Wintertime Surface Wind Patterns in the Colorado River Valley

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ABSTRACT

The diurnal variation of regional wind patterns in the complex terrain of the Grand Canyon area was investigated for wintertime fair weather days using a network of wind sensors on 10-m towers. Thermally driven along-slope and along-valley circulations were present at all sites within the region, but wind characteristics varied from site to site depending on nearby topography and exposure. Along the Colorado River upstream from the Grand Canyon, a series of subbasins produce a regional circulation system characterized by convergence of low-level air into the subbasins at night and divergence of air from the subbasins during the day. Contrary to valley wind theory expectations, locations down valley from the subbasin centers experience up-valley winds during nighttime and down-valley winds during daytime.

1. Introduction

In the winter of 1989–90, a Winter Visibility Study (WVS) was conducted in the region around the Grand Canyon of the Colorado River to determine the impact on visibility within Grand Canyon National Park of pollution plumes from the Navajo Generating Station, a 2300 MW coal-fired power plant located at Page, Arizona. An extensive network of 10-m meteorological towers was deployed throughout the Grand Canyon area of southern Utah and northern Arizona as part of this study. The wind data from the meteorological towers provided a unique dataset to investigate thermally driven circulations in this remote, undeveloped, and sparsely populated area. The dataset was collected in winter, a season that is underrepresented in previous studies of thermally driven complex terrain wind systems (Whiteman 1990), and the experiment was designed to provide a very good distribution of sites with elevation and land form type (Richards et al. 1991), a failing of many previous complex terrain meteorological studies.

In this paper, analyses of thermally driven regional wind systems in the Colorado Plateau region are presented using data from the WVS. Section 2 presents information on the study region, the measurement sites, the wind instrumentation, and the data. Section 3 describes the data processing and analysis procedures, section 4 presents the analysis results, section 5 discusses the results, and section 6 presents the conclusions.

2. Study region and measurements

a. The study region

The Grand Canyon region is an area of very complicated terrain features, including basins, valleys, plateaus, and canyons on a variety of different scales (Fig. 1). A key topographical feature of the Grand Canyon region is the large basin known as the Colorado Plateau that covers southeastern Utah, southwestern Colorado, northeastern Arizona, and northwestern New Mexico, and is bounded on the north and east by the Rocky Mountains. The Colorado Plateau has the meteorological characteristics of a basin (Whiteman et al. 1999b) and will be referred to here as the Colorado Plateau Basin or CPB to emphasize its basin character. A north–south line of plateaus and high mountains separates the western side of the CPB from the lower-elevation Basin and Range Province farther west. The Grand Canyon and Fredonia Pass are major gaps in this line.

The Colorado River is the main fluvial feature in the study area. It runs through the CPB from near the northeast corner of the map in Fig. 1 southwestward into the Bullfrog and Lake Powell subbasins of the CPB, and through the Grand Canyon to Lake Mead, where it turns southward through Lake Mohave and continues southward toward Mexico. Lake Powell (1128 m above mean

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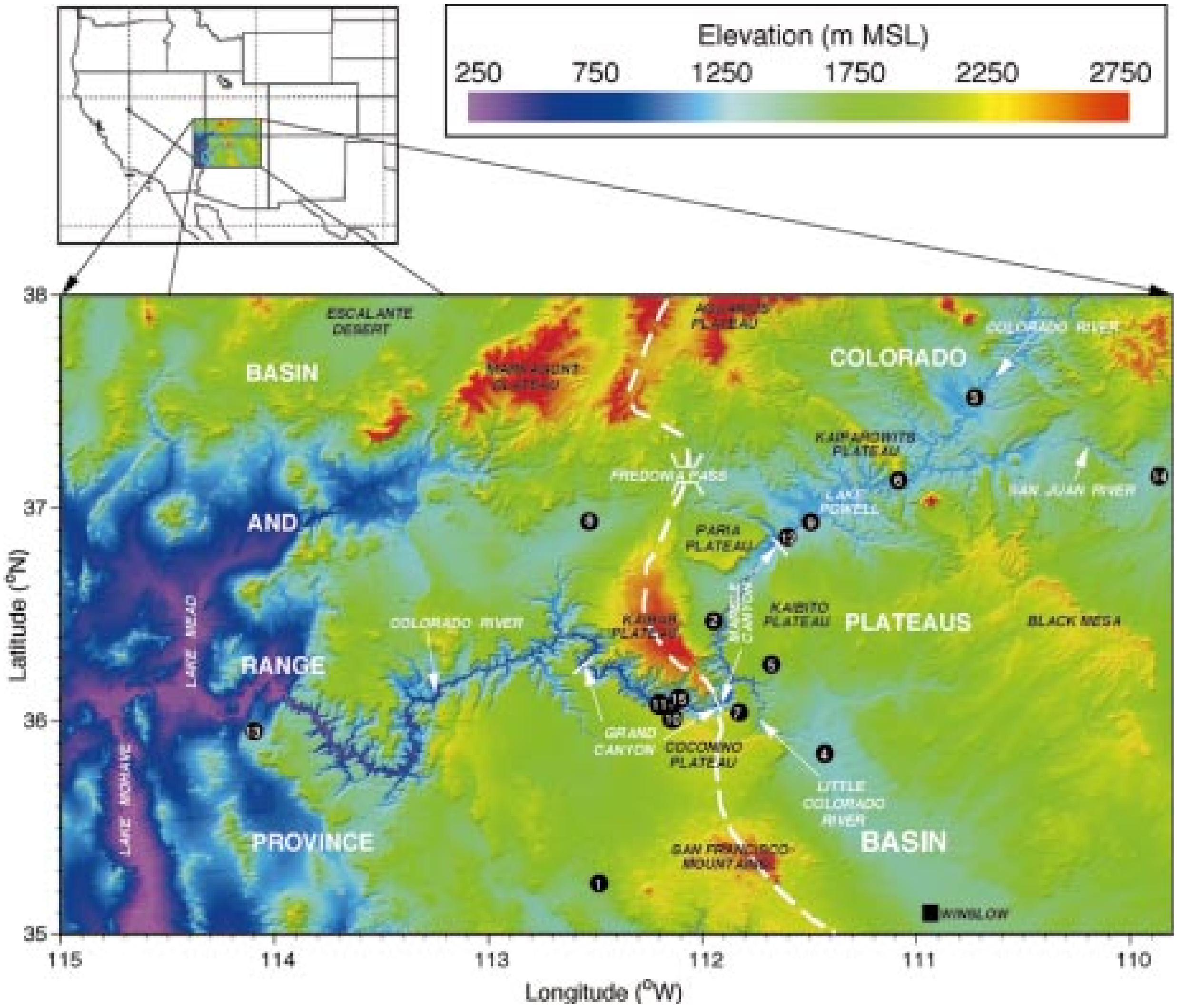

FIG. 1. Shaded relief digital elevation model of the experimental area, showing major topographic features and wind measurement sites. Sites are listed in Table 1.

sea level, MSL) extends up the Colorado River to a point 185 km northeast of the Glen Canyon dam, and a major branch of the lake extends nearly 50 km up the San Juan River. Lake Mead (366 m MSL), extends up the Colorado River from the Hoover Dam into the west end of the Grand Canyon. Lake Powell, Lake Mead, and Lake Mohave effectively create long segments of the Colorado Valley that have flat valley floors.

