

1 **Unique Aerial Photographs of Eddy Circulations in Marine Stratocumulus Clouds**

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Abstract

Aerial photographs of cyclonic, von Karman-like vortices in the marine stratocumulus clouds off the California coast, taken by a commercial pilot near Santa Cruz Island and Grover Beach, are presented. It is believed that these are the first photographs of such eddies taken from an airplane, to appear in publication.

Both eddies occurred with strong inversions above a shallow marine boundary layer, in the lee of high, inversion-penetrating terrain. Tower and surface wind measurements demonstrate that the Grover Beach eddy was not just a cloud-level feature, but extended through the marine atmospheric boundary layer (MABL) to the surface. 2-3C° temperature increases and then decreases during and after the eddy passage may be indicative of warm, dry inversion layer air being included into the eddy circulation, and also suggest a possible collapse of the MABL and descent of the temperature inversion to near sea level in conjunction with the eddy formation. Sequences of wind reversals at two different levels of a meteorological tower show that the eddy circulation at 10 m responds 15-30 minutes after that at 76 m, which is more closely synchronized with cloud level circulation features as seen in satellite imagery as it passes near the tower. Eddy formation mechanisms are discussed, but the subsynoptic observations are inadequate to resolve details and answer questions about the formation mechanisms, and ultimately a high resolution model simulation will be needed to address such questions.

1. Introduction

On July 16, 2006, and again on September 12, 2006, a pilot flying California coastal routes for SkyWest Airlines observed and photographed cyclonic vortices in marine stratocumulus clouds just off the coast (Capt. Peter Weiss, personal communication). The first (July 16) occurred on the north side of Santa Cruz Island (Figure 1) within what appeared from satellite imagery to be the southeasterly flow portion of a larger Catalina eddy circulation. The second (September 12) was spotted off Grover Beach downwind of a coastal headland (Fig. 2) southwest of San Luis Obispo, within a generally northwesterly marine atmospheric boundary layer (MABL) flow regime. Based on estimates from GOES satellite imagery, these eddy circulations in the clouds appeared to be on the order of 10-25 kilometers in diameter, placing them on the borderline between the meso-gamma and meso-beta scales of phenomena (2-20 km and 20-200 km, respectively, Orlanski 1975). Each contained a round cloud-free “eye” or hole of 2-3 kilometers diameter at their center.

Casual inspection of GOES satellite imagery of the West Coast region of North America reveals that similar eddies in the stratocumulus-topped MABL, on the order of tens of kilometers, are a relatively common occurrence near peninsulas, headlands, and downwind of islands. Many investigators have likened these relatively small-scale circulations, and similar features in other parts of the world, to von Karman vortices (Hubert and Krueger 1962; Chopra and Hubert 1965, Lyons and Fujita 1968; Thomson et al. 1977; Ruscher and Deardorff 1982; Etling 1989; Young and Zawislak 2006).

A number of meso-beta scale (20-200 km) eddies appear on a regular basis in the near-shore marine environment and have been described in the literature. They include

the Catalina eddy (e.g. Rosenthal 1968; Bosart 1983; Wakimoto 1987; Mass and Albright 1989; Eddington et al.1992; Thompson et al. 1997; Parish et al. 2013), the Gaviota and midchannel eddies (Kessler and Douglas 1991; Douglas and Kessler 1991; Hanna et al. 1991; Wilczak et al. 1991; Dorman and Winant 2000), the Santa Cruz Eddy (Archer et al. 2005; Archer and Jacobson 2005), and the Antalya Cyclone (Alpert et al. 1999). Eddies at this scale are important because they are persistent and large enough to influence local stratus cloud formation, air quality, and surface wind fields in coastal regions (Wakimoto 1987; Hanna et al. 1991; Archer et al. 2005). The preceding modeling and observational studies indicate that these eddies result from complex interactions between a strong boundary layer-topping marine inversion, inversion-penetrating terrain, synoptic scale wind and pressure fields, nighttime drainage flows, and daytime/nighttime wind reversals produced by diurnal radiative cycles.

The smaller borderline meso-gamma/meso-beta scale eddies photographed and investigated in the current research appear to be mechanically-driven transient features (see the discussion by Hubert and Kruger 1962), lasting several hours. Such order-10 km eddies are important as they have been hypothesized to play a role in mixing at the coastal margin and have been implicated in cross-inversion fluxes of ozone and momentum (Lester 1985). Furthermore, they could lead to unexpected wind shifts for sailors or pilots, and anecdotal reports suggest an environment of strong aircraft turbulence in the lee of islands that produce similar eddies (Bob Baxter, Paul Ruscher, personal communications). Indeed, strong turbulence in the lee of the Hawaiian island of Kauai was documented as a cause of the breakup and crash of NASA's ultralight unmanned aerial vehicle Helios (Porter et al, 2007). While the satellite imagery indicates

that their appearance and scale are similar to those found in Von Karman vortex streets (e.g., Young and Zawislak 2006), the eddies presented here occurred individually and not as part of a series, although evidence will be presented that the Grover Beach eddy actually was the second one to form in the area that morning.

While radiometric imagery of such features from weather satellites is common, the cases presented in this paper are notable in that *photographic* documentation of atmospheric eddies at this scale has been lacking in the meteorological literature. To our knowledge, these are the first close-up photographs of marine stratocumulus eddies, taken from an airplane, to appear in publication. Furthermore, because of their small scale, such eddies often pass between observation stations or occur within island wakes over the open ocean making them difficult to measure directly. This has left some basic questions not completely resolved, such as the nature of the cloud-free eye, and whether their circulations are only an inversion-level feature (as indicated by their cloud-free eye) or if they penetrate through the MABL all the way to the surface (Young and Zawislak 2006).

Given the relative frequency of mechanical eddies in satellite imagery, we have concluded that pilots on the U.S. West Coast must see them periodically, but the current examples seem to be one of the few times that actual photographs have come to light in a scientific context. Our speculations were anecdotally corroborated by a colleague who remembers seeing them nearly every day while flying routes between Monterey and El Toro, California for the U.S. Marine Corps (Frank Richey, personal communication).

The purpose of this paper is to present these unique photographic images of eddies near Grover Beach and Santa Cruz Island, to document the physical and

dynamical characteristics of the Grover Beach eddy, and to discuss hypotheses from the observational and theoretical literature pertinent to its formation. Since subsynoptic observations were found only for the Grover Beach case, the Santa Cruz Island eddy will be a subject for future research and will not be further discussed in this paper. Nevertheless, the uniqueness of the photograph merits its inclusion here. It is intended that information about the Grover Beach eddy will serve as a benchmark for verification and corroboration of numerical model simulations and studies on predictability of small-scale coastal effects. This paper demonstrates the value, but also the limitations of existing high resolution coastal monitoring sites for detailed understanding of coastal processes. Confirmation of the photographed cloud feature is provided in the form of corresponding satellite imagery, allowing nearly the complete eddy life cycle to be examined over a time span of approximately five hours. Soundings, surface, and tower data will demonstrate that the circulation occurred with a very strong temperature inversion above a relatively shallow MABL. Additionally, evidence of the inclusion of inversion air in the eddy circulation will be presented in the form of time series of winds and temperature as the Grover Beach eddy formed near or possibly passed directly over the PG&E instrument tower.

