NOAA Technical Memorandum NWS WR-120

SOME METEOROLOGICAL ASPECTS OF AIR POLLUTION IN UTAH WITH EMPHASIS ON THE SALT LAKE VALLEY

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Salt Lake City, Utah
June 1977

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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NATIONAL WEATHER SERVICE
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CONTENTS

FIGURES

SOME METEOROLOGICAL ASPECTS OF AIR POLLUTION IN UTAH WITH EMPHASIS ON THE SALT LAKE VALLEY

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In order to better understand air pollution in the Salt Lake Valley, we must first understand what air pollution is. It cannot be defined simply as the *"stuff coming from all those smoke stacks"* nor simply the fault of the automobile. Rather, it must be thought of as all airborne substances be they solid particles, liquid droplets, gases or various mixtures of these forms. They result from almost all complex phases of human activity and some natural phenomena.

The principal sources of these pollutants come from combustion of fuels. The primary pollutants emitted from combustion are compounds of sulfur, carbon, nitrogen, organic compounds, and solid particles called "particulates" which range from very fine to coarse.

These pollutants react with each other or with natural ingredients of air such as oxygen to form still other substances. These so-called secondary pollutants are often the most troublesome which air pollution control agencies are required to abate. One of the principal examples of this type is the photochemical pollutant.

A photochemical reaction can take place in the surrounding air when pollutants are exposed to strong sunlight.

In order for a compound to be affected by sunlight, it has to absorb the light energy and the energy has to be sufficiently high to rupture the electron bonds of the substance. Compounds of nitrogen and carbon are normally the agents involved. Large amounts of these compounds (oxides of nitrogen and hydrocarbons) are formed by high-temperature, high-compression combustion. A major source of this type of combustion is the internal combustion engine (cars and trucks) which do not have catalytic converters or other control mechanisms.

The higher the compression ratio and the leaner the fuel to air ratio, the greater the percentage of oxides of nitrogen. Poorly tuned engines also emit more hydrocarbons.

Nitrogen dioxide has a brownish color which absorbs light readily. The sunlight energy breaks nitrogen dioxide into nitric oxide and atomic oxygen which reacts with organic materials (hydrocarbons) to form ozone and other complex pollutant compounds known to be detrimental to humans and plants (Environmental Protection Agency 1971a; U. S. Department of Health, Education, and Welfare 1966).

Particulates found in the air are usually unburned products of combustion, grinding, drying, etc., or are wind-produced natural dust. They are primarily responsible for the soiling of clothing and furniture and the most important pollutant in visibility reduction. Visibility reduction is the one sensory effect which is universally acknowledged and plays a large role in the Salt Lake Valley, especially during periods of winter wind stagnation.

Natural particulates (mainly wind-produced dust and salt particles) are a category which is impossible to control. In fact, they play an important role in nature's scheme of things by providing necessary hydroscopic nuclei on which precipitation is formed.

The most common sulfur compounds are the oxides of sulfur. Research evidence seems to be quite conclusive that sulfur dioxide, in high concentrations, has detrimental effects on both humans and plants. The main sources are from the burning of fossil fuels, particularly coal and coke and from the processing associated with smelting of minerals. The use of coal as a home heating material in Utah has been largely replaced by natural gas and electricity during the last 30 years. However, coal and coke still find important applications in industry, especially in smelting of ores (Jackman 1968). Also with petroleum fuels likely to become increasingly scarce in the near future, a return to use of greater amounts of coal is highly probable. Many industries are actively engaged in installation or already have in operation various types of washers, scrubbers, and electrostatic precipitators to control sulfur dioxide emission. Another compound is sulfur trioxide. Although concentrations are very low, when available with water droplets (fog), minute droplets of sulfuric acid can form (Environmental Protection Agency 1971; U. S. Department of Health, Education, and Welfare 1966).

All of these pollutants are typical of an urban area, however, some areas have a predominance of certain types, e.g., Los Angeles is predominated by "photo chemical" because of the great number of automobiles and lots of sunlight (Los Angeles Air Pollution Control District 1962), while London is troubled by sulfur dioxide and particulates because so much coal is burned (Environmental Protection Agency 1971b). Salt Lake would have to be classified as a mixture of all types depending mostly on the time of year and associated weather conditions (Jackman 1968).

The onset of a pollution episode does not result from a sudden increase in pollution output but rather is directly related to meteorological conditions which trap pollutants near the ground. As the industry and population continue to grow, pollution sources also increase. This is offset somewhat in recent years by state and federal efforts in pollution control. Pollution concentrations can fluctuate abruptly due to meteorological conditions. High concentrations of some pollutants can occur when the air seems relatively clear, since they are gas compounds and invisible or odorless. For example, carbon monoxide is an important invisible pollutant. The major source of carbon monoxide is the automobile. Therefore, it must be considered when planning major highways and parking areas so that it will not become concentrated and reach dangerous levels. With the use of catalytic converters on newer cars, carbon monoxide levels will be greatly reduced.

Also on a "smoggy"-looking day some types of pollutant levels may still be very low. Therefore, it is not wise to rely entirely on our senses as an index of pollution seriousness.

More and more evidence is being compiled to substantiate theories that pollution has an effect on the environment as well as the environment affecting pollution. Certain plants are more susceptible to pollution damage than others. Pollution cuts down the amount of sunlight during the day and radiation at night, thus affecting temperatures. Pollution particulates act as nuclei around which fog droplets develop. Also, they may act as cloud-seeding agents to cause increased rainfall (Environmental Protection Agency 1971a; U. S. Department of Health, Education, and Welfare 1966; Environmental Protection Agency 1972).

The air pollution problem of Utah can be divided into definite types and periods. The most obvious period extends from the latter part of November through February, and could be classified as the winter problem. It is during this period that 78 percent of anticyclones (stagnant high-pressure areas) occur each year in the valley. This results in extended periods of stagnation with its accompanying temperature inversions. The strongest temperature inversions for the continental U. S. occur in our intermountain area, due to drainage of cool air down from mountains to valley areas and dry air which allows strong nighttime radiational cooling. Normal cloud cover and low sun angle at this time of year do not allow photochemical pollutants to become a noticeable problem. The main pollutants are trapped under the intense temperature inversion in the valley and can gradually increase in concentration as the number of days of stagnation are prolonged. This results in the period being characterized by poor visibility, with increasing accumulations of smoke and haze. Also during this period, fog is quite common since sufficient low-level moisture is normally present (Jackman 1968).

