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METEOROLOGICAL FACTORS IN THE FORMATION OF REGIONAL HAZE

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METEOROLOGICAL FACTORS IN THE FORMATION OF REGIONAL HAZE

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ABSTRACT

The purpose of this research project was to determine the role of meteorological factors in the formation of widespread areas of haze in the eastern United States.

Three case studies were made: A summer haze episode, an off-season haze episode and a non-haze episode.

Results showed that over the course of 2 or 3 days emissions from widely separated sources such as St. Louis, Chicago, Cincinnati and Pittsburgh are leafed together by vertical and horizontal shears and mixing by daytime convection to form a dilution volume many hundreds to well over a thousand km in extent and 2 or 3 km in depth. Almost all stations reporting haze during an episode were confined to this dilution volume and most of these in that part of the plume containing emissions that were 2 or 3 days old.

The dilution volume associated with the off-season episode was of about the same magnitude as that of the summer case, but was shallower and horizontally more extensive. Both of these 3-day haze volumes were much smaller than the dilution volume associated with the non-haze case which blanketed almost the entire eastern United States.

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SECTION 1

INTRODUCTION

Extensive areas of hazy air covering major portions of the Eastern United States have become a frequent summertime occurrence during the last few decades. This regional haze, though well described by satellite observations and the conventional surface synoptic network, Lyons (1978), is not as well understood as the smaller, meso-scale visibility blight associated with plumes from individual point or area sources such as power plants and urban complexes. A variety of models have been developed for these meso-scale plumes. But, as is reported in a recent study by the National Academy of Sciences, Middleton (1981), the modeling of regional haze is not nearly as far advanced.

The present study is directed toward improving our understanding of the meteorological mechanisms involved in the formation of such large volumes of more or less uniformly polluted air. It is a diagnostic enterprise. Its purpose is to provide information useful for constructing models of the regional haze formation process.

SECTION 2

CONCLUSIONS

Synoptic-scale motions revealed by rawinsondes and surface wind reports combined with daytime vertical mixing motions up to the 800 or 700 mb levels distribute emissions from widely separated continuous sources such as St. Louis, Chicago, Cincinnati and Pittsburgh over a widespread area hundreds of miles across and more than a thousand miles long in a period of 2 or 3 days.

The combined plumes (superposed dilution volumes) for these four cities, constructed in accordance with the observed flow fields at the surface, 950 mb, 900 mb, 850 mb and 800 mb levels, coincide well with observed areas of widespread haze.

When haze forms it tends to do so in emissions 2 or 3 days old and in mixtures of emissions from several locations.

Haze episodes appear to differ from non-haze situations in having smaller dilution volumes, the result of smaller vertical and horizontal shears and weaker winds.

The summertime haze episode examined occurred in the absence of persistent (day and night) strong stable layers in the lower atmosphere. Strong low level inversions were the rule at night, but during the day convection several kilometers deep was typical with towering cumulus reported within the haze in a number of locations.

Widespread haze areas occasionally develop in seasons other than summer when there is considerably more stability in the lowest layer of the atmosphere. Apparently in these cases mixing up to only about 1 or 2 kilometers is involved as are somewhat stronger shears, resulting in shallower but horizontally more extensive haze volumes.

Both vertical and horizontal shears significantly influence the horizontal spreading of the dilution volumes with the vertical shear being the dominant factor.

SECTION 3

METHOD OF ANALYSIS

Air quality simulation models describing the long-range transport of air pollution have been devised. Usually they are based on a requirement of mass balance. The processes and mechanisms included are: emission, chemical transformation, physical removal, turbulent diffusion and transport.

The air motions used in these models are observed atmospheric motions, not air movement calculated from fundamental physical principles. Typically they are the observed wind averaged over the depth of the polluted layer or the wind observed at some standard level interior to the polluted layer, often the 850 mb level, (Nordö et al., 1974; Eliassen et al., 1975; Pack et al., 1978; Eliassen, 1980). A certain amount of observed detail in the wind field is lost in the process of constructing vertically averaged wind fields or in accepting the wind at any one level as being representative of the vertically averaged flow. These neglected (dispersive) motions are parameterized in the models by eddy diffusion terms. Some air quality simulation models have taken vertical wind shear within the polluted layer into account, notably Hidy et al., (1978) and Veltishcheva (1979) for travel times out to 24 hours. In the work reported here the winds at all levels within the polluted layer are used to determine the long-range transport and dispersal of pollution out to 3 day's travel from the sources. It is done for a number of haze episodes chosen from 30 years of record (1948-1978). The purpose is to discover the meteorological mechanisms associated with the formation of these extensive volumes of hazy air.

The analysis consists of constructing the previous 3-day history of the hazy air. It is assumed that the responsible pollutants came from the major air pollution sources in the eastern United States (large cities, power plants, etc.). A 3-day dilution volume is constructed for each major source. These individual dilution volumes overlap to form a conglomorate volume which contains all of the air which passed over the major sources. It may be assumed that this large conglomerate volume would also contain air from any other source, of whatever size, located in the area intermediate in location to the major sources.

The analysis makes use of the U.S. National Weather Services' surface observational and rawinsonde network in the eastern United States (see Figure 1) to provide descriptions of the flow features involved in the transport and dispersion of pollutant emissions. The streamline patterns shown in Figures 2 to 6 provide examples of the sort of mixing motions that can be resolved using wind data from the synoptic observations network.

Figures 2 and 3 reveal the three-dimensional structure of several vortices over the eastern United States, a definite continuity of pattern existing level to level from 950 to 900 to 850 to 800 mb. And Figures 4, 5, and 6 show the continuity in time over a three-day period of a large anticyclonic vortex as it moves across the eastern United States. The range of eddy sizes resolvable using the rawinsonde network is well illustrated by comparing the small cyclonic vortex in southern Louisiana in Figure 3a with the large anticyclone in Figure 5b which practically covers the entire eastern United States. And a scan of the other streamline maps in these two map sets displays eddies of many intermediate sizes within this range.

In reconstructing the extensive volume of hazy air the major sources of emissions, i.e. the large urban centers, are taken as continuous point sources. Their nighttime emissions are treated as plumes moving with the surface winds as reported on the 3-hourly surface synoptic maps. Their daytime emissions are assumed to mix vertically by thermal convection through the lowest 2 or 3 km of the atmosphere and to move with the observed wind fields at each level (50 mb intervals) within that layer. The shearing motions and translation combined with the vertical mixing produce a dilution volume associated with the particular source. The effects of horizontal motions on a scale smaller than those described by the streamline analyses are neglected.

A number of techniques were tried before the method described below was adopted as the one providing the best approximation of the volume of contaminated air produced by arrays of continuous point sources over periods of one, two and three days. The evolution moved from the approximate determinations reported by Edinger (1980) to the more rigorous procedures represented schematically in Figures 7 and 8.

Referring to Figure 7, at the initial instant, taken as 00 GCT, the emissions of interest begin leaving the source. During the subsequent twelve hours, nighttime, a plume is laid down at or near ground level. Its location is determined by constructing a streakline from the three-hourly surface wind maps. This streakline is constructed by connecting the 12 GCT end points of the trajectories of the air parcels that passed over the source at times 00, 03, 06, 09 and 12 GCT. This plume is represented in Figure 7a. It is assumed that vertical mixing motions are absent during this twelve hour interval.

During the subsequent twelve hour, day-time interval, 12 to 00 GCT, mixing motions distribute the emissions vertically through the layer from the surface up to the 800 mb level. (The reasons for choosing 800 mb will be discussed later). It is assumed that at a time not far removed from 12 GCT the surface plume develops vertically into a curtain which is subject to winds at all levels up to 800 mb. Shears in the wind with height carry the emissions at the various levels off in different directions. Figure 7b pictures the streaklines extending from the source at five levels as seen at 00 GCT, 24 hours after emissions began. Figure 7c then describes the volume through which the vertical mixing motions have distributed the first days emissions by 00 GCT.

Figure 8 represents the further growth of this first day's 24 hour emissions (dilution) volume during the next 24 hours due to shearing motions in the vertical and another daytime period of vertical mixing. It also shows the transport of this volume away from the source. In this case emissions exist in diluted form at all levels up to 800 mb at the initial instant (Figures 8a and 8c). At each level the perimeter of a polluted area (Figure 8b) is carried forward 24 hours by constructing trajectories originating at significant points along each perimeter. The trajectories are not shown in the sketch but the resulting transport and deformation of the perimeters are indicated at each level (Figure 8b). The dilution volume resulting from the vertical mixing up and down of the pollution at these various levels is shown in Figure 8d.

To construct the dilution volume containing two days of continuous emissions from the source one needs to construct the next day's 24 hour dilution volume and add it to the volume shown in Figure 8d. These two 24 hour dilution volumes overlap and together constitute the two day polluted wake (48 hours dilution volume) of the continuous point source. In the case studies to be discussed below these procedures were repeated for a third day's emissions so that the dilution volume containing three day's emissions from a given source were obtained. As an example refer to Figure 9. The shaded area reveals the horizontal extent of three day's continuous emissions from St. Louis as seen at 00 GMT 2 July 1973.

The selection of the 800 mb level as the upper limit of the vertical stirring and mixing followed unsuccessful efforts to define the top of the mixing layer by inspecting the plotted radiosonde temperature and humidity profiles at all stations in the eastern United States at both the 00 and 12 GCT times. Careful analysis of the profiles together with the associated surface weather maps suggested that during typical summer haze episodes in the eastern United States there is no extensive daytime stable layer in the lowest few kilometers placing an upper limit on convective mixing. To the contrary reports of towering cumulus frequently appear here and there within the hazy volume suggesting that the mixing in some places reaches and exceeds the 500 mb level. The upper limit to the vertical stirring and mixing is at best ill-defined and irregular. In all of the case studies the top of the stirred layer was assumed first to be at the 800 mb level. In one case, in an attempt to improve the fit between the constructed haze volume and the actual haze observations the level was raised to 700 mb with some improvement of the fit with the observations. In the other case studies the fit with the observed haze distribution was so good using an 800 mb level top to the mixing that an adjustment in the level was considered unnecessary.

To select the major sources of emissions in the northeastern United States the statistics appearing in EPA reports (1978) were used. In preliminary case studies nine major urban industrial areas were chosen to represent the sources of emissions. Each was treated as a point source.

Several considerations resulted in the revision downward in the number of these sources to just four: St. Louis, Chicago, Cincinnati and Pittsburgh. They were: (1) Preliminary results suggested that it was emissions two or three days old that were the major contributors to the haze and some of the emissions from the cities along the Atlantic coast moved into the data void over the ocean in less than three days preventing the completion of the construction of their dilution volumes; (2) The two and three day dilution volumes from individual point sources overlapped each other to such a large extent that including sources more closely spaced than the four chosen would have only a small effect on the size of their combined dilution volume; and (3) A considerable saving in time and resources was realized by limiting the number of sources to four.

SECTION 4
CASE STUDIES

Summer Haze

This case study, 00 GCT 29 June 1973 to 00 GCT 2 July 1973, examines a new relatively unpolluted air mass that has just invaded the source area from the west following a cold front passage. (See Figures 10, 11, 12 and 13). It terminates when the next front arrives from the west and begins to replace the now hazy air mass over the northeastern United States. Presented here is the dilution volume through which three days' emissions from St. Louis, Chicago, Cincinnati and Pittsburgh are distributed as seen at 00 GCT 2 July 1973. This volume or plume is the consolidation of four, one from each of the cities.

Figure 9 shows St. Louis' 3-day plume at 00 GCT 2 July 1973. It extends all the way from the Mississippi River to the coast of New England and is about 400 km wide. The undulating line within the plume is the streakline for St. Louis at this time for the winds at the 850 mb level. It constitutes the locus at 00 GCT 2 July 1973 of all air parcels that passed over St. Louis at the 850 mb level during the three day period. The marks along the streakline indicate the locations of air parcels that passed over St. Louis at the hours of 1200 and 0000 GCT. The streakline is included only to provide a basis for comparing the plume as constructed here with model calculations in which expanding puffs are arrayed along a streakline to form the plume. Such a model plume compared with the plume in Figure 9 would in this instance be displaced to the south and be narrow in the west and wide in the east, but would, however, be of about the correct length.

Figure 14a shows the plume for Chicago at 00 GCT 2 July 1973. It stretches out in a more northeasterly direction than St. Louis' and extends beyond the edge of the map. It is somewhat narrower, averaging about 300 km in width. The 850 mb streakline again is indicated, its time marks suggesting that most of the first day's emissions have passed the boundary of the map. Apparently most of the Chicago dilution volume at this time is over Canada.

Cincinnati's plume is shown in Figure 14b. Its orientation is even more northeasterly than Chicago's but because of Cincinnati's location to the southeast of Chicago its plume exits the northern boundary of the map in almost exactly the same place as Chicago's. The width is a bit more variable than its predecessor's but averages about the same, somewhere between 300 and 400 km.

Pittsburgh's plume, Figure 15a, also exits the map near the northern tip of Maine and falls completely within the Cincinnati plume. Apparently about one half of Pittsburgh's emissions have moved beyond the map's boundaries at this time.

The superposition of these four plumes produces the dilution volume shown in Figure 15b. It is a volume about 600 km wide extending from Illinois 1500 km to the edge of the map in the vicinity of northern Maine and for an undetermined distance beyond. This result suggests that synoptic scale motions and diurnal vertical mixing up to the 800 mb level can distribute the emissions from the four continuous point sources over a 1,000,000 km^2 area in a period of three days. Black dots have been entered on the map to designate stations reporting haze or smoke at this time so that comparisons can be made between haze reports and plume location.

It is possible to indicate which part of this plume contains the one-day old, two-day old and three-day old emissions. Figure 16a shows the part of the plume containing material emitted during the last 24 hours, 1 July 1973. The plumes from the four sources have not yet merged. And very few of the haze reports fall within these young (one-day-old) plumes. Figure 16b indicates the location of the material emitted in the 24 hour interval, 30 June 1973, what was referred to above as two-day old emissions. This area encompasses most of the stations reporting haze in the northeastern United States. It misses a few in New England. The dilution volume for the three-day old emissions, those entering the atmosphere on 29 June 1973 from the four sources, includes all the stations reporting haze in the northeastern United States. (See Figure 17a). The results suggest that most of the haze forms in air containing emissions which are two or three days old.

The consolidated plume described above does not explain the cluster of haze reports in the vicinity of coastal Virginia and North Carolina. The technique used in constructing the plume was altered in two different ways in an attempt to resolve this problem. First a search for an additional point source was made using the emissions inventory in the EPA reports (1979). Unfortunately the contributions of such important sources as Philadelphia, New York and Boston could not be examined because of the lack of data over the adjacent ocean areas. Birmingham, Alabama seemed the most likely other candidate. So the dilution volume for this source was constructed. The results are shown in Figure 17b. It failed. The three-day Birmingham plume does not reach the coastal sections of North Carolina and Virginia. As a next try the plume for the four sources was reconstructed allowing the mixing to extend to the 700 mb level instead of just to the 800 mb level. The results are shown in Figure 18. The additional spreading provided by flow patterns at these higher levels extended the plume to the south and east to include the haze reports in question.

The size of the area containing one day's emissions (sort of a 24 hour urban puff) increased with time at all stations. Figure 19 shows a time graph of the magnitude of these areas averaged over the four stations. The areas are expressed in terms of equivalent radius, the radius of a circle having the same area. The graph suggests that for the first 2½ days the perimeter of the dilution volume of one day's emissions from a single point source moved radially out away from its centroid at something like 2 ½ ms^{-1}.

A new front moved into the midwest during 2 July 1973 and delivered a new non-hazy air mass to Michigan, Indiana and Illinois. The old air mass ahead of the front by 00 GCT 3 July 1973 had become even hazier. Figure 20 indicates the frontal position and the locations of the stations reporting haze at 00 GCT 3 July 1973.

Off-Season Haze

This particular haze episode, 00 GCT 26 February 1973 to 00 GCT 1 March 1973, was chosen for study as an example of the off-season (not summer) occurrence. It begins 00 GCT 26 February 1973 with the arrival in the source area of a fresh cold air mass. (See Figures 21,22,23 and 24). During the subsequent three day period ending at 00 GCT 1 March 1973 a ridge of high pressure slowly moves across the eastern United States from west to east and by the end of the third day an extensive area of haze has developed over the midwest that extends all the way from the Gulf of Mexico to the Great Lakes.

Figure 25a shows the plume from St. Louis at the end of the three day period, 00 GCT 1 March 1973, resulting from continuous emissions from 00 GCT 26 February 1973 to 00 GCT 1 March 1973. The location of the one-two- and three -day old emissions are indicated by the dashed, dotted and dot-dashed curves within the plume. At this time the one- and two-day old emissions are still in the vicinity of St. Louis but the three-day old emissions have moved off to the south and have spread out horizontally to cover most of the southeastern United States.

The three-day plume from Chicago is shown in Figure 25b. It is roughly the same size as St. Louis' plume but is displaced a little to the north and west. However, most of the plume overlaps the St. Louis plume in such a way that Illinois, Kentucky, Tennessee, Georgia, Alabama and Mississippi all are exposed to a blend of both Chicago and St. Louis emissions at this time.

At the beginning of the three-day period, 00 GCT 26 February 1973, the cold front had not yet passed Cincinnati. Consequently some of Cincinnati's three-day old emissions were delivered to the pre-frontal air mass and some to the new relatively unpolluted cold air mass behind the front. For this reason only one- and two-day old emission volumes are seen in Figure 26a. That portion of the emissions that entered the new air·mass on this, the first day, has been neglected and the plume entered in the figure contains only one- and two-day-old emissions.

The front had just passed Pittsburgh at 00 GCT 26 February 1973 so the plume shown in Figure 26b contains a full three days' emissions from Pittsburgh. It shows the same marked extension to the south due to the rapid expansion of the three-day old emissions volume on its third day out.

Figure 27a shows the consolidated plume resulting from the merger of the four individual plumes. It covers a large area, most of the United States east of the 95th meridian except the northeast states and southern Florida. A few scattered haze reports exist west of the plume. Otherwise all of the stations reporting haze fall within the constructed dilution volume.

Figure 27b shows the areas covered by one-day-old emissions. As in the previous case study only a small fraction of the haze reports are found here, 9 of the 52 reports or 17%. The two-day-old emissions, as seen in Figure 28a, encompasses 23 of 52 or 44% of the stations reporting haze. The remainder of the haze reports are located predominantly in the gulf states, in that part of the plume made up exclusively of three-day-old emissions, as seen in Figure 28b. 44 of 52 haze reports or 87% fall within it.

The majority of the haze reports are at locations where a superposition of emissions from different sources or different times occurs. In West Virginia haze is reported where both two- and three-day-old emissions from Pittsburgh appear together. In southwest Ohio both Cincinnati and Chicago plumes are present at the haze reporting stations. The edges of the St. Louis and Pittsburg plumes are close by. In the southern states there are 17 stations reporting haze within the overlapping Chicago and St. Louis plumes. The six haze reporting stations in Illinois are in two- and three-day-old emissions from Chicago and two-day-old emissions from St. Louis. It is apparent that much of the haze forms in aged emissions from more than one source and occurs sometimes at distances away from the sources that exceeds 1000 km.

Non-Haze Situation

This is a study of a non-haze episode, 00 GCT 2 October 1974 to 00 GCT 5 October 1974. A synoptic situation was chosen that resembled as closely as possible the typical haze episode but which, of course, generated no haze. It is a post-cold frontal situation in which a large anticyclone covers the entire eastern United States and over the course of three days, 2 October 1974 to 5 October 1974, gradually moves across the area to the east, as shown in Figures 29, 30, 31 and 32.

The plume generated for the emissions from St. Louis during these three days is shown in Figure 33a. It is very extensive stretching all the way from the Gulf of Mexico to southern Canada and from North Dakota to Pennsylvania. Chicago's plume is about the same size, perhaps even more extensive in the north-south direction and shifted a bit toward the east. See Figure 33b. Cincinnati's plume (Figure 34a) is a bit narrower but may be just as large. Like the others it extends past the limit of the map over the Gulf of Mexico. Figure 34b shows Pittsburgh's plume. It extends down the southeast Atlantic coastline spreading both east and west at its southern extremity to cover areas of unknown extent over the Gulf of Mexico and the Atlantic Ocean.

The consolidated plume (Figure 35a) containing emissions from all four sources covers most of the eastern United States extending from the 95th meridian on the west to the 75th meridian on the east and including part of southern Canada and an undetermined amount of the Gulf of Mexico and the Atlantic Ocean. The dashed lines interior to the plume indicate the boundaries of the St. Louis, Chicago, Cincinnati and Pittsburgh plumes.

Figures 35b, 36a and 36b show the area covered by the one-day-old, two-day-old and three-day-old emissions respectively. The one-day-old plumes are noticeably larger than those generated during the haze episodes discussed above. And the two-day-old emissions cover an area so large that it compares favorably with the largest of the three-day-old emissions volumes for the haze episodes discussed earlier. The three-day-old emissions volume is obviously much more extensive than its counterparts during the haze episodes. How much larger is impossible to state since the plume extends beyond the map border. No haze was reported at any time except at a station in southern Canada at 12 GCT 4 October 1974. It is apparent that much larger dilution volumes are generated in this no-haze case then in the haze cases.

SECTION 5

ABBREVIATED TECHNIQUES

Constructing the plumes presented in each of the case studies involved 24 surface maps, 28 streamline maps and something like 1000 trajectories. Before selecting such a difficult and elaborate technique a number of shorter but more approximate methods had been attempted such as the one described by Edinger (1980). And after the difficult long method had been applied to the three case studies described above new attempts were made to abbreviate procedures without significantly degrading the results. Described now is an abbreviated method that involves a great reduction in the number of trajectories required. Its results are compared with those of the long method.

In this method the first day's dilution volume was determined in exactly the same way as it was in the long method. Then the centroid of this volume (in the horizontal plane) was determined and entered at each level. 24-hour trajectories, constructed at each level carried the centroids forward one day. The perimeters of the volumes were reconstructed around the new positions. These new perimeters were the original ones expanded by amounts corresponding to the calculated average rate of separation of pairs of particles as shown in Figure 37, where rates of separation are given as a function of separation. In this case, separation is taken as the distance between significant points on opposite sides of the perimeter. In all other respects the long method was followed. The manner in which this rate of separation information was determined will be described in the next section.

Figure 38a compares the 3-day plumes generated for Pittsburgh 00 GCT 1 March 1973 using the approximate and the rigorous method. The shaded area designates the plume using the long procedure. The abbreviated method produces a two-day dilution volume (dashed line labeled 2) that is perhaps 50% too large. On the other hand the three-day volume is more nearly the right size, maybe 15% too big.

The combined plume from all four sources for 00 GCT 1 March 1973 as determined using the abbreviated method is very nearly the same size as that produced by the long method. Its location, shown by the dashed line in Figure 38b, is pretty close although it is shifted toward the east and in doing so misses seven haze reporting stations in the west.

Pittsburgh's plume for the no-haze case is an example of a rather poor fit between the results of the abbreviated and long methods. The comparison is made on Figure 39. Both the two- and three-day old dilution volumes differ markedly in shape. Obviously in this case the economy of tracking only centroids comes at the expense of missing marked changes in the shape and location of the dilution volumes.

The abbreviated method has not been adopted essentially because of its insensitivity to shape and location changes in the dilution volumes. Its determination of volume magnitude is pretty good and might be useful in applications where location is not as important as merely determining the dilution potential of a given synoptic situation.

SECTION 6

HAZE-RELATED METEOROLOGICAL QUANTITIES

The three synoptic situations involved in the case studies above provided three quite different haze conditions. The first was a fairly typical summer situation with the wide-spread haze area developing near the source areas and then moving out to the northweast. The second was a winter episode of very extensive haze that formed in the midwest. The last was an example of a large cold autumn anticyclone moving across the eastern United States, warming up as it drifted southeastward in which no haze developed.

What meteorological quantities are associated with the occurrence and non-occurrence of widespread areas of haze? In an attempt to answer this question a number of quantities considered to affect dilution were computed on a daily basis for six months running. The graph of these quantities versus time is shown in Figure 40.

As a measure of stability the vertical gradient between the 950 and 800 mb levels of the equivalent potential temperature was chosen. The approximate relationship $\Theta_e = \Theta + 3.0$ RH was used to compute the equivalent potential temperature, where RH is the relative humidity expressed as a fraction. The value plotted on the graph is the vertical gradient of the equivalent potential temperature, $d\Theta_e/dz$, averaged over the 00 GCT and 12 GCT times and the 12 radiosonde stations indicated on Figure 41.

