Summer Wind Flow Regimes over the Sacramento Valley

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ABSTRACT

This study utilized conditional sampling to identify three frequent wind regimes in the lower Sacramento Valley. The major flow features of the mean diurnal wind patterns in the southern Sacramento Valley and surrounding areas were analyzed for each wind regime. Afternoon wind directions at a pivotal observing site (Davis, CA) in the south-central part of the valley were used to classify the regimes as south wind (marine air intrusion), north wind (no marine air intrusion), and transitional wind days. In the summer of 1991, these occurred 72%, 14%, and 14% of the days, respectively. Daily data from 21 surface observing stations were segregated by wind regime, then averaged for quarters of the day to produce wind roses grouped by regime and time of day. These data were then plotted on a base map. The most frequent direction in each of these wind roses was used to construct streamlines for the area by quarter of the day for each regime. These analyses provide a climatology of the diurnal variation of the average wind flow for each of these frequent flow regimes, providing a wind climatology with greater spatial and temporal resolution than those in extant publications. These analyses are especially useful for evaluating transport patterns of air pollutants or contaminants.

1. Introduction

It is often useful to identify prevailing wind regimes in a region to access probable air pollutant transport patterns or to provide ‘‘typical’’ wind fields for transport calculations. In many regions there are a number of wind regimes that occur that share major characteristics but differ significantly from one another. In this paper we describe the use of conditional sampling criteria to select the 24-h periods in which individual wind regimes are present in the Sacramento Valley of California during the summer. In most locations, significant air quality degradation at a particular site is associated with a specific sequence of wind field patterns, that is, with specific scenarios. We believe characterization of such scenarios is important to understanding regional air quality variations in time and space. We also argue that regional wind patterns characterized in this manner can serve as basic flow patterns for use in airshed models of pollutant evolution and transport. In numerical models, such as the Urban Airshed Model (UAM), dependent variables are averaged over grid cells that are typically larger than 5 km on a side. Numerical filters produce further smoothing of the spatial and temporal distributions of these variables. Solution algorithms include highly parameterized representations of real processes, such as turbulence, that are based on averaging an ensemble of real events. Hence, we believe that these models are best used to simulate average events and scenarios rather than individual events or episodes. Therefore, instead of using prescribed wind fields from a diagnostic wind model (DWM), the wind flow scenarios identified in this study will provide sufficiently detailed data to initialize the UAM to examine air quality consequences of these averaged conditions. Model results can be verified by averaged pollutant concentrations associated with a given flow scenario.

Currently, the UAM is the only photochemical model recommended by the U.S. Environmental Protection Agency for use in air pollution abatement planning applications in urban areas. Briefly, the UAM is a three-dimensional, Eulerian, photochemical grid model that simulates transport and transformation of pollutants for 2–3-day periods. The model numerically simulates the effects of emissions, transport, advection, diffusion, photochemistry, and deposition. A DWM is needed to generate the flow fields used in the model. The wind data generated by the DWM are sets of hourly averaged horizontal wind fields for each layer of the model. The transport of pollutant species is then simulated by the advection of the species by the hourly averaged wind.

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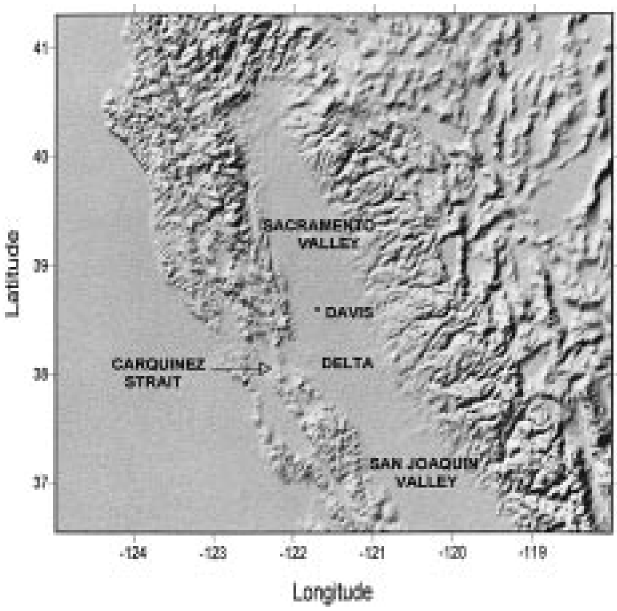

FIG. 1. Shaded relief map of northern and central California and western Nevada.

The UAM is fully described in Tesche et al. (1993). Typically, the model is used to simulate individual historical pollution episodes.

A limiting factor in using the UAM is the extensive amount of air quality and meteorological data required for model simulation and verification. The data necessary to meet the input requirements of the model are only partially measured by existing monitoring networks (Ireson et al. 1988). To collect sufficient data for model simulation, measurements are needed for emissions, meteorological, and air quality data both at the surface and aloft (Seigneur et al. 1981). Our proposed alternate approach to using the UAM may ease these limitations; that is, the UAM may provide better simulations of general scenarios than for single events. Using flows averaged over multiple occurrences of similar events, the UAM could be used to generate mean spatial and temporal pollutant distributions. These pollutant distributions can then be compared with concentrations averaged for periods when these specific wind flow scenarios are observed. In this study, a means to determine and to describe average diurnal wind flow associated with specific wind regimes is described.

2. Background

Figure 1 shows the general area of interest, which is centered over Sacramento. Both the topography and the proximity to the Carquinez Strait are of critical importance to the wind flow pattern present in the Sacramento Valley [California Air Resources Board (CARB) 1989]. The Carquinez Strait is a major gap in the Coast Ranges through which marine air penetrates into the Sacramento and San Joaquin Valleys (Schultz et al. 1961). The Strait lies at the northeastern end of the San Pablo Bay and extends eastward to the confluence of the Sacramento and San Joaquin Rivers, the Delta.