2. Satellite imagery and meteorological environment of the Grover Beach eddy

a. Special meteorological data sources

Three data sources provide direct evidence that the Grover Beach eddy's circulation extends down from cloud level (as seen in the photograph and satellite imagery) through the MABL all the way to the surface during the duration of its lifetime.

Locations of the most relevant of these stations in relation to the terrain that produced the eddy are shown in Figure 3. Directly north northwest of San Luis Bay is a headland containing the San Luis Range (also known locally as the Irish Hills) with the higher ridges extending to between 450 to 550 m (1500-1800 feet) MSL. The Los Osos Valley and San Luis Obispo can be found to the northeast. Pt. Buchon, the westernmost location on the headland is to the northwest of San Luis Bay while Grover Beach is to the south southeast. Much of the terrain all along the southwest flank of this steep headland formed by the San Luis Range rises to more than 300 m (1000 feet) MSL of elevation within a kilometer of the coastline.

The first special data source is a three-station network operated by Pacific Gas and Electric Company (PG&E) in support of their Diablo Canyon nuclear power plant (Thuillier 1987). These stations consist of a 10 m tower located at Pt. Buchon at an elevation of 12.2 m (40 feet), a 20 m tower on Davis Peak in the San Luis Range at an elevation of 549 m (1800 feet), and their “Primary Meteorological” site, a 76 m tower at the plant itself (hereafter referred to as the “meteorological tower”) at 32 m (105 feet) MSL. The tower measures winds at 10 m and 76 m AGL, and temperature at 10 m, 46 m, and 76 m AGL. Pressure and humidity are not measured. Data from these stations were available every 15 minutes. The second data source is from the meteorological station at the California Polytechnic State University (Cal Poly) Center for Coastal Marine Sciences Pier in San Luis Bay. This station contains a full suite of meteorological measurements on a four meter tower, archiving data every two minutes. The third data set comes from wind monitoring instruments operated by the San Luis Obispo County Air Pollution Control District (SLOAPCD), collecting observations every minute.

It should be noted that at the scales being examined in this paper, distances of less than a few kilometers and time periods of a few minutes become important for matching wind observations to satellite features. For example, at a speed of 3 m s^{-1} the eddy can move nearly 2.7 km, roughly the diameter of the cloud-free eye when photographed, in 15 minutes. Therefore, special care was taken to match images as closely as possible with the appropriate observation time. This involved calculating the time for the GOES-West Imager radiometer to scan to the latitude of the Diablo Canyon area, then determining the closest observations to that time for each of the three data sources, that is, the 15-minute PG&E data, the 2-minute Cal Poly data, and the 1-minute SLOAPCD data. There can be a 1-4 minute lag time between the beginning of the GOES-West scan, and the time it takes to reach the latitude of the Diablo Canyon area, depending on which sector it is scanning. Additionally there can be errors of 1-2 km in the satellite navigation. For these reasons there is some uncertainty in discerning exact locations of eddy formation and movement.

GOES satellite observations with the subsynoptic data superimposed using Unidata's Integrated Data Viewer (IDV) are presented in Figure 4. The satellite data were obtained from the NOAA (National Oceanic and Atmospheric Administration) Comprehensive Large Array-data Stewardship System (CLASS), remapped to a local perspective using McIDAS (Man computer Interactive Data Access System), then displayed and analyzed using GARP (GEMPAK [GEneral Meteorology PAcKage] Analysis and Rendering Program). During its lifetime on satellite imagery, the eddy was close enough to influence surface wind measurements at three different observing stations. The in situ wind measurements corroborate Li et al.'s (2000) synthetic aperture

radar results and Young and Zawislak's (2006) suggestion that the circulations of von Karman vortices observed in satellite imagery of island wakes can extend through the depth of the MABL to the surface.

The eddy originally emerged offshore just south of Pt. Buchon. Satellite images at 1445, 1500, 1530, and 1600 UTC show the initial boundary between clear and cloudy air pushing toward the southwest in line with the northeasterly winds *above* the MABL at Davis Peak, establishing the cloud-free eye feature by 1600 UTC. The sharpness of the boundary at least suggests the possibility of confluent air streams at cloud level between the northeasterly winds aloft descending in the lee of the San Luis range and the northwesterly winds in the MABL, although there is no evidence of such winds at tower level during this time. The steady northwesterly winds at both the 10 m and 76 m levels of the tower at 1445 and 1500 UTC within the advancing clear region imply a center of circulation to the northwest of the tower moving over it toward the southwest and causing eddy wind reversals to southeasterly at both levels by 1600 UTC. However, an alternative explanation is that we are witnessing the collapse of the MABL within the strong flow rounding Pt. Buchon and the *in situ* formation of the eddy in its lee to the southwest of the tower location. Koracin and Dorman (2001) documented clearing in the lee of Pt. Buchon and other capes along the California coast in the presence of "expansion fan" thinning of the MABL. In either case the eddy's position was close enough to the three-station monitoring network run by PG&E to allow for direct sampling of its surface and low level circulations and temperature structure, which will be described in section 2c.

The eddy subsequently moved toward the southeast then the east, passing by and influencing wind directions at the surface observing station on the Cal Poly Pier. As the eddy crossed San Luis Bay, winds at the Cal Poly pier swung from southerly (Fig. 4, 1700 UTC) to east southeasterly (1746 UTC). This is consistent with the eddy's cyclonic rotation as it passes to the south of the pier. Finally, after being photographed just offshore by the pilot, the eddy moved inland directly over SLOAPCD's wind monitoring station, causing a nearly 180 degree wind direction reversal over a period of one minute. Note that without the special high resolution non-synoptic data obtained from PG&E, SLOAPCD, and Cal Poly for this study, it would not have been possible to document meteorological details of the eddy feature's passage through the area, as the only synoptic stations in proximity are San Luis Obispo and offshore buoy 46011 (30 km southwest of Pt. Buchon), neither of which were affected by the eddy circulation.

b. Synoptic conditions

Synoptic scale weather conditions at the surface and 850 hPa at 12 UTC on September 12, 2006, are shown in Figure 5. The surface pattern is characterized by an inverted thermal trough over the coastal ranges of California. There is an onshore pressure gradient between buoy 46011 northwest of Santa Maria and the Cal Poly Pier (not shown), but a very weakly offshore gradient if buoy 46011 is compared with the 12 UTC METAR from San Luis Obispo (1013.7 hPa at buoy 46011 vs. 1013.9 hPa at KSBP, not shown). The prevailing air flow just offshore along the coast as indicated by buoy stations is northwesterly around 5 m s^{-1} (10 kts). Several stations in the vicinity of the south central California coast were reporting fog or mist. At 850 hPa there was a west-east oriented ridge of high pressure just north of the Grover Beach area resulting in

an offshore (easterly) flow above the boundary layer over the south central California coast.

