A CLIMATOLOGICAL STUDY OF THERMALLY DRIVEN WIND SYSTEMS OF THE U.S. INTERMOUNTAIN WEST

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Thermally driven wind systems in four regions of the Intermountain Basin are illustrated using analyses of meteorological data from the MesoWest network.

The complex topography of the western United States produces a variety of thermally and dynamically driven wind systems. Historically, the knowledge and understanding of these systems has been limited by a number of factors, including a lack of observational data. In the Intermountain West (IW, Fig. 1), the elevated semiarid area between the Cascade–Sierra and eastern Rocky Mountains, dry air, dry soil, and limited cloud cover promote intense diurnal fluctuations in sensible heat flux, a large diurnal range in air temperature, and strong thermally driven winds (Carter and Keislar 2000). Thermally driven wind systems in the mountainous IW consist of three major wind circulations: plain–mountain winds, valley winds, and slope winds. The different phasing and superposition of the valley and slope wind systems produces clockwise and counterclockwise diurnal rotations on the right and left banks (or sidewalls) of a valley, respectively, when facing down valley (Hawkes 1947; Whiteman 1990). In some regions of the IW, such as the Wasatch Front valleys (WFV) of northern Utah (Fig. 2a), mountains are located adjacent to lakes, and a fourth diurnal wind system is apparent: the lake–land breeze. The interaction of these four wind systems creates complex flow patterns that are a part of the everyday winds in complex terrain.

Over the past few years, high-density data from more than 70 independent meteorological networks have been gathered as part of MesoWest, a collection of cooperative mesonets in the western United States (see Horel et al. 2002). In this paper, we will use MesoWest data from 1997 to 2000 to illustrate the diurnal evolution of thermally driven winds in the IW.

AREAS OF STUDY. Four study regions were selected for investigation because they have high-density observations and illustrate typical thermally driven wind systems of the IW (Fig. 1). Here we introduce those regions, in turn, going counterclockwise around the IW.

The Salt Lake, Tooele, and Rush Valleys, designated here as the WFV (Fig. 2a) are bounded by three

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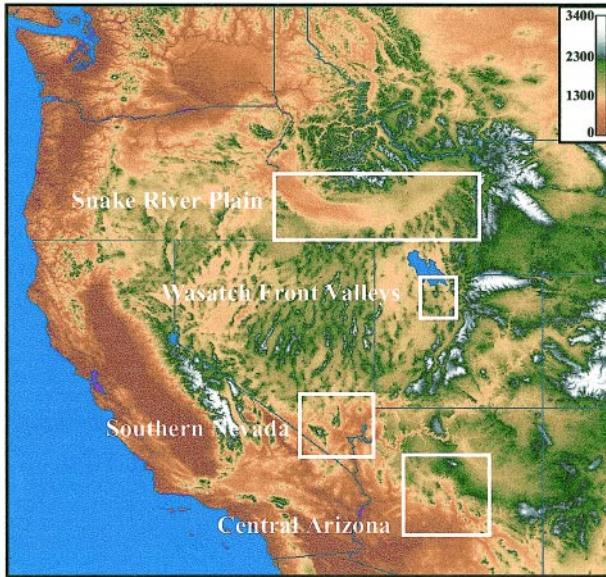E-mail: jstewart@fsl.noaa.gov

FIG. 1. Topography of the western United States with study regions annotated. Elevation (m) based on scale at upper right. State boundaries are purple; lakes and rivers are blue.

north–south mountain ranges that extend more than 3000 m above mean sea level (MSL): the Wasatch, Oquirrh, and Stansbury Mountains.[1] The Salt Lake Valley is a broad valley containing the extensive Salt Lake City urban area. This valley, bounded to the east by the Wasatch Mountains and to the west by the Oquirrh Mountains, drains northward into the Great Salt Lake (GSL, 1280 m). Several major canyons issue into the Salt Lake Valley from the Wasatch Mountains. The Salt Lake Valley is bounded to the south by the Traverse Mountains, a transverse mountain range that extends between the Wasatch and Oquirrh Mountains. A narrow gap exists in the Traverse Mountains where the Jordan River flows northward from Utah Val-

ley. The Tooele and Rush Valleys are bounded by the Oquirrh Mountains on the east, the Stansbury Mountains on the west, and the Tintic and Sheep Rock Mountains on the south. The broad Tooele Valley gradually slopes downward from the Stansbury and Oquirrh Mountains and to the north toward the GSL. It is bounded to the south by a transverse mountain range called South Mountain. The so-called Rush Valley is actually a basin with a minimum elevation of 1560 m located just south of the Tooele Valley. Passes between the Tooele and Rush Valleys are located on the east and west sides of South Mountain, and several low passes exist between the Rush Valley and the Utah Valley to the southeast. The region is semiarid, with vegetation at low elevations consisting mainly of grasses and low shrubs (mainly sagebrush). The GSL, with an average depth of only 4.8 m, exhibits little seasonal temperature lag relative to the mean daily air temperatures in the lake's surroundings (Steenburgh et al. 2000).

