The Catalina Eddy and Topographic Forcing over the Southern California Bight

Clive E. Dorman

Scripps Institution of Oceanography, San Diego, California
and
San Diego State University, San Diego, California

Eric Klimczak

San Diego State University, San Diego, California

Wendell Nuss

Naval Postgraduate School, Monterey, California

30 April 2002

Abstract

Ten Catalina Eddy events are examined for the year 1996 with an expanded network of surface and upper-air data sets. Included are a network of three east-west oriented surface stations and a radar profiler on the south side of the Santa Ynez Mountains that are in the path of any lee side flow which has been proposed as initiating the Catalina Eddy. The hypothesis that lee-side effects of the Santa Ynez Mountains causes the formation of Catalina Eddy fails in all events when examined with the expanded observation network not utilized earlier. Several Eddy events have marine air thinning or constant height in the San Diego area during the formation stage which conflicts with the hypothesis that "cold air damming" causes marine layer deepening and the first appearance of the eddy in the San Diego area. A summer atmospheric marine layer transcritical expansion fan imposes a semi-permanent pressure minimum in the Santa Barbara Channel not associated with Santa Ynez Mountain lee side flow nor Catalina Eddies.

A detailed study is presented of two Catalina Eddies. The 19 June 1996 event that has a leading cloud edge that moves from the Eastern Southern California Bight along the coast to Point Conception. The 1 August 1996 event formed a cyclonic eddy exclusive of the Santa Barbara Channel area which had no clouds nor special wind shifts associated with a Catalina Eddy.

A new hypothesis on the cause of the Catalina Eddy is proposed. The mean, daily surface marine layer in the Southern California Bight south of the Channel Islands has a cyclonic distribution capped by a stable layer. An increase in mid-level cyclonic or decreased anticyclonic conditions that does not eliminate the stable layer capping layer can cause the surface layer to form a cyclonic eddy with a stratus overcast. This hypothesis satisfies all of the structural variation of eddies that are observed by satellite, the upper air stations and the dense network of surface stations around the Southern California Bight.

Corresponding author address: Dr. Clive Dorman, IOD, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093-0209
E-mail:cdorman@ucsd.edu

1. Introduction

The interaction of synoptic-scale features with local, complex topography can result in complicated mesoscale structures that are difficult to understand or model for a variety of reasons, not least of which is that the measurements are usually insufficient. Sparse observations also prevent a critical examination of where and how models fail, which they must to some degree for no model is perfect. One example of an area with complex topography is the Southern California Bight (SCB) with a rugged coastline rising from sea-level to more than 2000 m within a horizontal distance of 10 - 60 km (Fig. 1a). Coastal mountain ranges on the east side of the bight extend from the southern edge of the greater Los Angeles area, past San Diego and into Baja California. Of special note for possible lee-side effects are the four parallel mountain ranges within 100 km of the northern coast of the Southern California Bight. Closest range to coast is the east-west oriented Santa Ynez Mountains with the higher points of 1200 - 1310 m, 700 m elevation just north of Santa Barbara, and the lowest elevation of 282 m at Nojoqui pass west of Santa Barbara and 6 km north of station 4. A stylized topographic section to the north from the coast at Santa Barbara is shown in Fig. 1b. The Santa Ynez Mountain ridge is encountered at 11 km followed by the San Rafael Mountains at 34 km with higher peaks of 1520 - 2070 m.

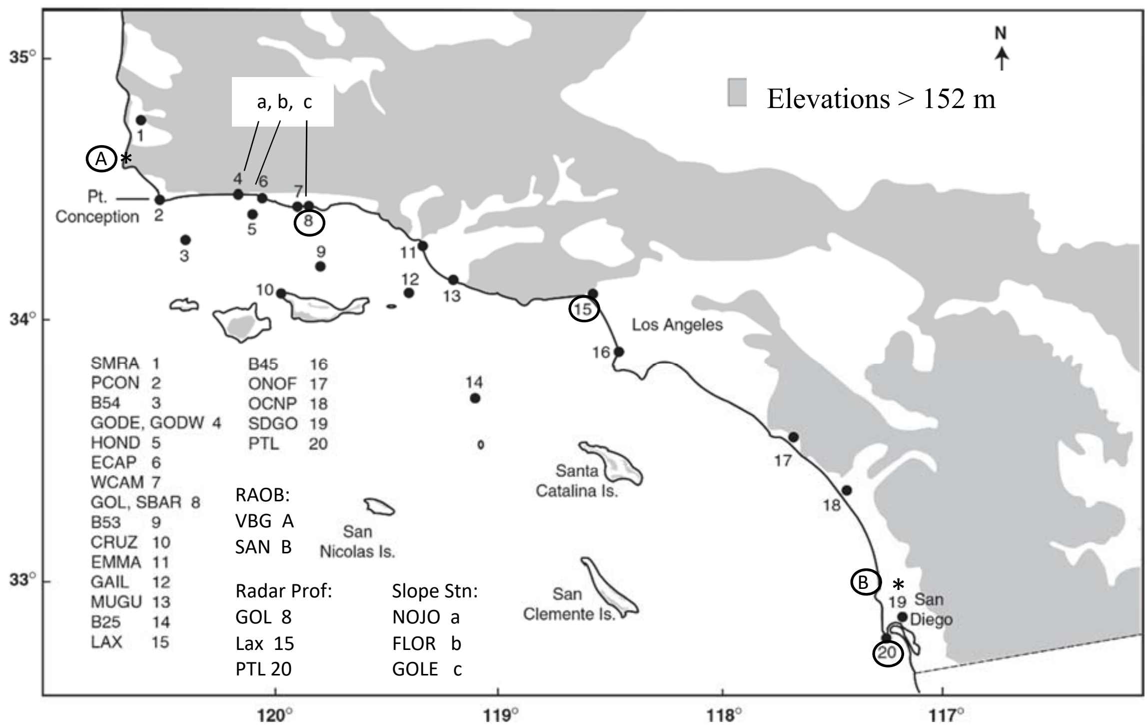

Figure 1a. Topography, surface, RAOB, and radar profiler stations. Open circles mark RAOB and radar profiler sounding station labels, some of which are shared with a surface station. Three south slope Santa Ynez Mountain surface stations (a, b, c, Table 4) have lines that point to locations.

A mesoscale event, the Catalina Eddy, is a unique feature produced when the atmospheric marine layer and capping inversion interact with the complicated coastal topography of the SCB. This feature is the focus of more than 10 publications based upon numerical modeling or limited observations. Substantially more surface and upper-air observations are available now to test these numerical models, as well as the proposed dynamic hypothesis which is the subject of this paper. It will be shown that the major structures in the expanded observations presented here contradict hypotheses presented in most of the previous publications.

In addition, all previous investigations failed to detect a major sea-level pressure feature on the east side of the bight.

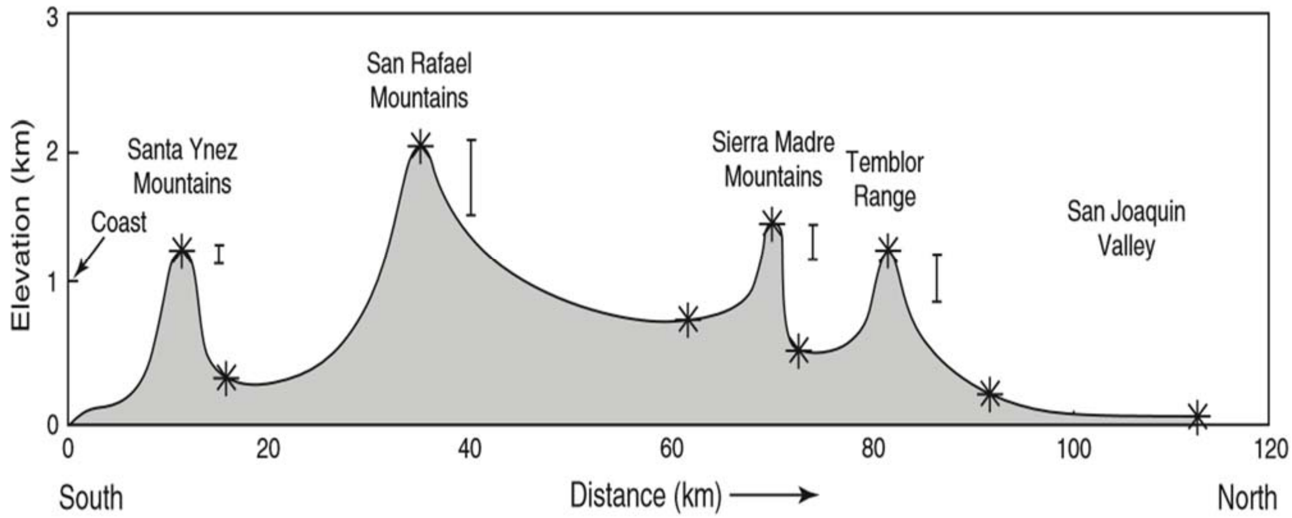

Figure 1b. Topographic cross section north of the coast at Santa Barbara. * 's are highest and lowest measured points connected with stylized topography. The vertical bar shows the general range of higher peaks for that range.

The basic local environment is established by a stable, cool, dense marine layer capped by a low, air temperature subsidence inversion which extends along the California and Baja California Coast (Neiburger et al. 1961). This marine layer is typically 200 - 300 m deep along the central California coast. In the SCB, it descends to its lowest elevation in the Santa Barbara Channel near Gaviota (~ 200 m) and typically rises only 100 - 300 m higher in the rest of the region (Dorman and Winant 2000; Dorman et al. 2000). The Santa Barbara Channel inversion minimum height is associated with lower surface pressures on the northern side of the channel. This results when marine air rounding Point Conception thins and accelerates at the western mouth of the Santa Barbara Channel, the site of one of the two summer U.S. West Coast monthly wind speed maxima (Dorman and Winant 1995).

