9.3 SYNOPTIC AND TOPOGRAPHIC VARIABILITY OF NORTHERN CALIFORNIA PRECIPITATION CHARACTERISTICS IN LANDFALLING WINTER STORMS OBSERVED DURING CALJET

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1. INTRODUCTION

Precipitation in the coastal zone can dramatically impact society, particularly when it occurs in large quantities and contributes to flooding. Northern California is a prime example of a coastal region that experiences these types of problems. The region has several hydrologically sensitive watersheds (e.g., Russian, Napa) in the midst of a large population base in the San Francisco and Sacramento metropolitan areas. Steep coastal orography has a distinct influence on the development, intensity and horizontal distribution of precipitation resulting from landfalling winter storms. However, the nature of this influence is not well understood, particularly as a function of the synoptic regimes embedded within each storm system. This study takes steps to bridge the gap in knowledge on this subject by examining ten storm systems observed in northern California from January to March 1998 during the California Landfalling Jets (CALJET) experiment (Ralph et al. 1999).

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2. DATA SOURCES AND CASE SELECTION

The CALJET experiment was designed to better observe and understand winter storm systems making landfall along the California coast, with an ultimate goal of improving 0-24 h quantitative precipitation forecasts. An extensive suite of specialized meteorological instrumentation was deployed strategically along the California coast to supplement the operational Of the former, this study observing system. emphasizes use of S-PROF, a vertically pointing S-band Doppler radar (White et al. 2000), a 915 MHz wind-profiler and a surface meteorological station with tipping-bucket rain gauge all located at Cazadero (CZD), a site in the coastal mountains north of San Francisco (Fig. 1). Operational observing systems employed include National Weather Service (NWS) rawinsondes deployed from Oakland (OAK), a NWS Doppler radar from Davis (KDAX) and several rain gauges from California's ALERT network. The ten largest rain-producing storm systems observed at CZD during the January to March 1998 time period are examined. They ranged in duration from 9-32 h and in storm-total accumulation from 58-203 mm.



Figure 1. Key observing systems employed in this study overlaid on a topographic base map of northern California.

3. PRECIPITATION CHARACTERISTICS

3.1 2-3 February Case Study

The case on 2-3 February 1998 is used here to illustrate some aspects of the evolution associated with these storm systems (Fig. 2). Although not the largest rain-producer at CZD, this storm produced extensive flooding along the California coast (Ralph et al. 2003; Neiman et al. 2003). Data from S-PROF indicates that the precipitation is generally stratiform in character with a persistent bright-band that varies in height from 1.8-2.4 km MSL. Radar echoes below the bright-band are mainly 20-30 dBZe, except for 2-3 h periods near 0000 and 0500 UTC on 3 February when reflectivities sometimes exceeded 40 dBZe, Coupled with the fact that these periods coincided with less distinct bright-bands and stronger upward motions (not shown), the precipitation at these times appears to be more convective in nature. The associated trace of precipitation accumulation from the collocated rain gauge indicates an average rate of 3-4 mm h⁻¹ over the 24 h period. Large deviations above this average occur near 0000 UTC $(\sim 11 \text{ mm h}^{-1})$ and 0500 UTC ($\sim 20 \text{ mm h}^{-1}$) where the radar data indicates convective structure.



Figure 2. Observations from CZD (Fig. 1) during the period 1400 UTC 2 February 1998 to 1400 UTC 3 February 1998. Top: Time-height cross-section of radar reflectivity from S-PROF with echo intensity coded according to the gray scale. Bottom: Time series of precipitation accumulation from tipping-bucket rain gauge. The gray dashed lines indicate separations between different synoptic regimes as explained in the text.

These datasets were used in conjunction with windprofiler and surface meteorology observations to classify synoptic regimes associated with this case. The cold sector was in place at the beginning of the event until there was evidence of tropospheric warming as manifested by a rising bright-band. This signaled the beginning of the warm frontal regime, which continued until warm frontal passage at the surface. During this period, the wind profile veered with height (not shown), suggestive of warm advection. The following warm sector existed until surface cold frontal passage was evident based on surface meteorological observations (not shown). This initiated the beginning of the cold frontal regime, which continued until the bright-band ended its downward descent. During this period, the wind profile backed with height (not shown), suggestive of cold advection. Thereafter, a cool sector was in place until the end of the event. The airmass behind the cold front is referred to as "cool' since it is slightly warmer than the cold sector airmass ahead of the warm front.