The experimental area is a complicated mosaic of land forms that extends through an elevation range from 250 to 2750 m MSL. Most of the country is dry and treeless, except at the higher elevations, and consists primarily of desert soils and exposed rock. During the winter experiments, the forest-covered high plateaus in the central northern portion of the experimental area (including the Kaibab Plateau just north of the Grand Canyon) maintained a permanent wintertime snow cover at their highest elevations. Their lower slopes, however, had continuous snow cover only temporarily, following major snowstorms.

b. The measurement sites

Many of the wind measurement sites were situated along the Colorado River and its tributaries up valley from the Grand Canyon. The locations of the 15 operational wind measurement sites during the WVS experiment are shown in Fig. 1. Site characteristics, including latitude, longitude, and elevation are listed in Table 1, which also include the periods of record for the sites. Site elevations ranged from 750 m MSL at Phantom Ranch on the floor of the Grand Canyon to 2283 m MSL at Desert View on the Grand Canyon's South Rim. Sites were generally operated between mid-December of 1989 and early April of 1990. Ash Fork, Fredonia, and Meadview were located in the Basin and

TABLE 1. Wind measurement sites.

Site name	Ident	Latitude	Longitude	Elevation (m MSL)	Period of record
Ash Fork	ASH	35°14′21″	112°29′00°	1588	14 Dec–2 Apr
Buffalo Ranch	BFL	36°28′11°	111°56′43″	1710	15 Dec–4 Apr
Bullfrog Basin	BUL	37°31′08″	110°43′30″	1130	18 Dec–3 Apr
Cameron	CAM	35°50′54″	111°25′39″	1350	19 Dec–4 Apr
Cedar Ridge	CDR	36°15′55″	111°40′35″	1786	12 Jan–1 Apr
Dangling Rope	DNG	37°07′48″	111°04′53″	1155	16 Dec–1 Apr
Desert View	DSV	36°02′29″	111°49′39″	2283	19 Dec–4 Apr
Fredonia	FDN	36°56′17″	112°31′46″	1420	15 Dec–6 Apr
Glen Canyon	GLC	36°56′06″	111°29′31″	1314	10 Jan–13 Mar
Hopi Point	HOP	36°04′16″	112°09′14″	2152	21 Dec–3 Apr
Indian Gardens	ING	36°04′45″	112°07′37″	1146	7 Jan–4 Mar
Lee's Ferry	LEY	36°51′48″	111°36′00″	994	22 Dec–4 Apr
Meadview	MVW	35°57′12″	114°05′46″	1070	14 Dec–2 Apr
Mexican Hat	MEX	37°08′56″	109°51′42″	1271	17 Dec–3 Apr
Phantom Ranch	PTN	36°06′55″	112°03′34″	750	10 Jan–19 Mar

Range Province; the remaining sites were located within the Colorado Plateaus Basin.

c. Instrumentation and data

At 13 of the sites, winds were measured on 10-m masts using identical new unheated R. M. Young, Inc., model 05103 aerovane-type wind sensors. The propeller's speed threshold was 0.9 m s^{-1} and the wind vane's thresholds were 1.0 m s^{-1} (10° displacement) and 1.5 m s^{-1} (5° displacement). The analog outputs from the wind sensors at each station were sampled once every 10 s by a Campbell Scientific, Inc., model CR-10 datalogger to produce the 1-h average vector-mean winds used in the analyses. Despite occasionally severe winter weather, the wind data quantity and quality were excellent from these remote, battery-powered, solar cell-assisted sites, which were operated by a small team of field personnel.

Two additional sites, Phantom Ranch and Glen Canyon, were not part of the WVS special wind network and used different wind measuring equipment. At Phantom Ranch, wind data were collected from a 3-m tripod using a Met One model 14A cup anemometer (starting threshold 0.4 m s^{-1}, accuracy $\pm$0.1 m s^{-1}) and model 24A wind vane (threshold 0.4 m s^{-1}, accuracy $\pm$5°). At Glen Canyon, winds were measured at the 10-m level using a Weathermeasure Skyvane model W102-P wind vane and anemometer (starting threshold 1 m s^{-1}, accuracy 0.5 m s^{-1}). The periods of record for the Phantom Ranch and Glen Canyon sites were significantly shorter than for the other 13 sites (Table 1).

The basic wind dataset from the 15 sites is composed of hourly vector-average winds. All analyzed winds are identified by the beginning times of the 1-h averaging periods over which they were computed, in mountain standard time (MST).

3. Data analysis procedures

a. Stratifying the data

Local and regional thermally driven circulations are a distinctive feature of the meteorology of complex terrain areas (Wagner 1938; Defant 1951; Blumen 1990). These circulations, which are produced by horizontal temperature differences that develop within complex terrain areas, are found within inclined convective or stable boundary layers that form over mountain sidewalls, valley floors, and other sloping surfaces, and are most apparent during fair weather when skies are clear or partly cloudy and the winds above the mountainous region are relatively weak. Thus, to investigate thermally driven circulations, the analyses were focused on the subset of experimental hours having fair weather, that is, weak synoptic winds and low cloudiness.

Synoptic wind strength was determined from twice daily rawinsonde soundings at Winslow, Arizona (35° 01′N, 110° 44′W, 1488 m elevation)—the nearest National Weather Service upper-air sounding site, located in the CPB southeast of the Grand Canyon (Fig. 1). Synoptic winds were considered weak over the entire experimental area and during the entire 12-h period centered on the rawinsonde observation time (2200–0900 MST for the 1200 UTC sounding and 1000–2100 MST for the 0000 UTC sounding) when 700-mb winds at Winslow were less than 6.7 m s^{-1}. Previous studies investigating the disturbance of mountain and valley drainage flows by synoptic-scale winds at ridgetop level make it clear that there is some disturbance even at low wind speeds (Barr and Orgill 1989; Doran 1991). The disturbances are strongest at ridgetop level and are reduced at lower altitudes, especially when the valley atmosphere has high stability. Davidson and Rao (1958) found that conditions were favorable for nighttime drainage when winds aloft were less than 6 m s^{-1}. Orgill and Schreck (1985), in California's Mayacmas Mountains, found that local drainage winds were susceptible to ambient winds above 5 m s^{-1}. Gerbier and Bérenger (1961) found that waves in the lee of ridges were weak and shallow when winds were below 8 m s^{-1}, while Nicholls (1973) found that waves formed downwind of ridges when speeds exceeded 7 m s^{-1} on low ridges and 14 m s^{-1} on high ridges. Since the wintertime CPB atmosphere is generally quite stable (Whiteman et al. 1999b) and the 700-mb level is considerably higher than much of the terrain in the study region, the cutoff value of 6.7 m s^{-1} appears reasonable.