The Sacramento Valley covers the northern third of the California Central Valley. It is surrounded on three sides by mountain ranges and merges with the San Joaquin Valley to the south. To the west of the Sacramento Valley lie the Coast Ranges, which are parallel to the Pacific coastline with the peaks extending 1.3 km above mean sea level (MSL) (Lorenzen 1974). The Sierra Nevada form the eastern side of the Sacramento Valley with peaks ranging from about 2.4 to 3.3 km. The Klamath and Cascade Ranges lie to the north, with peaks ranging from 2.4 to 3.0 km. The southern end of the Sacramento Valley, that is, the Delta area, is at or below sea level and the valley slopes slightly upward to about 160 m MSL to the northern end. The only significant topographic features on the valley floor are the Sutter Buttes located 77 km northwest of Sacramento with elevations up to 645 m MSL (Lorenzen 1974).

During the summer, the days in the Sacramento Valley are typically cloudless and warm and the nights are usually cool. According to Martini (1993), the prevailing wind in the city of Sacramento is southerly year-round due to the north–south orientation of the valley. Marine air flows through the Carquinez Strait, moves through the Delta, and then flows northward, up the valley. Occasionally, a strong high pressure region moves inland to the north or northeast, forcing strong northerly winds through the Sacramento Valley.

Figure 2a illustrates California's predominant surface wind flow pattern for the nonmountainous regions during the summer season (Hayes et al. 1984). The data used are twenty-four 1-h average resultant winds for each day from June through August during 1977–81. The 24-h resultant wind pattern in the Sacramento air basin is dominated by the marine air penetration and upslope mountain flows in the Sierra Nevada. The sea breeze acts in conjunction with a monsoon-type flow (Forsberg and Schroeder 1966), which arises as a result of the eastern Pacific subtropical high off the California coast and the thermal low that forms in the Central Valley. The high pressure system remains in a fairly constant position during the summer, isolating the Sacramento Valley from the Pacific storm track (Lorenzen 1974). Frontal systems that approach the California coast are steered well to the north and precipitation during the summer is rare on the valley floor and the adjacent foothills.

The interplay between the subsidence inversion produced by the subtropical high and topography plays a critical role in modulating airflow patterns. The northwesterly flow off the California coast either blows over the Coast Ranges when the inversion is high or is channeled through low-lying passes when the inversion is at a low altitude (CARB 1989). Figure 2a shows that the Carquinez Strait is a major penetration point for marine

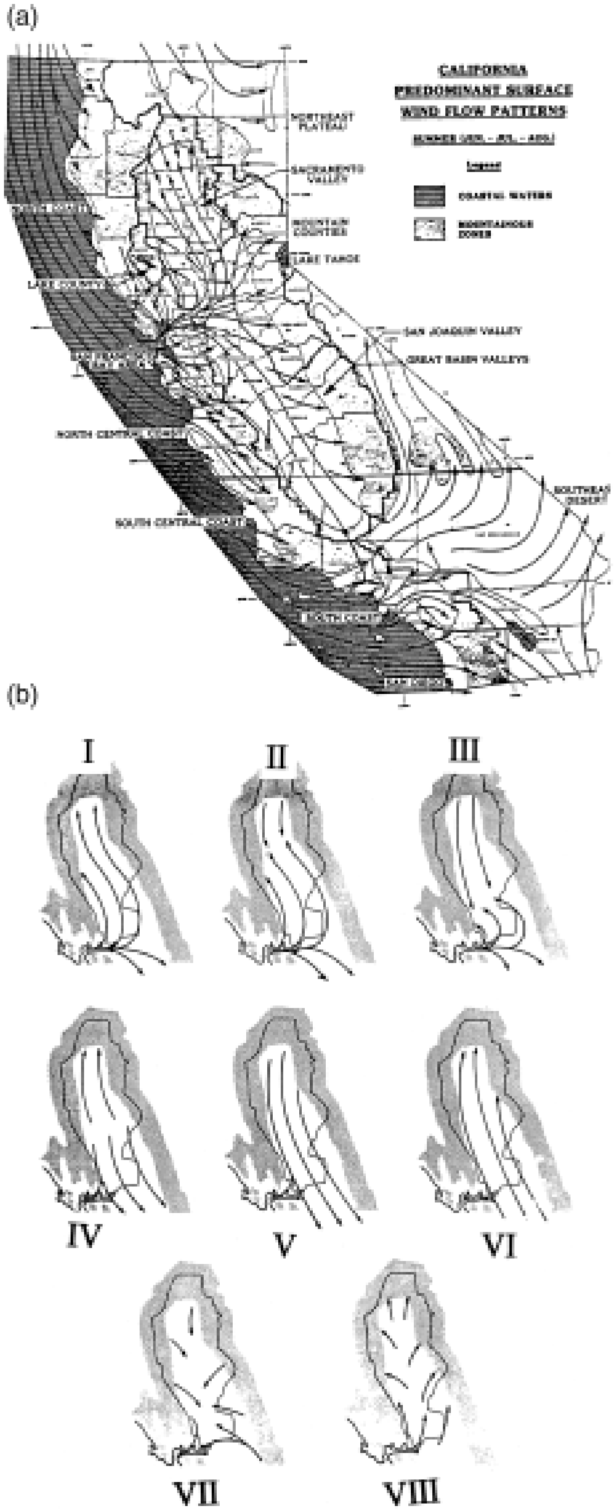

FIG. 2. (a) Predominant surface wind flow patterns during summer, reproduced from Hayes et al. (1984). (b) Sacramento Valley airflow pattern types, reproduced from Hayes et al. (1984): I, full sea breeze; II, upper valley convergence; III, lower valley convergence; IV, mid-valley divergence; V, northerly winds (>5 kt); VI, southerly winds, no marine intrusion; VII, downslope flows (≤5 kt); VIII, upslope flow (≤5 kt).

air to move inland into the Central Valley. Once inland, the flow splits to flow up the Sacramento Valley or down the San Joaquin Valley. The intensity of the marine air penetration also varies with a diurnal cycle, being strongest in the afternoon and evening hours (Schultz et al. 1976).

