Implication of Spatial Averaging in Complex-Terrain Wind Studies[1]

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ABSTRACT

Studies of wind over complex terrain have been conducted at three times and two locations in Northern California. Instrumentation included conventional cup-vane anemometers and optical anemometers with spatial averaging over path lengths of 0.6–1 km. Autospectra of the path-normal component of wind from the cup-vane and optical anemometers show consistent differences in slope for periods shorter than four hours. The spectral differences are associated more with changes in wind direction than with changes in wind speed.

1. Introduction

The exploitation of energy resources (such as petroleum-based and synthetic fuels, geothermal steam, and wind energy) in remote regions, has stimulated interest in atmospheric wind fields over complex terrain. However, measuring much less predicting, spatially representative wind fields in complex terrain is a formidable task, for both pollution dispersion modelers and wind energy prospectors.

To better understand the effects of complex terrain on air quality, the United States Department of Energy initiated a program in 1979 known as Atmospheric Studies in Complex Terrain (ASCOT). Most of the work described in this paper resulted from field studies conducted as part of ASCOT experiments (Dickerson and Gudiksen, 1980) in The Geysers geothermal region of Northern California (July 1979 and September 1980). The purpose of these studies was to quantify the average speed of drainage winds down a small sloping valley that had few locations offering reasonable instrument exposure for cup-vane anemometers.

Point and cross valley averaged wind measurements were compared to determine averaging times, when the two measurements showed similar variations, so the results could be used to test and validate numerical wind field models. The optical paths used to determine the down and up-valley wind speeds, and the same wind component derived from 10 m tower cup-vane conventional anemometers, were compared when both systems were located deep within valleys. Both measurement systems were well below the 50–100 m deep drainage transition layer as determined from acoustic sounder and tethersonde data, and they experienced the same daytime up-valley and mesoscale sea breeze winds as well.

The comparison of point and spatially averaged winds in complex terrain provides some information about the relationship of time and space averages in similar situations. This is an important and recurring problem due to the practical limitations on grid size for models and the fact that wind fields over complex terrain are usually sampled by one, and at most a few, tower mounted anemometers. We found that spatially averaged winds (measured over paths of 0.5–3 km) generally exhibited significantly smaller time variability for periods under two hours than the winds measured at a point in the same flow regime (with cup-vane anemometers).

The fact that complex terrain influences turbulence, has been documented by comparing wind fluctuations from regions with and without complex terrain (Panofsky *et al.*, 1981). Additional insight is gained by comparing autospectral densities of point and spatially averaged wind measurements. We found that spatial wind averaging reduces terrain influences for periods less than four hours. We hope to use this effect to separate terrain influences from synoptic variations when nearby homogeneous terrain does not exist.

The instrumentation for these studies consisted of commercial laser (Lawrence *et al.*, 1972) and light diode optical anemometers (Fritz and Lawrence, 1981) that operated over optical paths that crossed downsloping valleys. Tower-mounted cup-vane anemometers were generally situated near one end of each path. Optical anemometers were used for long term data collection. Short term studies were conducted with incoherent optical systems to ensure the absence of optical turbulence saturation (Ochs *et al.*,

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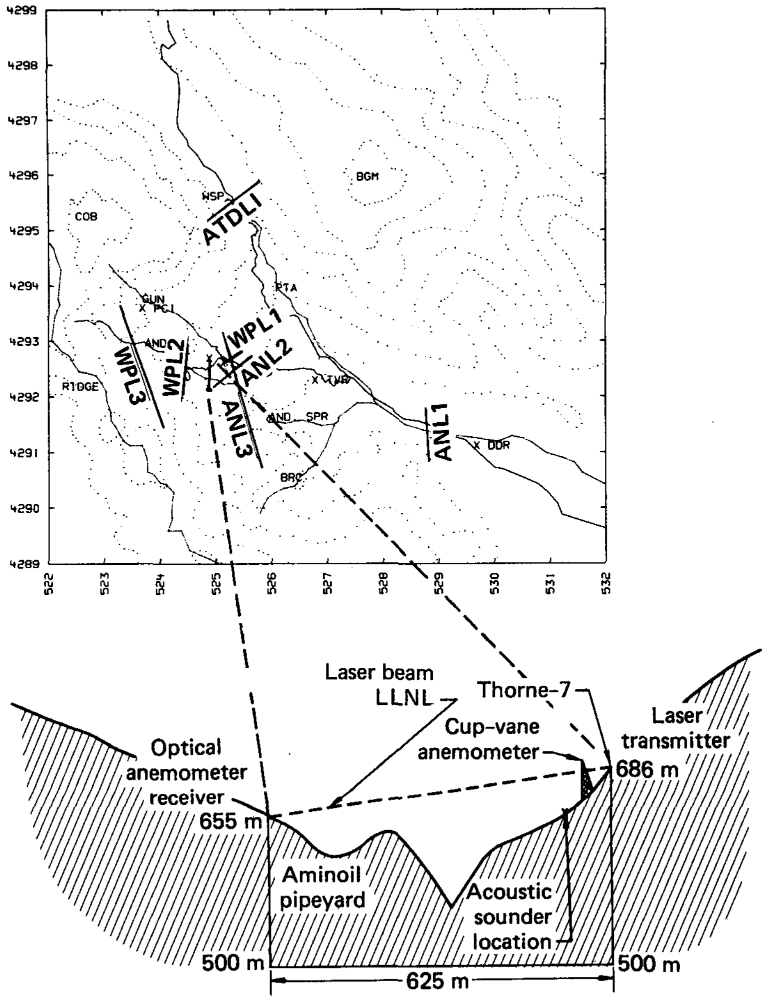