Dorman et al. (2000) has proposed that the dynamical explanation for this structure in the western mouth of the Santa Barbara Channel is a marine layer transcritical expansion fan (Rogerson 1998). A supercritical atmospheric marine layer was first observed near Point Arena, California (Dorman 1985b; Winant et al. 1988). Subsequently, supercritical or near supercritical atmospheric marine layers have been found and documented by aircraft measurements in the lee of all major north-facing capes from Southern Oregon to Point Conception, California (Rogers et al. 1998; Dorman et al. 2000). Numerical modeling of west coast supercritical flow interacting with topography have been carried out for stylized cases (Burk et al. 1999), for the California coast (Koracin and Dorman, 2001), applied to Cape Mendocino (Tjernström and Grisogono 2000; Haack and Burk 2001) and to Point Sur (Burk and Haack 2000).

Central to the premise of this paper is published information on the complicated structure of the marine winds in Santa Barbara Channel. As mentioned previously, mean northerly summer sea-level winds accelerate around Point Conception and down the Santa Barbara Channel to a maximum velocity in the western mouth. Half-way down the channel, the winds slow and either exit the eastern end near the Ventura River valley or follow the coast toward Los Angeles. These winds are in sharp contrast to winds at stations near the edge of the Santa Barbara coastline east of Point Conception, which are mostly weak and mostly parallel to the coast (Dorman and Winant 2000).

Above the marine layer, weak winds tend to be onshore in the afternoon and offshore at night. Observations and modeling by Douglas and Kessler (1991) and Kessler and Douglas (1991) have suggested the importance of topography, diurnal heating, and the local circulation over the Santa Barbara Channel and the mountains behind it in establishing this predisposition for easterly morning winds in the absence of a Catalina Eddy. Similarly, occasional Santa Ynez Mountain down-slope, lee-side heating events, called "sundowners," occurring after sunset, tend not to reach the coast, and are independent of Catalina eddies (Ryan 1996; Blier 1998). Strong "sundowner" events with high winds occur in winter once every few years, in association with a brief, sharp trough passage.

The focus of this paper, though, is the Catalina Eddy, a mesoscale, cyclonic circulation in the marine layer of the bight (Rosenthal 1968). This eddy forms once or twice a month, especially spring through fall, is preceded by a trough, lasts for one to five days, and ends with a trough sweeping through. A major characteristic of the eddy is southerly winds at San Diego, a thickened marine layer, and a stratus overcast that persists for most of the day. On some occasions during the formation stage, a stratus overcast and southerly or easterly winds advect clouds along the coast on the eastern side of the SCB, then closing off to form an overcast cyclonic eddy. However, in most cases, the stratus overcast covers the bight only at sunrise. Rosenthal's discovery of this structure caught the attention of observers and numerical modelers who have written 10 papers on the Catalina Eddy (Table 1).

Table 1. Elements of Catalina Eddy Publications.

1. Pub	2. Type/ spacing (km)	3. Event	4. Up Cross Wind	5. Cross SBA	6. SBA Low	7. SNA Low	8. Cold Air Damming
B83	Obs	27-29/05/ 1968	?	Y			
D85	Obs	5-7/06/ 1981					
W87	Obs	8-12/08/ 1984	NI	NI	NOL	NOL	
M&A89	Obs	26-30/06 1988	Y	Y	Y	NO	Y
C&D91	Obs	5-12/07/ 1987	Y		Y	NO	
U&R93	Model 25	26-30/06/ 1988	Y		Y	NO	Y
C94	Model	Idealized	Y				
UHR&V95	Model 14	26-30/06/ 1988	Y	Y	Y	NO	Y
TB&R97	Model 20	5-12/07/ 1987	Y	Y		NO	Y
SR&K00	Model	Idealized					P
DL&M01	Model 6.7	26-30/06/ 1988	Y	Y	Y	NO	Y
This	Obs	19-21/06/ 1996	NO	NO	NO	Y	ANTI
This	Obs	1-6/08/ 1996	NO	NO	NO	Y	ANTI

1. Investigation.
2. Type, Obs=observational, Model=model, number is minimum grid spacing in km .
3. Event date or Idealized.
4. Cross Santa Ynez winds 600-1500 m, ~ day, creating lee side effects:Yes - needed for hypothesis, modeled, or claimed, but no direct observation, NI = no indication found, NO = conflicts with Radar Profiler, P = possible, no direct data.
5. N winds across broad area of Santa Barbara Coast: Yes - modeled or claimed, NI = no indication found, NO = conflicts with multi-surface station observation.
6. Sea level low forms over Santa Barbara Channel, moves south to become center of mature eddy: Yes - modeled or claimed, NI = no indication found, NO = conflicts with multi-surface station observation, NOL = conflicts with limited station data, ? = data too sparse.
7. Sea level pressure low forms over Santa Ana, moves west to become center of mature eddy: Yes - modeled or claimed, NI = no indication found, NO = conflicts with multi-surface station observation, NOL = conflicts with limited station data, ? = data too sparse.
8. Cold Air Damming: Y - modeled, claimed, or based upon San Diego RAOB, ANTI - cold air thinning based on radar profilers, P = possible.

B83: Bosart, MWR 1983
D85: Dorman, MWR 1985
C&D91: Clark & Dembek, MWR 1991
M&A89: Mass & Albright MWR, 1989
C94: Clark, MWR 1994
SR&K00: Skamarock, Rotunno & Klemp, AMS Conference 2000
DL&M01: Davis, Low-Nam & Mass, MWR 2001
TB&R97: Thompson, Burk & Rosenthal, MWR, 1997
U&R93: Ueyoshi, Rodes & MWR, 1993
UHR&V95: Ulrickson, Hoffmaster, Robinson & Vimont, MWR 1995
W87: Wakimoto, MWR 1987

To explain the formation of the eddy, Bosart (1983) initially proposed the dynamical importance of lee-side flow effects of the Santa Ynez Mountains and damming of cold air flow near San Diego by mountains along the SCB. Another widely accepted synoptic situation credited for an eddy's formation is the approach of a trough from the northwest (Wakamoto 1987, Mass and Albright 1989, Clark and Dembeck 1991, and others). This idea is formalized by Mass and Albright (1989 - hereafter referred to as M&A89) who assembled a large-scale, synoptic composite of 50 cases occurring between May and September in the years 1968 - 1975. They defined an eddy as existing when a southerly wind of at least 1.5 m s^{-1} is recorded at the San Diego airport for 18 continuous hours, with a minimum of four of those hours showing a southerly component of 4 m s^{-1} or greater.

The publications on the mesoscale formation of the Catalina Eddy may be organized into three general themes. The first is the aforementioned Santa Ynez/San Rafael mountains lee-side flow effects. M&A89 hypothesizes that the eddy is initiated with down-slope flow that forms a low in the lee of the Santa Ynez Mountains. This low eventually drifts southeast to near Catalina Island, where it forms the center of the mature eddy's cyclonic circulation, while increased westerly flow against the mountains east of San Diego causes the marine layer to deepen (cold air damming). However, M&A89 produce no direct observation of lee-side flow, assuming that the Vandenberg RAOB station represents the flow over the San Rafael/Santa Ynez Mountains to the east. Subsequent numerical modeling papers that explore dynamical aspects of the Catalina Eddy (Ueyoshi and Rodes 1993, Ulrickson et al. 1995, Thompson et al. 1997, Davis, Low-Nam and Mass 2001) basically accept the M&A89 mesoscale analysis and assumptions. They offer little new observational data and all but one (Thompson et al. 1997) revisit the same 26 - 30 June 1988 event originally analyzed by M&A89.

The second organizational theme is proposed by observers who have examined other Catalina Eddy events using essentially the same stations as M&A89 but who come to different conclusions. Wakimoto (1987) analyzes a 8 - 12 August 1984 event and concludes that horizontal shear is the dynamic cause of the eddy. His analysis is unique in that the event did not produce easterly winds or clouds in the Santa Barbara Channel nor does he find evidence of Santa Ynez Mountain down-slope flow. Clark and Dembeck (1991) analyze a 5 - 12 July 1987 Catalina Eddy event finding that sparse observational data and the organization of the weak sea-level pressure field make it difficult to identify streamlines or reach other than tentative conclusions. They concluded from the limited number of RAOB sounding stations that there was weak subsidence over the SCB. Santa Ynez Mountain lee-side flow effects and a trapped response on the eastern portion of the bight are suggested as the eddy's possible dynamic causes.

The third organizational theme proposes that Kelvin wave-type trapping might play a role in the eddy's formation. Dorman (1985a) suggests that the surging stage of a Catalina Eddy (discussed below) could be a solitary Kelvin wave in the marine layer. Wakimoto (1987) does not share this view, while Clark and Dembeck (1991) find that it is consistent with their analysis. Clark (1994) follows up by modeling a stylized setting to show the role that a Kelvin wave could play in the formation stage of a Catalina Eddy.

By the mid-1990's, the number of hourly surface stations in and around the Santa Barbara Channel were greatly increased. Also, hourly radar profiler observations were added at critical locations of the Santa Barbara Channel (in the immediate lee of the Santa Ynez Mountains), Los Angeles and San Diego. This offers an opportunity to reexamine mesoscale events in the crucial Santa Barbara Channel area and in the SCB. The objective of this paper is to investigate the initiation phase of the Catalina Eddy to test the hypothesis that Santa Ynez Mountain lee-side effects play a significant role in its formation.

This paper is organized around two primary examples representative of the diversity of Catalina Eddy events using modern observations. The first occurred 18 - 21 June 1996 and was accompanied with a cloud surge and easterly winds in the Santa Barbara Channel. The second took place 1 - 6 August 1996 and occasioned no cloud surge and no easterly winds in the Santa Barbara Channel. In addition, ten 1996 season events and their characteristics are examined, followed by a review of how previous studies compare with modern observations. Finally, an alternative hypothesis is proposed for the main dynamic cause of most Catalina eddies.

