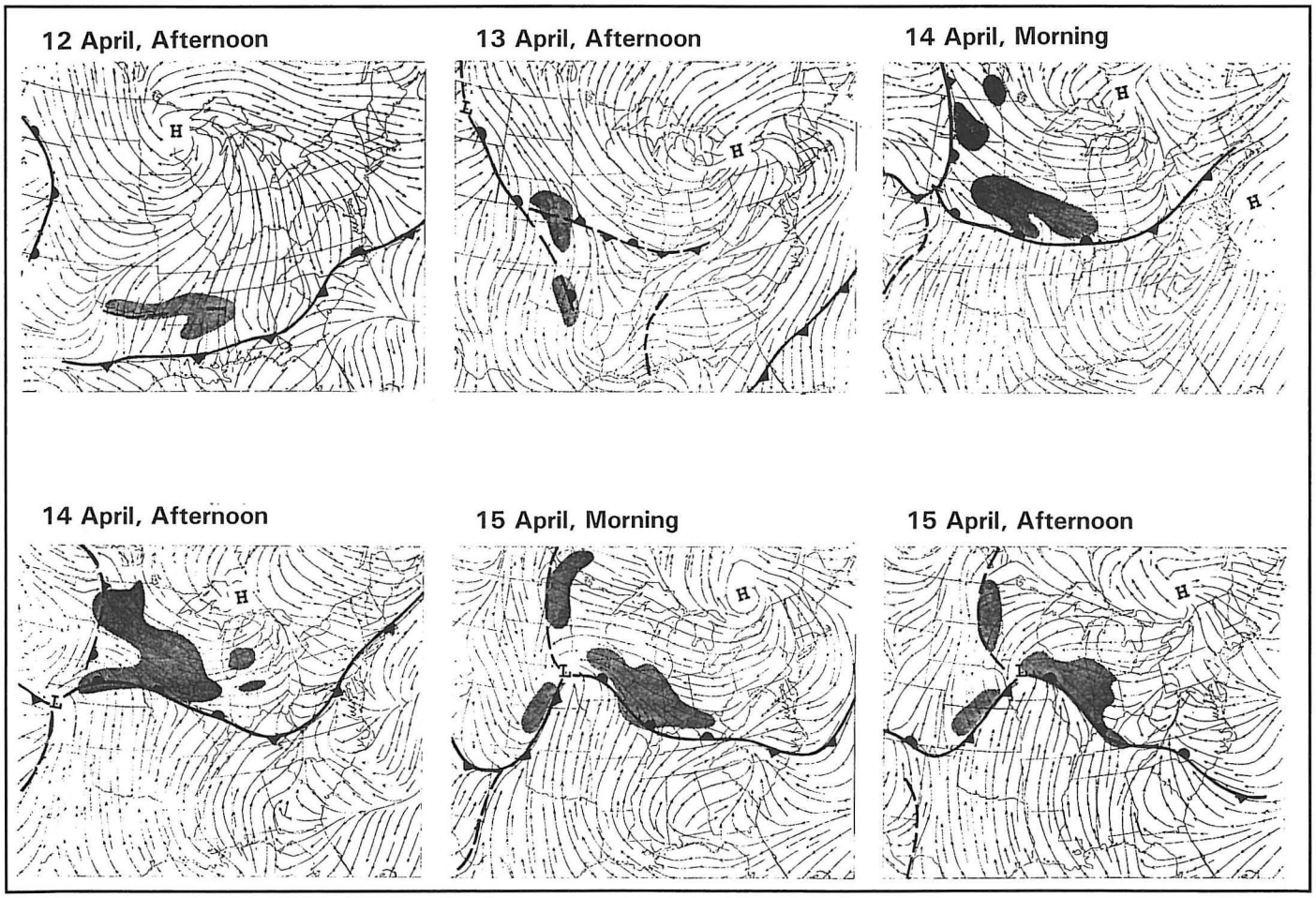


Fig. 7. Surface fronts and streamlines associated with an early season haze event (12–15 April 1992) over the north central U.S. Haze areas (as reported in surface airway observations) shaded.