Daily total incoming solar radiation was used as a proxy indicator of cloudiness. These data were available at Ash Fork (14 December–15 January) and at Cedar Ridge (15 January–1 April). A day (2200–2100 MST, to correspond to the rawinsonde observation time blocks above) was considered clear or partly cloudy if the ratio of daily incoming to theoretically determined extraterrestrial solar radiation was greater than 64% on that day. On clear days, the daily incoming radiation was found to be about 80% of the daily extraterrestrial total, so that the 64% cutoff effectively defined partly cloudy days as those days receiving 80% or more of the clear day radiation totals.

All hours during the WVS experimental period were classified into fair weather and non–fair weather categories, using the synoptic wind speed and cloudiness criteria described above. These categories apply to all data from the WVS experiment, regardless of site. The number of fair weather hours in the period of record at a given site depends, naturally, on the length of the period of record (Table 1). The number of fair weather hours used to calculate the vector averages for the 24 h of the day varied from site to site and from hour to hour, ranging from a low of 12 at Phantom Ranch (PTN) (which had a shorter period of record than other stations) to 25 at Buffalo Ranch (BFL), Dangling Rope (DNG), Fredonia (FDN), and Meadview (MVW). The total number of days of data in the period of record ranged from a low of 67 at PTN to a high of 104 at MVW. Considering all the stations, approximately 22% of the winter experiment hours were classified as fair weather hours, and wind fields obtained from data on these fair weather days are considered to represent thermally driven winds.

b. Analysis procedures

For each station, an average fair weather wind was determined for each of the 24 h of the day by performing a vector average of hourly wind values for that hour of the day for all the fair weather hours in the station's period of record. Further, as an aid to interpreting these computed hourly vector winds, the variability of the winds used in computing the vector average was determined using *wind persistence.* Wind persistence (Panofsky and Brier 1965) is the ratio of vector mean wind speed and scalar wind speed. This ratio is 1 when all fair weather days have identical wind directions at the hour indicated and is less than 1 when the wind direction at a particular hour varies from day to day. The ratio is 0 when a wind is equally likely from all directions or when it blows half the time from one direction and half the time from the opposite direction. The results of the persistence analysis are shown in Fig. 2 and the vector average winds are plotted on plan maps of the experimental area at 3-hourly intervals in Fig. 3. The indicated times are the beginning of the 1-h averaging period of interest. The first column of subfigures in Fig. 3 shows nighttime winds at 2100, 0000, 0300, and 0600 MST. The second column shows daytime winds at 0900, 1200, 1500, and 1800 MST. For reference, sunrise and sunset times on 15 February at latitude 36°N and longitude 112°W occurred at 0721 and 1805 MST, respectively. The focus of this analysis method was on the spatial variation of winds within the study area and the changes of the spatial patterns with time.

Vector diagrams (Fig. 4) were used to investigate diurnal changes in wind direction and speed, and hourly winds at times not shown in Fig. 3. Each of the fair weather vector diagrams contains a cross (a wind coordinate origin) and 24 dots, one for each hour of the day, with labels in MST. The vector mean wind for any given hour can be constructed from the figures by drawing a vector from the coordinate origin to the dot labeled with the hour of interest. The vector's orientation represents the wind direction, and the wind speed is determined from the scale at the bottom of the figure. The 24 dots in each vector diagram are connected in time order and the enclosed area is shaded. From the time notations, one can determine whether the fair weather winds shift in a clockwise or counterclockwise direction with time. For sites exposed to both valley and slope wind systems, the direction of turning is related to the orographic slope of the wind site (Hawkes 1947). When looking up a valley (Fig. 5), sites on the left sidewall experience a clockwise turning with time, while sites on the right sidewall experience a counterclockwise turning. The focus of the vector diagram analysis was on the changes of wind with time at individual stations and on the direction of wind turning.

4. Results

a. Persistence

Because wind variability is an important parameter affecting the interpretation of computed vector resultant winds, wind variability or persistence will be discussed before considering the fair weather resultant winds. The

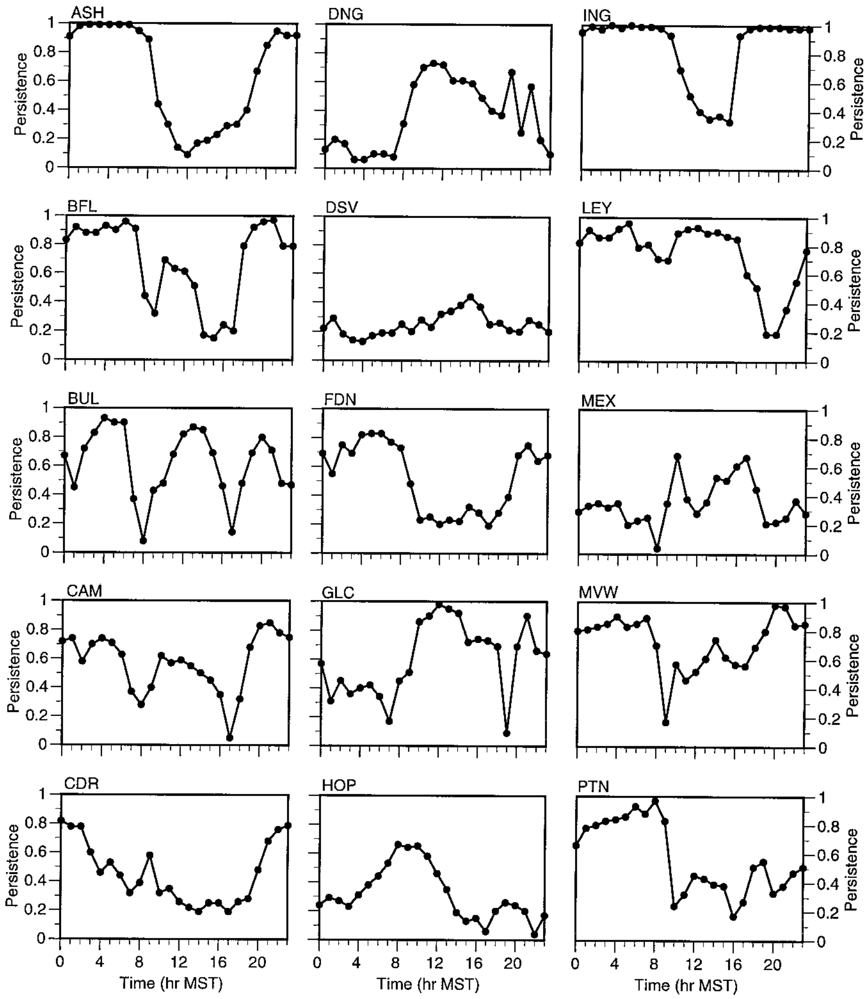

FIG. 2. Diurnal variation of wind persistence on fair weather days at the WVS sites.