2. Published Observations on the Santa Barbara Channel that Conflict with Hypothesis and Models on Lee-side Conditions

It is important to remind the reader about published observations on summer conditions in the Santa Barbara Channel area are not widely consulted for many studies. It will be shown later that these *in situ* surface and radar profiler observations conflict directly with numerical modeling studies based upon data taken at distant locations and well as with the use of the distant Vandenberg RAOB sounding data to represent the conditions over the Santa Barbara Channel. The following summaries are based upon observations in the Santa Barbara Channel (Dorman and Winant 2000), fixed and aircraft observations along the California Coast (Rogers et al. 1998; Dorman et al. 1999; Dorman et al. 2000).

● A summary of the Santa Barbara radar profiler measured winds:

Winds between the marine layer top to Santa Ynez mountain crest height (~300 m - 700 m) are weakly onshore during the day and offshore at night.

Winds above the Santa Ynez mountain crest (700 m - 1500 m) are predominantly from the east.

Cross-crest winds > 7 m s^{-1} and lasting more than a few hours are very unusual.

● A summary of the Santa Barbara surface coastal winds:

Flow is predominantly east-west with a weak on-offshore component.

Significant cross-shore flow is rare other than around isolated canyons.

Away from the coast, marine layer winds are from the W.

Central channel winds from the east lasting > 3 hours or stronger than > 5 m s^{-1} are rare.

● A summary of the Santa Barbara Channel sea-level pressure and marine layer height minimum:

This is a semi-permanent feature which stands out in the mean and individual analysis. It is a transcritical flow of the marine layer around Point Conception expanding into the western mouth of the Santa Barbara Channel. It cannot be attributed to lee-side flow, which conflicts with Santa Barbara radar profiler and the network of surface stations on the Santa Ynez lee slope and coast.

● A summary of the Vandenberg operational sounding below 1.5 km:

This feature is not representative of a Santa Barbara area sounding – compare Figure 16 in M&A89 with Figure 11 in Dorman and Winant (2000). It is poorly related to the Santa Barbara sounding (shown later). It can differ with Santa Barbara sounding winds by 90 - 180 degrees in direction and more than a factor of 2 in speed (to be shown later).

3. Data Sources

An extensive number of Southern California Bight surface stations are used in this study. (Those close to the coast are listed in Table 2a.) Automated hourly winds and pressure were taken at five National Data Buoy Center (NDBC) buoys and one coastal station. The Minerals Management Service (MMS) funded the Scripps Institution of Oceanography as part of a Santa Barbara Channel/Santa Maria Basin oceanographic study to make minute averaged wind, pressure and air temperature measurements at five islands and oil platforms. Air pollution agencies (Santa Barbara County Air Pollution Control District and Ventura County Air Pollution Control District) operated seven, hourly-averaging, automated surface stations along the Santa Barbara Channel coast. Likewise, the San Diego County Air Pollution Control District and nuclear power plants (Southern California Edison's San Onofre; Pacific Gas and Electric's Diablo Canyon) wind and temperature records, as well as National Weather Service (NWS), Federal Aviation Administration (FAA), and military airport weather observations --although some did not take 24-hour observations.

Time is UTC in this manuscript. Local time is 8 hours after Greenwich.

Table 2a. Surface stations. See Table 4 for FLOR, GOLE and NOJO.

Station	Symbol	Map #	Lat Long	Elev (m)	Type	Vbls	Operator
Buoy 46025	B25	14	33° 45' 119° 03'	0	B	wtp	1
Buoy 46028			35° 43' 121° 51'	0	B	wtp	1
Buoy 46045	B45	16	33° 50' 118° 27'	0	B	wtp	1
Buoy 46051			34° 29' 120° 41'	0	B	wtp	1
Buoy 46053	B53	9	34° 15' 119° 51'	0	B	wtp	1
Buoy 46054	B54	3	34° 16' 120° 29'	0	B	wtp	1
Camp Pendleton			33° 18' 117° 21'	23	A	wtp	10
El Capitan	ECAP	6	34° 28' 120° 01'	39	L	wt	4
Emma Woods	EMMA	11	34° 17' 119° 19'	3	L	wt	8
Gail	GAIL	12	34° 08' 119° 24'	30*	P	wtp	5
Gaviota E	GODE	4	34° 28' 120° 10'	34	L	wt	4
Gaviota W	GODW	4	34° 28' 120° 13'	29	L	wt	4
Hondo	HOND	5	34° 23' 120° 07'	44*	P	wtp	5
Imperial Beach			32° 34' 117° 07'	6	A	wtpc	9
Los Angeles	LAX	15	33° 56' 118° 23'	38	A	wtpc	2
Long Beach			33° 49’ 118° 9'	17	A	wtpc	2
Mirimar NAS			32° 52' 117° 08'	146	A	wtpc	9
Oceanside	OCNP	18	33° 11' 117° 22'	27	L	wt	3
Oxnard			34° 12' 119° 12'	13	A	wtpc	2
Point Arguello			34° 35' 120° 39'	32	L	wtp	1
Point Conception	PCON	2	34° 27' 120° 28'	18	L	wt	4
Point Mugu	MUGU	13	34° 07' 119° 07'	3	A	wtpc	9
San Clemente Is			33° 01' 118° 35'	55	A	wtpc	9
San Diego	SDGO	19	32° 44' 117° 10'	4	A	wtpc	2
San Nicolas Is			33° 14' 119° 27'	154	A	wtpc	9
San Onofre	OCOF	17	33° 22' 117° 33'	8	L	wt	7
Santa Ana			33° 41' 117° 52'	12	A	wtpc	2
Santa Barbara		8	34° 26' 119° 50'	3	A	wtpc	2
Santa Cruz Is	CRUZ	10	34° 04' 119° 56'	20	L	wtp	5
Santa Maria	SMRA	1	34° 53' 120° 27'	74	A	wtpc	2
Santa Rosa Is			34° 00' 120° 15'	17	L	wtp	5
West Campus	WCAM	7	34° 25' 119° 53'	12	L	wt	4

Elev: * = platform anemometer height above the water.
Type: surface station, A=airport, B=automated buoy, L=automated land, P=automated platform.
Vbls: w=wind, t=air temperature, p=pressure, c=cloud.
Operator: 1=National Data Buoy Center, 2= National Weather Service, 3= San Diego Country Air Pollution Control District, 4= Santa Barbara Country Air Pollution Control District, 5=Scripps Institution of Oceanography, 6= South Coast Air Monitoring District, 7=Southern California Edison, 8=Ventura County Air Pollution Control District, 9=US Navy, 10=US Marine Corps.

In addition to surface stations, five upper-air stations within the bight provided data (Table 2b). Three of these are hourly-averaged, radar profilers with RASS, one (GOL) is located at the Santa Barbara airport in the immediate lee of the Santa Ynez Mountains. Twice-daily, balloon-borne, RAOB stations are released in the San Diego area (Miramar) and at Vandenberg Air Force Base. Two additional upper-air balloon stations at San Nicolas Island and Point Mugu are not very useful as their soundings are made at short, irregular intervals which makes it hard to separate out synoptic induced trends and diurnal variations with mesoscale responses on the order of hours and days.

Table 2b. Upper air stations.

Station	Symbol	Map #	Lat Long	Type	Operator
Vandenberg	VBG	A	34° 45'120° 34'	RAOB	U
Goleta	GOL	8	34° 26' 119° 51'	Radar Profiler	N
Los Angeles	LAX*	15	33° 56' 118° 26'*	Radar Profiler	S
Point Loma	PTL	20	32° 40' 117° 15'	Radar Profiler	D
San Diego	SAN**	B	32° 51' 117° 07'**	RAOB	NWS

*= profiler located on beach berm, off west end of airport runway, **=RAOB located 16 km NNE of San Diego airport, U=USAF, N=NOAA/ERL/ETL/Boulder, S=South Coast Air Pollution Control District, D=San Diego Country Air Pollution Control District, NWS=National Weather Service

4. Catalina Eddy Case of 19 June 1996

4.a. Defining the Eddy

We have selected a Catalina Eddy event that occurred 19 - 21 June 1996, which appears routine, is representative of the others that occurred in 1996 and the data coverage is relatively good. To facilitate comparison with earlier publications, all events discussed in this paper use the M&A89 Catalina Eddy criteria noted above (a southerly wind of at least 1.5 m s^{-1} at the San Diego airport for 18 continuous hours, with a minimum of four of those hours showing a southerly component of 4 m s^{-1} or greater). By this criteria, this eddy started at 1500 UTC 19 June and ended at 0200 UTC on 21 June. However, as will be noted later and is characteristic of most of the eddy events for 1996, the southerly winds at San Diego began on the afternoon before. This afternoon before initialization of the eddy is more consistent with the working operational definition that an eddy event begins with the start of semi-continuous southerly winds at San Diego lasting more than a day and is coincident with the appearance of a cyclonic marine cloud eddy over the SCB by next sunrise.

