A Climatology of 500-hPa Closed Lows in the Northeastern Pacific Ocean, 1948–2011

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ABSTRACT
The northeastern Pacific Ocean is a preferential location for the formation of closed low pressure systems. These slow-moving, quasi-barotropic systems influence vertical stability and sustain a moist environment, giving them the potential to produce or affect sustained precipitation episodes along the west coast of the United States. They can remain motionless or change direction and speed more than once and thus often pose difficult forecast challenges. This study creates an objective climatological description of 500-hPa closed lows to assess their impacts on precipitation in the western United States and to explore interannual variability and preferred tracks. Geopotential height at 500 hPa from the NCEP–NCAR global reanalysis dataset was used at 6-h and 2.5° × 2.5° resolution for the period 1948–2011. Closed lows displayed seasonality and preferential durations. Time series for seasonal and annual event counts were found to exhibit strong interannual variability. Composites of the tracks of landfalling closed lows revealed preferential tracks as the features move inland over the western United States. Correlations of seasonal event totals for closed lows with ENSO indices, the Pacific decadal oscillation (PDO), and the Pacific–North American (PNA) pattern suggested an above-average number of events during the warm phase of ENSO and positive PDO and PNA phases. Precipitation at 30 U.S. Cooperative Observer stations was attributed to closed-low events, suggesting 20%–60% of annual precipitation along the West Coast may be associated with closed lows.

1. Introduction
Closed and cutoff lows can have a significant influence on precipitation in the western United States. Understanding these systems adds value to analysis of precipitation variability and provides insights for water resource management in this region. Precipitation exhibits high spatial and temporal variability throughout the western United States, with the Southwest being notably arid and having large year-to-year fluctuations in precipitation totals (Cayan et al. 1998). Interannual storm variability has strong implications for California’s water supply; the difference of a few large storms in a year can dictate drought or wet conditions (Dettinger et al. 2011).

Water demands continue to increase in California, where the population is currently over 37 million and is expected to grow to over 50 million by 2050. Water resource concerns are exacerbated by the fact that roughly 65% of the state’s precipitation occurs in the northern one-third of the state while 75% of the water demand lies in the southern one-third of the state. (California Department of Water Resources 2005). Nevada faces issues that are similar to those of California. It is the most arid state in the United States, with only 10% of precipitation falling in the state resulting in stream runoff or groundwater recharge. The remaining 90% is lost to evaporation and transpiration (Nevada Division of Water Planning 1999). Nevada’s population grew by 74% between 2000 and 2010 (U.S. Census Bureau 2012). This high rate of growth puts severe strains on Nevada’s water resources (Nevada Division of Water Planning 1999).

Results of modeling studies also give reason for concern about the future of water resources in the West. A study of model projections of precipitation in the Southwest out to 2100 by Seager et al. (2007) utilized 19 climate models involved in the Intergovernmental Panel on Climate Change Fourth Assessment Report and used the A1B scenario in which carbon dioxide emissions increase until midcentury and then decrease modestly. An increase in temperature and decrease in precipitation...
for the region was favored by 16 of the 19 projections. Other modeling studies using the National Center for Atmospheric Research (NCAR)–U.S. Department of Energy Parallel Climate Model for the western United States indicated small changes in annual precipitation but a marked decrease in snowfall and an earlier snow-melt (Leung et al. 2004; Cayan et al. 2008). With these projections of potential water resource impacts, understanding precipitation variability is vital to management of water resources in the West.

a. Closed lows

A closed low is defined as an area of low pressure with a distinct center of cyclonic circulation that can be completely encircled by one or more height contours (NOAA 2011). Definitions in the literature are similar but vary the necessary contour interval. Bell and Bosart (1989) consider a closed low to be “defined by at least one closed 30 m contour around a central minimum...” and Parker et al. (1989) require “the existence of at least one closed (approximately) 6-dekameter height contour around low...heights...”. Figure 1 presents an example of a closed low off the coast of California in a visible satellite image and a contour plot of 500-hPa isohyges.

In this study, the term “closed low” is inclusive of both closed lows that remain attached to the mean westerly flow as well as cutoff lows—closed lows that are completely displaced from the mean westerly flow. Closed low pressure systems are typically cold core because of the origin of the central air mass in high latitudes in the mid- to upper-level troughs from which they originate. The easterly, cyclonic flow on their polar side opposes the mean westerly flow of the jet in which the feature is or was embedded and thus retards its downstream propagation. Closed and cutoff low pressure systems have been observed to remain stationary, meander, and even retrograde and are therefore capable of affecting weather over an area for a sustained period of time (Nieto et al. 2008).