FIG. 1. Topographic relief below the cross-valley light path for the July 1979 ASCOT experiment. This path and the cup-vane anemometer tower were deep within the Anderson Creek valley shown in the topographic map with contour intervals of 120 m. The solid lines on this map represent creeks. The UTM coordinates are in kilometers.

1976) and to determine the distribution of optical turbulence along the light path. These studies demonstrated: a) the utility of space-averaging anemometry for the remote sensing of winds in complex terrain, and b) the applicability of spatially averaged wind spectra for isolating terrain influences.

2. Experiments using optical anemometry

Three experiments have been conducted near the Northern California coast to determine the effect of spatial averaging of winds over complex terrain. The first experiment was conducted in July 1977. Thirty-minute averaged wind speed and direction were obtained from a cup-vane anemometer system at one end of the 1 km long light path that crossed windy Patterson Pass, ~5 km east of Lawrence Livermore National Laboratory (LLNL), Livermore, CA. In addition, 10–15 min average wind data were collected in two shorter experiments (2–3 weeks) over a 600 m long light path at Anderson Creek in The Geysers geothermal region of Northern California (July 1979 and September 1980). These two experiments, which were conducted at nearly the same location, were part of the ASCOT program.

Patterson Pass and Anderson Creek are in significantly different meteorological regimes. During the measurement period, Patterson Pass wind patterns were influenced strongly by summer sea breezes that had average speeds of close to 10 m s^{-1}. The average wind speeds at Anderson Creek were much lower (~2 m s^{-1}) because of the influence of local topography and nighttime drainage winds.

Similar instrumentation was used in the three experiments. Most optical-anemometer wind data were obtained with a laser beam system described by Lawrence *et al.* (1972). The optical anemometers measured the spatially averaged cross-path component of wind between the source and receiver, using a weighting function to minimize the influence of the light path ends. These anemometers were previously calibrated over homogeneous terrain by comparison with a linear array of anemometers. The comparisons showed agreement for means over periods shorter than the average 10 min sampling period used in these experiments.

Parallel measurements were also made along the light path across Anderson Creek, using a white light photodiode-array system developed at LLNL (Porch and Green, 1980). This system, although capable of wind-speed determination, was used to test that the optical turbulence was uniformly distributed along the light path, which is important in interpreting the results of the laser cross-wind system. The horizontal movement of density fluctuations due to temperature, manifested as optical turbulence, is used to determine the average cross-path wind. Optical turbulence is recorded as the standard deviation of laser light intensity. At no time during the three experiments did this parameter reach a value that would imply optical turbulence saturation (Ochs *et al.*, 1976). A tower-mounted cup-vane anemometer system was operated at one end of the light path in each experiment.

An example of the experiment geometry is shown in Fig. 1. This figure shows The Geysers regional topography, an enlargement of the topographic cross section along a light path with a meteorological tower across Anderson Creek, and the location of seven other laser paths used in the 1980 ASCOT experiment. The 10 m anemometer tower selected for detailed comparison was located at Thorne 7, a geothermal well pad. The laser receiver used in both the 1979 and 1980 experiments was placed across the valley at an Aminoil pipeyard, as shown in the inset in Fig. 1. Both systems were located within the Anderson Creek valley which extended upward for ~300 m on both sides of the path. The average height of the laser beam above topography was 32 m. When the optical turbulence weighting function associated with the cross-path sensor is convolved with the path height above terrain, the weighted mean height above terrain becomes 40 m because this function goes to zero at each end of the path. The relative height difference between the two systems made little difference in the average wind component sensed by the optical and cup-vane anemometers. An acoustic sounder located below the light path in the Anderson Creek experiments revealed a relationship between the optically detected index-of-refraction-structure function (C_n) and the acoustically determined temperature-structure function (C_T) (Porch, 1981), and showed both systems to be sensing the same general flow.