4.b. Satellite Observations

The progression of the eddy is first shown with satellite images. The GOES West visible image for 1530 UTC 18 June revealed a finger of coastal stratus overcast extending from Baja California to just south of Los Angeles (Fig. 2). Overnight, a westward surging stratus overcast and wind reversal moved along the coast so that the leading edge was near on the next morning at 1400 UTC 19 June (not shown), and reached Point Conception in the 1445 UTC 19 June image (not shown). By 1530 UTC 19 June, the coastal stratus overcast extended just west of Point Conception (Fig. 3), appearing as a cyclonic Catalina Eddy cloud in the early stage of formation as first described by Rosenthal (1968). The timing of the westward surge along the Santa Barbara Channel with a wind switch to winds from the east at mid-channel stations or from the south at Los Angeles Airport (LAX, Fig. 1a # 15), the first low overcast observed at airports and satellite-derived western cloud edge distance along the coast from LAX is shown in Table 3. Based upon these observations, the leading edge moved along the coast at a fairly steady 4 m s^{-1}. However, the stratus cloud did not continue to curl cyclonically as in the Rosenthal sequence to close off, forming an overcast over the whole bight. Instead, by 2000 UTC 19 June (Fig. 4), cloud filaments existed along a shear line due south of Point Conception, marking the western edge of the bight circulation, while the stratus cloud clears in the inner portion. By daylight at

1445 UTC 20 June (Fig. 5), a coastal stratus overcast extended from Baja California to Southern Oregon.

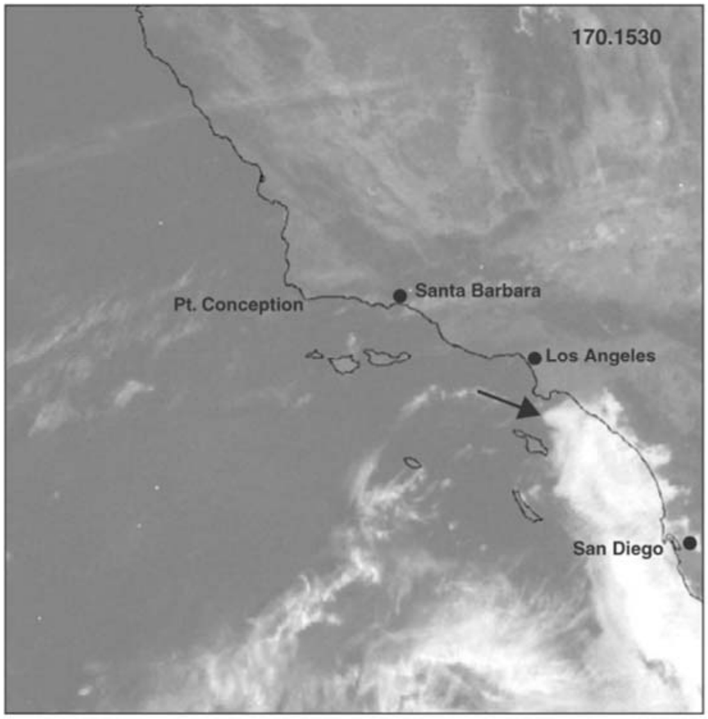

Figure 2. Stationary satellite visible image for 1530 UTC 18 June 1996. A finger of stratus overcast extends along the coast from northern Baja California, over San Diego, to just south of Los Angeles (marked by arrow).

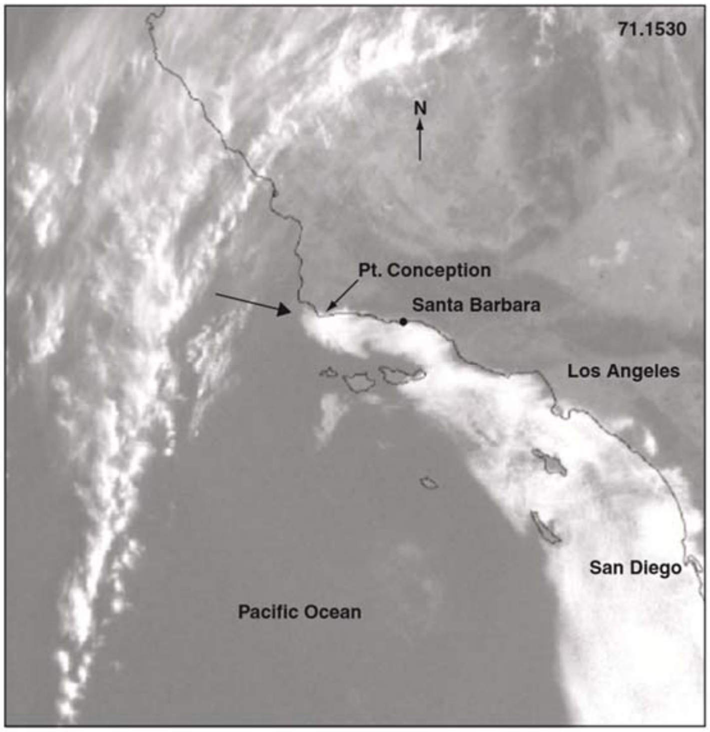

Figure 3. Stationary satellite visible image for 1530 UTC 19 June 1996. The coastal stratus overcast extends just beyond Point Conception (arrow points to overcast leading edge).

Table 3. Timing of the leading edge passage of reversal to easterly winds based upon surface stations and overcast cloud based upon station observations and GOES satellite visual images. Distance is poleward, along the coast from LAX (Fig. 1a, # 15)

	Distance (km) from LAX	Wind Shift Hr and day (UTC)	Stratus OVC
PCON	205	E 1600 19a	1445 19b
	186		1400 19b
SBA	149	E 0147 19c	1352 19e
B53	146	E 1500 19d	
GAIL	88	E 0900 19d	
LAX	0	S 0851 19c	1026 19e

a= coastal station wind near beach, b=satellite cloud edge,
c=station wind on coastal plain, d=mid-channel platform or buoy wind,
e=station cloud cover

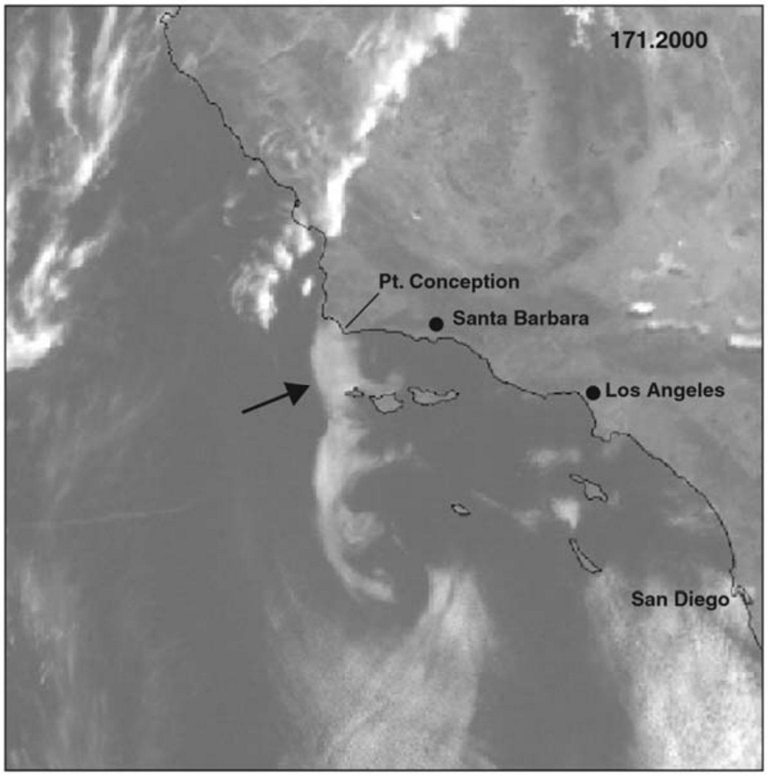

Figure 4. Stationary satellite visible image for 2000 UTC 19 June 1996. Remnants of the eddy stratus (arrow) extend south of Point Conception. Diurnal heating has eliminated the stratus in the central portions of the bight.

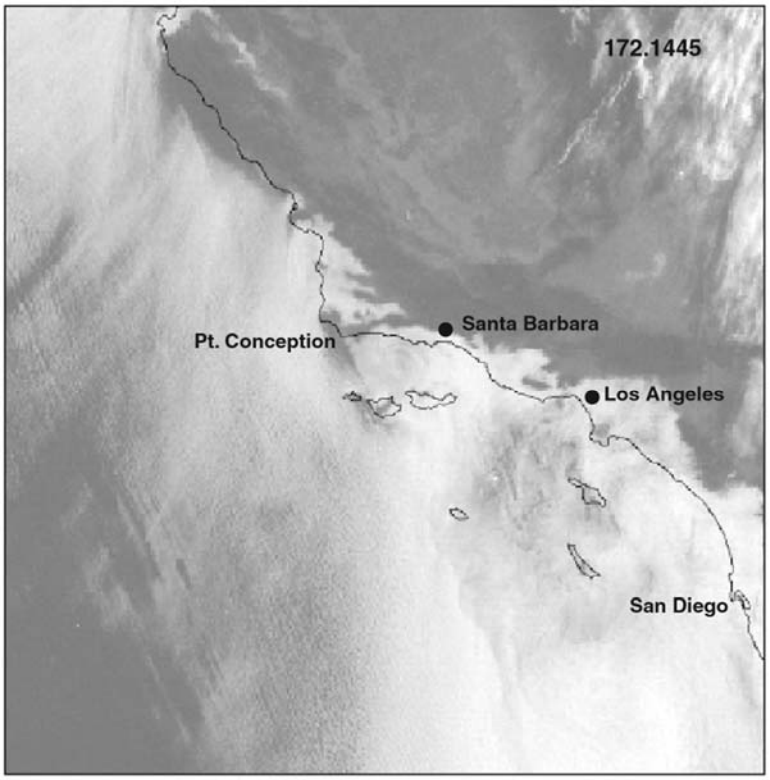

Figure 5. Stationary satellite visible image for 1445 UTC 20 June 1996. A stratus overcast extends along the coast from Baja California to southern Oregon.

4.c. Upper-air Data

First, we examine the flow above Santa Barbara as measured by the Goleta radar profiler (GOL, Fig. 1a, # 8) in the immediate lee of the Santa Ynez Mountains. The hourly-averaged winds at 50 m intervals are further averaged in 200 m intervals (Fig. 6). No evidence of significant, persistent northerly cross-ridge flow is apparent above 800 m (the Santa Ynez mountain ridge is mostly higher than this) on June 17 - 18 before the eddy formed. On the contrary, on 17 - 18 June, at 800 - 2200 there is a weak flow with the dominant direction from the east. Around sunrise, below 800 m, a modest from the north flow (maximum speed less than 7.5 m s^{-1}) is routine on most non-eddy days, as a result of local thermal circulations without significant, cross-ridge forcing flow above. Similar flow is associated with most of the other Catalina Eddy events of 1996 and is in direct conflict with the mountain lee-side effect hypothesis (to be presented in later section and Table 5).