b. Closed lows in previous research

Abundant research has shown the northeastern Pacific Ocean to be one of several preferential locations in the Northern Hemisphere for the formation of closed lows (Bell and Bosart 1989; Parker et al. 1989; Kentarchos and Davies 1998; Smith et al. 2002; Nieto et al. 2005, 2008). Current understanding suggests several factors lead to closed-low development in the region. Planetary wave breaking has been identified as one of the main producers of cutoff lows (Nieto et al. 2008), and the northeastern Pacific has been shown to be one of the more favorable locations for wave-breaking activity (Postel and Hitchman 1999; Abatzoglou and Magnusdottir 2006). Blocking patterns commonly develop over the eastern Pacific and North America and disrupt the westerly flow. These can lead to the development of quasi-barotropic, slow-moving closed-low features (Weaver 1962; Monteverdi 1976).

Previous work has examined the spatial and seasonal distributions and durations of 200-hPa cutoff lows in the Northern Hemisphere (Kentarchos and Davies 1998; Nieto et al. 2005) and the spatial and temporal distribution of 500-hPa closed lows in the Northern Hemisphere (Bell and Bosart 1989; Parker et al. 1989; Smith et al. 2002). Several climatological descriptions of extratropical cyclones in the northeastern Pacific have also been developed on the basis of sea level pressure conditions...
minima (Zishka and Smith 1980; Favre and Gershunov 2006). Nguyen and DeGaetano (2012) developed a climatological description of 500-hPa closed lows over the northeastern United States and explored associated trends in surface precipitation. Absent in the body of work on low pressure systems in the northeastern Pacific is a climatological description of tracks of midtroposphere closed lows, interannual variability, and impact on precipitation in the western United States.

c. Study outline

To address the significance of closed lows, this study 1) develops a database of closed-low events in the northeastern Pacific from 1948 to 2011, 2) examines tracks and characteristics of closed lows, 3) assesses the role of closed lows in precipitation delivery, and 4) relates closed-low properties to large-scale circulation patterns. This study tests the hypotheses that closed lows are ubiquitous and important precipitation-generating systems in the western United States, that they exhibit variability over the study period, and that this variability may be explained by one or more atmospheric modes.

2. Methods

a. Data

National Centers for Environmental Prediction (NCEP)–NCAR global reanalysis data for 64 years (1948–2011) were used in this analysis (Kalnay et al. 1996). The global reanalysis data were preferred over the higher-resolution North American Regional Reanalysis because of their longer period of record: 1948–present versus 1979–present. The closed-low analysis used 500-hPa geopotential height (gpm) at the global reanalysis native 2.5° × 2.5° spatial resolution and for four daily times (0000, 0600, 1200, and 1800 UTC). The 500-hPa surface was chosen for the analysis to minimize terrain effects on the flow and to relate surface phenomena with midtroposphere flow in addition to allowing for comparison with other analyses at this level. The study area lies between 20° and 50°N and between 105° and 150°W and is shown in Fig. 2. To perform analyses along the edges of this domain, data were utilized to four grid points beyond the study area, thus incorporating data from 10° to 60°N and from 95° to 160°W. This region of study was selected on the basis of locations of closed lows as cited in previous literature (Bell and Bosart 1989; Nieto et al. 2005) and for interest in events affecting the U.S. West Coast. The area most commonly defined as the northeastern Pacific in literature and satellite information from the National Oceanic and Atmospheric Administration (NOAA) extends over the Pacific Ocean to the Bering Sea in the north, southward to the Mexico–Guatemala border, and westward to the international date line (Croom et al. 1995; NOAA Satellite and Information Service 2012). This study area encompasses a majority of this region (Fig. 2) and thus is referred to as the northeastern Pacific. The range of the study area was restricted in an attempt to exclude tropical cyclones as well as the climatological Aleutian low.