The marine layer in the central and southern California coastal region was very shallow. For example, the 12 UTC Oakland sounding (left panel, Figure 6) indicated a surface-based inversion with a temperature at 3 m of 14.4 °C, versus a temperature of 19.4 °C at 122 m. The inversion top had a temperature of 27.4 °C at 805 m and 925 hPa. The San Diego sounding (right panel, Fig. 6) indicated an inversion base of 17.2 °C at 251 m and 983 hPa, but with nearly saturated air up to 376 m. The temperature of the inversion top was 26.4 °C at 709 m and 933 hPa. It would be preferable to use the sounding from the much-closer Vandenberg RAOB site to characterize the environment of the Grover Beach eddy, but crucial data were missing from its lower levels. Nevertheless, easterly to northeasterly flow aloft (seen most clearly in steady northeast winds at PG&E's Davis Peak station at an elevation of 550 m (1800 feet) and the very shallow depth of the MABL combine with the coastal terrain to limit inland penetration of the marine stratocumulus. Satellite imagery indicates that stratocumulus is widespread over the ocean, but confined to the immediate coastal region over land. These weather characteristics are common during September in coastal California, indicative of marginal Santa Ana conditions that often prevail at this time of year.

c. Grover Beach eddy description and analysis

The Grover Beach eddy was photographed at approximately 11:28 PDT (18:28 UTC) looking toward the west southwest (Fig. 2). Visible satellite imagery (Fig. 4) corroborates the existence of this flow feature and allows us to track the eddy's life cycle and estimate the dimensions of its circulation. Satellite imagery and data from Davis Peak

245 demonstrate that the terrain that produced the feature penetrated through the MABL into
246 the inversion layer. For example, the temperature at Davis Peak at 1430 UTC was 26°C
247 compared with 11°C at the meteorological tower. The 1830 UTC satellite image
248 (eleventh panel in Fig. 4) is the time closest to the photograph time. Estimates made
249 using GARP indicate that the eddy had a width of 9 km, was 17 km in length, and
250 contained a cloud-free eye of 2.5-3 km at the time the photograph was taken. When first
251 evident on the satellite imagery as it emerges from the coastline, the cloud-free eye is 6-7
252 km in diameter, but shrinks to 2-3 km as it turns from moving southwestward to moving
253 toward the east. The shrinkage of the eye is similar to that of von Karman vortices seen
254 downwind of islands (Young and Zawislak 2006), suggesting a non-steady state
255 boundary layer flow characterized by pressure gradient force, centrifugal force, and
256 friction. It is interesting to note some features seen early in the eddy's life at 1600 UTC
257 (Fig. 4): a band of clouds in the northwesterly flow piling up against the northwest face
258 of the headland containing the San Luis Range, and a very similar band on the northwest
259 flank of the cloud-free eye. Outside that is a dark band of apparently thin, less reflective
260 clouds. These dark and light bands appear as the result of convergence between the
261 southeasterly flow on the back side of the eddy, and the oppositional northwesterly flow
262 over the ocean. The result is a smooth rim of thick, bright clouds surrounded by a dark
263 area of thin clouds that at subsequent times is advected by the eddy circulation and
264 encircles the eye. Thus the satellite imagery demonstrates the origins of the interweaved
265 dark and light bands in the aerial photograph of the eddy (Fig. 2, corresponding to the
266 1830 UTC image in Fig. 4) spiraling in toward the eye and completely surrounding it.

Figure 7 shows two panels of a time series of winds and temperatures from PG&E's meteorology tower covering the periods 0900-1400 UTC, and 1400-1900 UTC on September 12, 2006. Based on the satellite imagery (Fig. 4) the Grover Beach eddy formation and passage occurs approximately between 1445 and 1645 UTC. The 1415 through 1445 UTC images show the apparent remnants of a previous eddy affecting the winds at the Cal Poly pier. The top panel on Fig. 7 showing time series of the meteorology tower between 0900 and 1400 UTC is included because it also contains an apparent previous eddy passage between approximately 1015 and 1230 UTC that may be the same one seen in Fig. 4 at 1415 UTC near the Cal Poly Pier. There are many similarities between the time series of the 1015 UTC eddy and the "Grover Beach eddy," so it will be instructive to compare the two as the earlier eddy demonstrates how an eddy passage affects temperature at the tower in the absence of solar radiation effects, since it is occurring before sunrise.

The 1415 and 1430 UTC satellite images (Fig. 4) indicate strong cyclonic shear with northerly winds of approximately 7.5 ms^{-1} rounding Pt. Buchon just prior to the apparent eddy formation while the tower winds are lighter and westerly at 1415 UTC, then shift to easterly at 10 m and southerly at 76 m at 1430 UTC. This cyclonic horizontal shear likely contributes to the eddy formation process. As the sun comes up and the eddy first becomes apparent in the GOES-West imagery from 1430 to 1500 UTC, a strand of clouds begins to encircle the dry air that becomes the cloud-free eye. By 1445 and 1500 winds at both 10 and 76 m are northwesterly. The subsequent shift to southeasterly could be a result of the eddy center passing over the tower, or it could be explained as a manifestation of the eddy forming in situ to the southwest of the tower

with the southeasterly flow on the northwest flank of the forming eddy replacing the prevailing northwesterly winds. The data do not permit a firm conclusion on this question. It is interesting to note the wind shift to southeasterly at 76 m seen in the 1530 UTC panel of Fig. 4 preceeding that at the 10 m level, which is still northwesterly, by 15 minutes (see Fig. 7). In general, the 76 m winds seem to respond sooner and with more apparent synchronicity to features in the satellite imagery than do the winds at the 10 m level. This is seen again from 1630 to 1700 UTC where the changes in wind direction at 10 m seem to lag those at 76 m, and the apparent eddy position at cloud top as indicated by the satellite features. The better agreement between cloud features and the 76 m level winds presumably is owing to their position nearer to cloud level, and suggests the possibility of the eddy tilting with height. One can imagine the surface levels of the eddy “dragging behind” due to the greater restraining effect of surface friction on the advection of the eddy at 10 m than at 76 m or cloud level. For example, Dorman and Koracin (2008), citing aircraft soundings showing that surface-level buoy winds underestimate the layer wind speed, multiplied buoy winds by a factor of 1.15 to estimate representative wind speeds of the MABL for the calculation of Froude numbers.

The temperature curves in Figure 7 (bottom panel) show that prior to the eddy formation the entire 76 m tower was within the well-mixed MABL. Temperatures were close to 11°C for all three tower levels. At 1445 UTC temperatures at 76 m begin to slowly climb within the northwesterly wind regime, unambiguously emerging from the well-mixed regime after about 1515 UTC. The greatest rate of temperature increase occurs within the “return flow” southeasterly winds on the northeast and north side of the cloud-free eye, with temperature peaking at 14°C at 1615 UTC *after* the eye has already

313 moved to the south. At that point temperatures begin to cool in earnest when the wind
314 swings back to a northerly direction. The 10 m and 46 m temperatures lag those at 76 m,
315 beginning to rise at 1515 UTC starting within the northwesterly wind regime, then rising
316 faster within the southeast wind regime and establishing a surface-based temperature
317 inversion starting at 1545 UTC. Their peak occurs at 1700 UTC well after the cloud-free
318 eye has moved southeastward and during the transition of the surface winds back to the
319 prevailing westerlies outside the eddy.