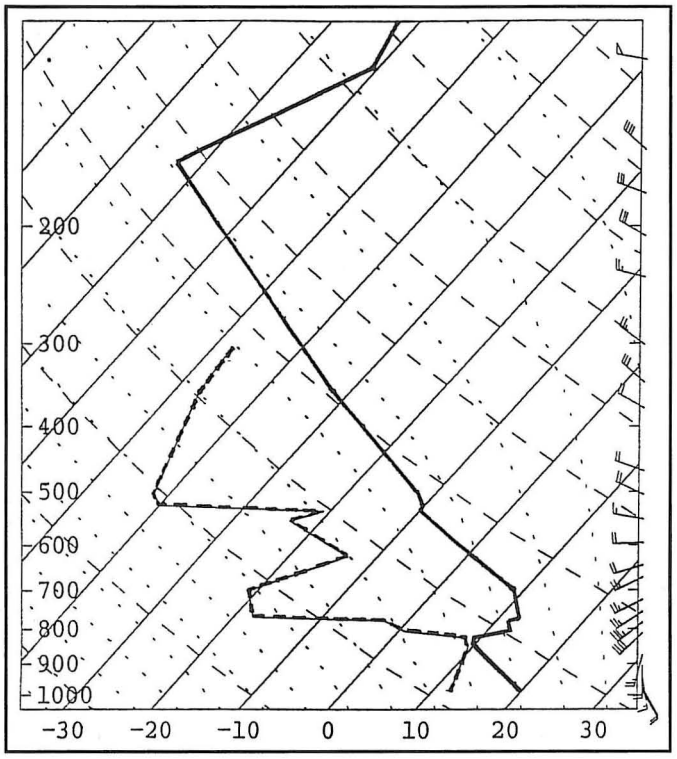


Fig. 8. SkewT-logP diagram for Topeka, KS 0000 UTC 14 April 1992. Temperature and dew point lines solid and dashed, respectively; wind speeds in knots. Sounding shows presence of pronounced frontal inversion near 825 mb.

Detroit and Milwaukee contributed to the haze which spread as far west as the Nebraska high plains.

As Fig. 7 shows, the haze formed in modified polar air, not tropical air; the haze-producing air mass never moved south of the Ohio River. It is also worth noting that some of the haze which affected the north central states during this event did, however, arrive from the south—in the form of a returning ''blob'' that had been pushed into Arkansas and Oklahoma by a cold frontal passage earlier in the week.

d. Haze and tropical cyclones

Some of the worst haze episodes in this country are associated with the blocking of polluted air masses over the Ohio Valley or Midwest when tropical cyclones are present along the East Coast. Figure 9 shows how a mass of hazy air which formed over the Ohio Valley was forced to remain over that region for two additional days as Hurricane David (1979) moved up the Eastern Seaboard. Once David reached New England, northwest winds in the wake of the storm carried the heavy pollution burden southward *behind* a cold front into the Carolinas, Georgia and the Gulf Coast States. The GOES 7 depiction of a more recent hurricane-related haze event is shown in Fig. 10. In this case (Emily 1993), northeast winds on the fringe of the tropical system drove a plume of dense haze that had been resident over the mid-Atlantic States southwest into the Carolinas.

Even in the absence of tropical activity it is not uncommon for haze to follow the passage of weak summer time cold fronts over the Gulf Coast region and the Southeast. This is because the post-frontal air typically originates over the Ohio Valley or mid-Atlantic States. Embryonic sulfate aerosols born in these SO_2 source regions move south with the subsident post-frontal