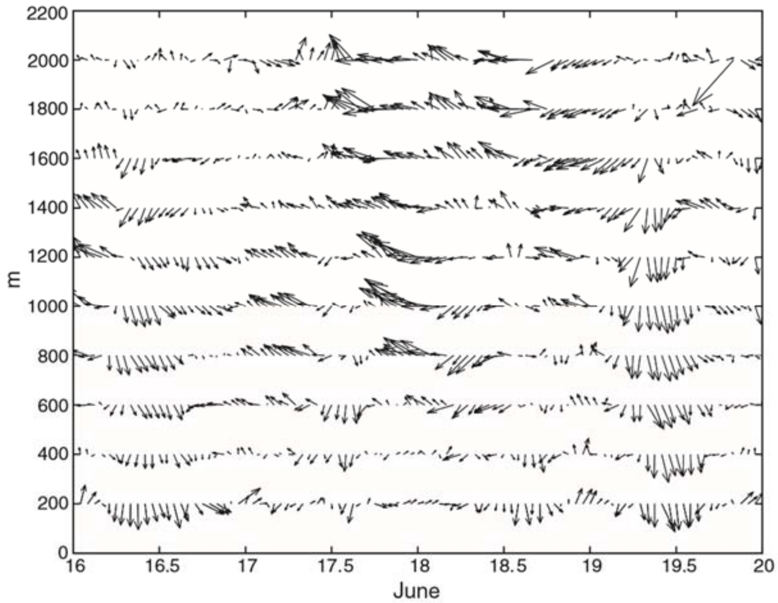

Figure 6. Goleta (Santa Barbara area, Table 2b and GOL, Fig. 1a, # 8) radar profiler winds on June 1996. A vector with the length of 0-200 m distance along the vertical axis has a speed of 10 m/s. This profiler is on the coast near Santa Barbara approximately 11 km south of the Santa Ynez ridge (~ 700 m due north) and is in an excellent position to detect lee side effects due to air flow from the north.

The most striking aspect of the Vandenberg (VBG, Fig. 1a, # A) RAOB data (Fig. 7) is how poorly this sounding station represents the flow over Santa Barbara both above and below the Santa Ynez Mountain crest. For example, 800 - 2000 m, at 00 UTC 18 June, the flow is from the east at Goleta but from the north or NW at Vandenberg. Below 800 m, the winds are strong and from the NW above Vandenberg but from an easterly direction at 600-800 m and very weak at 200-400m over Santa Barbara. This disparity between sounding locations is not surprising if one considers that the Vandenberg station is located off the extreme western end of the east-west oriented Santa Ynez Mountains, directly exposed to the Central California, along-coast marine layer flow. As the sounding balloon ascends to above 2 km, it is carried mostly to the south and well out of the lee of the higher Santa Ynez Mountains (40 - 115 km to the east) and the higher San Rafael Mountains (60 - 100 km to the east). On the other hand, the Santa Barbara profiler is dead in the lee of northerly flow over the higher Santa Ynez and San Rafael Mountains. Of course the 12-hourly Vandenberg RAOB also captures diurnal changes poorly and nothing the scale of hours unlike the radar profiler.

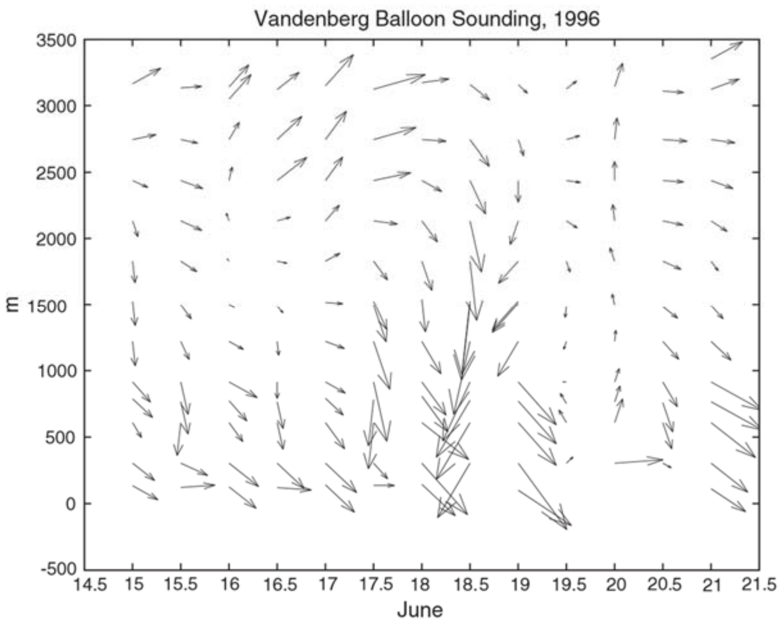

Figure 7. Vandenberg (VBG, Fig. 1a, # A) June 1996 RAOB winds. Arrows point downwind and toward the South is down. A vector with the length of the 0-500 m distance along the vertical axis has a speed of 10 m/s. These winds correlate poorly with the Goleta (GOL, Fig. 1a, # 8) radar profiler winds shown in Fig. 7.

On the southeast side of the bight, another profiler fails to support the “cold air damming hypothesis” as the cause for the increased marine layer depth during the eddy formation. The San Diego radar profiler winds are dominantly weak and along coast from 16 June until after 1200 UTC 19 June when the mature eddy begins (Fig. 8). After this time, the flow is along-coast and from the south well up into the inversion. The air temperature inversion base height decreases to a minimum at San Diego, Los Angeles and Santa Barbara between 2200 UTC 18 June and 10 UTC 19 June (Fig. 9), followed by an increase that is confirmed by the National Weather Service RAOB sounding at San Diego (not shown). A decrease in inversion base height in the formation stage with initial San Diego southerly winds and along-coast marine layer flow might be called “cold air thinning”, the opposite of cold air damming. The lack of significant on shore winds at San Diego (or winds significantly different from non-eddy days) and the decrease in marine layer depth directly conflicts with the “cold air damming” hypothesis (Item 8, table 1).

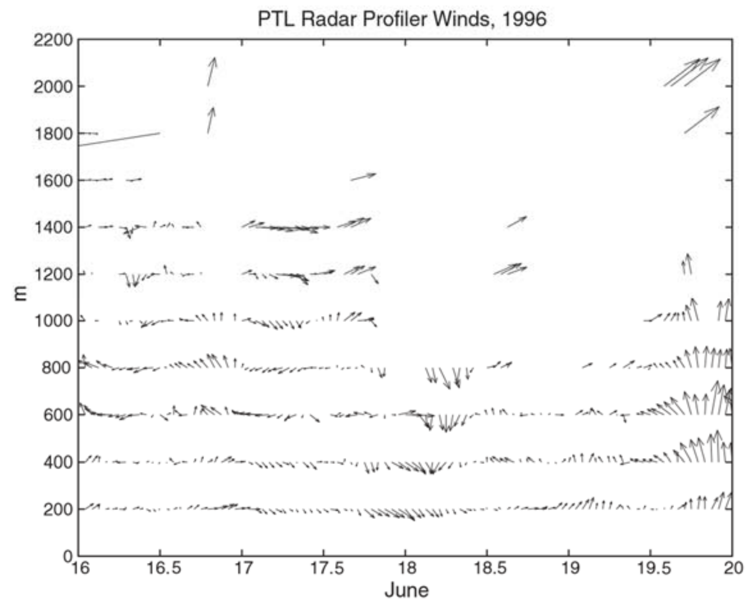

Figure 8. Point Loma (PTL, Fig. 1a, # 20, San Diego area) radar profiler wind time-series. A vector with the length of 0-200 m distance along the vertical axis has a speed of 10 m/s. Winds below 800 m are weak with an onshore component from 16 June until around 1500 UTC on 19 June when the eddy starts according to the M&A criteria. After this, the winds below 1000 m are from the south for this event.

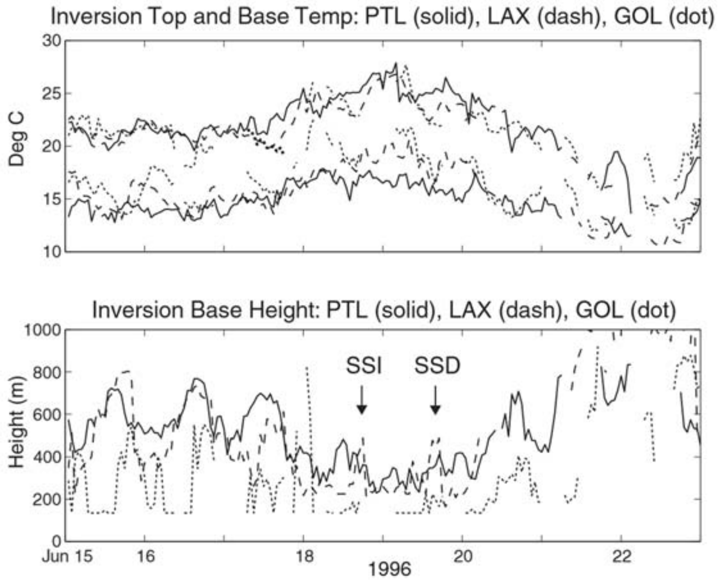

Figure 9. Radar profiler with RASS air temperature inversion properties at Point Loma (PTL, Fig. 1a, # 20, San Diego area), Los Angeles airport (LAX, Fig. 1a, # 15, Los Angeles area) and Goleta (GOL, Fig. 1a, Station # 8, Santa Barbara area) radar profilers in June 1996. Upper frame are the inversion top and base air temperatures. The bottom frame are the inversion base heights. The marine air over the eastern half of the SCB is capped by an inversion base that thins from the mid-16th until late on the 18th (SSI arrow). Thereafter, it tends to increases slightly from near 0000 UTC on the 19th until near 0000 on the 20th when it increases more rapidly. SSI marks the start of southerly winds at San Diego and SSD marks the start of the Catalina Eddy event at San Diego according to the M&A criteria. Station are in Fig. 1a and Table 2a.