320 What is the explanation for these temperature increases in the vicinity of the
321 eddy? Possible sources of warm air include the temperature inversion above, advection
322 of air from warmer locations, and solar heating after sunrise. While there appears to be a
323 solar heating component, given that post-eddy temperatures are warmer than those prior
324 to the eddy at all three levels, the greater amplitude of the temperature rise at 76 m
325 (roughly 3 Celsius degrees) vs. those at 10 and 46 m (about 2-2.5 Celsius degrees) and
326 the resulting temperature inversion indicate that solar radiation is not the most important
327 source of warming here. Indeed, examination of temperature changes occurring with the
328 earlier eddy between 1015 to 1230 indicate that warming of approximately 3 and 1.5
329 Celsius degrees at 76 m and 46 m, respectively, occurred in the absence of solar radiation
330 before sunrise. Beyond that, it is difficult to separate possible effects of a lowering of the
331 temperature inversion vs. advection of warmer air. In this area of rugged coastline any
332 wind direction between about 320° and 120° would have a downslope component. Under
333 these shallow MABL conditions and in light of the steepness of the local terrain, any
334 “downslope” air motion would almost certainly carry inversion-layer air to tower level.
335 Yet even during periods of general “eddy warming” at 76 m (i.e., from 0930 to 1115

UTC and from 1445 to 1615 UTC), roughly half of wind direction observations (8 values) are from an oceanic direction 120° to 320° and almost half (7 values) are from the “downslope” sector, with five out of seven being between 320 and 360° . This suggests that downslope advection is not a dominant factor in the warming. The warming may simply be related to a local lowering of the inversion by an “expansion fan” phenomenon that has been documented downwind of capes all along the California coast in general, and also specifically for the area south of Pt. Buchon, by Koracin and Dorman (2001). An expansion fan is a thinning of the MABL and consequent acceleration of wind speeds to supercritical values within the thinned layer (Dorman and Koracin 2008). The 76 m warm anomalies on the time series (Fig. 7) extend beyond the apparent bounds of both the earlier eddy and the Grover Beach eddy. This indicates that the descent of the inversion to the surface is not confined strictly within the eddy, and therefore provides some evidence for its interpretation as an expansion fan. Ultimately the data do not permit a solid conclusion to this question, and model simulations are being conducted to shed light on its possible relationship to eddy formation. Theoretical literature on eddy formation mechanisms will be discussed in section 2d.

d. Froude number and possible eddy formation mechanisms

Many investigators have employed a version of the Froude number (Fr) based on shallow water theory to characterize the MABL along the California coast in analogy to hydraulic theory (Rahn et al. 2013; Dorman and Koracin 2008; Archer and Jacobson 2005; Burk and Thompson 2004; Haack et al., 2001, to name a few). This version of Fr can be written as

$$Fr = \frac{U_{MABL}}{\sqrt{gH \frac{(\theta_t - \theta)}{\theta}}} \quad (1)$$

359 where U_{MABL} is the undisturbed wind speed in the MABL upwind of the eddy-producing
 360 terrain, g is the acceleration of gravity, H is the depth of the MABL, θ_t is the potential
 361 temperature at the top of the inversion, and θ is the potential temperature of the MABL.
 362 Following the procedure of Dorman and Koracin (2008) wind speed values, U , from
 363 buoys were multiplied by a factor of 1.15 to obtain the U_{MABL} values. Since the
 364 Vandenberg sounding was missing crucial data, it cannot be used to calculate quantities
 365 crucial for the Fr , so we used local values from the tower data, Davis Peak, and estimated
 366 ranges of winds and inversion depths to constrain the possible range of Fr . In practice,
 367 we used a formulation of potential temperature referenced to sea level since there are no
 368 pressure observations at the meteorology tower. Estimates to constrain U are
 369 subjectively determined based on winds from buoy 46028 (105 km northwest of Pt.
 370 Buchon) and buoy 46011. Winds from Pt. Buchon were not used because these winds are
 371 part of the disturbed flow impinging on the headland. Examination of the buoy winds
 372 suggests that the maximum value of U was about 6 ms^{-1} , while the minimum was around
 373 3 ms^{-1} ; an average value of U from buoy 46208 for the period from 0000UTC to 1200
 374 UTC was about 5 ms^{-1} . It is likely that the minimum is an underestimate of the true
 375 undisturbed winds considering that Pt. Buchon experienced its maximum wind speeds of
 376 the day between 1400 to 1500 UTC of 5.6 to 7.5 ms^{-1} . θ was calculated as an average of
 377 the values from the meteorological tower at 10 and 76 m, while θ_t was calculated from
 378 the temperature at Davis Peak. One of the crucial unknowns is the depth of the MABL,

379 H, so a range of values can be estimated. Prior to eddy formation, the meteorology tower
380 was completely within the MABL, so its depth is at least 108 m (76 m + 32 m of
381 elevation). At the high end, terrain elevation contours plotted on visible satellite imagery
382 (not shown) suggest that the marine layer did not penetrate past an elevation of at most,
383 200 m. Table 1 presents estimates of the Fr using the preceeding bracketing values of
384 wind and MABL depth. The results suggest that prior to eddy formation values were
385 most likely between 0.5 and 0.8. Rogerson (1999) describes transcritical flow as regions
386 containing both subcritical ($Fr < 1$) and supercritical ($Fr > 1$) values, while Dorman and
387 Koracin (2008) define transcritical flow as Fr values between 0.5 and 1.0. which is
388 expected to lead to hydraulic features in the MABL such as supercritical expansion fans
389 and hydraulic jumps. The thinning MABL in an expansion fan and acceleration of the
390 flow speed results in a transition to supercritical flow. The likely transcritical values in
391 the present case suggest that a transition to supercritical flow was possible. The possible
392 collapse of the MABL in an expansion fan in the present study is evident in the lowering
393 of the inversion to ground level as indicated by the meteorological tower measurements.
394 Since the tower is 32 m above sea level we employ this value as a lower bound for
395 MABL depth. This gives supercritical ($Fr > 1$) values for the two more probable U's of 6
396 and 5 ms^{-1} , in agreement with results of previous studies showing supercritical expansion
397 fans in the lee of capes (Koracin and Dorman 2008). On the other hand, using an
398 unlikely, but possible, estimated minimum value of $U = 3 \text{ ms}^{-1}$ with the constraining
399 values of H (i.e., 108 m and 200 m), yields values of Fr of 0.3 to 0.4, within the “low Fr”
400 range studied by Smolarkiewicz and Rotunno (1989) and others.

401 Smolarkiewicz and Rotunno (1989) used idealized inviscid model simulations
402 with uniformly stratified flow in order to understand wake vortex formation in the lee of
403 the Hawaiian Islands. They were the first to show that an inviscid mechanism, i.e., tilting
404 of vorticity generated baroclinically due to sloping isentropes, could produce lee eddies
405 without boundary separation, as boundary separation cannot happen in an inviscid model.
406 Their results suggest the importance of Froude number (Fr) in the range 0.1-0.5, that
407 they term “low Froude number flow,” in eddy formation by their inviscid mechanism.
408 They noted that eddies did not occur in their simulations at $Fr > 0.5$, suggesting to them
409 that wake eddies forming due to boundary layer separation may be important at values
410 above 0.5, the more likely range of the Fr for the Grover Beach eddy.