The following quantity was used to represent the effect of vertical shear $\overline{\Delta d_{12}} = [(u_1t-u_2t)^2 + (v_1t-v_2t)^2]^{1/2}$ where subscripts 1 and 2 refer to different levels at the same station and u and v are wind speed components and t is 12 hours. The plotted value is the average over the three 50 mb layers from 950 to 800 mb averaged over all stations. It is a measure of the relative 12 hour horizontal displacement of a pair of air parcels originally separated only in the vertical. A running 5 day mean was taken to smooth the trace.

The effect of horizontal shear is given by the 12 hour change in horizontal separation between horizontally separated pairs of air parcels as computed using the following expression

$$\overline{\Delta \ell_{12}} = [(u_1 t - u_2 t + \ell_{xo})^2 + (v_1 t - v_2 t - \ell_{yo})^2]^{1/2} - [\ell_{xo}^2 + \ell_{yo}^2]^{1/2}$$

The subscripts refer to different stations and u, v and t are as defined above. ℓ_{xo} and ℓ_{yo} are the horizontal components of the initial separation. Computations were made at each level individually and for each of the 66 pairs of rawinsonde stations represented by the lines between stations on Figure 41. The value plotted is the average over all 66 pairs for the 800 mb level. (The line of best fit for $\Delta \ell_{12}$ plotted against the initial separation produces the graph shown in Figure 37, that was used earlier in the approximate method of constructing perimeters.)

Translation, $\overline{V}$, was represented by the average resultant wind speed averaged over all stations and all levels from 950 to 800 mb.

As a measure of the haziness of the day in question the number, H, of surface weather stations reporting haze at 1800 GCT within the area circumscribed by the heavy line in Figure 41 was determined.

The results as shown in Figure 40 reveal an obvious seasonal change in the incidence of haze, a marked increase from winter to summer. Seasonal trends in the meteorological variables are most pronounced in the stability variable, the vertical gradient of the equivalent potential temperature. It clearly shows a decrease in stability from winter to summer. This associates summer, the hazy season, with the least stability, a result contrary to common experience with meso-scale air pollution situations in which low level stable layers are a requirement.

This poses a number of questions. Does low stability and the associated enhanced vertical mixing in some way contribute to the formation of summer haze? Is a deep layer of mixing required to allow vertical shears to leaf together emissions from a number of large urban sources? Do emissions distributed through a layer of small stability 2 or 3 km deep have a longer residence time in the atmosphere than those trapped below a stable layer based at 1 or 2 km?

The other meteorological variables are associated with the horizontal spreading of emissions. Their seasonal changes are not so obvious but do show some decrease in value from winter to summer. Generalizing, one might conclude that winter dilution volumes are shallower but more expansive horizontally than summer dilution volumes which are deeper but of smaller horizontal extent. It is not clear which has the smaller volume and therefore the highest average concentration of primary pollutants.

Husar (1979) has pointed out that in the last few decades summer, previously the time of best visibility, has become the season with the poorest visibility. It is not likely that the meteorological patterns have changed to that extent. Perhaps changes in the seasonal pattern of emissions has tipped the scales, scales that are not too far from balance if the seasonal change in dilution volumes is small.

The average values of the above meteorological variables were calculated for the summer haze case study, 00 GCT 29 June 1973 to 00 GCT 2 July 1973. They were averaged over all times, levels (up to 800 mb) and stations or station pairs. The effect of hozirontal shears expressed in terms of pair separation speed was about 1 1/2 ms^{-1}. Vertical shears produced a 3 1/2 ms^{-1} pair separation speed. And the average translation speed as 5 ms^{-1}.

These results suggest that, in this case at least, vertical shears exert a greater influence on the horizontal spreading of dilution volumes than do horizontal shears. They also suggest that the expanding 24 hour dilution volumes are advected away from their sources fast enough to separate from them. That this is so can be seen in Figure 17a which shows the location of the three-day-old 24 hour emissions volume separated from St. Louis and Chicago for this case. That it need not always be so can be seen in Figure 25b for the other haze case study, where one-two- and three-day old dilution volumes simultaneously cover the source, Chicago.

Figure 1. Network of Rawinsonde Stations

b

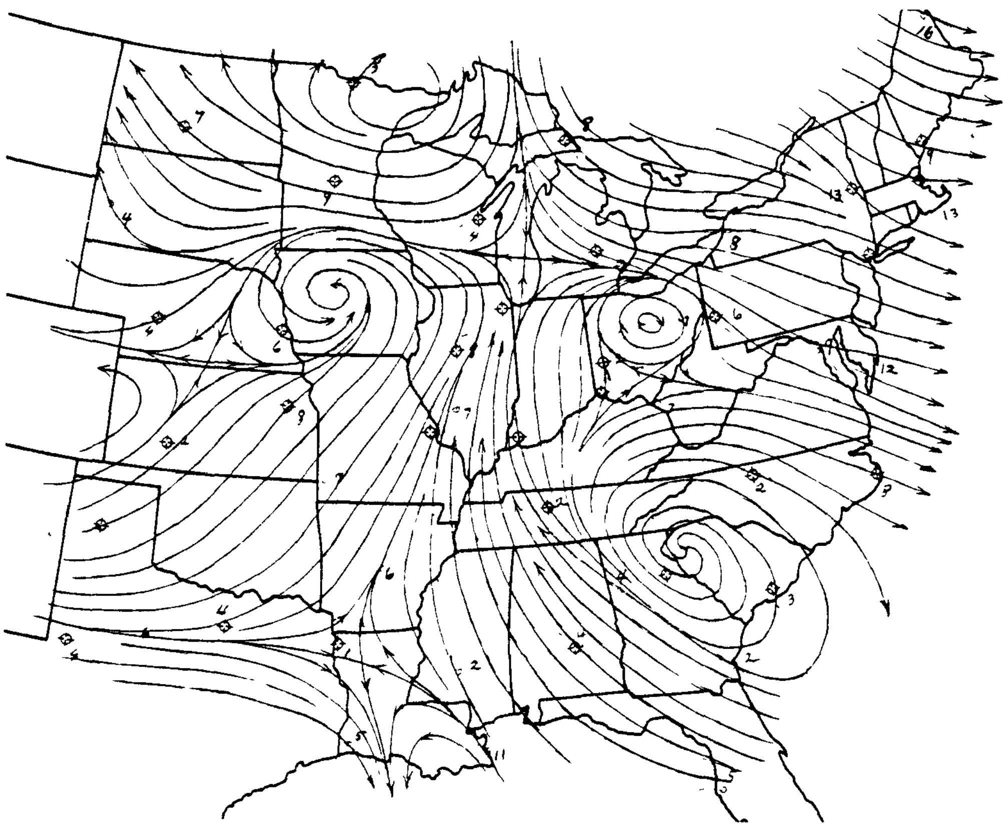


Figure 2b. Streamline map , 00 GCT 25 February 1973, at 900 mb level .

a

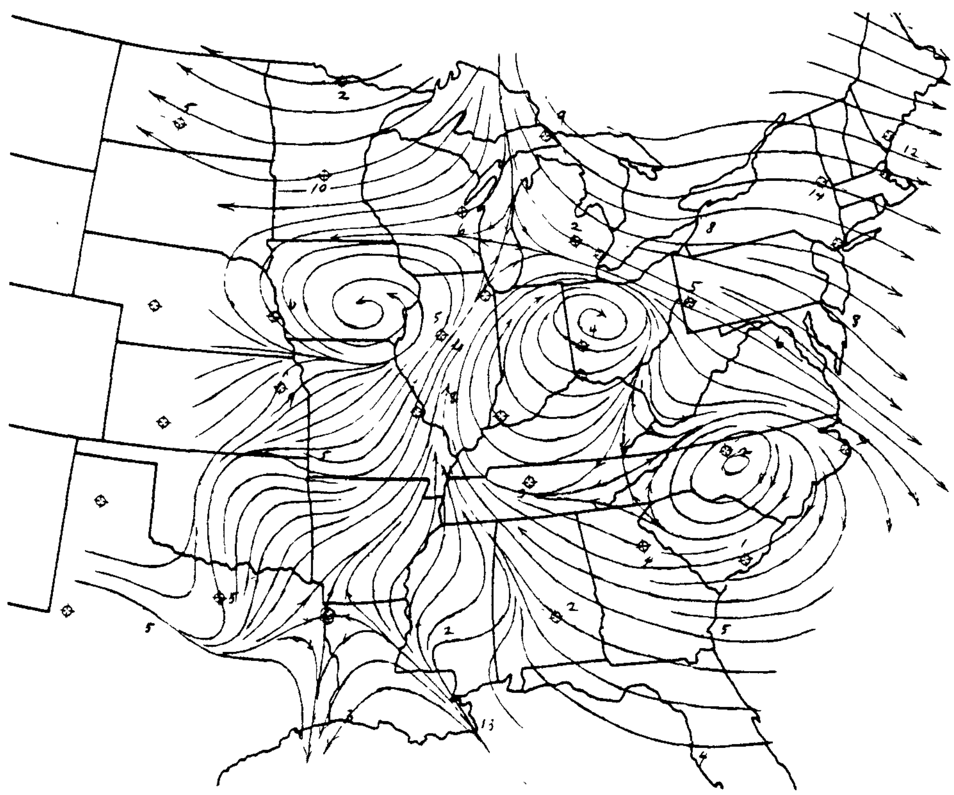
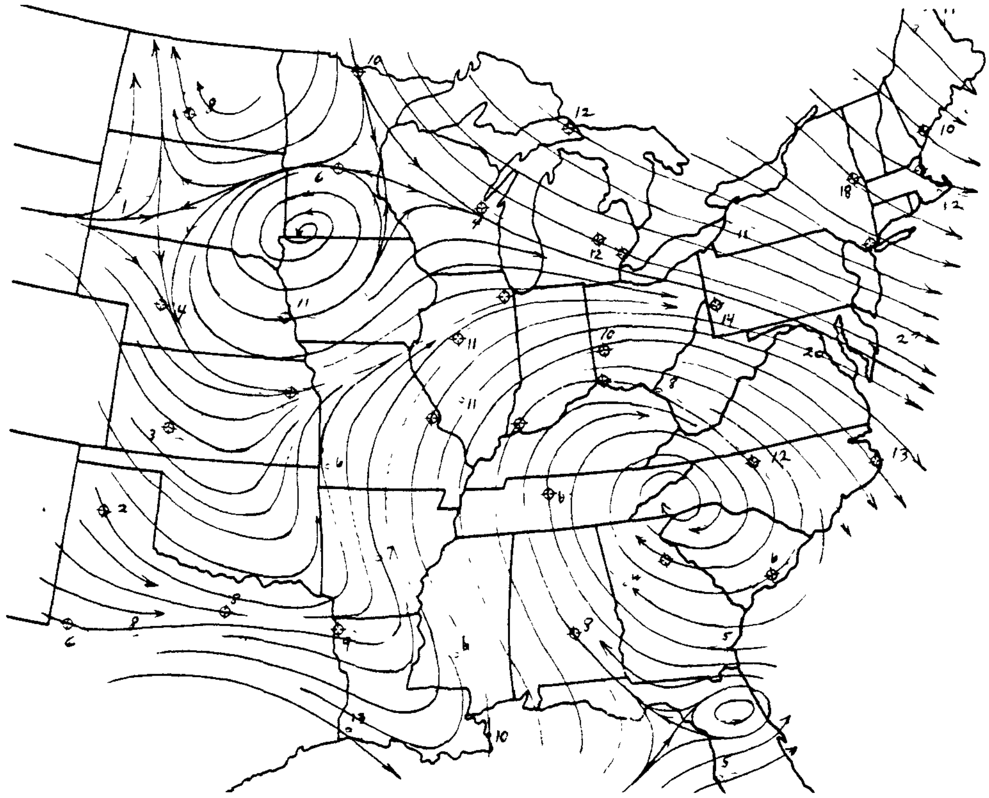
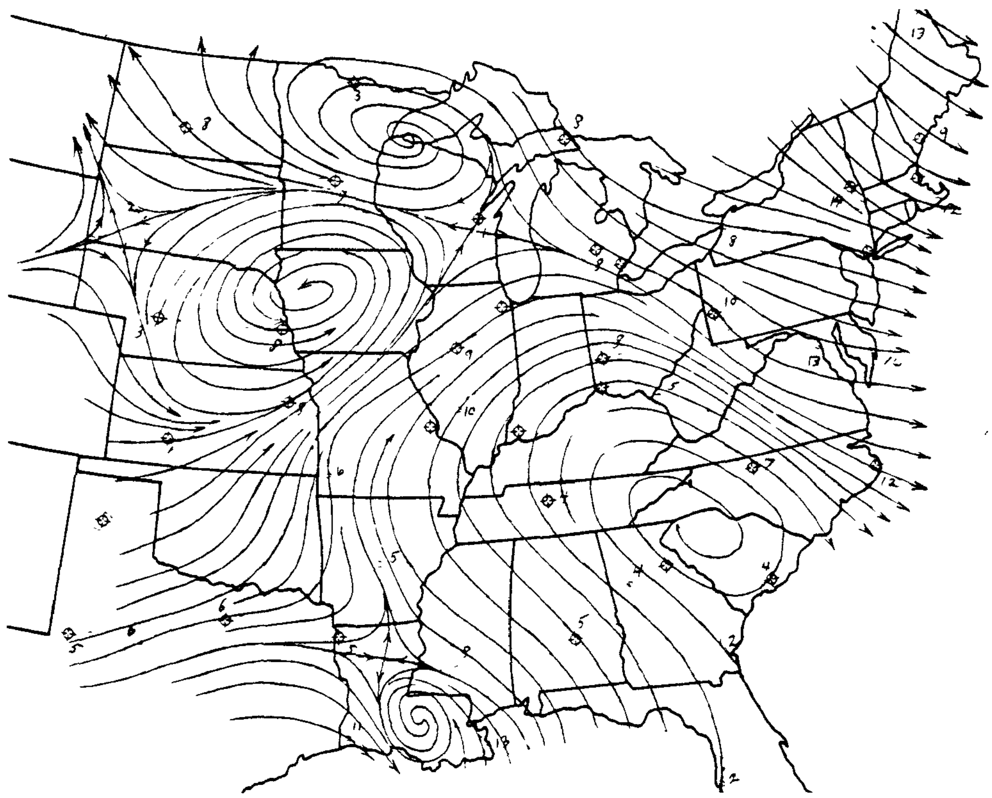


Figure 2a. Streamline map , 00 GCT 25 February 1973, at 950 mb level .



b

Figure 3b. Streamline map , 00 GCT 25 February 1973 at 800 mb level .



a

Figure 3a. Streamline map , 00 GCT 25 February 1973 at 850 mb level .

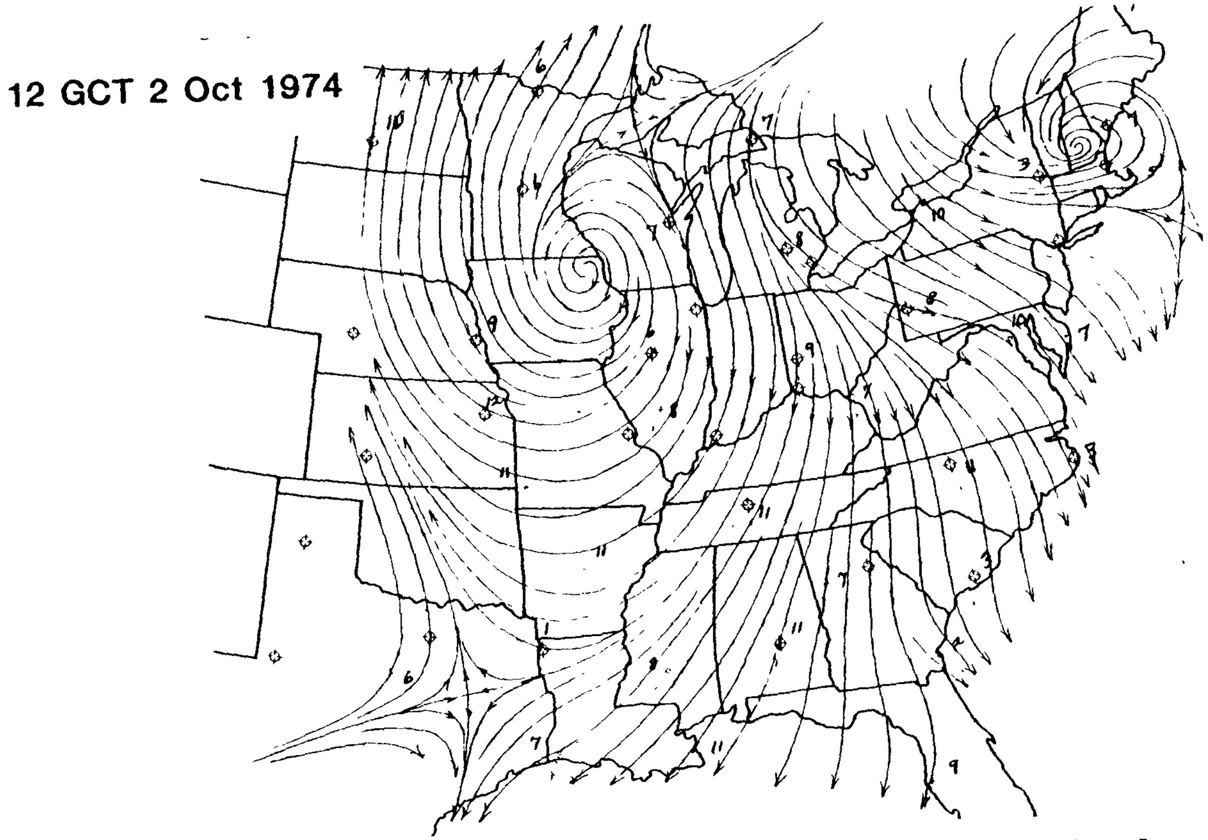


Figure 4. Streamline map, 12 GCT 2 October 1974, 950 mb level.

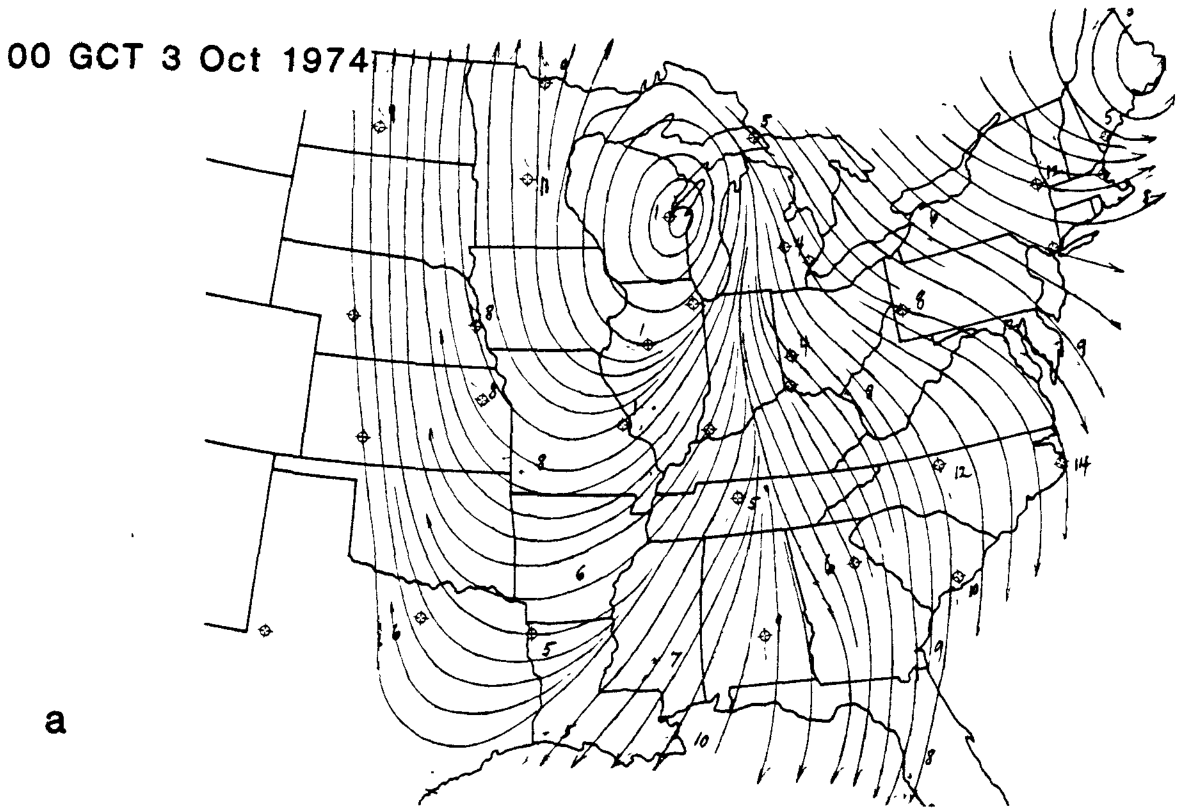


Figure 5a. Streamline map for 00 GCT 3 October 1974, 950 mb level.

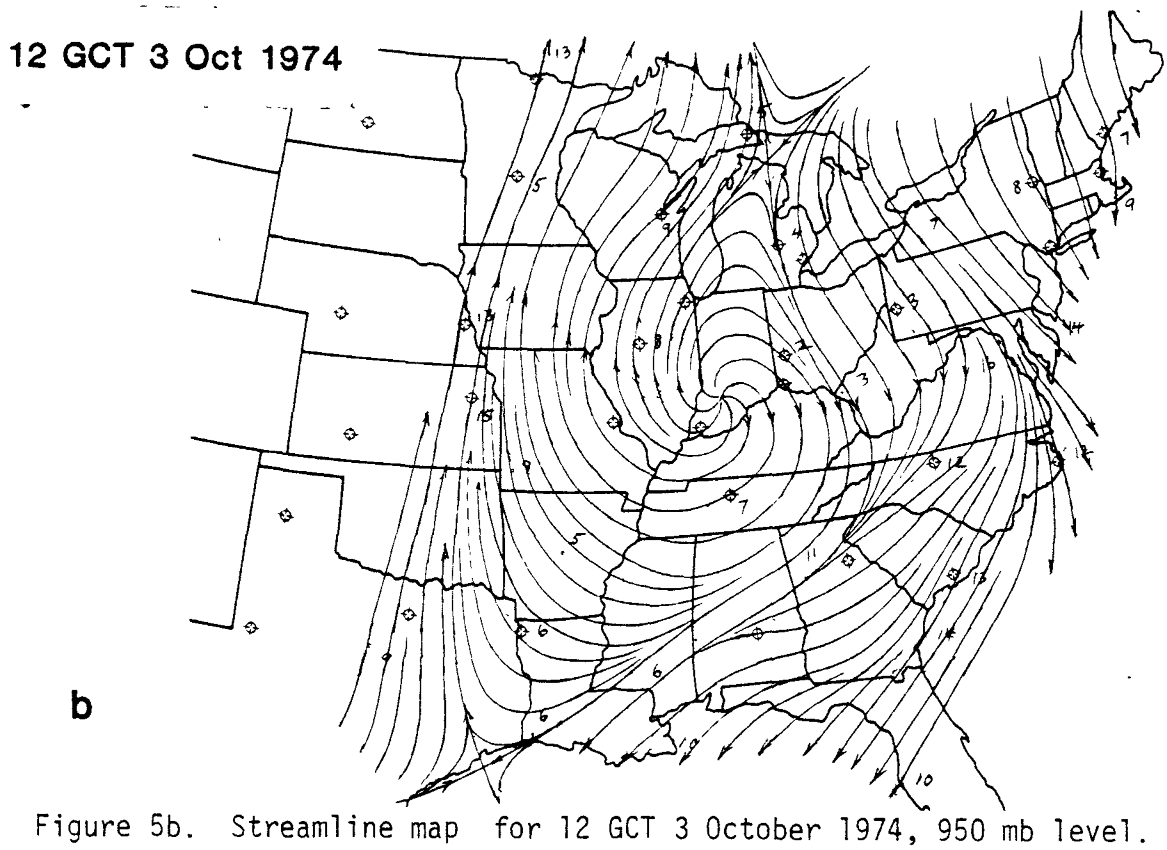


Figure 5b. Streamline map for 12 GCT 3 October 1974, 950 mb level.

