The Role of Upstream Midtropospheric Circulations in the Sierra Nevada Enabling Leeside (Spillover) Precipitation. Part I: A Synoptic-Scale Analysis of Spillover Precipitation and Flooding in a Leeside Basin

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ABSTRACT

Pacific-originating storms that produce heavy leeside liquid precipitation in the Sierra Nevada are rare compared to those that generate windward slope rainfall. However, these leeside precipitation events have a profound effect on the flood hydrology of leeside basins in the Sierra Nevada. This study identified 12 storms that affected the Truckee River basin in northeastern Nevada. The storms produced both moderate and extreme flooding in this leeside basin. A synoptic-scale analysis of conditions leading to leeside storms was produced using a compositing procedure. Composites for multiple pressure levels and multiple parameters were produced for class 1 storms—those storms producing moderate flood flow in the Truckee River basin—and class 2 storms—those producing extreme flooding [\(>10\ 000\ \text{cubic feet per second (cfs)}, \text{or}\ 283\ \text{m}^3\ \text{s}^{-1}\) in this basin. The analysis confirms that the two flood populations are in fact generated by Pacific-originating storms with observably different synoptic-scale circulations. The class 2 storms are moister through a great depth in the troposphere (saturated to 750 hPa), and they occur coincident with warmer conditions in the lower and midtroposphere. Class 2 events exhibited more favorable upper-level jet streak structures in the eastern Pacific and over western North America. Both classes of leeside storms were shown to differ substantially from Pacific-originating storms that exclusively affect the windward slope of the Sierra and the coastal mountain ranges of California (California storms). The leeside storms were much warmer than California storms through much of the lower and midtroposphere, and the onshore flow was predominantly from the west-southwest in leeside storms compared to southerly flow in California storms. The findings suggest the existence of a midlevel atmospheric river delivering moisture to leeside basins of the Sierra Nevada.

1. Introduction

Winter-season storms originating over the central and eastern Pacific Ocean commonly make landfall on the West Coast of the United States. The hydrometeorological outcomes of these storms range from light coastal precipitation to heavy precipitation in the coastal mountain ranges of California and in the Sierra Nevada (James and Houze 2005; Marwitz 1987). For this study, the winter season refers to that portion of the calendar year from October to March when a higher frequency of storm development is observed in the central and eastern Pacific Ocean.

Flooding rainfall in the coastal mountain ranges of California and in basins on the windward slope of the Sierra Nevada is possible when winter storms are preceded by a strong onshore flow of low-level moisture. Often this moisture has origins in the southern Pacific Ocean and is transported via a vigorous low-level jet (LLJ) as a narrow filamentary feature. Ralph et al. (2004) referred to these filamentary horizontal fluxes of water vapor ahead of cold fronts as atmospheric rivers (ARs). Zhu and Newell (1998)
suggested that 90% of total meridional water vapor flux in the midlatitudes is accomplished via ARs and that these ARs are distinguishable from the broad circulation of the “warm conveyor belt,” as proposed by Browning (1986).

The California Land-falling Jets Experiment (CALJET) was established in 1998 to observe the LLJ and to examine the moisture fluxes that were in part modulating orographic precipitation in the coastal region of California (Ralph et al. 2004). CALJET along with the Pacific Land-falling Jets Experiment (PACJET) produced a number of insights into the low-level moisture fluxes and frontal deformation during winter storms affecting the coast of California (Neiman et al. 2004; White et al. 2003; Neiman et al. 2002; Kingsmill et al. 2006).

A number of studies have identified common synoptic-scale circulations at the surface and in the upper atmosphere preceding heavy windward slope precipitation from Pacific-originating winter storms. Dettinger et al. (2004) illustrate that mature midlatitude cyclones often track onshore, producing large amounts of orographic precipitation in the Sierra Nevada. Ralph et al. (2004) identified a series of two frontal zones approaching the California coast during the 26 January 1998 winter storm. The first frontal zone acted to advect moisture into the region via a warm conveyor belt, and the second frontal zone provided lift as it made landfall. A persistent omega block (with high pressure centered near the Gulf of Alaska) was observed at the 500-hPa pressure level during a single storm event studied by Rauber (1992). The 500-hPa flow during this event split into two branches, with the southern branch digging equatorward, producing a broad trough across the eastern Pacific. The active region of the 500-hPa flow (trough to ridge) was oriented as to intersect the California coastline. Galewsky and Sobel (2005) detailed the synoptic-scale evolution of a storm from 24 December 1996 through 1 January 1997, observing that a 500-hPa trough deepened initially near 150W longitude. A distinct ridge axis was observed just off the west coast of North America as the trough was deepening in the central Pacific. During the period of flooding precipitation in the Sierra Nevada, the trough advanced eastward and strong south-southwesterly flow dominated the onshore flow at 500 hPa. Reeves et al. (2008) reviewed the literature concerning heavy orographic rainfall on the windward slopes of the Sierra Nevada and defined five synoptic regimes that are common preceding such precipitation episodes.

Heavy liquid precipitation in the lee of the Sierra Nevada is not as frequent as windward precipitation during landfalling Pacific storms; however, intense leeside liquid precipitation has a profound effect on the flood hydroclimatology of river basins on the east slopes of the Sierra Nevada. Over the past 50 years, river basins in California and Nevada—including the Truckee and Carson River basins—have experienced their most extreme flooding events in conjunction with winter storms, producing copious leeside liquid precipitation.

