Conf-9209163--2

PNL-SA--20899

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SINGLE-STATION INTEGRAL MEASURES OF ATMOSPHERIC STAGNATION, VENTILATION, AND RECIRCULATION

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September 1992

Presented at the
6th Conference on Mountain
Meteorology
September 29- October 2, 1992
Portland, Oregon

Work supported by
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

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1. INTRODUCTION

In air pollution work, terms such as stagnation, ventilation, and recirculation have come to be used to indicate special types of flow conditions that produce important effects on the dispersion of air pollutants. Stagnations are events where atmospheric flows decrease in speed, or stop altogether, allowing pollutants to build up in stagnant air in the vicinity of the pollutant sources. Ventilations, on the other hand, are events in which a confined polluted air mass is driven away and replaced by fresh air. Finally, a recirculation is an event in which polluted air is initially carried away from the source region but later returns to produce a high pollution episode.

The three terms, when used in air pollution work, are often used in a general sense, but rarely are defined mathematically to allow a numerical evaluation of the flow character. In the present work we develop mathematical definitions of these terms by focusing directly on the relevant atmospheric transport conditions, irrespective of pollution levels. The mathematical definitions of several single-station integral quantities representative of stagnation, ventilation, and recirculation are described, and the approach is applied to a wind data set from a radar profiler at Page, Arizona.

2. METHODOLOGY

Consider a discrete time series of N data point pairs (U_i, D_i) of meteorological wind speed and wind direction (direction from which the wind is blowing; clockwise from north). This meteorological wind data can be expressed as horizontal wind vectors (direction toward which the wind is blowing) where the series of vectors is resolved into north-south (positive toward north) and east-west (positive toward east) components, respectively, as follows:

$$u_i = U_i \cos(D_i - 180) \qquad (1)$$

$$v_i = U_i \sin(D_i - 180) \qquad (2)$$

This results in a discrete time series of horizontal wind vectors, represented as:

$$\vec{V}_i = u_i \vec{i} + v_i \vec{j}\ , \quad i = 1, 2, \ldots, N \qquad (3)$$

We were able to use simple trigonometric relationships in (1) and (2) by defining the positive x-axis to be north and the positive y-axis to be east. This allowed the angle convention of the meteorological wind direction (clockwise from north) to match the angle convention of a standard "right-hand" coordinate system (angle proceeding from positive x-axis toward positive y-axis). Subtracting 180 degrees from the meteorological wind direction in (1) and (2) converts the resulting wind vector from representing the direction from which the wind is blowing to the direction toward which the wind is blowing.

The time, t_i, of each data point is

$$t_i = t_0 + (i-1)T \qquad (4)$$

where t_0 is the time of the first data point and T is the averaging interval of the data. The individual vectors in the time series may represent, for example, a series of hour-average wind vectors from a surface wind station, or half-hourly observations from each level of a remote sensing device such as a Doppler sodar or radar profiler.

We then define a set of discrete integral quantities that are computed at each time in the data set as follows:

$$S_i = T \sum_{j=i}^{i+p} \left|\vec{V}_j\right| \qquad (5)$$

$$X_i = T \sum_{j=i}^{i+p} u_j \qquad (6)$$

$$Y_i = T \sum_{j=i}^{i+p} v_j \qquad (7)$$

$$L_i = \sqrt{X_i^2 + Y_i^2} \qquad (8)$$

$$\begin{aligned} \theta_i &= \arccos\left(\frac{X_i}{L_i}\right), & Y_i \geq 0 \\ \theta_i &= 360 - \arccos\left(\frac{X_i}{L_i}\right), & Y_i < 0 \end{aligned} \qquad (9)$$

$$R_i = 1 - \frac{L_i}{S_i}, \quad (0 \le R \le 1) \tag{10}$$

where

$$i = 1, \ldots, N-p$$

$$p = 1 - \tau/T, \quad 0 \le p < N, \quad [T \le \tau < NT]$$

τ is the desired integration time, and (5)-(10) represent, respectively, the wind run, the transport distance in the north-south direction, the transport distance in the east-west direction, the resultant transport distance, the resultant transport direction (clockwise from north), and the recirculation factor. The transport direction is the direction toward which a parcel will travel. Figure 1 illustrates the calculation of the integral quantities determined from (8)-(10).

