Conf-9209163--4

PNL-SA--21181

DE93 001559

THE COUPLING OF SYNOPTIC AND VALLEY WINDS IN THE TENNESSEE VALLEY

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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

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MASTER

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1. INTRODUCTION

The interaction of winds in a valley with the winds above the valley is of interest for both practical and theoretical reasons. For example, the forecasting of conditions affecting air quality, emergency preparedness, or aerial spraying of pesticides requires the ability to relate local valley circulations to ambient synoptic conditions. While empirically derived relationships may be useful, it is also desirable to develop an understanding of the mechanisms responsible for the observed behavior. In this paper we combine results from analyses of measurements and model-generated data to provide insight into factors affecting the climatology of the winds in the Tennessee Valley.

We begin by discussing four mechanisms that can determine the behavior of winds in a valley. The conditions can be illustrated in terms of the expected joint frequency distributions of the surface and geostrophic winds, and are summarized in Figure 1.

The first mechanism to be considered is thermal forcing, in which winds within the valley are caused by locally developed along-valley pressure gradients. These pressure gradients are produced hydrostatically from temperature differences that form along the valley axis, and are a feature of the meteorology of many valleys (e.g., Whiteman 1990). Such locally driven thermal wind systems produce upvalley winds during daytime and downvalley winds during nighttime and are commonly observed in areas with large diurnal cycles in surface sensible heat fluxes, especially under conditions when upper-level winds are weak. Figure 1a illustrates the idealized joint frequency distribution that would result from this mechanism, assuming a valley axis that runs northeast-southwest, as in the Tennessee Valley.

A second possibility is that strong downward transport of horizontal momentum from above the valley would produce wind directions within the valley that are similar to the geostrophic wind directions aloft. Because of friction, a slight turning (~25 °) of the geostrophic wind toward lower pressure would be expected as the ground is approached (Fig. 1b). This process would be most likely to occur during neutrally-stratified conditions in wide, flat-bottomed valleys with low sidewalls. In such valleys, thermally driven winds would be less likely to develop and channeling along the valley axis by the valley sidewalls would be relatively ineffective.

A third possibility is that above-valley geostrophic winds will be forced to align with the valley axis by channeling, so that valley wind direction and speed depend on the sign and magnitude of the component of the upper wind projected along the valley's axis. In this scenario , winds would blow up or down the valley's axis, depending on the direction of the geostrophic wind relative to that axis. The joint frequency distribution (Fig. 1c) produced by the forced channeling would show winds predominantly along the valley axis but with sudden shifts in direction when geostrophic winds shift across a line normal to the valley axis.

The fourth process we wish to consider is that of pressure driven channeling, in which the winds in the valley are generated by the component of the geostrophic pressure gradient along the valley's length. This mechanism was proposed by Fiedler (1983) and by Gross and Wippermann (1987), and was found to be an important factor in the climatology of the Rhine Valley winds. If there is no locally developed along-valley pressure gradient within the valley to counteract the geostrophic pressure gradient, the latter will tend to drive winds along the valley axis; the resulting joint frequency distribution is shown in Figure 1d. The along-valley component of the pressure gradient force will be zero only when the geostrophic wind is directed along the valley's axis (i.e., from the northeast or southwest in the figure). Winds in the valley will shift from up- to downvalley or from down- to upvalley when the geostrophic wind direction shifts across the valley axis. Thus, the joint frequency distribution for pressure driven channeling will have winds blowing predominantly along the valley axis, as in the case of forced channeling, but the valley wind reversal will occur for geostrophic wind directions 90° different from those characteristic of the forced channeling mechanism.

In practice, these four mechanisms (or others not considered here) may contribute in varying degrees to the climatology of a given valley. Although the width of the Tennessee Valley is comparable to that of the Rhine Valley, its depth is substantially larger. Thus, it was not apparent that the pressure driven channeling found in the Rhine would be found in the Tennessee Valley as well. The moist climatic environment suggested that the diurnal cycle of sensible heat would be substantially smaller than those found in valleys in the western U.S., where thermally driven flows frequently occur. Finally, as noted below, valley winds are often light so that downward momentum transfer would be expected to be relatively unimportant in determining valley wind directions. In the following discussion we attempt to identify the principal features that determine the wind behavior in the Tennessee Valley.

