6.1 THE SANTA CRUZ EDDY: OBSERVATIONS AND NUMERICAL SIMULATIONS

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1 INTRODUCTION AND MOTIVATION

A shallow, cyclonic circulation is found to occur in the summer time in the Monterey Bay (California). Since it is often centered offshore from the city of Santa Cruz, it is named "Santa Cruz Eddy" in this study. With its horizontal size of 10-20 km, the Santa Cruz Eddy represents the only non-severe weather example of a meso-γ circulation in the atmosphere, i.e., with horizontal size of 2 to 20 km and lifetime of the order of hours. It forms in the late afternoon and it can either last a few hours or continue over night until the sea breeze breaks it down the morning after. The Santa Cruz Eddy is important for local weather because it causes surface winds along the Santa Cruz coast (i.e., the north-eastern Monterey Bay) to blow from the east instead of from the north-west, which represents the climatological summer pattern for this area. Furthermore, cool and moist air is advected from the south and south-east into the Santa Cruz area, bringing both relief from the heat and fog to the city. An example is shown in Figure 1, where the eddy is centered in the only fog-free area in the Monterey Bay. A tongue of fog is starting to rotate counter-clockwise from the south-eastern part of the Bay.

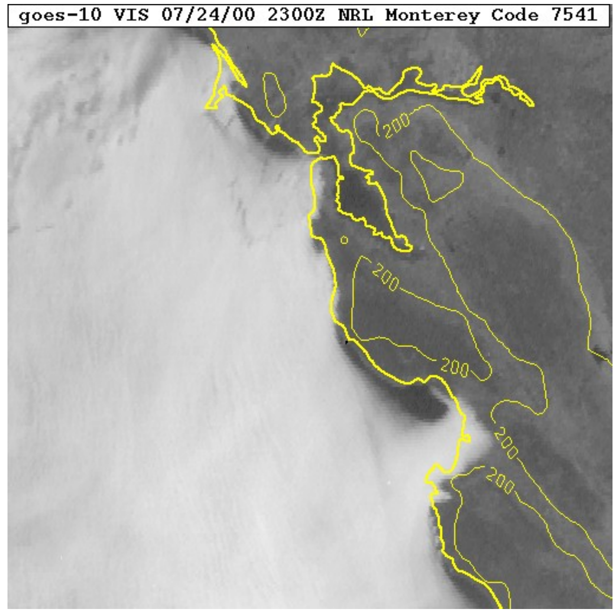

Figure 1: 1 km GOES-10 satellite visible image of the Monterey and San Francisco Bays showing a Santa Cruz Eddy forming in the late afternoon of July 24th 2000 (from Navy Research Laboratory, Monterey, California)

Eddies similar to the Santa Cruz one, but larger in either horizontal, vertical, or time scale are found in other locations in the world. The most studied is the Catalina eddy, which occurs sporadically in the summer time in the so called Southern California Bight. With its horizonital size of 100-200 km and its vertical extent of about 1 km, the Catalina eddy belongs to the meso-β scale. Three different mechanisms have been proposed to explain its formation. The first one assumes that strong northerly or north-westerly flow at the low levels with high Froude number is necessary to form the Catalina eddy (Bosart 1983, Mass and Albright 1989, Thompson *et al.* 1997, Ueyoshi and Roads 1993, Ulrickson *et al.* 1995, Davis *et al.* 2000). Such a flow would overcome the west-to-east oriented Santa Ynez Mountains and form a mesoscale lee trough. Ageostrophic southerly flow would then initiate the eddy. The second theory is based on the opposite assumption, i.e., that a low Froude number flow at the lower levels would initiate the eddy, due to either the vortex shedding mechanism or the inviscid theory of Smolarkiewicz and Rotunno (1989). The vorticity necessary to start the eddy would be formed by the acceleration of the surface north-westerly flow around the topography, and not over it (Wakimoto 1987, Eddington *et al.* 1992, Clark and Dembek 1991, Ueyoshi and Road 1993, Ulrickson *et al.* 1995). The third theory relates the eddy formation to a Kelvin wave. Such a wave is identified as a "bump" in the marine layer inversion height (and accompanying high surface pressure) that moved northward from Baja California with a speed of about 5-8 m/s. The Catalina eddy would form because the wave could not progress past the

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sharp bend in the coast at Point Conception and because at the mean northerly wind suppressed any progression of the Kelvin wave (Dorman 1985, Clark 1994).

