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AN EVALUATION OF DATA REQUIREMENTS AND
OBJECTIVE ANALYSES TECHNIQUES APPROPRIATE FOR
REGIONAL SCALE ATMOSPHERIC TRANSPORT

Larry L. Wendell
Battelle Pacific Northwest Laboratories

Abstract

With increasing concern about the fate of atmospheric pollutants on a scale of 100 to 1000 km, the accuracy of the transport calculations on this scale takes on a new importance. Realistic post analyses of wind and temperature distributions are essential in computing historical transport for environmental impact assessments. They are also necessary for providing initial conditions for transport prediction models used for accidental releases of toxic contaminants into the atmosphere. Recent investigations in several mesoscale areas (50-100 km) in the western United States have shown that mildly variable topographic features can cause significant horizontal variability in the flow as well as dramatic vertical shear in horizontal wind direction. The significance of the influence of this mesoscale variability in regional scale flow determinations is examined in terms of the density and type of wind observations required. Several objective techniques for flow determination are compared and evaluated for application on the regional scale.

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INTRODUCTION

Until recently almost all experiments conducted to determine how the atmosphere diffuses pollutants were carried out on a scale of a few kilometers. Transport of the polluting material was accomplished by a mean wind of fairly constant direction and speed through the course of each experiment. The main purpose of the experiments was to study the nature of the diffusion. However, the transport philosophy of these experiments seemed to carry over into diffusion models covering scales of tens of kilometers (mesoscale) as well as operational practices of determining the areas affected by an effluent from an accidental release or a long term continuous stack release. The models assumed a steady transporting wind and the operational procedures were set up to use the source wind as if it applied for the entire distance of concern.

Results of some work by Wendell⁽⁵⁾ has demonstrated that the wind over a mesoscale region cannot be counted on to be uniform and that much of the spatial variability can be related to relatively mild terrain variation. Trajectory studies by Angell, et al.⁽¹⁾ have also revealed transport complexities which have a direct bearing on pollution transport.

With the advent of sophisticated pollution models, advancing computer technology and the rapid development of pollution sensing equipment, a system has been suggested in which an illegally high concentration of some pollutant measured at a particular sensor could be quickly traced back to the offending industrial site. One of the weakest links in a system such as this would be the transport assumptions. The complexity of the flow in the boundary layer, especially under the influence of terrain variation,

could make transport determinations from a single location to be so misleading that results from the system would be completely erroneous.

The purpose of this paper is to review briefly some recent work showing mesoscale spatial variability in wind fields and the resulting effects on transport and also to present some terrain induced mesoscale phenomena which appear strongly to influence transport.

MESOSCALE FLOW AND TOPOGRAPHIC FEATURES

In an attempt to determine the mesoscale horizontal variation of the wind in the lower portion of the planetary boundary layer, hourly averaged wind data from a randomly spaced collection of 21 wind stations within an area of 12,420 km² has been used to make a preliminary investigation of the problem.⁽⁵⁾

The scale of concern in this work is about an order of magnitude smaller than the synoptic scale. This is shown by an outline of the computational grid (rectangular box in southeastern Idaho) on a map of the western United States in Figure 1. The grid is approximately 86 km wide and 130 km long. The topography of the area is shown in Figure 2. The severe height variation is shown only qualitatively through a shadowed photograph of a relief map. The gentle height variation over the relatively flat plain is depicted by the height contours. The area in which the terrain is less than 5,000 ft. is stippled to emphasize the large fishhook-shaped depression in the plain. The solid black dots show the locations of the towers with the wind sensors. The sensor heights were 15 m or above. All calculations were restricted to the area to the right of the dashed line.

The basic calculation was an interpolation of the wind components measured at the non-regularly spaced towers to a regularly spaced grid of points. The interpolation technique involved a weighted averaging of the velocity components from several of the stations nearest to each of the grid points. The weighting factors used were the inverse squares of the distances from stations to grid points.

When the wind components are obtained at the grid points they may be used in several types of analyses. However, they may also be used to enhance the appearance of a plot of the raw data for visual observation. Computer produced plots of the wind fields at 6 hour intervals have been made by Wendell⁽⁶⁾ for the entire year of 1969. An example of these plots is shown in Figure 3. The winds measured at the tower locations are plotted in the standard format of shaft and barbs. The winds interpolated to the grid points are plotted as vectors, with their length directly proportional to the speed. In these plots the 5,000 ft. contour is included with the outline of the U. S. Atomic Energy Commission's National Reactor Testing Station.