2. TOPOGRAPHY

The Tennessee Valley is a broad (~70 km or more) valley lying between the Cumberland Mountains, rising to the north and west 700 m above the valley floor, and the Great Smoky Mountains to the southeast, which reach as much as 1700 m above

the valley floor. In the vicinity of the Oak Ridge National Laboratory (ORNL), the valley is oriented along a 53°-233° axis (i.e., NE-SW or ENE-WSW). The valley has a relatively flat floor but is "corrugated" by parallel ridges 50 to 150 m high, spaced 2 to 3 km apart. The area is heavily wooded with a mixture of deciduous and evergreen trees. West of ORNL the valley curves to the south, while to the northeast of ORNL the valley floor begins to rise more steeply. Figure 2 shows the topography of the area as well as the locations of the tower data sites discussed below.

3. DATA

— a little confusing

To study the behavior of the near-surface winds, long-term data were obtained from four sites in the Tennessee Valley: the 100-m X-10C tower at ORNL, a 110-m tower at Phipps Bend, a 93-m tower at Watts Bar, and a 91-m tower at Sequoyah. Rawinsonde data were also obtained for four locations: Athens, Georgia; Nashville, Tennessee; Greensborough, North Carolina; and Huntington, West Virginia. Data for these four stations and three of the towers were available for the time period January 1984 through December 1988. Unfortunately, data for this time period were not available for Phipps Bend, and the period of September 1977 through August 1981 was used instead. Figure 3 shows the locations of the tower and radiosonde sites.

Geopotential heights at the 850 mb (85.0 kPa) and 700 mb (70.0 kPa) pressure levels at the rawinsonde stations were used in a $1/r^2$ interpolation method to estimate the geostrophic winds at the 850 mb and 700 mb levels above each of the tower sites using Equation 1:

$$\mathbf{V}_g = (1 / f)\,(\mathbf{k} \times \nabla\Psi) = (g_0 / f)\,(\mathbf{k} \times \nabla Z) \qquad (1)$$

where $f = 2\Omega \sin \phi$, Ω is the angular velocity of the earth (2π day^{-1}), ϕ is the latitude, g_0 is the gravitational acceleration and $Z = \Psi/g_0$ is geopotential height.

The 850 mb pressure level is typically found at about 1460 m MSL, an elevation roughly equivalent to that of the mountains on the southeastern side of the valley. The 700 mb level is at about 3010 m MSL. Geostrophic winds were calculated twice per day using the 0000 and 1200 UTC rawinsonde soundings. Geostrophic winds above the towers were subsequently compared to concurrent wind measurements at the towers. The hour-average tower winds at 0600-0700 and 1800-1900 EST were used for the comparison, because these times encompassed the actual rawinsonde release times (2315 and 1115 UTC).

Because the rawinsonde ascent times often occurred near the morning and evening transition periods, the data from these times are not ideally suited to distinguish among

stability-dependent effects. Nevertheless, it is a fair approximation to associate the 1800 EST data with daytime or unstable conditions and the 0600 EST data with nighttime or stable conditions.

4. RESULTS

The 850 mb geostrophic wind direction rose for the ORNL site is shown in Figure 4. The winds have a predominant westerly component with a preferred orientation from the southwest, almost directly along the valley axis in the Oak Ridge region. The wind direction distributions at the other sites are similar to that found at Oak Ridge, and the 700 mb winds are closely correlated with those at the 850 mb level. In the following discussion, the 850 mb winds are frequently referred to as ambient winds, and the terms will be used interchangeably. Similarly, winds measured on the tower are referred to as valley winds.

Figure 5 shows the wind roses at the tops of the towers (elevation ~ 100 m) at each of the four sites; the directions at lower tower levels are also well-correlated with those found at the upper levels. There is a strong tendency for winds to lie along the local valley axis, blowing either upvalley or downvalley. The broader wind direction distribution for the 850 mb winds is not mirrored in the surface winds; in particular, the northeasterly winds found at the surface are almost entirely absent in the upper-level distribution. The northeasterly surface winds cannot be simply ascribed to thermal forcing because, with the exception of Phipps Bend, up - and downvalley winds are common in both the 0600 EST and 1800 EST data. (In the Phipps Bend data there is a marked tendency for downvalley winds to occur preferentially at 0600 EST, which indicates the development of katabatic winds during this period. At the remaining sites, the thermal effects appear to be significantly less important.)