In addition to analyzing the predominant wind pattern for the summer, Hayes et al. (1984) classify the annual wind of the Sacramento air basin into nine flow types, which includes one for calm conditions (Fig. 2b). The datasets used in this analysis are from meteorological maps prepared by California Air Resources Board meteorological staff showing the surface airflow patterns for 0400, 1000, 1600, and 2200 Pacific standard time (PST). Four flow types prominently occur during the summer season: (I) the full sea breeze, occurring 55% of the time and most prevalent during the late afternoon; (II) upper valley convergence, occurring 16% of the time and most prevalent during the early morning hours; (III) lower valley convergence, occurring 13% of the time and most commonly during the early morning hours; and (V) the north wind type, occurring 9% of the time and most prevalent during the midmorning hours. The remaining classifications (IV, VI, VII, VIII) occur 2% of the time or less during the summer, and the calm scenario for the summer occurs 3% of the time.

The analysis shown in Fig. 2a utilized 24-h resultant winds. Since the daytime marine intrusions and upslope flows in the mountains are much stronger than the nocturnal downslope flows or land breezes moving westward through the Carquinez Strait, the streamlines shown in Fig. 2a are dominated by daytime conditions. As shown below, while marine intrusion is the most frequent summer event, there are a significant number of days with strong day-long north winds throughout the Sacramento Valley. The analysis of resultant winds does not show this.

In our analysis, we group data by days during which marine intrusion dominates, days when north winds dominate, or transitional days. We then analyze each group by quarters of a day, that is, 0000–0559, 0600–1159, 1200–1759, and 1800–2359 PST. This allows us to examine typical diurnal variation of flow patterns during each of these conditions.

3. Methodology

Surface observations from 21 meteorological sites within and around the Sacramento Valley were collected from three sources: CARB, the California Irrigation Management Information System (CIMIS), and the University of California, Davis (UCD). The study period was 153 days from 1 May through 30 September 1991, which coincides with a regional air quality study during which observations from additional measurement sites were available. While this represents only one summer season, we believe that the characteristics of wind regimes identified here would be the same in other years,

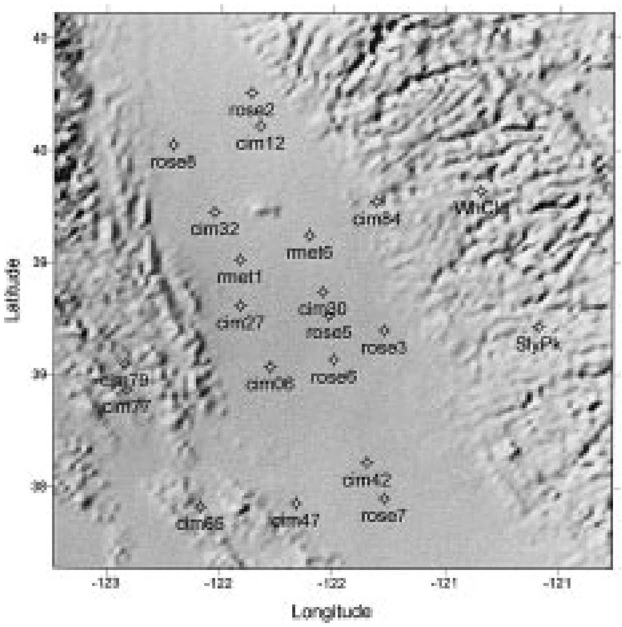

FIG. 3. Shaded relief map of the study area showing the surface observation sites listed in Table 1.

although the relative frequency of these regimes will vary among years. The locations of the surface observation sites are shown in Fig. 3 and the relevant information is listed in Table 1. The site names indicate the data source. A prefix of ''rose'' or ''rmet'' indicates the data are from CARB, a prefix of ''cim'' indicates that the data are from the CIMIS network, and those sites with abbreviated place names are UCD sites. All sites report hourly averaged meteorological data, including wind speed, wind direction, and ambient air temperature.

The CIMIS network contains more than 85 computerized weather stations operated by the California Department of Water Resources. These data are automatically transmitted to a centralized location in Sacramento, where these data are analyzed for accuracy and then stored. The CIMIS stations report meteorological variables every minute and store them as hourly averages. The UCD data are obtained from a network of sites used for the Sierra Cooperative Ozone Impact Assessment Study (Van Ooy and Carroll 1994). CARB data are part of a network of meteorological measurement and air quality monitoring stations that operate throughout California year-round.

This study identifies three types of scenarios: no marine air intrusion (north wind), well-developed marine air intrusion (south wind), and transitional days, based on the afternoon conditions at the Davis site. The Davis site was chosen because it is a location at which morning northerly winds associated with the ''Schultz'' eddy are easily identified and will have afternoon winds from the south only when the marine air intrusions occur. The classification scheme for each day was based on two conditions: the wind direction and its persistence during the afternoon hours. We choose a local wind to distinguish the regime since the regional pressure gradient and synoptic-scale features do not correlate well with the wind flow in the Sacramento Valley. It is primarily the depth of the coastal marine layer (i.e., the height of the subsidence inversion along the coast) that controls the flux of marine air through and over the coastal mountains, which is not a simple function of the current synoptic conditions. The wind direction was categorized by quadrants, where each quadrant was centered about one of the four principal compass directions. We choose 90° quadrants over 45° octants as the former are sufficient

TABLE 1. Site reference, data source, location, and elevation.