day-to-day variability of fair weather winds is higher at some of the WVS sites than at others, and there are significant diurnal variations in persistence at many of the sites that follow distinctive patterns (Fig. 2). First, for protected sites deep within the topography where thermally driven winds blow up valley or upslope during daytime and down valley or downslope during nighttime, persistence is high during both daytime and nighttime, but low during the morning and evening wind reversal periods. The wind reversals occur at around 0800 and 1700 MST at most sites but can be expected to vary with cloud cover, synoptic-scale pressure gradients, and shading by surrounding topography. BFL, Bullfrog Basin (BUL), and Cameron (CAM) exhibit this pattern. Second, ridgetop sites exposed to varying synoptic-scale winds have low persistence at all times of the day. Desert View (DSV) and Hopi Point (HOP) are good examples. Third, midelevation sites on open slopes that drain consistently during nighttime, but become coupled to the variable synoptic flows during daytime when unstable boundary layers grow upward from the heated ground, have high persistence during nighttime but low persistence during daytime. All three sites in the Basin and Range Province [Ash Fork (ASH), FDN, and MVW] exhibit this behavior. Fourth, sites in stagnant cold air pools that form behind valley constrictions experience light and variable winds during nighttime. During daytime, winds become more persistent as air flows out of the pools in an up-valley direction. DNG and Mexican Hat (MEX) exhibit this behavior. Fifth, sites that are in shadow on north-facing slopes during winter have persistent downslope winds all day. Indian Gardens (ING) is an example, although persistence decreases somewhat at this site during midday when the sun makes a brief appearance. The low-persistence values are spread broadly over the midday period because the time of wind reversal varies with cloudiness, and the coupling of the surface winds with winds in the near-neutral Grand Canyon atmosphere (Whiteman et al. 1999a) is somewhat variable in time depending on

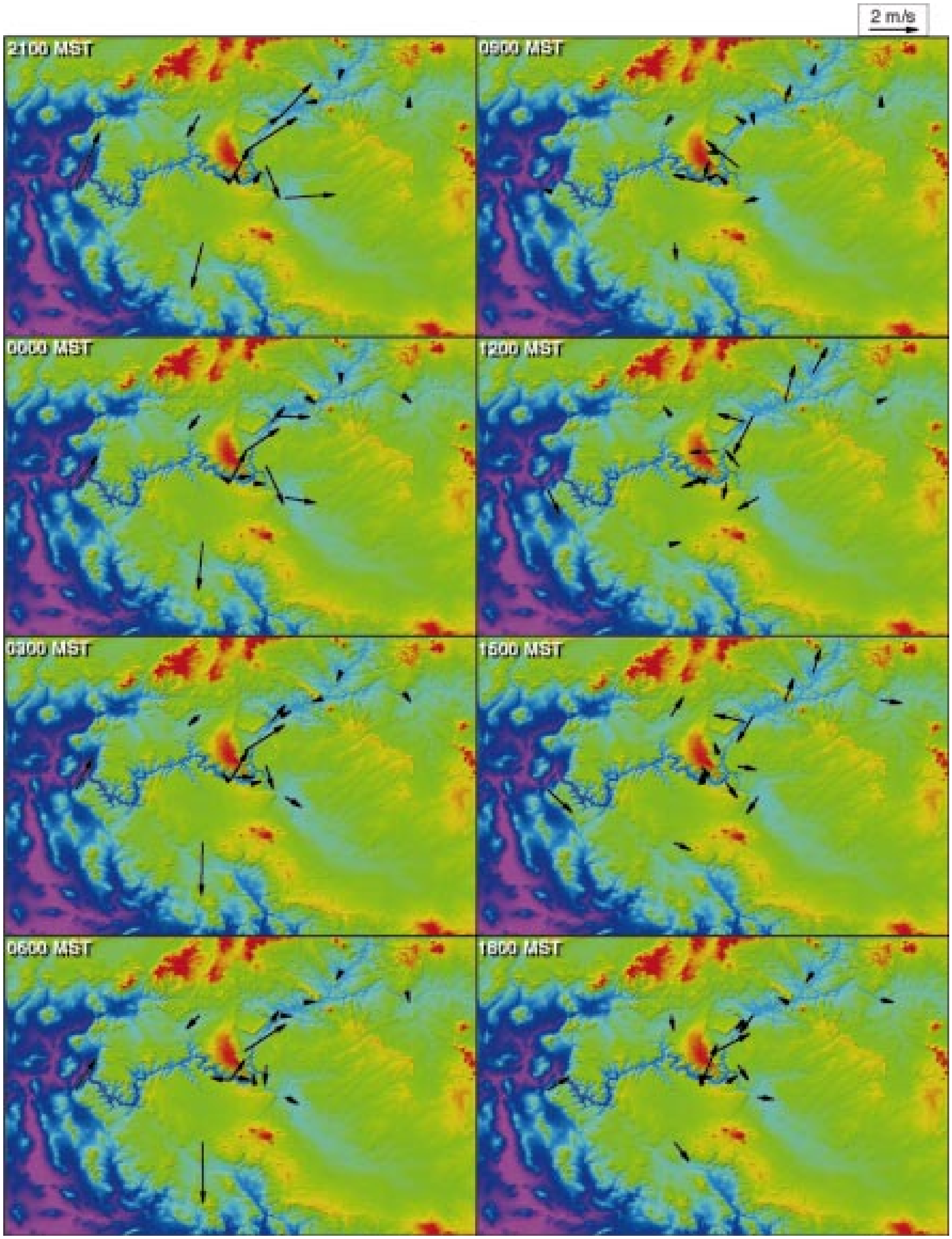

FIG. 3. Fair weather wind directions and speeds at the times (MST) indicated. The stations are located at the origins of the vectors. Vector orientation indicates wind direction, and vector length indicates wind speed in m s^{-1}, using the scale shown.