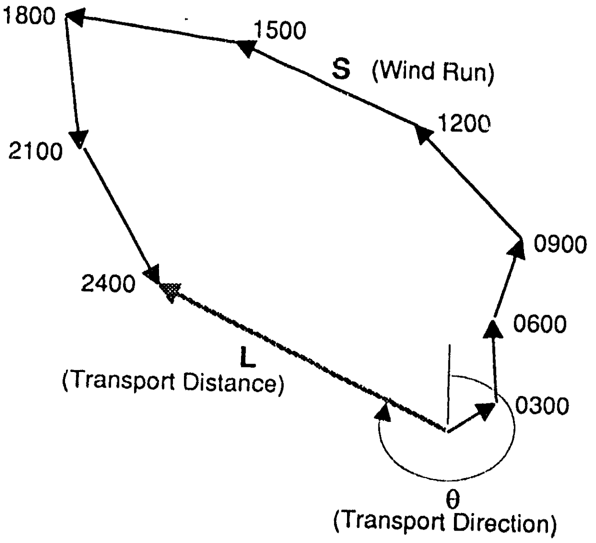

Fig. 1. Illustration of the definitions of wind run, S, and transport direction, θ, assuming a 24 h integration time and 3-h-average observations.

Equations (5) through (10) give a "running" determination of the integral transport quantities. That is, at every observation time, t_i, the integral transport quantities are calculated. The integral quantities are based on the time t_i as the transport start time, and the time $t_i+\tau$ being the transport end time. The resultant transport distance and direction define the ending location of a parcel at time $t_i+\tau$ that "left" the sensor location at time t_i. The quantity S is a measure of the total distance that the parcel traveled from time t_i to time $t_i+\tau$. These quantities would be a correct measure of transport in an ideal homogeneous wind field. However, a homogeneous wind field is not normally experienced in real situations, especially in complex terrain. Consequently, these integral measures of transport are not true measures of the transport of a plume, but rather should be considered as characteristics of the flow at the measurement point. The intent is that these single-station quantities will prove to be useful for characterizing the air pollution transport characteristics of various air sheds and regions.

The wind run S divided by the integration time τ is the scalar average wind speed, L divided by τ is the vector average wind speed, and θ–180° is the vector average meteorological wind direction (direction from which wind blows, clockwise from North). The recirculation factor R gives an indication of the presence of local recirculations on time-scales comparable with τ. When R is equal to 0, straight-line transport has occurred with no recirculation; when R is equal to 1, zero net transport has occurred over the time interval τ, and there has been a complete recirculation.

The above equations apply to any time series of wind vectors at a single station and, for example, could be applied to remotely sensed wind profile data from a ground-based device, such as a Doppler sodar or radar profiler from which vector time series are available at a number of range gates (i.e., height intervals). In this case, comparison of the integral quantities in (5) through (10) at various heights provides useful information on the wind relationships with height.

3. APPLICATION

In this section, the methodology outlined above is applied to a wind data set from the Navajo Generating Station Winter Visibility Study of January-March 1990 (Richards et al., 1991). As part of this study a network of remote sensing wind profilers and towers was installed throughout the Colorado Plateaus Basin to determine the regional evolution of three-dimensional wind structure. The region was known from previous work to be influenced by deep wintertime inversions and to undergo lengthy periods of stagnation and recirculation. (See, for example, the accompanying paper by Whiteman (1992) for a summary and description of the wintertime meteorology of the Colorado Plateaus Basin region.)