411 Young and Zawislak (2006) provide a comprehensive summary of the evolution
412 of ideas in the literature about atmospheric eddy formation mechanisms over recent
413 decades, including emphasis on flow-blocking due to strong stratification (which in our
414 study is provided by the pronounced subsidence inversion). Schär and Smith (1993) use
415 a shallow water framework while Schär and Durran (1997) employ three dimensional
416 continuously stratified numerical simulations to explain lee eddies in terms of potential
417 vorticity flux generated by dissipation either in a breaking mountain wave
418 region/hydraulic jump or in an elongated wake region. Epifanio and Durran’s (2002)
419 simulations agree with Smolarkiewicz and Rotunno (1989) that tilting of baroclinically-
420 generated vorticity contributes to vortex formation, but also show that this vorticity is
421 amplified by stretching in hydraulic jumps similar to the results of Schär and Smith
422 (1993) and Schär and Durran (1997). Relevant to our study, Young and Zawislak (2006)
423 link mountain wave formation and consequent “lee side clearing” and mixing (Lyons and

Fujita 1968) with eddy formation based on the theoretical literature, citing Smolarkiewicz and Rotunno (1989), Schär and Smith (1993) and Schär and Durran (1997). Mountain wave formation is more pronounced at Froude number values from 0.5 to 1.0 than at the lower Fr's in the 0.1 to 0.5 range where there is more of a “flow-around” regime and less of a “flow-over” regime (Schär and Durran 1997; see, e.g., their experiment with non-dimensional mountain height = 1.5 equivalent to Fr = 0.67; Smolarkiewicz and Rotunno's 1989 Fr = 0.66 experiment; and Epifanio and Rotunno's 2005 experiment with non-dimensional mountain height = 2, equivalent to Fr = 0.5). In the shallow water framework, a non-dimensional mountain height

$$M = \frac{h_m}{H} \quad (2)$$

is needed in addition to the Fr to discriminate flow-over vs. flow-around regimes where h_m is the height of the terrain that produced the eddy and H is again the depth of the undisturbed MABL. Values of $M > 1$ indicate that the mountain is taller than the fluid depth, or in our case, the MABL depth. Using our constraining range of H, this could range from 2.75 to 5.1 for the Grover Beach pre-eddy environment. Our case with Fr most likely between 0.5 and 1 appears similar in some respects to Schär and Smith's (1993) “pierced fluid surface” experiment using a shallow water model with Fr of 0.5 and M of 2.0 which they classify as “Regime III,” featuring some reversed flow in the wake. It is not clear whether a direct comparison between results from our shallow water formulation of Fr with those of the continuously stratified studies is appropriate, since $0.5 < Fr < 1$ for those is the flow-over regime. Additionally, Rahn et al. (2013) point out that interpretation of Fr for the real atmosphere is imprecise due to departures from theory.

Our calculations suggest that expansion fan dynamics may be more relevant for the Grover Beach case than mountain wave dynamics, but again, detailed model simulations of this case are being conducted to sort out issues about the relevance of different theoretical perspectives to the real atmosphere case presented here.

Both Smolarkiewicz and Rotunno (1989) and Schär and Durran (1997) predict warm core eddies and Smolarkiewicz and Rotunno (1989) suggest the presence of warming as an observational test (p. 1164) for their mechanism. The meteorological tower data provide some evidence with respect to Smolarkiewicz and Rotunno's (1989) suggested observational test (p. 1164) that such vortices should have a warm core (see also Schär and Durran 1997). This is seen in the previously-noted temperature increases at all three tower levels during eddy passage (Fig. 7). Under Smolarkiewicz and Rotunno's (1989) mechanism this warming is provided in a possible mountain wave-like sinking in the lee of the high terrain (and in theory could provide the dry air for the cloud-free eye). However, in our observational study, the Grover Beach eddy is accompanied by temperature increases at 76 m, but these temperature increases apparently begin even before the eddy circulation develops at the tower and end after it has moved downwind. Additionally, temperature increases at the 10 m and 46 m levels continue even after the eddy appears in satellite imagery to have moved downstream; this observation suggests that temperatures at those levels may be a result of processes not directly related to eddy formation. Ultimately even the subsynoptic data sources being used here are inadequate to determine the mechanism(s) of eddy formation.

The present case is different than the theoretical studies in another respect, given that there is significant vertical shear in the wind field which has not been studied in the

idealized simulations cited above. In our case, if there is a tilting component in the vorticity, it would be important to quantify how much is due to tilting of horizontal vorticity generated initially by the vertical shear field. Heuristically, it would appear that cyclonic vortices formed to the right of the terrain centerline looking downwind with the flow would be countered by the maximum sinking in the lee of the terrain centerline, but would be promoted by tilting in the upward motion of a hydraulic jump.

Casual examination of visible satellite images in the years since we received the eddy photographs has revealed that it is not unusual for eddies to come spinning off the raised terrain of the San Luis Range. Its prominence as terrain that protrudes westward into the marine environment, while frequently penetrating the inversion above, creates conditions that are likely to produce eddies in ways similar to large islands like Santa Cruz and Catalina. The presence of the Diablo Canyon Nuclear Plant and potential for toxic releases suggest that model simulations not only are necessary to better understand eddy formation mechanisms, but also would be useful to better characterize the complex flow characteristics in this region.

3. Summary and conclusions

Unique aerial photographs of cyclonic eddies in the marine stratocumulus taken by a commercial pilot off the California coast have been presented. The eddies were similar in scale and appearance to Von Karman vortices seen in high resolution satellite imagery and described in the literature. Each had a cloud-free eye, and occurred under strong inversion conditions with a shallow MABL. While satellite imagery of such features has previously been presented, to our knowledge, these are the first photographic images of such features, taken from an airplane, to appear in publication.

492 The eddies occurred in the lee of inversion-penetrating high terrain of Santa Cruz
493 Island and the San Luis Range, a headland near San Luis Obispo. The latter eddy then
494 drifted toward Grover Beach where it was photographed by the pilot.

495 GOES satellite imagery, along with sub-synoptic meteorological observing sites
496 shed light on the movement and evolution of the Grover Beach eddy, but also highlight
497 the limitations of existing subsynoptic data for determining details and mechanisms of its
498 formation. The Grover Beach eddy appeared from satellite imagery to move
499 southwestward over the three-level 76 m instrumented tower run by PG&E for
500 monitoring at their Diablo Canyon nuclear power plant, in line with the northeasterly
501 inversion layer winds. However, an alternative scenario is that the eddy formed in situ to
502 the southwest of the tower. It is not possible to determine the correct option with only the
503 data we have. Regardless, winds and temperatures on the tower responded to the eddy's
504 circulation, showing nearly 180° wind reversals at 10 and 76 m. Winds at 76 m show
505 more synchronicity with satellite-observed eddy features than the winds at 10 m. The
506 winds at 10 m showed similar responses but lagged those at 76 m by 15-30 minutes,
507 suggesting that the eddy was tilting with height. The eddy influenced the winds at the
508 Cal Poly Pier as it passed by that station to the south, and caused a 180° wind direction
509 reversal as it passed over SLOAPCD's wind monitoring site at Grover Beach shortly
510 after being photographed by the pilot. Fr calculations suggest that the MABL was
511 transcritical prior to eddy formation and that a transition to supercritical flow in the lee of
512 Pt. Buchon may have accompanied a collapse of the MABL during which time tower
513 data showed that the temperature inversion descended to at least 32 m above sea level, if
514 not lower. Ultimately a very high resolution model simulation will be needed to answer

questions about the relevance of mechanisms of eddy formation described in the theoretical literature, and to determine the relative roles of both horizontal and vertical shear. Such simulations are under development in our lab.