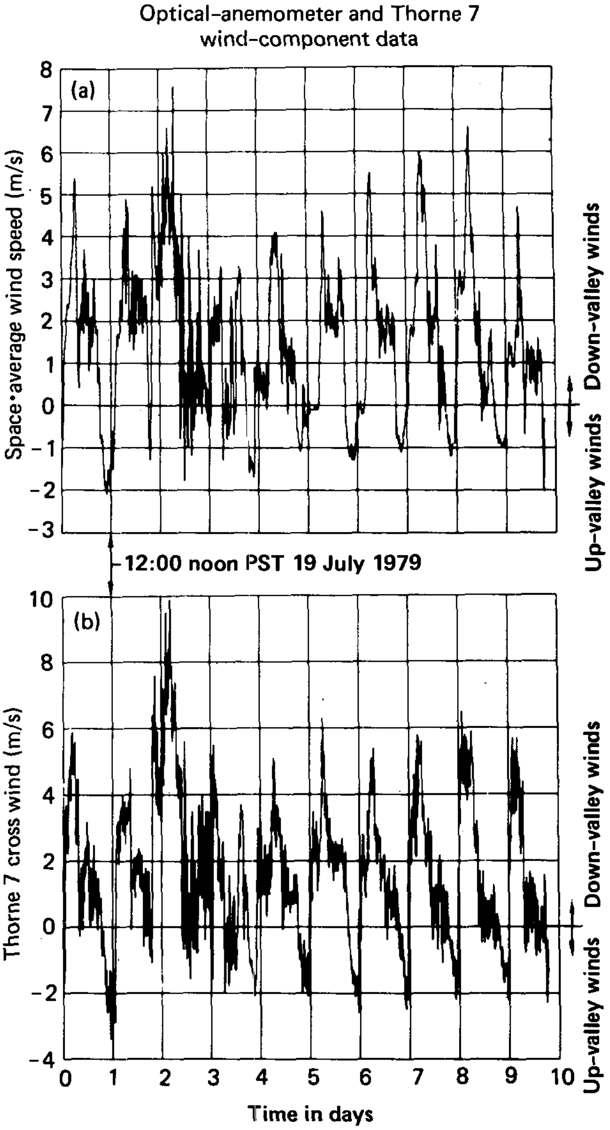


FIG. 2. Time history plots of: (a) optical, and (b) cup-vane anemometer-derived cross-path wind speeds for a 10-day period, beginning 1200 PST, 18 July 1979, in the July 1979 ASCOT experiment shown in Fig. 1.

Drainage-wind tracer experiments were also conducted in 1980 by releasing oil fogs ~2 km higher up Anderson Creek from the Thorne 7 location. The motion and depth of the oil fogs were monitored using searchlight-aided nighttime photography. These studies also substantiated that the particular optical and tower anemometer systems comparison detailed in the next section were both experiencing the same general down-valley flows.

3. Results

The day to day variability of cup-vane and optical anemometer cross-wind measurements is compared

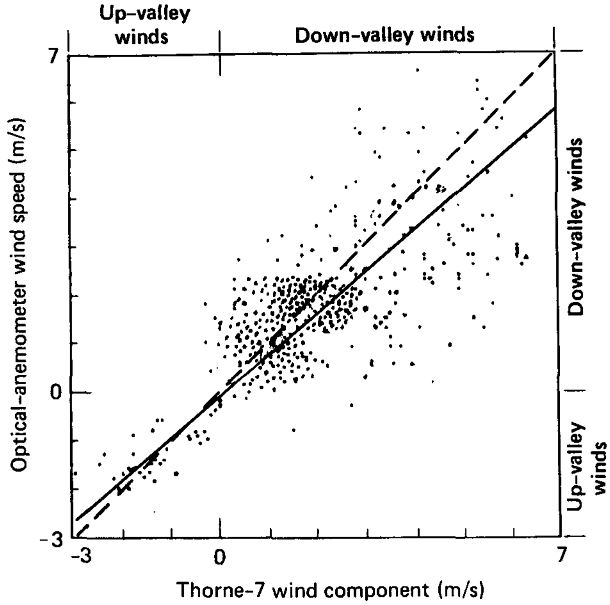


FIG. 3. Scatter plot of 400 values for variables shown in Fig. 2, chosen to exclude period of unsettled weather (dashed line for perfect correlation, and solid line for observed regression).