A typical stagnation episode of this type occurred in January of 1976. A cold front moved across Utah on January 11 and 12 dropping some light snow. High pressure moved into the area behind the front and by the 14th was centered at the surface over Utah (Figure 1). It became stationary and gradually stronger with time. As the light snow melted the moisture content of the air near the ground increased and additional moisture was added from the Great Salt Lake.

Visibility in the Salt Lake Valley was 30 miles or more on the 13th gradually lowering to 5 miles with smoke by the 15th and 2 miles by the 16th. Between the 16th and 24th it varied down to as low as zero when fog developed (Figure 2). Pollution trapped under this stagnant high gradually increased. In fact, sulfur dioxide levels in the west portion of the valley threatened to go above state ambient levels. A large copper processing plant in the area voluntarily closed down operations, rather than risk exceeding these levels (Figure 3) (Utah State Department of Health 1976).

Most episodes are ended by the approach or passage of a cold front. If the air mass behind the front is colder than the trapped stagnant air, it will displace it resulting in a dramatic termination of the episode

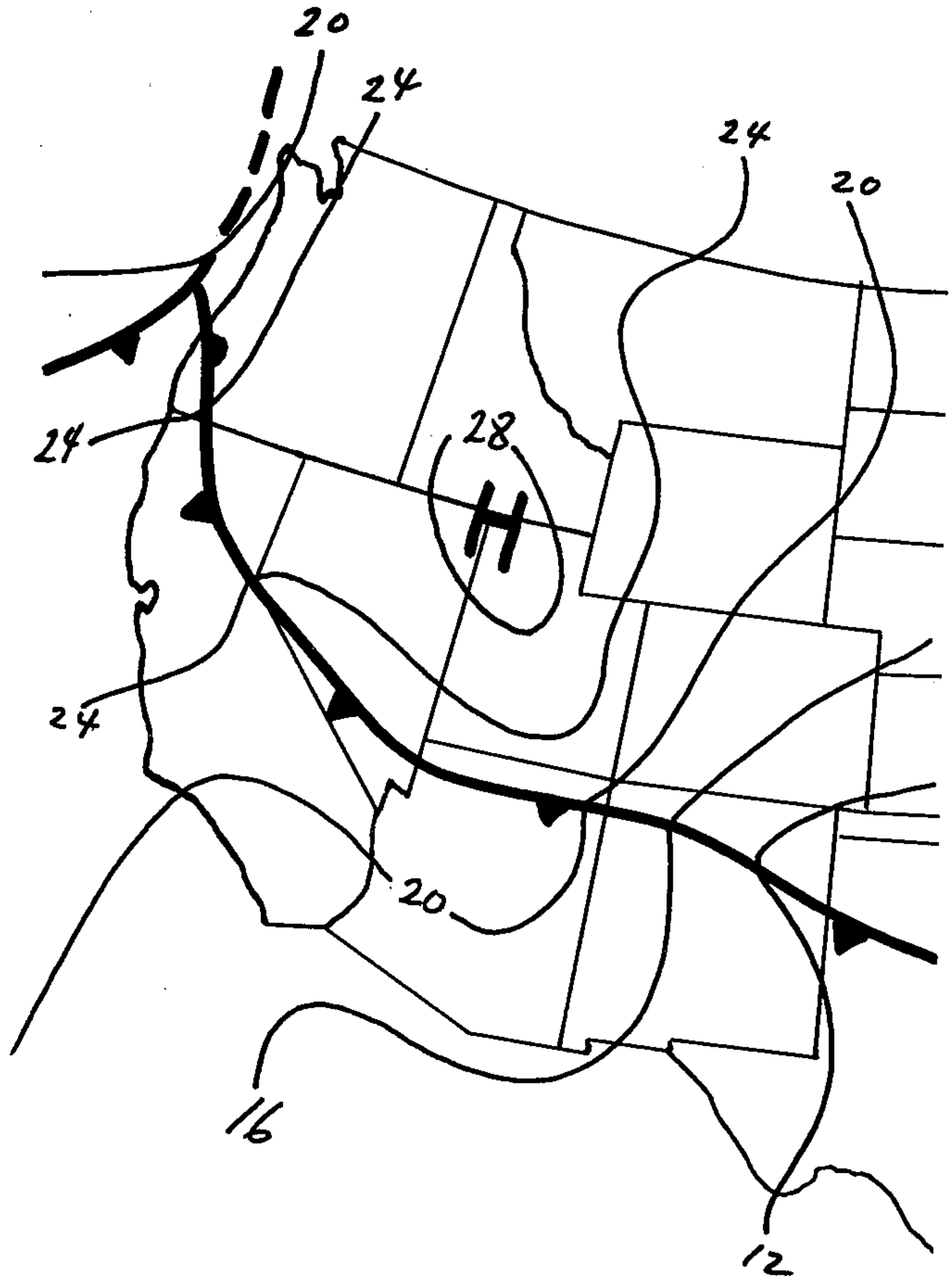

FIGURE 1. 12 Z January 13, 1976, Surface Map

High pressure and light winds develop over Northern Utah.

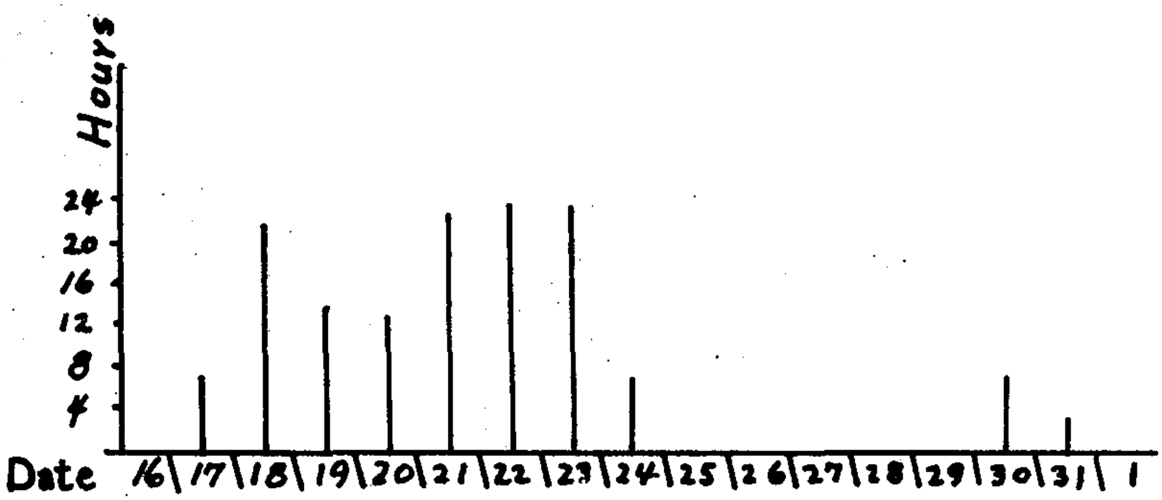

Figure 2.
Daily hours visibility reduced below two miles by smoke or fog at Salt Lake Airport during January 1976.