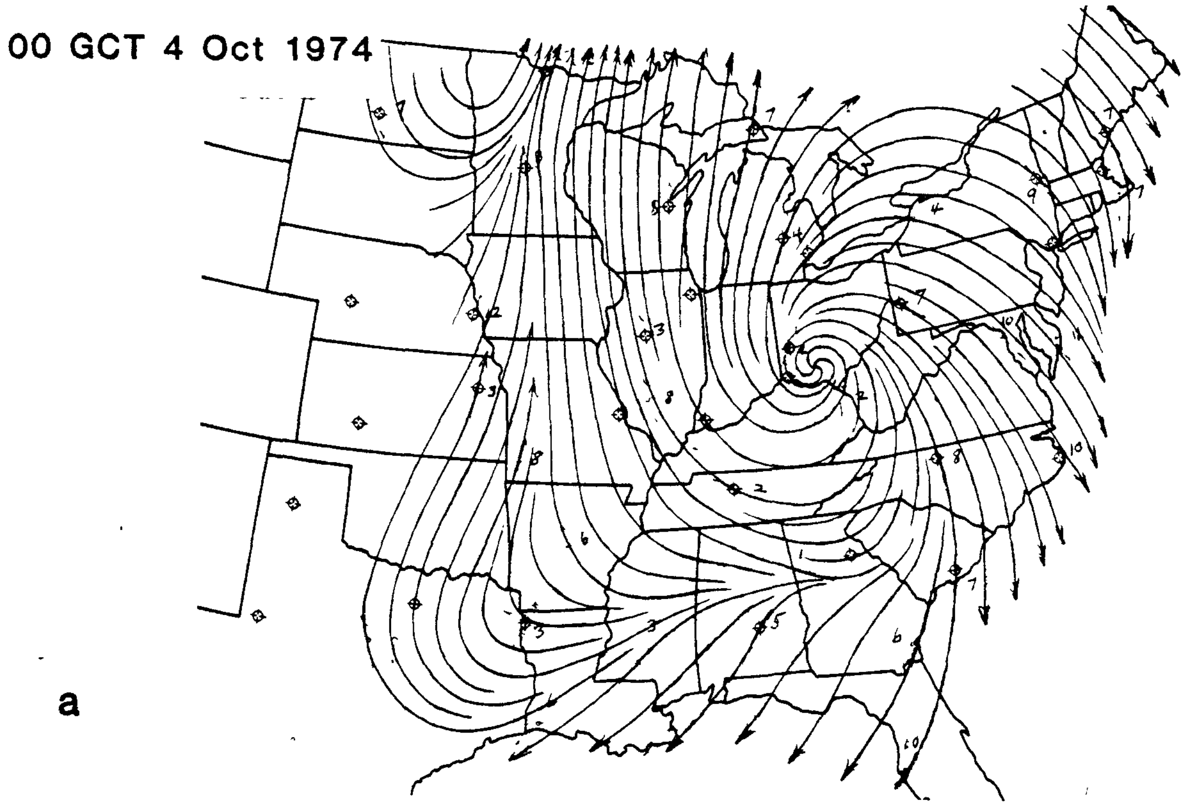


Figure 6a. Streamline map for 00 GCT 4 October 1974, 950 mb level.

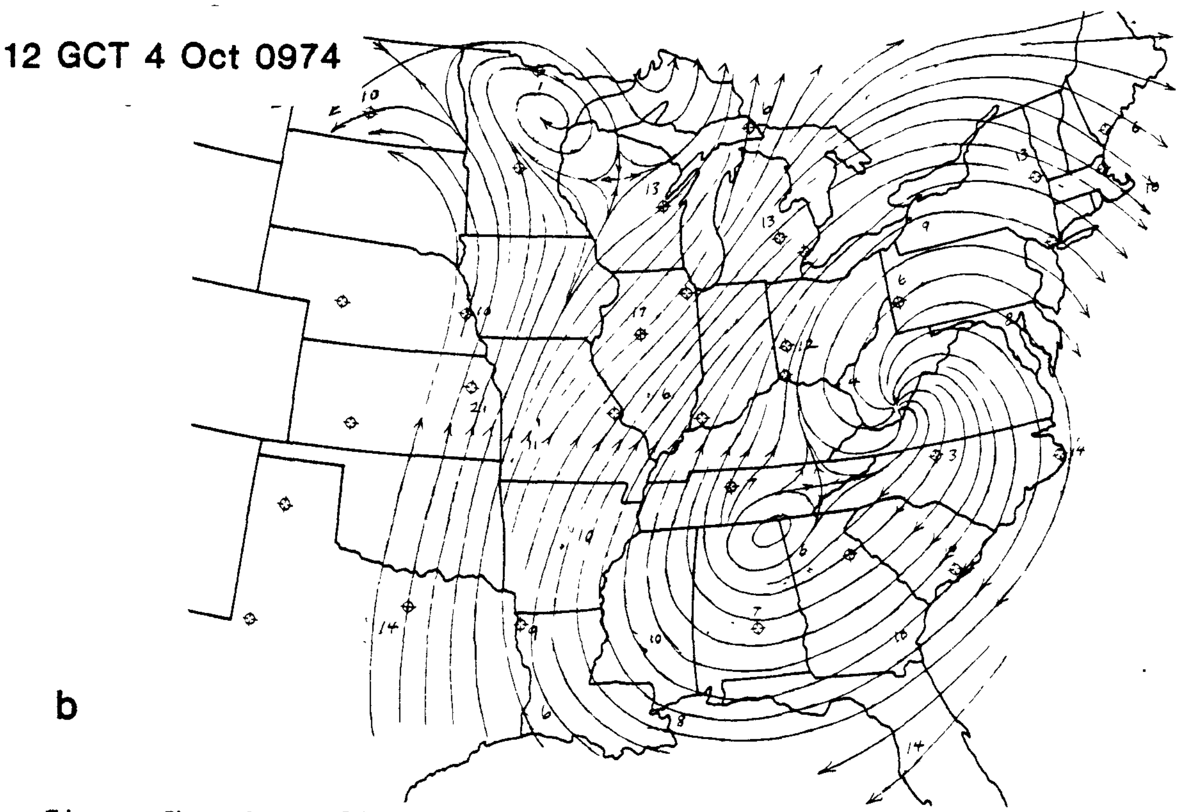


Figure 6b. Streamline map for 12 GCT 4 October 1974, 950 mb level.

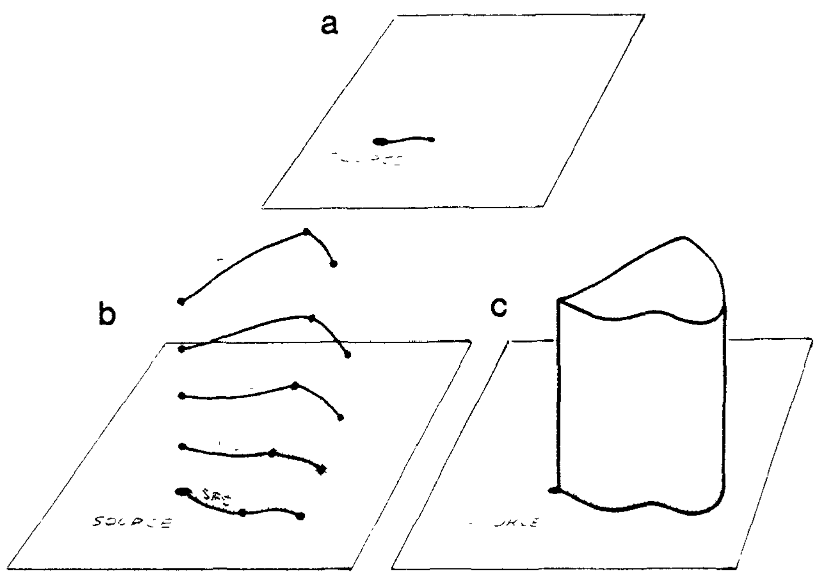


Figure 7. Technique for constructing the initial 24 hr dilution volume.

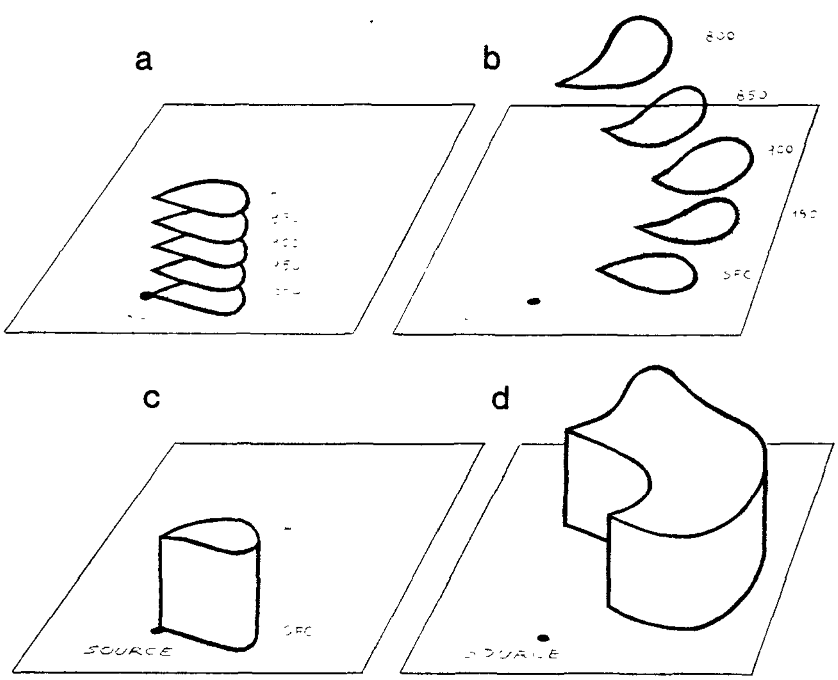


Figure 8. Technique for constructing the subsequent 24 hr growth and transport of already existing dilution volume.

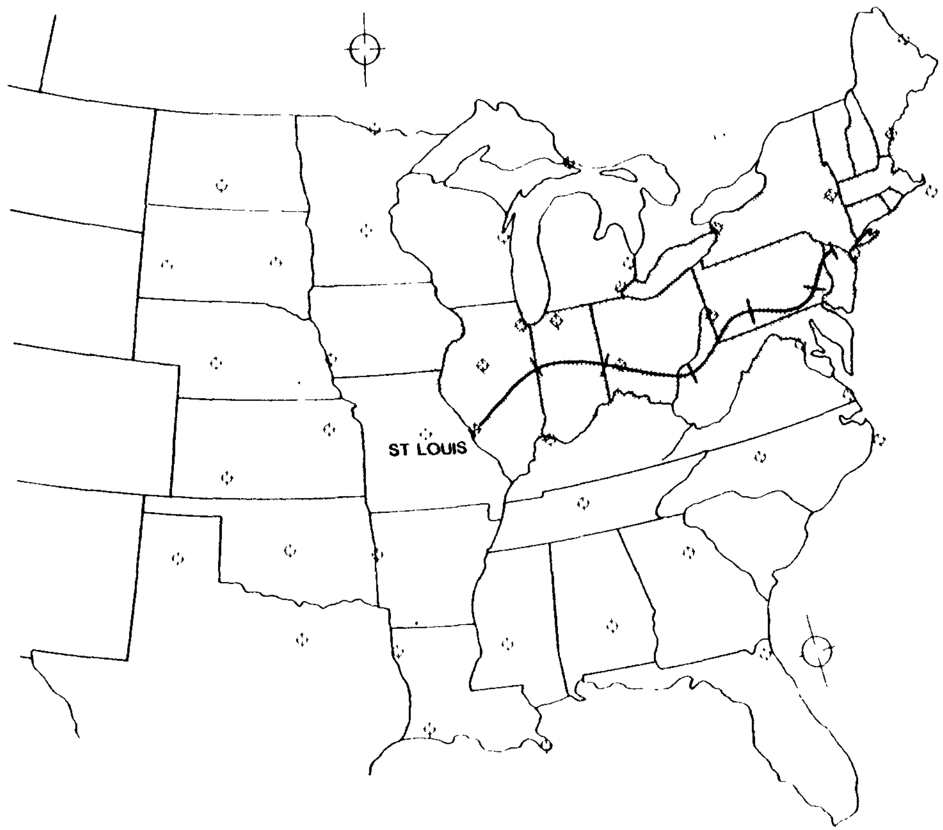


Figure 9. Plume from St. Louis at 00 GCT 2 July 1973 resulting from 3 days of continuous emissions.

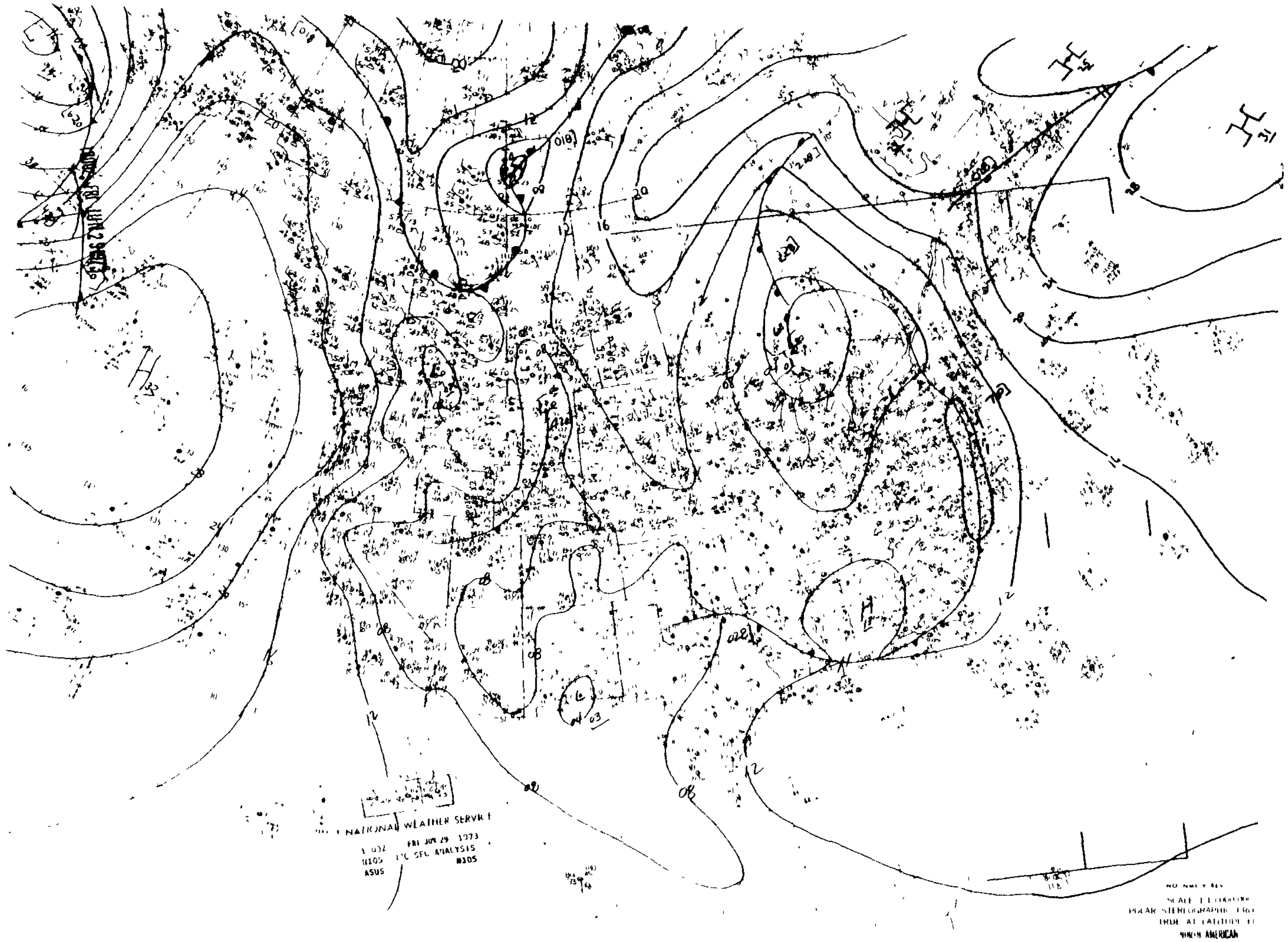


Figure 10. Synoptic maps, 29 June 1973.

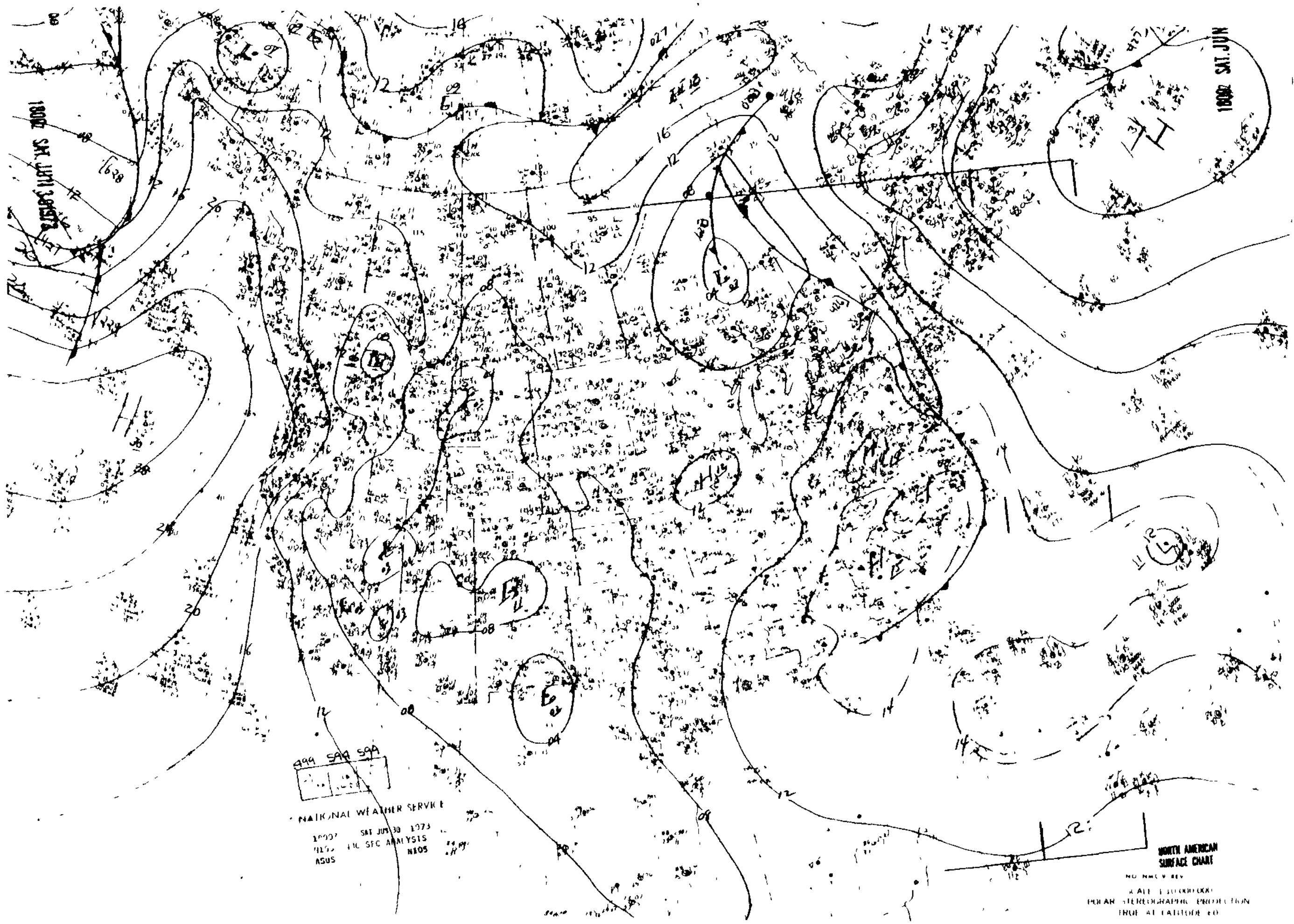


Figure 11. Synoptic maps, 30 June 1973.

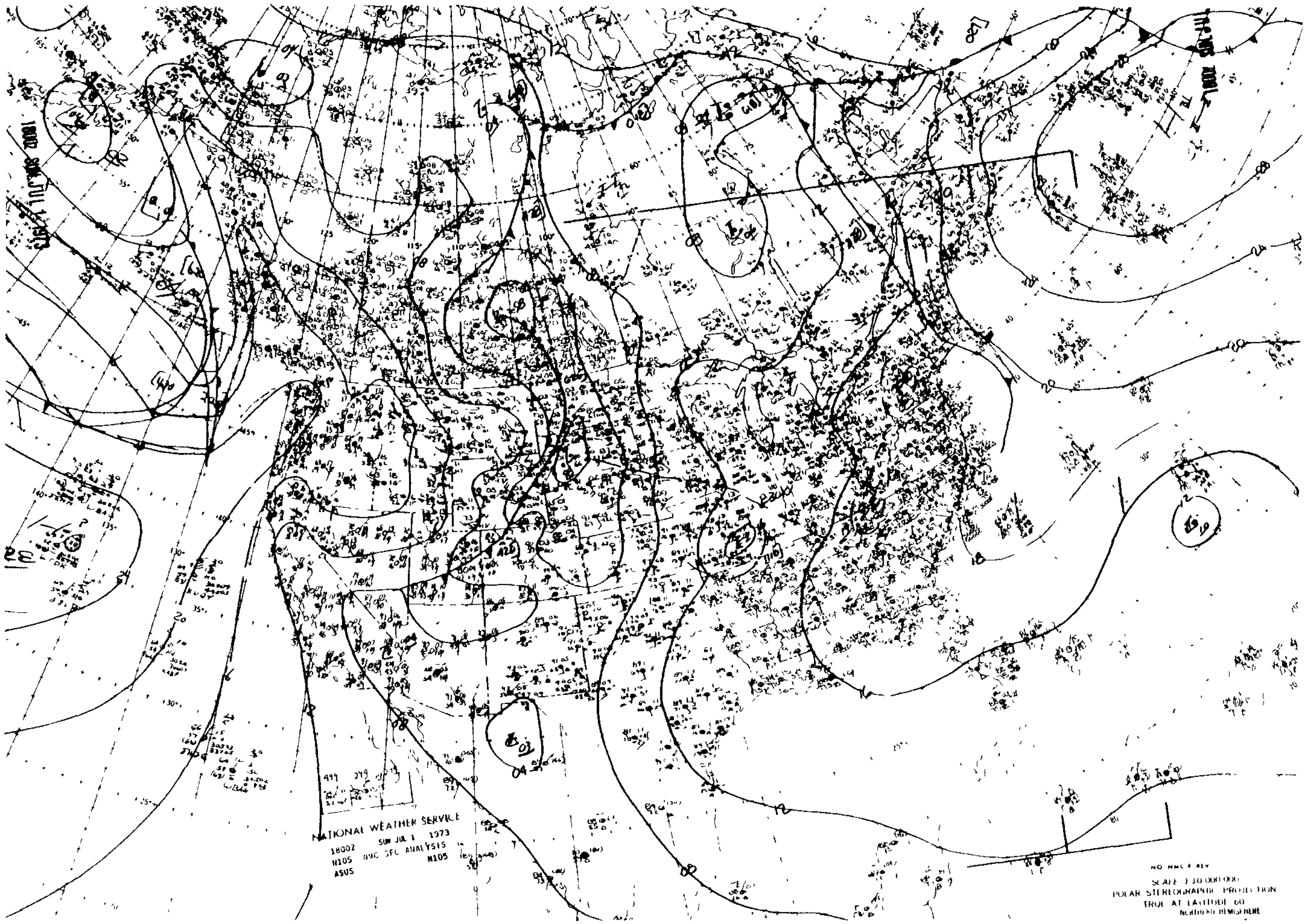


Figure 12. Synoptic maps, 1 July 1973

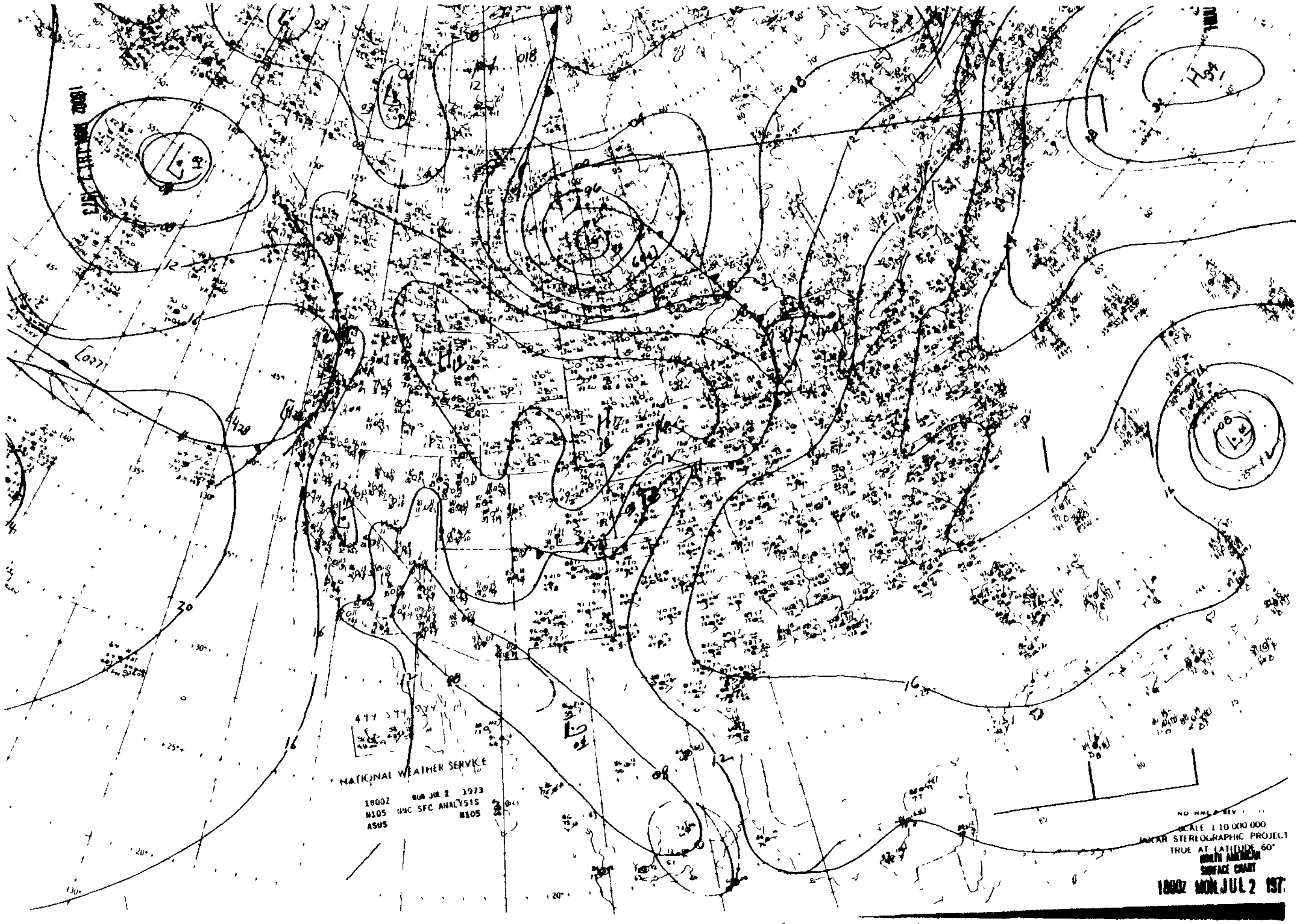


Figure 13. Synoptic maps, 2 July 1973.