b. Diagnosis of 500-hPa closed lows

An automated routine was developed to identify and track closed lows that was based on trials of methods encountered in the literature (Bell and Bosart 1989; Nieto et al. 2005; Nguyen and DeGaetano 2012). The basic concept to identify closed lows discussed in the literature was to find a height minimum among adjacent surrounding grid points and then to add in other criteria to verify that a closed low is present. The algorithms presented in the literature varied both the height difference required between the central and surrounding points and the number of surrounding points (of 8) that must have height values greater than the central point. Trials to develop the algorithm presented in this study began with a restrictive requirement of a 30-gpm difference between a center and adjacent surrounding grid points and then to add in other criteria to verify that a closed low is present. The algorithms presented in the literature varied both the height difference required between the central and surrounding points and the number of surrounding points (of 8) that must have height values greater than the central point. Trials to develop the algorithm presented in this study began with a restrictive requirement of a 30-gpm difference between the center and all eight surrounding points. Each trial in the development of the algorithm underwent a subjective comparison with 500-hPa height-contour plots of the NCEP–NCAR global reanalysis data for calendar year 2011 (e.g., right panel of Fig. 1) to determine whether the desired closed-low features were captured. After the initial trial with 30 gpm and all eight points proved to be too restrictive, smaller geopotential-height differences (20, 10, 5, and 1 gpm) between a center and adjacent points were tested. In addition, trials experimented with requiring only 5, 6, or
7 of the 8 surrounding points to be greater than the central point. Trials that failed the subjective comparison with contour plots typically did so because they excluded large, saucer-shaped closed lows or included features such as trough appendages or lobes of irregularly shaped troughs. The final algorithm to identify the presence of a closed low, explained in Fig. 3, requires that the central point of all eight adjacent points be less than or equal to the surrounding points; requiring a larger height difference proved to be too exclusive to track continuous closed-low events. In addition, points on the adjacent surrounding 10° × 10° and 15° × 15° grids must have height values greater than the central point. Last, all central minima must have height values of less than 5690 gpm. The algorithm examines each point on the study area grid at each 6-h time step for 1948–2011 to determine whether these conditions are met.

The threshold of <5690 gpm was applied to central minima of closed lows to prevent the capture of minor concavities in ridges, and a few other undesirable features, as closed-low events. This value was determined by performing sensitivity tests to identify a threshold that, by visual inspection, included desirable closed-low events without returning any “false positives.” By imposing this threshold, a bias was introduced against closed lows forming south of 30°N or those that occur in a field of very high geopotential heights. Two to four desired events per year (roughly 5%–8% of events) were not captured by the algorithm and thus are not represented in the dataset. Events are missed in all seasons, although most frequently they are missed in September and October in agreement with the period during which the highest annual geopotential heights are often observed over the northeastern Pacific. For the analyses of interest in this paper, we feel this amount of error is acceptable given the benefit of excluding unwanted events, given the coarse nature of the NCEP–NCAR reanalysis dataset, and given that the results of the analyses performed would not be altered significantly by the inclusion of the missed events.

c. Tracking 500-hPa closed lows and determining events

After closed-low minima were identified for all time steps in all years, they were categorized into events on the basis of several criteria. A closed-low “event” in this study is defined as beginning when a height minimum identified by the algorithm first appears within the study area bounds (20°–50°N, 105°–150°W). This onset occurs when a closed low either 1) enters the study area or 2) forms within the bounds of the study area. A closed-low event ends when the closed low either 1) exits the study area or 2) dissipates within the study area such that the algorithm no longer identifies a height minimum associated with the event. Tracking a closed low requires that there must be only one representative point for an event at each time step. In the case of a flat-bottomed closed low, the height field at a given time may contain more than one minimum point representative of the same closed low. In these cases, the northernmost and westernmost point was chosen as the minimum to track as it would likely be the point closest to the general circulation as performed in Nieto et al. (2005).

Temporally consecutive closed-low centers are considered to be part of a continuous event and are retained in the final dataset if the following condition is met:

1) After appearance in the study area, the closed low must be present over a minimum of four consecutive
time steps (18 h) to be considered to be part of the event database.

If condition 1 is met, conditions 2 and 3 are tested to see if the event will persist beyond the 18-h minimum or if a new event is established:

2) If there is an interval of more than five time steps (24 h) between temporally consecutive points identified as closed lows, a new event begins at the later point and the event in progress ends at the earlier point.

3) If there is a change of latitude or longitude of greater than 7.5° between temporally consecutive points identified as closed lows, a new event begins with the later point and the event in progress ends at the earlier point.

Thus, a closed-low minimum that is present at 0600 UTC, is not identified at 1200 UTC, and is again present at 1800 UTC within 7.5° of the 0600 UTC position would be identified as a persistent 18-h closed-low event and would be included in the events dataset. As this example demonstrates, there may be one or more time steps that are desired as part of an enduring closed-low event for which the algorithm does not capture the feature as a closed low because of the temporary change in geometry of the feature such that it no longer meets algorithm requirements. Because it is desirable to include these time steps to create a continuous path of the closed-low event, interpolation was used to identify a height minimum for the time steps of an event not identified by the algorithm. Interpolation was also advantageous for creating and displaying smooth trajectories of the closed lows. At the coarse 2.5° × 2.5° native resolution of the data, closed-low event tracks appear as jagged lines and overlap since only 247 unique gridpoint location values are otherwise possible.