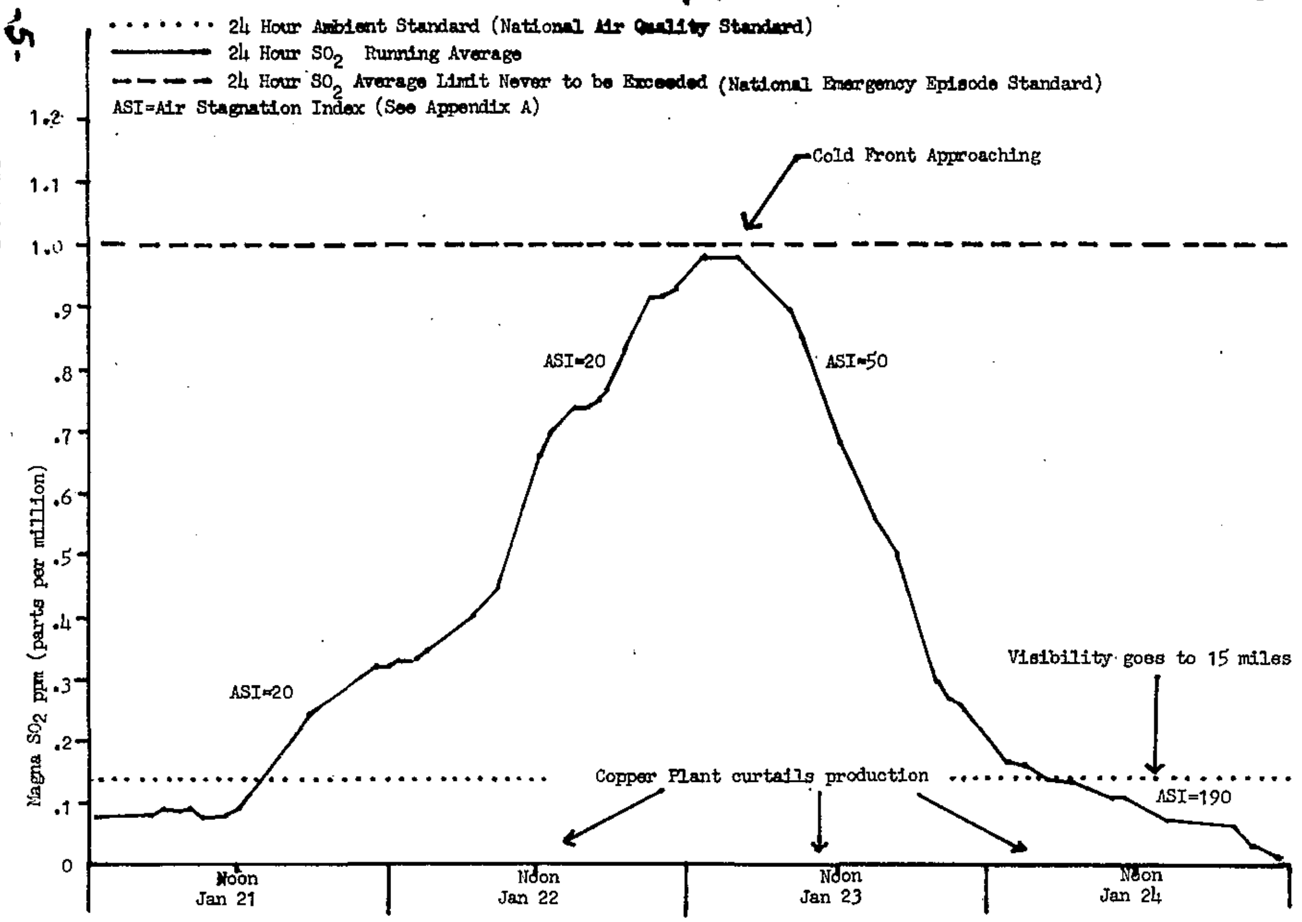

Figure 3. Peak concentration of SO_2 at Magna, Utah, January 1976 - Data Courtesy of Utah State Division of Health

(visibility will improve from less than two miles to above 15 miles in an hour or so).

Southerly winds ahead of a front will ride above the trapped cold air. It has been found subjectively, when they reach about 20 to 25 knots, the eddy mixing along the boundary of warm and cold air slowly works downward starting a slow, improving trend possibly ending the episode before the front arrives. Also if the air mass behind the front is warmer than the cold, trapped stagnant air, it too will initially ride over the top. However, associated turbulent mixing will begin at the boundary layer slowly working downward and this accompanied by any precipitation with the front will begin a gradual improving trend. On the 23rd of January this is the case (Figure 4). Apparently southerly winds ahead of the front and then the front riding over the top of the stagnant, cold air initiated a slow improving trend on the morning of the 23rd which lasted till the afternoon of the 24th when the process resulted in visibility improvement to 15 miles.

The Salt Lake winter-type pollution has disturbing similarities to episodes which occurred in London (1952) and Donora, Pennsylvania (1948). These episodes were widely recognized as serious threats to health and property. The similarities are: (1) the occurrence of a trapping temperature inversion and very stable atmosphere for long periods of time, (2) weak wind field, (3) the simultaneous occurrence of fog giving a combination of small water droplets, and (4) a high industrial source of gaseous pollutants, which are easily assimilated in the lungs (Environmental Protection Agency 1971a; U. S. Department of Health, Education, and Welfare 1966). Also, the poor visibility becomes a hazard to automobile travel and particularly hazardous to aircraft operation. Since temperatures in the fog are often below freezing, fog seeding with dry ice has been successfully used to temporarily dissipate the fog at the airport so scheduled airlines can continue to operate. However, this does not noticeably clear the smog from the air mass.

The worst extended period of smog and fog in the Salt Lake Valley was recorded during the winter of 1951 when near 20 (19-2/3) consecutive smoggy days were registered. Figure 5 is a graphical representation of episode periods. These data include only extended periods (96 hours or more rounded to whole days) of visibility three miles or less in smoke or a combination of smoke and fog during the months of November through February from 1934 to January 1977. Brief fluctuations above three miles were discounted.