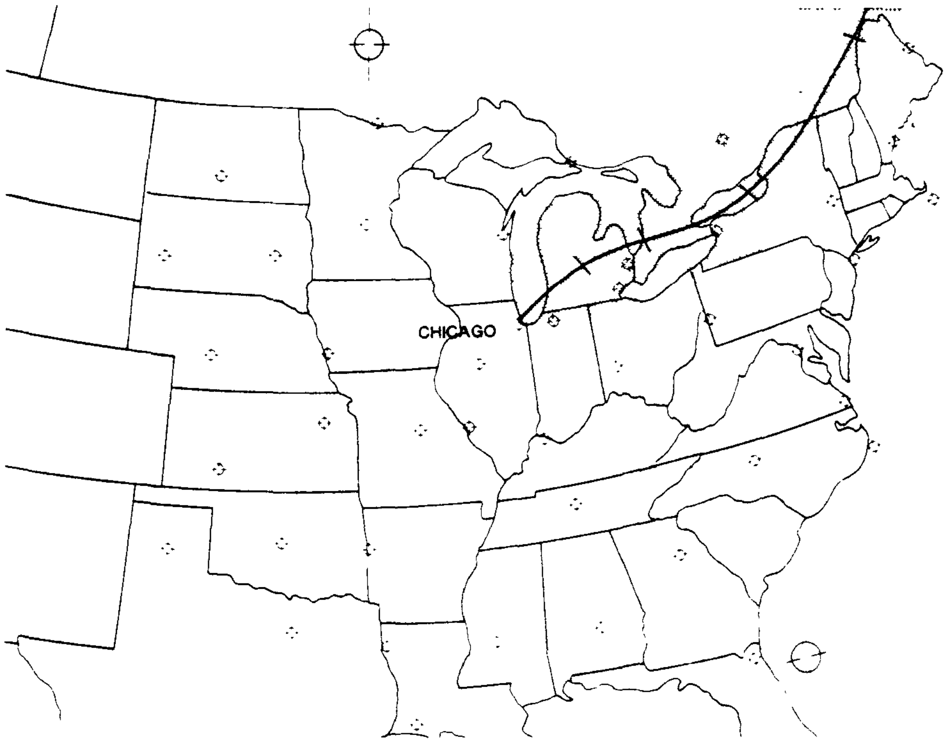


Figure 14a. Plume from Chicago at 00 GCT 2 July 1973 resulting from 3 days' continuous emissions.

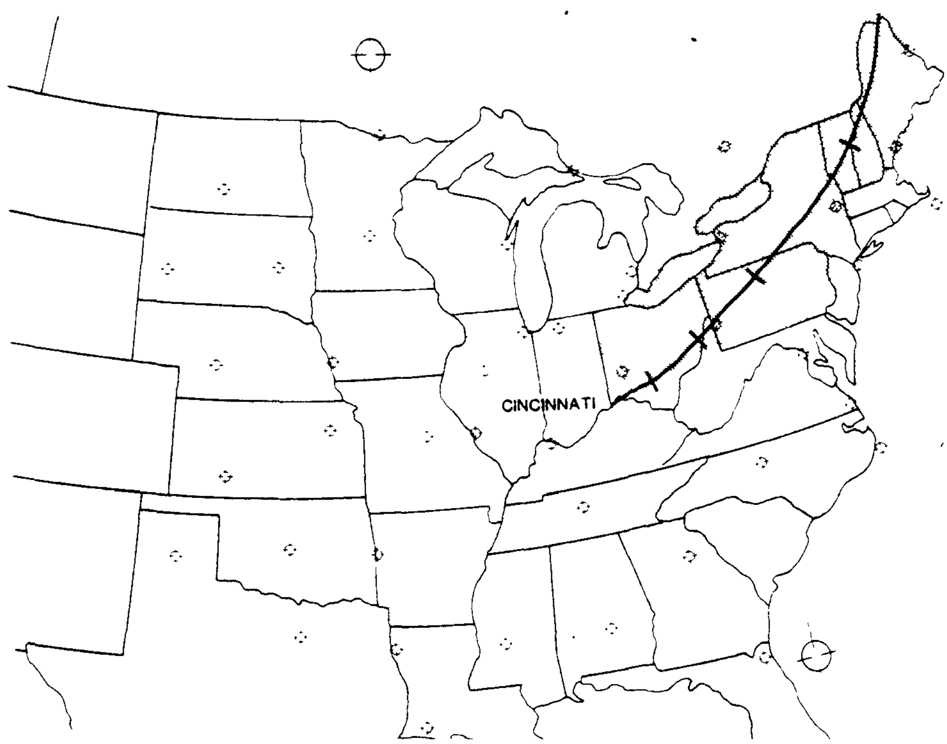


Figure 14b. Plume from Cincinnati at 00 GCT 2 July 1973 resulting from 3 days' continuous emission.

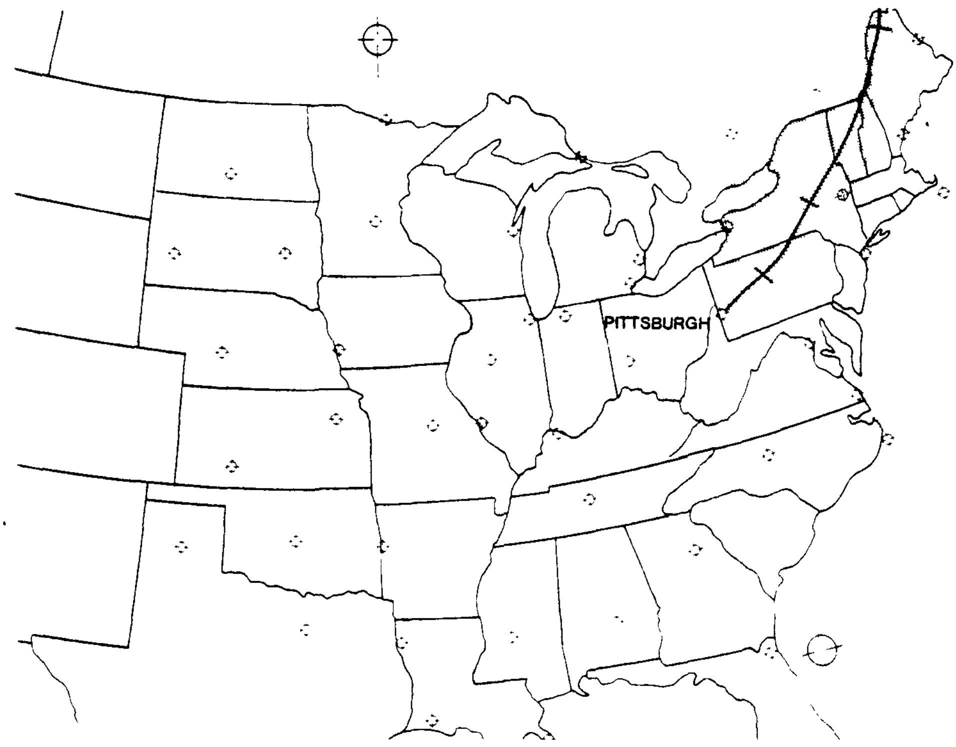


Figure 15a. Plume from Pittsburgh at 00 GCT 2 July 1973 resulting from 3 days' continuous emissions.

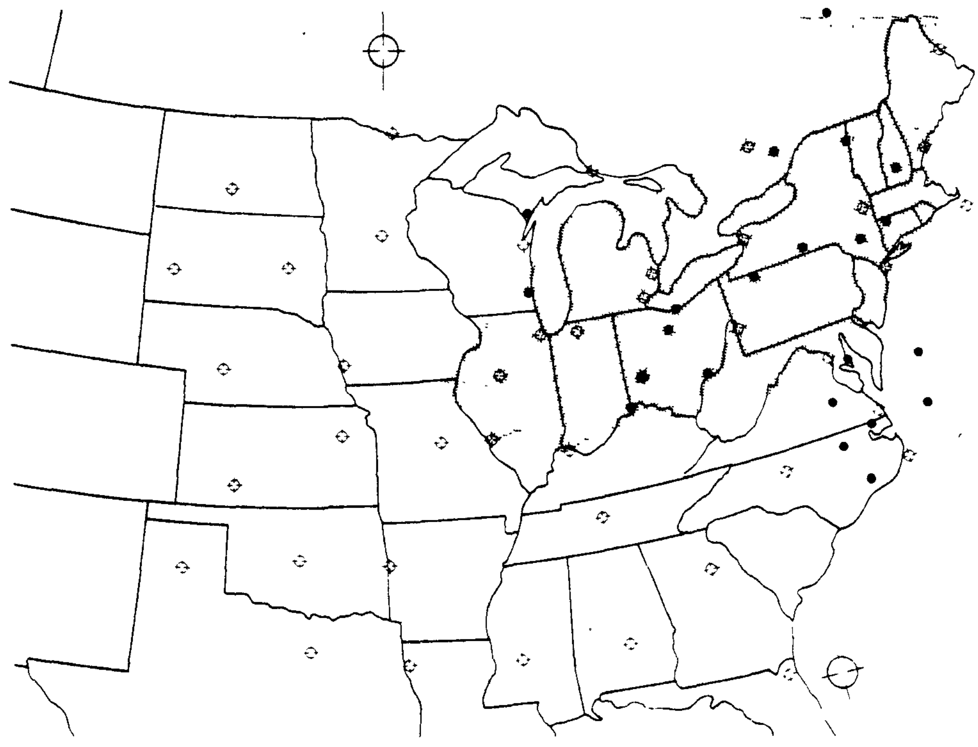


Figure 15b. Consolidated plume containing 3 days' emissions from St. Louis, Chicago, Cincinnati and Pittsburgh as seen at 00 GCT 2 July 1973.

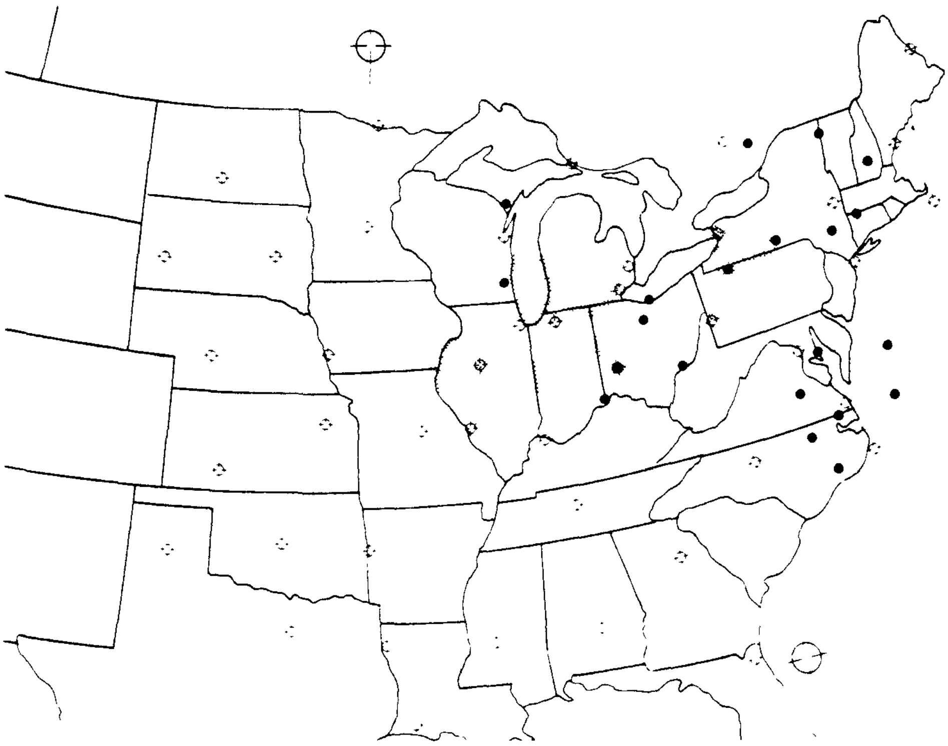


Figure 16a. One-day-old emissions from St. Louis, Chicago, Cincinnati and Pittsburgh, 00 GCT 2 July 1973.

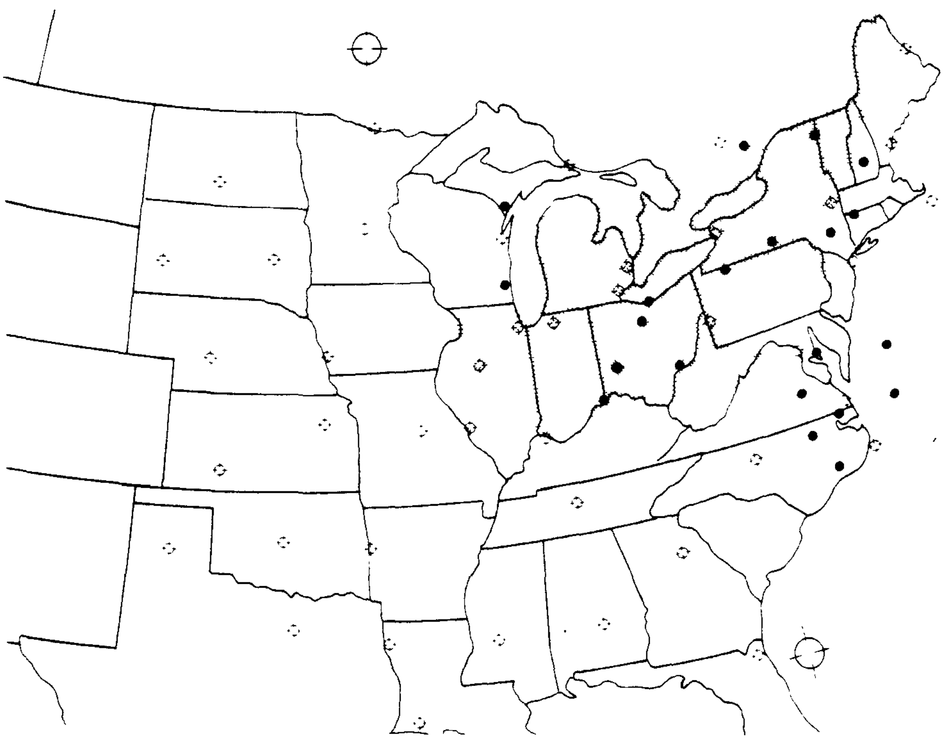


Figure 16b. Two-day-old emissions from St. Louis, Chicago, Cincinnati and Pittsburgh, 00 GCT 2 July 1973.

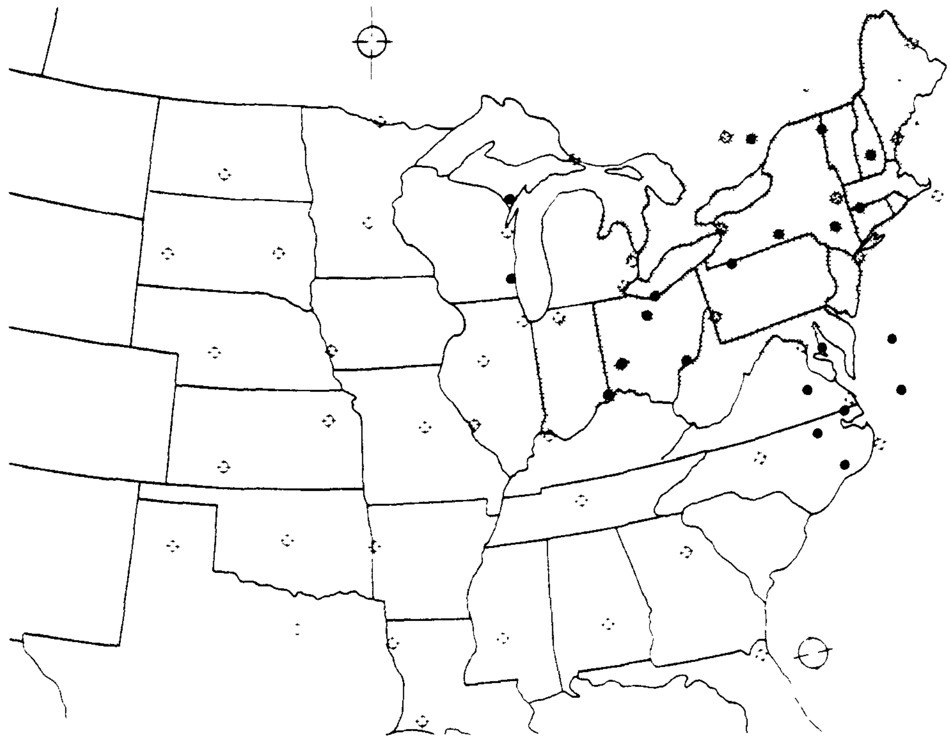


Figure 17a. Three-day-old emissions from St. Louis, Chicago, Cincinnati and Pittsburgh, 00 GCT 2 July 1973.

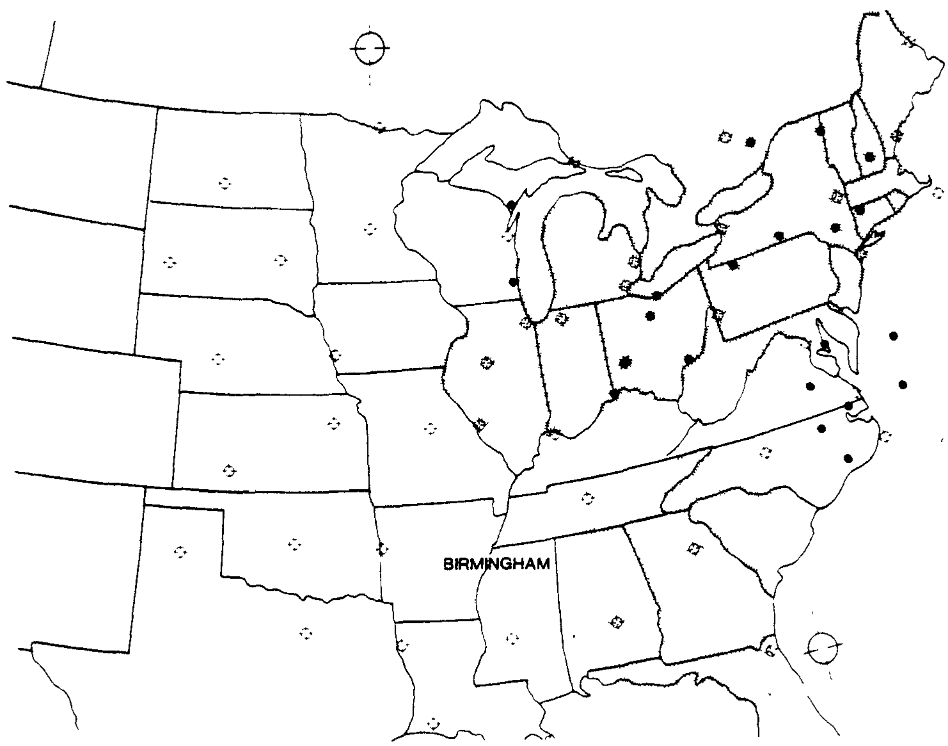


Figure 17b. Three-day consolidated plume from the four sources and Birmingham's plume as seen at 00 GCT 2 July 1973.

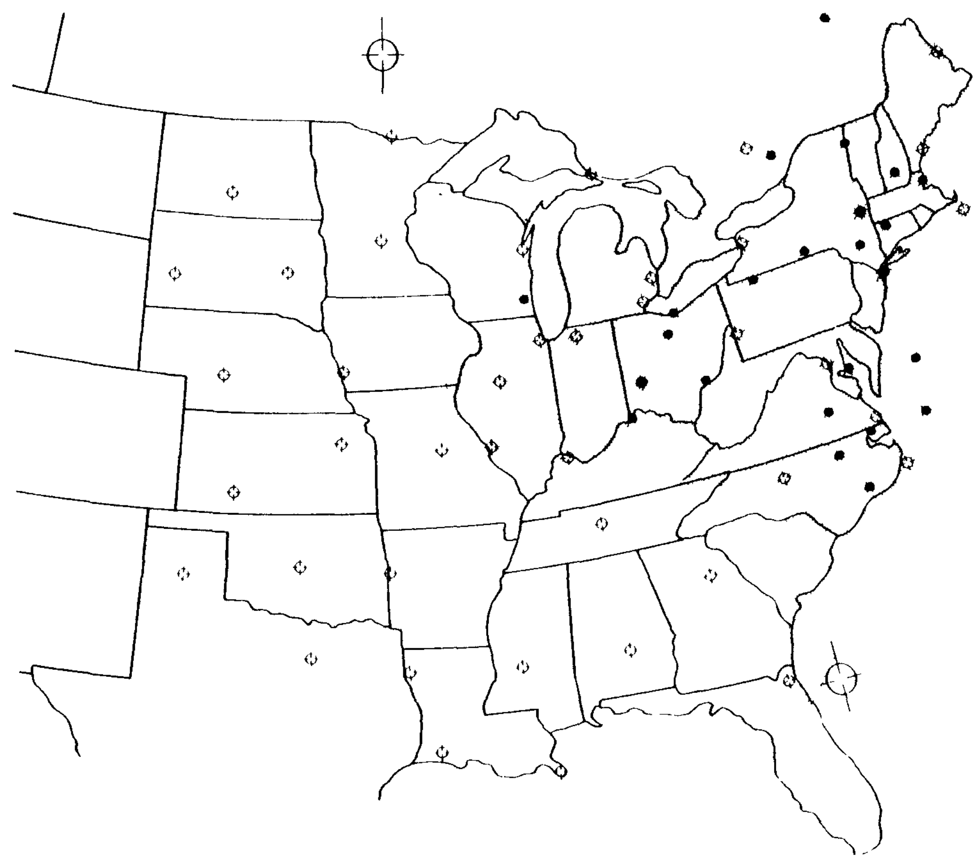


Figure 18. Consolidated 3-day plume from St. Louis, Chicago, Cincinnati and Pittsburgh, 00 GCT 2 July 1973, assuming mixing up to 700 mb level.