To smooth the trajectories and provide minima values for missing time steps, values on a 15° × 15° grid centered on each closed-low minimum were interpolated from the native 2.5° × 2.5° resolution to a fine-mesh grid of 0.01° × 0.01°. A Delaunay triangulation-based cubic interpolation technique was used in which the new interpolated surface passes through all original data points. The location and minimum of the resultant surface were determined from the interpolated fine-mesh grid, and a new latitude, longitude, and height minimum were assigned to each closed-low center with a precision of 0.01°. For time steps of an event for which a closed-low center is not defined by the algorithm, the same interpolation method was used centered on the mean of the latitude and longitude of the points preceding and following the missing time step. After continuous events were determined, all paths were smoothed with a two-point running-mean filter before plotting. The smoothing provides improved readability on plots of closed-low trajectories and is necessary to produce images of the probable continuous movement of the closed-low height minimum as it evolves throughout the duration of the event.

d. Determining depth and radii of closed lows

At each time step of an event, a radius and depth of the closed low were determined. The desired properties were the distance from the height minimum and the lowest depth at which, hypothetically, an equivalent closed-low basin filled with liquid would first begin to empty out. To calculate these values, a 25° × 25° grid about each center was interpolated to a finer-scale grid of 0.5° × 0.5° resolution, again using Delaunay triangulation-based cubic interpolation. A coarser grid was used in this instance than for the interpolation because unique values were not as necessary and to reduce computational time. On each interpolated grid, eight radial arms were extended out from the interpolated center point to the grid’s edges in the eight basic compass directions. Along each such arm, starting at the height minimum, heights every 0.5° (maximum of 50 points on each arm) were tested to check whether they were greater than at the point next most inward toward the minimum. When the first decrease occurred along an arm, the location of the point preceding that decrease was taken as the endpoint of the radius along that arm. After all eight arms were analyzed, the shortest radius was assigned as the radius of the closed low at that time step. The shortest radius will typically point toward where the closed low attaches to the mean westerly flow. The longer radii generally extend to south, southeast, and southwest, where heights continually increase with distance from the closed low. Depth of the low at that time step was then defined as the height value of the endpoint of the shortest radial arm minus the height value of the minimum of the closed low.

e. Precipitation associated with closed lows

To assess the relation of closed lows to precipitation, data from 30 daily U.S. Cooperative Observer Network (COOP) stations on the U.S. West Coast (Table 1) were analyzed. These data are part of the National Climatic Data Center “DSI3200” database and were obtained from the Western Regional Climate Center (WRCC 2012). A majority of the COOP stations selected were located at airports and should be relatively free of instrument biases.

Precipitation was assigned to a closed low if a station was within the radius of the closed low when precipitation occurred. Daily recording time varied both
temporally during individual station histories and among the 30 stations. To accommodate this timing uncertainty and to account for closed lows leaving lingering convective precipitation after they pass over an area, a 3-day window was allotted. Precipitation occurring 1 day preceding or following the presence of a station within a closed-low radius was attributed to the closed low as well. Closed-low times were converted from their UTC date to local calendar date in Pacific standard time (PST): 1200 UTC (0400 PST) and 1800 UTC (1000 PST) represent the current PST day and 0000 UTC (1600 PST) and 0600 UTC (2200 PST) are date shifted backward 1 day from the UTC date to the PST calendar date. Precipitation days attributed to closed lows were not counted more than once in the 3-day range for consecutive closed-low time steps.

3. Results

a. Closed-low climatological description

The number of closed-low events identified in the study area between 1 January 1948 and 31 December 2011 totaled 3157. There were an average of 49 closed-low events per water year (WY; defined as October of one year through September of the following year and labeled with the end year), with a maximum of 65 events in WY 1973 and a minimum of 37 in WY 2008. The mean of event counts per season did not vary greatly between the cool-season (October–March) average of 25.7 events and the warm-season (April–September) average of 23.7 (Fig. 4). The cool season had more interannual variability, with a range of 17–40 events in a given season; the warm season varied between 15 and 31 events.

The spring months had more closed lows than did other seasons, with the average annual maximum of 6.1 events occurring in April. Summer typically had the fewest closed lows; August experienced a 64-yr average of 2.4 events. Closed-low events typically lasted between 24 and 48 h, and their duration decreases nearly exponentially beyond 48 h (Fig. 5). The longest event in the dataset began on 19 May 1958 and persisted for 15 days.

Closed-low events generally achieve their maximum radius and depth over Southern California, Nevada, and Arizona (Figs. 6a,b). A secondary maximum is apparent in the northwestern corner of the study area. These

### Table 1. COOP stations used in precipitation analysis in order of descending latitude by column. All locations are airports except Shasta Dam, California; Eureka, Nevada; and Fort Bragg, California.