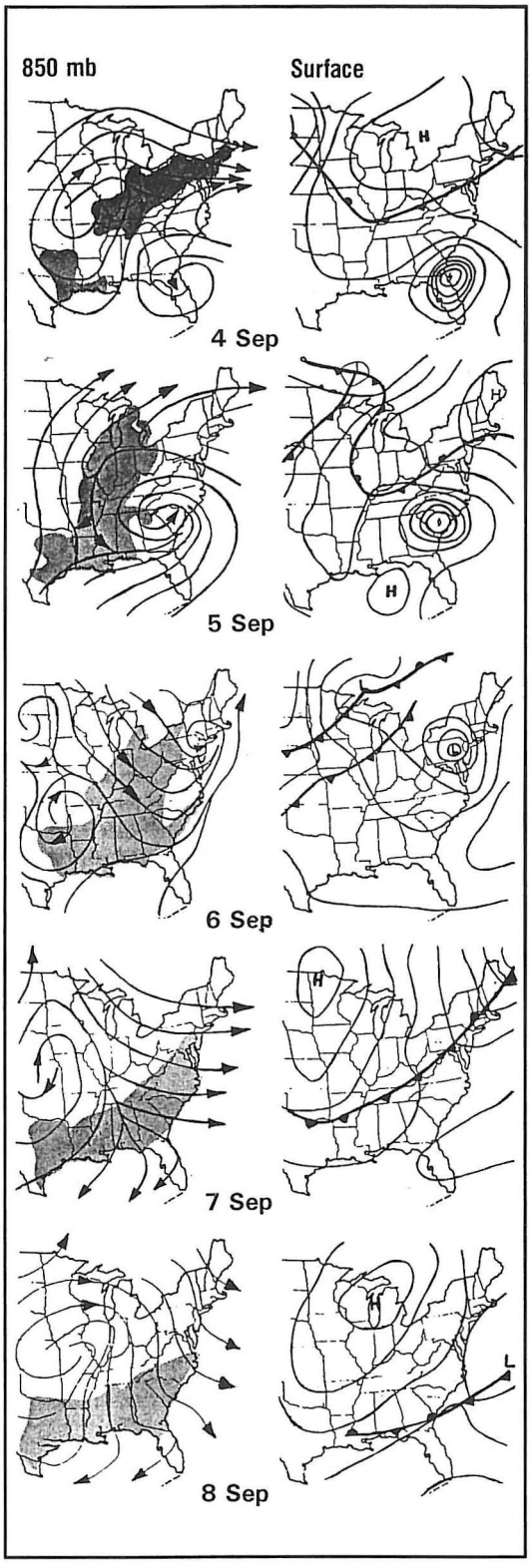


Fig. 9. Surface and 850-mb level evolution during a haze event affected by Hurricane David, September 1979. Map times: 1200 UTC (After Wolff et al. 1982).