It is likely that some of the same atmospheric elements that combine to produce heavy precipitation in the coastal ranges of California and on the windward slope of the Sierra Nevada contribute to leeside liquid precipitation in the Sierra Nevada because the storms originate in the same region, and the leeside storms are often precipitation producers on the windward slopes as well. This paper will identify those common elements and discern those processes and patterns that are unique in producing leeside precipitation during a number of historical winter storms in the Sierra Nevada. Storms producing spillover precipitation have been shown to exhibit unique moisture and motion characteristics in other mountain regions (Sinclair et al. 1997; Chater and Sturman 1998). Further, this paper will stratify the hydrometeorological response to heavy leeside precipitation and investigate the synoptic-scale elements that define differing flood magnitudes in a leeside basin. The working hypothesis for this paper is as follows: Winter-season floods of varying magnitudes in leeside basins have correspondingly varied synoptic-scale circulation patterns prior to the leeside precipitation episode and subsequent flooding. Furthermore—and most importantly—there are definable synoptic signals that separate moderate from extreme flooding events at least 48 h prior to the heaviest leeside rainfall.

This paper is the first of a series of papers that will investigate winter-season storms that produce heavy leeside precipitation in the Sierra Nevada. This paper will develop a synoptic-scale analysis based on 12 storms that produced flooding in the Truckee River basin in northern Nevada from 1950 to 2005. Part II of the study (Kaplan et al. 2009) will investigate the dynamics and unique midlevel moisture transport mechanisms that allow for heavy liquid precipitation during two of the largest winter-season flooding events in the Truckee River basin and will focus on mesoscale processes and orographic effects. The papers will present key dynamical processes linking climatology to analyses of synoptic and mesoscale transport processes. This study is unique because it focuses on extreme precipitation cases in the lee of the Sierra Nevada as opposed to coastal precipitation events.

2. Research methodology

a. Stream gauge location and basin characteristics

This research will use river stage and discharge data from the U.S. Geological Survey (USGS) gauging site in Reno, Nevada (REV), as the primary source for
streamflow information (Fig. 1). This gauge is located on the Truckee River in the downtown area of Reno. Daily data from this streamflow gauge allow for the identification of moderate and extreme flooding events in this leeside basin of the Sierra Nevada. The quality of the streamflow record at the Reno site dictates the analysis period (1947–2007) for this research. The USGS streamflow data at the Reno site are intermittent from 1906 through 1947; therefore, this period is excluded from the analysis. Two additional stream gauges were incorporated to ensure that flood flows were in fact widespread in the Truckee River basin. One gauge upstream from Reno (Truckee River at Farad) and one gauge downstream from Reno (Truckee River at Vista) were analyzed for stream discharge anomalies on the dates of flooding in Reno.

b. Identification of flood events at the Reno site

The hydrological response to heavy leeside rainfall in Sierra Nevada is represented in the daily streamflow data from the USGS and in the form of a hydrometeorological guidance provided by the National Weather Service (NWS) River Forecast Center (RFC) in Sacramento, California. The RFC guidance for the Truckee River in Reno suggests that a river stage of 9 ft [discharge ~5000 cubic feet per second (cfs), or 142 m³ s⁻¹] results in light-to-moderate flooding in the lowest portions of the flood plain outside the downtown (Reno) area. A stage of 11 ft (discharge ~10 000 cfs) is the bank-full flood flow at the downtown gauge on the Truckee River. A stream discharge greater than 10 000 cfs produces extreme overbank flooding in the downtown Reno area. All flood flows above 5000 cfs at the Reno site for the study period are included in the study. The guidance from the RFC is used in this research to define two populations (classes) of hydrometeorological events: class 1 are those rainfall events that produce moderate flood flows (5000–10 000 cfs) at the USGS streamflow gauge in downtown Reno and class 2 are those leeside precipitation events that generate extreme flooding (>10 000 cfs) at the downtown Reno stream gauging site. It is assumed that the atmospheric conditions leading to a moderate hydrometeorological event will be different from those conditions producing an extreme event. To confirm large-scale flooding in the Truckee River basin, the Farad and Vista stream discharge data were reviewed for each date indentified as a flood flow at Reno. Confirmation of extensive basin flooding required both the Farad and Vista daily discharge levels to fall above the 95th percentile of all daily discharge data for that station. In each Reno flood event, this was in fact the case (Tables 1 and 2).

c. Synoptic-scale compositing procedure

From the 14 flooding episodes identified in the Truckee River basin (1950–2007), two populations of storms were defined—those producing class 1 streamflow and those producing class 2 streamflow—at the Reno site. Seven storms compose each of these two classes (Tables 1 and 2). However, two of the class 1 floods were recorded in May and were the result of multiday persistent rainfall on snowpack. These two events were removed from the analysis and thus confining the research to winter-season storms. A synoptic-scale composite analysis of various atmospheric parameters was carried out for each of the two groups at 24-h temporal intervals. These parameters include mean sea level pressure (MSLP), 1000–500-hPa thickness, 850-hPa heights and wind, 700-hPa heights and mixing ratio, 500-hPa heights and absolute vorticity, and 250-hPa heights and wind. The 0000 UTC observation on the day of peak streamflow at the Reno site was set as the zero hour (00) of each storm, with the prior 24- and 48-h periods identified as T₋₂₄ and T₋₄₈, respectively. These
time-relative composites were produced using North American Regional Reanalysis (NARR) and the National Centers for Environmental Prediction (NCEP) reanalysis data gridded datasets. The Unidata Integrated Data Viewer (IDV) was used to construct synoptic-scale composites. Methods for this analysis were similar to those used in Mote et al. (1997) and Underwood and Meentemeyer (1998). A preliminary screening of each case study was conducted to ensure the cases were appropriate for a compositing analysis.

3. Synoptic-scale analysis of moderate flooding (class 1) events at the Reno site

a. Composite MSLP and 1000–500-hPa thickness

Synoptic-scale circulations and parameters associated with class 1 flooding events at the Reno site are assessed in this section. Figure 2 illustrates the composite patterns for MSLP and 1000–500-hPa partial thickness for $T_{24}$, $T_{24}$, and $T_{00}$. This 3-day sequence reveals a deep surface low dominating the entire area of the Gulf of Alaska with a central closed isobar at 980 hPa. The 980-hPa closed low expands and shifts eastward during the 3-day period.