<table>
<thead>
<tr>
<th>Station code</th>
<th>Name</th>
<th>Station code</th>
<th>Name</th>
<th>Station code</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEA</td>
<td>Seattle, WA</td>
<td>EKO</td>
<td>Elko, NV</td>
<td>FAT</td>
<td>Fresno, CA</td>
</tr>
<tr>
<td>YKM</td>
<td>Yakima, WA</td>
<td>RBL</td>
<td>Red Bluff, CA</td>
<td>PRB</td>
<td>Paso Robles, CA</td>
</tr>
<tr>
<td>PDT</td>
<td>Pendleton, OR</td>
<td>EUN</td>
<td>Eureka, NV</td>
<td>BFL</td>
<td>Bakersfield, CA</td>
</tr>
<tr>
<td>PDX</td>
<td>Portland, OR</td>
<td>FTB</td>
<td>Fort Bragg, CA</td>
<td>SLO</td>
<td>San Luis Obispo, CA</td>
</tr>
<tr>
<td>EUG</td>
<td>Eugene, OR</td>
<td>RNO</td>
<td>Reno, NV</td>
<td>LAS</td>
<td>Las Vegas, NV</td>
</tr>
<tr>
<td>BOI</td>
<td>Boise, ID</td>
<td>ELY</td>
<td>Ely, NV</td>
<td>SBA</td>
<td>Santa Barbara, CA</td>
</tr>
<tr>
<td>OTH</td>
<td>North Bend, OR</td>
<td>SAC</td>
<td>Sacramento, CA</td>
<td>LAX</td>
<td>Los Angeles, CA</td>
</tr>
<tr>
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<td>Medford, OR</td>
<td>TPH</td>
<td>Tonopah, NV</td>
<td>DAG</td>
<td>Barstow, CA</td>
</tr>
<tr>
<td>EKA</td>
<td>Eureka, CA</td>
<td>SFO</td>
<td>San Francisco, CA</td>
<td>BLH</td>
<td>Blythe, CA</td>
</tr>
<tr>
<td>SHA</td>
<td>Shasta Dam, CA</td>
<td>BIH</td>
<td>Bishop, CA</td>
<td>SAN</td>
<td>San Diego, CA</td>
</tr>
</tbody>
</table>

**Fig. 4.** Time series of 500-hPa closed-low events in the study area for (a) the warm season (April–September) and (b) the cool season (October–March), covering 1948–2011. The mean event count (red) and a 9-yr centered running mean (black) are superimposed on the bar graphs.
events were found to be transient features and were likely an artifact of the domain size rather than a true representation of an area where closed lows reach their maximum radius and depth. They pass into the northwestern corner of the study area, persist the required 18 h, and exit to the northeast before reaching 135°W. Given their lack of direct influence on the western United States, they are included here but are not explored in detail. The average maximum radius for the study period was 1231 km, and the average maximum depth was 164 gpm. Maximum depth and maximum radius typically occurred in the same location, as observed in Figs. 6a and 6b. The deepest events and those with the largest radii occurred in the summer months. These events typically remained north of 40° N (Fig. 6d). More shallow events with smaller radii were found in the winter season, with maxima as far south as beyond the Mexican border (Fig. 6c). Maximum radii and depths by season are summarized in Table 2.

The annual average 6-h distance covered by closed lows for the study period was 233 km at an average speed of 39 km h⁻¹. Seasonal speeds and distances varied only slightly, with events generally moving fastest in the spring and slowest in the summer. Average speeds and distances traveled by closed-low events are summarized in Table 2.

b. Closed-low trajectories

Closed-low tracks over the Pacific were highly variable and exhibited movements in a variety of directions over the length of the study period (Fig. 7). Summer closed-low tracks are typically dominated by the northward shift of the Pacific high, with closed lows forming in the northern portion of the study area and dropping...
down the eastern flank of the high as seen in 1965 (Fig. 7b). Several summers did, however, exhibit more southerly events. One such summer, 1998, is shown in Fig. 7d. Winter tracks were more variable, with closed lows moving in all directions within the study area (Figs. 7a,c). In both seasons, events that came onshore were found to favor a track with a strong meridional component, traveling from northwest to southeast.

To observe the tracks of landfalling closed lows on the U.S. West Coast, the mean start point and 12-, 24-, and 48-h tracks of all events entering six regions were calculated; they are shown for the warm season in Fig. 8 and the cool season in Fig. 9. In the cool season, events coming onshore tend to track southeast during their first 48h (Fig. 9). As events come onshore south of 40°N during this season, they typically take a northeasterly turn near the southern Sierra Nevada and then continue tracking eastward into Arizona or southern Nevada. During the warm season (Fig. 8), similar behaviors are displayed, only with a more pronounced northeasterly component as events reach 40°N, with paths into Nevada.