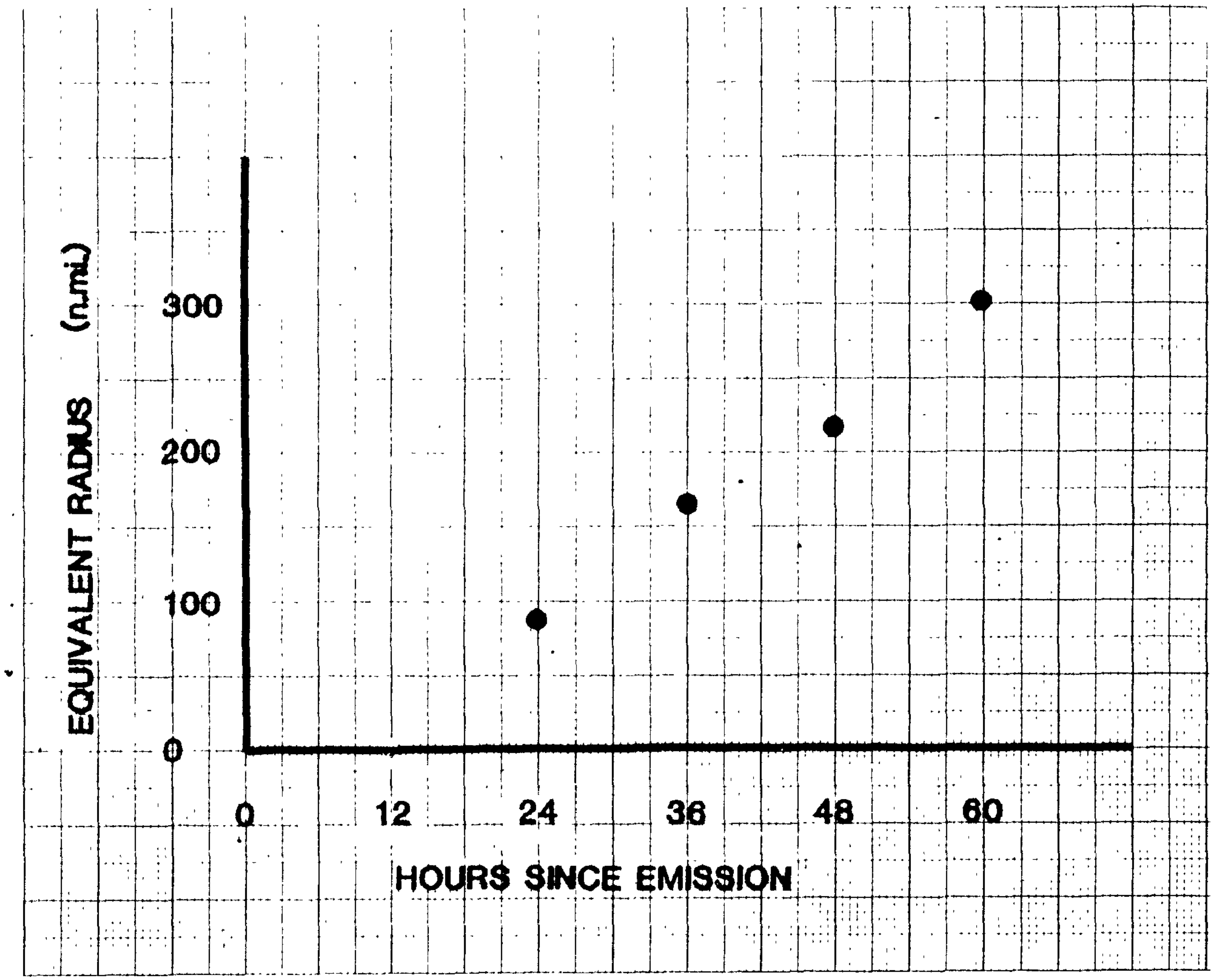


Figure 19. Average horizontal area covered by the dilution volume containing 24 hours of emissions as a function of time since emissions began, 00 GCT 28 June 1973 to 12 Z GCT 1 July 1973.

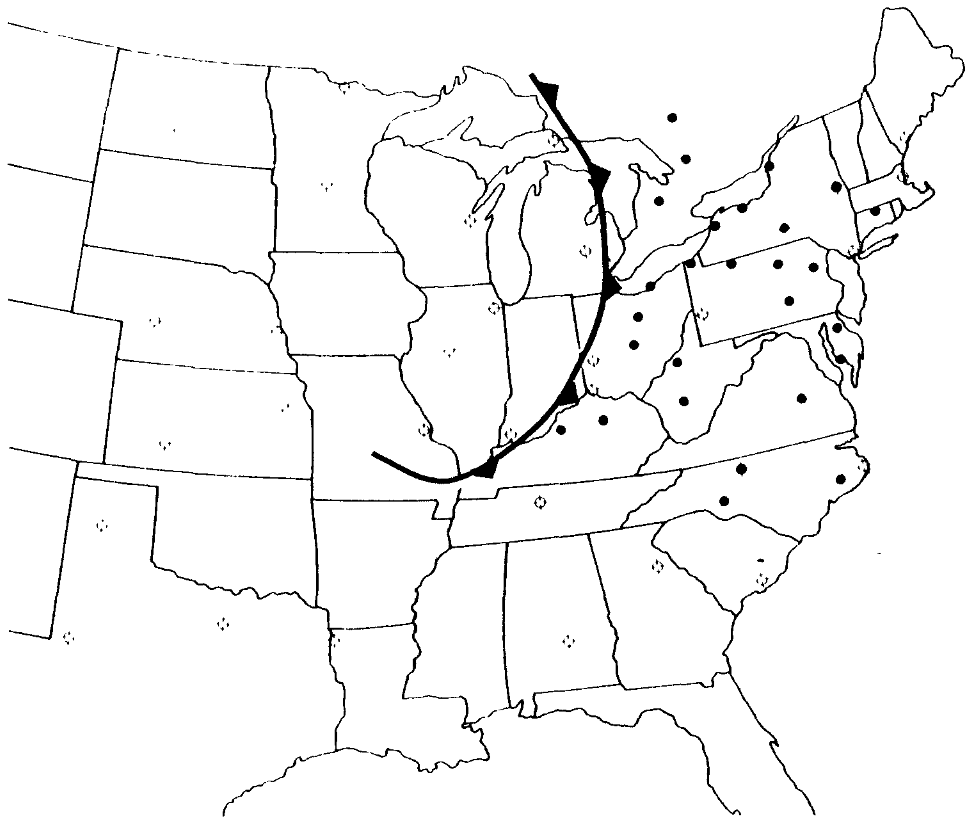


Figure 20. Position of cold front and distribution of haze, 00 GCT 3 July 1973.

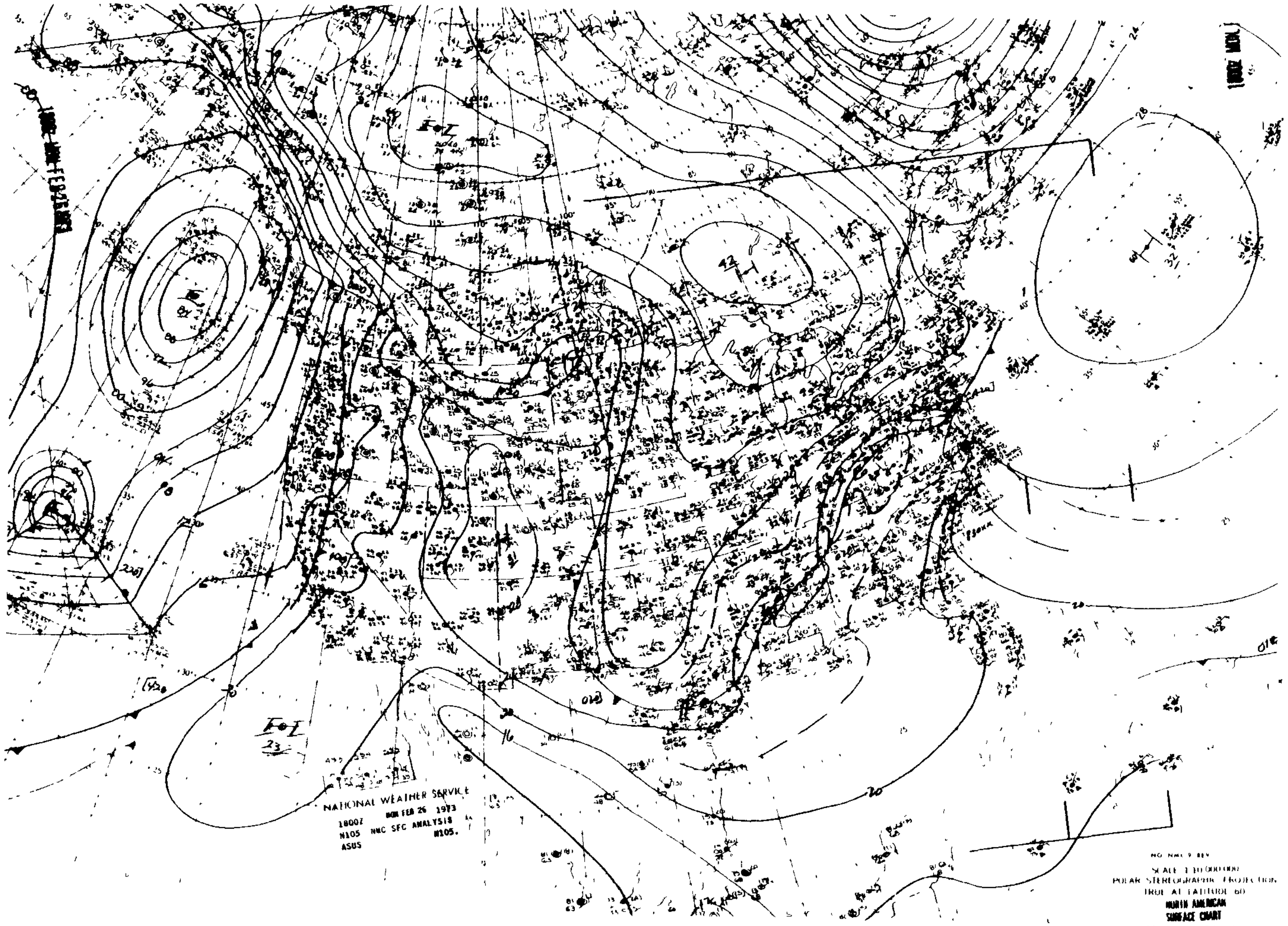


Figure 21. Synoptic maps, 26 February 1973.

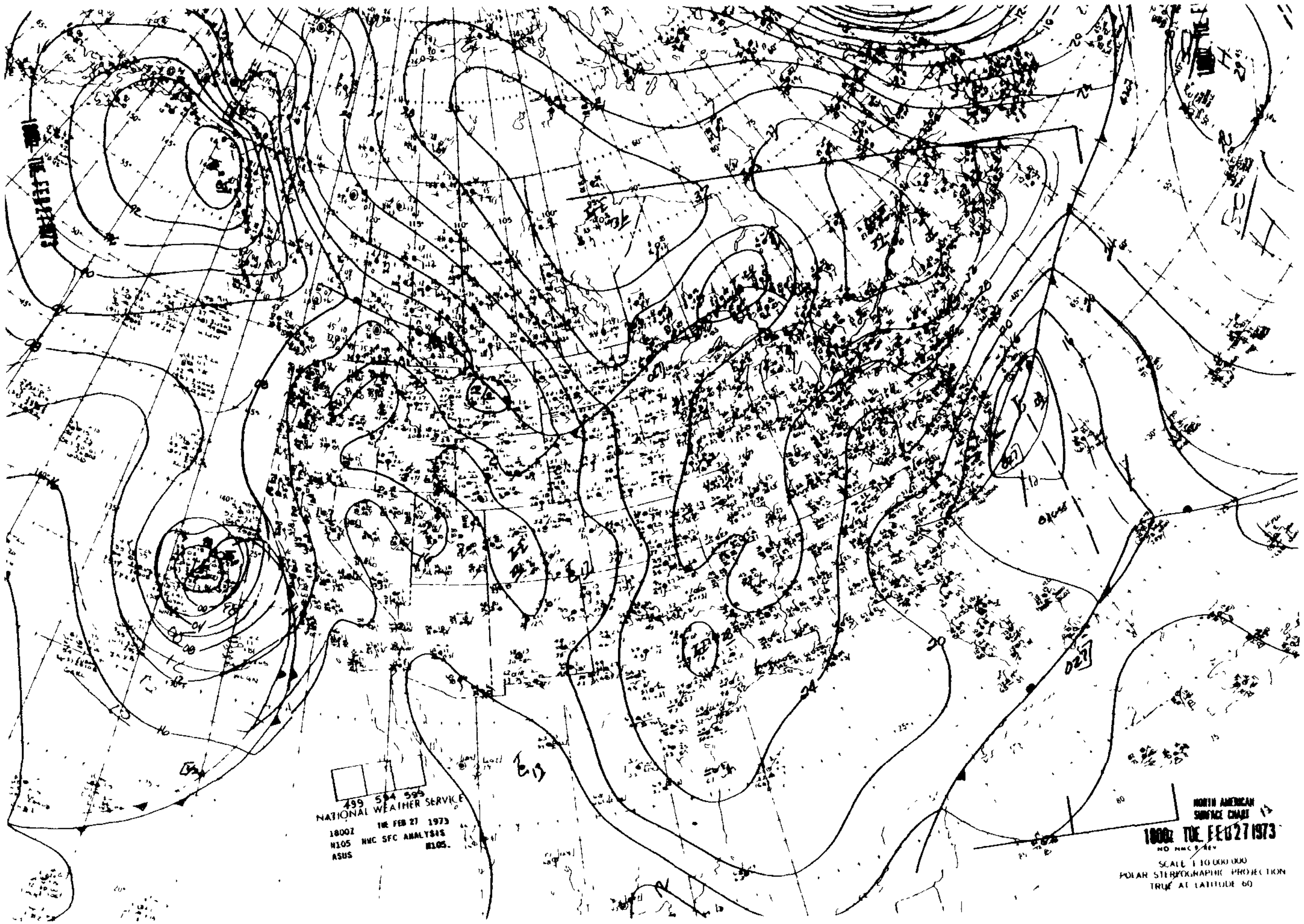


Figure 22. Synoptic maps, 27 February 1973.

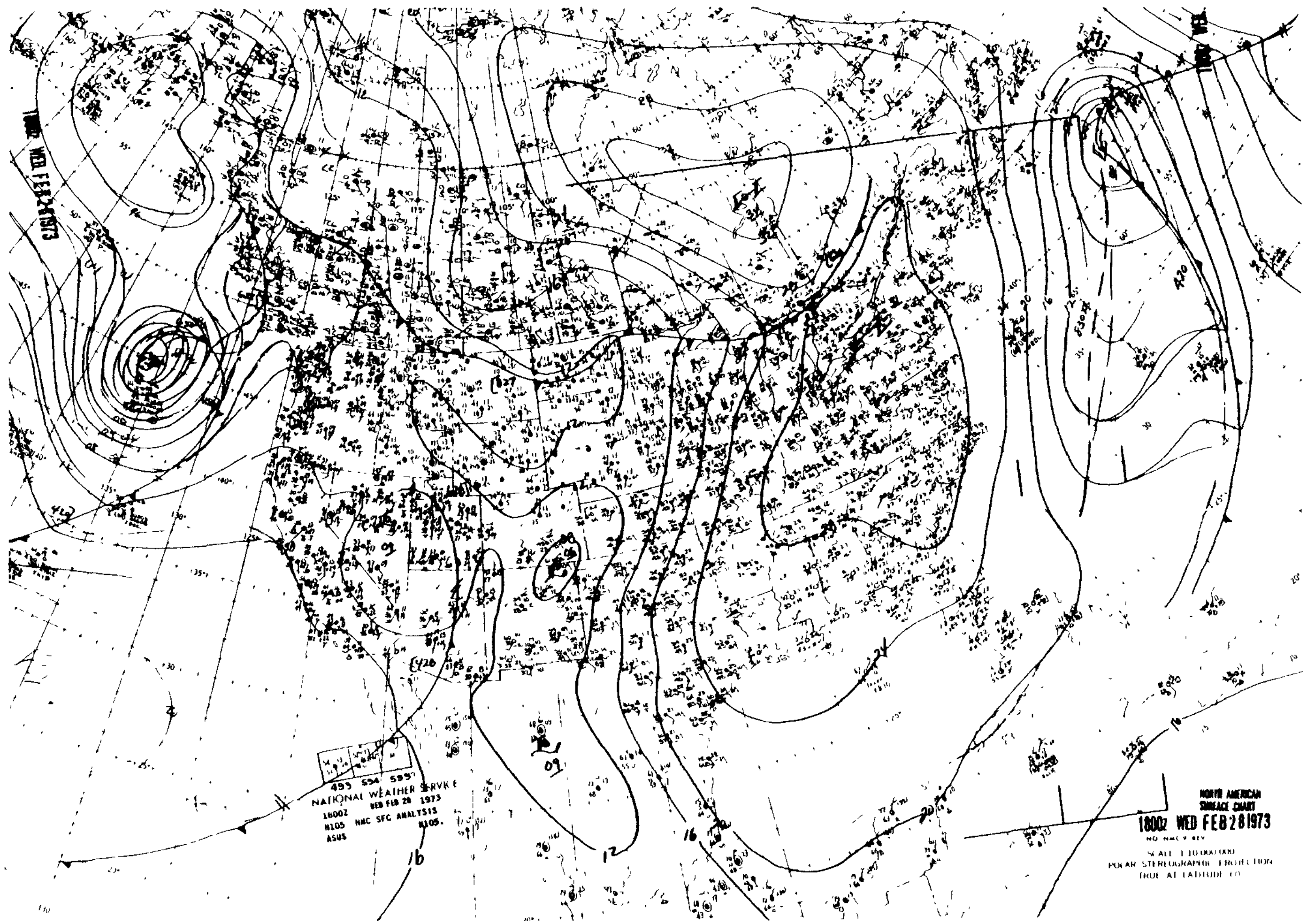


Figure 23. Synoptic maps, 28 February 1973.

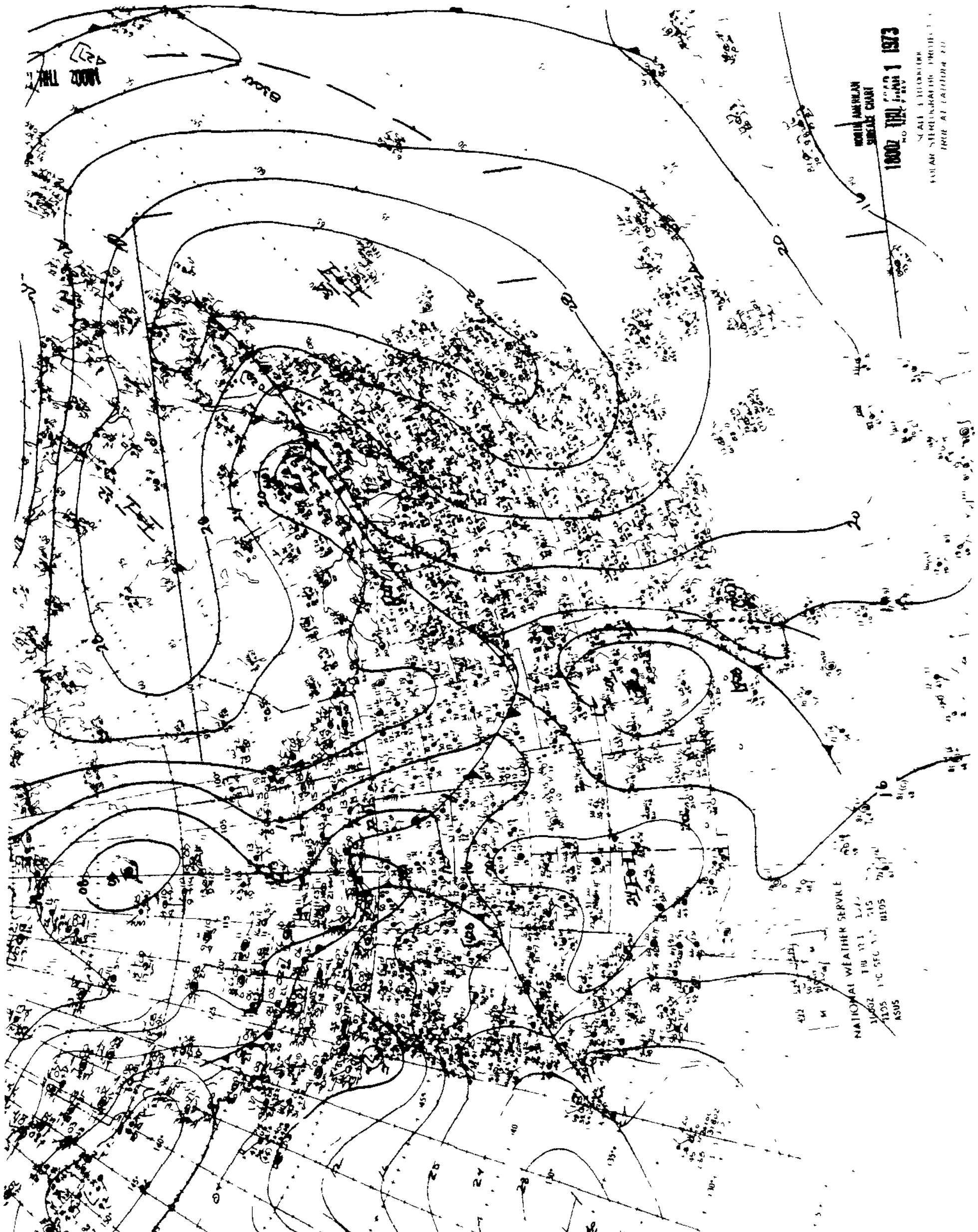
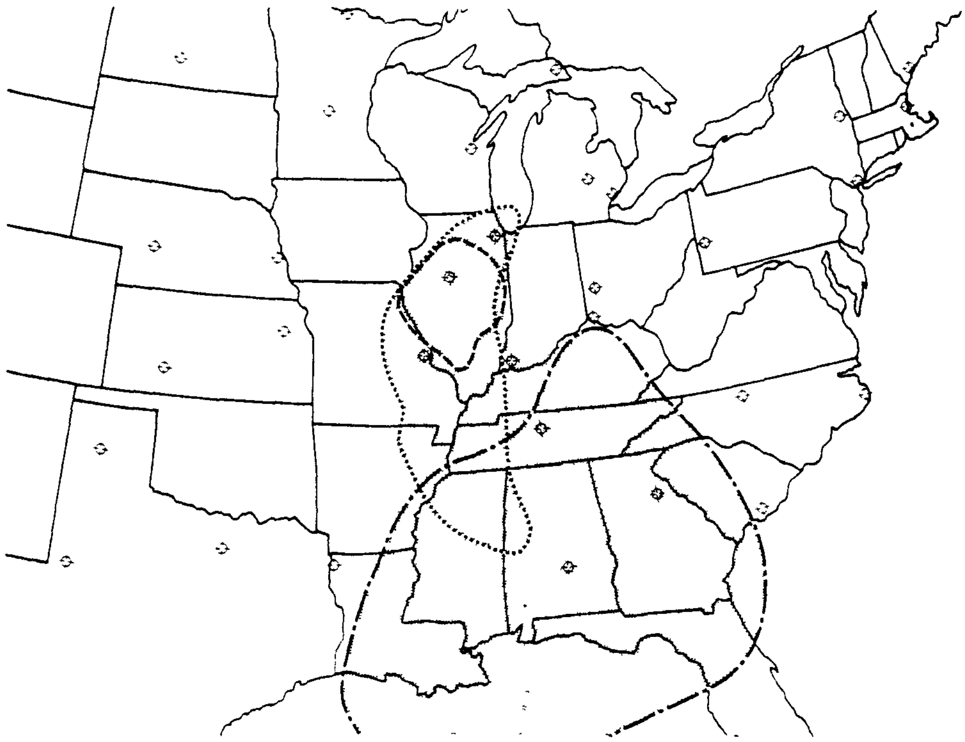
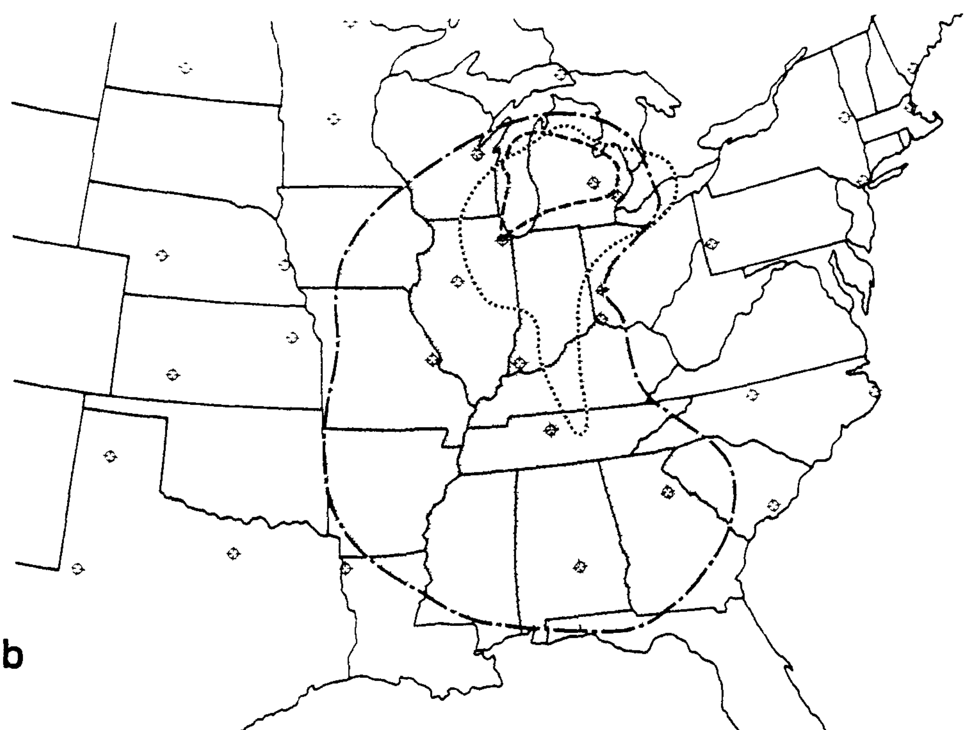


Figure 24. Synoptic maps, 1 March 1973.



a

Figure 25a. Plume from St. Louis at 00 GCT 1 March 1973 resulting from 3 days' continuous emissions.



b

Figure 25b. Plume from Chicago at 00 GCT 1 March 1973 resulting from 3 days' continuous emissions.