3.2 Overall Variability

One method to compare and contrast the precipitation structures of all ten cases is to examine their mean vertical profiles of reflectivity at CZD (Fig. 3). Relative to the ten case mean profile, the 2-3 February case matches it very well (Fig. 3e) and cases on 11-12 January and 5-6 February (Figs. 3b, f) show close correspondence, especially at low levels.. Cases on 18-19 January, 6-7 February and 23-24 March (Figs. 3c, g, j) exhibit generally higher reflectivity while the remaining cases exhibit generally lower reflectivity.

A common feature in all the profiles is the radar bright-band. Not surprisingly, it is located in close proximity to the range 0° C altitudes observed from the OAK rawinsondes launched during the course of each precipitation event. Note that the 0° C altitude ranges are biased slightly higher than the corresponding bright-band altitudes, a result that can attributed to the fact that OAK is located almost 100 km south of CZD and is therefore likely to be somewhat warmer. The vertical sharpness of the bright-band varies from case-to-case; some are compact (Figs. 3a-d) while others are smeared in the vertical (Figs. 3e-j). These variations are not always well correlated with variations in the range of 0° C altitudes.

Another common reflectivity profile attribute is a distinct change in slope about 2-3 km above the brightband that takes the shape of a shoulder. This feature manifests itself as a large reflectivity increase with decreasing altitude transitioning to a much smaller reflectivity increase with decreasing altitude. In some cases, this transition is so abrupt that it appears like an elevated bright band (Figs. 3a, e, i). The transition level corresponds closely with the altitude range of the -15° C isotherm observed from OAK. This is a key temperature for ice particle growth, both from diffusion and aggregation, which perhaps provides some explanation for the rapid precipitation growth implied by the reflectivity profile just above the shoulder.

Relating reflectivity to rain rate at CZD is another metric for characterizing the precipitation in these storm systems. A 16 min averaging period was used for these



Figure 3. Mean vertical profiles of S-PROF reflectivity at CZD for the ten cases in this study. (a) 1-2 January, (b) 11-12 January, (c) 18-19 January, (d) 26-27 January, (e) 2-3 February, (f) 5-6 February, (g) 6-7 February, (h) 19-20 February, (i) 21 February and (j) 23-24 March. The overall ten-case mean profile is plotted as a thick gray line. For each case, the altitude ranges of the OAK rawinsonde based 0° C and -15° C isotherms are indicated by the small black ovals.

Figure 4. Relationship between S-PROF reflectivities and collocated gauge derived rain rates at CZD for the ten cases in this study. All 16 min averaging periods are plotted in (a) while panels (b-d) stratify the data points as a function of the BB (black-filled square), HYB (white-filled triangle) and NBB (gray-filled circle) rain categories, respectively. Reference relationships from Marshall-Palmer and the WSR-88D are plotted with the thick solid and dashed lines, respectively, in each panel. Linear fits for each set of data are indicated by the thin solid lines.

calculations, which means that the minimum resolvable rain rate from one tip of the rain gauge (0.25 mm) is a little under 1 mm h⁻¹. Data from the first good range bin of S-PROF, centered at 260 m AGL (770 m MSL), was used to calculate an average reflectivity over this period. The ten case composite results are shown in Fig. 4a. Note that almost all of the points are situated below the reference lines for the Marshall-Palmer and WSR-88D reflectivity-rain rate relationships. The linear fit to the data suggests a similar slope but smaller intercept. This structure implies that for a given reflectivity, the observed rainfall falls at a larger rate than dictated by the established relationships. One explanation for this trend is that the observed rainfall is composed of greater numbers of smaller drops.

Following the technique employed by White et al. (2003), the precipitation for each 16 min averaging period was partitioned into three different categories based on S-PROF data. Profiles containing no evidence of a bright band were categorized as non bright-band (NBB) rain. They were characterized by reflectivity that increased monotonically to the surface from relatively shallow echo tops, suggesting that a collision-coalescence process may be active with limited or no contribution from the ice phase. Profiles containing a bright-band and constant or decreasing reflectivity below the bright-band were categorized as bright-band (BB) rain. This structure implies a seederfeeder process involving the ice phase with little or no contribution to precipitation growth through the collisioncoalescence process. Hybrid (HYB) rain was categorized for profiles containing a bright-band and increasing reflectivity below the bright-band, a structure that implies a combination of the seeder-feeder and collision-coalescence precipitation growth processes.