One of the most interesting features of the 1969 wind field plots was the strong conformity of the flow patterns to the fishhook-shaped depression. Varying degrees of this conformity were observed during some portion of about 60 percent of the days of the year. The two series of plots shown in Figure 3 are examples of this phenomenon. During about 12 percent of the days of 1969 the cyclonic bending of the flow in the upper portion of the grid developed into a distinctive circular shaped eddy which persisted for several hours. Occasionally the formation of the eddy could be detected

visually during daylight hours through the formation of a very striking and unusual cloud formation.

In Figure 3A a zone of convergence may be seen forming in the first two frames as the northerly winds in the northern portion of the site intercept the strong southwesterly flow. If the air from the southwest contains sufficient moisture a cloud will form in it as it is lifted by the air moving down from the north. The cloud has some very striking characteristics. (An example is shown in Figure 4.) It seems to emanate from a stationary location and grow as it moves rapidly downwind. This gives it the appearance of a plume from an invisible stack except that it does not decrease in density through diffusion because the convergence is apparently increasing downwind. The cloud serves to delineate this terrain induced convergence zone (although it is several miles from any irregular terrain features) in the boundary layer in the same fashion that standing lenticular clouds indicate mountain waves at higher levels. It is dramatic evidence of mesoscale spatial variability in the flow in the boundary layer.

It is quite obvious that flow patterns of the type just discussed would be very poorly represented by the wind at a single location. Flow patterns that would have been well represented by a wind measurement at one location were observed to occur during some portion of only 21 percent of the days of 1969.

WIND-FIELD DERIVED TRAJECTORIES

To get a more direct observation of the effect of temporal and spatial variability of mesoscale wind patterns on transport, the hourly averaged

wind data, interpolated to the regular grid, was used to construct trajectories of hypothetical particles introduced serially into the flow. Computer produced plots of trajectories of these particles, released once an hour, were also obtained for the entire year of 1969.⁽⁶⁾ Examples of these plots are shown in Figure 5. These two series of trajectories indicate the path of 12 particles released one hour apart beginning at the times shown above each plot. The numbers at the ends of the trajectories indicate the order of release and the letters along the trajectories indicate the locations of the particles at hourly intervals after release. Like letters may be connected to form a streak line and may be used to estimate the time change of the position of a plume center line.

A long series of trajectory plots of this type can provide an estimate of a climatology of the transport from a given release point for selected release periods.⁽⁵⁾ The trajectory pattern types are selected and are ranked according to percentage of occurrence during the entire year, regardless of release period. However, an associated table showing percentages of occurrence according to release period and season provides a fairly detailed picture of the variation of transport conditions for the given release location.

It may be noted from some of the trajectory pattern types that the spatial variability in the flow has played a large part in determining the pattern. To obtain a more direct comparison of the wind field and single station produced trajectories, several sets of trajectories were recomputed using only the source wind as if it applied over the whole grid. Some of these results are shown in Figure 6. The trajectories in the

upper plots (WF) were obtained from the wind fields while those in the lower plots (SS) were obtained using the source wind only. The differences in the transport are quite apparent. Comparisons similar to these were made using wind data from a 9-station network in Oklahoma.

The area of the study was an 80 x 112 km network centered around Oklahoma City, Oklahoma. The overall terrain variation was somewhat less than on the Idaho grid but on the scale of one kilometer it had more variation. A quantitative comparison was made of the discrepancy between trajectories produced by wind fields and those produced by the source wind. For almost 250 cases the average separation was about 1.6 km for the first 16 km traveled, 8 for 32 km and 14.5 for 48 km. The separation is obviously not linear with travel distance and indicates that even in mildly varying terrain discrepancies can become significant beyond a few km from the source.

It should be pointed out that the transport, calculated from wind measurements from these towers, is restricted to a layer in which these measurements are representative. During stable conditions most of the material released would remain in this layer and the tower winds should provide a reasonable estimate of the transport and generally a much better estimate than one from a single station.

WIND-FIELD DERIVED DISPERSION

To relate the wind-field derived transport of a contaminant to the measurements of an environmental pollution sensor one may incorporate these transporting winds into a K theory type of model. This has been done for short term cases by several investigators including Lamb and Neiburger (2) and MacCracken, et al. (3) An alternative approach is to

superimpose the diffusion onto wind-field derived trajectories. This has been done by Start and Wendell⁽⁴⁾ through a technique of dividing a continuous release into serially released discrete puffs which diffuse in a Gaussian manner controlled by distance travelled, mixing depth and stability class. This type of model is simpler and can be run for an extended period of time without great expense. An example of a puff release approximating a continuous plume is shown in Figure 7. The dots correspond to puff center positions and the circles represent contours of the minimum concentration of interest. The circles grow in size as the puffs diffuse. This release period is the same as the one shown for the March 4, 1969 case in Figure 6.