The period between March and the forepart of May can be classified as the most pollution free period in the valley (Figure 6). This is the period when weather fronts from the Pacific move through with the most regularity resulting in frequent changes of air mass and much cloudiness and wind. This causes the period to be the wettest of the year. Inversions are at a minimum during these months and only five percent of the yearly anticyclones occur during the period.

From the latter part of May through the forepart of September, when the sun angle becomes high, the temperatures become high enough and sunlight strong enough to allow photochemical pollution to become important. Only

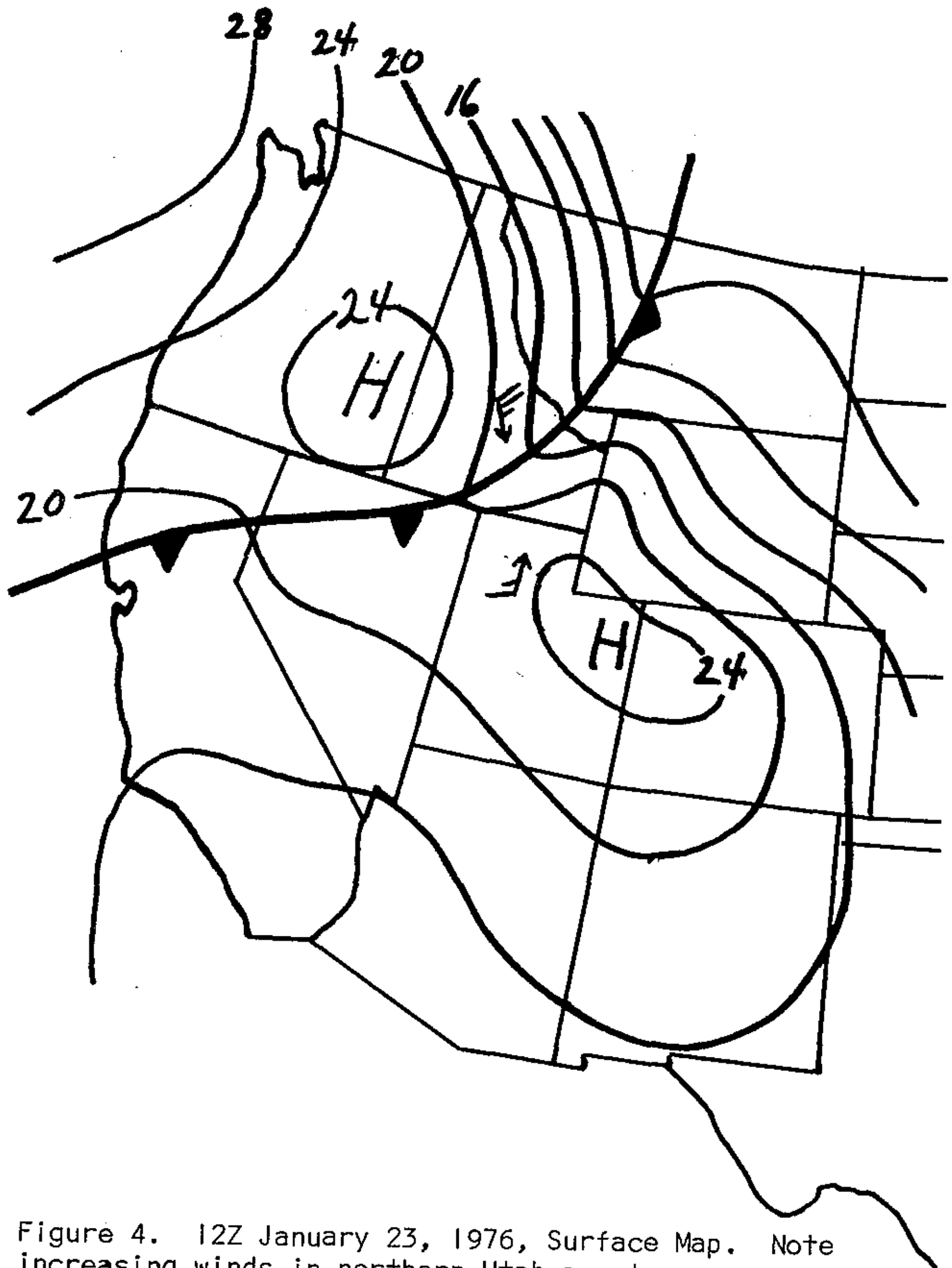

Figure 4. 12Z January 23, 1976, Surface Map. Note increasing winds in northern Utah as stronger pressure gradient along frontal zone moves toward Utah.