Figure 6 shows the joint probability distribution for 850 mb and 100-m winds at Oak Ridge. For geostrophic winds with an easterly component, the surface winds blow preferentially downvalley from the northeast. As the winds aloft turn more to the south and west, the surface wind directions jump to a predominantly southwest or upvalley direction. This bimodal behavior is consistent with the pressure driven channeling discussed earlier and found in the Rhine Valley. However, there are several features of the joint frequency distribution that complicate such a relatively simple explanation. There are a number of cases in which winds aloft blow from the west or northwest but surface winds blow from the northeast. These cases correspond to the contoured area in the lower right portion of the figure. Closer examination of the data shows that such events often occur for especially light geostrophic winds and preferentially at 0600 EST rather than 1800 EST. These characteristics are consistent with the development of drainage winds down the Tennessee Valley, i.e., when the pressure gradient forcing is sufficiently weak, katabatic effects may be discerned. A second feature of the distribution is that as the 850 mb winds shift still further to the north, the surface winds

often exhibit similar behavior rather than remaining straight upvalley. These cases generally occur with somewhat stronger geostrophic winds and at 1800 EST, when convective mixing would be more likely to couple the surface winds with winds aloft. These characteristics can be explained by the downward momentum transport mechanism described earlier. Thus, the joint frequency distribution shows contributions from at least three of the forcing mechanisms suggested in the introduction.

5. NUMERICAL MODEL

A hydrostatic numerical model was used to provide additional insight into the physical processes governing the near-surface winds in the Tennessee Valley. The model was adapted from one originally developed by Pielke (e.g., Mahrer and Pielke 1977, McNider and Pielke 1984) but modified to incorporate a turbulent exchange scheme based on the prognostic turbulent kinetic energy formulation of Mellor and Yamada (1982). This version of the model has been applied successfully to other complex terrain flow simulations (e.g., Doran and Skyllingstad 1992), and was used in the present case to carry out a series of numerical experiments to examine the response of valley winds to changes in synoptic forcing.

Calculations were done on a 37 x 32 grid with 11-km grid spacing. The grid spacing was insufficient to resolve smaller scale terrain features, such as the corrugations on the valley floor, but it captured the principal topographic features of the area and also allowed a relatively large number of simulations to be carried out in a reasonable time. Although it was impractical to attempt to simulate all the conditions that contribute to the climatology of the region, it was possible to choose a set of experiments that illustrate many of the principal observed features. The 850 mb winds in the Oak Ridge area are generally light, with approximately 2/3 of them 8 m/s or lower. For the numerical experiments, geostrophic wind speeds were fixed, and wind directions were varied over a range of 360°. An initial slightly stable temperature profile was chosen. Simulations were begun at sunset, after an initial 4-h spinup period, and carried out for 12 h. The results should correspond more closely to the data collected at 0600 EST; additional simulations that focus on the 1800 EST results are in progress.

As the valley atmosphere cooled, decoupling from the winds aloft occurred and the effects of pressure driven channeling became apparent. Drainage winds also developed, particularly near the valley sidewalls and toward the northeastern end of the valley. Winds ~~16 m above~~ the surface were light, in keeping with data obtained from the four towers mentioned earlier. Figure 7 shows the relationship between the ambient wind directions and the wind directions 10 m above the surface for 8 m/s geostrophic winds. Results are shown for two locations, one near ORNL (squares) and one about 22 km to the east (circles) and closer to the center of the valley.

The solid lines in Figure 7 show the locus of points that would be expected if pressure

driven channeling alone were responsible for the winds' behavior and if the valley were a straight channel oriented along an axis of 53° - 233°. There is good agreement with this behavior near the center of the valley, although the transition from downvalley to upvalley winds is shifted somewhat to the left of the idealized curve. (For a geostrophic wind direction of 0°, the winds at this site were essentially calm and no datum is shown.). At the grid point corresponding to the ORNL site, the valley winds tend to align more with the geostrophic winds when the latter range from NW to N; there is ~~also~~ some indication of this in the 0600 EST data as well.