On the northeast side of the bight, the LAX profiler (LAX, Fig. 1a, # 15) shows the marine layer winds (400 m and below) from 16 June to 2000 UTC 19 June to be weak, or peaking broadly from the SW around sunset in response to thermally driven circulations (Fig. 10) which occur at this profiler on many non-eddy days. On the 19th, the winds become southerly from the surface to above the observation height limit of 2200 m in response to the eddy formation. This profiler reveals two important aspects related to the Catalina Eddy. One is that marine layer winds (400 m and below) from the SW over LAX as shown by a numerical model (Davis et al. 2000) are not particular to an eddy but are routine occurrences during non-eddy days. Secondly, significant southerly winds form uniformly along the east side of the bight and extend well above the marine layer and into the air temperature inversion. This supports the hypothesis that mid-level conditions over the eastern side of the California Bight play a role in eddy formation.

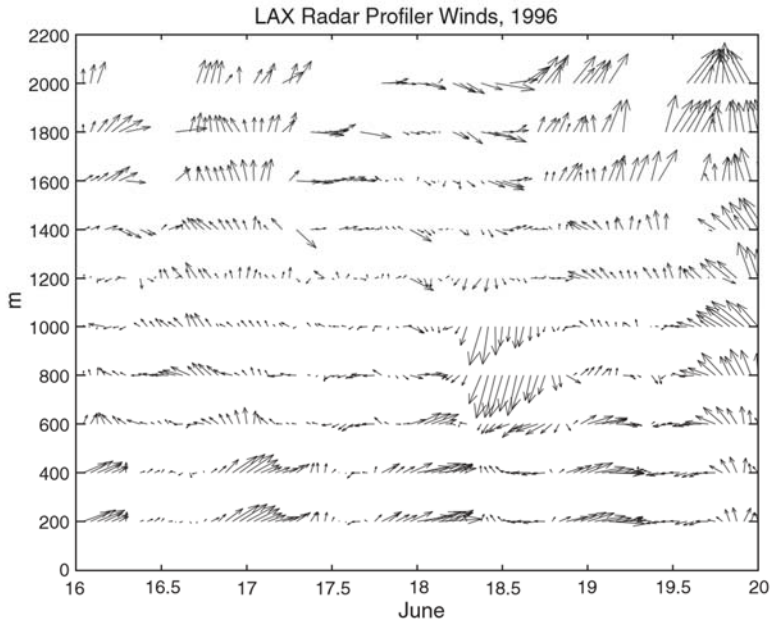

Figure 10. Los Angeles airport (LAX, Fig. 1a, # 15) radar profiler winds during June 1966. A vector with the length of 0-200 m distance along the vertical axis has a speed of 10 m/s.

4.d. Surface Wind and Temperature Observations

Some of the available surface wind data are examined in geographical groups to highlight possible relationships. One of these is the area along the eastern bight that extends from San Diego to B45 (Fig. 1a, # 16) in the Los Angeles area. Using the M&A89 criteria, the eddy southerly winds extend from 1500 UTC 19 June (arrow designated by SSD) to 0200 UTC on 21 June (Fig. 11). However, the general period of San Diego southerlies begins the day before at 1800 UTC 18 June (arrow designated by SSI) and continued into early 21 June (arrow designated by SSE). Moving up the coast, the one-kilometer offshore B45 has no southerly winds from 18 - 20 June except for four hours early on the 22nd. Farther offshore, B25 has a brief easterly wind pulse that begins seven hours before the M&A89 start time and lasts for only 11 hours (note orientation of B25 axis to 270 degrees). Significantly, for these and all other available surface stations along this section, there is no detectable phase shift in the winds to from the south that Starts at San Diego and progresses to north along the eastern SCB coast. This phase shift should be observed if the leading edge of a cyclonic eddy was moving along this coast toward the north.

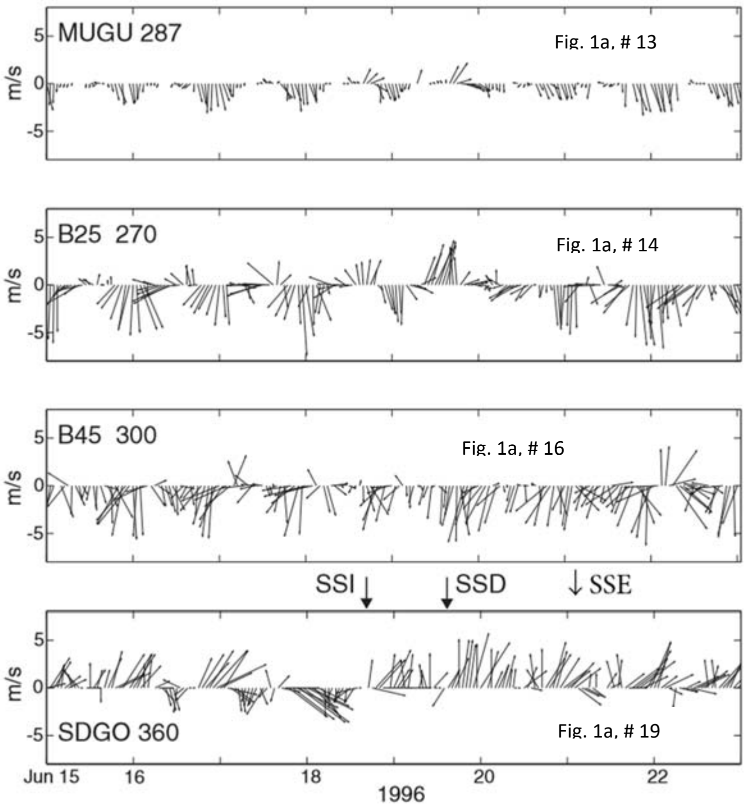

Figure 11. Winds measured at stations along the southeastern portion of the Southern California Bight. Winds are rotated into the principle axis (direction of maximum variation) which is the number posted alongside the station name. Although the eddy began at 1500 UTC 19 June at San Diego (SDGO, Fig. 1a., # 19) according to the M&A criteria (SSD arrow), southerly winds started at San Diego nearly a day earlier (SSI arrow) and continued into 21 June (SSE arrow). Stations are in Table 2a and Fig. 1a.

To show that the dominant winds are from the west over the Santa Barbara Channel even during an eddy, over-water winds are represented by a line of buoys and platforms along the center of the Channel (Fig. 12). The strongest and longest easterlies are at GAIL platform (Fig. 1a, # 12) in the eastern mouth (start is marked by EGAIL arrow in Fig. 12). B53 (Fig. 1a, # 9) near center of the channel in W-E sense and N-S sense, has easterly winds > 1 m s^{-1} only for three hours late on 19 June (start marked by B53 arrow in Fig. 12). B54 (Fig. 1a, # 3) at the western mouth has no easterly winds on the 19th although the opposing winds from the west are weakest coincident with the strongest winds from the east at B53. Hondo platform (HOND, Fig. 1a, # 5), six kilometers from the coast, has easterly winds from 01 UTC (denoted by EHOND arrow in Fig. 12) and ending at 17 UTC on 19 June. However, this station routinely has diurnal reversals between night easterlies and afternoon westerlies (Dorman and Winant, 2000).

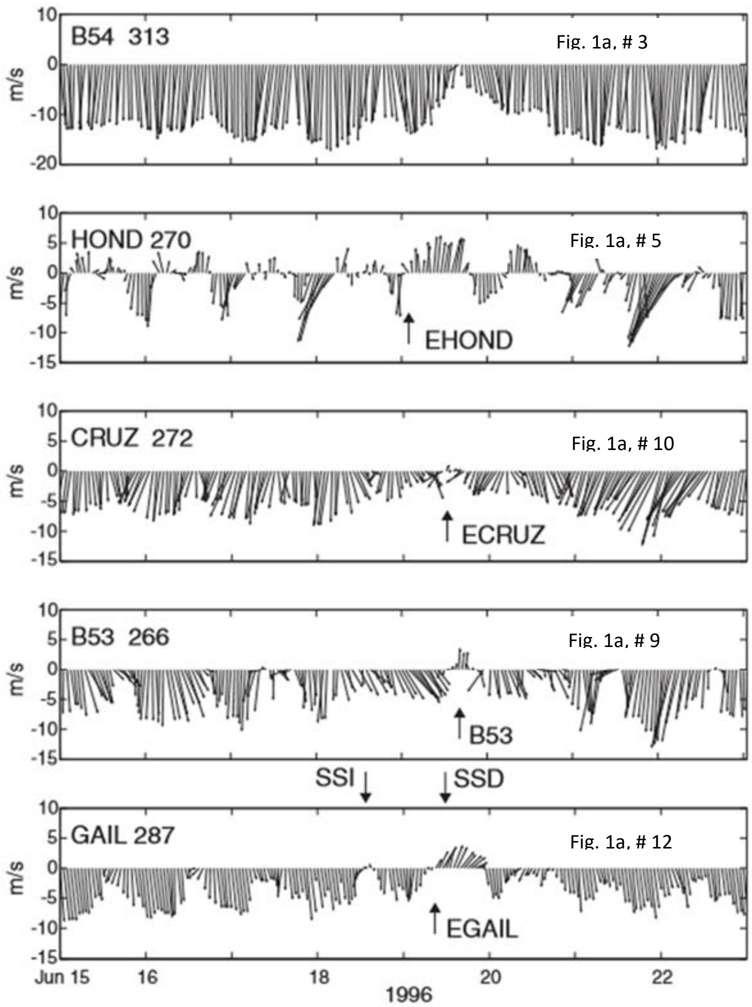

Figure 12. Winds measured at over-water stations along the Santa Barbara Channel. Winds are rotated into the principle axis (direction of maximum variation) which is the number posted alongside the station name. A surge of along coast wind occurs simultaneously, from the east at Gail Platform (GAIL, Fig. 1a, # 12) and from the south at B25 (winds in Fig. 11, location Fig. 1a. # 14) that is coincident with a stratus band leading edge advection toward the west along the Santa Barbara Channel. Stations are in Table 2a.