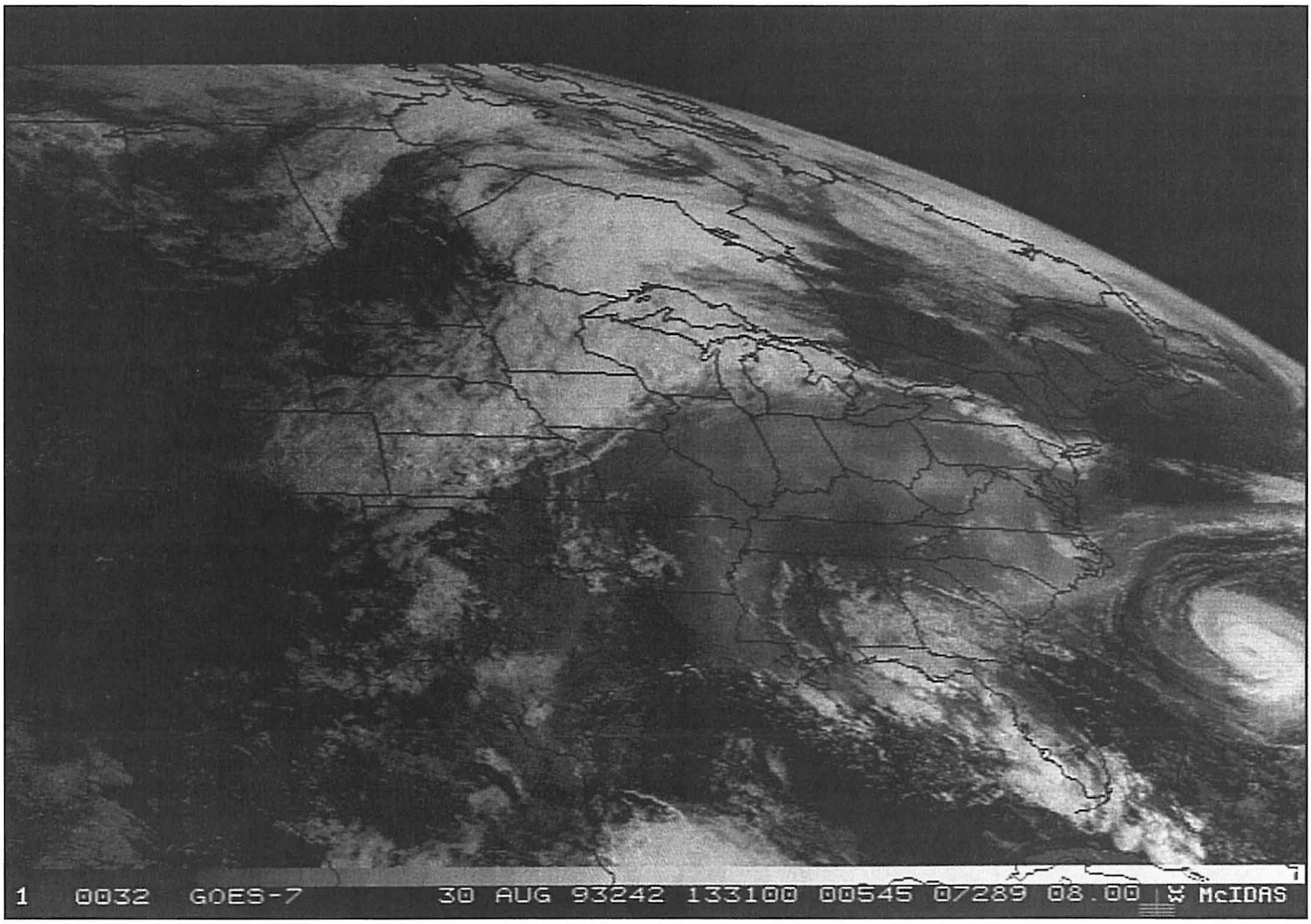


Fig. 10. GOES 7 visible data view of the eastern United States at 1331 UTC 30 August 1993 showing Hurricane Emily over the western Atlantic. A haze band which originated over the mid-Atlantic States is being driven south into the Carolinas ahead of a weak cold front on the northwest fringe of Hurricane Emily.

flow, eventually growing into haze as they encounter increased humidity and sunshine over the Gulf and south Atlantic Coast States. Post-frontal haze is also sometimes observed when shallow summertime fronts undercut an aerosol-laden air mass early in the day. Surface visibility in these situations typically improves with frontal passage, only to deteriorate once again later in the day as convective overturning brings what had been an elevated haze layer back to the surface (Lyons et al. 1978).

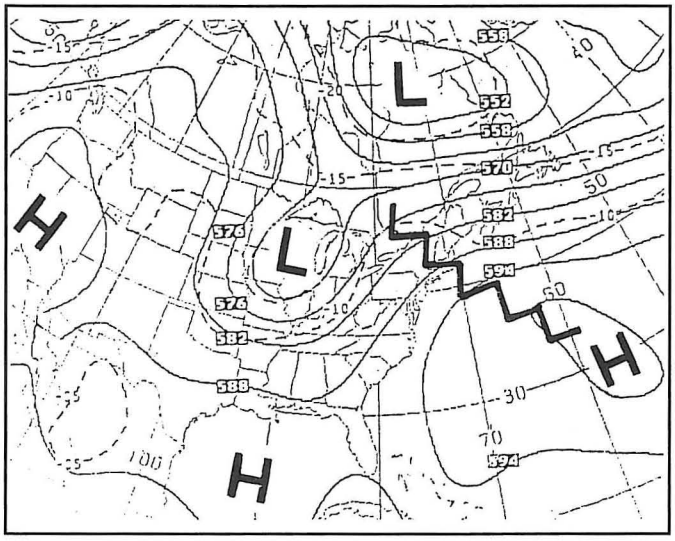
5. Tropical Surges

One of the more pleasant though uncommon characteristics of the normally hazy summer months over the mid-Atlantic States and the Northeast is the arrival of subtropical air from the western Atlantic in the form of a "tropical surge." These events occur when the main axis of the Bermuda High rotates clockwise from its usual east/west orientation along 30 or 35 degrees north latitude. This may happen in response to the development of a strong trough over the Mississippi Valley, or in response to the development of a closed circulation along the south Atlantic Coast. Both scenarios result in deep south to south-southwesterly flow over the mid-Atlantic States and the Northeast (Fig. 11).