It was suggested above that the winds found in the lower right section of Figure 6 were ~~indicative of~~ drainage winds ~~in~~ down the Tennessee Valley. To test this, a simulation was carried out with geostrophic winds of only 3 m/s at 325°. The simulation was begun at sunrise and carried out for 24 hours. The resultant winds 10 m above the surface are shown in Figure 8 after 12 and 24 hours. At 12 hours, during the early evening of the first day, the surface winds are out of the west, reflecting a combination of pressure driven channeling and downward momentum transfer in the relatively well-mixed atmosphere. At dawn of the next day, drainage winds have developed over large regions of the valley, particularly to the northeast where the valley floor begins to rise more steeply. This wind pattern is not evident for higher ambient wind speeds. With the current resolution of the model we did not find valley drainage winds near ORNL; instead, drainage winds from the Cumberland Mountains flow over the ORNL area from the NNW. Two grid points to the east, however, there is a drainage flow down the valley. There are several low ridges running parallel to the valley between the Cumberlands and the X-10C tower at ORNL. These ridges could shield the tower from the Cumberland drainage while leaving it exposed to a larger scale valley drainage. In the model, these ridges are not resolved and one must move farther from the Cumberlands before the valley drainage flow is seen. Thus ~~T~~the model does not specifically verify the contribution of drainage winds to the joint frequency distribution of wind directions at ORNL, but it does suggest their potential importance under conditions with low ambient wind speeds.

We have also evaluated the model's performance by comparing its output with profiles of wind speed and temperature obtained from tethered balloons flown at a number of locations in the Tennessee Valley during a field experiment in March of 1990. Results were encouraging although surface inversions are too shallow in the model, and the simulated valley winds turn to line up with the geostrophic winds too close to the surface. This tendency was seen in the numerical experiments used in the climatological analysis as well. The model's failure to resolve corrugations along the floor of the Tennessee Valley may also be important here. Nonetheless, the wind characteristics in the lowest layer of the model mimic the climatological behavior quite well.

6. CONCLUSIONS

Analysis of tower and rawinsonde data show that wind directions in the Tennessee Valley are governed by several processes. Downward momentum transport and thermal forcing are relatively important for strong and very weak geostrophic winds, respectively. For light and intermediate strength winds, which are most common, pressure driven channeling is the dominant forcing mechanism. This behavior is similar to that found in the Rhine Valley. Simulations with a hydrostatic model support ~~some of~~ these conclusions; additional simulations of daytime conditions and with finer resolution are planned.

7. ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy (DOE) under Contract DE-AC06-76RLO 1830. The study was carried out under the auspices of the Atmospheric Studies in Complex Terrain (ASCOT) program. Pacific Northwest Laboratory is operated for DOE by Battelle Memorial Institute.

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FIGURE CAPTIONS

Figure 1. Joint probability distributions of geostrophic and surface wind directions for four possible forcing mechanisms: (a) thermal forcing, (b) downward momentum transport, (c) forced channeling, and (d) pressure driven channeling.

Figure 2. Topography of Tennessee Valley, with locations of four surface stations indicated.

Figure 3. Locations of rawinsondes (circles) and towers (stars). Tower sites: (1) Phipps Bend, (2) Oak Ridge X-10C, (3) Watts Bar, and (4) Sequoyah. Rawinsonde sites: AHN - Athens, Georgia; BNA - Nashville, Tennessee; GSO - Greensborough, North Carolina; and HTS - Huntington, West Virginia