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Table 1. Froude Number estimates from Equation (1) where U represents approximate maximum, minimum, and mean wind values subjectively determined from buoys 46028 (105 km northwest of Pt. Buchon), and 46011 (30 km southwest of Pt. Buchon). These values are multiplied by 1.15 to obtain U_{MABL} . H represents constraining values for the depth of the MABL prior to eddy formation, and a value based on its maximum depth after the inversion had descended to ground level and possibly “collapsed.” θ was determined from the average of the 10 m and 76 m tower values at 1400 UTC, while θ_t was determined from the simultaneous temperature value at Davis Peak. 1400 UTC is just prior to eddy formation when the entire tower was within the MABL.

	H (max) = 200 m	H (min) = 108 m	H (collapse) = 32 m
U (max) = 6 ms⁻¹	0.6	0.8	1.5
U (mean) = 5 ms⁻¹	0.5	0.7	1.3
U (min) = 3 ms⁻¹	0.3	0.4	0.8

Figure Captions

Figure 1. Aerial photograph of stratocumulus cloud vortex just north of Santa Cruz Island on July 16, 2006 at 11:26 PDT (18:26 UTC), viewing toward the southwest. (Photo by “KB” courtesy of Capt. Peter Weiss of SkyWest Airlines).

Figure 2. Aerial photograph of stratocumulus cloud vortex just offshore from Grover Beach, California, on September 12, 2006 at 11:28 PDT (18:28 UTC). (Photo by “KB” courtesy of Capt. Peter Weiss of SkyWest Airlines).

Figure 3. Terrain that produced the Grover Beach eddy, with the locations of relevant monitoring stations superimposed and numbered as follows: 1) Pt. Buchon 2) Diablo Canyon Nuclear Power Plant meteorological tower 3) Davis Peak 4) Cal Poly pier 5) SLOAPCD Grover Beach site. Just to the north northwest of San Luis Bay is the San Luis Range (also known locally as the Irish Hills) which has ridges extending to between 450 to 550 m (1500-1800 feet) MSL. (Base map courtesy of San Luis Obispo County Planning Department, Geographic Technology and Design Section).

Figure 4. GOES-west images from 14:15 to 19:11 UTC on Sept. 12, 2006 showing the Grover Beach eddy. The satellite image at 1830 UTC shows the same cloud as figure 2. Analysis of the image shows shows a length of 17 km, width of 9 km, and cloud-free eye of 2.5-3 km. Half barbs represent wind speeds of approximately 2.5 ms^{-1} . Whole barbs represent wind speeds of approximately 5 ms^{-1} , and a shaft with no barb represents wind speeds of less than approximately 1.3 ms^{-1} but greater than 0.26 ms^{-1} . Circles depict wind

speeds of less than approximately 0.26 ms^{-1} . Temperatures are in $^{\circ}\text{C}$. The meteorological tower 76 m level temperatures and winds are plotted in orange with larger symbols on top of the 10 m temperatures and winds.

Figure 5. Top: Surface analysis for 12 UTC, September 12, 2006 from the Weather Prediction Center's Daily Weather Maps archive. Bottom: 850 hPa chart for 12 UTC, September 12, 2006 from the Storm Prediction Center archive. 850 hPa winds from the Oakland and San Diego soundings can be seen along the central and southern California coast. Heights are in decameters and winds are in knots. The red dot shows the location of the Grover Beach eddy.

Figure 6. Left: Oakland (KOAK) sounding for 12 UTC September 12, 2006.. Right San Diego (KNKX) sounding for the same time.

Figure 7. Temperature ($^{\circ}\text{C}$) time series (curves) from three levels, and wind time series (barbs) from two levels collected by the instrumented tower at the Diablo Canyon nuclear power plant, as the eddy passed over or formed nearby. The dotted curve is from 76 m, dashed curve is from 46 m, and the solid curve is from 10 m above ground level (AGL). The top row of winds is from 76 m and the bottom row is from 10 m AGL. Half barbs indicate approximately 2.5 ms^{-1} and whole barbs approximately 5 ms^{-1} . Time is in UTC. Based on satellite imagery, the eddy passage is roughly between 1445 UTC and 1615 UTC. Vertical lines mark the times of the observations. Note that the fastest winds and the warmest temperature at 76 m during the period occur in the southeasterly flow of the

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680 m occurred roughly between 1015 UTC and 1215 UTC.
681