A few hypotheses can be made as to why closed-low tracks take a northeasterly turn when they reach the southern two-thirds of California. The southern Sierra Nevada, located in southeastern California, exceeds 4000 m. If it is assumed that potential vorticity is conserved, that is, \( \frac{d}{dt}(\zeta + f)/H = 0 \), where \( \zeta \) is relative vorticity, \( f \) is the Coriolis parameter, and \( H \) is the depth of the air column, a dynamical adjustment occurs on the lee side when a closed low passes over the Sierra Nevada. As the closed low passes over the Sierra Nevada, the depth of the column decreases because of the presence of terrain. To compensate, relative vorticity must become negative and the closed low acquires an anticyclonic

### Table 2. Summary of average maximum radius, depth, speed, and daily distance traveled for 500-hPa closed lows in the study region for the period 1948–2011 and broken up into 3-month seasons for the length of the study period: December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON).

<table>
<thead>
<tr>
<th>Period</th>
<th>Radius (km)</th>
<th>Depth (gpm)</th>
<th>Speed (km h(^{-1}))</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1948–2011</td>
<td>1231</td>
<td>164</td>
<td>39</td>
<td>233</td>
</tr>
<tr>
<td>DJF</td>
<td>1128</td>
<td>139</td>
<td>40</td>
<td>242</td>
</tr>
<tr>
<td>MAM</td>
<td>1232</td>
<td>167</td>
<td>41</td>
<td>249</td>
</tr>
<tr>
<td>JJA</td>
<td>1420</td>
<td>198</td>
<td>34</td>
<td>206</td>
</tr>
<tr>
<td>SON</td>
<td>1108</td>
<td>160</td>
<td>38</td>
<td>225</td>
</tr>
</tbody>
</table>

![Fig. 7. Tracks of 500-hPa closed lows in the study region for (a) October–March 1964–65 (30 total), (b) April–September 1965 (26 total), (c) October–March 1997–98 (35 total), and (d) April–September 1998 (30 total). Cool-season events are depicted in blue; warm-season events are depicted in red. Black dots indicate location at which an event was first identified, and red dots indicate where it dissipated or left the study area. The area of the map extends 5° beyond the study area to the north, east, and west to allow the reader to see events on the margins. Event tracks crossing over the study area bounds are the result of interpolation of position.](image)
trajectory. As the parcel is displaced southward, $f$ decreases as well. Once the parcel crosses the Sierra Nevada and its column is again vertically stretched, relative vorticity must become positive to compensate for the decrease in $f$ and increase in column depth, and the closed low acquires a cyclonic trajectory (Holton 2004). This cyclonic turn is enhanced by adiabatic warming and surface convergence on the lee side of the Sierra Nevada to give the closed lows a notable cyclonic turn. The cyclonic curvature of the tracks in the lee of the Sierra Nevada is more pronounced in the warm-season months (Fig. 8) when parcels moving inland are relatively cool because of diabatic cooling by the California Current and surface sensible heating is at a maximum over the Great Basin and deserts of Southern California. High pressure develops over the coastal region of California, guiding the closed-low tracks anticyclonically to the southeast. The strong surface sensible heating in the Great Basin leads to more pronounced lee side troughing in this season, and the curvature of the tracks is amplified. This can be seen in the more pronounced cyclonic curvature of the mean tracks in the warm season (Fig. 8) and much less pronounced to almost no cyclonic curvature in the average 48-h tracks of events in the cool season (Fig. 9). Also of note is that the southernmost track in the cool season (Fig. 9) displays the most curvature of all cool-season tracks. This track passes over the deserts of Southern California, where temperatures remain higher than surrounding areas even through the winter months. This configuration provides a pressure distribution similar to that of the warm-season scenario and drives enhanced cyclonic curvature of the track.

c. Closed lows and precipitation in the western United States

The fraction of precipitation associated with closed lows at each COOP climate station for the 64-yr study period was calculated on the basis of the station’s presence within a closed-low radius on a day when precipitation was recorded. The results of this analysis show an increase in closed-low contribution to total precipitation with decreasing latitude for the study period. For stations south of 40°N, between 40% and 60% of 1948–2011 precipitation is associated with closed lows while stations to the north have less than 40%. A similar pattern is present during the cool season, with most stations in Southern California and southern Nevada receiving 40%–70% of their cool-season precipitation within closed lows (Fig. 10b). In the warmer months (Fig. 10a), the variation is more longitudinal. Closed lows display a 60%–80% contribution west of the Sierra Nevada, whereas their contribution at stations east of the Sierra Nevada is less than 60%. Closed-low contribution minima of less than 25% are seen at Las Vegas (LAS), Barstow (DAG), and Blythe (BLH)—locations that typically receive a large portion of their summer precipitation from the North American monsoon (Adams and Comrie 1997).