in Fig. 2. The figure shows the cross-path component of the wind over a 10-day period, averaged over 10 min by both the optical anemometer and with the cup-vane anemometer located at Thorne 7. Both instruments show the same diurnal cycle which was interrupted for two days during a passing disturbance that produced a thunderstorm on 20 July. Although clear nights followed the thunderstorm, the associated weather pattern's influence on the drainage wind lasted several days. Note that the 10-day wind pattern for the spatially averaged optical measurement (Fig. 2a) is much smoother than that for the point measurement.

The differences in the measurements are more obvious in Fig. 3, which shows a scatter plot of stable meteorology period cross-wind values from the 1979 ASCOT experiment (excluding the period of the disturbance). The cluster of points around 2 m s^{-1} resulted from the predominance of steady nighttime drainage winds. The cup-vane anemometer system consistently indicated slightly lower wind speeds than the optical system due to the difference in effective height of the two systems (10 and 40 m, respectively). However, this is slightly less of a difference than would be expected over flat terrain. This lessened wind shear is supported by tethersonde measurements made at night near Thorne 7. During morning up-valley wind, some of the difference between the two systems is due to the fact that the cup-vane system was located on the side of the valley shaded from the rising sun for a period of ~30 min longer than the other side.

Although a correlation coefficient of 0.79 was obtained for the two measurements, individual pairs of values sometimes differed by several meters per second. These differences in values occurred most often for the Anderson Creek data, when higher down-valley sea breezes occurred alone or in combination with the late evening formation of a drainage wind layer. One way to avoid nonrepresentative wind speeds without the help of spatially averaged winds during times like these would be for numerical models to average the wind speeds over longer periods.

The overall wind patterns were not as regular for the 1980 ASCOT experiment, because of the less frequent development of nighttime drainage winds. However, a comparison of the optical and point measurements gave a correlation coefficient of 0.90. During this experiment, the intensity correlation function

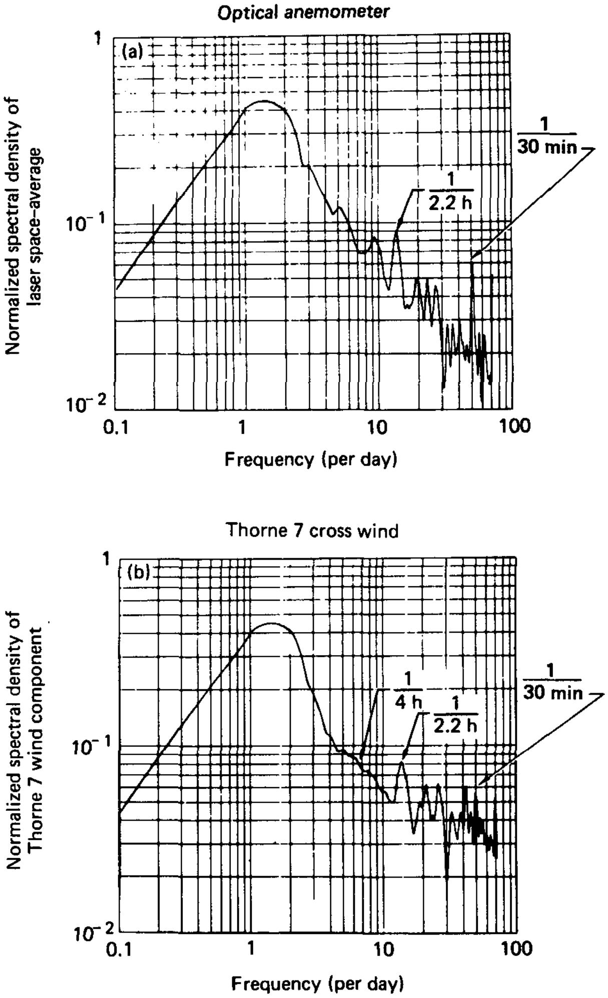


FIG. 4. Normalized autospectral densities for (a) optical-anemometer-derived cross-path winds; and (b) cross-path component of wind from the tower-mounted cup-vane anemometer for 10-min averaged data during July 1979, showing difference in spectral slope for periods of <4 h.

was occasionally measured with a photodiode-array incoherent light. Although the distribution of optical turbulence remained fairly uniform throughout the night, an optical turbulence maximum appeared at sunrise on the side of the valley being illuminated by the sun. Once both sides of the valley were illuminated by the sun, the optical turbulence maximum shifted back toward the center of the path (Porch and Green, 1981).