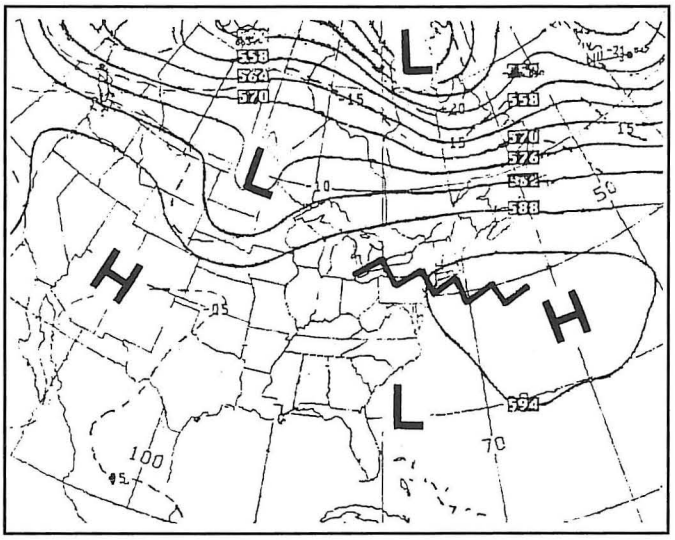
Having had a long over-water trajectory, air streams of this type are noticeably clean and unpolluted despite their high moisture content—in sharp contrast to the murky air masses they replace. Since the maritime air is usually buoyant, cumulus buildups dot the sky and some grow into small thunderstorms. An example of a typical tropical surge sky is given in Corfidi (1993). There is often a stronger-than-normal southerly component to the wind at the surface.

A series of surface observations depicting the midday arrival of a tropical surge at Wilmington, Delaware on 20 July 1994 is shown in Fig. 12. This particular set of observations was chosen since it clearly illustrates the increase in visibility that occurs during a surge in the absence of a major change in dew point. The sequence is also largely free of diurnal effects. In this case, visibility increased from 5 miles in haze at noon local time (1550 UTC) to 12 miles at 1800 LST (2150 UTC). The dew point, meanwhile, remained in the mid 70s.

The doubling of visual range is significant since typically little or no afternoon visibility change is observed over this region during the summer in the absence of a frontal passage.



(a)



(b)

Fig. 11. Standard NWS/NCEP 500-mb analyses associated with tropical surge events over the mid-Atlantic States. In (a), anomalous southerly flow along the eastern seaboard is related to an unusually deep trough over the Mississippi Valley (1200 UTC 4 August 1974). In (b), a closed circulation east of Georgia produces a south to southeast flow along the mid-Atlantic Coast (1200 UTC 4 August 1988). Ridge axes depicted by serrated lines.

In a sense, of course, there *was* a frontal passage—strongly modified continental polar air with a high sulfate content was replaced by a cleaner air mass of Caribbean or west Atlantic origin.

But surge ''fronts'' are not easily diagnosed by even the most sophisticated of today's objective analysis techniques. For example, the arrival of a surge generally produces no detectable change in surface equivalent potential temperature (theta-e). Automation of the surface observation network has exacerbated the detection problem since less information is now available on visibility changes above 6 miles. Although the advance of a tropical surge can sometimes be tracked by satellite,[7] clouds often interfere with the view. As there are no plans to include ''airborne particulate mass'' in routine surface observations anytime soon, it is probably safe to say that surge detection and tracking will continue to pose problems for forecasters for some time to come.

The 500-mb analysis sequence for the Wilmington surge event is shown in Fig, 13. In this case, the combination of a seasonably strong trough over the upper Great Lakes with a weaker trough along the south Atlantic Coast together produced anomalously deep southerly flow along the mid-Atlantic coast. Backing of the upper flow as far north as Pennsylvania and New York on 21 July allowed the surge to sweep northeast into New England the following day (Fig. 13d). Arrival of the surge in this area was rather abrupt, and elicited the comments from the Boston area National Weather Service Forecast Office (NWSFO) shown in Fig. 5b.

On average, tropical surges occur about once each summer along the mid-Atlantic Coast. They are, however, notably absent in some years (e.g., 1992 and 1993), while several might occur in others (e.g., 1994). Their frequency decreases from south to north along the eastern seaboard, and their effects usually do not extend west of the central and northern Appalachians. Tropical surges are also observed in the deep south, when the large scale circulation allows Caribbean or western Atlantic air to overspread the Gulf Coast States (Note comment regarding east-to-west flow in the forecast discussion shown in Fig. 5a).

Surge events usually come to an end with the approach of a short-wave trough in the westerlies. When these systems are weak, their passage is marked by only a modest veering of the mean tropospheric flow. This shunts the maritime air mass east into the Atlantic, allowing hazy continental air from the lower Great Lakes or Ohio Valley to return. If the short-wave is seasonably strong, however, a more decided veering of the large scale flow occurs. This generally ushers in a continental air mass of more poleward origin, and the haze-free maritime flow is replaced by relatively clean air from northern Canada.