The average number of closed-low events associated with precipitation at each station is latitude dependent during the warm season (Fig. 11a), with Pacific Northwest stations receiving an average of 8–12 events per
warm season and stations in Southern California typically receiving only 1–4 events. The average number of precipitation-producing closed lows shows more even distribution across latitude in the cool season (Fig. 11b), with all stations ranging between 4 and 10 events per cool season.

Precipitation associated with closed lows was found to be highly variable from year to year at all 30 stations examined. For the October–May period, when the maximum numbers of closed-low events occur, precipitation associated with closed lows ranged from 15% to 95% of the total for the season at each station. Stations north of 40°N, as represented by Portland, Oregon (PDX), in Fig. 12a, exhibited the least variability, with average decadal contribution varying by ±5%. Coastal stations south of 40°N, as represented by Los Angeles, California (LAX), in Fig. 12b, had much greater interannual and decadal variability of closed-low contribution to precipitation, varying by ±10%.

d. Closed lows and modes of atmospheric variability

Analyses were performed to determine whether relationships were apparent between closed lows and several modes of atmospheric variability. Indices of El Niño–Southern Oscillation (ENSO) were examined first, as ENSO is known to have a dominant influence on U.S. West Coast winter weather patterns (Redmond and Koch 1991; Cayan et al. 1999). Cool-season (October–March) closed-low counts for the study area were examined for correlation with October–March averages of several widely used ENSO indices: Southern Oscillation index (SOI), equatorial Southern Oscillation index
(EqSOI), multivariate ENSO index (MEI), and oceanic Niño index (ONI). Magnitudes of Pearson product-moment correlation coefficients $r$ range between $|r| = 0.35$ and $|r| = 0.43$, with $p < 0.01$ (Snedecor and Cochran 1967), indicative of a moderate relationship between ENSO and closed-low counts (Figs. 13a,b). Correlations are positive for MEI and ONI and negative for SOI and EqSOI, suggesting that El Niño years favor a greater number of closed-low events than do La Niña or neutral years in the large study area. Spearman’s rank correlation coefficients $\rho$ range between $|\rho| = 0.27$ and $|\rho| = 0.36$, indicative of a weak-to-moderate relationship between ENSO and counts of closed-low events. Contingency tables and chi-square tests of the data also suggest a tendency toward a greater-than-average number of closed-low events in El Niño winters and fewer events for La Niña (Table 3).

October–March closed-low frequency also exhibits a significant correlation with the October–March average Pacific decadal oscillation (PDO) index at $r = 0.42$ ($p < 0.01$) and $\rho = 0.43$ (Fig. 13c). This result suggests that the positive phase of the PDO is associated with a greater number of closed-low events in the study area. This relationship is also displayed in the oscillations of the 9-yr running mean in Fig. 4. There is a trend toward low event counts before 1976 and an increase after 1976. The 1976 increase is followed in the late 1990s by a decline of events. These variations are in agreement with the suggested phase shifts of the PDO that were described by Mantua and Hare (2002). Contingency tables and chi-square tests for PDO and closed-low counts also indicate a weak-to-moderate relationship (Table 3). The average October–March index of the Pacific–North American (PNA) pattern shows the strongest relationship with counts of closed-low events (Fig. 13d), with correlations of $r = 0.45$ ($p < 0.01$) and $\rho = 0.46$. This result indicates that when the PNA is in its positive phase (ridging over the U.S. West Coast), a greater-than-average number of closed-low events typically occur. Further research is necessary to determine the causation mechanism of these relationships. Correlations for various periods and lags for the Arctic Oscillation (AO), Atlantic multidecadal oscillation (AMO), and North Atlantic Oscillation (NAO) were weak, with $|r| < 0.2$ ($p > 0.05$).

The same statistical tests were performed for the region encompassing only California and Nevada (a rectangular region bounded by 32°N to the south, 42°N to the north, 114°W to the east, and 125°W to the west) to observe whether there is a difference in relationships between ENSO and closed-low count in this smaller region when compared with the large study area. Pearson correlation coefficients for ENSO indices, PDO, and PNA were all found to be significant at $p < 0.05$ and of the same sign as for the larger study area, although the magnitudes of the correlations were weaker. Thus, there

![Fig. 11. Average number of events associated with precipitation at each station for (a) April–September and (b) October–March 1948–2011.](image-url)
is a tendency in the region of California and Nevada to have a greater number of closed-low events in El Niño winters or winters for which PDO and/or PNA are positive.