Autospectral analysis techniques were used to further investigate the regular features of the time variability of the wind. Fig. 4 is a comparison of the normalized autospectral densities for the data shown in Fig. 2. These data were smoothed with a 30 point triangular filter. Both data sets in Fig. 4 show similar spectral density features for frequencies less than six per day (4 h period) and a relatively strong peak at a frequency of ~ 11 per day (2.2 h period).

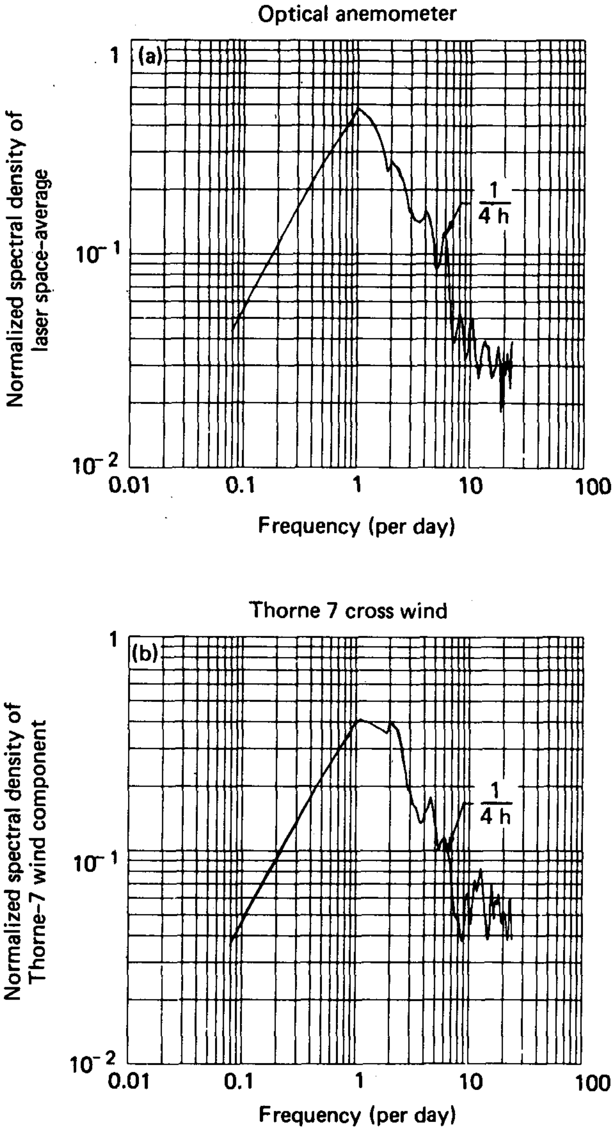


FIG. 5. Spectral comparison analogous to that shown in Fig. 4 for the September 1980 ASCOT experiment, with 30-min averaged data, again showing divergence in spectral slope at higher frequencies.