DURATION & FREQUENCY OF AIR POLLUTION EPISODES - SALT LAKE VALLEY

EPISODES 4 DAYS AND LONGER

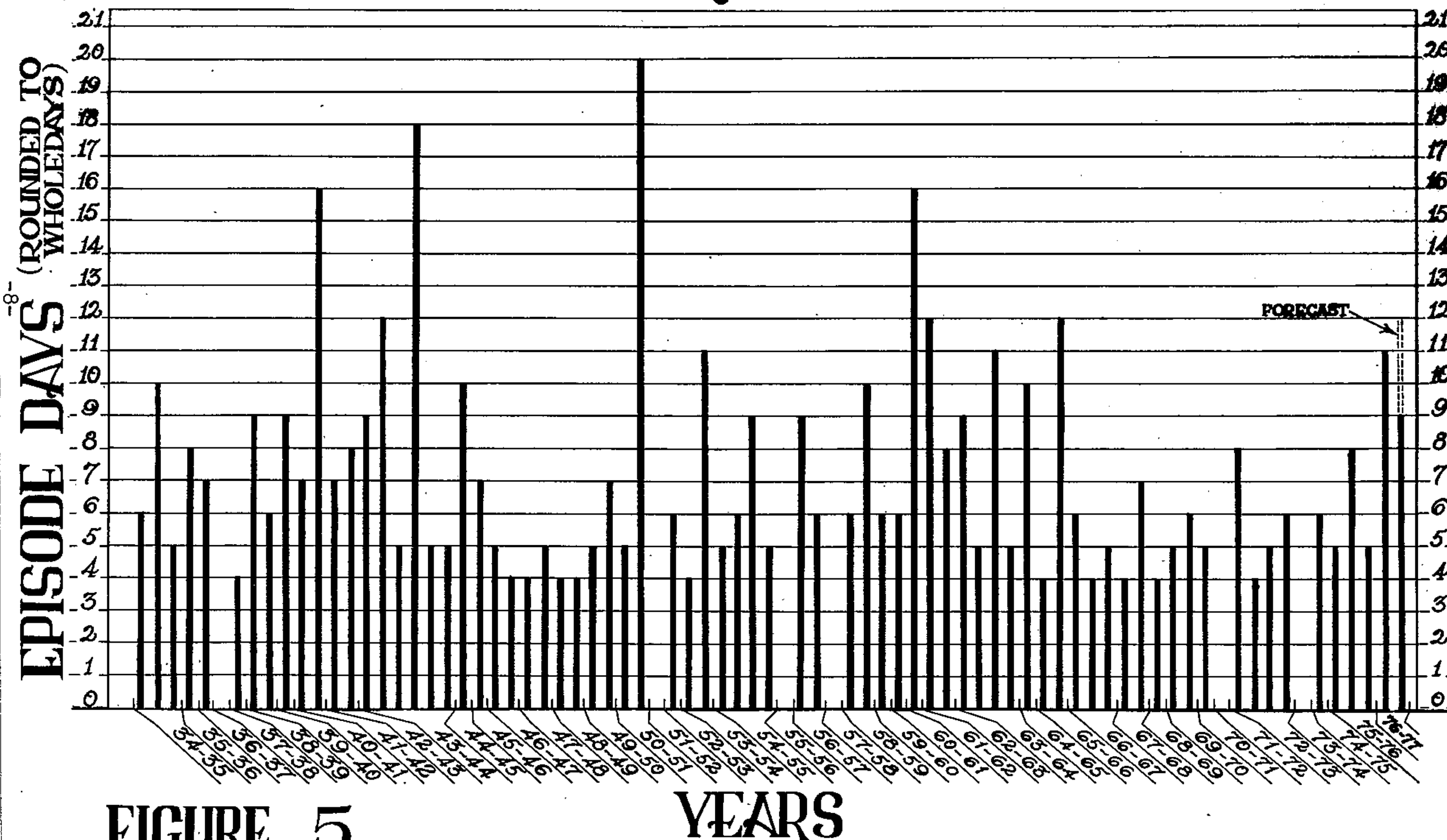

FIGURE 5

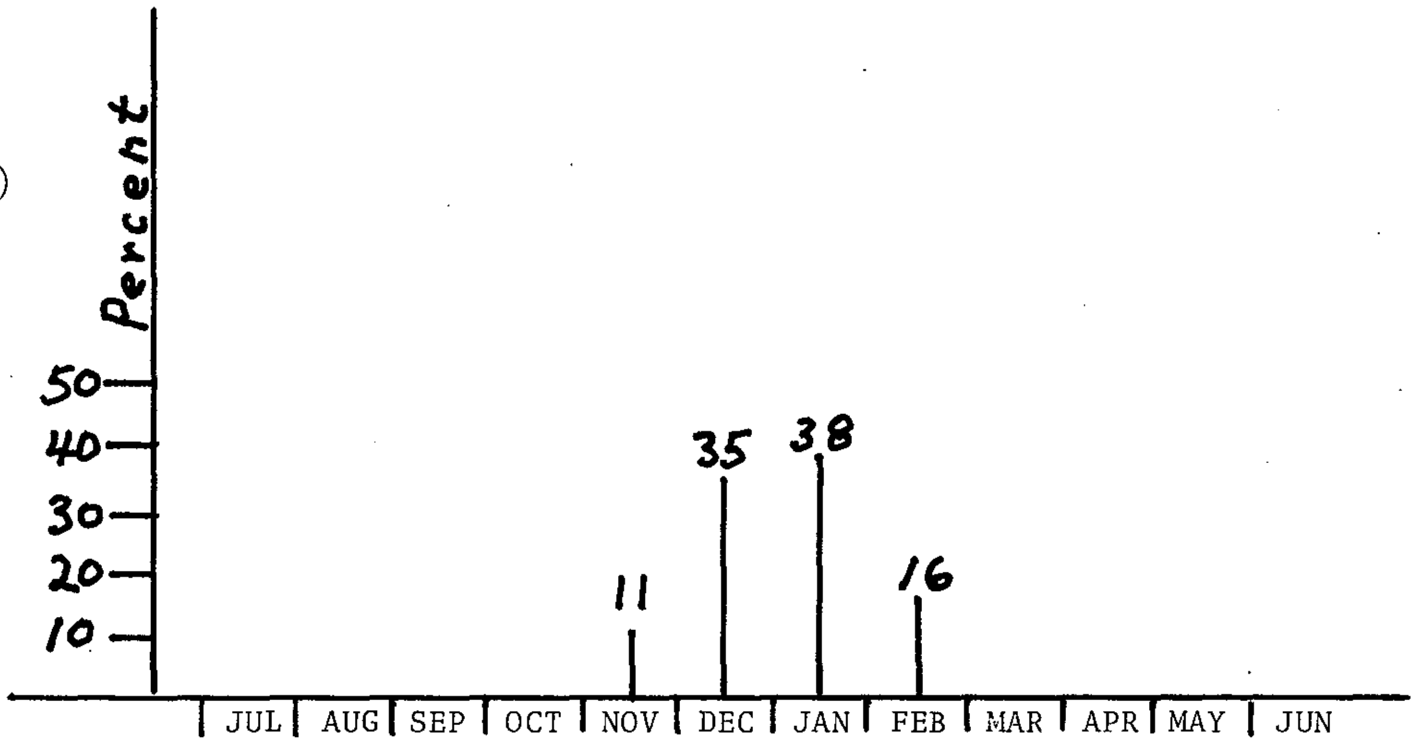

Figure 6. Average percent of episodes by month.

two percent of the anticyclones occur in this period but large numbers of clear nights allow shallow but strong temperature inversions to build up almost nightly. Studies made at the University of Utah show that ozone levels, which are a result of photochemical reactions, can rise higher than those found in Chicago, Boston, and Beltsville, Maryland, and similar levels to Philadelphia, Cincinnati, St. Louis, and San Francisco; but two to three times lower than levels in Los Angeles (Hill and Tingey 1967). This seems to prove that there is a photochemical pollution problem in the Salt Lake Valley during the summertime. This is probably the reason the Wasatch and Oquirrh Mountains are becoming nearly indistinguishable from the center of the valley at times due to an opaque, bluish haze on hot summer afternoons. Local air quality control officers are of the opinion that the automobile is at least 50 to 60 percent responsible for photochemical pollution with this factor increasing to 80 percent along congested freeways. Fortunately this is one pollutant problem which can be solved. Pollution control devices are now being added to all new cars and trucks sold and in time should gradually relieve the problem of photochemical pollutants. (The period between late September and early November is a transition period which can be characterized by both winter- and summer-type pollution but usually is not severe or prolonged.)