A strong surface pressure gradient is established along the west coast of Canada and the northwestern United States. At $T_{24}$ and $T_{48}$, the pressure gradient takes on a distinct southwest–northeasterly tilt-orienting flow onshore along the northwestern coast of the United States. From $T_{24}$ to $T_{48}$ there is compression of the surface isobars along the northern coast of California. This stronger pressure gradient coincides with an initial surge of colder air that is juxtaposed with strong warm-air advection from the south and southwest in advance of the front boundary, as evidenced by the 1000–500-hPa thickness analysis at $T_{48}$.

At $T_{24}$, a strong thickness gradient exists across the central and eastern Pacific—the result of warm temperatures in the tropics and the southward advance of multiple cold pools from north of 50°N. This baroclinic environment gives rise to 1000–500-hPa thickness estimates of 5700 gpm at 25°N and 5200 gpm at 50°N, with a distinct thickness ridge off the northwestern U.S. coast. Looking at surface charts for individual storms constituting the composite analysis, one or multiple cold frontal boundaries are found proximal to 130°W at $T_{24}$, which are similar to findings from Dettinger et al. (2004), who looked at heavy precipitating storms in the Sierra

### Table 1. Streamflow observations (cfs) for class 1 flooding events at three USGS gauging stations. Also included is the 95th percentile streamflow at both Farad and Vista. The observed discharge on the dates listed can be compared to the 95th percentile discharge to determine the magnitude of the flood flows at both Farad and Vista on dates when the Reno gauging station recorded a flood flow.

<table>
<thead>
<tr>
<th>Flood date</th>
<th>Streamflow at Reno (cfs)</th>
<th>Precipitation at leeside station (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 Jan 1970</td>
<td>7400</td>
<td>—</td>
</tr>
<tr>
<td>14 Jan 1980</td>
<td>8630</td>
<td>25</td>
</tr>
<tr>
<td>20 Dec 1981</td>
<td>8690</td>
<td>8</td>
</tr>
<tr>
<td>13 Mar 1983</td>
<td>7230</td>
<td>19</td>
</tr>
<tr>
<td>8 Mar 1986</td>
<td>9140</td>
<td>26</td>
</tr>
</tbody>
</table>

### Table 2. Same as Table 1 for class 2 flooding events.

<table>
<thead>
<tr>
<th>Flood date</th>
<th>Streamflow at Reno (cfs)</th>
<th>Precipitation at leeside station (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 Jan 1970</td>
<td>6360/2820</td>
<td></td>
</tr>
<tr>
<td>14 Jan 1980</td>
<td>6880/2050</td>
<td></td>
</tr>
<tr>
<td>20 Dec 1981</td>
<td>7990/2570</td>
<td></td>
</tr>
<tr>
<td>13 Mar 1983</td>
<td>6280/2850</td>
<td></td>
</tr>
<tr>
<td>8 Mar 1986</td>
<td>11 400/2830</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3. Same as Table 1 for class 2 flooding events.

<table>
<thead>
<tr>
<th>Flood date</th>
<th>Flow (cfs) at Vista on Reno flood date/95th percentile flow at Vista</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 Nov 1950</td>
<td>8750/1970</td>
</tr>
<tr>
<td>23 Dec 1955</td>
<td>—</td>
</tr>
<tr>
<td>1 Feb 1963</td>
<td>17 400/2700</td>
</tr>
<tr>
<td>23 Dec 1964</td>
<td>10 700/2740</td>
</tr>
<tr>
<td>18 Feb 1986</td>
<td>15 200/2910</td>
</tr>
<tr>
<td>2 Jan 1997</td>
<td>16 100/2430</td>
</tr>
<tr>
<td>31 Dec 2005</td>
<td>11 300/3280</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flood date</th>
<th>Flow (cfs) at Farad on Reno flood date/95th percentile flow at Farad</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 Nov 1950</td>
<td>11 000/1050</td>
</tr>
<tr>
<td>23 Dec 1955</td>
<td>13 400/2450</td>
</tr>
<tr>
<td>1 Feb 1963</td>
<td>7960/2160</td>
</tr>
<tr>
<td>23 Dec 1964</td>
<td>9090/2450</td>
</tr>
<tr>
<td>18 Feb 1986</td>
<td>6620/2500</td>
</tr>
<tr>
<td>2 Jan 1997</td>
<td>12 400/2050</td>
</tr>
<tr>
<td>31 Dec 2005</td>
<td>7130/2210</td>
</tr>
</tbody>
</table>
Nevada. From $T_{24}$ and $T_{48}$, the partial thickness ridge begins to flatten with the advance of the cold front; however, warm air is observed through the lower and midtroposphere over the study area as 1000–500-hPa thickness values of 5500 gpm are estimated in the composite analysis as late as $T_{00}$.

b. Composite 850-hPa heights and wind

A deep closed low is present at 850 hPa in the Gulf of Alaska throughout the 3-day composite analysis (Fig. 3). The closed isobars associated with the low at 850 hPa shift eastward during the 3-day analysis period. At $T_{48}$, strong winds (55 kt or 28 m s$^{-1}$) are apparent in the westerly flow north of the Hawaiian Islands. At $T_{24}$, the wind speeds of 20 m s$^{-1}$ are observed at approximately 130$^\circ$W. Also at $T_{24}$, the 850-hPa flow from 130$^\circ$W to the California coast shifts and becomes southwesterly, bringing warm air into the Sierra Nevada. This shift in flow is forced in part by the southward deepening of the Gulf of Alaska low in concert with a building ridge of high pressure off of Baja California. As the ridge builds into the Four Corners region of the United States, the southward-shifting low off the coast produces a steep southwest–northeast-oriented onshore pressure gradient. East of the low pressure area, the 850-hPa height contours diverge as a shortwave ridge builds into western British Columbia. The 850-hPa height gradient east of the Gulf of Alaska weakens appreciably as the flow comes onshore and encounters the ridge in western Canada. The trough-to-ridge flow at $T_{24}$ is aligned over the study region, providing warm-air advection to the central Sierra Nevada. At $T_{00}$, there is still vigorous southwesterly flow coming onshore along the central and northern California coast, and the eastward advance of the low pressure center also acts to flatten the shortwave ridge over the study region.