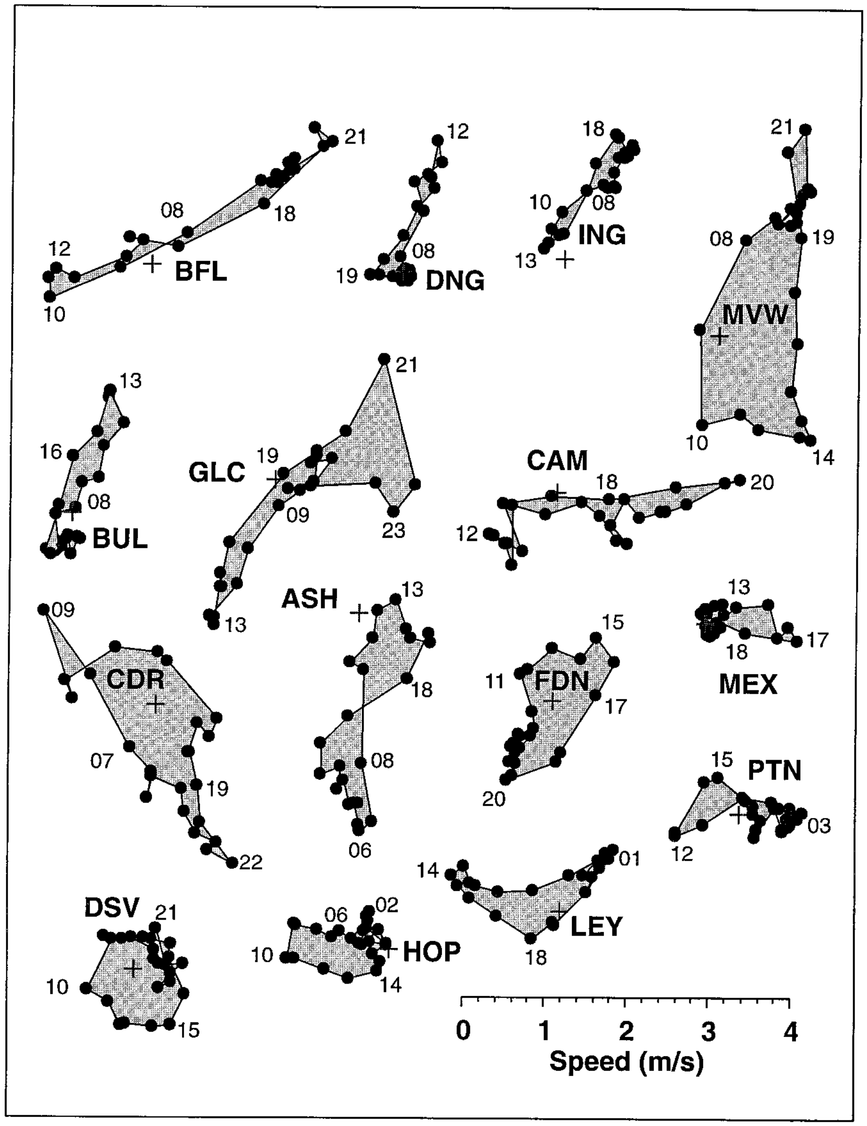

FIG. 4. Fair weather vector diagrams for the WVS stations. The origins of the individual vector diagrams are indicated by crosses, the dots indicate the hourly wind values, and the numbers give the time of day in hours MST.

the strength of the winds in the canyon. The sixth diurnal persistence pattern is a miscellaneous category in which persistence variations are not closely coupled to sunrise and sunset times. These persistency patterns are produced by a number of different mechanisms that will be discussed for the individual sites in the next section. Glen Canyon (GLC) experiences low persistence from midnight to sunrise, but high persistence during the day and in the evening hours. Lee's Ferry (LEY) has low persistence in the evening hours, and PTN has low persistence during the daytime and evening hours. Cedar Ridge (CDR) has high-persistence values in the middle of the night, but otherwise sees a broad minimum in persistence centered in the midafternoon.

b. Patterns of mean resultant vector winds

The time evolution of winds (Fig. 3) in the experimental area will be summarized for three groups of wind stations—stations in the Basin and Range Province, stations within and on the ridges above the Grand Canyon, and stations within the CPB along the Colorado River and its tributaries.

1) BASIN AND RANGE PROVINCE

MVW is southwest of the western end of the Grand Canyon, on a northeast-facing hillside above Lake Mead. During nighttime, south-southwesterly down-

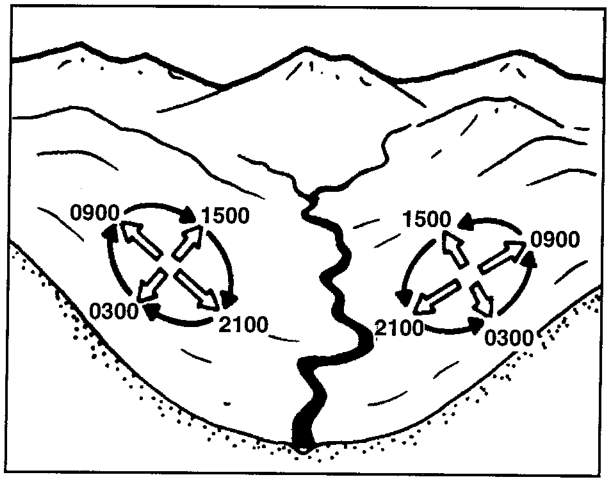

FIG. 5. Thermally driven winds turn clockwise with time on the left sidewall of a valley (looking up valley), while turning counterclockwise with time on the opposing sidewall. Adapted from Hawkes (1947).

slope winds drain off this hillside into Lake Mead. Drainage flows are initially strong but decrease in strength through the night. The winds die after sunrise, and then reverse to upslope (to NW winds) and strengthen during the day. They shift in a counterclockwise direction in the late afternoon to reattain their nighttime SSW direction.

ASH is on an open south-facing slope west of the San Francisco Peaks. Northerly downslope winds persist here throughout the night as cold air drains off the higher elevations to the north. During daytime, the drainage flows decrease, reversing briefly in midday, and turning in the direction of nearby heated terrain (San Francisco Mountains) during the afternoon.

FDN is at the upper end of the Kanab Creek drainage on the west side of the Kaibab Plateau. During nighttime, weak NE winds drain into Kanab Creek. These winds decrease slightly in strength during the night. Winds change to upslope and up valley during midday as the south-facing slope to its north is heated by the sun.

2) THE GRAND CANYON

DSV and HOP are scenic overlooks on the south rim of the Grand Canyon. Thermally driven winds are weak at these ridgetop sites during both nighttime and daytime, as they have no drainage area above them and are well exposed to the prevailing synoptic flows above the canyon. The persistence of the winds is low, indicating that the resultant fair weather day vector wind speed is much smaller than the arithmetic average speed and that wind directions are quite variable from day to day at these sites.

ING is located within the Grand Canyon. It is nearly 1000 m below Hopi Point in the Garden Creek drainage that flows north-northeastward into the Colorado River just west of Phantom Ranch. Because ING is in the shadow of the south rim during most of the day, the rather strong nighttime SSW drainage flows persist nearly all day at this site, reversing only briefly (and weakly) when the site is in direct sunlight.