The data set to be analyzed consists of hour-average wind data from the radar wind profiler (UHF radar system) operated by NOAA's Wave Propagation Laboratory at Page, Arizona. The period of record is the 86-day period from 8 January (Julian day 8) through 3 April 1990 (Julian day 93). Winds were measured through twenty-100-m-thick layers, where the midpoint elevation of the first layer is 1470 m MSL (150 m AGL) and the midpoint elevation of the top layer is 3397 m MSL (2077 m AGL).

Radar wind profilers depend on turbulence-produced refractive index fluctuations of both temperature and humidity and their cross-correlations for determining winds from Doppler-shifted frequencies (Neff, 1990). Since radars depend on the presence of turbulence for the scattering of the radio waves, they, at times, suffer from a lack of valid signal returns (signal strength comparable to noise level) from the portions of the atmosphere where turbulence is weak. A decrease in the number of valid returns occurs at the upper sampling heights in the Page wind profile, as is shown in Fig. 2, where the percentage of all possible hours (maximum of 2064 hours) with valid returns is plotted versus height. Some of the higher elevation range gates in the data had few observations. In the analyses given below only the 11 layers with approximately 25% or greater sample recovery are considered. The midpoint elevation of the first layer is 1470 m MSL and of the midpoint elevation of the eleventh layer is 2484 m MSL.

The integration period, τ, in this analysis was 24 h and the starting time for each period was 0000 LST. This integration period of 24 h is a natural first choice because of the various thermally driven flows that oscillate diurnally in complex terrain. Some examples are mountain-valley winds, slope winds, and land-sea breezes. The daily transport statistics for midnight of each day are given rather than at every time step (hourly), to simplify the preparation of the figures given below. These results are equivalent to "block" averaging rather than a "running" average. Only the results for the 24 h integration interval are given here, in order to demonstrate the methodology. Ideally, the transport characteristics should be computed over a range of τ's, to identify the dominant time-scales of motions responsible for recirculation and the frequency and duration of periods of stagnations and ventilations.

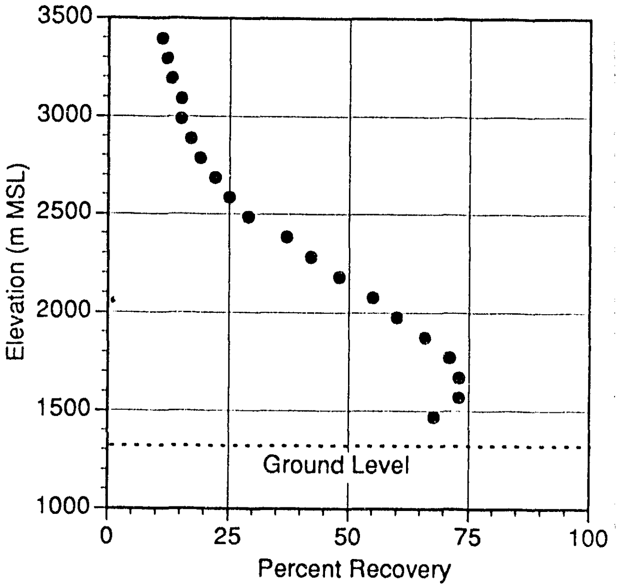

Fig. 2. Percentage of total hours in the study period when the winds were successfully measured at Page using the high-resolution radar wind profiler.

Plots of the the daily wind run, the daily transport direction, and the daily recirculation factor for Page are given in panels (a)-(c) in Fig. 3, respectively. These transport quantities are plotted versus height for the 86-day period of record. It should be noted that a 6-day period (julian days 46-51) of data is missing, as indicated by the white areas in the figure. Also a few values in each plot in Fig. 3 were not calculated because less than 5 hourly observations were available at a given height for that day. In these cases, the values were estimated by linear interpolation from the surrounding calculated values, or by using the nearest calculated value. When more than 5 hourly observations were available, the daily transport quantities were calculated at each height by assuming that the winds varied linearly in time between available observations.