c. Composite 700-hPa heights and mixing ratio

The composite analysis at the 700-hPa level shows a broad moisture fetch well developed from west of Hawaii to the California coast at $T_{48}$. Here 700-hPa mixing ratio values of 4.5 g kg$^{-1}$ are observed just off the California coast, and this moisture plume extends south–north from 30$^\circ$ to 45$^\circ$N (Fig. 4). A deep low pressure area in the Gulf of Alaska is apparent at 700 hPa, with closed height contours at 2640 gpm. In the $T_{24}$ composite, there is evidence of a strengthening height gradient near 130$^\circ$W and a downstream 700-hPa ridge across British Columbia. The Gulf of Alaska low strengthens and shifts to the southeast at $T_{24}$ in conjunction with ridging in the height pattern at 30$^\circ$N associated with the high off of Baja California. This configuration forces the flow onshore from the southwest. The 3-day composite analysis suggests that a large volume of moisture originating at latitudes south of 25$^\circ$N and west of 150$^\circ$W is delivered to the study area in southwesterly flow at 700 hPa.
Moisture advection into the study region is confirmed in the $T_{00}$ composite as mixing ratio values greater than 5 g kg$^{-1}$ are in place across the Sierra Nevada and mixing ratio values of 4.5 g kg$^{-1}$ are evident into the Great Basin. This value of the mixing ratio is impressive for such a high level in the atmosphere because it indicates 700-hPa temperatures near or above 0°C at saturation. This represents a warm anomaly for this latitude.
at this time of year and suggests that liquid precipitation is likely across much of the elevated terrain of the Sierra Nevada.

d. Composite 500-hPa heights and absolute vorticity

Figure 5 illustrates the composite circulation at the 500-hPa pressure level. In the $T_{-48}$ composite, a broad trough is present from 125°W to 160°W, with the base of the trough extending southward to approximately 25°N. A downstream ridge is building at 115°W. The western flank of the ridge is building to the northwest, and the onshore flow at 500 hPa is from the west-southwest. At $T_{-24}$, the 500-hPa trough axis in the Pacific shifts eastward and the height gradient strengthens east of Hawaii. The near-shore flow along the West Coast of the United States is accelerated by the height gradient, whereas the ridging in the height field at 115°W suggests increasing flow velocity proximal to the study region. The flow into the Sierra Nevada from $T_{-24}$ to $T_{00}$ is from the southwest, and there is positive vorticity advection poleward of 35°N and negative vorticity advection south of this latitude. This feature (positive/negative vorticity couplet) may be the result of ageostrophic. At $T_{00}$, there remains strong onshore flow from the southwest and modest diffluence in the midtroposphere. The combination of positive vorticity advection and diffluent flow at 500 hPa with warm-air advection through the 1000–500-hPa layer and strong moisture advection at 700 hPa provides the needed ingredients for a heavy liquid precipitation event in the lee of the Sierra Nevada.

e. Composite 250-hPa heights and winds

The 250-hPa composite for the class 1 flooding events shows a persistent jet flow across the central and eastern Pacific Ocean, which is the result of a multiple cold pools advecting southward from polar latitudes and a warm tropical region (Fig. 6). At $T_{-48}$, a jet streak is identified as extending from 135°W to the international date line. Wind speeds at the core of the jet are in excess of 75 m s$^{-1}$. The 250-hPa flow begins to ridge as it makes landfall, and a prominent ridge axis is evident at 115°W. As the composite analysis transitions to $T_{-24}$, the jet flow makes landfall in northern California and the winds from 130°W to the coast becomes more southwesterly. This shifting of the upper-level flow is in part forced by the southeasterly digging of the upper-level trough at this pressure level. As the eastern flank of the trough becomes negative in its tilt, the downstream ridge builds westward and the flow south of the trough is forced to bend to the northeast from a pivot point at approximately 130°W. The southwesterly flow continues at $T_{00}$, with the jet streak exit region proximal to the study region (lee side of Sierra Nevada). The ageostrophic circulation associated with the exit region of the jet streak is positioned to enhance upward vertical motion in the region of the eastern Sierra Nevada, which has seen

FIG. 5. Same as Fig. 2 but for 500-hPa heights (gpm) and absolute vorticity ($3 \times 10^{-5}$ s$^{-1}$).
f. Composite soundings

Confirming the synoptic-scale analysis of warm and moist air arriving in the lee of the Sierra Nevada, the upstream radiosonde site at Oakland, California (OAK), shows moisture increasing from $T_{-48}$ to $T_{00}$ from the surface to 875 hPa (Fig. 7a). Wind speeds increase from 13 to 21 m s$^{-1}$ at 700 hPa for $T_{-48}$ to $T_{00}$, from 15 to 28 m s$^{-1}$ at 500 hPa, and from 31 to 44 m s$^{-1}$ at 250 hPa. Wind direction at each of the three time steps is from the south-southwest from the surface to 500 hPa and from the west above 300 hPa. The sounding also reveals that air temperature at OAK is above 0°C from the surface to 700 hPa at $T_{-48}$ and $T_{-24}$ and from the surface to 675 hPa at $T_{00}$. This upstream (from Reno) atmospheric profile provides evidence that the lower and midtroposphere were anomalously warm during the storms that produced moderate (class 1) flooding in the lee of the Sierra Nevada. Additionally, a midlevel jet (700–500 hPa) is seen in conjunction with the upper-level jet. Figure 7b shows the 48-h sequence at REV. In this sounding sequence from Reno, very strong southweste-ly winds are observed from 700 through 200 hPa. The sounding begins to moisten from the surface to 700 hPa from $T_{-24}$ through $T_{00}$, with the temperature sounding warmer than 0°C to levels above 700 hPa. This moisture and warm air along with speed shear in the mid and upper troposphere provides evidence of the cross Sierra advection of moisture that provides the preconditions for heavy liquid precipitation.