Other eddies are: the Vancouver Island eddy (Mass and Albright 1987); the midchannel and Gaviota eddies in the Southern California Bight (Smith *et al.* 1983, Wilczak *et al.* 1991, Kessler and Douglas 1991, Dorman and Winant 2000); the Gulf of Antalya eddy in the Mediterranean Sea (Alpert *et al.* 1999); the Point Arena and Cape Mendocino eddies (Dorman 1985); the South Island eddy in New Zealand (Laing and Reid 1999); the Denver cyclone (Wilczak and Glendening 1988, Wilczak and Christian 1990).

In summary, mesoscale eddies are common in the atmosphere. However, all the eddies mentioned above occur sporadically, when certain unusual weather conditions verify, whereas the Santa Cruz Eddy is unique because it forms almost every day in the summer time. Furthermore, they all belong to the meso-β scale, with the only exception of the Gaviota eddy, which, however, has been recently reclassified as a shear-zone by Dorman and Winant (2000). Even with this differences in mind, the literature review emphasized that topography orientation, presence of an area of low pressure in the lee side of the mountains, and ageostrophic circulations may play an important role in the formation of the Santa Cruz Eddy as well.

2 OBSERVATIONS AND DATA ANALYSIS

Data were collected for the summer 2000 from two main sources: the National Weather Service (NWS) through the Unidata data feed, and the Naval Postgraduate School (NPS) of Monterey through the REINAS database, for a total of ten stations, three of which are buoys (Figure 2).

Although over twenty Santa Cruz Eddy cases were analyzed, the present work will focus on the 24-25 August 2000 event. The synoptic conditions at 500 mb are characterized by a trough located right off the Western U.S. coast and high pressure over the Midwest, a combination that causes a south-westerly flow at the upper levels over California. At the surface, the typical Pacific High in conjunction with the inland low causes the main flow to be from the north-west along the coast. The eddy starts forming at about 2300 UTC on August 24, when the wind at Watsonville (WVI) shifts from south-westerly to purely southerly. Within an hour, the eddy reaches the Santa Cruz area, as indicated

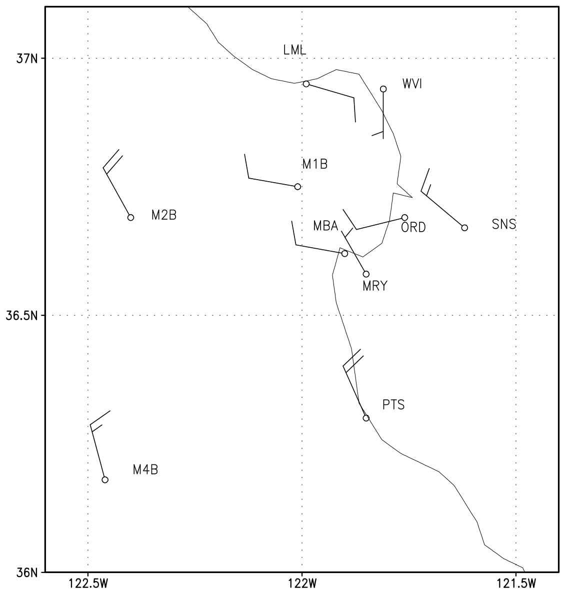

Figure 2: Station locations and surface wind [knots] at 0100 UTC on 25 August 2000

by the wind shift at Long Marine Lab (LML) from westerly at 15 knots to easterly at 5 knots. The eddy is fully developed by 0100 UTC on August 25 (Figure 2), when it occupies about a half of the Monterey Bay; it then seems to dissipate from 0500 to 1000 UTC.

Since the literature findings emphasized the importance of surface pressure patterns in eddy formation, the sea level pressure trends are analyzed for four key locations (see Figure 2 for station locations): Monterey (MRY), Long Marine Lab (LML), Salinas (SNS), and Watsonville (WVI). Figure 3 shows such trends for the 24 hour period starting at 1800 UTC on August 24. A north-to-south pressure gradient can clearly be seen, as the most northern location (LML) has an average sea level pressure that is about three mb lower than the southernmost Monterey, with a maximum difference of 3.5 mb at 0000 UTC on August 25, when the eddy reaches LML.