The Snake River Plain (SRP) is a broad, flat-floored, arc-shaped valley in southern Idaho that slopes downward to the west from 1500 to 900 m (Fig. 2b). The valley is bounded to the north by the central Idaho Mountains, which reach elevations above 3000 m, and to the south by several mountain ranges that reach elevations of around 2100 m. Major canyons issue onto the SRP from the surrounding
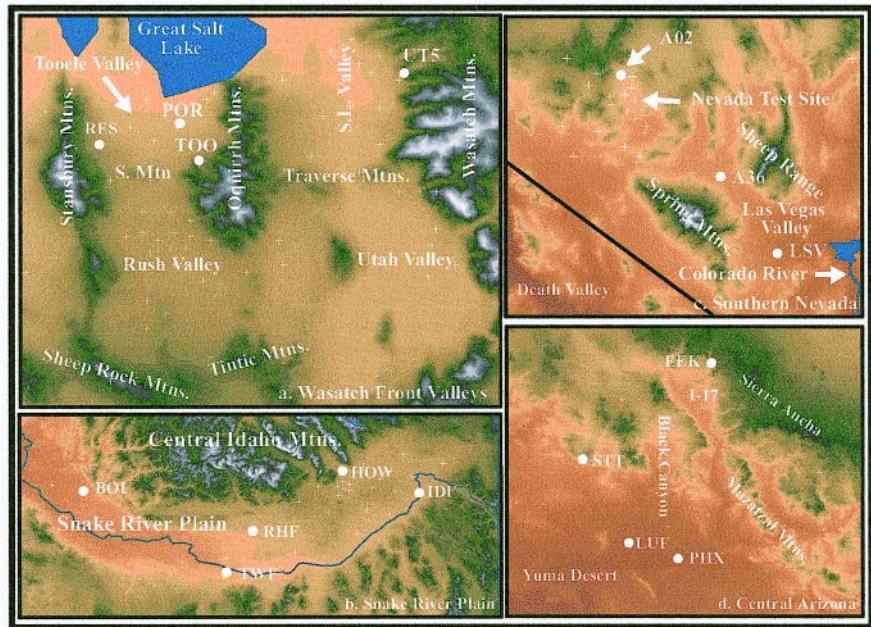

FIG. 2. Place names and wind station locations for each study region. Terrain shading and color scheme as in Fig. 1. (a) Wasatch Front valleys, (b) Snake River Plain, (c) southern Nevada basin and range province, and (d) central Arizona. The dots represent stations that are referenced by their three-letter identifiers in the text; pluses are used for the other stations.

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[1]Unless otherwise indicated, all elevations specified in the remainder of this paper are relative to mean sea level.

mountains, with three especially prominent canyons entering the east end of the SRP from the central Idaho Mountains. The SRP is arid or semiarid with vegetation consisting of short grasses and shrubs (mainly sagebrush) at the lower elevations and low-density coniferous forests at higher elevations.

The southern Nevada landscape is part of the basin and range province, a geomorphological province characterized by many narrow mountain ranges that are oriented approximately north–south, reach elevations around 3000 m, and are separated by broad alluvial basins (Fig. 2c). The lowest elevations in the southern Nevada region are to the southwest, in California's Death Valley (-86 m), and to the southeast, along the Colorado River (360 m). The Las Vegas Valley extends northward and westward from Las Vegas (LSV) and separates the high-elevation Spring Mountains from the Sheep Range. The climate is semiarid except on the highest mountain ranges. Vegetation is sparse, with short grasses and shrubs at mid-elevations and low-density forests at the highest elevations. Barren ground and arid vegetation are found at lower elevations.

The central Arizona region lies to the west of the Sierra Ancha (Fig. 2d). The general terrain slopes from the Sierra Ancha (1900 m) southwestward to the Yuma Desert (200 m). The Mazatzal Mountains are a 1500-m barrier between the Sierra Ancha and Phoenix (PHX). From the Sierra Ancha and surrounding mountain ranges, several canyons issue into the lower Phoenix basin, including the Black Canyon north of Phoenix through which Interstate 17 runs. Central Arizona is arid, with intense solar heating throughout much of the summer. Only sparse vegetation survives the lack of precipitation, leaving large areas of barren ground. Low shrubs and grasses survive at midelevations, and low-density coniferous forests are found at the highest elevations.

DATA AND METHODS. Surface observations were provided by MesoWest, a collection of independently operated mesonets across the western United States (see Horel et al. 2002). Managed jointly by the National Oceanic and Atmospheric Administration (NOAA) Cooperative Institute for Regional Prediction at the University of Utah and the Salt Lake City National Weather Service Forecast Office, MesoWest provides high-density observations in regions that are not well sampled by the conventional Federal Aviation Administration/National Weather Service/Department of Defense network. Data are collected via phone modems, Internet connections, or radio transmissions and archived at the University of Utah,

Site	Lat (°N)	Lon (°W)	Average sunrise time	Average sunset time
Wasatch Front Valleys	40.600	112.000	0520 MST	1943 MST
Central Arizona (Phoenix Encanto)	33.479	112.096	0537 MST	1927 MST
Snake River Plain	43.000	113.000	0517 MST	1953 MST
Southern Nevada	36.000	115.000	0443 PST	1844 PST

TABLE 1. Mean times of sunrise and sunset during the three month (Jun–Jul–Aug) summer period. The Wasatch Front Valleys, Central Arizona, and Snake River Plain regions observe mountain standard time (MST) in summer; the Southern Nevada region observes Pacific standard time (PST).

where an automated quality control process removes erroneous values.