The plume, shown at two-hour intervals in Figure 7, undergoes a 90° bending about 10 miles south of the site boundary. This type of deformation cannot be produced with the source wind alone as was demonstrated in Figure 6. A wind reversal at the source is indicated to have occurred just prior to 2300 MST 03/04/69. This new plume segment bends to the east as the oldest portion of the plume bends in the opposite direction toward it. By 0500 both new and old material are sweeping southward across the site as a line source.

To provide a quantitative presentation of the effect of the plume transport and dispersion the total integrated concentration is calculated on an array of grid points and is displayed in contour form at six-hour intervals in Figure 8, for the March 4 case. Eighteen hours after release the splitting and bending plume observed in Figure 7 leaves a doughnut-shaped ring of high total integrated concentration. It is difficult to imagine a sensor measurement northeast of the site and the receptor wind having any success at all in the location of the source.

TRANSPORT ESTIMATES FROM TETROONS

Using a network of wind towers to estimate transport is an indirect approach. A more direct method involves the tracking of a constant density balloon. A fairly complete list of references is provided by Angell, et al.⁽¹⁾ to the work done in recent years in which the radar-tetroon-transponder system has been developed and utilized to study various characteristics of air motion in the planetary boundary layer.

Tetroon trajectories have been compared with wind field derived trajectories with widely varying results for individual comparisons. This is illustrated by the comparisons shown in Figure 9. One would have to say, in summary of observations thus far, that if the tetroon flies low enough or there is little vertical wind shear the trajectories are generally quite similar. However, under the conditions of strong temperature inversions and local topographic anomalies, the trajectories can be very different. This does not mean that one type of trajectory is more correct than the other. It simply means that when the tetroon flight level is above the tower sensors, the difference in the trajectories is a reflection of the wind shear. This is dramatically illustrated in the next section by trajectory data from a pair of tetroons. This suggests that the two methods of investigating mesoscale circulation of the planetary boundary layer should be used to complement each other.

TOPOGRAPHICALLY INDUCED VERTICAL WIND SHEAR

The increase in wind speed with height above the ground surface is familiar to everyone and a certain amount of direction shear is generally

acceptable. However, a drastic change in wind direction in the first 50 m above the surface is a curiosity as evidenced by the notoriety received by the photograph of the smoke travelling in different directions from different levels on the Brookhaven tower. Photographs similar to this were taken by Air Resources Laboratories personnel during an early morning diffusion experiment in Idaho. One of these pictures taken from an aircraft is shown in Figure 10. Smoke was released from the surface as well as 30 and 60 m up on the tower. The smoke from the surface indicated a layer of wind from about 250° while the smoke at the other two levels indicated a wind direction of about 50° . This is a direction shear of about 160° between the two layers. Photographs and other observations from the surface indicated that the level next to the surface was about 30 feet thick. The transition between the layers was very abrupt and was primarily responsible for the dispersion of the lowest plume. The lower edge of this plume was about 3 m above the surface and very smooth.

The cause of this phenomenon seems to lie in the surrounding topography. Referring back to Figure 2, we can see that the overall slope of the terrain is downward from northeast to southwest, but that local slope in the vicinity of the tower (dot marked T) is in the opposite sense. Thus when the surface layer in this area is cooled sufficiently gravity will cause it to move toward lower ground even in opposition to the general drainage flow. This phenomenon was observed in data recorded several times since the smoke picture. The effect of fairly mild topographic variation on surface flow during periods of low pressure gradient and high stability seems to be one that should be given serious consideration.

It points up a need for routine wind measurements near the surface as well as at stack height. Knowledge of source configuration is also shown to be important for transport determinations.

Another example of the effect of vertical shear on transport was discovered in the trajectories of a pair of tetroons released one minute apart about 10 km south of the Wave Propagation Laboratory's tower in southeastern Colorado. The tetroons were separately tracked by two ARL radars. The horizontal and vertical depiction of the two trajectories is shown in Figure 11. The horizontal trajectory plots begin with the tetroons quite close together but separating rapidly. Tetroon 30B proceeds in a north-northeasterly direction over the mild ridge in the topography, while 30A seems to follow the curve of the 4400 ft. contour. The vertical depiction of the trajectories shows 30A dropping to near the surface about 30 minutes after the beginning of the track. The WPL tower is plotted on the vertical plot as a reference point. Flight 30B seemed to be reflecting the winds measured at the tower top for the entire flight, while 30A showed fair agreement with the winds measured by the mesoscale network of 15 m towers indicated by the crosses in 11a. This case would also seem to show that a light prevailing wind can be overcome by a local drainage wind in the surface layer.