The two most important meteorological conditions with respect to pollution in an area are (1) how well the pollutant can be mixed in the vertical or stability of the atmosphere and, (2) the horizontal transport of pollutants or wind speed. Under stagnant, high anticyclonic (high-pressure) conditions, winds in the Salt Lake Valley are very light, controlled mainly by interaction of the nearby Great Salt Lake and mountains. Due to these two features, winds show a diurnal regime blowing from land to water at night and reversing during the day. In any case under a stagnant high, they remain very light.

In an attempt to portray the long-term trend of pollution in the valley, a graph using 5-year running averages of two-day (48 hours) or more episodes of high pollution using visibility as the indication, was developed. The periods 1934 to 1976 were researched and are found in Figure 7.

In the authors' opinions, some fluctuation of the curve can be explained rather easily while others are rather puzzling. For example, the strong peak during World War II is likely due to rapid industrial expansion and use of coal for heating. The rapid decrease around 1945 likely reflects the change over from coal to natural gas as a home heating fuel. The rapid increase again around 1958 is due to rapid increase in number of cars and trucks and population increase during the period. The decrease in late 60's is not too clear other than a period when winters were characterized by their storminess and a low number of stagnant highs. Finally, it would seem we are in a rising trend again with increasing stagnant periods (see dotted forecast line of Figure 7). To a degree, this is verified by almost continuous stagnation during December 1976 when a high-pressure ridge dominated the western United States.

Data based on periods 48 hours or longer of visibilities 3 miles or less in smoke or a combination of smoke and fog during the months of November thru February 1934 to 1975. (brief fluctuations above 3 miles were discounted)

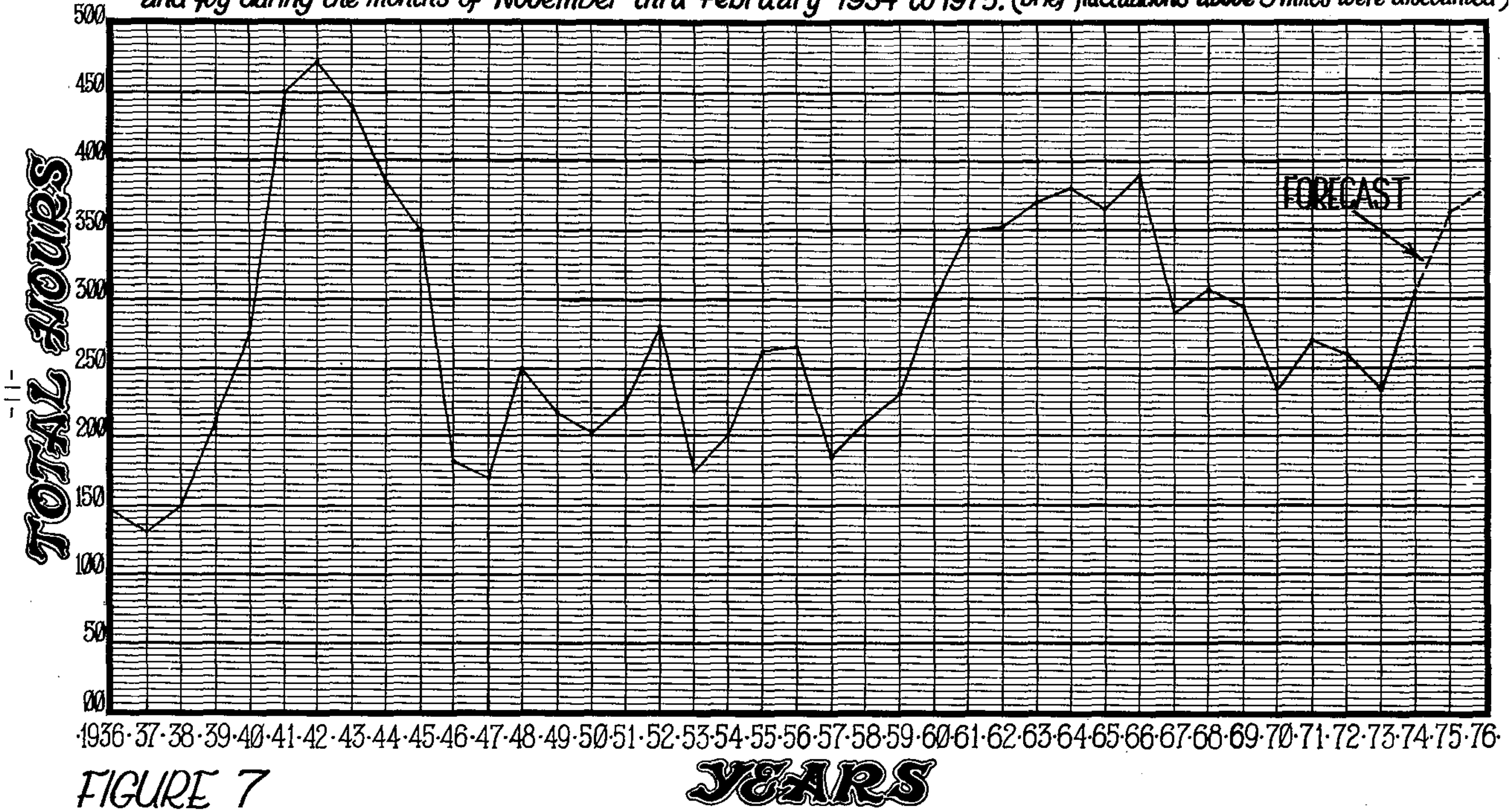

FIGURE 7

RUNNING 5 YEAR AVERAGE OF AIR POLLUTION EPISODES AT SALT LAKE CITY
(EPISODES 48 HOURS AND LONGER)

It should be emphasized that this does not necessarily reflect the increase or decrease of all pollutants but is rather a measure only of visibility fluctuation. Visibility is the only long-term parameter available which may reflect pollution.

A summary of the 42 years of data (1934-76) of air-pollution episodes for Salt Lake City indicates the following:

Average number of yearly episodes (4 days or more) = 1.7 per year.
Average number of yearly episodes (6 days or more) = 1.0 per year.
Average number of episodes (15 days or more) = 1 each 10 years.

38 percent of all episodes occur in January.
35 percent of all episodes occur in December.
16 percent of all episodes occur in February.
11 percent of all episodes occur in November.