PTN is located on the north side of the Colorado River where the Bright Angel Canyon enters the Grand Canyon from the northeast. The sensitive anemometer at this site was exposed 3 m above the ground, but winds were generally variable in direction and very weak at this site. There was, nonetheless, a tendency for the winds to blow down the Colorado River during daytime and up the river during nighttime. Surprisingly, there seemed to be little wind influence from the Bright Angel Canyon, as winds were only infrequently from northeast or southwest. The relatively high persistence of up-valley winds at this site during the midnight to sunrise period was noted in Fig. 2, but its explanation is not yet clear.

3) THE COLORADO RIVER AND ITS TRIBUTARIES

The remaining sites are located along the Colorado River and its tributaries. Wind data will be described for sites in the Little Colorado drainage, in the San Juan drainage, and in the main Colorado River drainage.

(i) The Little Colorado River drainage

The CAM and CDR sites are located in the Little Colorado Valley, which enters the east end of the Grand Canyon from the southeast. The lower end of the valley is in the form of a broad basin that is drained by a narrow canyon. CAM is at a low elevation on the western edge of the basin, and nighttime winds here drain from the W or WNW into the basin. The drainage winds decrease very significantly in strength during the night and reverse during daytime.

CDR is located at a relatively high elevation on the southeast side of a drainage divide that separates the Little Colorado Valley from Marble Canyon. During nighttime, winds flow from the NNW off this drainage divide into the Little Colorado watershed. Wind speeds are moderately strong in the early evening, but decrease through the night. In the morning, when sunlight heats the southeast-facing slope at Cedar Ridge, the winds shift to upslope, reversing once again to downslope by 1500 MST. Winds are variable at this site during much of the day, although persistent northwesterly flows occur at midnight as air flows over the drainage divide into the Little Colorado Valley. The lack of persistence (Fig. 2) during much of the rest of the day appears to be caused by a sensitivity of the flow direction to synoptic-scale pressure gradient influences.

(ii) The San Juan River drainage

MEX is located in a small basin on the San Juan River (rather like the basin in the Little Colorado Valley) that is up valley from a narrow tortuous canyon. At night, a stagnant cold air pool builds up behind the constricted canyon. During the afternoon an up-valley flow removes air from this pool.

(iii) The Colorado River drainage

BUL is the northernmost site in the experimental area and is located in a subbasin on the Colorado River. It experiences weak down-valley winds at night and stronger up-valley winds during daytime.

DNG is located on the north bank of the Colorado River in the Lake Powell Basin south of the Kaipairowits Plateau. The station is located a few hundreds of meters south of the foot of a south-facing cliff nearly 1000 m tall. Winds at this site are calm at night and blow up the Colorado Valley during daytime.

The wind directions at BUL and DNG, as at all the other sites discussed to this point, are in accordance with valley wind theory (Wagner 1938), exhibiting downslope or down-valley winds during nighttime (or, for sites that are in shadow, during periods with negative radiation balances) and upslope or up-valley winds during daytime when positive radiation balances are expected. The remaining sites along the Colorado River are part of a distinctive diurnal thermally driven regional wind system, in which up-valley winds occur during nighttime and down-valley winds occur during daytime, in contradiction to the expectations of valley wind theory. Daytime and nighttime wind directions at individual sites in this area are steady and the wind patterns exhibit an overall spatial coherence among the different sites.

BFL is located near the eastern foot of the Kaibab Plateau at the edge of Marble Canyon, a deep (nearly 700 m deep near the site), narrow canyon cut by the Colorado River into the Marble Platform—the distinctive triangular block of tilted strata separating the Kaibab, Paria, and Kaibito Plateaus. The Marble Platform tilts downward to the NE, while the Colorado River flows across it from NE to SW (Fig. 6). The slope of the river is thus in direct opposition to the slope of the platform (explaining why the Marble Canyon deepens so rapidly as the Colorado River flows across the platform). The strong SW nighttime winds at Buffalo Ranch blow down the local slope of the Kaibab Plateau in a direction that corresponds to an up-valley direction in the Colorado Valley. These winds continue all night with little decrease in speed. During daytime, the winds blow up the local slope of the Kaibab Plateau in a direction that corresponds to a down-valley direction in the Colorado Valley.

LEY is located at the bottom of the canyon where the Colorado River emerges from Glen Canyon and begins to flow southwestward across the Marble Platform. A cold air pool builds up over LEY in the evening as air flows northeastward off the Marble Platform and Kaibab Plateau. As the pool fills, the flow becomes light and variable, exhibiting low persistence (Fig. 2). Once the pool fills sufficiently to overtop the Glen Canyon, weak southwesterly up-valley winds are initiated at LEY, blowing up valley toward the Lake Powell Basin (considered to extend from the Glen Canyon dam to the Kaipairowits Plateau) and increasing in speed and persistence during the night. During the day the winds shift to an easterly or southeasterly direction, blowing toward the nearby heated cliffs of the Paria Plateau and up the Paria River. Winds at LEY, located on the right bank of the Colorado River, are expected to turn clockwise with time but, in fact, turn counterclockwise.

GLC is within the Lake Powell Basin and is located on a hillside above the lake close to the Glen Canyon dam. Winds here blow downslope into the Lake Powell Basin during nighttime and upslope out of the basin during daytime. The nighttime flow off the Paria Plateau, which is initially strong from the SW, shifts to the west, weakens and becomes more variable (Fig. 2) after midnight as the Lake Powell Basin fills with cold air. The daytime flow is from the NE, carrying air from the Lake Powell Basin down the Colorado River Valley, but with a slight component up the side of the heated Kaibito Plateau.

c. Vector diagrams

Several features of wind direction and speed evolution are seen during composite fair weather days at individual sites (Fig. 4). Many sites exhibit clockwise (FDN, GLC, and CDR) or counterclockwise (MVW, DSV, HOP, and LEY) turning of wind direction with time. In fact, FDN and GLC are located on the right sidewalls of their respective valleys, and MVW is located on a left sidewall, thus following the general rule illustrated in Fig. 5. Exceptions to the rule abound, however, in the extreme complexity of the WVS terrain, where along-valley flows are unusually weak. The CDR site follows the rule, if we consider it to be on the right sidewall of a minor tributary north of the Colorado–Little Colorado confluence that flows into the Grand Canyon from the east. The counterclockwise turning of winds at LEY, on the other hand, is probably related to the daytime solar heating of cliffs to the west and, later, east of the site on the edges of the Paria and Kaibito Plateaus. At the HOP and DSV ridgetop sites on the Grand Canyon's south rim, the turning is primarily a weak daytime phenomenon caused by the differing directions of upslope flows produced on the ridgetops as the sun illuminates first the southeast-facing slopes and, later, the southwest-facing slopes of the Coconino Plateau below the sites. Thus, the turning of winds with time in the complex terrain of the WVS study area is not as good an indicator of the station's sidewall location as expected from previous studies on the sidewalls of simpler valleys [e.g., Colorado's Brush Creek Valley, as reported by Whiteman et al. (1989)].