Site ref. and source	Site name	Air basin	Location	Elevation (m)
rmet1-CARB	Arbuckle	Sacramento	2 mi west Hillgate Rd.	41.8
rmet6-CARB	Yuba City, Ag Building	Sacramento	142 Garden Hwy.	18.0
rose2-CARB	Chico-Manzanita	Sacramento	468 Manzanita Ave.	61.6
rose3-CARB	Citrus Heights	Sacramento	7400 Sunrise Blvd.	27.4
rose5-CARB	Pleasant Grove	Sacramento	7310 Pacific Ave.	14.6
rose6-CARB	Sacramento	Sacramento	1309 T St.	6.1
rose7-CARB	Stockton	San Joaquin Valley	1601 East Hazelton	4.0
rose8-CARB	Willows	Sacramento	263 North Villa Ave.	41.1
cim06-CIMIS	Davis	Sacramento	Yolo County	15.2
cim12-CIMIS	Durham	Sacramento	Butte County	9.1
cim27-CIMIS	Zamora	Sacramento	Yolo County	15.2
cim30-CIMIS	Nicolous	Sacramento	Sutter County	9.8
cim32-CIMIS	Colusa	Sacramento	Colusa County	16.8
cim42-CIMIS	Lodi	San Joaquin Valley	San Joaquin County	7.0
cim47-CIMIS	Brentwood	San Francisco	Contra Costa County	13.7
cim65-CIMIS	Walnut Creek	Sacramento	Contra Costa County	134.1
cim77-CIMIS	Oakville	North Coast Valley	Napa County	57.9
cim79-CIMIS	Angwin	North Coast Valley	Napa County	524.3
cim84-CIMIS	Browns Valley	Sierra foothills	Sierra foothills	286.5
slypk-UCD	Sly Park	Sierra foothills	El Dorado National Forest	1127.8
whcld-UCD	White Cloud	Sierra foothills	Tahoe National Forest	1325.9

TABLE 2. Statistics for wind rose analysis for the Davis observation site. Note that percentages may not add up to 100% due to rounding off.

	N	NE	E	SE	S	SW	W	NW	Calm	Total
0000–0559 PST										
Number of observations	46	1	28	220	304	96	57	100	66	918
Mean direction (°)	11	38	104	137	181	221	270	320		
Mean temperature (°C)	15	14	15	14	14	13	12	14		
Percent occurrence	5.0	0.1	3.1	24.0	33.1	10.5	6.2	10.9	7.2	
Mean speed (m s^{-1})	2.0	0.8	1.2	1.6	2.4	1.7	1.2	2.5		
0600–1159 PST										
Number of observations	222	18	17	58	221	93	95	149	45	918
Mean direction (°)	11	38	95	146	183	223	273	319		
Mean temperature (°C)	23	24	24	23	21	19	18	20		
Percent occurrence	24.2	2.0	1.9	6.3	21.1	10.1	10.3	16.2	4.9	
Mean speed (m s^{-1})	2.8	1.2	1.2	1.6	2.6	1.7	1.7	2.6		
1200–1759 PST										
Number of observations	107	12	8	39	540	119	25	57	11	918
Mean direction (°)	11	42	86	148	184	217	270	324		
Mean temperature (°C)	31	30	20	30	28	28	26	28		
Percent occurrence	11.7	1.3	0.9	4.2	58.8	13.0	2.7	6.2	1.2	
Mean speed (m s^{-1})	3.4	2.0	2.1	2.3	3.7	3.6	3.1	2.8		
1800–2359 PST										
Number of observations	19	6	7	104	619	103	20	34	6	918
Mean direction (°)	12	42	101	146	182	218	274	323		
Mean temperature (°C)	24	26	15	19	19	20	20	20		
Percent occurrence	2.1	0.7	0.8	11.3	67.4	11.2	2.2	3.7	0.7	
Mean speed (m s^{-1})	2.7	1.2	4.5	1.7	3.1	2.9	2.1	3.4		

to identify the nearly opposite northerly or southerly wind directions. The persistence criterion was that the wind direction be in the same quadrant for four out of the six 1-h periods between 1200 and 1759 PST. The days that do not satisfy either of these criteria were considered transitional days.

Once these days were identified, data from all sites in the valley were grouped by date as belonging to one of the three types, and each group was analyzed to create wind roses for each site. For this analysis, the winds for each quarter of a day were divided into eight 45° sectors and for the same 6-h periods, as previously described. The concurrent wind roses were then plotted on a topographic map and streamlines drawn to follow the most frequent wind directions at each site. In most areas of these maps, there are well-defined, dominant wind directions from which to draw the streamlines. However, near singularities or lines of confluence or difluence, the directional frequencies are more random since small variations in the locations of these features will produce highly variable local wind directions. We show the wind roses rather than compute resultant wind directions so as to display, in the figure, the degree of variability of the data.

4. Results

For the 1991 summer, 21 days are classified as transitional wind cases, 22 days as north wind cases, and 110 days as south wind cases (14%, 14%, and 72% of the summer, respectively), essentially the same as for the 1977–81 observations reported by Hayes et al. (1984). Wind data analyses for the Davis site, depicting the frequencies of the wind direction, mean speeds, and mean ambient air temperature, are listed in Table 2 and shown in Fig. 4 for the four daytime periods for the summer of 1991. The wind roses represent the wind direction by sectors of 45° ± 22.5° about each of the four principal (north, east, south, west) and secondary (northeast, southeast, southwest, northwest) compass directions. For example, the east category, at 90°, includes all the observations with nonzero wind speed for direction values between 67.5° and 112.5°. The percentage of calm conditions is denoted in the center of the wind rose. Calm conditions are defined as wind speeds equal to 0.5 m s^{-1} or less.

a. Wind rose analysis for Davis

The early morning wind rose for Davis, 0000–0559 PST (Fig. 4a), indicates that the most frequent wind direction is from the south with a frequency of 33.1%, with a secondary maximum from the southeast with a frequency of 24.0%. The mean wind speeds for the observations among all sectors ranged from 0.8 to 2.5 m s^{-1}. The strongest winds are from the northwest sector at 2.5 m s^{-1} and from the south at 2.4 m s^{-1}. The weakest winds occur from the northeast at 0.8 m s^{-1}. Calm conditions are most prevalent during this period compared to later periods of the day, occurring 7.2% of the time.