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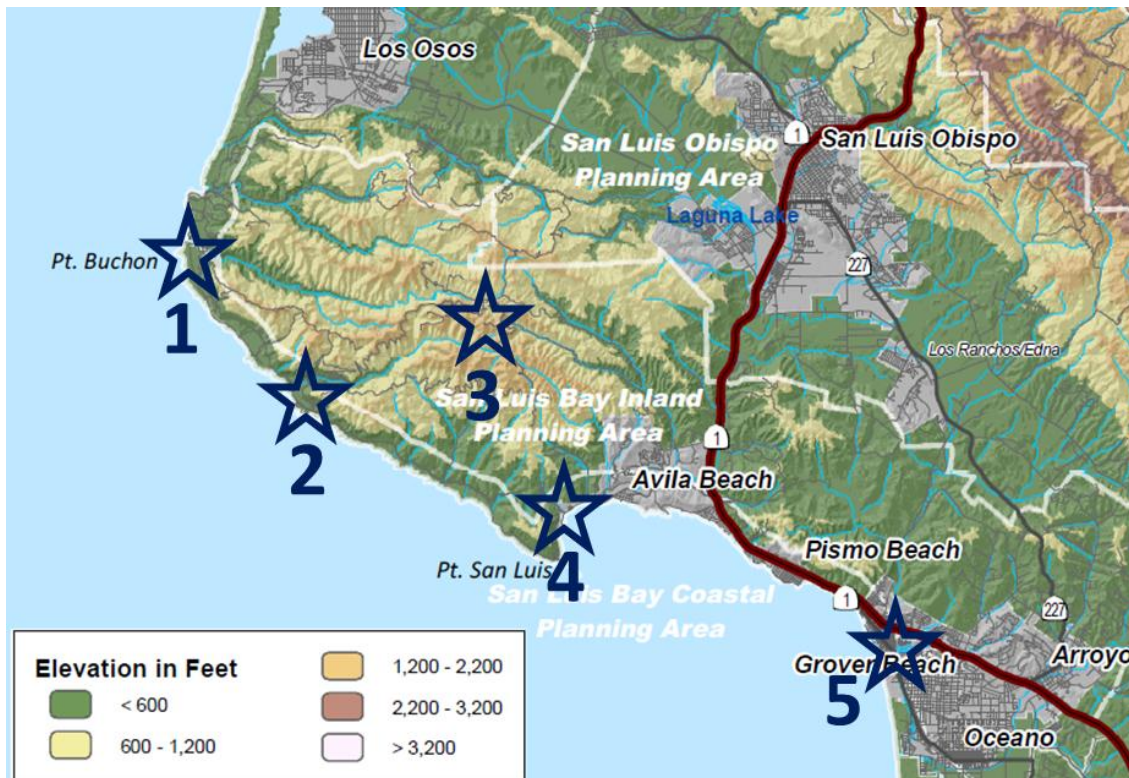
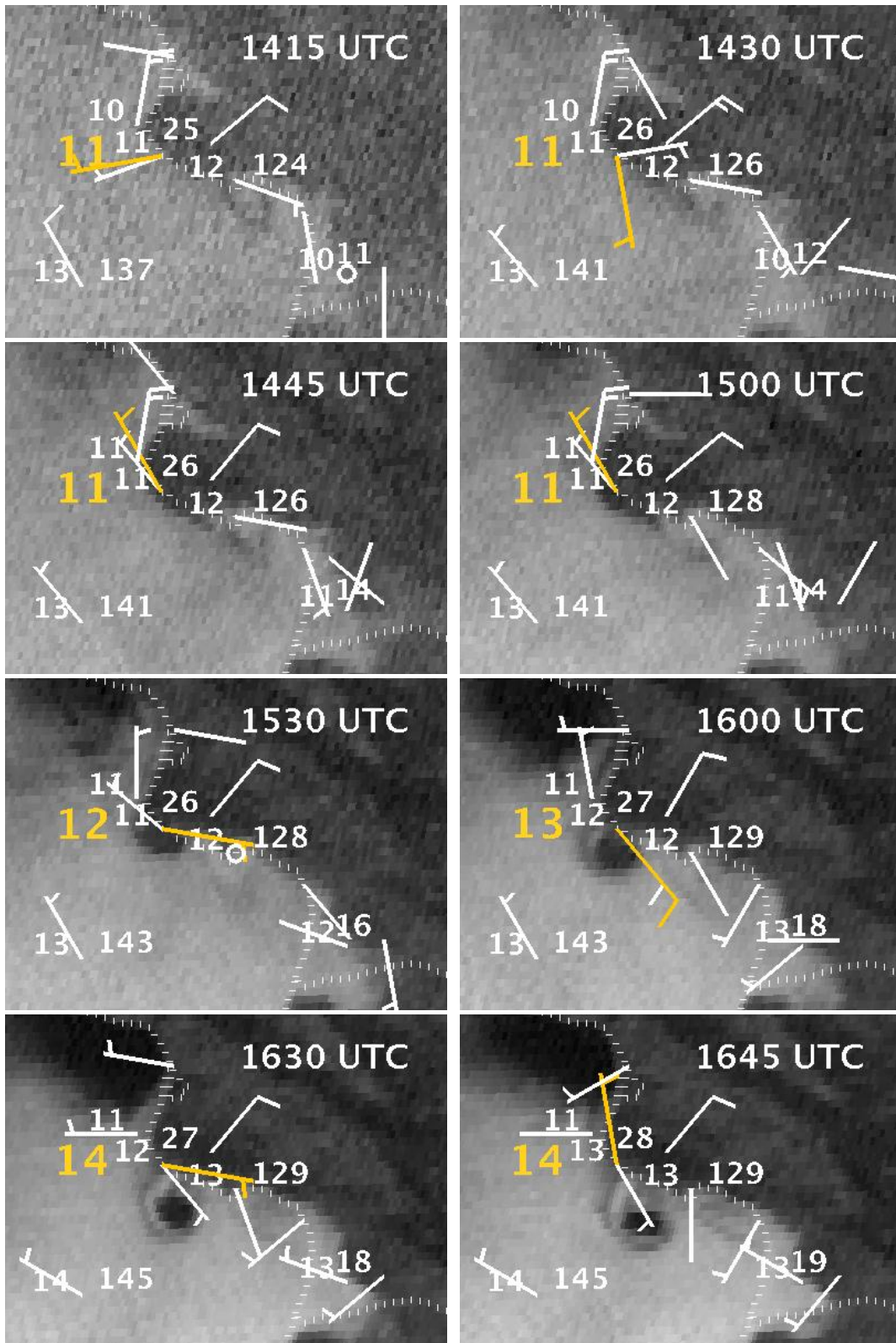


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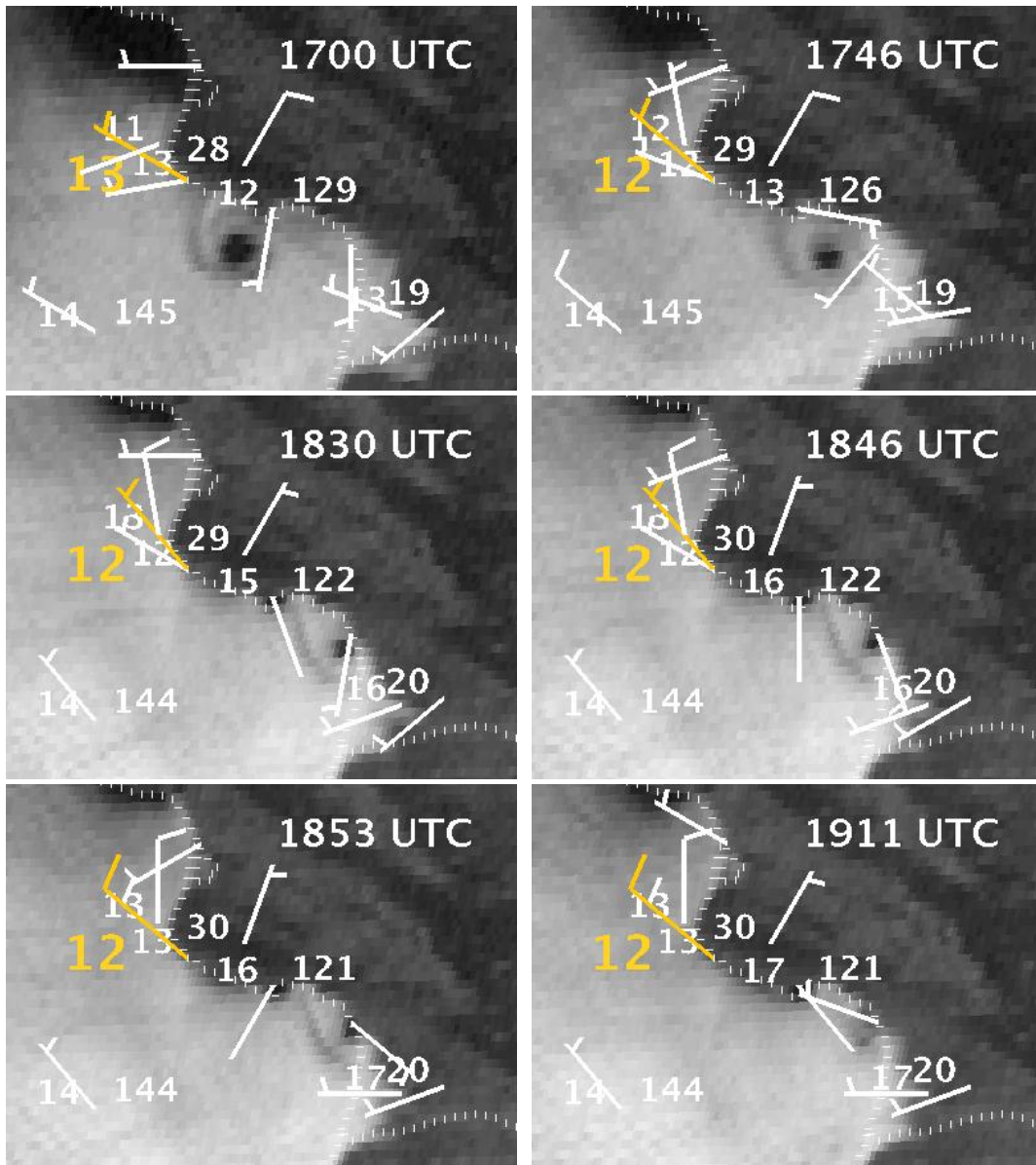
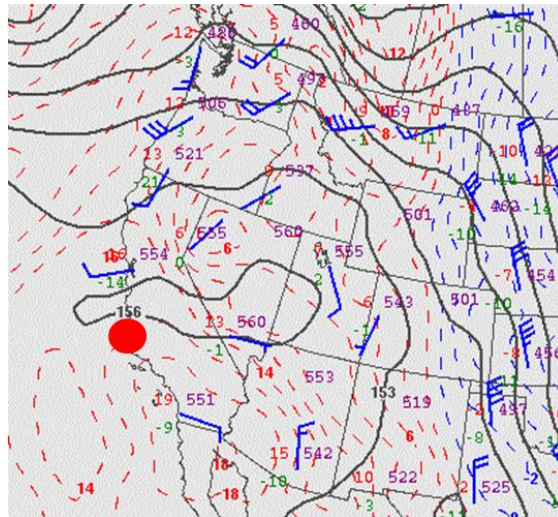
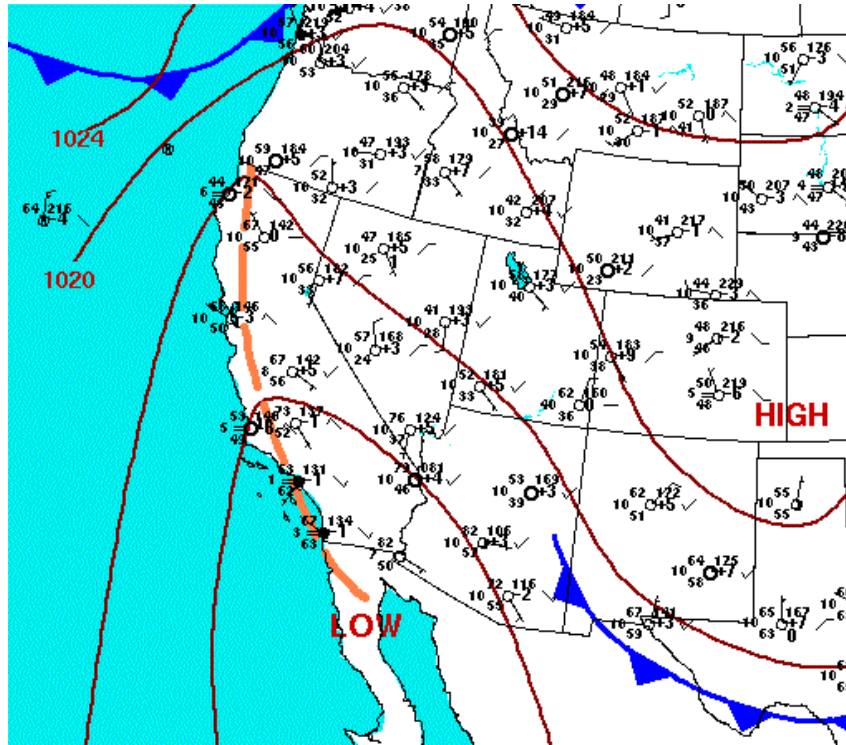