This composite analysis suggest that the storms that produce moderate leeside flooding in the Sierra Nevada are warm and moist through much of the lower and midtroposphere, which is a broad area of surface low pressure that, over a 48-h period, extends southward to produce a southwest–northeast-oriented pressure gradient that is evident to 500 hPa. This pressure gradient modulates the onshore flow of moisture that eventually reaches the Sierra Nevada. Leeside storms that produce class 1 floods are also characterized by strong winds through the depth of the troposphere that help to advect moisture over the Sierra Nevada crest.

4. Synoptic-scale analysis of extreme flooding (class 2) events at the Reno site

a. Composite MSLP and 1000–500-hPa thickness

The $T_{-48}$, $T_{-24}$, and $T_{00}$ composites are shown in Fig. 8. In each of the composite plots, there is a large area of low pressure occupying the Gulf of Alaska and stretching westward to 165°W. The low expands eastward during the 3-day period and at $T_{-24}$ begins to extend southward, creating a synoptic-scale trough with its axis intersecting...
FIG. 7. (a) OAK and (b) REV composite 0000 UTC soundings for the class 1 flooding events at the Reno site. Plot sequence (−48, −24, −00) is the same as in Fig. 2.
the Hawaiian Islands. The surface low is juxtaposed with a stationary high-pressure area extending from 25°N into southern California. The eastward shift of the Gulf of Alaska low and the high-pressure ridge forces an increase in the pressure gradient and reorients the gradient from east–west to southwesterly off the coast of the northwestern United States.

The $T_{-48}$ and $T_{-24}$ composite thickness analyses present a scenario in which a well-defined baroclinic zone exists across the entire central and eastern Pacific Ocean. Cold temperatures and attendant lower thickness values ($<5300$ gpm) dominate the Pacific above 45°N, whereas warm air and higher thickness values ($>5550$ gpm) are found at 30°N. A 1000–500-hPa thickness ridge along the U.S. coastline provides evidence that warm air is advecting into the study region at $T_{-24}$ and $T_{00}$. As this thickness ridge develops at $T_{-24}$, the 5400-gpm contour intersects the coast at the United States–Canada border and the partial thickness estimate across the central Sierra Nevada is 5500 gpm. At $T_{00}$, the thickness ridge shifts further eastward; the central Sierra Nevada is still under the 5500-gpm thickness contour, suggesting that prior to and during the heavy precipitation in the Truckee River basin temperatures are warm (above freezing) through the lower and midtroposphere.

b. Composite 850-hPa heights and wind

In the composite analysis at 850 hPa, one can see a pattern very different from the class 1 storms. There is an elongated closed low off the coast of the northwestern United States at $T_{-48}$ that shifts southward at $T_{-24}$. In the instance of moderate flooding (class 1 storms), the low remained centered in the northern reaches of the Gulf of Alaska (Fig. 9). The trough associated with the low-pressure area is positively tilted at $T_{-24}$ and becomes more so at $T_{00}$. The intensification of the low in conjunction with a building high-pressure ridge in the southwestern United States/northern Mexico produces a steep height gradient oriented from southwest to northeast at $T_{-24}$. The $T_{-24}$ trough axis is located at 150°W, and the downstream ridge axis is found at 115°W. The orientation of the trough-to-ridge flow brings wind speeds in excess of 21 m s$^{-1}$ (a low-level jet) onshore over the central portion of the Sierra Nevada at $T_{-24}$, with wind speeds slowing to 18 m s$^{-1}$ at $T_{00}$ as the downstream ridge flattens. The southwesterly flow at 850 hPa extends from the trough axis at 20°N and consistently advects warm moist air into the lower troposphere above the study region for the three days of the analysis. This is in contrast to the class 1 events in which a rather flat trough amplifies equatorward to only 35°N.

c. Composite 700-hPa heights and mixing ratio

The 700-hPa composite analysis reveals that the height field above 40°N resembles an omega-blocking configuration (Fig. 10). A large amplifying anticyclone is flanked east and west by two closed lows (the west flanking low is not shown in the figure). The downstream flanking low of
The omega circulation is aligned with the surface low that was analyzed in the southern portion of the Gulf of Alaska. This cold-core low is centered at 45°N, 145°W at T₀₀ while a warm anticyclone is amplifying and producing a ridge centered near the Gulf of California.

The eastward-flanking low of the omega structure also plays a role in modulating the onshore flow direction at 700 hPa as the time sequence progresses from T₋₄₈ to T₀₀. At T₋₄₈, the eastward-flanking low is positioned with its major axis oriented west–east and a broad

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**Fig. 9.** Same as Fig. 3 but for class 2 flooding events.

**Fig. 10.** Same as Fig. 4 but for class 2 flooding events.
trough observed from 125° to 160°W. At $T_{-24}$, the eastward-flanking low begins to dig equatorward, relieving the positive tilt of the trough in the Gulf of Alaska. As the Gulf of Alaska low pivots and the eastward-flanking trough shifts its orientation from west–east to southwest–northeast, the ridge in the region of the Gulf of California simultaneously amplifies. This produces a strong height gradient from 150°W to the California coast and also produces a turning of the onshore flow from westerly to southwesterly.