The following steps were implemented to identify thermally driven circulations in the four study regions. First, data for the summer months of June, July, and August were extracted from the MesoWest archive for the years 1997–2000. Summer was chosen because large-scale flows during this season are usually weak, frequently allowing thermally driven flows to dominate local circulation patterns. Then, fair weather periods having weak winds aloft and clear to partly cloudy skies were identified in 12-h blocks [1700–0400 UTC (1000–2100 MST) and 0500–1600 UTC (2200–0900 MST)] centered on rawinsonde observation times [typical rawinsonde release times are 2300 UTC (1600 MST) and 1100 UTC (0500 MST), respectively]. In the 12-h blocks, winds aloft were considered to be weak if the observed 700-hPa wind speed was 7 m s^{-1}. Following Whiteman et al. (1999), skies were considered clear to partly cloudy for the two 12-h blocks of a day if the observed total daily solar radiation was 65% of the theoretical extraterrestrial solar radiation for that day as computed by a solar model (Whiteman and Allwine 1986). The mean times of sunrise and sun-

TABLE 2. Solar radiation and 700-hPa wind observation sites.		
Region	Solar observation site [lat (°N), lon (°W), altitude (m MSL)]	700-hPa wind observation site [lat (°N), lon (°W), altitude (m MSL)]
Wasatch Front valleys	William Browning Building WBB (40.77, 111.85, 1497)	Salt Lake City SLC (40.78, 111.97, 1288)
Central Arizona	Phoenix Encanto AZM15 (33.48, 112.10, 335)	Tucson TUS (32.12, 110.93, 779)
Snake River Plain	Grid III RID (43.59, 112.94, 1476	Boise BOI) (43.57, 116.22, 874)
Southern Nevada	Mohave AZM20 (34.97, 114.61, 146)	Desert Rock DRA (36.62, 116.02, 1009)

from all directions, or blew half the time from one direction and half the time from the opposite, the consistency was 0. This definition of wind consistency is similar to Panofsky and Brier's (1965) definition of wind *persistence,* the steadiness of the wind over a continuous time period. We prefer the term wind consistency because we deal with a discontinuous dataset (only fair weather days and observations at a given hour of the day).

RESULTS. *Wasatch Front valleys.* The WFV region is located south of the GSL where Hawkes (1947), Smidy (1972), Astling (1986), and Stone and Hoard (1990a,b) investigated the interactions between the diurnal land–lake and mountain wind systems. These previous studies did not, however, attempt to isolate the thermally driven component of the flow by considering only situations with clear skies and weak synoptic-scale forcing.

set in the four study regions during the summer period were also determined from the solar model, and are shown in Table 1. Three of the four regions observed mountain standard time (MST), while the Southern Nevada region observed Pacific standard time (PST). Times in the analyses are given in local standard time (LST). Rawinsonde and solar radiation observing sites used for each study region are listed in Table 2. After identifying all 12-h periods in the period of record that met both criteria, subhourly averaged data (e.g., 5 , 15, or 30 min) during the 12-h periods were averaged over 1-h intervals, with the indicated time being the end of the 1-h averaging period.

Hourly observations meeting the above criteria were then composited to determine a mean vector wind and mean arithmetic wind speed for each of the 24 h of a fair weather day. Only stations with 50 or more observations for each hour of the day were used in the analysis. The mean vector winds were then plotted on maps and a video loop was prepared to investigate the diurnal evolution of winds in each region. Although not presented in this manuscript, wind roses were also calculated. The video loops and wind roses can be viewed online at www.met.utah.edu/jimsteen/jstewart/mtnwind.html.

To determine the fair-weather-day to fair-weather-day variance of wind direction for each hour of the day, we defined *wind consistency* as the ratio of the vector mean and arithmetic mean wind speeds for each hour of the day. If the wind was from the same direction at a given hour on all fair weather days, the consistency was 1; if it was equally likely

Winds in the WFV are the result of lake–land breezes, slope flows, and valley flows. During the night (0400 LST, Fig. 3a), downslope and down-valley winds are observed in the Salt Lake and Tooele Valleys. The down-valley winds are reinforced by off-shore flow induced by the GSL. Weaker down-valley winds (1–3 m s^{-1}) are found in the Tooele Valley over the low-angle slopes near the GSL, whereas stronger (3–4 m s^{-1}) down-valley winds are found over the steeper slopes near South Mountain. In the Rush Valley, an elevated basin with few low gaps for winds to exit, the slope of the land is gentle over the basin except over the slopes of the surrounding mountains. Light (~1 m s^{-1}) downslope winds converge over lower portions of the valley. At higher-elevation sites, stronger downslope winds (1.5–4 m s^{-1}) are found. Along the South Mountain divide, 4–5 m s^{-1} southerly winds illustrate the nocturnal flow of air across the divide from the Rush Valley to the Tooele Valley; the southwest wind observed near the summit of the Traverse Mountains in the Salt Lake Valley illustrates a similar flow pattern between the Utah and Salt Lake Valleys (small-scale terrain effects result in southwesterly rather than southerly flow at this site). These conditions persist until the morning transition period.

The morning transition period starts at sunrise (~0520 LST) and continues through about 1100 LST. During this period, downslope and down-valley winds weaken and shift to upslope and up-valley, with the slope flow transition preceding the valley flow transition by about 2 h. By 1000 LST (Fig. 3b), roughly the midpoint of the morning transition period, many observing stations develop an upslope wind component or are experiencing weakening downslope winds, and the GSL breeze is beginning to move southward into the Tooele Valley. The leading edge of the GSL breeze is first observed near the GSL shoreline at 0700 LST and advances southward through the Tooele Valley to South Mountain by 1100 LST (not shown). The southward lake-breeze penetration is slower over the Salt Lake Valley (Fig. 3b).