4. Discussion

The spatial variability and temporal variability of closed lows found in these results were generally in agreement with the works of Parker et al. (1989) and Bell and Bosart (1989), who found that there was generally a maximum frequency of closed-low events over the western United States in the spring and a minimum in the summer months. Numbers of closed-low events per year displayed strong variability over the study period. A linear trend fit to the annual totals shows an increase of approximately four events (8%) over the 64-yr study period. Of interest is that Nguyen and DeGaetano (2012) displayed very similar results for their study of closed lows in the northeastern United States. They found an increase of two events (10%) in a portion of their study area over their 60-yr (1948–2007) study period. Results of precipitation analyses in this study agree with results from Monteverdi (1976), who demonstrated that 20%–50% of precipitation at San Francisco, California, from 1966 to 1975 could be attributed to single airmass disturbances—features that are analogous to closed lows. The results presented here, in which 42% of San Francisco (site SFO) precipitation over the 64-yr study period is associated with closed lows, fits in the proposed range. Other attributions of precipitation to closed lows for this region were not found in the literature.

A more in-depth analysis of the relationships of closed lows with atmospheric oscillations is necessary to develop
a predictor for closed-low activity along the West Coast. Higher-order statistical analyses involving singular-value decomposition (e.g., principal components analysis) would offer an ideal subsequent step for determining these relationships. These analyses could help to depict and possibly to explain spatial and temporal variability in closed-low activity. Also valuable would be an analysis that examines the relationships between ENSO, PDO, and PNA concurrently with closed-low properties.

This study suggests that closed lows are associated with precipitation in the West. Modeling studies that we reviewed (Leung et al. 2004; Seager et al. 2007; Cayan et al. 2008) seek to identify future precipitation trends in the western United States. Assessments of various models to observe whether they are generating closed lows on spatial and temporal scales comparable to those found in the reanalysis data may assist in improving the models. If the models are found not to properly resolve closed lows, the frequency and spatial distribution of closed lows found in reanalysis data and associated precipitation can be used to help to assess model precipitation error. Medium-range weather forecast models have been cited in literature (Smith et al. 2002; Nieto et al. 2005) as handling closed and cutoff lows poorly. In the National Weather Service “Area Forecast Discussion” for 1058 Pacific daylight time 8 October 2012, the forecaster remarks about a closed low as follows: “The challenge with today’s forecast package will be the evolution and track of the upper low off the NorCal [Northern California] coast. Weather models are notorious for handling upper lows poorly” (San Francisco Bay Area Weather Forecast Office; see online at http://met.nps.edu/uppef/archive/20121008/2012100811.nws-discussion.html). If these short-term models have

![FIG. 13. Scatterplots and correlation coefficients for October–March counts of closed-low events for 1948–2011 in the study area and the corresponding October–March 1948–2011 averages of the indices: (a) MEI, (b) EqSOI, (c) PNA, and (d) PDO. Standard deviations of ±1 for each index are shown in gray.](image)

<table>
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<tr>
<th>Table 3. Contingency table for MEI, EqSOI, PDO, and PNA relationships with closed-low count.</th>
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<tbody>
<tr>
<td>MEI</td>
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<td>Event No. &gt; avg</td>
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<td>Event No. &lt; avg</td>
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<td>PDO &lt;</td>
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difficulty with closed lows, it is likely that long-term climate models face serious issues with closed lows as well that affect their representations of West Coast precipitation.

Several other properties of closed lows remain to be explored. Spatial and temporal variability of retrograding closed-low events could be examined. The closed-low identification algorithm could be refined to extract cutoff lows and to determine their relationship with summertime thunderstorms in the Southwest. Analyses describing the variability of the magnitude of precipitation associated with closed lows and differentiating between precipitation totals from closed-low events and precipitation totals of other types of synoptic features would be valuable as well. Also of interest would be to assess the relationship between closed-low tracks and large-scale atmospheric circulations.

5. Conclusions

Closed lows have been cited in literature over the last 40 years as significant atmospheric features but have not been closely analyzed for the role that they play in precipitation for the U.S. West Coast or their relation to larger-scale circulation patterns. This study demonstrates several properties of closed lows and their contribution to precipitation, summarized as follows:

- The number of closed-low events in the study area exhibits considerable interannual variability in both the large northeastern Pacific study area and the California/Nevada area subset.
- The maximum number of closed-low events is observed during the spring season (March–May), and closed-low events are at a minimum in the late summer and early autumn (July–September).
- Closed-low events in the study area typically persisted between 24 and 48 h for all seasons.
- Roughly 20%–60% of U.S. West Coast precipitation is associated with closed lows at 30 selected locations over the 64-yr study period. Annual precipitation and seasonal precipitation associated with closed lows are highly variable at each station throughout the study period.
- There is a marked and systematic latitudinal dependence in this precipitation association from October to March, with a notable increase south of 40°N.
- Closed lows making landfall in the western United States display a favored trajectory. They approach the coast from the west-northwest and then track east until they turn to the northeast in the vicinity of the southern Sierra Nevada.
- Greater numbers of closed-low events were observed in the study area during El Niño winters and the positive phases of PDO and PNA.

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