What causes such a pressure gradient? As highlighted by the literature findings, the topography is believed to play a role in this sea level pressure pattern. In fact, the Santa Cruz mountains to the north of the Monterey Bay, although not perpendicular but rather parallel to the main north-westerly flow, protect the Santa Cruz area from the cold marine air. This allows increased surface heating which results in an average summer temperature that is about 4 degrees higher than close-by Monterey. Such surface heating is believed to cause the localized area

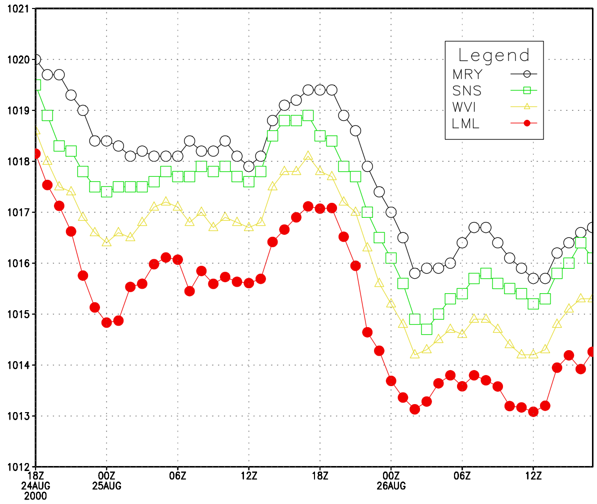

Figure 3: Sea level pressure [mbar] 24-hour trend for Monterey (MRY), Salinas (SNS), Watsonville (WVI), and Long Marine Lab (LML) starting on August 24 at 1800 UTC.

of low surface pressure in the north-eastern part of the Monterey Bay which the data seem to support. Furthermore, the Big Sur Mountains to the south of the Bay act as a block against the main north-westerly flow. It is believed that they are responsible for raising the marine layer in the southern Bay, thus causing a localized area of higher surface pressure in the Monterey area, which is consistent with the data in Figure 3.

Given the lack of observations at the upper levels for the Monterey Bay area, a modeling approach was chosen. The goals are to verify the hypothesized sea level pressure patterns, to study the vertical structure of the marine boundary layer in the Bay and its effects of the Santa Cruz Eddy, and finally to run sensitivity analyses to verify the importance of factors such as topography, surface heating, main flow characteristics.

3 MM5 SIMULATIONS

The Fifth-Generation Mesoscale Model (MM5) Version 3 is used in this study to simulate the 24-25 August 2000 Santa Cruz Eddy event. The model is run for two 1-way nested domains, with horizontal resolutions of 5 km (Domain 1) and 1 km (Domain 2) respectively; both grids have 150x120 grid points and 30 vertical levels. The initial and boundary conditions are provided by the 2.5 x 2.5 degrees horizontal resolution NCEP (National Center for Environmental Prediction) global analyses. The boundary layer parameterization is the Eta Mellor-Yamada and no cumulus parameterization is used. The runs start on August 24 at 1200 UTC and end 48 hours later on August 26 at 1200 UTC.

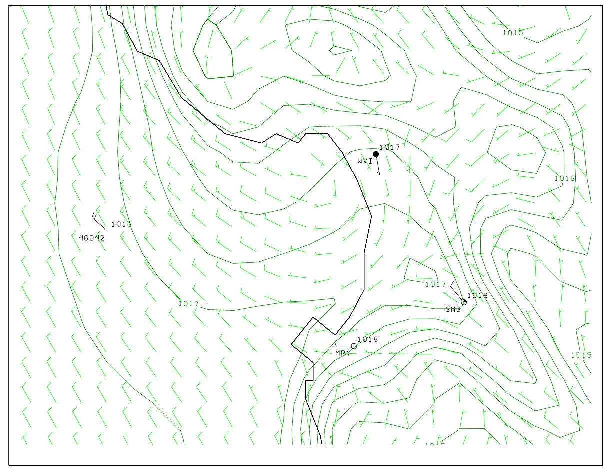

Figure 4: MM5 sea level pressure [mb] and 10 m winds [knots] with observed values at Monterey, Watsonville, and Salinas on August 25 at 0200 UTC.