To reveal the nature of the weak and along-coast winds, data from selected stations along the Santa Barbara coastline are presented from the eastern third to the western end of the Channel (Fig. 13). Stations from EMMA to GODE oscillate between weak offshore winds in the late morning to onshore winds in the afternoon. These stations switch irregularly to easterly without any apparent east-to-west station order. Further, the easterly winds at these stations on the night of 18/19 June are typical of the non-eddy days in general (Dorman and Winant 2000) and specifically of the four preceding days. The only strong offshore wind is for two hours at the start of 18 June at GODE which is at the mouth of the Gaviota Gap Canyon. There is a strong offshore, along-river valley wind from the east at MUGU at the eastern end of the Santa Barbara Channel (Fig. 11) that initiates at the same time as those at GAIL.

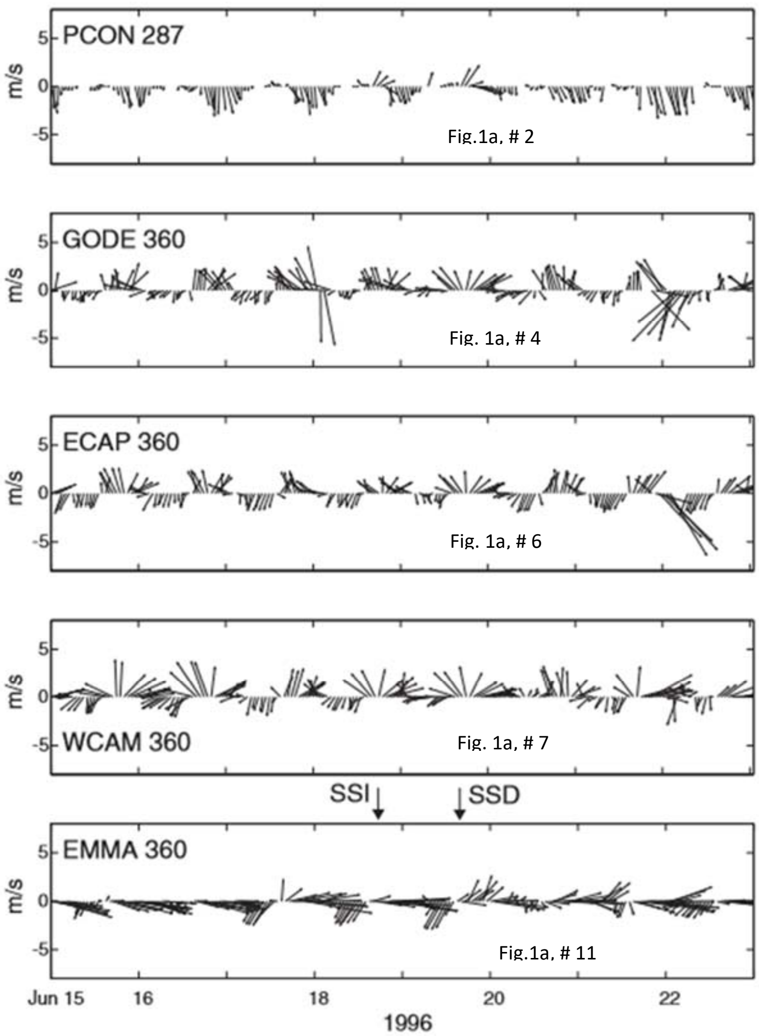

Figure 13. Coastal station winds along the north shore of the Santa Barbara Channel. For these stations north is up and vectors fly with the wind. Significant off-shore winds before or during the event in the western section occur only at GODE (Gaviota E) at 0100-0200 on 18 June, more than a day before the event, and unrelated to the surge of easterly winds in the eastern portion of the Santa Barbara Channel. Point Mugu (MUGU, Fig. 11) had offshore, down valley winds on most mornings of this period, but was strongest and best organized on the morning of 19 June. Stations are in Table 2a.

The air temperatures for the coastal stations compared to B53 (characteristic of the undisturbed marine layer) do not indicate extended lee heating (Fig. 14). Only GODW (0200 UTC, 18 and 19 June 1996) and GODE (0200 UTC 18 June 1996) near the Gaviota gap and canyon have an anomalously large, brief air temperature increase beyond the usual diurnal trend which is more than a day before the easterly surge in the Santa Barbara Channel.

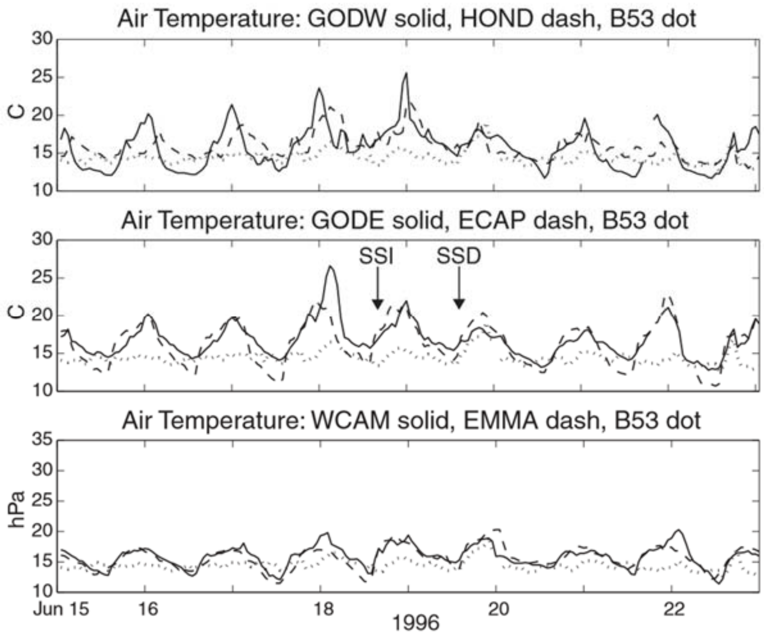

Figure 14. Air temperatures at surface stations along the Santa Barbara Channel coast. The B53 temperature is a reference for unmodified marine air in the center of the Santa Barbara Channel. GODW is # 4, HOND is # 5, B53 # 9, GODE is # 4, and ECAP is # 6, in Fig. 1a and Table 2a.

The lack of broad, cross-ridge, lee effects are confirmed by data from all three surface wind stations (Table 4, Fig. 15) 3-6 km north of the Santa Barbara Coast and on the south slope of the Santa Ynez Mountains. Highest and well above the typical marine layer top is NOJO, at 307 m near a crest 2.5 km north of the Santa Ynez Mountain ridge itself (station # a, Fig. 1a.) FLOR is in a canyon at 190 m elevation (station # b, Fig. 1a). The elevation of FLOR is near that for the mean marine layer top which should be pushed below the station with offshore lee flow of any consequence. Finally, GOLE at 16 m elevation is on the northern side of the Santa Barbara coastal plain (station # c, Fig. 1a). All basically had weak diurnally reversing winds in the five days before the eddy. The brief pulse of northerly down-canyon winds around 0000 UTC 18 June at GODE (Fig. 13) and FLOR (Fig. 15) was too short and not coincident with southbound winds at other stations to indicate broad, lee flow down a significant portion of the southern side of Santa Ynez Mountains. The increase in afternoon peak temperatures on the 17 - 18th were not directly correlated with increasing offshore winds at the surface along the Santa Barbara Channel coast or above the GAVIOTA profiler and was more consistent with weak, broad subsidence over the SCB. The summary is that stations on the Santa Ynez mountain lee and Santa Barbara coast do not support a lee side, down slope flow of significance during the formation stage of Catalina Eddy.

Table 4. Three stations on the south slope of the Santa Ynez Mountains. Two are near the ridge crest and one is on the north side of the coastal plain, at the base of the foothills. Variables include winds and air temperature. Stations owned by Santa Barbara Country Air Pollution Control District.

	Lat N	Lon W	Elev (m)	Dist N of Coast (km)	Map Char.
NOJO	34° 31’38.78”	120° 11’45.52”	307	6.1	a
FLOR	34° 29’20.91”	120° 02’48.62”	173	2.5	b

GOLE	34° 26’43.80”	119° 49’42.47”	13	3.2	c

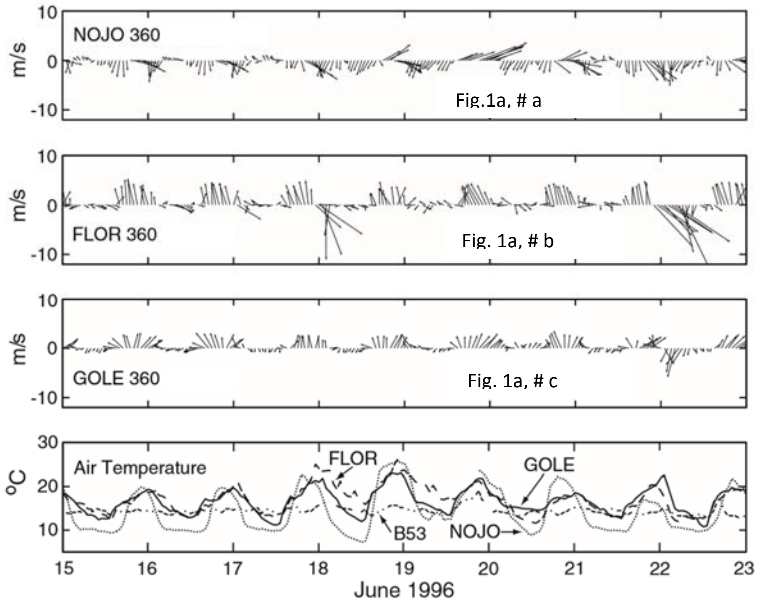

Figure 15. Ridge crest and Santa Ynez Mountain lower, southern slope station winds and air temperatures. There is no suggestion of lee side, down slope flow over a significant portion of the Santa Ynez Mountain slope. North is up. See Table 4 and Fig. 1a.