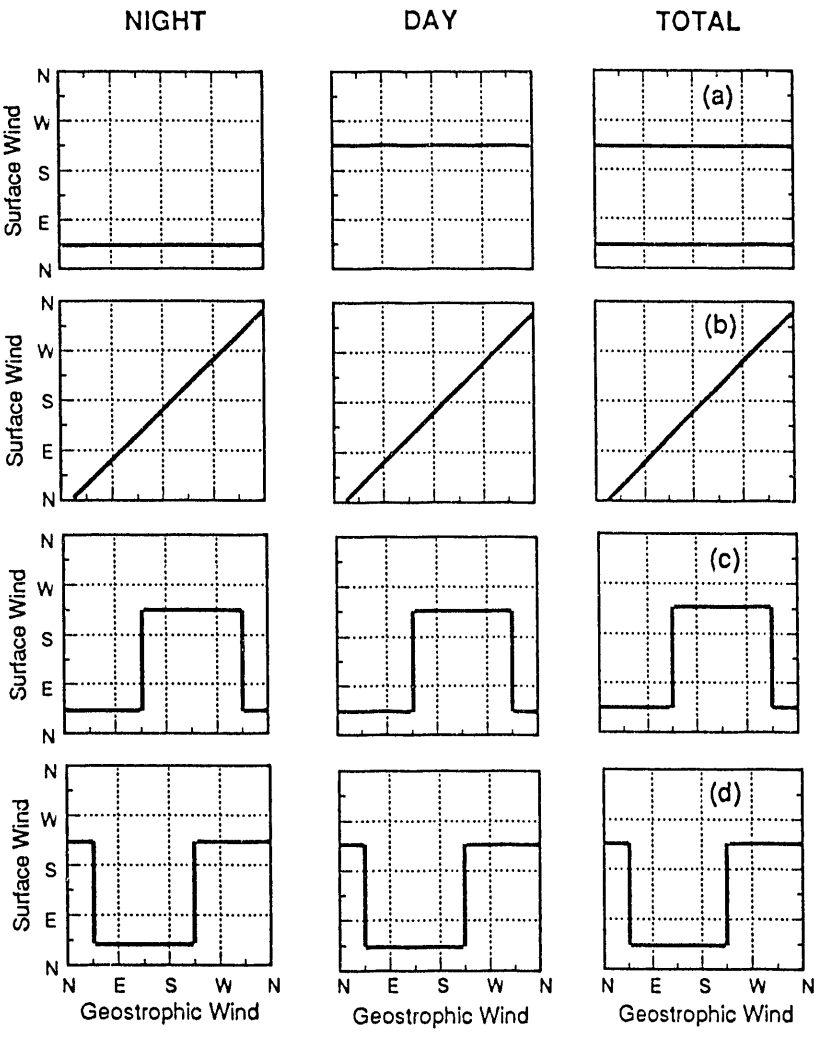
Figure 4. 850 mb wind direction rose for Oak Ridge, Tennessee.

Figure 5. Wind direction roses at ~100 m for four sites in the Tennessee Valley.

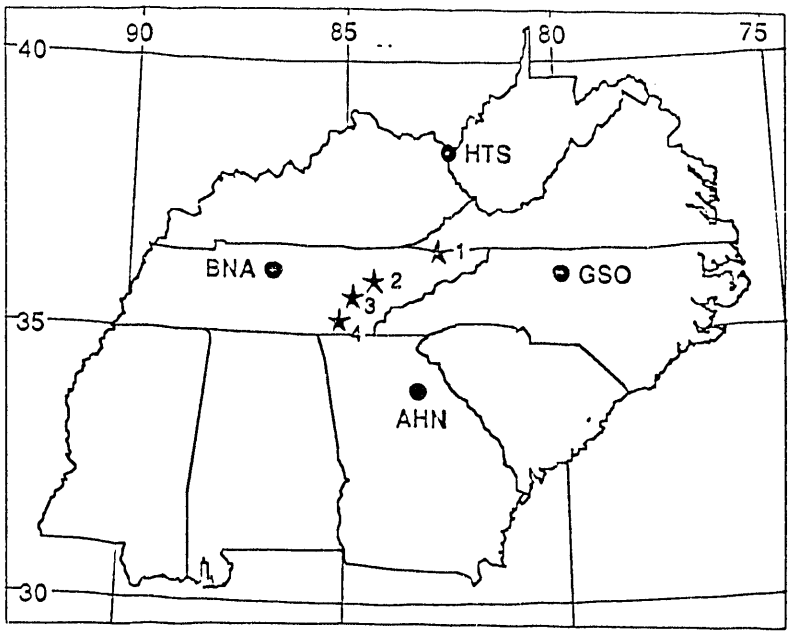
Figure 6. Joint probability distribution of 850 mb geostrophic and 100 m valley wind directions for Oak Ridge.

Figure 7. Simulated valley wind directions as a function of ambient wind directions for 8 m/s geostrophic winds. Squares: ORNL; circles: 2 grid points (22 km) east of ORNL. The solid lines indicate the locus of points expected for pure pressure driven channeling in a valley lying along a 53° - 233° axis.