Since 1967, the National Weather Service Forecast Office at Salt Lake City has been calculating an "Air Stagnation Index" (ASI) daily. The index is a nondimensional number reflecting the atmosphere's ability to disperse pollutants. Using the morning radiosonde at Salt Lake City, parameters are forecast for the afternoon (period of maximum mixing), and an index is calculated as well as the outlook for the next day. This is furnished to the Utah State Health Department which is responsible for air-pollution matters in Utah. On the basis of the index, burning permits are issued or refused. Empirically, we have noted that visibilities three miles or less during stagnation periods correlate well with ASI values of 500 units or less and severe periods with 200 or less. A new index is currently being tested in cooperation with the U. S. Forest Service and Utah Department of Health which will be more appropriate to higher elevations (6,500 feet and above). Methods of deriving indexes for areas of the state where radiosonde data are not available, e.g., valleys of eastern Utah, have also been developed. See Appendix A for more detailed discussion of ASI calculation.

Another special problem is computing an index for hot pollution sources, such as rocket testing. Some thoughts on this problem may be found in Appendix B.

Holzworth (1967) developed a method which theoretically combines all the important meteorological parameters affecting air-pollution buildup, to allow the air-pollution "potential" of various cities to be compared during the morning and afternoon periods. He has used the method to compare the pollution potential in New York, St. Louis, Salt Lake City, and Los Angeles. When actual city size is used, Salt Lake City is second only to Los Angeles in high pollution potential. If one considered all the cities to be the size of Los Angeles, Salt Lake City takes over the first place during the morning for highest potential pollution. This is due to the high frequency of early morning, intense, shallow inversions in the valley (Holzworth 1967). Later research by the Air Resources Laboratory, a branch of the National Oceanic and Atmospheric Administration

(NOAA), indicates Salt Lake City ranks fifth in air-pollution potential when compared to 25 high-potential cities across the country (Air Resources Laboartory 1969).

Of course, these are only theoretical calculations, but it does point out the potential for severe situations to develop in the Salt Lake Valley and the necessity of continuing to work to control pollution.

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APPENDIX A

UTAH AIR STAGNATION INDEXES (ASI)

The air-pollution potential of an area is directly related to two variables. First, the vertical diffusion of pollutants, conveniently called the "mixing depth". Second is the wind speed in this mixing depth which results in the horizontal transport of pollutants.

In order to evaluate the pollution potential of an area, these variables must be analyzed if specific data are available or "inferred" from the synoptic situation if specific data are not available. Radiosonde data of vertical structure of winds, temperature, and humidity would be the prime source of specific data, while surface and upper air weather maps, as well as knowledge of local topography and climatology, must be used in other areas.

In an attempt to quantitatively assess these variables in Utah valleys and mountains, an air-stagnation index has been developed. These are numerical nondimensional values ranging from less than 50 in the worst stagnation conditions, to more than 1000 in the least stagnant conditions.

In Utah, the worst stagnation occurs for prolonged periods with stationary high pressure, both at the surface and aloft, mainly in the months of November through February. Cold air trapped in valleys, combined with good radiation conditions and snow cover, result in strong surface inversions. Usually warm-air advection above the inversion, associated with the high-pressure aloft, tends to strengthen the stable condition at the surface. This stagnant layer is generally confined to below 6,000 feet ASL. Under these conditions, diurnal heating is unable to destroy the stable layer making the mixing depth very shallow. Winds are largely controlled by local topography rather than pressure gradients, so are very light and often show a diurnal reversal limiting any horizontal transport. At the same time, elevations above 6,500 feet often enjoy good ventilation due to the warm advection resulting in mild temperatures and good mixing depths. Also, winds at these elevations are usually still controlled by pressure gradients and are frequently stronger. Valley indexes frequently drop below 200, while higher elevations may have 600 or greater. In later discussions, this type will be referred to as Type I.

Another situation which allows somewhat more mixing in valleys, but may present greater problems at higher elevations, is that caused by the subsidence inversion or stable layer. This results from the settling of warm air at high altitudes and the development of a stable layer between about 6,000 and 12,000 feet ASL. Surface heating usually allows mixing to the base of this stable layer which gives a moderate mixing depth in valleys. However, the base of the stable layer may be at or just above higher mountain areas, and may severely restrict the vertical transport of pollutants. Indexes between 200 and 1,000 are common with this situation. This type will be referred to as Type II in later discussions, and could be of great significance to forestry personnel concerned with smoke management. These conditions frequently occur during the fall when controlled burning is in progress.

A third situation, and one which presents the least threat of stagnation in Utah, is when the vertical temperature lapse rate approaches the dry adiabatic rate. This occurs almost every afternoon during the summer and during stormy weather at other times. Mixing depths may exceed 20,000 feet during the hot summer days due to thermal convection. Mixing during stormy weather is due to a combination of things, e.g., vertical motions associated with cyclonic pressure patterns, mechanical mixing with strong winds and due to topography, and also "washout" associated with precipitation. Indexes with this type are often more than 1,000 and will be referred to as Type III in later discussions.

These three "types" by no means cover all of the possible combinations or situations which develop. However, they probably cover the majority.

FORECASTING AIR STAGNATION INDEXES (ASI) IN UTAH

Along the Wasatch Front where specific data are available:

I. Type I: Strong surface inversions or stable layer not destroyed by diurnal heating.

   A. Forecast maximum afternoon temperature and follow that potential temperature line up until it intersects the 12Z sounding temperature trace. This is the forecast mixing depth (L).

   B. Forecast the average afternoon wind in the mixing depth L. This is (A).

   C. Then: ASL = (L) (A)/100.

II. Type II: Diurnal heating to base of subsidence inversions or stable layer between 6,000 and 12,000 feet ASL.

   A. Forecast any change in height of base by 00Z. This is mixing depth (L).

   B. Forecast average afternoon wind in L. This will be (A).

   C. ASI = (L) (A)/100.

III. Type III: Miscellaneous situations. May cover hot summer afternoons to winter storms. Professional judgment in applying the method must be used by the forecaster to arrive at a reasonable value to express the situation. The method uses a formula to calculate the lifting condensation level (LCL) to assess the mixing depth. It is further "massaged" in an attempt to account for unrealistically low indexes which would occur under saturated conditions, as well as to account for washout and entrainment during precipitation.

A. If a cold frontal passage or upper trough strong enough to result in complete change of air mass is forecast by 00Z, then forecast ASI = 1,000 + without further computation.

B. Otherwise: Mixing depth L = LCL = 220 $(T_{max}-\bar{T}_D)$ $\bar{T}_D$ is approximated by 850mb DP except when Temp-DP spread is less than 5C. Then subjectively it was found the 750mb DP gave a more realistic value (American Meteorological Society, 1959).