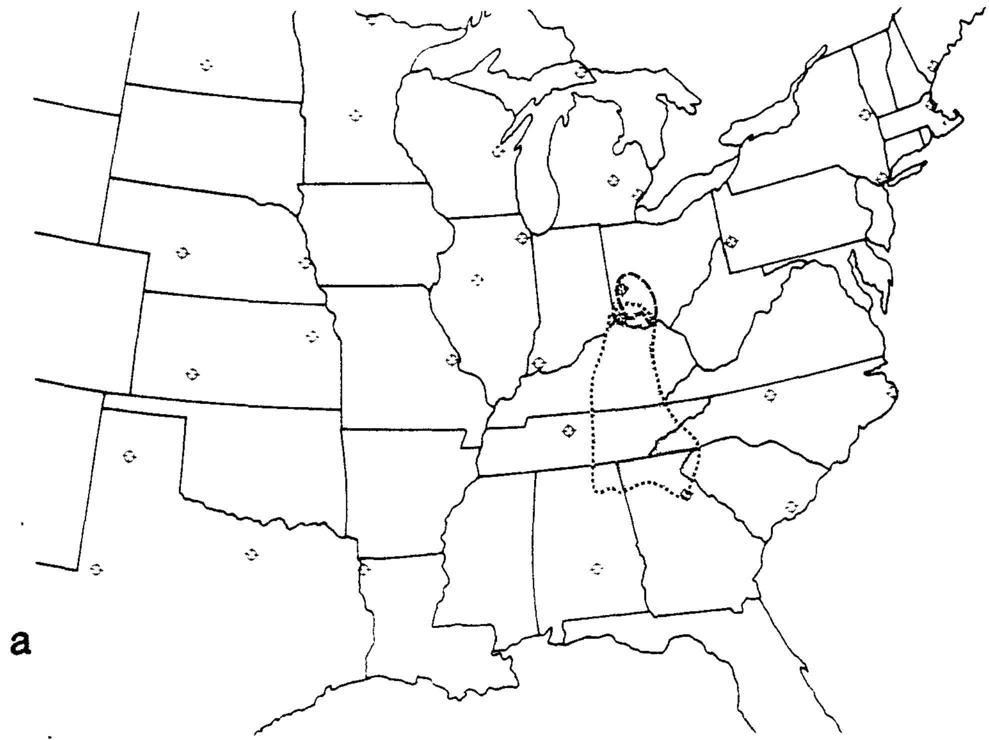


Figure 26a. Plume from Cincinnati at 00 GCT 1 March 1972 resulting from 2 days' continuous emissions.

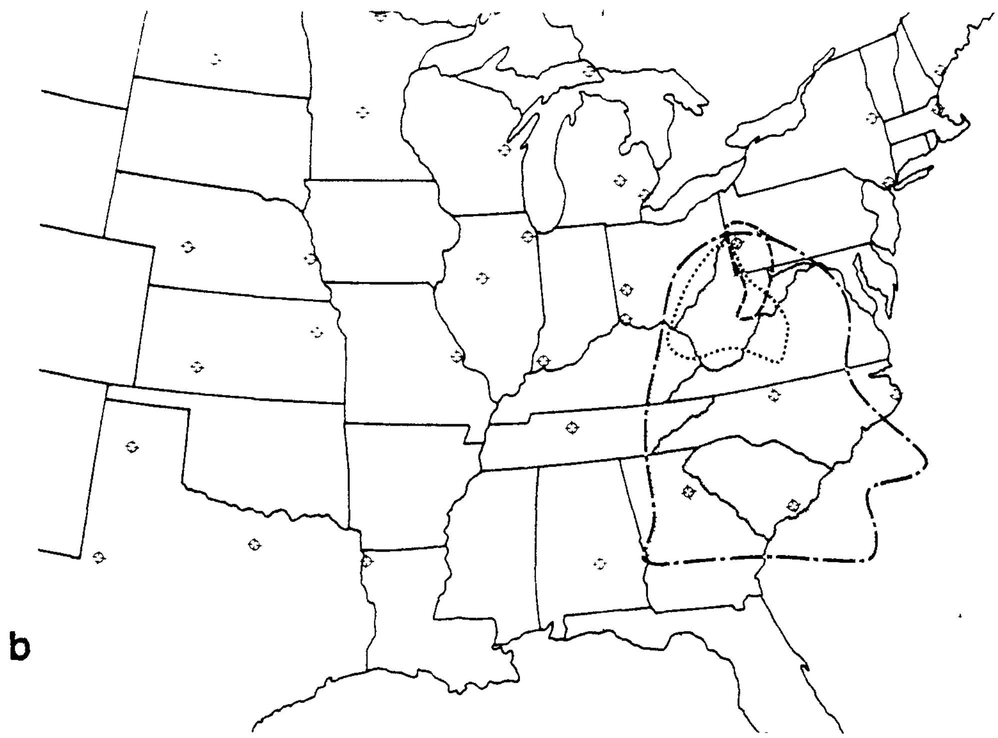


Figure 26b. Plume from Pittsburgh at 00 GCT 1 March 1973 resulting from 3 days' continuous emissions.

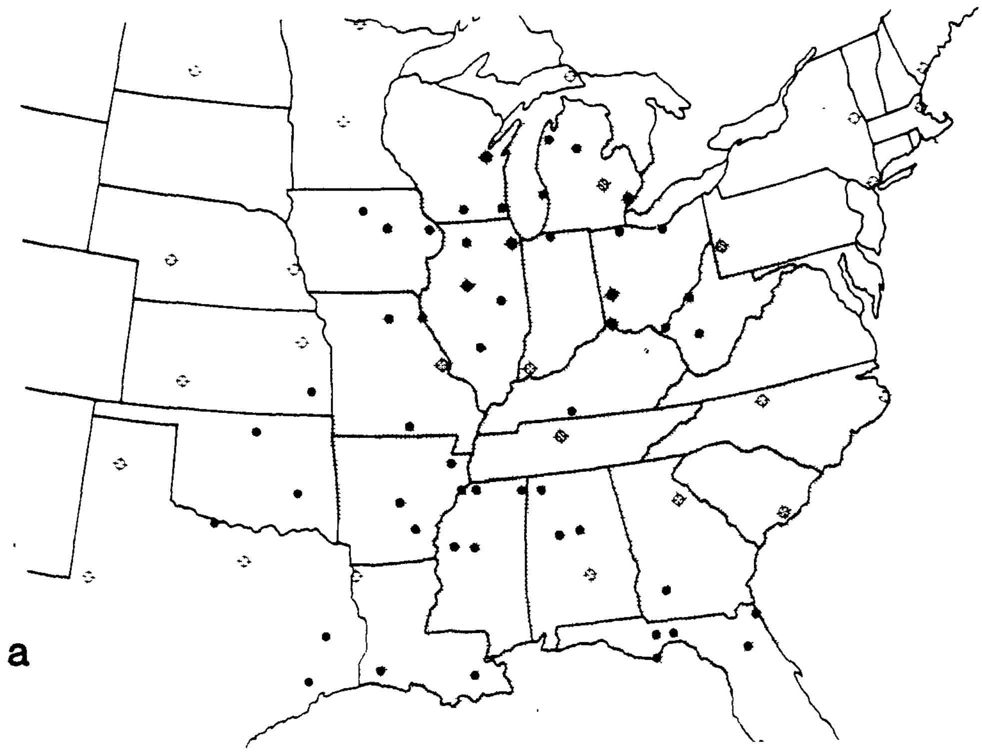


Figure 27a. Consolidated plume containing 3 days' emissions from St. Louis, Chicago and Pittsburgh and 2 days' emissions from Cincinnati as seen at 00 GCT 1 March 1973.

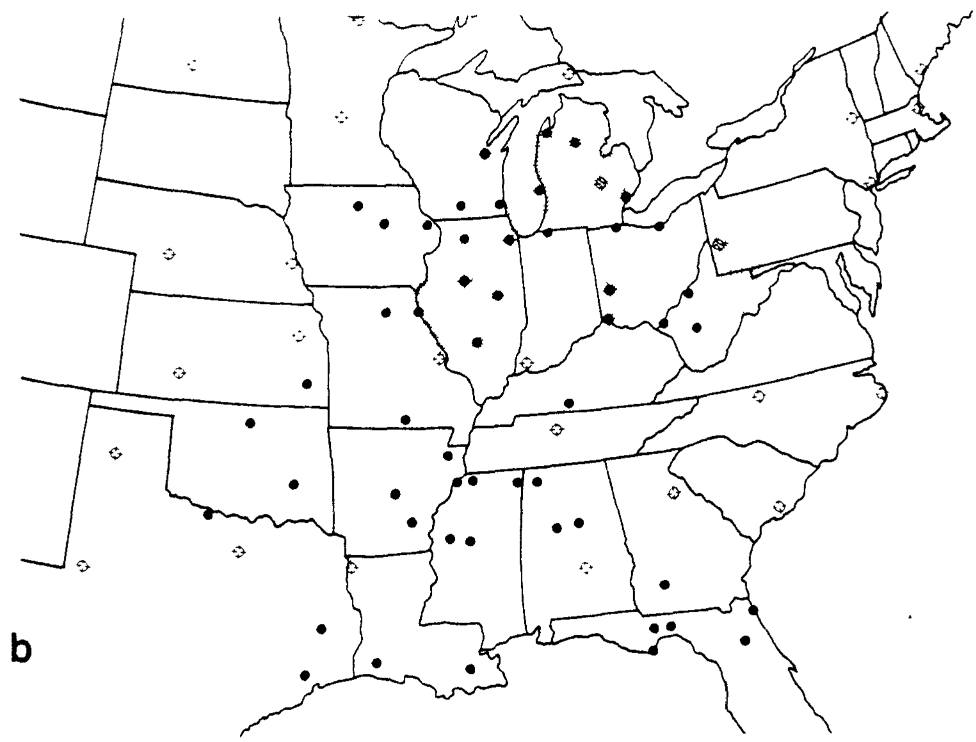


Figure 27b. One-day-old emissions from St. Louis, Chicago, Cincinnati and Pittsburgh, 00 GCT 1 March 1973.

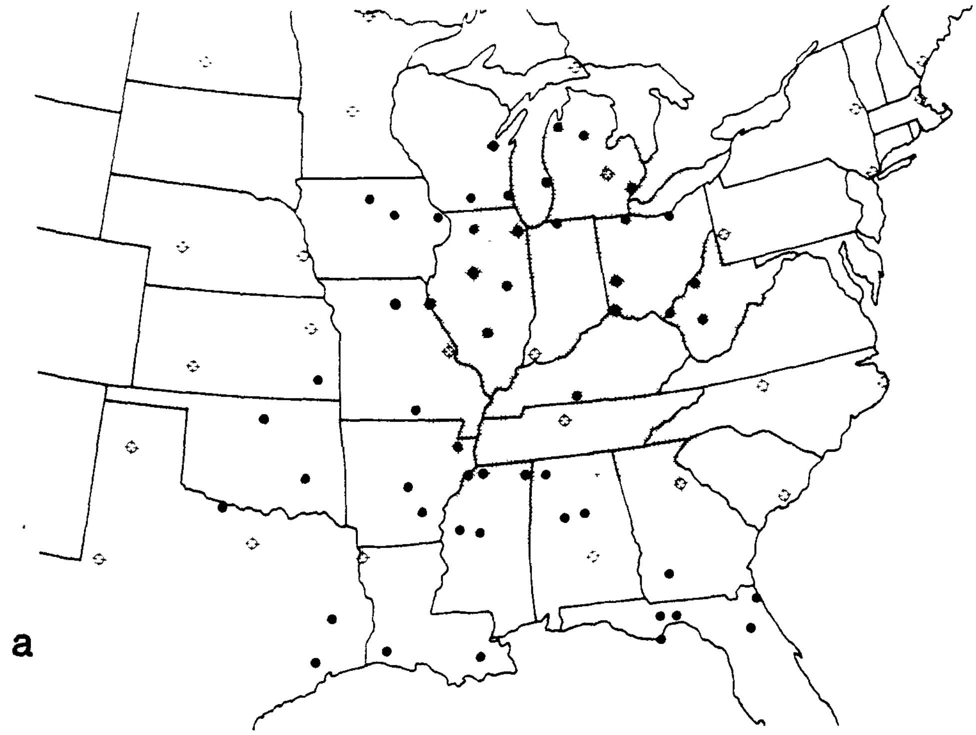


Figure 28a. Two-day-old emissions from St. Louis, Chicago, Cincinnati and Pittsburgh, 00 GCT 1 March 1972.

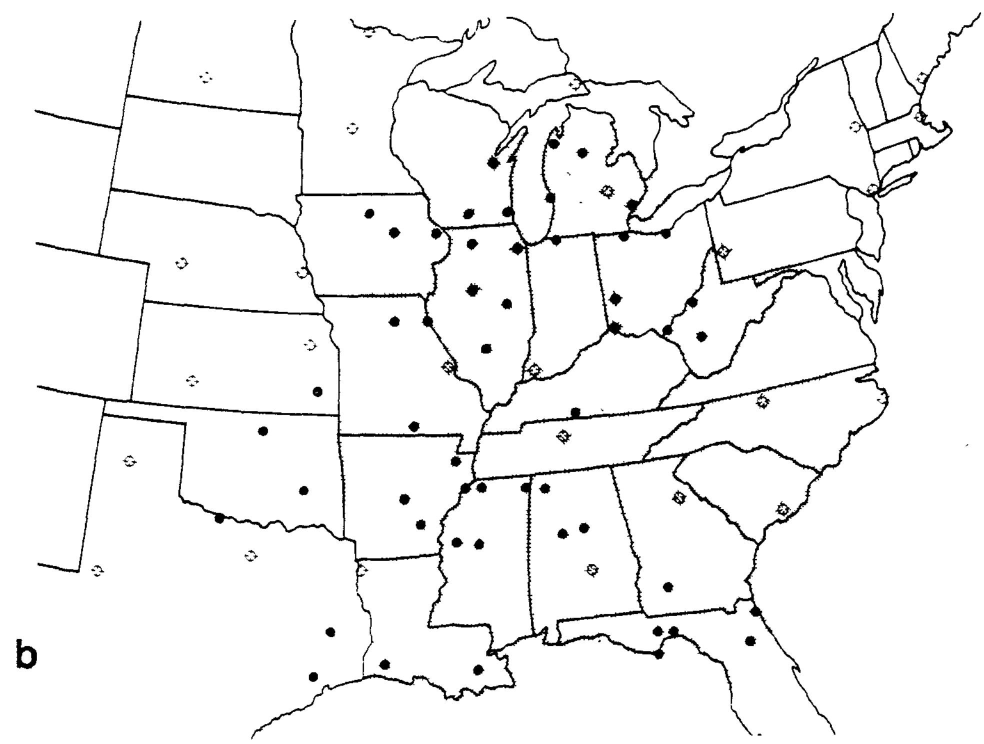


Figure 28b. Three-day-old emissions from St. Louis, Chicago and Pittsburgh, 00 GCT 1 March 1973.

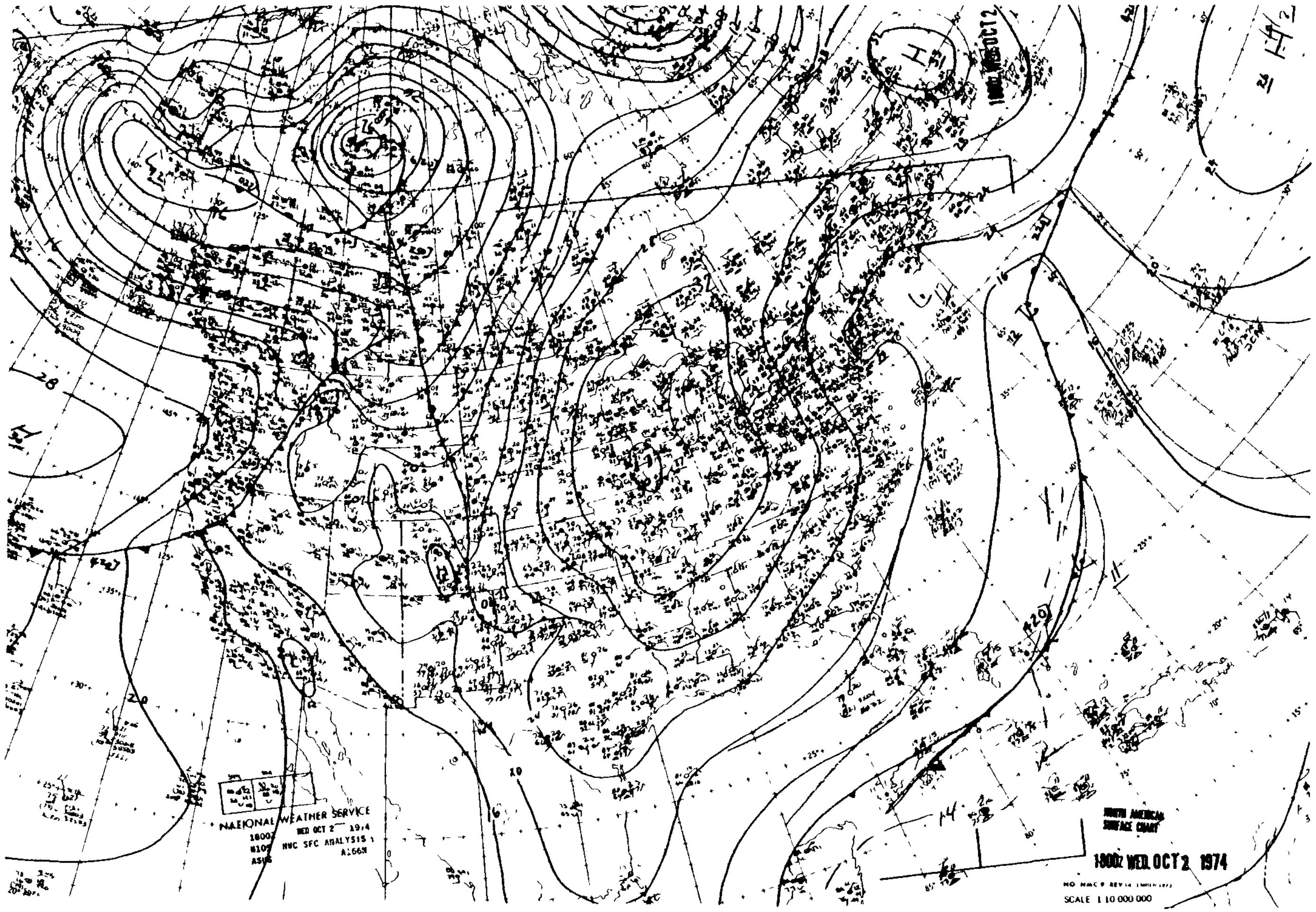


Figure 29. Synoptic maps, 2 October 1974.

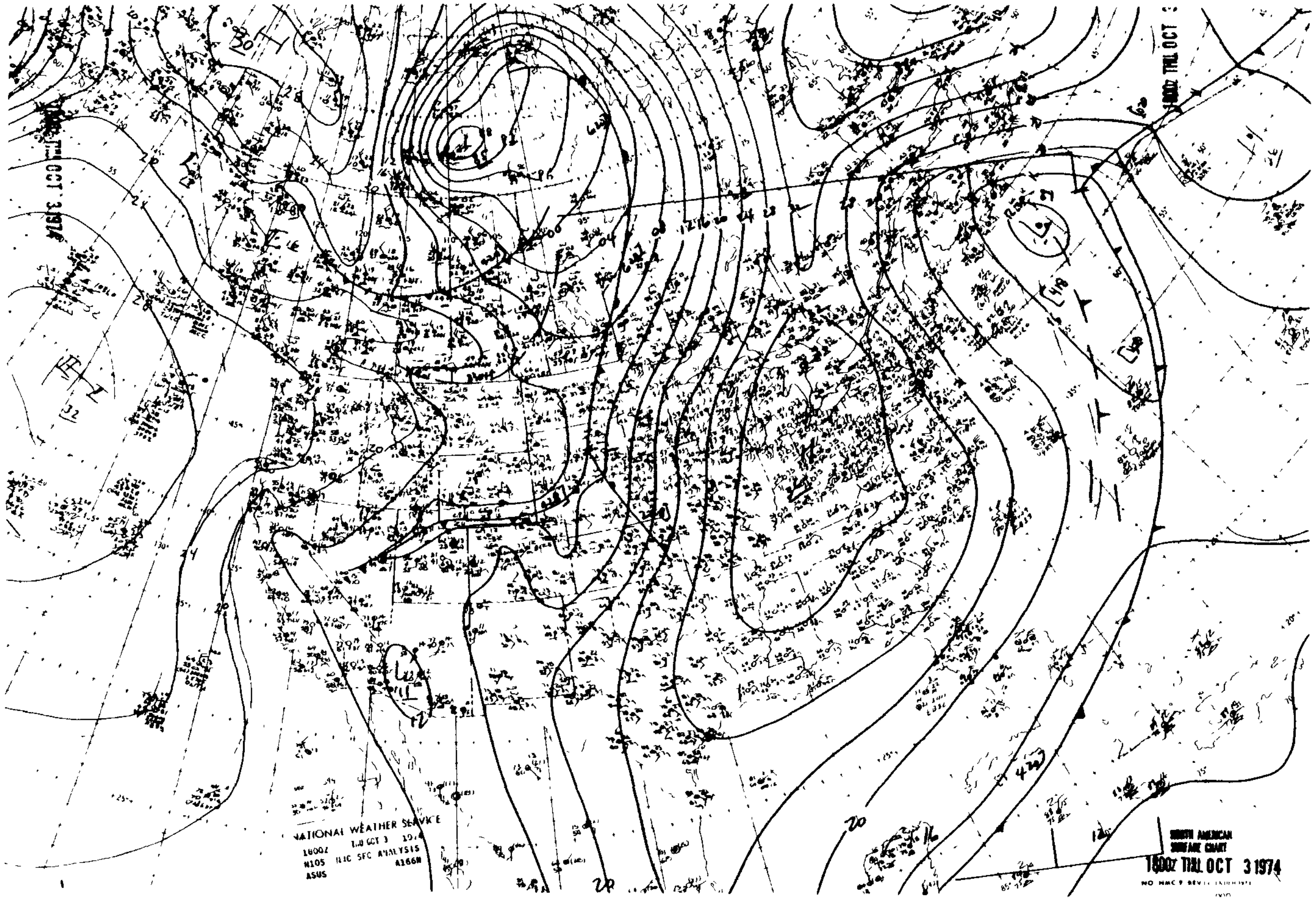


Figure 30. Synoptic maps, 3 October 1974.