The relationship between reflectivity and rain rate was stratified by the BB, HYB and NBB precipitation growth categories (Figs. 4b-d). Relative to the Marshall-Palmer and WSR-88D relationships, the linear fits to the data indicate increasing slopes and decreasing intercepts when progressing from the BB-HYB-NBB categories in succession. This trend implies a large variation in precipitation character between the categories at rain rates of 1-2 mm h⁻¹ with smaller variation at rain rates of 10-20 mm h⁻¹.

3.3 Synoptic Variability

To examine the variability in precipitation characteristics as a function of synoptic regime, the classification techniques described for the 2-3 February case (section 3.1) were applied to the other nine cases. We found that the warm frontal regimes produced the largest amount and longest duration of precipitation, with an average rate of 7 mm h⁻¹. The most intense precipitation occurred during cold frontal regimes, with an average rate of 11 mm h⁻¹. This is consistent with the S-PROF data that shows the cold frontal regimes to have the largest values of reflectivity (Fig. 5d). The other synoptic regimes are characterized by reflectivity values that are generally the same or lower than those indicated by the ten case mean profile (Figs. 5a-c, e).

Figure 5. Mean vertical profiles of S-PROF reflectivity at CZD for the ten cases in this study. (a) Cold sector regime, (b) warm front regime, (c) warm sector regime, (d) cold front regime and (e) cool sector regime. The overall ten-case mean profile is plotted as a thick gray line.

Bright-band heights and thicknesses varv considerably. The lowest bright-bands occur during the cold sector regime (Fig. 5a), which is consistent with the fact that this regime is the coldest of the five. Likewise, the highest bright-bands occur during the warm sector regime (Fig. 5c), which is the warmest of the five. The warm sector bright-band height is bimodal in character because of one case (19-20 February) that was associated with a much colder airmass than the other cases. The least distinctive bright-band is associated with the cold frontal regime (Fig. 5d). One explanation for this structure is the propensity for convection during these periods. Another cause may be large variations in bright-band height that occur as a result of large and rapid temperature decreases in association with cold frontal passages.

Reflectivity profiles above the bright-band also exhibit significant differences as a function of synoptic regime. The most distinct shoulder features, with the most dramatic changes in reflectivity slope occur in the cold sector, warm sector and cold frontal regimes (Figs. 5a, c, d). The latter differs from the first two in that there is only a small depth below the shoulder where reflectivity increase with decreasing altitude is minimized. Above the shoulder, the profile of reflectivity gets progressively more erect in transitioning from the cold sector to warm front to warm sector regimes (Figs. 5a-c), which is likely an indication of deepening echoes as the storm systems evolve through these stages. The cool sector regime has the most erect profiles at these altitudes, a trend that may be attributable to the sporadic occurrence of post-frontal convection.

Reflectivity-rain rate relationships stratified by synoptic regime indicate that the largest departures from the Marshall-Palmer and WSR-88D relationships occur during the warm front, warm sector and cool sector regimes (Figs 6b, c, e). Not coincidently, the longest duration and largest amount of NBB rain occurs during these regimes. In contrast, very little NBB rain occurs during the cold sector and cold front regimes (Figs. 5a, d), which may explain the limited scatter and better agreement with the Marshall-Palmer and WSR-88D reference relationships.

3.4 Topographic Variability

We now examine how the precipitation characteristics of each storm system varies between the coastal mountain site at CZD and an area in the lee of the coastal mountains that surrounds the NWS Doppler radar KDAX near Davis (Fig. 1). The ALERT rain gauges nearby KDAX collected on average only onesixth the amount of precipitation that fell at CZD when examining the aggregate totals from all ten cases. This suggests that some differences exist between the two regions.

One way to explore this subject is through comparative analysis of vertical profiles of reflectivity between CZD and KDAX. Since KDAX operates in a scanning rather than vertically pointing mode, an alternate analysis approach was employed. Mean vertical profiles of reflectivity were constructed from the 360° surveillance volumes of KDAX data out to a range

Figure 6. Same as Fig. 4 except subdivided by (a) cold sector regime, (b) warm front regime, (c) warm sector regime, (d) cold front regime and (e) cool sector regime.