SUMMARY AND CONCLUSIONS

It has been demonstrated that regional boundary layer flow can be significantly more complex than the standard assumption of a mean wind speed and direction over the whole area. Under conditions of weak

synoptic scale pressure gradients and high stability even mild mesoscale terrain variations can cause horizontal, as well as vertical, variations in the flow which are only detectable through a fine enough network of wind measurements. Trajectories constructed from these networks of wind measurements indicate the magnitude of the discrepancies which can exist in transport deduced from the source wind alone. Transport estimated from tethered flights has also indicated a strong influence from local topographic variation as well as land water proximity. The topographic variation has also been shown to cause a large enough vertical shear of wind direction to cause a potential hazard, especially if the existence of the phenomenon is not suspected.

The regional scale transport and dispersion models now in existence have never been verified on more than a very short term, special case basis. With the development of new tracers and sensors a long term verification program now looks like a definite possibility. This type of program should allow a quantitative assessment of the importance of some of the complexities in regional boundary layer flow on the transport and dispersion of pollutants. Since these complexities arise during the conditions of least dispersion, it would appear that an understanding of their effects on pollutant transport is essential.

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Fig. 1. Location and extent of computational grid for mesoscale wind observations. The solid border of the rectangular box in southeastern Idaho contains all the observation locations, but no calculations are carried out for the area northwest of the dashed line. The solid black area represents the geographical extent of the National Reactor Testing Station (Wendell).⁽⁵⁾

Fig. 2. Relief map of the Upper Snake River Plain in southeastern Idaho. The values shown on the few contour lines over the plain are in hundreds of feet. The stippled area within and adjacent to the grid indicates the terrain with an altitude less than 5,000 ft MSL. The tick marks along the border of the grid indicate the grid point separation, 8.53 km. The solid dots show the location of the wind towers.⁽⁵⁾

Fig. 3. Examples of the flow pattern over the grid conforming to the topography. A four-hour series is shown for (A) winter [Feb. 9, 1969], and (B) spring [May 13, 1969]. The 5,000 ft contour is included for reference purposes (see Fig. 1). The wind data from each station are plotted in standard form, and the interpolated winds are plotted as vectors at each grid point. The lengths of the wind vectors are proportional to the speed.⁽⁵⁾

Fig. 4. Plume-shaped cloud in area of convergence during formation of mesoscale eddy. The visible moisture in the cloud was moving from left to right at 10 to 15 m S⁻¹, but the apparent source point and general shape remained essentially the same for over two hours.

Fig. 5. Trajectories of hypothetical particles released hourly and transported by a time series of objectively interpolated wind fields. The numbers at the ends of the trajectories indicate the order of release, and the letters along the trajectories represent hourly positions. (5)

Fig. 6. Comparison of (A) trajectories derived from the wind field with (B) trajectories derived from the source wind applied over the whole grid for the corresponding time periods (1300 MST on days indicated). (5)

Fig. 7. Discrete number of puffs (3 per hour) approximating a continuous plume. Puff center positions are shown every two hours as dots which form an approximate plume centerline. The circles are contours of the minimum concentration of interest for each puff.⁽⁴⁾

Fig. 8. Contours of total integrated concentration at six-hour intervals for the March 4, 1969 case shown in Figure 7. The numbers are indicators of relative concentration from a unit source (1 is the lowest TIC).

Fig. 9. Comparisons between tetraon (solid line) and wind field-derived surface (dashed lines) trajectories. The surface air trajectories were originated at the time and place of the tetraon trajectories. The dots along the trajectories are at one-hour intervals, while the dotted lines are isochrones connecting tetraon and surface trajectory positions for the same time. The tetraon flight numbers are given at the ends of the solid trajectories. (1)

Fig. 10. Aerial photograph of smoke plumes generated at the bottom, middle and top of the 60 m ARL tower at the National Reactor Testing Station in Idaho.

Fig. 11. Tetraon trajectory plots for flights 30A and 30B beginning at 0128 CST, August 12, 1972. The horizontal depiction in (a) shows the trajectories as a solid and dotted line with dots at half-hour intervals and letters at one-hour intervals. The height contours are shown as dashed lines and labeled in 100's of feet MSL. The vertical depiction in (b) shows the trajectories with the same symbolism. The solid hatched area represents the terrain under 30A and the dashed hatched area the terrain under 30B.

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L. L. WENDELL

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