During the afternoon regime, circulations within the WFV are the result of interactions between upslope flows, up-valley flows, and the GSL breeze. At 1600 LST (Fig. 3c), observations in the Tooele Valley show a coupling between upslope and up-valley flows, which are in phase with the GSL breeze and produce a diffluent up-valley wind pattern. A similar but weaker flow pattern in which upslope flows are more dominant is observed over the Salt Lake Valley. In contrast to the Tooele and Salt Lake Valleys, there is little evidence of upslope and up-valley winds within the Rush Valley. Instead, the GSL breeze has crossed the South Mountain divide, and by 1600 LST has penetrated into the central Rush Valley (Fig. 3c), providing an example of how an external thermally driven wind system can overwhelm local slope and valley flows.

The evening transition period begins around sunset (~1943 LST). Within 3 h of sunset (2200 LST, Fig. 3d), downslope and down-valley flows are already well developed in the Tooele and Salt Lake Valleys. In fact, downslope and down-valley flows are strongest during this period. In contrast to the morning transition, which required 5–6 h to complete, the evening transition is accomplished in only 2–3 h.

Time series from selected observing sites are presented in Figs. 3e–h. Stations on the west side of

the Tooele Valley exhibit a counterclockwise rotation of the wind with time (e.g., RES, Fig. 3e), while stations on the east side of the valley feature a clockwise rotation (e.g., TOO, Fig. 3f). This is consistent with the conceptual model of the diurnal turning of the winds over valley sidewalls presented by Hawkes (1947), since the thermally driven lake–land and up–down valley circulations are in phase and are superimposed on the up–down slope circulations (Whiteman 2000).

Well-developed, coupled thermally driven wind systems have high consistency at POR (Fig. 3g), which is in the middle of the broad Tooele Valley, 8 km from the eastern sidewall and 14 km from the western sidewall. At this site, mean winds flow only in two directions, with a 180° wind reversal. At POR the day-to-day wind consistency at individual hours is above 90% during the nighttime hours when offshore and down-valley flows dominate, then drops below 20% at 1000 LST due to day-to-day variations in the time of the reversal of the lake and valley circulations. Consistency rises above 80% in the afternoon (1300–1600 LST) when the lake breeze and up-valley circulation typically are well developed.

High consistency in nighttime downslope flow over the Tooele Valley is also evident at Grantsville Reservoir (RES, Fig. 3e). At 2100 LST downslope winds are developed and persist for 9 h with a consistency above 85%. The strongest downslope winds (4–5 m s⁻¹) at RES and other sites occur for the first 2 h after sunset.

Finally, there are several major canyons that issue into the Salt Lake Valley from the east. Of these,
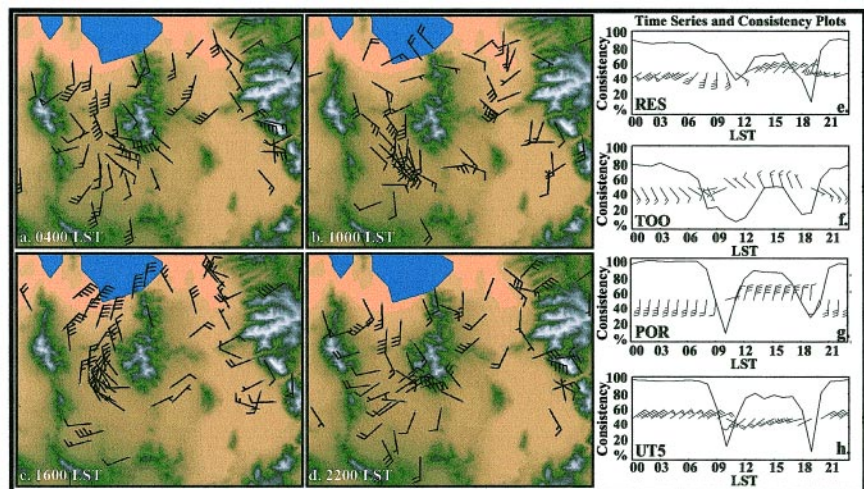

FIG. 3. Mean summer season vector winds in the WFV. Full and half barb denote 1 and 0.5 m s⁻¹, respectively. Terrain shading and color scheme as in Fig. 1: (a) 0400 LST, (b) 1000 LST, (c) 1600 LST, (d) 2200 LST, (e) RES time series, (f) TOO time series, (g) POR time series, and (h) UT5 time series.

Parley's Canyon is known to produce strong outflow into the Salt Lake Valley during the night and early morning hours. The Parley's Canyon (UT5, Fig. 3h) time series shows that this outflow develops typically around 2000 LST, produces nighttime speeds of 4–5 m s⁻¹, reaches a peak magnitude of 5.5 m s⁻¹ near sunrise, and lasts until 0900 LST. Such outflow has a consistency near 95%.

Snake River Plain. A dense network of meteorological observing stations is found on the eastern SRP in Idaho at the Department of Energy's Idaho National Engineering Laboratory. These stations have provided data for several climatological studies focused on transport and diffusion (e.g., Wilkens 1955; Yanskey et al. 1966; Wendell 1972; Clements 1979; Clawson et al. 1989). The eastern SRP generally experiences plain-parallel flows from either the southwest or the northeast. Southwesterly flows are caused by the channeling of the prevailing westerlies by the surrounding mountains or by daytime, thermally driven, up-plain circulations, while northeasterly flows are caused by channeling of winds from easterly directions or by nocturnal down-plain flows (Clawson et al. 1989). The strong up-valley flow can persist for many hours after sunset (Clawson et al. 1989). While the typical eastern SRP wind flows are well documented, little information exists for flow patterns over the central and western SRP, and prior studies have not attempted to isolate the thermally driven flow component.