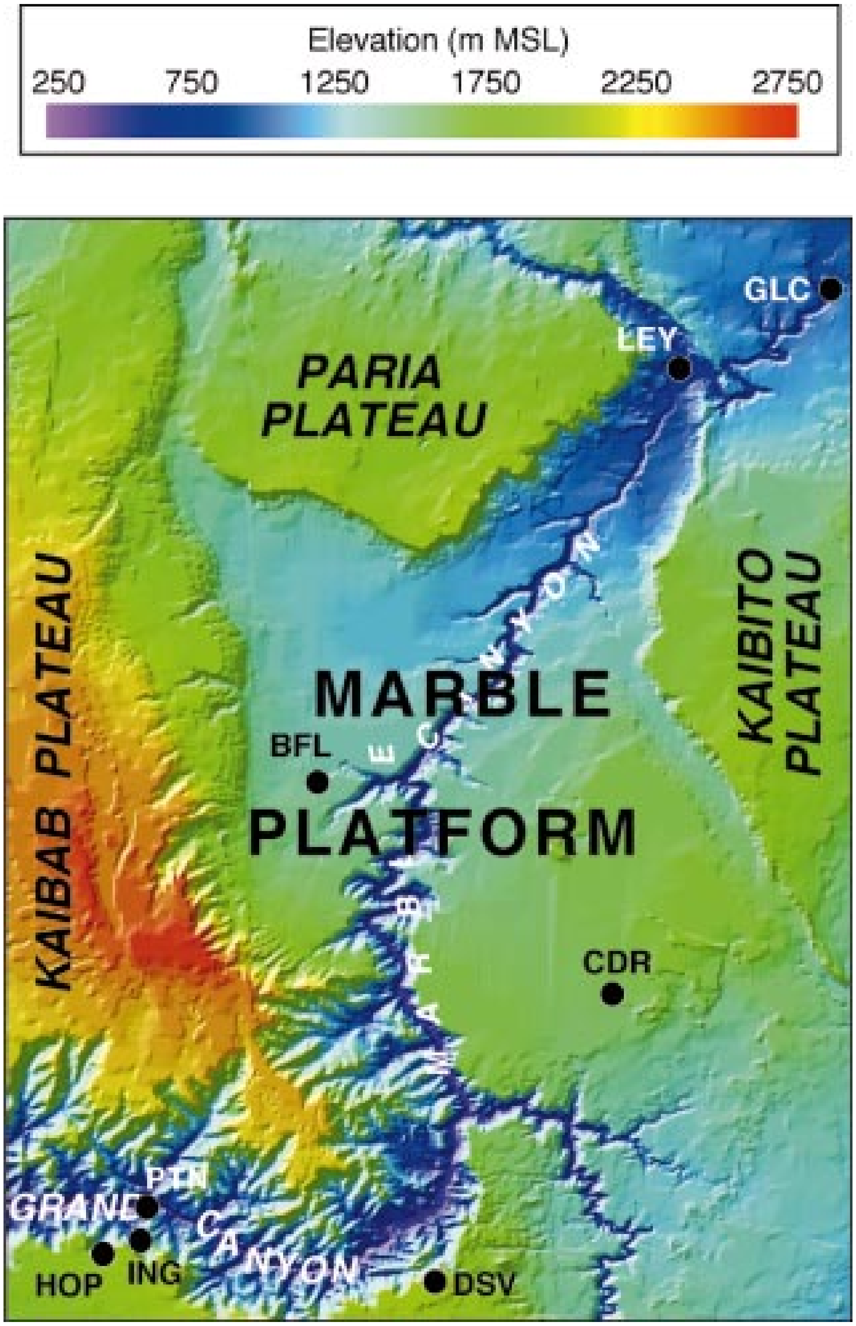

FIG. 6. Shaded relief digital elevation model of the Marble Platform area.

5. Discussion

One surprising feature of the wintertime wind patterns in the experimental area is the general weakness of the thermally driven winds. The vector-average winds are less than 1 m s^{-1} at many of the sites. Further, the winds that are blowing in along-slope directions are somewhat stronger than winds blowing in along-valley directions. The weakness of the along-valley winds is caused by the formation of deep temperature inversions within the confined Colorado Plateaus Basin that are not destroyed diurnally and can persist for many days (Whiteman et al. 1999b). The slope of the basin floor is slight (and nonexistent above the surface of Lake Powell) and the isentropes tend to become horizontal within the pooled air mass in the CPB, reducing the horizontal temperature and pressure differences that are necessary to produce along-valley flows. On the floor of the basin, temperature differences can form between subbasins, but the narrow and tortuous canyons that connect the subbasins in the Grand Canyon region restrict the interbasin flows and cause stagnant cold air pools to form within the basins. The horizontal floor of the Colorado Valley, represented by the level surface of Lake Powell (1128 m MSL) extending more than 200 km to the northeast of the Glen Canyon dam, cannot, by itself, explain the weak along-valley winds since along-valley winds can be produced even in valleys with horizontal floors if different rates of cooling or warming are experienced along the valley's axis due either to along-valley variations in the surface energy budget or along-valley differences in cross-valley geometry (Steinacker 1984; McKee and O'Neal 1989; Whiteman 1990).

Slope flows are produced when cold or warm air layers form above sloping surfaces and buoyancy forces cause the air to be carried up or down the slope (Vergeiner and Dreiseitl 1987). The loss or gain of net allwave radiation on the slope and its conversion to sensible heat flux are key determinants of the flow strength. In the experimental area, the strongest thermally driven winds are slope flows that form on the sides of snow-covered plateaus. In the lower elevations of the CPB, downslope flows are initially strong in the late afternoon or early evening, but decrease in flow strength through the night as static stability increases within the subbasin topography. This nighttime decrease in downslope flow speed is much less apparent at the higher elevation sites.

The regional-scale flow in the Colorado Valley that produces up-valley winds during nighttime and down-valley winds during daytime at some of the sites [section 4b(3)iii] was first observed in analyses of long-term data from the Glen Canyon site by Balling and Sutherland (1988). They suggested that the winds might be a lake breeze associated with Lake Powell or might represent the upper return flow of an along-valley wind system carried at lower elevations in Glen Canyon. Sutherland and Ostapuk (1989), using a month of supplementary wintertime wind data from a site located at lake level, were able to reject the return flow hypothesis, but there were too few data to draw firm conclusions concerning the lake breeze concept. The additional data from the WVS experiment show that anomalous winds occur not only at Glen Canyon, but also at LEY and BFL. From a regional perspective, the Colorado Valley has a series of terrain constrictions and narrow canyons that separate the valley into a chain of topographical subbasins. The winds appear to be part of a wind pattern in which drainage flows converge into the shallow subbasins from all directions during nighttime and diverge out of the subbasin centers during daytime. Wind stations on the down-valley sides of the subbasin centers will therefore exhibit drainage winds that flow toward the subbasin center (i.e., up valley) during nighttime and upslope winds that flow away from the subbasin center (i.e., down valley) during daytime. This explanation for winds blowing in apparent violation of valley wind theory was suggested previously by Munn (1966).