The 700-hPa flow south of the omega structure has a $T_{-24}$ trough axis at 20°N, 160°W. The environment encounter by this broad trough in the tropical latitudes is moist and warm. Extensive moisture advection is seen in both the $T_{-24}$ and $T_{00}$ composites at 700 hPa. Mixing ratio values of 5 g kg$^{-1}$ are present in the $T_{-24}$ composite just off the central California coast. At $T_{00}$, a vast plume of moisture is analyzed across the Sierra Nevada and extends into the Great Basin. Mixing ratio values greater than 5 g kg$^{-1}$ are observed from the San Francisco Bay in California to central Nevada at this time. The combination of the deepening low in the Gulf of Alaska along with vigorous onshore moisture advection provides an environment conducive for heavy precipitation in the Sierra Nevada. In each of the seven cases in this composite analysis, a cold front associated with the surface cyclone in the Gulf of Alaska moved onshore between $T_{-24}$ and $T_{00}$, finding conditions in the central Sierra Nevada warm and moist through 600 hPa. The saturation level in the class 2 events is 100 hPa higher in the troposphere than the class 1 events.

d. Composite 500-hPa heights and absolute vorticity

The composite analysis of 500-hPa heights illustrates the advent of the omega-blocking pattern north of 45°N (Fig. 11). The large-scale anticyclone in the center of the omega circulation occupies all of continental Alaska, and the flanks of the anticyclone at this level are occupied by deep troughs. On the eastward flank of the omega circulation is a positively tilted trough with its $T_{-48}$ axis at 150°W. The 500-hPa flow equatorward of the omega structure at $T_{-48}$ is meridional across much of the Pacific Ocean (between 20° and 45°N). In similar fashion to what was seen at 700 hPa, the 500-hPa eastward-flanking trough in the omega circulation becomes less positively tilted and shifts eastward from $T_{-24}$ to $T_{00}$. This shift and reorientation of the upper-level trough coincides with a building ridge from 20°N, approximately centered over the Gulf of California. This combination increases the intensity of the height gradient from 140°W to the California coast and allows the 500-hPa flow to shift from westerly to southwesterly at $T_{-24}$ and $T_{00}$. At $T_{-24}$, the trough-to-ridge flow in the 500-hPa field is aligned with the central Sierra Nevada at its center. The spreading of height contours as the flow encounters the western portion of the continent suggests diffuuent flow at this pressure level coincident with positive vorticity advection into the central Sierra Nevada. This combination allows for vigorous vertical
motion near the study region. This vertical motion is occurring in an environment that is warm and near saturation from the surface to 600 hPa.

e. Composite 250-hPa heights and winds

The baroclinic environment described in section 4a, which includes most of the central and eastern Pacific, gives rise to a vigorous jet flow at 250 hPa. The jet flow is equatorward of the ridge and trough pattern whose base is at 45°N and resembles the omega-blocking circulation that has been seen from 700 through 500 hPa (Fig. 12). At T_{24}, the polar jet splits and the southerly branch flows between the latitudes of 25° and 45°N over the Pacific. The jet stream at T_{24} flows west–east in a meridional pattern from the westward edge of the analysis box to just west of the North American coastline (~125°W). There is a downstream ridge in the 250-hPa flow at approximately 110°W. The T_{24} wind speeds in the jet flow are maximized east of Hawaii at 55 m s^{-1}.

The jet flow begins to accelerate at T_{24} and T_{00}. The acceleration can be attributed to the east-flanking trough of the omega circulation digging southward from the Gulf of Alaska (from 45° to 35°N) and the downstream ridge amplifying and becoming broader in spatial extent. The wind speed in the southerly branch of the polar jet at T_{24} is maximized at 60 m s^{-1}, and there are two jet streaks identified in the 250-hPa flow. The jet streaks at T_{24} are oriented in a fashion that supports coupling of ageostrophic circulations from the exit region of the upstream jet streak (thermally indirect ageostrophic circulation) and the thermally direct ageostrophic circulation from the entrance region of the downstream jet streak. The coupling of ageostrophic circulations has been noted by Uccellini and Kocin (1987) during winter storms on the east coast of North America, and this configuration can provide broad-scale vertical lift in the region of coupling. This is the case for class 2 flooding at the Reno site, as the heaviest rainfall in a majority of the leeside storms occurred from T_{24} to T_{00} in the presence of two adjacent jet streaks. At T_{00}, the flow at 250 hPa accelerates with maximum wind speeds in the jet streak making landfall at 65 m s^{-1}. The orientation of this single (but expansive) jet streak is such that the exit region’s ageostrophic circulations can continue to assist in vertical motion across the Sierra Nevada and into the interior of the western United States.

f. Composite soundings

The final analysis for the class 2 storms is a composite view of the OAK sounding (Fig. 13a). The composite soundings from T_{24}, T_{24}, and T_{00} confirm what has been seen at the synoptic scale from the surface to the 250-hPa level—most notably the increase in moisture and temperature through a deep layer of the troposphere and the existence of multiple jet flows from 850 hPa to the top of the troposphere. The T_{24} sounding reveals an atmosphere with saturated conditions at the surface and moist conditions (dewpoint depression less than 4°C from 850 to 300 hPa). As noted in the Ralph

FIG. 12. Same as Fig. 6 but for class 2 flooding events.
FIG. 13. Same as Fig. 7 but for class 2 flooding events.
et al. (2005) study, strong Pacific storms often show evidence of a low-level jet and a low-level atmospheric river as they make landfall. The jet is evident at 850 hPa in the $T_{24}-T_{00}$ composites as winds accelerate to speeds greater than 25 m s$^{-1}$ at this level.

Looking to the $T_{00}$ composite sounding, there is evidence of a deep moisture layer. The composite troposphere is saturated to just below 700 hPa, and the moist neutral sounding is less than 3°C from saturation to pressure levels above 600 hPa. This moist layer above 850 hPa and the accelerating wind speeds from 850 to 600 hPa (15 to 28 m s$^{-1}$) suggests the existence of a secondary atmospheric river above the low-level jet and the atmospheric river identified by Ralph et al. (2004, 2005). This secondary filament of moisture is at a level (600 hPa) that would allow the strong west-southwesterly winds to advect the moisture over the Sierra Nevada crest and make that moisture available for leeside precipitation. As we have seen in the synoptic-scale analysis, there is a near-perfect confluence of dynamic forces to provide vertical motion and the formation of liquid precipitation in the lee of the Sierra Nevada. The composite OAK soundings confirm that the conditions for class 2 flooding events are substantially different from the class 1 events and are also different from storms that produce heavy rainfall exclusively on the windward slopes of the Sierra Nevada.