Inspection of panel (a) in Fig. 3 reveals that the daily wind run, S, is less than ~200 km (average wind speed less than ~2.3 m/s) below roughly 1900 m MSL for approximately 65% of the study period. Some days exhibited S values below 200 km at elevations above 1900 m MSL. This is evident, for example, during days 58 and 89. The daily wind run results indicate that the atmosphere below about 1900 m MSL in the vicinity of Page is stagnant roughly 65% of the time during the winter. The stagnation periods can last from a day to several days with the average being about 4 days. Here stagnation is defined as having a daily wind run of less than 200 km.

Daily recirculation factors of greater than 0.6 were encountered at Page during 25% of the study period at elevations less than about 1700 m MSL [panel (c) in Fig. 3]. Above 1900 m MSL (to ~2500 m MSL, top of the analysis), the majority of days exhibited R values less than 0.2. However, some days with values greater than 0.4 at elevations above 1900 m MSL were observed, and in two cases (days 54 and 88), near complete recirculation (values greater than 0.8) was observed at roughly 2200 to 2400 m MSL (~900 to 1100 m AGL). If recirculation is defined as R greater than 0.6, then the Page area experiences recirculations about 25% of the time during winter at elevations below ~1700 m MSL.

On some days the recirculation factor was less than 0.2 through the full profile, indicating that wind direction was nearly invariant with height for the entire 24-h period. Such was the case on day 18 when winds were from the northeast. This is clear from panel (b) in Fig. 3 where the daily transport direction is southwest through the entire sounding depth. Panel (a) in Fig. 3, shows the daily wind run to be from 400 km to greater than 600 km through a majority of the profile. This translates to an average wind speed of from ~4.6 m/s to greater than ~6.9 m/s through a majority of the profile. If periods with recirculation factors less than 0.2 through the entire profile are considered as ventilation periods, then from panel (c) in Fig. 3, ventilation is experienced roughly 10% of the time during winter.

Days 54 to 64 exhibited features of recirculation and stagnation through a significant depth of the record. The daily transport direction is variable during this period and pollution generated within the Colorado Plateaus Basin could possibly remain in the basin atmosphere for several days because of the high potential for recirculation and stagnation below 2000 m MSL.

4. SUMMARY AND CONCLUSIONS

Integral single-station measures of stagnation, ventilation, and recirculation are defined. These measures of atmospheric transport characteristics can be applied to wind data collected at fixed time intervals and at fixed heights in the atmosphere. They are especially suitable for use with new ground-based remote wind profiling sensors.

These single-station integral measures of transport are not true measures of the transport of a plume, but rather should be considered as characteristics of the