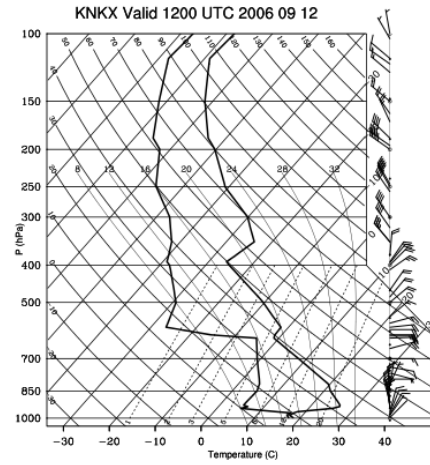
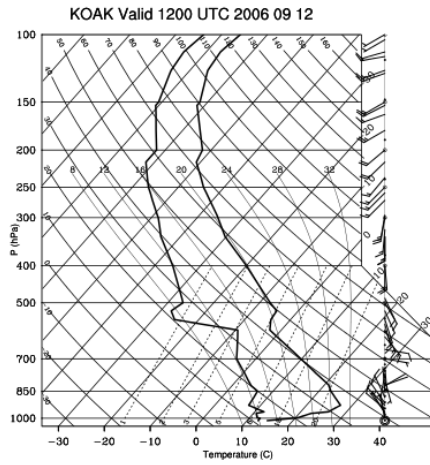
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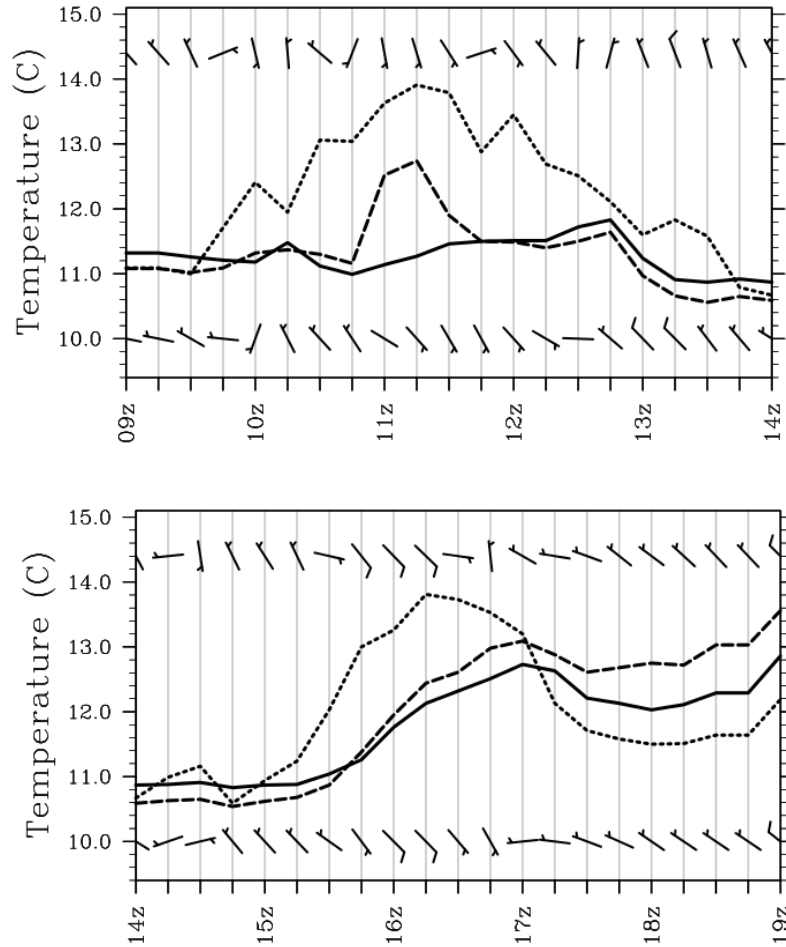


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