Figure 13b illustrates the 48-h sounding sequence at REV. In this sounding sequence from Reno, very southwesterly winds are stronger than those observed in the class 1 composites from 850 through 200 hPa. The sounding begins to moisten more quickly than the class 1 sounding as saturated conditions are observed to 850 hPa in the $T_{24}$ composite. A deep moist layer and strong midlevel and upper-level jets are also prominent in the $T_{00}$ sounding at REV.

The class 2 events are identifiable by the depth of warm moist conditions in the troposphere, consistent with stronger westerly-southwesterly flow from the surface to 500 hPa. Saturation of the lower and midtroposphere in the class 2 episodes has a profound effect on the cross-mountain flux of moisture to the leeside basins of the Sierra Nevada.

5. Discussion of class 1 versus class 2 flooding precipitation events

This study began with an assumption that there were two distinct populations of winter storms producing leeside precipitation in the Sierra Nevada and flooding in the Truckee River basin. The initial assumption was based solely on hydrologic data, with moderate and extreme flood flows in the Truckee River basin serving to distinguish the two populations. The atmospheric fields and parameters tested in this study confirm that there are in fact two distinct atmospheric flow scenarios that produce leeside precipitation in the Sierra Nevada (Fig. 14).

Highlighting the dissimilarity between the class 1 and class 2 circulation patterns is the position of the low-pressure center in the northeastern Pacific Ocean and the synoptic-scale circulation configuration in latitudes above 45°N prior to peak streamflow. Coincident with storms that produce extreme flooding at the Reno site, the 700-, 500-, and 250-hPa composite analysis fields all resemble an omega-blocking circulation pattern above 45°N. The low-pressure area and trough on the eastward
flank of the omega structure provides storm-specific circulation for class 2 flooding events. Flow south of the omega-blocking pattern is characterized by a broad trough across most of the eastern Pacific and southwesterly flow at 700, 500, and 250 hPa. In contrast, the storms that produce class 1 flood flows (moderate flooding) at the Reno site do not show this omega circulation structure above 45°N. Instead, these storms are dominated by a large area of low pressure that extends across the Gulf of Alaska and an amplified ridge downstream along the western portion of the North American continent.

The midtropospheric flow as seen in the 500-hPa composite analyses provides evidence that the storms producing extreme flooding in the lee of the Sierra Nevada have a deeper trough across the central Pacific Ocean as a result of the omega-blocking flow. The easterly flanking low in the omega structure in these events is centered just off of British Columbia and is positively tilted throughout the 48-h composite analysis. This is in contrast to a negatively tilted midtropospheric trough at 500 hPa in the class 1 composite analysis. The positively tilted trough in the class 2 events shifts to the northeast between the $T_{-24}$ and $T_{00}$ composites, and at $T_{00}$ the trough axis begins to migrate southward. This produces a steep onshore pressure gradient that extends from the California coast to the Sierra Nevada. This strong pressure gradient and southwestern flow through the midtroposphere enhances the flow of moisture across the Sierra Nevada peaks and assists in modulating the heavy rainfall required to produce extreme flooding in leeside basins.

The midlevel moisture flow in the class 1 storms is also weaker than in the class 2 storms. The class 2 composite analysis at the 700-hPa level shows an extensive and continuous band of moisture from well south of Hawaii stretching northeast to the continent. The class 2 composite analysis suggests that prior to the peak flood flow at the Reno site, 700-hPa mixing ratio values in excess of 5 g kg$^{-1}$ exist along the coast of California. In the class 1 composite at 700 hPa, the moisture plume is limited in spatial extent with its origins just north of the Hawaiian Islands. Maximum mixing ratio values were 4.0–4.5 g kg$^{-1}$ off the coast prior to moderate flooding at the Reno site.

Another distinct difference in the class 1 and class 2 populations is the depths of moisture and warm air upstream of the study region. An atmospheric sounding at Oakland was used for this analysis. At all three composite time steps ($T_{-24}$, $T_{-48}$, and $T_{00}$), the class 2 events are more moist (closer to saturation) than the class 1 events and the moisture is available to a greater depth in the troposphere compared to class 1 events. In the composite sounding coincident with peak streamflow at the Reno site, the class 2 atmosphere at OAK is saturated to 700 hPa and dewpoint depressions are less than 3°C to 600 hPa. At the same time in the class 1 events, the atmosphere is saturated to 850 hPa with dewpoint depressions less than 3°C to 775 hPa. Wind speeds measured at OAK also confirm that the class 2 events possess midtropospheric conditions conducive to transporting large volumes of moisture over the Sierra Nevada crest. In particular, the wind speeds above 700 hPa are in excess of 26 m s$^{-1}$ in concert with a near-saturated environment. Temperature profiles for both classes of leeside flooding events reveal warm temperatures (above freezing) to 700 hPa. The class 2 events are warmer than $-10°C$ to nearly 500 hPa, whereas the class 1 events cool to $-10°C$ at 550 hPa.

In conclusion, the hypothesis for this study—that winter-season floods of varying magnitudes in leeside basins of the Sierra Nevada have correspondingly varied synoptic-scale circulation patterns—is confirmed. This hypothesis was confirmed through a composite analysis of synoptic-scale fields. Confirmation of the hypothesis is based on the observed departure in magnitude of analysis fields, primarily those describing moisture, wind speed, and temperature in the midtroposphere.

6. Discussion of class 2 events versus storms affecting the windward Sierra Nevada

It is clear from both the literature discussing heavy rainfall on the windward side of the Sierra and the composite analysis in this study that there are similarities in these two populations of storms. In fact, two of the storms incorporated in this composite analysis (December of 1997 and 2005) were also the subject of studies focused on heavy precipitation in California (Galewsky and Sobel 2005). However, there are discernable patterns at the synoptic scale that suggest that heavy liquid precipitation in the lee of the Sierra Nevada results from processes that are either more intense or of differing character (direction, depth, and proximity) from those of storms affecting only the California coastal mountains and the west slope of the Sierra Nevada (for this discussion, these storms will be called “California storms”). This conclusion is based on a comparison of the class 2 composite results from this analysis to previously published analyses of storms producing heavy liquid rainfall in the mountains of California. In this comparison, the authors looked at California storms from 12 February 1986 (Rauber 1992), 26 January 1998 (Ralph et al. 2004), and 17 February 2001 (Ralph et al. 2005).