6. Conclusion

The origin and nature of sulfate haze over the central and eastern United States have been discussed. Persistent misconceptions about haze have been examined, and information has been provided so that forecasters may better anticipate its formation and movement. Although the impact of haze as a meteorological phenomenon is not immediate like that of a tornado, flash flood or hurricane, its long-term effects are no less significant.

It is worth noting that there has been a slight *decrease* in the incidence of sulfate haze over some parts of the Midwest and the Northeast U.S. in recent years due to a reduction in the use of high-sulfur coal (Husar 1990). In the Southeast U.S., SO_2 emissions have decreased as a result of stricter air pollution standards imposed by the 1970 Clean Air Act and its subsequent amendments.

However, continued population growth and the increased demand for electrical power suggest that large-scale haze will remain a problem for some time to come. In addition, regional

[7]In cloud-free areas, the remote detection of haze and other forms of pollution has improved significantly with the commissioning of next generation satellites GOES 8 and GOES 9 (See Menzel and Purdom 1994).

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ILG SA 1350   16  SCT              5H 216/85/75/2604/017
ILG SA 1450   25  SCT              5H 218/87/75/2507/018/ 500 1500
ILG SP 1524           M21 BKN     5H           1605/018/TCU OVHD
ILG SA 1550   21  SCT M28 BKN     5H 218/87/75/1707/018/TCU W
ILG SP 1626   25  SCT E70 BKN     6H           1908/018
ILG SA 1650   45  SCT              7 218/88/76/1707/018
ILG SA 1750   30  SCT              7 211/88/76/1710/016/ 807 1200
ILG SA 1850   40  SCT             10 210/91/72/1912/015
ILG SA 1954   41  SCT             10 208/92/73/2010/015/MDT CU SE-S
ILG SA 2054   41  SCT             10 205/91/73/1709/014/MDT CU SE-S
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ILG SA 2254   55  SCT             12 203/87/76/1610/013
ILG SA 2354  100  SCT             12 205/86/76/1606/014/ 500 1071
ILG SA 0054  250  SCT             12 208/84/72/2006/015
ILG SA 0154  250  SCT             12 211/83/71/1908/016
ILG SA 0252  250 -SCT             12 211/81/71/2007/016/ 107 1001
ILG SA 0352  250 -SCT             12 211/79/72/2007/016
ILG SA 0452  250 -SCT             12 208/78/72/1905/015
ILG SA 0550  250 -SCT             12 205/77/73/2005/014/ 807 1009
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Fig. 12. Sequence of surface airway observations depicting the arrival of a tropical surge at Wilmington, DE around 1900 UTC (1300 LST) 20 July 1994.

haze which is not predominantly sulfate-based but is still traceable to anthropogenic sources has begun to affect visibility in other parts of the country, such as the scenic national parks of Arizona and Utah (National Research Council 1990; Sisler et al. 1993).

Haze, therefore, will continue to present operational meteorologists with a challenge—a challenge to not only better understand it, but to also heighten public awareness that most haze is not natural and that more should be done to eliminate it.

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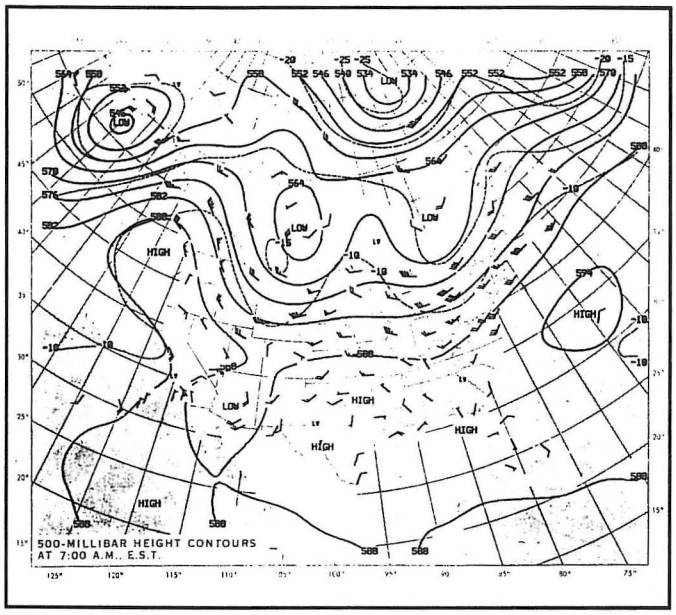
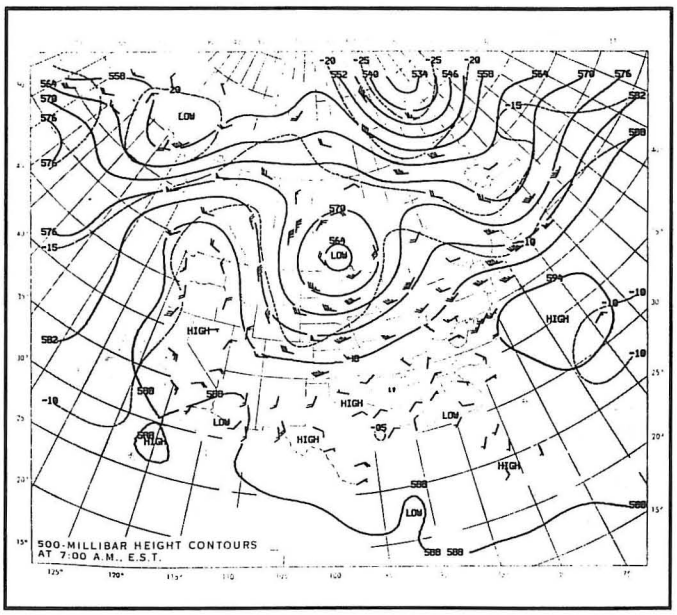