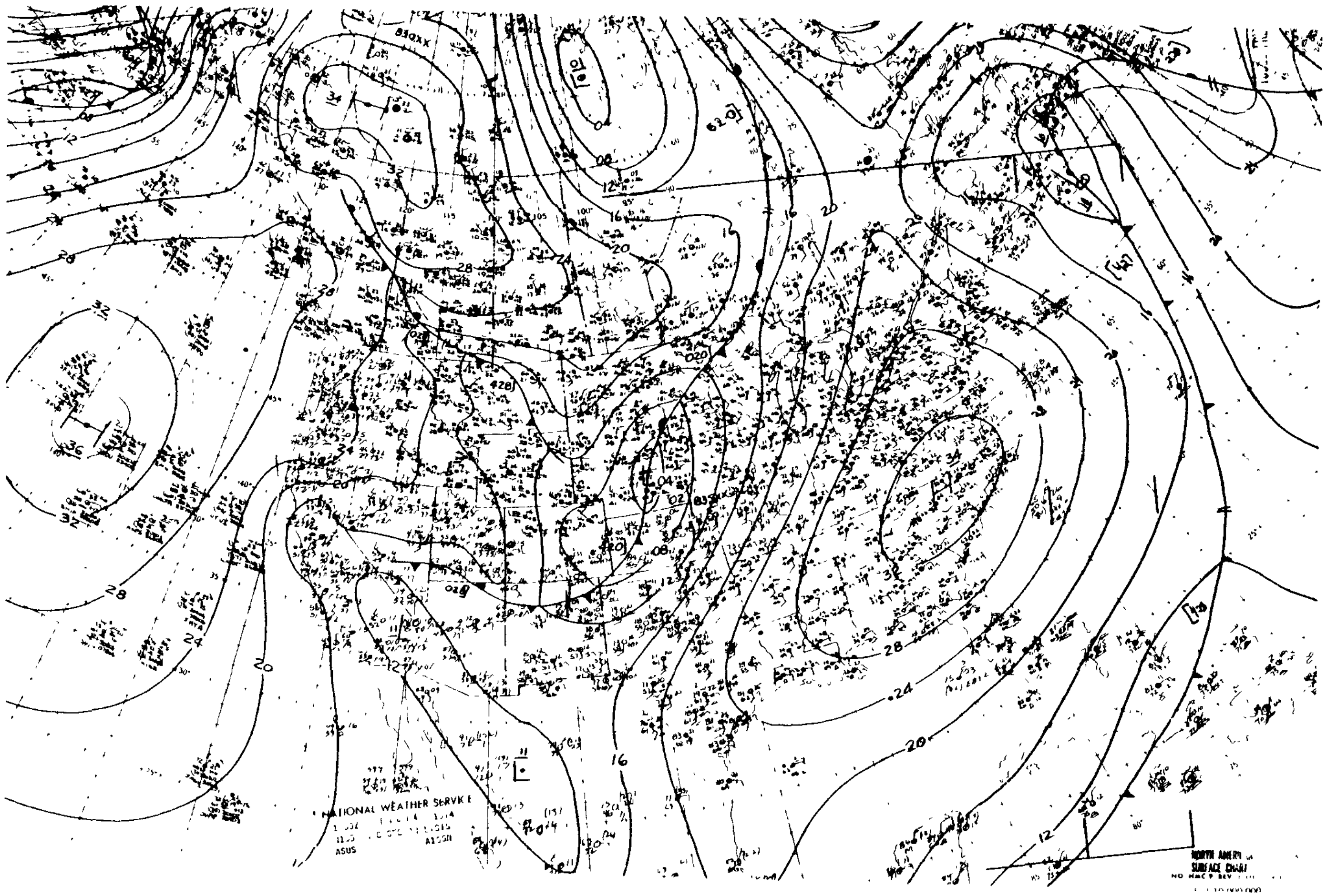


Figure 31. Synoptic maps, 4 October 1974.

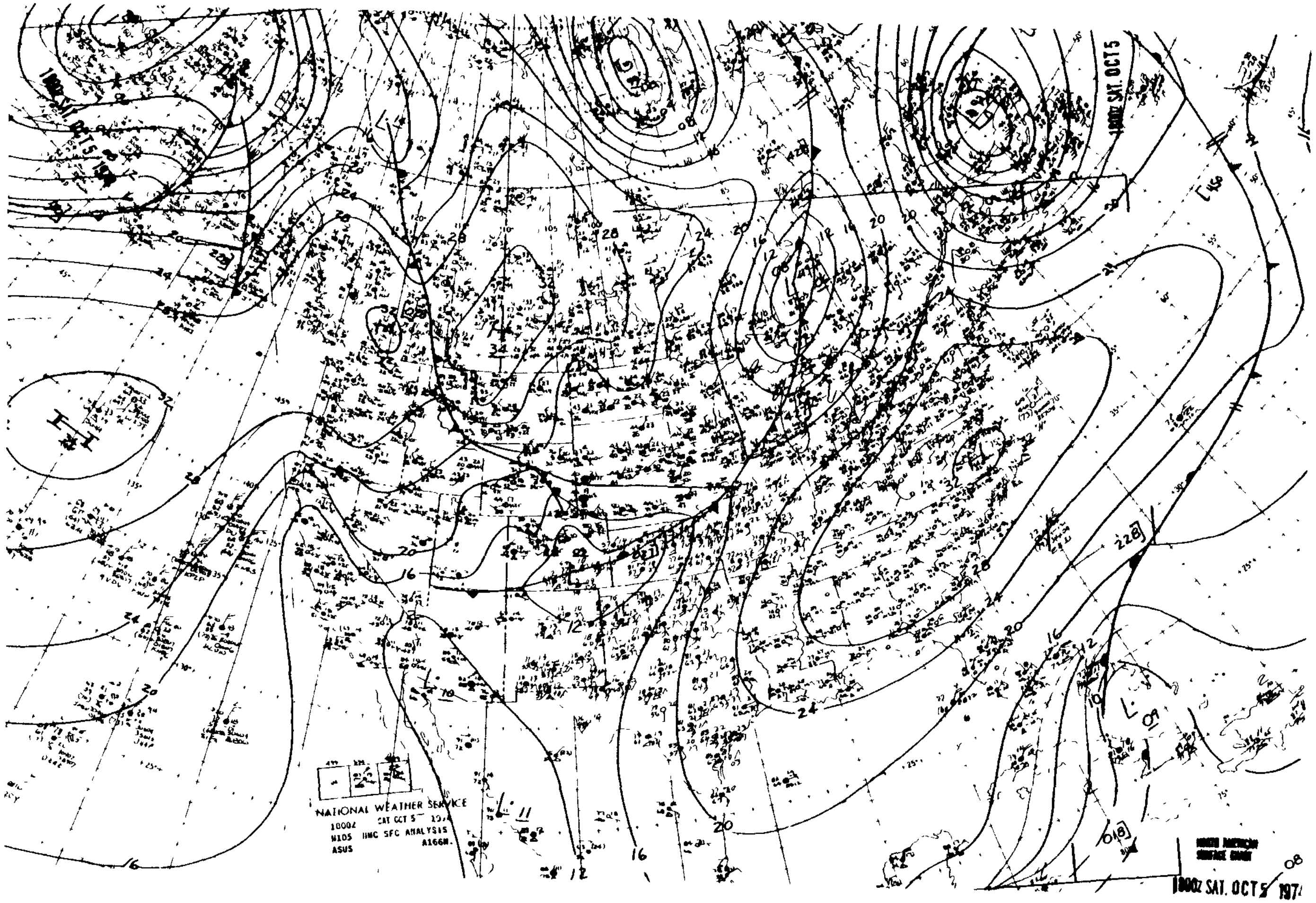
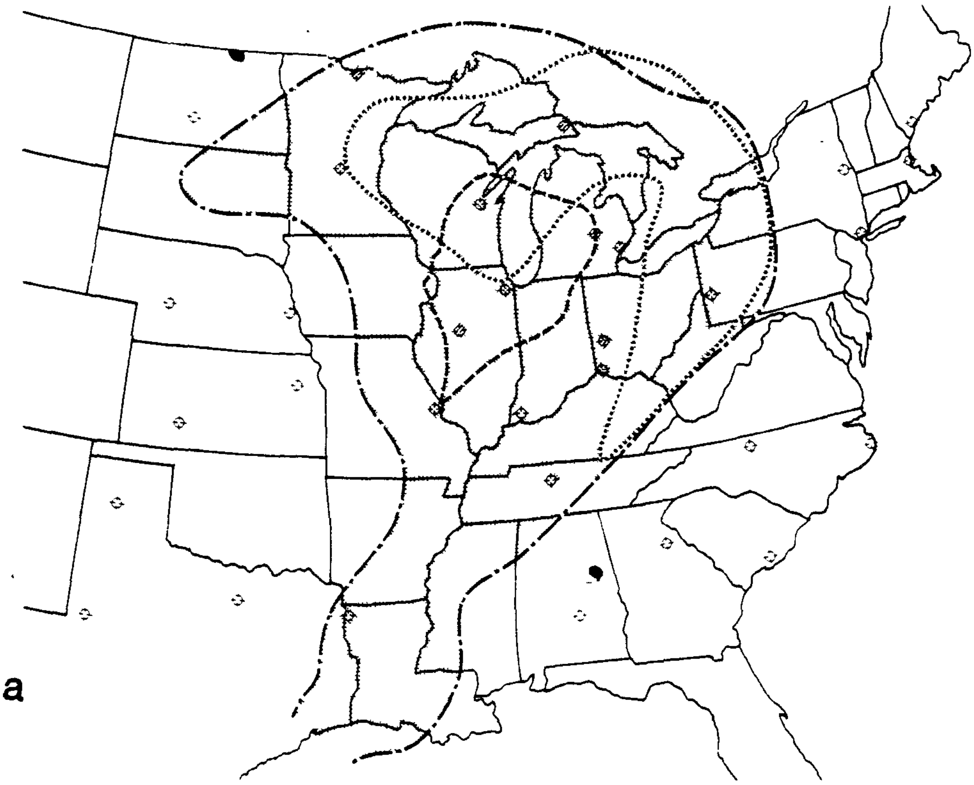
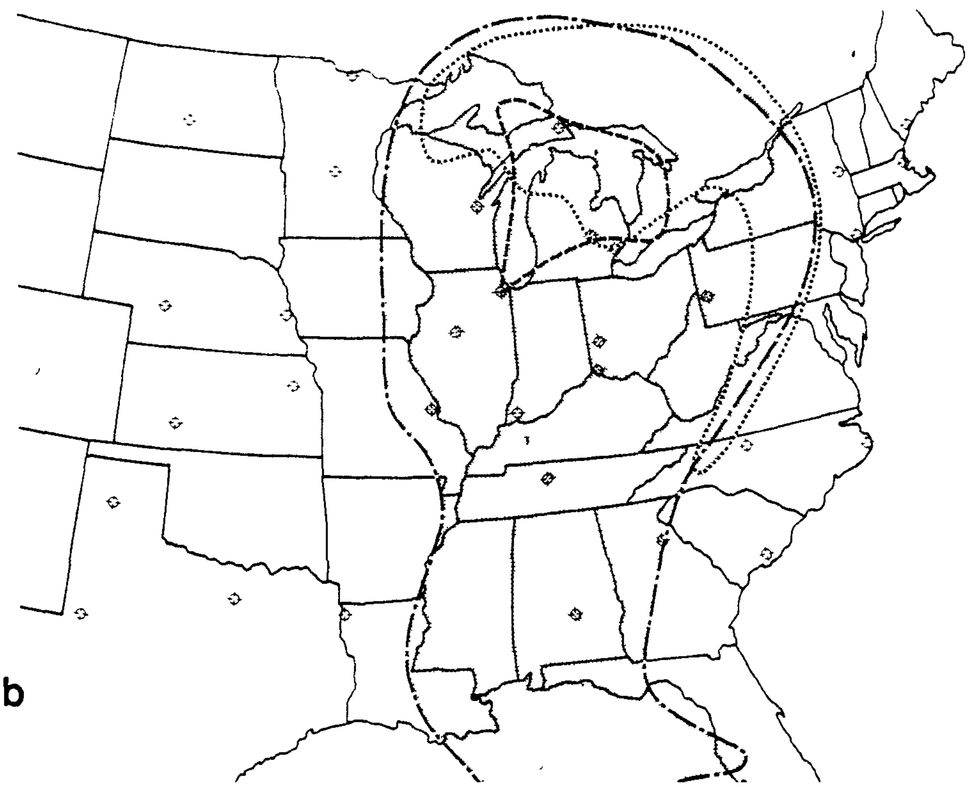


Figure 32. Synoptic maps, 5 October 1974.



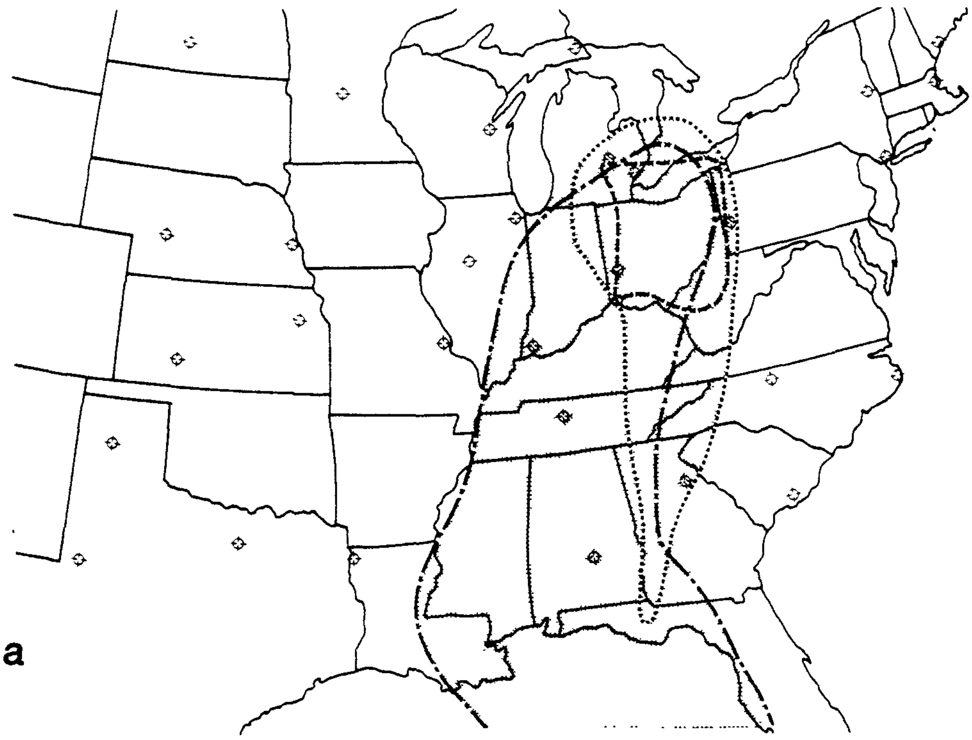
a

Figure 33a. Plume from St. Louis at 00 GCT 5 October 1974 resulting from 3 days' continuous emissions.



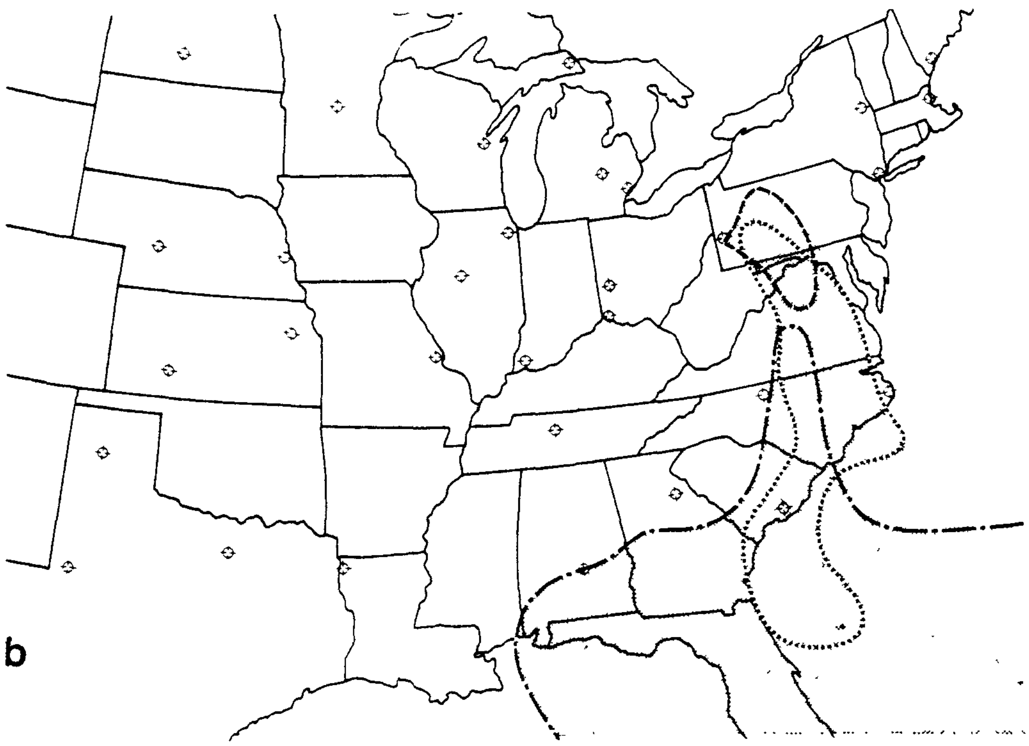
b

Figure 33b. Plume from Chicago at 00 GCT 5 October 1974 resulting from 3 days' continuous emissions.



a

Figure 34a. Plume from Cincinnnati at 00 GCT 5 October 1974 resulting from 3 days' continuous emissions.



b

Figure 34b. Plume from Pittsburgh at 00 GCT 5 October 1974 resulting from 3 days' continuous emissions.

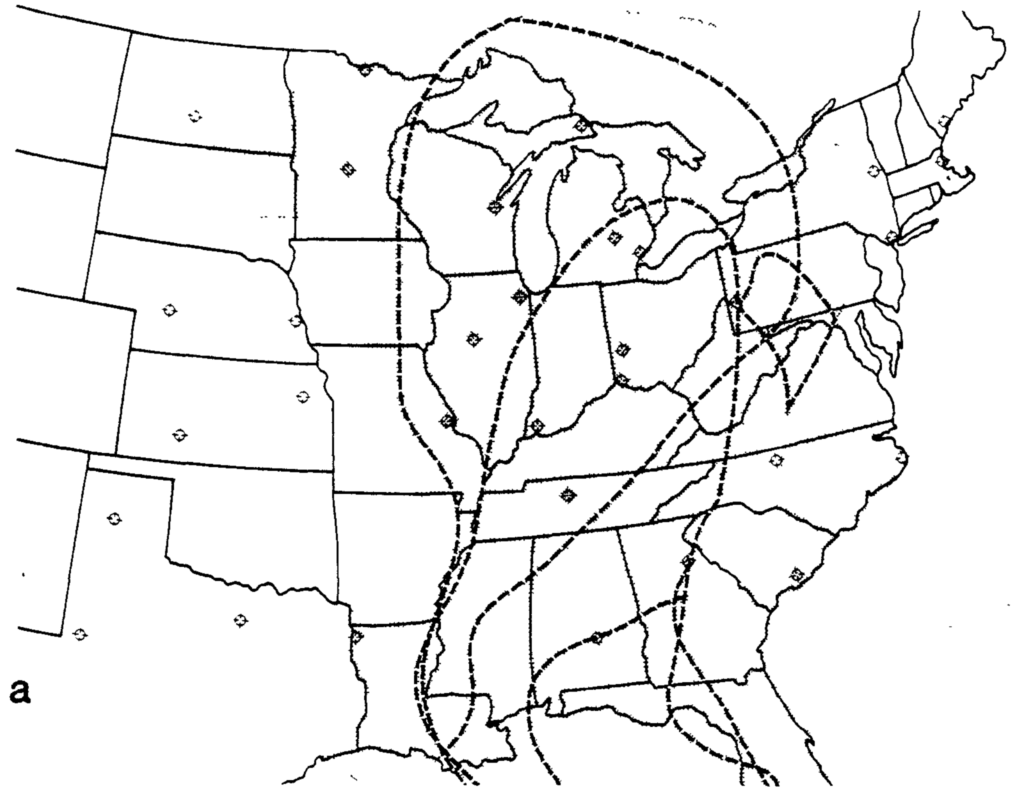


Figure 35a. Consolidated plume containing 3 days' emissions from St. Louis, Chicago, Cincinnati and Pittsburgh as seen at 00 GCT 5 October 1974

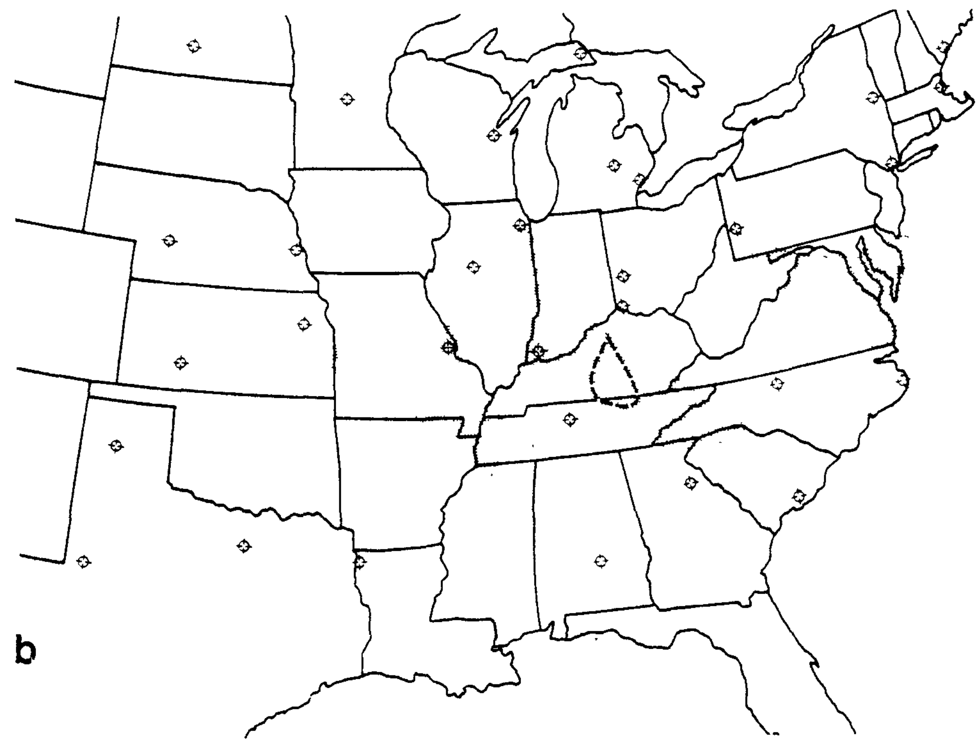


Figure 35b. One-day-old emissions from St. Louis, Chicago, Cincinnati and Pittsburgh, 00 GCT 5 October 1974.