Features that distinguish the class 2 storms from California storms include the position and the amplification of the low and attendant trough centered in the
Gulf of Alaska. In the California storms, the low is positioned farther south and eastward and is much deeper than the class 2 storms. The resulting onshore flow from the surface to 500 hPa in the California storms has a stronger meridional component. The southerly flow coming onshore therefore has the potential flow along the windward slope compared to the west-southwesterly onshore flow in the class 2 storms that is normal to the Sierra Nevada crest.

To further illustrate the difference in class 2 and California storms, two cases (one class 2 and one California) are compared at similar stages in their development. The date of the representative class-2 storm is 17 February 1986 and the representative California storm occurred on 17 February 2001. The 1986 storm produced 85 mm of rainfall at stations in the lee of the Sierra, whereas the 2001 storm produced only a trace of precipitation in leeside basins. These storms are comparable because both occur on the same calendar date, both originate in the central Pacific, and both storms occur during winters in which the Pacific Ocean exhibited a modestly negative multivariate ENSO index (MEI) value (Wolter and Timlin 1993; Wolter 1987). The discussion below is based on 500-hPa geopotential height plots, OAK soundings, and 250-hPa plots from each storm. No figures are provided, but the reader can produce these easily using a number of online resources.

A comparison of 500-hPa heights suggests that an omega-blocking circulation is dominant above 45°N in the class 2 storm; however, this pattern does not exist for the representative California storm. The upper-troposphere low in the California storms is centered at 40°N, 130°W, and the trough axis at 130°W is amplified southward to 20°N. The class 2 storm has a 500-hPa low centered at 40°N, 155°W, and this low is the easterly flank of an omega-blocking circulation pattern with a large anticyclone centered at 60°N, 165°W. Both storms have a ridge developing downstream of the synoptic-scale trough. The downstream ridge in the California storm is centered at 115°W and is tilting from this origin point to the extreme northwestern United States and British Columbia. The downstream ridge in the class 2 storm is centered at 125°W and does not have the northwesterly tilt of the California storm. This configuration of the low, trough, and downstream ridge produces a strong onshore gradient for both storms; however, the gradient in the California storm is oriented to bring flow onshore from the southerly direction, which is in contrast to the class 2 storm that exhibits onshore flow from the west-southwest. This flow dissimilarity is found from the surface to 500 hPa; therefore, the class 2 storm has a longer fetch over the moist environment of the south-central Pacific Ocean compared to the California storm. Additionally, the southerly flow exhibited in the California storm is nearly parallel to the Sierra Nevada after landfall compared to flow that is nearly perpendicular to the Sierra Nevada crest in the class 2 storm. Further, it is the case that class 2 storms possess mid- and upper-level wind speeds that are stronger than the California storms, giving the class 2 storms a greater propensity for advecting moisture across the topographic barrier and producing heavy rainfall in leeside basins.

The moisture content of the air upstream from the Sierra Nevada is another element that is in disagreement between the California storms and the class 2 storms. The OAK sounding suggests that the atmosphere is saturated from the surface to 700 hPa at 1200 UTC 17 February 1986 and that the winds at 700 hPa are from the west-southwest at 28 m s⁻¹. At 0000 UTC 18 February 1986, the OAK sounding is saturated to 500 hPa and the winds are strong—above 26 m s⁻¹ from 800 to 300 hPa. The atmosphere in the class 2 storm is also warm at 0000 UTC as temperatures greater than −10°C are observed to 550 hPa. The OAK sounding for 1200 UTC 17 February 2001 (California storm) reveals that the wind is southerly from the surface to the troposphere. Moisture is limited to the lower portion of the troposphere (below 750 hPa), and the warm layer is shallower than in the class 2 storm. At 0000 UTC 18 February 2001, the OAK sounding is still dominated by southerly flow with moderate wind speeds in the lower troposphere. Winds speeds reach 26 m s⁻¹ at 600 hPa. The sounding is near saturation to 700 hPa and then dries with height. Temperatures are less than −10°C to 600 hPa.

This sequence of soundings confirms what the composite analysis suggested—that the class 2 storms have more upstream moisture available compared to California storms, the lower and midtroposphere are warmer in class 2 storms compared to California storms, and the winds in the class 2 storms are more westerly and more vigorous through a greater depth of the troposphere than the California storms.

A final comparison of the two representative storms looked at the synoptic-scale flow and jet streams at 250 hPa. As the class 2 composite analysis showed in section four, the jet streak position was crucial in providing vertical motion (via ageostrophic circulation) in the lee of the Sierra Nevada. The class 2 storm from 17 February 1986 sees a broad jet streak over the Sierra Nevada at the time of heavy rainfall in the lee of the mountain range. The core of the jet flow possesses wind speeds greater than 75 m s⁻¹, and the exit region circulation is positioned favorably for intensification of vertical motion east of the Sierra Nevada crest. In the California storm of 17 February 2001, a tropical branch of the jet
provides southerly flow into California; however, the flow is muted with wind speeds less than 50 m s\(^{-1}\). Also, there is no discernable jet streak in the onshore flow and thus little intensification of vertical motion in the troposphere.

This study has shown that there are indeed two distinct flow regimes that produce moderate and extreme flooding in the Truckee River basin. The study has also suggested that the class 2 floods are the result of storms that differ from those Pacific-originating storms that produce heavy rainfall exclusively in the coastal mountains and on windward slopes of the Sierra Nevada in California. The deeper moisture layer (to 600 hPa) and more vigorous wind profile in the class 2 storms prove to be of great importance in distinguishing leeside rainfall events from California storms.

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