Figure 4 shows the 10 m winds calculated by MM5 for Domain 1 and the observed winds at MRY, SNS, and WVI. The results are in good agreement with the observations but the timing is off by a few hours. In fact, as discussed above, a full eddy developed by 0100 UTC on August 25, whereas the simulation showed a closed circulation ony at 0300 UTC, i.e., two hours later. The sea level pressure pattern agrees well with the hypothesis of a localized area of low pressure in the Santa Cruz area and relatively high pressure in the southern Bay. Note the ridge of high pressure being pushed northward by the southerly wind in the eastern Bay, which is also responsible for advecting high relative humidity air from the southern Bay up to the Santa Cruz area (not shown).

A north-south cross section, from the mountains to the north of Santa Cruz down to those behind Monterey, is shown in Figure 5 for potential temperature and winds up to 800 mb. The main flow aloft is from the south-west, whereas at the lower levels the flow is north-westerly. As expected, the marine layer is tilted, with higher elevations in the south Bay, as a consequence of the blocking effect of the Big Sur Mountains. An area fo high wind speed forms right offshore from LML (not shown), possibly an expansion fan, which is believed to contribute to the formation of cyclonic vorticity via shear.

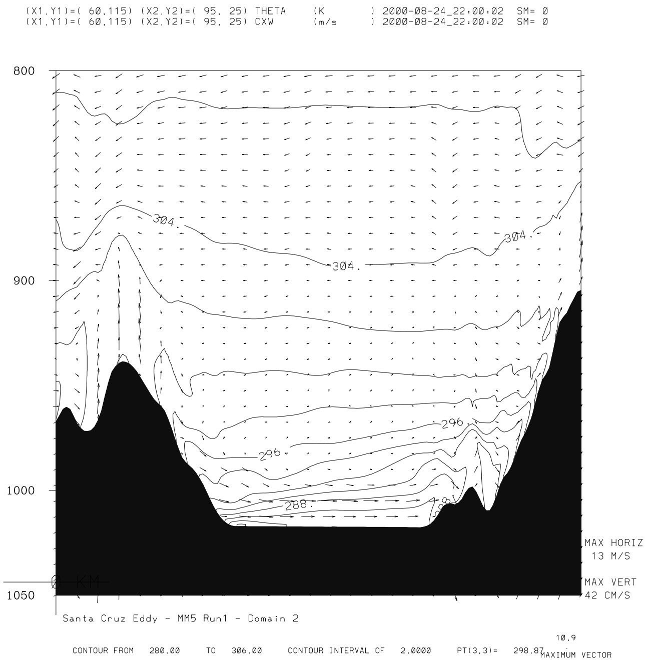

Figure 5: MM5 sea level pressure [mbar] and 10 m winds [knots] with observed values at Monterey, Watsonville, and Salinas

4 CONCLUSIONS

A meso-γ, cyclonic circulation, occurring in the Monterey Bay, is investigated in this study for the first time. Since it is centered offshore of the city of Santa Cruz, and since the microclimate of Santa Cruz is supposed to be a key factor in its formation, this circulation is named "Santa Cruz Eddy." This circulation has a horizontal size of 10-20 km and a vertical extent of about 200 m. Data collected during the summer 2000 showed that the Santa Cruz Eddy forms almost every day in the late afternoon; it can last only a few hours or all night and it dissipates in the morning at the latest. Analyses of sea level pressure data show that a pressure gradient from the north to the south is likely to be present in the Bay, with low pressure in the Santa Cruz area and high in the Monterey area. Such a gradient is believed to be responsible for establishing an ageostrophic flow from the south, which would initiate the eddy. The MM5 model was run to verify the presence of such a gradient and to investigate possible mechanisms of formation via sensitivity tests. Results from some preliminary runs do confirm that a pressure gradient is present in the Bay. Furthemore, they indicate that the higher pressure in the southern Bay is caused by the tilting of the marine boundary layer in the Bay, lower in the north and higher in the south. It is believed that such tilting is caused by the blocking effect of the Big Sur Mountains behind Monterey on the main northwesterly flow. MM5 also showed that an area of high wind speeds, possibly an expansion fan, forms off of Santa Cruz. Such a fan would contribute to the formation of cyclonic vorticity through shear.

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