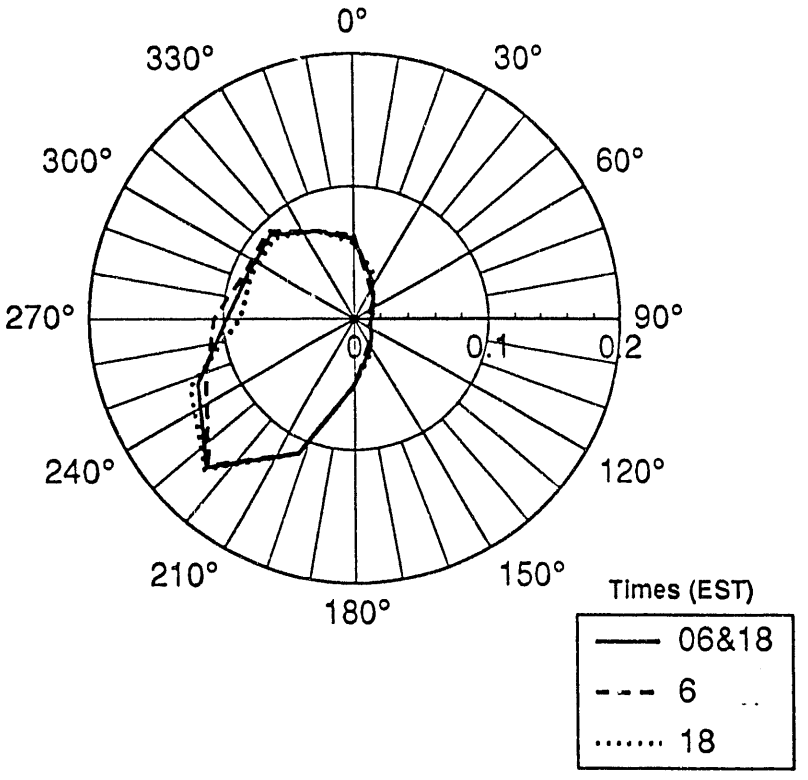
FIgure 8.Simulated wind fields in the Tennessee Valley (a) 12 hours and (b) 24 hours after sunrise for a geostrophic wind speed of 3 m/s at 325°.

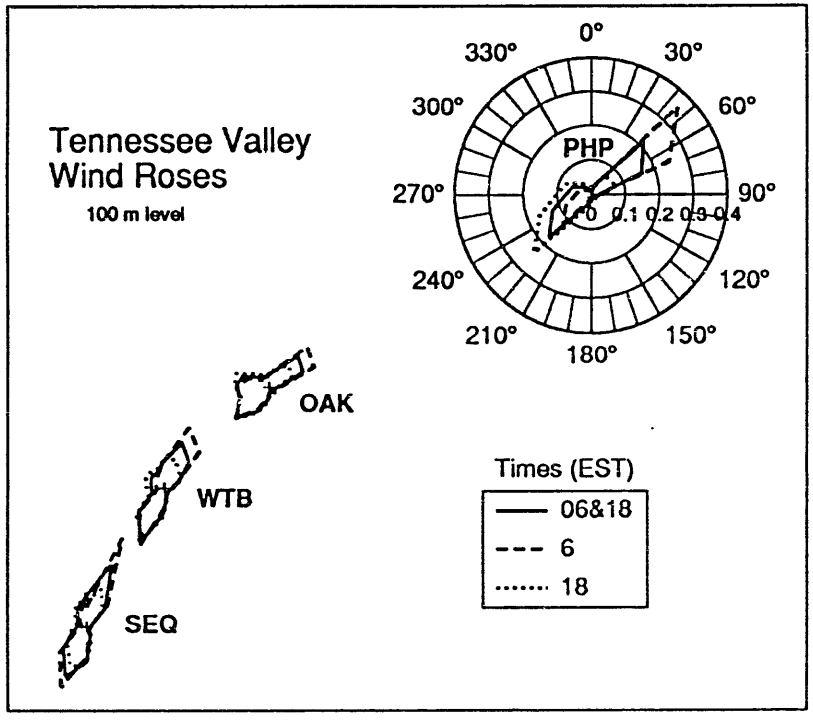

NIGHT
DAY
TOTAL
(a)
(b)
(c)
(d)
Surface Wind
N
W
S
E
N
N E S W N
Geostrophic Wind