During the 0600–1159 PST period (Fig. 4b), the wind direction is almost as likely to be from the south (21.1%)

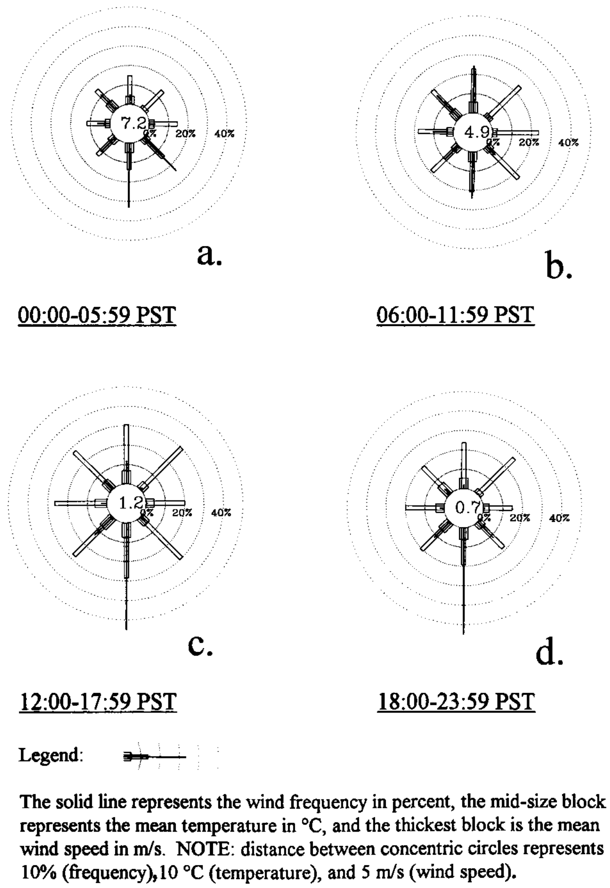

FIG. 4. Wind and temperature roses for Davis for the summer of 1991 for each quarter of the day: (a) 0000–0559, (b) 0600–1159, (c) 1200–1759, and (d) 1800–2359 PST.

as it is from the north (24.2%). During this period, 16.2% of the observations are from the northwest, 10.3% from the west, and 10.1% from the southwest. The mean wind speeds are highest in the north sector at 2.8 m s^{-1} with comparable speeds from the south and northwest sectors, each with a mean speed of 2.6 m s^{-1}. As expected the mean temperatures are 6°–9°C greater then the previous period, ranging from 18° to 24°C. Calm conditions for this period occur for approximately 5% of the total observations.

Between 1200 and 1759 PST (Fig. 4c), the most dominant wind direction is from the south (58.8%) with secondary maxima from the southwest (13.0%) and north (11.7%). During this period, the south wind has higher wind speeds, averaging 3.7 m s^{-1}. This indicates that at least 70% of the time marine air penetrates into the Sacramento Valley. Calm conditions during this period were less than 2% of the observations.

The wind rose pattern for the late evening period, 1800–2359 PST (Fig. 4d), is very similar to the 1200–1759 PST conditions. However, the south wind dominates with an even greater frequency (67.4%), which along with the southeasterly (11.3%) and southwesterly (11.2%) sectors implies some form of marine air intrusion on almost 90% of the evenings. The mean temperatures with southerly winds are about 6°C cooler than with northerly winds. The mean wind speeds are slightly lower than the afternoon but remain high for the south sector (3.1 m s^{-1}) and sectors with a westerly component (2.1–3.4 m s^{-1}). Calm conditions during this period are at a minimum—less than 1% of the summer observations.

The streamline analysis from the resulting wind roses for the transitional, north, and south wind cases is shown in Figs. 5–7. The evolution of the flow fields for 6-h periods from early morning, midmorning, afternoon, and night is discussed in detail by case. Two sites, CIM77 located in a valley and CIM79 located on a ridge in Napa County, are plotted in the figures but generally are not used in the analysis because they are influenced by the local topography and local channeling of wind through passes.

b. Transitional wind case

Figure 5 shows that in the transitional case, the dominant flow is downslope from the central Sierra Nevada during the late evening and early morning, primarily from the east or northeast. During the late morning the flow reverses, with an upslope flow that persists through the late afternoon. In the Delta region, the flow throughout the day is dominated by a persistent westerly component.

The flow within the Sacramento Valley is complex in the transitional case, and there is no continuity in the flow features between time periods. During the early morning, a deformation zone exists in the southeast portion of the Sacramento Valley and an eddy, the Schultz eddy, exists along the western side of the valley. A convergence line is found in the northern region of the Sacramento Valley. The transitional flow field is similar to the Hayes et al. (1984) flow type II: upper valley convergence.

During the late morning period (Fig. 5b), the Schultz eddy no longer exists and northerly flow dominates the area. The deformation zone remains intact and a counterclockwise eddy now exists on the east side of the Sacramento Valley. In the following period, 1200–1759 PST (Fig. 5c), a divergence line forms and extends diagonally across the Sacramento Valley from the southwest to the northeast. This is similar to Hayes et al. (1984) type VIII: upslope flow. During this period, the flow is mainly out of the Sacramento Valley and into the Sierra Nevada and Coast Ranges. The deformation zone that was present in the previous periods no longer exists as the upslope flow dominates along the Sierra. In the final (late evening) period, the features from the early morning reestablish themselves with the exception of the convergence line to the north.