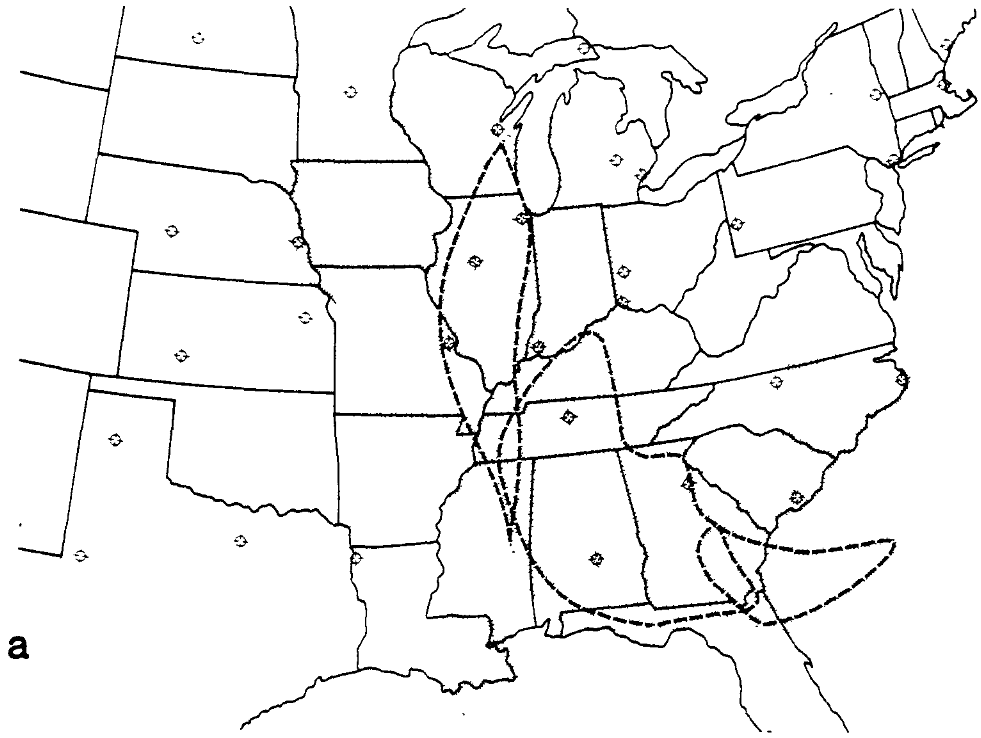


Figure 36a. Two-day-old emissions from St. Louis, Chicago, Cincinnati and Pittsburgh, 00 GCT 5 October 1974.

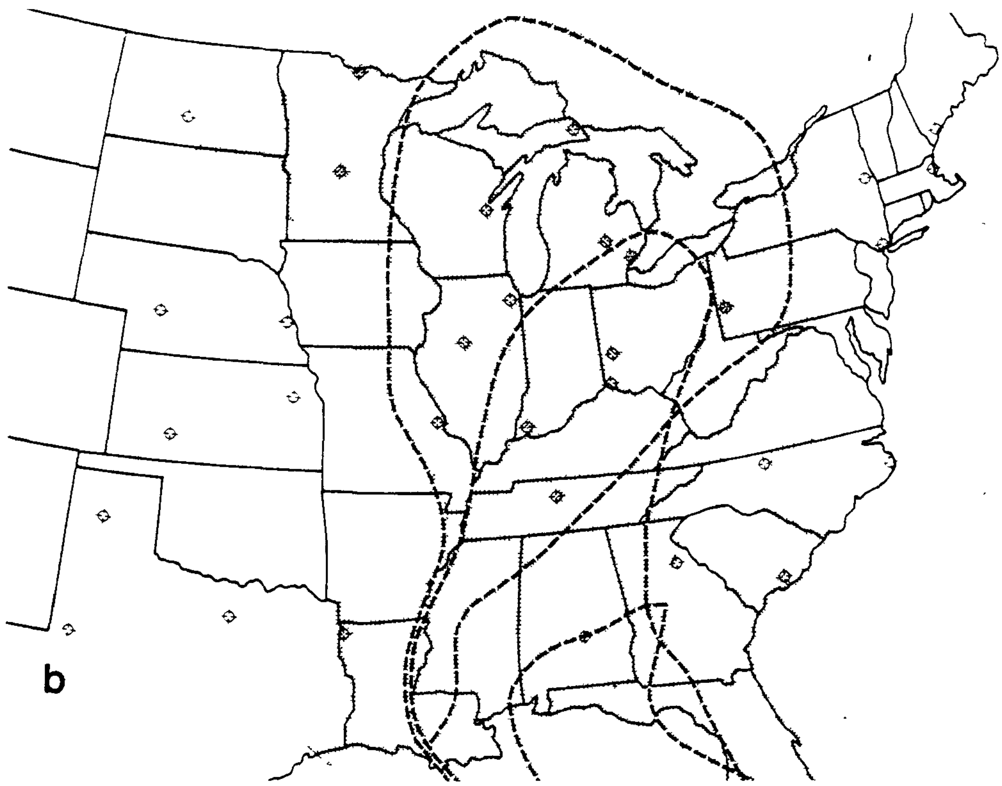


Figure 36b. Three-day-old emissions from St. Louis, Chicago, Cincinnati and Pittsburgh, 00 GCT 5 October 1974.

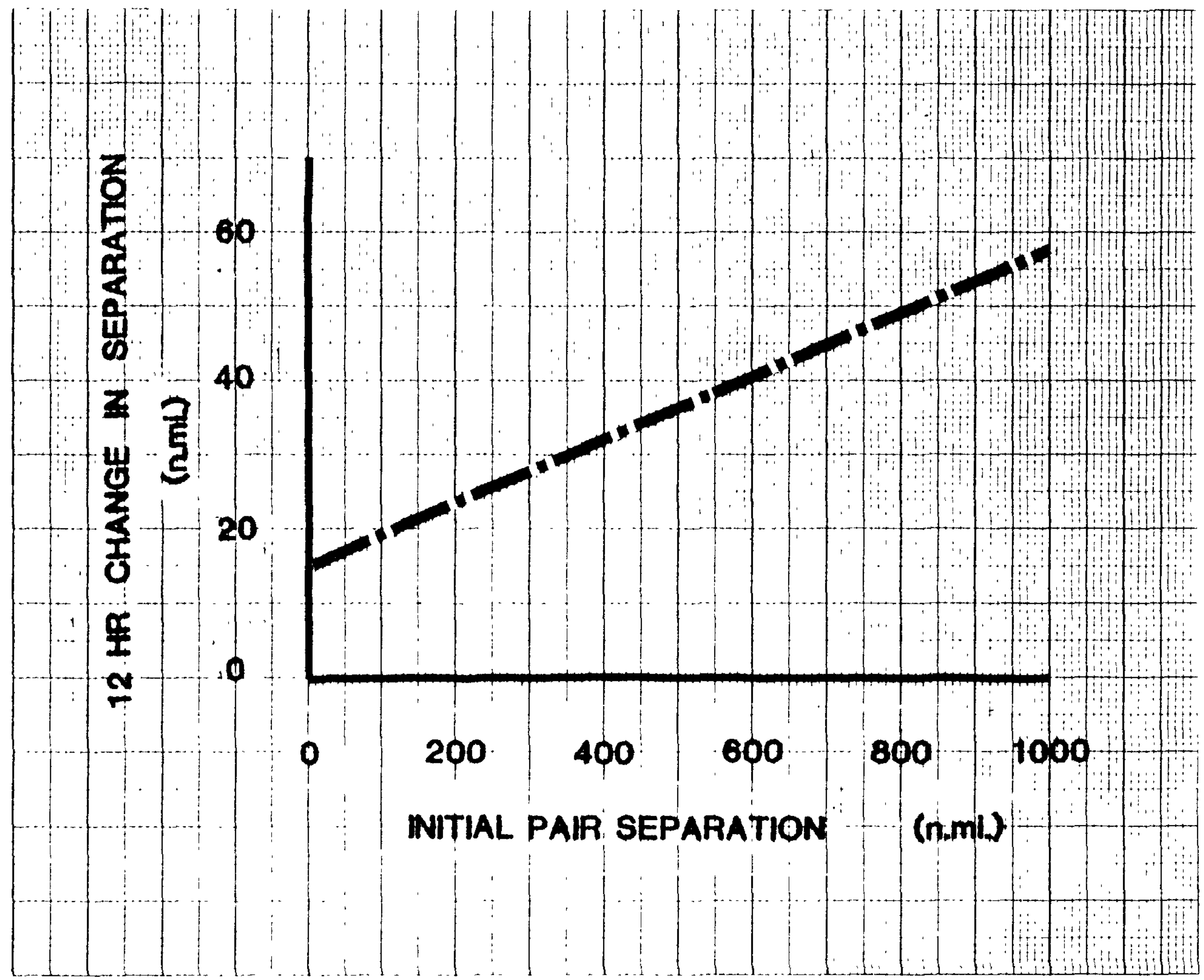


Figure 37. Average 12 hour change in distance between pairs of air parcels as a function of initial separation.

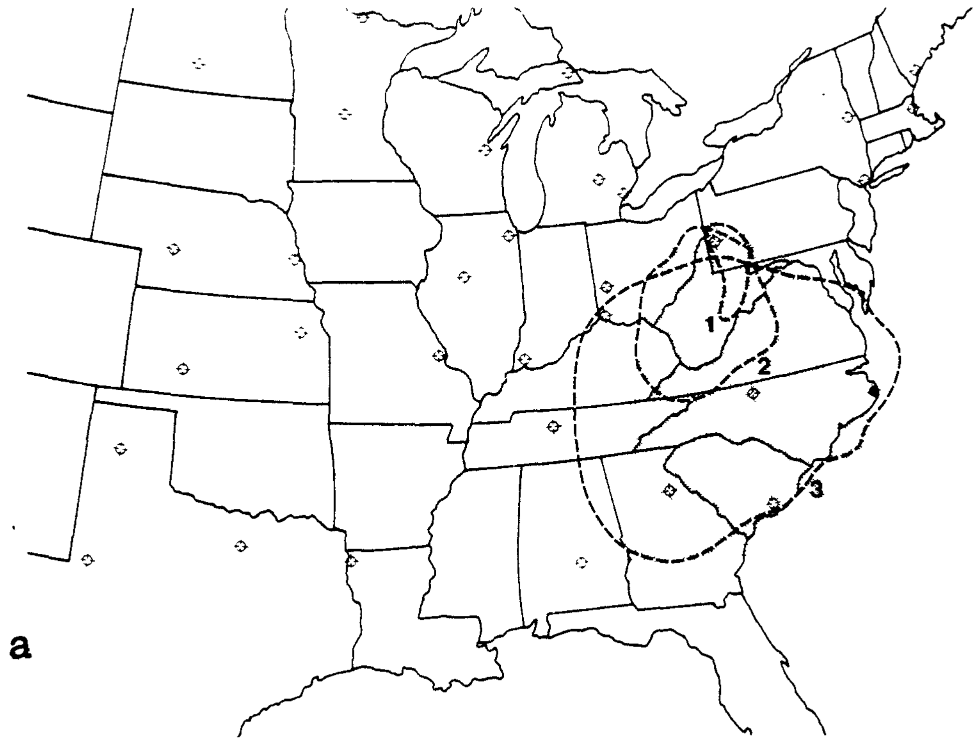


Figure 38a. Comparison of plumes constructed by the long and short (approximate) methods, Pittsburgh, 00 GCT 1 March 1973.

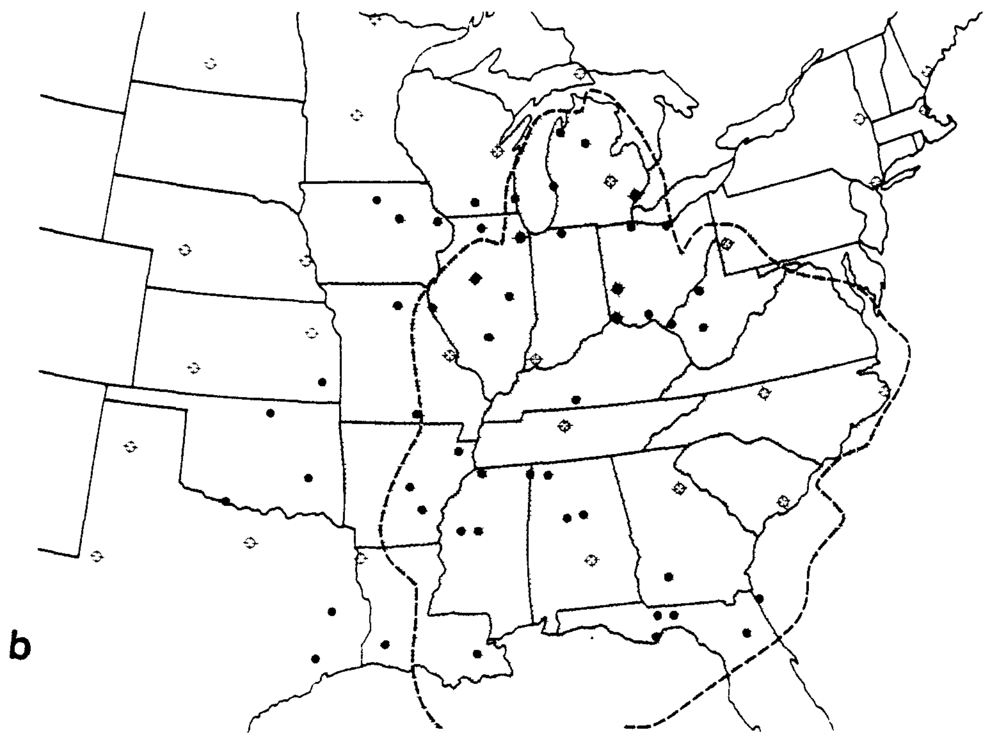


Figure 38b. Comparison of consolidated plumes constructed by the long and short (approximate) methods, 00 GCT 1 March 1973.

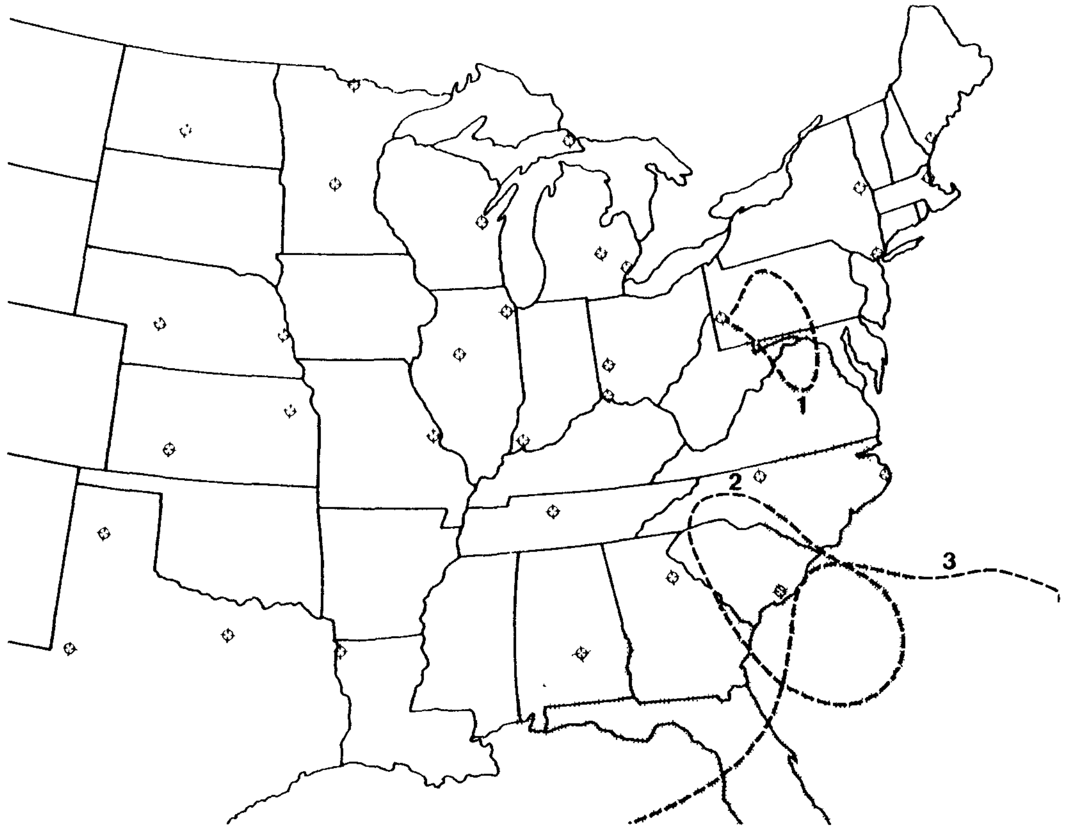


Figure 39. Comparison of plumes constructed by the long and short (approximate) methods, Pittsburgh, 00 GCT 5 October 1974.

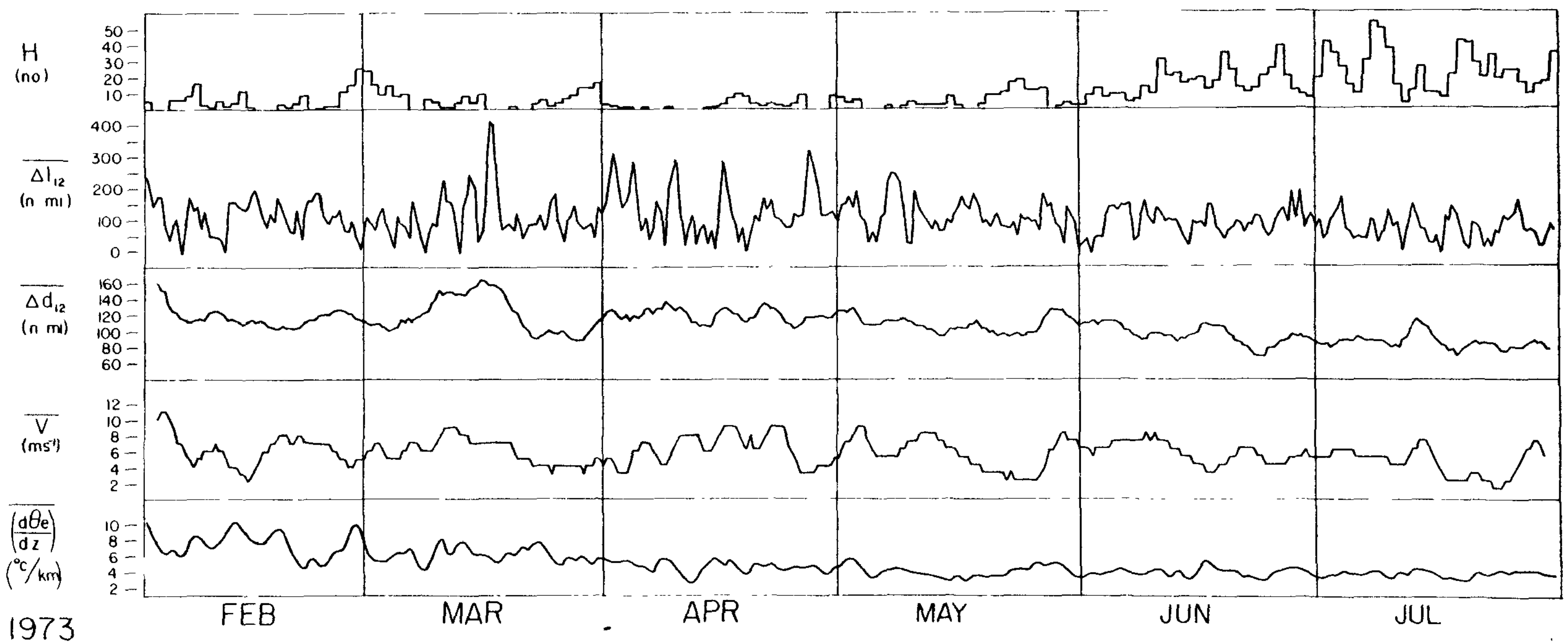


Figure 40. Time variation of: number of haze reports, H; average 12 hour pair separation due to horizontal shear, $\overline{\Delta \ell_{12}}$; average 12 hour pair separations due to vertical shear, $\overline{\Delta d_{12}}$; average wind speed, $\overline{V}$; average rate of equivalent potential temperature with height, $d\Theta_e/dz$.

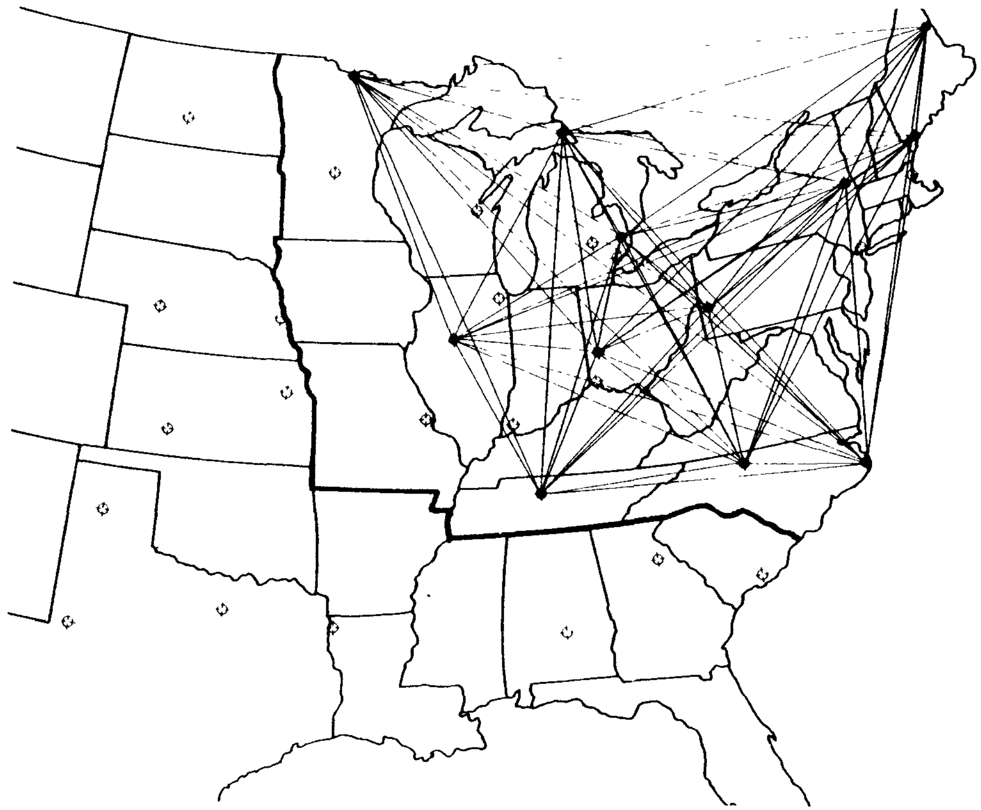


Figure 41. Map of area covered by statistical study. Lines connecting rawinsonde stations identify the 66 station pairs.

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TECHNICAL REPORT DATA

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1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
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16. ABSTRACT

The purpose of this research project was to determine the role of meteorological factors in the formation of widespread areas of haze in the eastern United States. Three case studies were made: A summer haze episode, an off-season haze episode and a non-haze episode.

Results showed that over the course of 2 or 3 days emissions from widely separated sources such as St. Louis, Chicago, Cincinnati and Pittsburgh are leafed together by vertical and horizontal shears and mixing by daytime convection to form a dilution volume many hundreds to well over a thousand km in extent and 2 or 3 km in depth. Almost all stations reporting haze during an episode were confined to this dilution volume and most of these in that part of the plume containing emissions that were 2 or 3 days olds.

The dilution volume associated with the off-season episode was of about the same magnitude as that of the summer case, but was shallower and horizontally more extensive. Both of these 3-day haze volumes were much smaller than the dilution volume associated with the non-haze case which blanketed almost the entire eastern United States.

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