(a)



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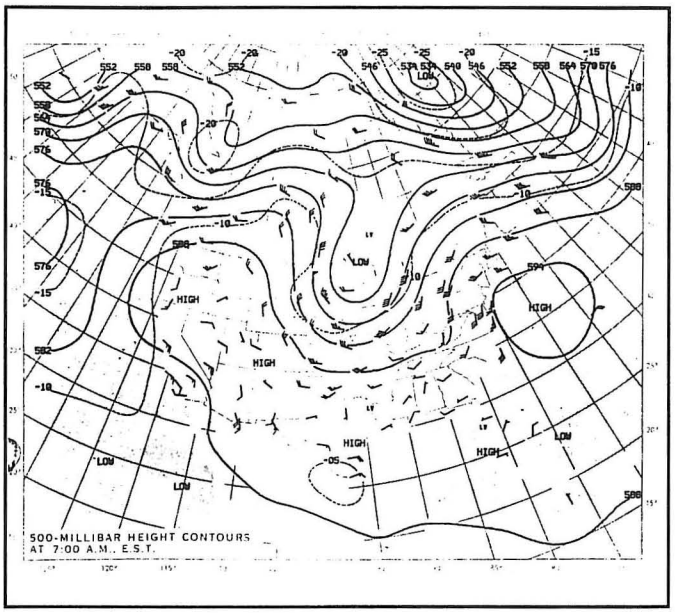

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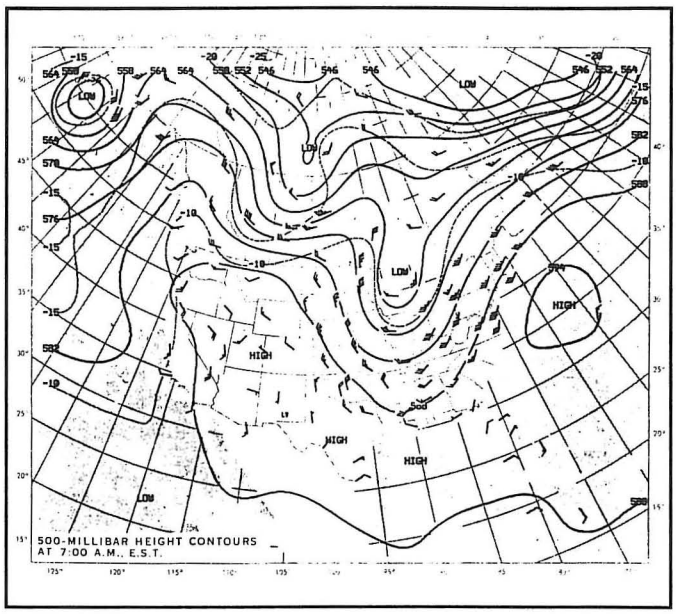

(d)

Fig. 13. Standard NWS/NCEP 500-mb analyses for 1200 UTC (a) 19 July, (b) 20 July, (c) 21 July and (d) 22 July 1994 showing evolution of mid-level flow during the tropical surge depicted in Fig. 12. The surge reached Wilmington, DE on the 20th and reached southern New England the following day.

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