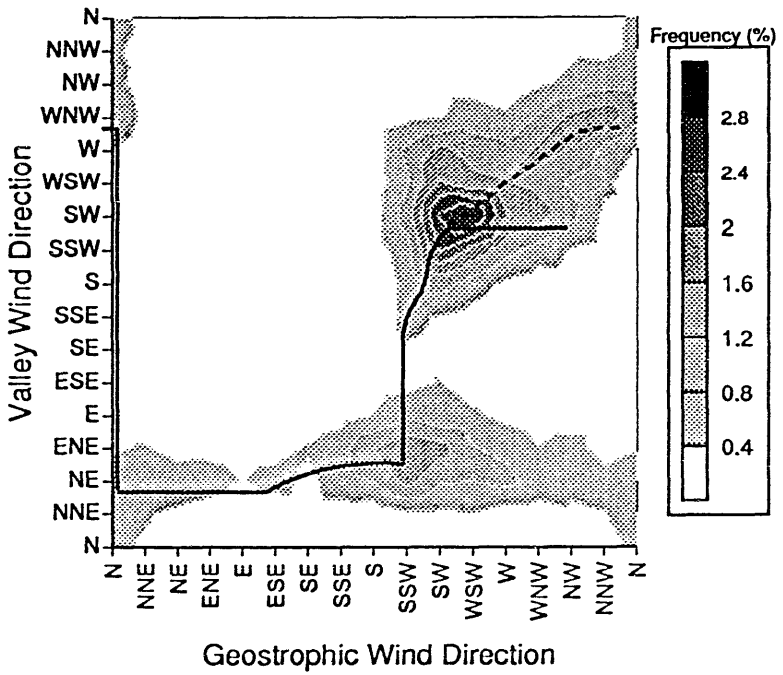
Height (m)
0
500
1000
1500
North-South (km)
80
130
180
230
280
East-West (km)
50
100
150
200
250
300
350
400

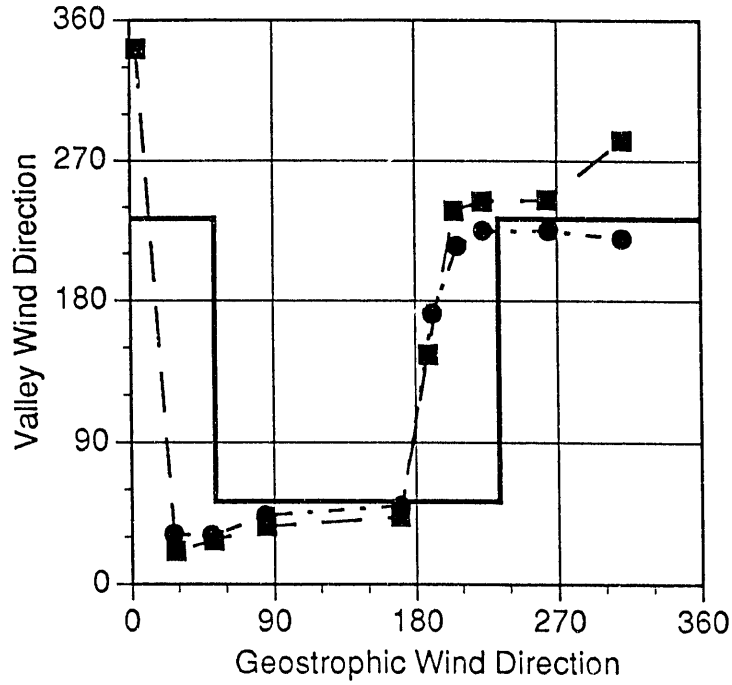

90
85
80
75
40
35
30
HTS
BNA
GSO
AHN
1
2
3
4

OAK 850 mb Wind Direction Rose




Tennessee Valley
Wind Roses
100 m level
0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
PHP
0
0.1
0.2
0.3
0.4
OAK
WTB
SEQ
Times (EST)
06&18
6
18


Frequency (%)
2.8
2.4
2
1.6
1.2
0.8
0.4
Valley Wind Direction
N
NNW
NW
WNW
W
WSW
SW
SSW
S
SSE
SE
ESE
E
ENE
NE
NNE
N
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
N
Geostrophic Wind Direction


360
270
180
90
0
Valley Wind Direction
0
90
180
270
360
Geostrophic Wind Direction

CONTOUR FROM 0 TO 12000 CONTOUR INTERVAL OF 1000 PTS/IN 14000
MAXIMUM VECTOR

END

DATE
FILMED
12/18/92