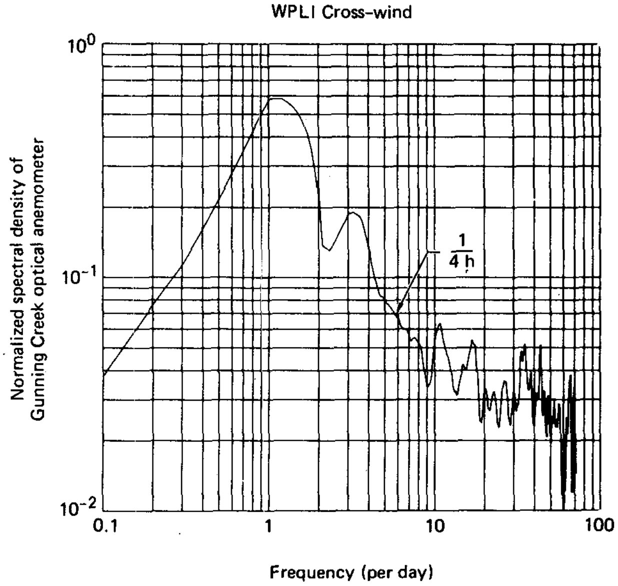
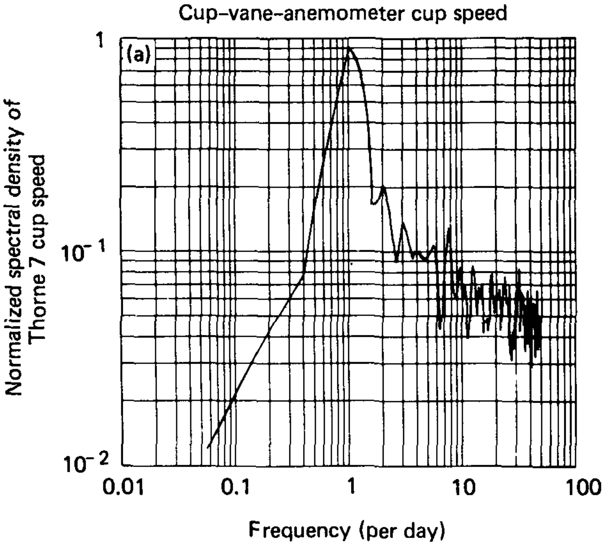


FIG. 6. Spectrum analogous to the spectra shown in Figs. 4 and 5 for an infrared optical system used across Gunning Creek (a smaller creek in the Anderson Creek drainage area).

The slope of the autospectral density curve for the point measurement flattens when compared to the space-averaged measurement; i.e., it shows greater variability for periods of <2–4 h. This flattening effect is even stronger in Fig. 5, showing 30-min averaged September 1980 data. Strong smoothing was again used to emphasize the statistical significance of the slope change and the individual peaks. The overall shape and slope of these spectra were not changed by the length of the triangular filters. The 2.2 h peak was also observed from a tower located at the outflow of the drainage layer (Doran and Horst, 1981). In the Patterson Pass data, which were collected under much windier conditions, the point wind spectral density actually increased for periods of <4 h (Porch *et al.*, 1979).

Fig. 6. shows an analogous spectrum from a different type of optical wind system (Fritz and Lawrence, 1981). This system was used across Gunning Creek, a small creek near Thorne 7, shown as WPL1 in Fig. 1. The light path length was 416 m and had a weighted mean height of 25 m above terrain. This spectrum shows about half the energy associated with periods of <4 h, as found in the nearby cup-vane wind component shown in Fig. 5b. Comparison of the various cross-wind paths shown in Fig. 1 showed that drainage winds were influenced to a greater degree by larger scale flows higher up the valley sides and closer to the mountain ridge. However, this did not affect


Cup-vane-anemometer cup speed

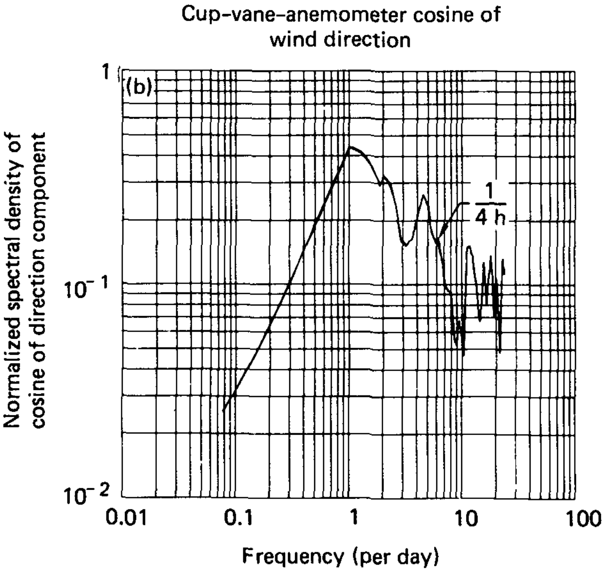

Cup-vane-anemometer cosine of wind direction

FIG. 7. Normalized autospectral densities of 1980 tower measurements of (a) cup-vane anemometer-derived wind speed; and (b) cosine of cross-path wind-direction component, showing that the difference between the point and spatially averaged cross-wind spectral slopes results primarily from changes in wind direction.

the variability at periods <2 h, except that in general the very long paths showed less variability.

Observed spectral differences are more likely to be associated with the influences of complex terrain than with differences in instrument systems. This is apparent from: a) the high correspondence (correlation and mean) between long-term data from the cup-vane and space-averaging anemometer systems (shown in Fig. 2), and b) the <10 min correspondence times found in homogeneous terrain studies.