The part of this regional flow between the Grand Canyon and the Lake Powell Basin is especially interesting, as the winds here have a somewhat different, but related, explanation. Nighttime downslope winds are strong on the sidewalls of the snow-covered Kaibab Plateau. These downslope winds flow northeastward across the sloping Marble Platform. The plane surface of this platform slopes downward to the northeast—exactly opposite to the direction of the Colorado River, which flows southwestward across it, incising the deep Marble Canyon. Cold air draining northeastward down the slope of the Marble Platform builds up over Lee's Ferry on the northeast edge of the platform during nighttime. Once it attains a sufficient depth (about 150 m), it can flow through the Glen Canyon and over the Glen Canyon dam into the Lake Powell basin. Winds reverse during daytime to flow in directions that are generally down the Colorado River. Thus, the airflow on the Marble Platform is downslope during nighttime and upslope during daytime, but these directions are counter to the along-valley flows expected solely from a knowledge of the river flow direction.

In section 4, a detailed description of wind characteristics was given for individual WVS sites. Here, we synthesize the data from all sites to describe the wintertime thermally driven wind characteristics of the region as a whole. These wind characteristics are as follows.

- Near-surface flows within the experimental area are, by and large, directed downslope at night (MVW, ASH, ING, and BFL). In well-defined valleys, however, these flows can be turned in the direction of the down-valley wind component (FDN and, to some extent, stations from LEY to BUL). The daytime flows are generally upslope (BFL) and/or up valley (DNG and BUL) but may be turned toward nearby strongly heated land surfaces. This daytime turning of the wind toward nearby heated terrain (LEY and MVW) can sometimes be recognized when angular separations less than 180° are seen between the main day–night lobes of vector diagrams (Fig. 4). These angular separations, however, can also be produced at sites located on valley bends.
- Flow directions are quite steady during the long winter nights (ASH, BFL, and ING). Downslope flows are strongest at midelevations on long uninterrupted slopes draining high plateaus (ASH and MVW) where the ambient atmosphere has lower static stability than at lower elevations. These downslope flows can be especially strong when the plateaus are covered with snow (BFL). Wind speeds decrease during the night at low elevation sites (CAM and GLC) as ambient stability increases within the lowest-lying terrain. Sites at higher elevations (HOP, DSV, and ING) see little change in ambient stability and so continue to drain at a steady speed.
- Day-to-day variability in fair weather winds is generally highest during the morning and evening tran-

sition periods and during daytime. Sites located on the floors of subbasins behind constricted canyons (DNG, BUL, and MEX), where cold air pools build up at nighttime, experience their highest wind variability or lowest wind persistence at night when speeds are very low; up-valley or upslope flows remove air from these pools during daytime.

- Thermally driven flows are weak on ridges and mountaintops (HOP and DSV). The small amount of land surface area at these altitudes is inefficient in heating or cooling the air at these heights, and the effects of large-scale horizontal advection and mixing decrease the horizontal temperature contrasts that produce thermally driven circulations. The high-elevation sites are, nonetheless, well exposed to synoptic-scale flows and have generally high wind speeds, even though thermally driven flow components are low.
- Sites in the shadows cast by higher topography may continue to drain downslope during both night and day (ING).

6. Conclusions

Wintertime thermally driven wind systems were investigated for the Grand Canyon region using hourly wind data from a network of short towers distributed over a range of elevations and land form types within the region. The dataset provided a unique opportunity to investigate wintertime thermally driven wind systems in this isolated, data-sparse region. About 22% of the mid-December to early April period was made up of fair weather days that were undisturbed by strong upper-level winds or cloudy conditions. Vector averages were used to composite hourly data from these fair weather periods to obtain hourly wind vectors for a representative clear-sky, weak-upper-wind mean day at each station. Wind persistence computations proved useful in understanding wind mechanisms at individual sites.

On fair weather days, thermally driven winds were apparent at all of the sites. Winds were generally upslope and up valley during daytime, and downslope and down valley during nighttime, as expected from theory. A persistent wintertime temperature inversion appears to be responsible for the weakness of along-valley flows within the Colorado Plateaus Basin, a large basin up valley from the Grand Canyon. The along-valley flows are also weak there because of the blocking of airflow by narrow and tortuous canyons that connect the subbasins.

Unusual winds blowing up valley during nighttime and down valley during daytime were encountered at several sites along the Colorado Valley upstream from the Grand Canyon. These winds appear to represent a low-level convergence of cold air into the subbasins from the surrounding topography during nighttime and the divergence of warmed air from the center of the basins during daytime. Unusual winds in the Marble Canyon area are explained by the downward slope of the Marble Platform to the northeast, in a direction opposite to the flow of the Colorado River. Air draining off the Kaibab Plateau at night appears to form a cold pool in the Marble Canyon basin, which then pours over Glen Canyon into the Lake Powell Basin. During daytime, winds reverse and flow out of the Lake Powell Basin in all directions, including a flow to the southwest over Glen Canyon, up the Marble Platform and up the Kaibab Plateau.

Interesting wind behavior peculiarities were found at individual sites. A site on the north-facing sidewall inside the Grand Canyon was shaded by the canyon's south rim. Downslope winds persisted here during both day and night. Other sites experienced winds that turned toward nearby heated terrain features during daytime when solar radiation was most intense. Sites located in shallow subbasins along the Colorado River and on tributaries to the Colorado River experienced nighttime stagnations. Well-exposed ridgetop sites on the Grand Canyon's south rim experienced weak thermally driven circulations and responded primarily to the larger-scale prevailing winds. The strongest thermally driven flows in this area of complicated topography were found at midelevations on the basin sidewalls, where nighttime downslope flows were fed by air cooled over the wintertime snowpack on the plateau tops. High-elevation valleys experienced the best along-valley wind systems.

Analyses of near-surface wind observations are the focus of this paper. These winds occur within inclined stable and convective boundary layers that form and grow over the floor and sidewalls of the CPB and the surrounding study areas. An accompanying paper (Whiteman et al. 1999b) discusses the evolution of the vertical wind and temperature structure in the CPB, providing further information on the depths of convective and stable boundary layers and the winds within them, using data from upper-air soundings.

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