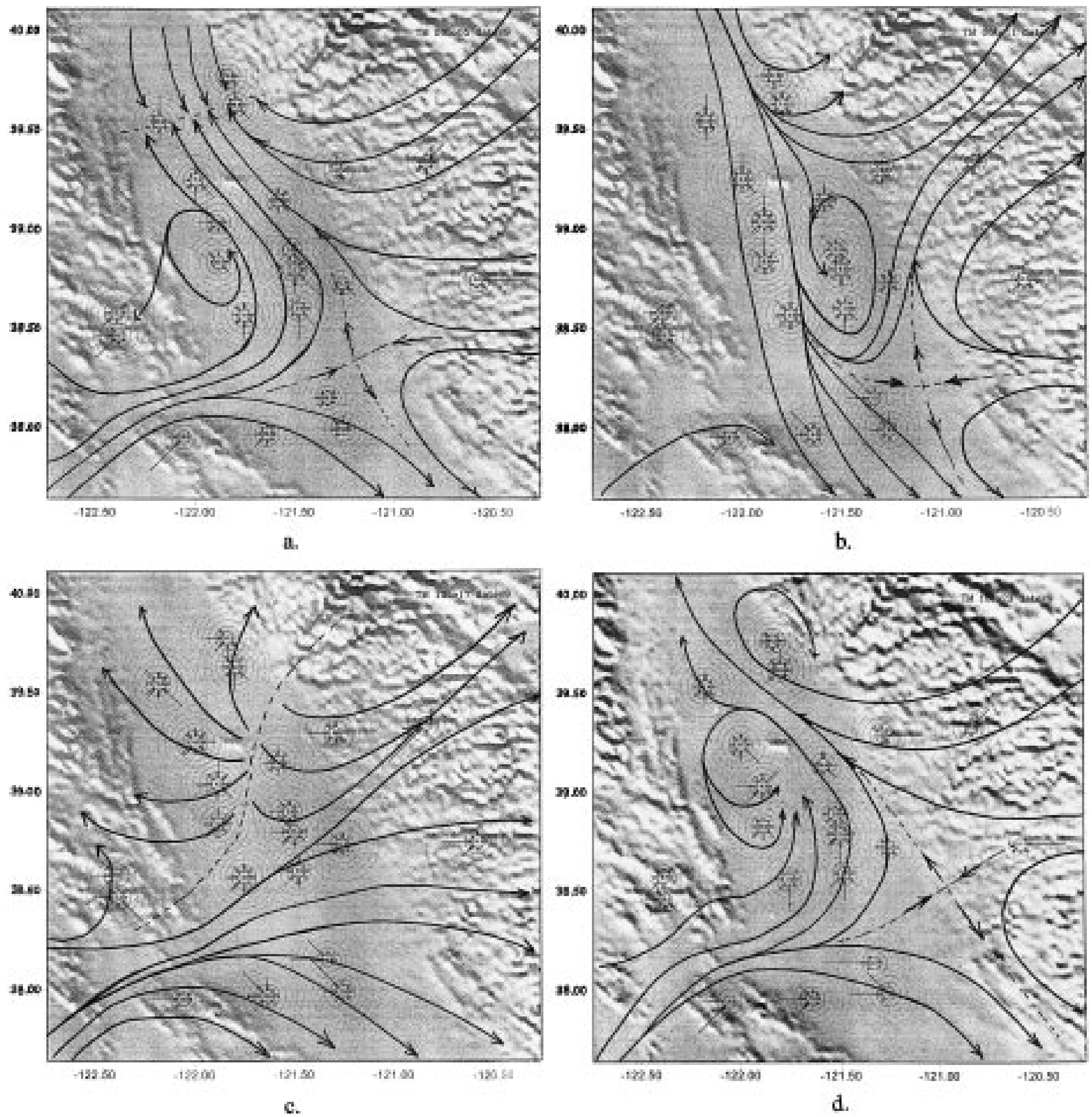

Fig. 5. Wind roses and streamline analyses for the transitional wind case: (a) 0000–0559, (b) 0600–1159, (c) 1200–1759, and (d) 1800–2359.

c. North wind case

During the late evening and early morning, the flow features for the north wind case (Fig. 6) are similar to the transitional case. The differences lie in the location of the Schultz eddy, which changes due to the northerly winds along the western side of the valley. From 0000 to 0559 PST, the flow from the Sierra Nevada merges with the northwesterly flow, generating an eddy. This eddy disappears during the 0600–1159 PST period, as the downslope flow reverses to upslope and the flow becomes northerly throughout the valley. This flow is similar to the northerly flow pattern identified as flow type V in Hayes et al. (1984).

The deformation zone seen in the 0000–0559 PST period persists into the midmorning period. During the late morning the northwesterly flow passes through the Delta into the San Joaquin Valley with no marine air intrusion. This flow pattern persists throughout the afternoon, at which time the deformation zone disappears. By the last period, 1800–2359 PST, the westerly flow of the early morning reemerges through the Carquinez Strait and downslope flows develop along the Sierra.