Since the spectra presented are of down and up-valley wind components, one might question whether this divergence of spectral slope results more from changes in total wind speed or from changes in wind direction component. Although the wind speed spectrum in Fig. 7 is somewhat flatter than the optical-anemometer spectrum, the spectrum of the cosine of wind direction shows a large spectral gap between 2.5 and 4 h. The dominance of wind direction changes was also observed in the data sets for Patterson Pass (Porch *et al.*, 1979) and the 1979 ASCOT experiment. One tentative explanation for this dominance is that, since complex terrain increases the standard deviation of wind direction at high frequencies (Perry *et al.*, 1978), the energy comes from somewhere else in the spectrum. Perhaps this energy is subtracted from eddies associated with changes in wind direction within 4 h periods. Simply put, the optical system measures the down and up-valley flow, which is influenced by the sum of slope flows acting along the length of the valley. Averaging over the longer spatial scales associated with the optical anemometer apparently averages out or diminishes the smaller-scale effects of complex terrain.

The elongation of eddies for down-valley winds (Lumley and Panofsky, 1964) also appears as a shift to longer-period eddies in the cross-valley winds. Individual wind velocity measurements on the valley slope show greater energy in the high-frequency component. Analyses of wind spectral differences show that point measurements in complex terrain should be averaged for 1–2 h, to better represent wind variability over spatial scales of 600–1000 m. Two hour averaging would fold the spectra from the cup-vane anemometer system over to begin at a Nyquist period of four hours, thus eliminating high-frequency differences. This is an important result because it affects the averaging times needed to ensure the representativeness of point wind measurements in complex terrain.

Having found evidence of one effect of complex terrain on the wind spectrum, we questioned whether peaks in the spectrum can be related to regular variability in the terrain. The statistical significance of the two peaks shown in Fig. 4 (2.2 h and 30 min periods) were >50%. However, since the statistical significance of peaks in short data sets is low, we tried to find relationships between spectral peaks in the wind autospectra for both the 1979 and 1980 ASCOT experiments. In 1980, the two major peaks seem shifted slightly to lower frequencies related to the overall decrease in wind speeds experienced that year. These peaks and the shift to lower frequencies were also found when only relatively steady drainage wind conditions were considered. It is important to realize that even during nighttime drainage, these winds were being influenced by changes in mesoscale sea breeze wind flow in the same direction. The peaks at ~2.2 h and 30 min were then compared to spatial regularities in a two-dimensional Fourier transform of

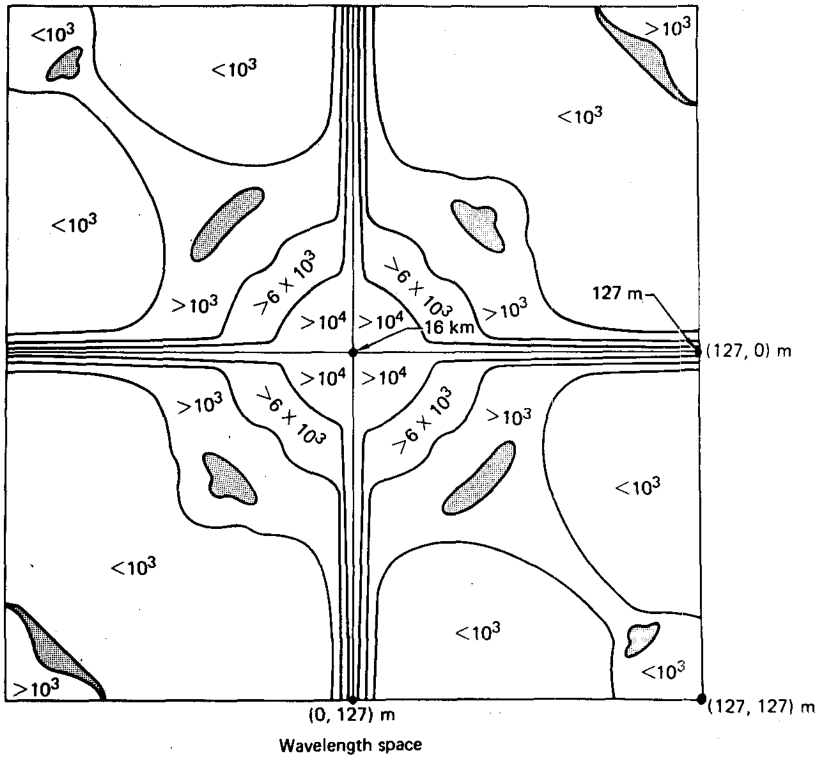


FIG. 8. Contours of two-dimensional Fourier transform coefficients of 63.5 m resolution topography data over a 16 km^2 area centered on The Geysers geothermal region, where data in the previous figures were obtained. Dark patches represent relative spatial peaks.