Although winds in the SRP are generally oriented along the plains' longitudinal axis, they are also influenced by up- and downslope flows from the adjacent sidewalls and outflow from canyons that enter the plain from surrounding mountain ranges. During the nocturnal regime (0300 LST, Fig. 4a), 2–4 m s⁻¹ down-plain flow extends along much of the SRP. Nevertheless, at central SRP sites near adjoining mountain ranges (e.g., RHF), downslope flow is observed and, near canyons in the southeastern central Idaho Mountains, outflow is evident at several sites, such as HOW. Localized, northerly downslope flow is observed at sites located on the terrain slope between the upper and lower plains of the eastern SRP (see Fig. 2 for location).

The morning transition begins shortly after sunrise (0517 LST). At 0900 LST, down-plain flow persists at most stations, but this flow is not continuous along the entire SRP, since a few stations (e.g., BOI and IDF) have already developed up-plain flow (Fig. 4b). Near valley sidewalls, some stations have already transitioned from downslope to upslope flow (e.g., TWF). Ultimately, the transition from down- to upslope flow occurs in 3–4 h, while the down- to up-plain transition takes 5–6 h (not shown). The slope flow transition is quicker in the SRP than in the WFV, whereas the valley flow reversal is slower. At RHF, downslope north-northeasterly flow persists until about 0800 LST when the flow begins to veer, and becomes briefly down-plain, then upslope, and eventually up-plain by 1500 LST (Fig. 4f). During the afternoon regime (1500 LST) the up-plain flow becomes the dominant pattern throughout the SRP, reaching a magnitude of 3–5 m s⁻¹ (Fig. 4c). Only a limited upslope flow component is observed near adjacent mountain ranges.

Following sunset (~1953 LST), the evening transition period begins. By 2100 LST (Fig. 4d), many stations in the eastern SRP briefly develop southerly or southeasterly flow as winds slowly back from up-plain to down-plain (Fig. 4d). Outflow from canyons in the southeastern central Idaho Mountains converges with this southerly to southeasterly flow. Meanwhile, stations near valley sidewalls in the central SRP have already transitioned
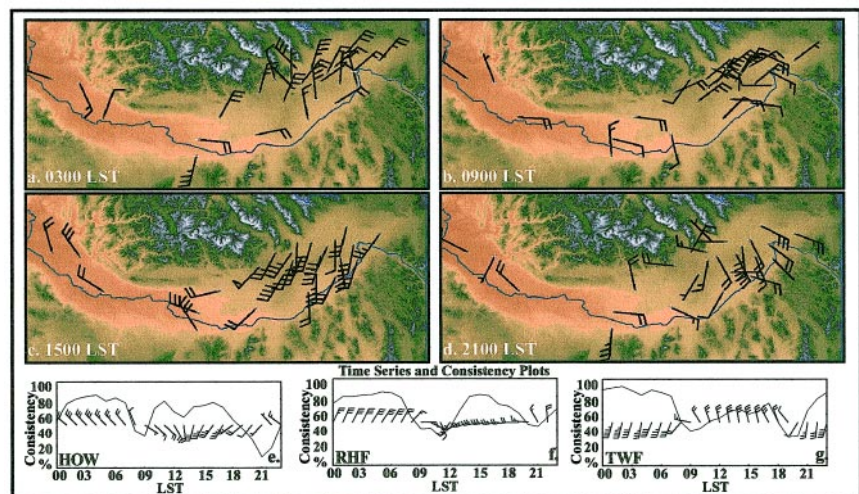

FIG. 4. Mean summer season vector winds in the SRP. Full and half barb denote I and 0.5 m s⁻¹, respectively. Terrain shading and color scheme as in Fig. I: (a) 0300 LST, (b) 0900 LST, (c) 1500 LST, (d) 2100 LST, (e) HOW time series, (f) RHF time series, and (g) TWF time series.

to downslope. Thus, the upslope–downslope transition takes 1–2 h, whereas the up- to down-plain transition takes 5–6 h, eventually resulting in the reestablishment of the evening regime (Fig. 4a).

Time series from selected observing sites in the SRP are presented in Figs. 4e–g. Consistent with the Hawkes (1947) conceptual model for the diurnal turning of the winds over valley sidewalls, winds rotate clockwise with time at stations on the north side of the plain (RHF, Fig. 4f) and counterclockwise with time at stations on the south side of the plain (TWF, Fig. 4g). At these sites, consistency remains above 80% throughout the night, similar to stations in the WFV region (0000–0600 LST, Figs. 3g,h and 4e,f). The transition period for slope flow lasts 3 h at TWF (Fig. 4g), whereas the valley flow transition requires 6 h (e.g., RFH, Fig. 4f), with consistency values near or below 40%. During the daytime heating hours (1200–1800 LST) consistency remains near 60% until the evening transition period (~2100 LST) when consistency values drop to near 30% at TWF (Fig. 4e) and near 50% at RHF (Fig. 4f). Once the nocturnal regime is developed, consistency values return to 80%, completing the cycle.