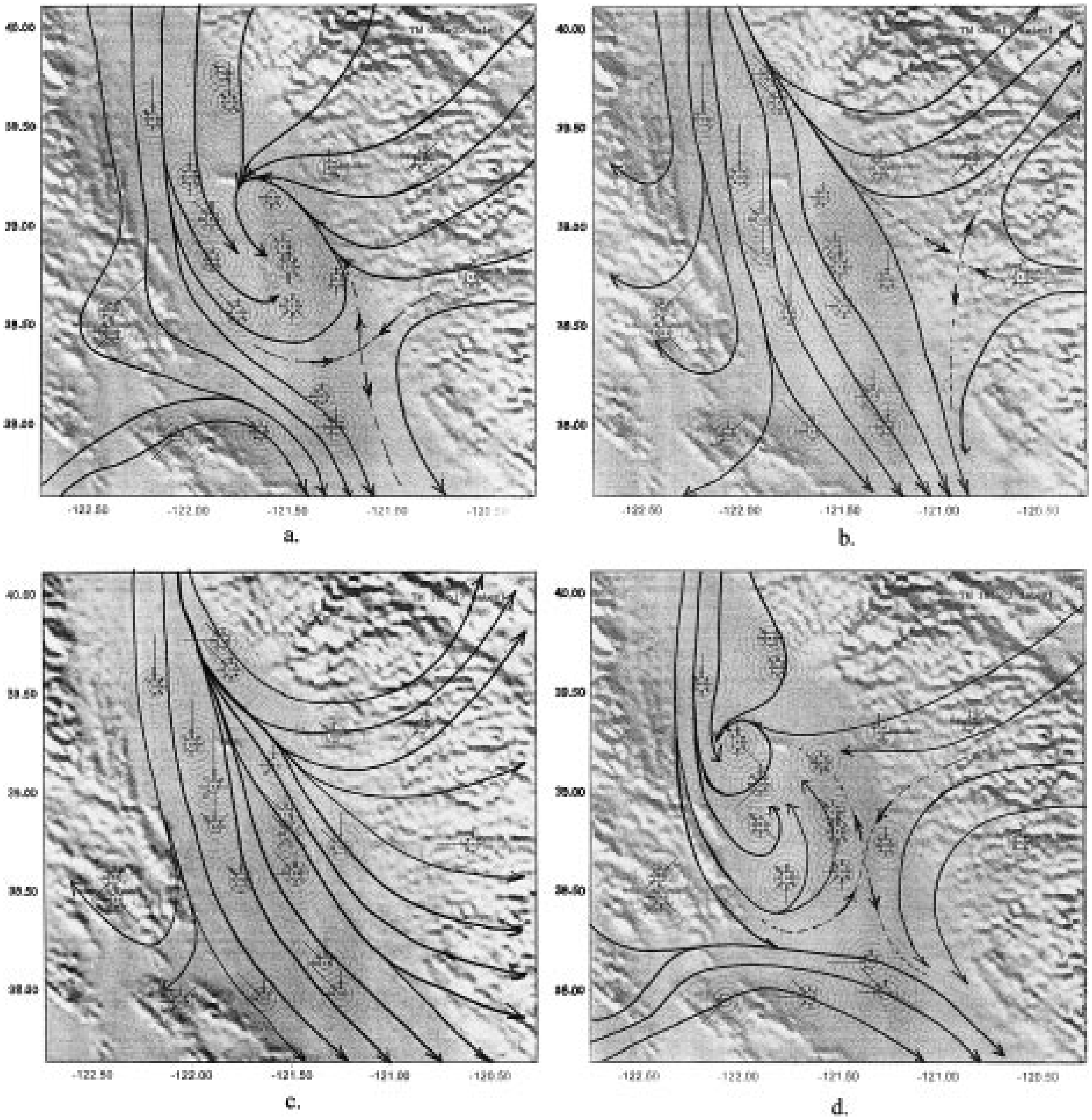

FIG. 6. Wind roses and streamline analyses for the north wind case: (a) 0000–0559, (b) 0600–1159, (c) 1200–1759, and (d) 1800–2359.

The deformation zone and the eddy of the early morning period also reappear. However, since the flow through the Delta during the evening is more westerly than during the morning flow, the deformation zone is forced northward and the eddy is forced westward.

d. South wind case

In the early morning, there is flow through the Carquinez Strait that penetrates into the Sacramento Valley and then flows to the northwest, as shown in Fig. 7. An eddy is present over the western portion of the Sacramento Valley, and a deformation zone exists in the southeast end. During the late morning, the eddy expands to cover a larger area, and the deformation zone present in the southeastern Sacramento Valley disappears as the flow along the Sierra reverses to upslope flow.

In the afternoon, there is little change in the flow pattern, except that the eddy that was present along the western portion of the Sacramento Valley no longer exists as the southeast winds dominate the area. Upslope flow persists over the Sierra Nevada and the flow