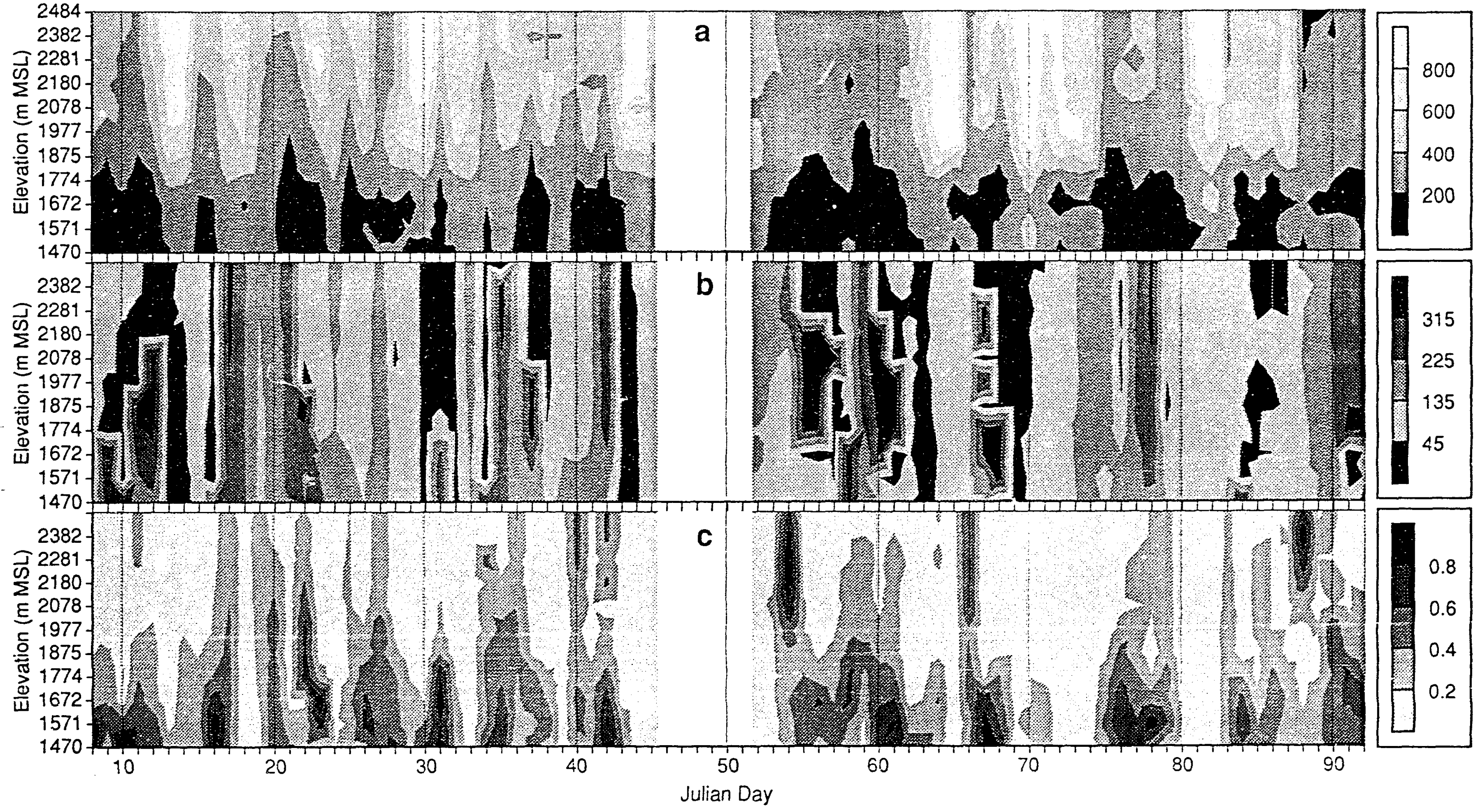

Fig. 3. Time-height cross-sections of (a) daily wind run (km), (b) daily transport direction (deg CW from North), and (c) daily recirculation factor at Page, Arizona.

flow at the measurement point. The intent is that these single-station quantities will prove to be useful for characterizing the air pollution transport characteristics of various air sheds and regions. The transport characteristics should be computed over a range of integration intervals to identify the dominant time-scales of motions responsible for recirculation, and the frequency and duration of stagnations and ventilations.

Application of the single-station measures of stagnation, ventilation, and recirculation is illustrated using wintertime radar wind profiler data at Page, Arizona, in the Colorado Plateaus Basin. This analysis indicates that the Page area has frequent stagnations (~65% of the time) and recirculations (~25% of the time) during the winter at heights below ~400 m AGL. In general, the daily integral transport characteristics reveal many periods of recirculation and stagnation behavior at various heights throughout the study period, especially below 2000 m MSL. Assessing the transport of material within the Colorado Plateaus Basin during these periods would be difficult, especially in conjunction with a time-varying surface mixing layer, which can move material to other heights having different transport characteristics.

5. ACKNOWLEDGMENTS

Data were provided by Arizona's Salt River Project. The U.S. National Oceanographic and Atmospheric Administration's (NOAA) Wave Propagation Laboratory (WPL) collected the radar profiler data. Analyses were funded by Arizona's Salt River Project and by the U.S. Department of Energy (DOE) under Contract DE-AC06-76RLO 1830 as part of DOE's Atmospheric Studies in Complex Terrain (ASCOT) program. The Pacific Northwest Laboratory is operated for DOE by Battelle Memorial Institute.

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