The IDF and HOW stations illustrate the evolution of winds at two locations in the eastern SRP. At IDF, northerly flow is observed during the nighttime regime. This is largely a down-plain flow that may also be influenced by the terrain gradient between the upper and lower plains (see Fig. 2). Up-plain southwesterly flow develops from 0800 to 1200 LST. Eventually, the flow backs to more southerly, possibly due to localized upslope flow from the lower to upper plains. After 2100 LST, the flow begins to back farther as down-plain flow develops. HOW (Fig. 4e) provides an example of a site strongly influenced during the evening regime by canyon outflow. At this site, localized 2–3 m s^{-1} northwesterly canyon outflow is observed during the nighttime. After 0800 LST the canyon outflow weakens and down-plain flow is observed. Up-plain flow develops from 1300 to 1600 LST as winds gradually veer to the southwest. Canyon outflow redevelops around 2200 LST.
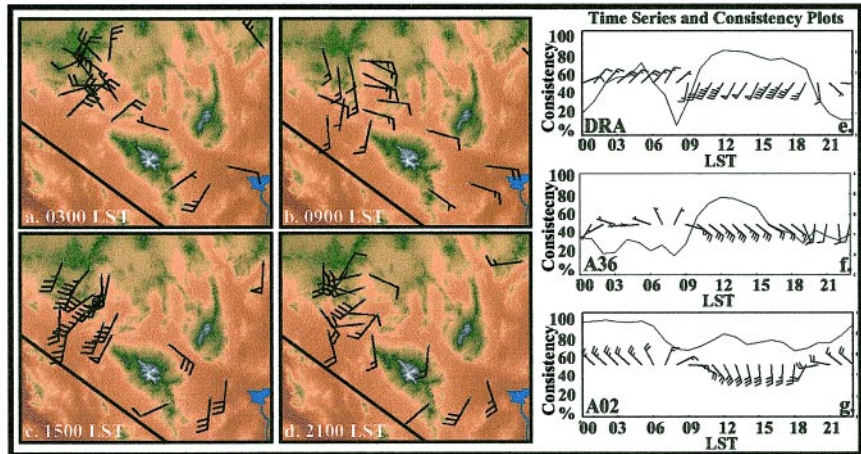

FIG. 5. Mean summer season vector winds in the southern Nevada basin and range province. Full and half barb denote 1 and 0.5 m s^{-1}, respectively. Terrain shading and color scheme as in Fig. 1: (a) 0300 LST, (b) 0900 LST, (c) 1500 LST, (d) 2100 LST, (e) DRA time series, (f) A36 time series, and (g) A02 time series.

Southern Nevada basin and range province. Winds within the southern Nevada region are influenced by local thermally driven flows (i.e., valley and slope flows) and by regional-scale thermally driven flows (i.e., a southwesterly plain–mountain circulation). Winds during the nocturnal regime are dominated by locally forced downslope and down-valley flows (0300 LST, Fig. 5a). In the southern half of the study region, downslope flows from the east and southwest converge into Las Vegas, and downslope flow is observed northeast of the Spring Range. Winds in the northern portion of the domain show little mesoscale organization. Instead, a wide variety of wind directions and speeds are observed as flows converge into the isolated basins.

During the morning transition period, widespread southeasterly to southerly flow develops at most southern Nevada observing sites, with weak confluence evident over the Nevada Test Site (0900 LST, Fig. 5b). As the convective boundary layer grows, 3–4 m s^{-1} southwesterlies eventually dominate the flow pattern over the Nevada Test Site during the afternoon regime (1500 LST, Fig. 5c). These plain–mountain winds are regional-scale southwesterly flows that arise from regional-scale contrasts in elevation and surface heating, including the contrast between the land and the nearby Gulf of California. They have a high consistency that exceeds 70% in midday (e.g., DRA, Fig. 5e). At many locations, the southwesterly flow overwhelms the upslope flows that one might expect from local topographic features. One area where the local topography appears to have a more pronounced influence on afternoon flows is the Las Vegas Valley.

Southeasterly up-valley flow is able to develop in this low-elevation feature, which is surrounded by high topography, particularly to the southwest. This southeasterly up-valley flow converges with the larger-scale southwesterlies in the lowland region north of the Spring Mountains.

During the evening transition (2100 LST), the southwesterly flow weakens and nocturnal drainage flows begin to develop (Fig. 5d). Stations near Las Vegas and within the Las Vegas Valley are the last to complete the transition, and at 2100 LST are still experiencing strong southwesterly winds or southeasterly up-valley flow.

Wind consistencies at most southern Nevada observing sites are relatively high, particularly in the afternoon. For example, the Nellis Range observing site (A36), which is located in the central Las Vegas Valley near the base of the lower slopes of the Spring Mountains, experiences up-valley flow by 1000 LST, which attains 3–4 m s^{-1} during the afternoon (Fig. 5f). The consistency of this up-valley flow reaches more than 70% during the hours from 1000 to 1500 LST; even higher consistencies are found at stations where southwesterly plain–mountain flows dominate (e.g., DRA, Fig. 5e). Some stations, such as Area 2 (A02) at the Nevada Test Site, have very high consistencies through most of the diurnal cycle, with only small reductions in consistency during transition periods (Fig. 5g). This suggests that day–night and night–day transitions at this station are regular and rapid.

Central Arizona area. Thermally driven winds within the central Arizona region can be separated into two categories: those protected from, and those exposed to, a plain–mountain flow from the Yuma Desert. Exposed stations show similarity to those in the southern Nevada region with wind consistency highest during the afternoon. Protected stations observe less regularly afternoon flows with relatively low wind consistencies.

During the night (0300 LST, Fig. 6a), both protected and exposed observing stations experience downslope or down-valley winds driven by local topographic features. Convergence of weak (1–2 m s^{-1}) downslope flow is

found over the Phoenix basin. The morning transition begins after sunrise (~0537 LST). By 0900 LST (Fig. 6b), the winds have switched from downslope and down-valley to upslope and up-valley. Downslope to upslope transition times (~1 h) are shorter than up- to down-valley transition times (~3–4 h).