The Geysers area terrain and related through the mean wind speed.

Nighttime drainage winds were, except when disrupted by large scale weather patterns, persistent during The Geysers experiment. A data set comprised of only drainage wind periods was constructed for each of the two ASCOT experiments. These periods, which lasted approximately 8 h, began ~2200 PST. We attempted to start these periods at times when the data would more smoothly match the last data taken during the previous day. Because the data sets were obtained in different months (July and September), some differences in drainage winds were expected and observed. Specifically, the drainage winds were almost 30% weaker in September 1980 than they were in July 1979 (1.2 and 1.6 m s^{-1} mean drainage component, respectively).

Regular variability in complex terrain can be determined from a two-dimensional Fourier transform of the site topographic relief (Porch, 1981). This transform is used in complex terrain studies to determine repetitive terrain features. It is also a useful tool for comparing terrain complexity in different regions and for determining the relative importance of small terrain features, as they relate to the spatial averaging associated with cell sizes chosen for numerical wind-field models. Digitized topography with 63.5-m resolution was obtained for the area encompassing the two ASCOT experiment sites. The topography was represented by a 256 × 256 array of cells corresponding to a 16 × 16 km area. The corners and sides of the transform correspond to wavenumber space representations of Fourier components along the two horizontal axes (Fig. 8). The Nyquist spatial wavelength is twice the maximum resolution (127 m). The high values at the center and along the major axes of the transform imply that a complicated map would reproduce itself exactly at a spatial wavelength corresponding to the size of the map. This is the reason the high values follow the axes.

The variation in transform along the diagonals is important. The lower right to upper left diagonal of the transform represents the variability associated with a southeast to northwest change in terrain. Fig. 8 shows that the topography varies more regularly (less variation in short spatial wavelength) along this diagonal than it does along the southwest to northeast diagonal, which is aligned perpendicular to approximately eight valley ridge systems. The dark patches in Fig. 8 represent relative maxima in the Fourier coefficients and correspond to wavelengths of ~2 and 11 km (the outer and inner shaded areas, respectively). Since the original topographic array was only 16 km on a side, there are fewer data to support the statistical significance of the 11 km peak than to support the 2 km peak. When the mean drainage wind speeds of 1.6 and 1.2 m s^{-1} for the two ASCOT experiments are considered, these spatial wavelengths seem to correspond to both a 2.2 h peak and a 26–36 min peak in the drainage wind spectra from the two optical cross-path wind systems (across Anderson and Gunning Creeks) and the cup-vane system at Thorne 7. The 2.2 peak, if it is related to terrain at all, is consistent with larger scale influences on winds measured during the drainage wind period. It is possible to speculate that the two peaks may be showing the separate effect of short wavelength regularities (regular spacing of creek inflows along the drainage valley) and long wavelength sea breeze oscillations (induced by regularly spaced valleys). While this correspondence suggests that regular oscillations in rolling hills may affect the temporal pattern of wind speed during drainage wind periods, more data are needed to prove that the peaks in the transform and those in the drainage wind spectra are significantly related. In fact, Doran and Horst (1981) suggest that the 2.2 h peak resulted from oscillatory behavior induced by cool air drainage and adiabatic heating. Whether larger scale flow changes caused by regular variations in terrain or by natural oscillations in drainage layer flow dominates has not been resolved.

4. Conclusions

Using optical techniques, we have gained valuable insight into the spatial-temporal influence of topography by comparing wind velocities and spatially averaged cross-path winds. Such comparisons are helpful in modeling wind fields over complex terrain. First, the spatially averaged wind component may be used directly in the model grid cell to represent the area covered by the optical path. Second, the optical anemometer-derived wind speeds can be used to verify numerical wind field models. Third, the autospectral comparison of temporal wind variations implies that point measurements in the region should be averaged for a relatively long time (~2 h) to better represent the wind over a cell. Autospectral analyses of drainage wind fluctuations suggest that a relationship may exist between prominent spectral peaks and regular variations in complex terrain relief. The spatial variability in complex terrain can be represented by the two-dimensional Fourier transform of the terrain relief.

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