Figure 7. Mean vertical profiles of reflectivity at KDAX (black) and S-PROF at CZD (gray) for the ten cases in this study.

of 30 km. This allowed a vertical resolution of 300 m. To facilitate comparison with these profiles, the 105 m vertical resolution CZD profiles were degraded to 300 m vertical resolution. In addition, KDAX reflectivity directly over the CZD site was compared with S-PROF reflectivity to arrive at a relative calibration between the two radars. This relative calibration was then applied to the KDAX data. The resulting mean profiles from KDAX and CZD, averaged over all ten cases, show two distinct differences (Fig. 7). In the lee of the coastal mountains, reflectivity is lower by 3-6 dBZe and the bright-band altitude is lower by ~300 m. The former is consistent with the observation of significantly less precipitation accumulation near KDAX compared to CZD while the latter may be related to the presence of consistently cooler continental airmasses trapped in the California central valley compared to the more moderate marine airmasses affecting the windward slopes of the coastal mountains.

Comparison of reflectivity-rain rate relationships is also a useful method for examining the differences in precipitation characteristics between the two regions. To accomplish this task for the region in the lee of the coastal mountains, rain rate estimates from each of the ALERT gauges, normally spanning 1 h, were paired with low-level KDAX reflectivity values over each of the corresponding ALERT gauge sites that were averaged over the same period used for the rain rate estimates. To facilitate comparison with these gauge-radar pairs. the time resolution of the CZD gauge-radar pairs was degraded to 1 h from 16 min. Also, the relative calibration between the two radars discussed earlier was applied to the KDAX data. The resulting reflectivityrain rate relationships for the ten case composite expose significant differences between the two regions (Fig. 8). Although their slopes are similar, the intercept associated with the linear fit to the data in the lee of the coastal mountains is almost three times larger than the intercept at the coastal mountain site. In fact, the leeside data corresponds very closely with the reference relationships, particularly the one associated with the WSR-88D. These results indicate that the preponderance of small drops hypothesized to be present at CZD is not evident in the lee, which implies that the NBB rain process was likely insignificant in this region.

Figure 8. For the ten cases in this study, relationships between (a) S-PROF reflectivities and collocated gauge derived rain rates at CZD (+'s) and (b) KDAX reflectivities and nearby ALERT gauge derived rain rates (x's). Reference relationships from Marshall-Palmer and the WSR-88D are plotted with the thick solid and dashed lines, respectively, in each panel. Linear fits for each set of data are indicated by the thin solid lines.

4. SUMMARY

The ten largest rain-producing storm systems observed during January to March 1998 at Cazadero, a site in the coastal mountains north of San Francisco, were examined to determine the variability of precipitation characteristics as a function of synoptic regime and how these characteristics differed in the lee of the coastal mountains. Analyses incorporated both operational datasets and research datasets collected during CALJET. At Cazadero, the warm frontal regimes of landfalling storm systems produced the largest amount and longest duration of precipitation, with an average rate of 7 mm h^{-1} . The most intense precipitation occurred during cold frontal regimes, with an average rate of 11 mm h⁻¹. The two levels of most rapid precipitation growth occurred around the -15 C level and just above the melting level. Growth in the intervening layer was slower, particularly during the warm sector and cold sector regimes. The relationship between rainfall rate and radar reflectivity exhibited a similar slope but smaller intercept relative to the Marshall-Palmer and WSR-88D reference relationships, suggesting the presence of larger numbers of smaller raindrops. The intercept was particularly small during the warm frontal, warm sector and cool sector regimes when a large amount of precipitation occurred in the

absence of a bright-band and was associated with growth below the melting level, suggestive of a collisioncoalescence process. In the lee of the coastal mountains, near Davis, there was on average only onesixth the amount of precipitation that fell in the coastal mountains to the west. Comparison of vertical profiles of reflectivity at the two locations indicated weaker echoes and a somewhat lower bright-band in the lee. The relationship between rainfall rate and radar reflectivity is also different in the lee, exhibiting larger intercepts that closely correspond to the Marshall-Palmer and WSR-88D relations.

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