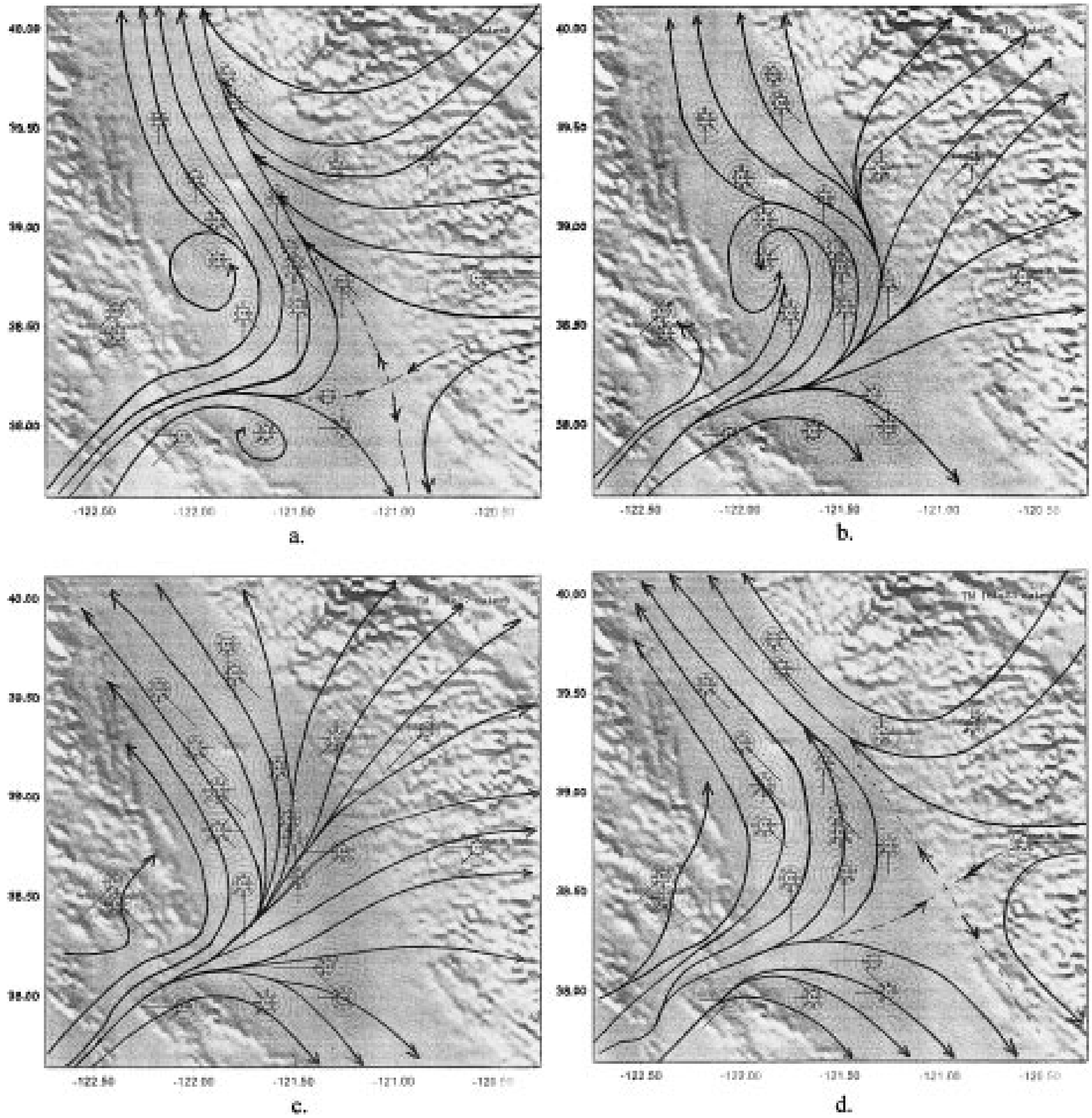

FIG. 7. Wind roses and streamline analyses for the south wind case: (a) 0000–0559, (b) 0600–1159, (c) 1200–1759, and (d) 1800–2359.

through the valley is from the southeast. In the evening (Fig. 7d), the flow over the Sierra Nevada reverses to the nocturnal downslope flow, re-creating the deformation zone seen in the early morning. The flow through the Delta region turns to the north or to the northwest up the Sacramento Valley or to the southeast down the San Joaquin Valley.

5. Summary and conclusions

We have presented a methodology to classify the wind patterns in an area such as the lower Sacramento Valley, where a set of well-defined, frequent wind regimes occurs. Table 3 lists the most common flow features for the three main regions in this study: the Sierra Nevada, the Carquinez Strait, and the Sacramento Valley. The resulting wind field patterns are consistent with previous studies for the region but provide much greater spatial and temporal detail. During the summer of 1991, 110 of 153 summer days (70%) were classified as days when the afternoon wind at Davis was from the south, which is consistent with Martini's assertion that the prevailing wind in the city of Sacramento is from the south.

Hayes et al. (1984) show that the resultant wind in

TABLE 3. Summary of predominant wind flow features by case. CCW = counterclockwise.

Case	Transitional wind	North wind	South wind
0000–0559			
Sierra Nevada	Downslope	Downslope	Downslope
	Easterly or northeasterly	Easterly or northeasterly	Easterly or northeasterly
Carquinez Strait	Southwesterly	Southwesterly	Southwesterly
Delta region	Westerly or southwesterly	Westerly or southwesterly	Westerly component
Sacramento Valley			
Along the east	Southerly or southeasterly	(CCW) eddy develops	Southerly or southeasterly
Along the west	(CCW) eddy develops	Northerly or northwesterly	(CCW) eddy develops
Southern end	Deformation zone	Deformation zone	Deformation zone
0600–1159			
Sierra Nevada	Transitional or upslope	Transitional or upslope	Transitional or upslope
	Westerly or southwesterly	Deformation zone	Southerly or southwesterly
Carquinez Strait	Southwesterly	Northerly or northwesterly	Southwesterly
Delta region	Northwesterly	Northerly or northwesterly	Northwesterly
Sacramento Valley			
Along the east	(CCW) eddy develops	Northerly	Southerly or southeasterly
Sacramento Valley			
Along the west	Northerly	Northerly or northwesterly	Eddy
Southern end	Deformation zone		Southerly
1200–1759			
Sierra Nevada	Upslope	Upslope	Upslope
	Westerly or southwesterly	Westerly or southwesterly	Westerly or southwesterly
Carquinez Strait	Westerly component	Northerly or northeasterly	Westerly or southwesterly
Delta region	Westerly or northwesterly	Northerly or northwesterly	Westerly or northwesterly
Sacramento Valley			
To the northwest	Southeasterly		
To the southeast	Northwesterly		
Along western side		Northerly	Southerly or southeasterly
Along eastern side		Northerly or northwesterly	Southerly
1800–2359			
Sierra Nevada	Downslope	Downslope	Downslope
	Easterly or northeasterly	Easterly or northeasterly	Easterly or northeasterly
Carquinez Strait	Southwesterly	Southwesterly	Southwesterly
Delta region	Westerly or northwesterly	Westerly or northwesterly	Westerly or southwesterly
Sacramento Valley			
Along the west	(CCW) eddy develops	(CCW) eddy	Southerly or southeasterly
Along the east	Southeasterly flow	Deformation zone	Southerly or southeasterly
To the south	Deformation zone		Deformation zone

the Sacramento Valley is characterized by the marine air entering the Carquinez Strait and upslope flow over the Sierra Nevada. In our analysis, the marine air penetration is common to all regimes, except during the daytime periods of the north wind case. Over the Sierra Nevada, the daytime upslope flow is present in all regimes during the late morning and afternoon hours and nocturnal downslope flow is present over the Sierra Nevada in all cases during the early morning and nighttime.

Three of the four most prominent flow types identified by Hayes et al. (1984): (I) the full sea breeze, (II) upper valley convergence, and (V) the north wind are confirmed. The fourth flow type, lower valley convergence (III), was not found, and the upslope flow (VII), an infrequent flow type in the Hayes et al. analysis, is identified here only during the afternoon in the transitional wind case. The Schultz eddy that develops on the Sacramento Valley floor exists during the late night or early morning, which is consistent with previous studies.

Although there are sufficient meteorological sites within the Sacramento Valley and in the foothills to identify major flow features, it is evident from the streamline analysis that additional meteorological sites are needed to resolve more precisely where deformations, lines of convergence or divergence, and other important flow features are most frequent. For air pollutant transport climatologies the locations of these singularities are very important. Conversely, this type of analysis can help to identify where critical data voids are present.

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