Throughout the afternoon regime (1500 LST, Fig. 6c) southwesterly plain–mountain flow is observed at most sites. Winds are strongest at sites near Phoenix and the Yuma Desert (4–5 m s^{-1}), particularly at sites with southwestern exposure. Vector-mean wind speeds at the sheltered sites and in the Sierra Ancha remain around 1–2 m s^{-1}, and the wind direction at these sites contrasts with the general southwesterly flow.

The wind consistency at Luke Air Force Base (LUF, Fig. 6e), a site exposed to the afternoon southwesterly plain–mountain flow from the Yuma Desert, reaches 70%–90% in the afternoon. This high afternoon consistency is similar to that found at many observing sites over southern Nevada. In contrast, afternoon winds at locations that are not directly exposed to the plain–mountain flow are less regular, with consistencies below 50% and often less than 30% (e.g., EEK, Fig. 6f). At these locations there is considerable variability in the afternoon wind direction and the vector-averaged wind speed, and direction is not dominated by a regular afternoon flow pattern.

As soon as the sun sets (~1844 LST), the evening transition period begins and downslope and down-valley winds begin to develop by 2100 LST (Fig. 6d). The slope wind transition requires about 1 h, whereas
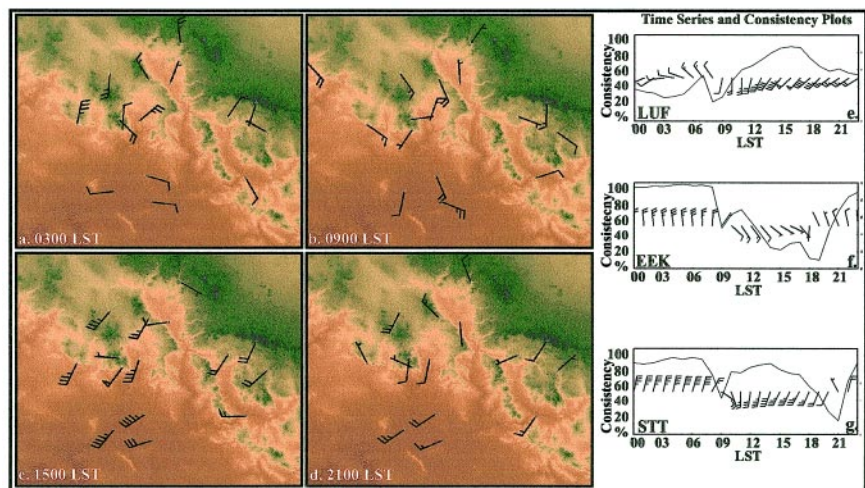

F$_{IG}$. 6. Mean summer season vector winds in central Arizona. Full and half barb denote 1 and 0.5 m s^{-1}, respectively. Terrain shading and color scheme as in Fig. 1: (a) 0300 LST, (b) 0900 LST, (c) 1500 LST, (d) 2100 LST, (e) LUF time series, (f) EEK time series, and (g) SST time series.

the valley wind transition takes 3–4 h. Northern stations are the first to transition, while stations near Phoenix observe southwesterly plain–mountain flows for an additional hour before transitioning. After the transition, wind speeds across the area are 1–2 m s^{-1}, with downslope flows at some mountain stations reaching 3 m s^{-1}.

The time series in Fig. 6 further illustrate the contrast in wind evolution and consistency between sheltered locations and those exposed to the southwesterly plain–mountain flow. At EEK, a sheltered location in the mountains, nocturnal downslope and down-valley winds reach 1–3 m s^{-1} and have a high wind consistency (95%, Fig. 6f). Upslope and up-valley flow develops by midmorning, but afternoon winds become irregular and have a consistency that at times is less than 20%. Downslope and down-valley flow redevelops immediately after sunset and the wind consistency increases to more than 90%. This evolution of wind consistency is similar to other sheltered locations in the Sierra Ancha. Near the Yuma Desert, at STT, there is high wind consistency (greater than ~80%) overnight (Fig. 6g). During the morning transition the consistency drops below 50%, but increases to more than 70% by 1100 LST, indicating the persistent nature of the southerly to southwesterly afternoon plain–mountain flow at this location. Most other stations near the Yuma desert, including LUF (Fig. 6e), observe consistent southwesterly plain–mountain flow during the afternoon.

SUMMARY AND CONCLUSIONS. Using surface data collected by the MesoWest cooperative networks, the diurnal evolution and day-to-day consistency of thermally driven winds in the Wasatch Front valleys (WFV, encompassing the Salt Lake, Tooele, and Rush Valleys) of northern Utah, Snake River Plain (SRP) of southern Idaho, southern Nevada region, and central Arizona region have been described. These regions were selected because of the availability of high-density surface observations. The results are expected to be broadly representative of thermally driven wind climates in the Intermountain West. The analysis has illustrated the following:

- At observing sites that are not influenced by external flows, winds on the valley sidewalls conform to the Hawkes (1947) conceptual model, with clockwise and counterclockwise diurnal turning of the wind on the right and left valley sidewalls, respectively, when facing down valley.
- Narrow canyons with a constricted outlet can produce strong outflow into broader plains or valleys. Several stations illustrate this, including UT5 in the WFV (Fig. 3h) and HOW in the SRP (Fig. 4e).
- Larger-scale thermally driven winds at many locations overwhelm local thermally driven winds. For example,

the Great Salt Lake (GSL) breeze overwhelms afternoon upslope flows in the Rush Valley.
- Except at sites that are sheltered or located in deep valleys, a southwesterly plain–mountain flow driven by regional-scale heating contrasts dominates local thermally driven flows over the desert Southwest (i.e., southern Nevada and central Arizona) during the daytime.
- Thermally driven wind convergence is found in many areas and can be produced by both daytime or nighttime flows. For example, wind convergence is evident at the leading edge of the daytime GSL breeze, between nocturnal down-plain flow and localized canyon outflow over the eastern SRP, between afternoon southwesterly plain–mountain and southeasterly up-valley flows at the northwestern terminus of the Las Vegas Valley, and from nocturnal downslope flows near the center of the Phoenix basin.
- The timing of day–night and night–day wind reversals is generally consistent from region to region. During the morning transition period, downslope winds changed to upslope shortly after sunrise, followed by the down-valley to up-valley wind reversal. Similarly, the upslope to downslope transition occurred shortly after sunset and the up- to down-valley transition was delayed. Downslope winds are strongest during the first few hours after sunset and were generally stronger than the daytime upslope winds.
- Day-to-day wind consistency is generally high at night (~90%), moderate during the day (~60%), and low during the transition periods (~20%), although less variable daytime flow is found over the desert southwest where the consistency of afternoon southwesterly plain–mountain flow is near 80%. The drop in consistency during transition periods reflects day-to-day variability in the timing of wind reversals. Lower daytime consistencies compared to nighttime may be related to wind speed and direction variations caused by convection.

The analysis presented in this paper is expected to be of value to boundary layer and air-pollution meteorologists, fire weather forecasters, operational meteorologists, and other scientists concerned with the meteorology of the western United States and understanding wind flow patterns in complex terrain. To more fully examine the thermally driven flows in each of the four regions discussed in this paper, animation of wind roses and vector-averaged winds at hourly intervals is available online at www.met.utah.edu/jimsteen/jstewart/mtnwind.html. Continued improve-

ment in our understanding of Intermountain West wind systems should be possible in the near future with the continued maintenance and expansion of MesoWest.

REFERENCES

Astling, E. G., 1986: A study of mesoscale wind fields in mountainous terrain. TECOM Project 7-CO-R87-DP0-009, U.S. Army, Dugway Proving Ground, Dugway, UT.

Carter, R. G., and R. E. Keislar, 2000: Emergency response transport forecasting using historical wind field pattern matching. *J. Appl. Meteor.,* **39,** 446–462.

Clawson, K. L., G. E. Start, and N. R. Ricks, 1989: *Climatology of the Idaho National Engineering Laboratory.* 2d ed. NOAA/Air Resources Laboratory, 155 pp.

Clements, W. E., 1979: Experimental design and data of the April, 1977 multitracer atmospheric experiment at the Idaho National Engineering Laboratory. Los Alamos Scientific Laboratory Informal Rep. LA-7795-MS, Los Alamos Scientific Laboratory, Los Alamos, NM, 100 pp.

Hawkes, H. B., 1947: Mountain and valley winds—With special reference to the diurnal mountain winds of the Great Salt Lake region. Ph.D. dissertation, Ohio State University, 312 pp.

Horel, J. D., and Coauthors, 2002: MesoWest: Cooperative mesonets in the western United States. *Bull. Amer. Meteor. Soc.,* in press.

Panofsky, H. A., and G. W. Brier, 1965: *Some Applications of Statistics to Meteorology.* The Pennsylvania State University, 224 pp.

Smidy, K. I., 1972: Diurnal and seasonal variation of the surface wind in the Salt Lake Valley. M.S. thesis, Dept. of Meteorology, University of Utah, 122 pp.

Steenburgh, W. J., S. F. Halvorson, and D. J. Onton, 2000: Climatology of lake-effect snowstorms of the Great Salt Lake. *Mon. Wea. Rev.,* **128,** 709–727.

Stone, G. L., and D. E. Hoard, 1990a: Daytime wind in valleys adjacent to the Great Salt Lake. Preprints, *Fifth Conf. on Mountain Meteorology,* Boulder, CO, Amer. Meteor. Soc., 216–223.

——, and ——, 1990b: An anomalous wind between valleys—Its characteristics and a proposed explanation. Preprints, *Fifth Conf. on Mountain Meteorology,* Boulder, CO, Amer. Meteor. Soc., 209–215.

Wendell, L. L., 1972: Mesoscale wind fields and transport estimates determined from a network of wind towers. *Mon. Wea. Rev.,* **100,** 565–578.

Whiteman, C. D., 1990: Observations of thermally developed wind systems in mountainous terrain. *Atmospheric Processes over Complex Terrain, Meteor. Monogr.,* No. 45, Amer. Meteor. Soc., 5–42.

——, 2000: *Mountain Meteorology: Fundamentals and Applications.* Oxford University Press, 355 pp.

——, and K. J. Allwine, 1986: Extraterrestrial solar radiation on inclined surfaces. *Environ. Software,* **1,** 164–169.

——, X. Bian, and J. L. Sutherland, 1999: Wintertime surface wind patterns in the Colorado River valley. *J. Appl. Meteor.,* **38,** 1118–1130.

Wilkens, E. M., 1955: A discontinuity surface produced by topographic winds over the upper Snake River Plain, Idaho. *Bull. Amer. Meteor. Soc.,* **36,** 397–408.

Yanskey, G. R., E. H. Markee Jr., and L. P. Richter, 1966: Climatography of the National Reactor Testing Station. USAEC Rep. IDO-12048, U.S. Dept. of Commerce Environmental Science Service Administration Institute for Atmospheric Science, Air Resources Field Research Office, Idaho Falls, ID, 226 pp.