C. Forecast average afternoon wind in L. This is (A).

D. ASI = (L) (A)/100.

E. Multiply above ASI by precipitation factor K where:

K = 1.5 when forecast PoP is 40%-50%.
K = 1.7 when forecast PoP is 60%-70%.
K = 1.9 when forecast PoP is 80% or higher.

F. If value is greater than 1,000, use 1,000+.

Other areas where specific data are not available:

1. Fabricate sounding for area, physically or mentally.

   A. Fabrication tools:

      1. Maximum and minimum temperatures.

      2. 850mb, 700mb, and 500mb charts to estimate temperatures and winds over the specific area.

      3. Surface winds or knowledge of topography to estimate surface winds under specific synoptic situation.

   B. Check surrounding radiosonde sounding (Ely, Grand Junction, Winslow, Salt Lake City, Boise, Winnemucca, or Las Vegas) to detect subsidence inversions.

   C. In mountain areas, consider the following:

      1. Mountain valleys likely to have intense but shallow surface inversions, but mountain slopes are not likely to develop inversions due to drainage.

2. Forecasting average winds consider Venturi effect along ridges and also diurnal drainage winds.

D. Use previous methods to calculate ASI. With no specific data available, forecaster may want to consider a range of ASI rather than specific value.

Verification:

1. The morning forecast ASI is verified by using the afternoon sounding, as well as forecaster's professional judgment. The same method is used to make verification as was used to make forecast, e.g., use Type III with K precipitation factor when used in the morning, etc.

2. If the afternoon sounding is not representative of the general area, then judgment is used in calculating a verification value, e.g.,

   A. Canyon wind situation.

   B. Inversion already formed at very low levels on the afternoon sounding which probably was not there at time of maximum heating.

   C. Use maximum temperature rather than the current temperature at surface of sounding.

   D. During winter consider times when a very shallow layer is trapped at the airport which is not present over the majority of the valley.

   E. Inversions which have resulted from cold frontal passage should not be used in calculation, rather use 1,000+.

APPENDIX B

THOUGHTS ON RELATIONSHIP OF ASI TO HOT POLLUTION SOURCES

Current methods of calculating ASI values do not adequately cover those sources of pollution which burn at very hot temperatures. Examples would be rocket testing and controlled burning of piled slash by the Forest Service.

The heat generated from these sources results in a buoyancy force which must be considered when estimating the vertical rise of associated pollutants. Also in the case of rocket testing the momentum of the effluent should be considered. Another factor which is not well understood and will be ignored in the paper is deposition of both particulate and gaseous airborne materials. This is accomplished by such things as gravitational settling, scavenging by precipitation, surface impaction, electrostatic attraction, absorption and chemical reaction. Only those pollutants which are gaseous or sufficiently small to be carried aloft will be considered.

A hot source will emit a volume of gas with a buoyancy and possibly some velocity. It behaves according to the magnitude of the heat and velocity parameters and the prevailing meteorological conditions of the atmosphere in which it is released.

Relative to its total travel, an effluent quickly attains the speed of the surrounding air mass into which it is thrust. However, it rises (or its buoyancy is determined) by its heat and molecular weight differences.

Rise of a plume is affected at first by entrainment with surrounding air and later as it slows, by atmospheric turbulence, which becomes the dominant feature.

There have been more than 20 formulas developed which attempt to calculate plume rise. None are universally accepted, primarily because of the lack of substantiating test data. The fact that the plume is often still rising after becoming invisible through turbulent mixing complicates the picture.

The formulas fall into three categories: (1) empirical, (2) semiempirical, and (3) dimensional-analysis.

Test data available seem to support the dimensional-analysis as the best solution (U. S. Atomic Energy Commission 1968).

Since momentum rise does not add much to the problem, it reduces to determining buoyancy. Briggs (1965) has developed dimensional-analysis formulas for buoyant sources which give consistently good results for all sources, sizes, and distances downwind and which take into account atmospheric stability. The best of these is the equation for buoyant transitional rise. Transitional rise is defined as the trajectory before the final height is approached and is not much dependent on stability.

Since dimensional-analysis cannot predict constants, they must be determined empirically. Empirical data do not exist to calculate constants under calm-transitional or calm-neutral stability conditions. Briggs' formulas are presented below:

WIND	TYPE OF ATMOSPHERE	FORMULA
Calm	Transitional	$\Delta h = \text{constant } F^{1/4} + t^{3/4}$
	Stable	$\Delta h = 5.1\ F^{1/4}\ S^{-3/8}$
	Neutral	$\Delta h = \text{constant } F^{1/4}\ t^{3/4}$
Windy	Transitional	$\Delta h = 2.0\ F^{1/3}\ \bar{u}^{-1}\ x^{2/3}$
	Stable	$\Delta h = 2.6\ (F/\bar{u})^{1/3}\ S^{-1/3}$
	Neutral	$\Delta h \simeq 10^3\ F\bar{u}^{-3}$.

Also developed was a conservative equation for estimating the final height of plume rise:

$$\Delta h > 400\ \left(\frac{F}{\bar{u}^3}\right) .$$

List of Symbols Used

Δh = Plume rise.

Q_h = Rate of heat emission of a continuous source.

F = Buoyancy flux = $g\ (\Delta T/T_s)\ wr^2$.

S = Stability parameter = $\frac{2}{T}\ (\partial\theta/\partial z)$ where $\partial\theta/\partial z = \underline{T} + 9.8°c/km$.

$\bar{u}$ = Average value of wind component in the direction of the mean horizontal vector.

X = Downwind distance.

T, T_s = Absolute temperature of ambient and plume air, respectively.

W = Effluent velocity.

r = Radius of discharge unit.

g = Gravitational acceleration.

Data gathered by Van Blect and Boone (1964) from exhaust clouds of horizontally fired rocket motor under windy conditions enable us to calculate transition plume rise:

When $Q_h = 7.2 \times 10^6$ cal/sec.

$F = 31{,}600$ ft $^4/\text{sec}^3$.

$\bar{u}$ varies from 7 to 19 ft/sec.

Choosing x as 1,000 ft and $\bar{u} = 10$ft/sec.

$$\Delta h = \frac{2.0\ (31{,}600)^{1/3}\ (10^3)^{2/3}}{10} = 1362 \text{ ft}.$$

Final rise height $\Delta h > 400 \dfrac{31{,}600}{1{,}000} > 12{,}640$ ft.

If a Q_h and proper meteorological parameters are known or can be estimated, then an estimated rise value can be calculated using the above formula. This rise value could be considered a mixing depth and then used in calculating an improved ASI value for hot sources or the rise value could be considered as the point of release and data from this point and upward used to calculate some type of improved ASI.

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