4.e. Sea-level pressure

Sea-level pressure analysis conflicts with the hypothesis that a lee-side low forms in the Santa Barbara Channel and moves to the south to become the center of the mature Catalina Eddy. It also reveals the unrecognized feature of a large pressure minimum in the southeastern portion of the bight that is in place well before any stratus spreading and easterly wind surge occurs along the Santa Barbara Channel. At 2100 18 June, an isolated low occurs southeast of Los Angeles that is coincident with the start of the extended period of southerly winds at San Diego (Fig. 16). This feature is consistent with the warm temperatures below a 500 hPa ridge situated over the coast at this time. On the other hand, this east side low is isolated from the Santa Barbara Channel semi-permanent low by several stations and cannot be associated with Santa Ynez Mountain lee affects.

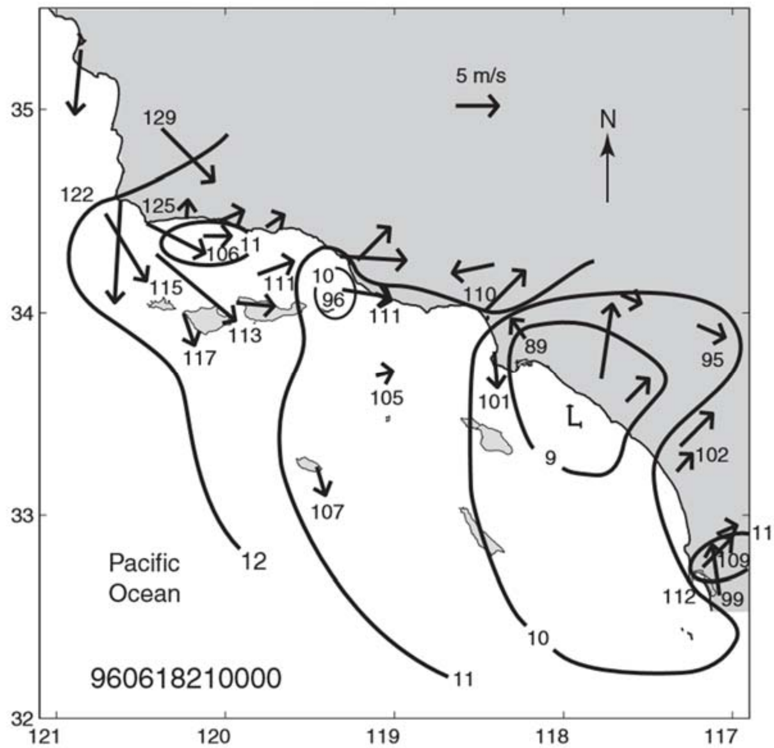

Figure 16. Sea-level pressure and surface station winds for 2100 UCT 18 June 1996 over the Southern California Bight. Isobars are in hPa minus 1000. Station values are in hPa minus 1000 times 10. The minimum pressure is in the southeastern portion of the bight, isolated from the Santa Barbara Channel low by a weak-pressure ridge over B25 (Fig. 1a, # 14), MUGU (Fig. 1a, # 13) and the Channel Islands.

Three hours later at 0000 UTC on 19 Jun 1996 (Fig. 17), the minimum pressure in the bight occurs in the Santa Barbara Channel with an expanded relative minimum centered in the southeastern portion of the bight. This latter low covers a greater area and remains separated from the Santa Barbara Channel low by a weak high pressure ridge. Without an observation near San Clemente Island, which of the two pressure minimums has the lowest value could not be determined. At 0500 UTC on 19 June 1996 (Fig. 18), the two previously isolated lows have joined with the location of the absolute minimum still uncertain due to limited data coverage over water. Later at 1200 UTC 19 June 1996 (Fig. 19) and 1500 UTC 19 June 1996 (Fig. 20), observations show that the low center and the lowest pressure is in the center of the Bight is near B25 (Fig. 1a, # 14) which indicates a westward shift of the surface low center over the previous 12 hours.

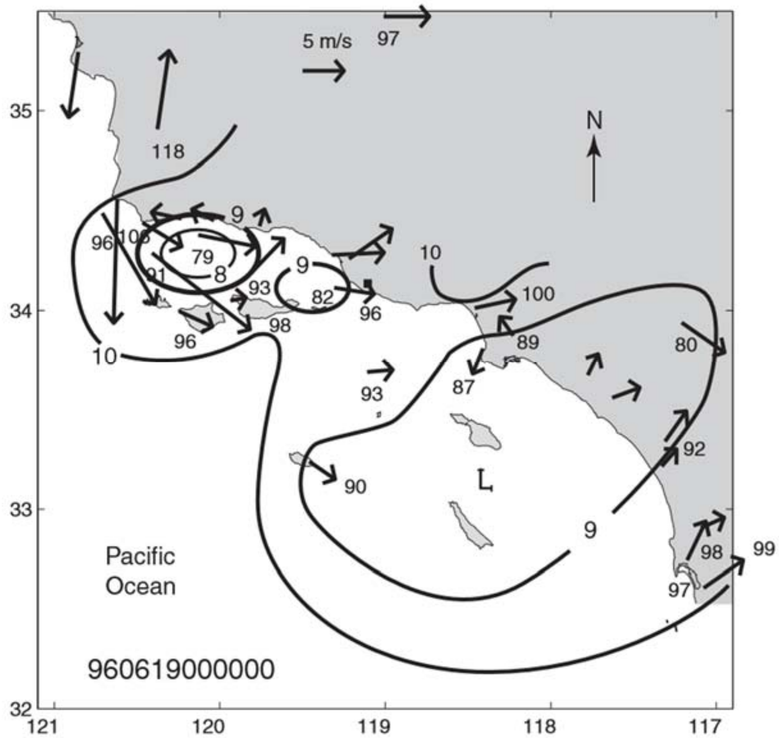

Figure 17. Sea-level pressure and surface station winds for 0000 UCT 19 June 1996. Isobars are in hPa minus 1000. Station values are in hPa minus 1000 times 10. An isolated low exists in the southeastern portion of the bight but no station is near enough to the center to record the minimum.

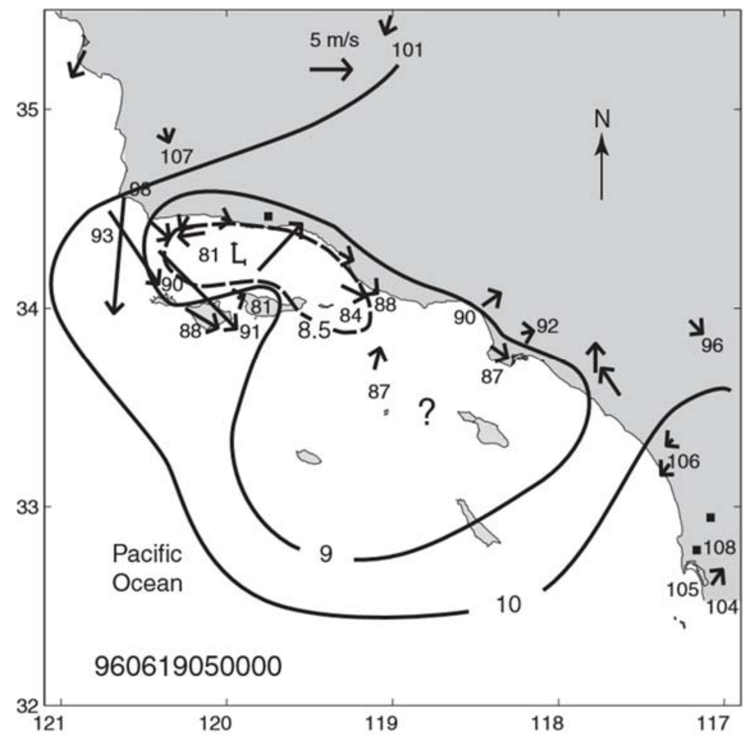

Figure 18. Sea-level pressure and surface station winds for 0500 UCT 19 June 1996. The low-pressure centers at the Santa Barbara Channel and southeastern portion of the bight have merged. Which location shows the lowest value cannot be determined due to the lack of observations in the bight center. Isobars are in hPa minus 1000. Station values are in hPa minus 1000 times 10.

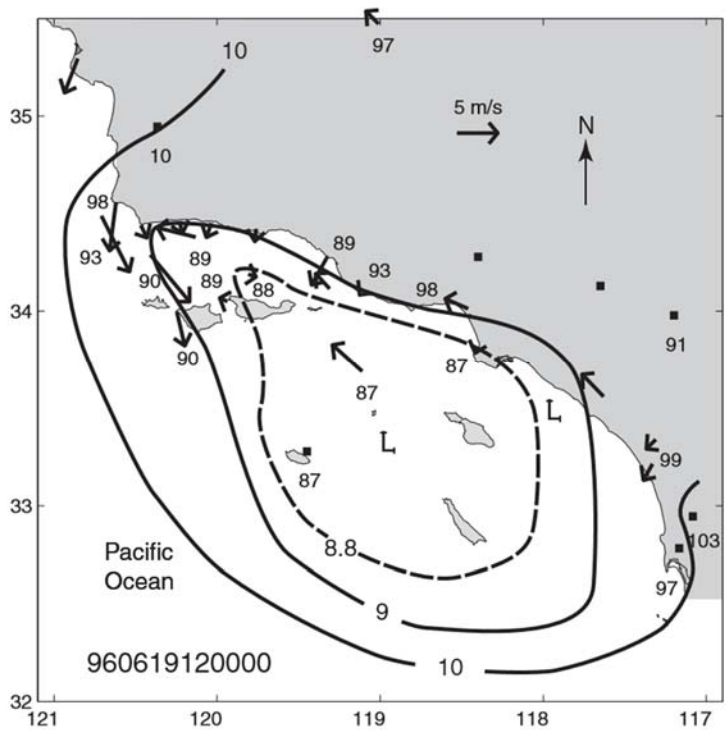

Figure 19. Sea-level pressure and surface station wind vectors for 1200 UCT 19 June 1996. Isobars are in hPa minus 1000. Station values are in hPa minus 1000 times 10.

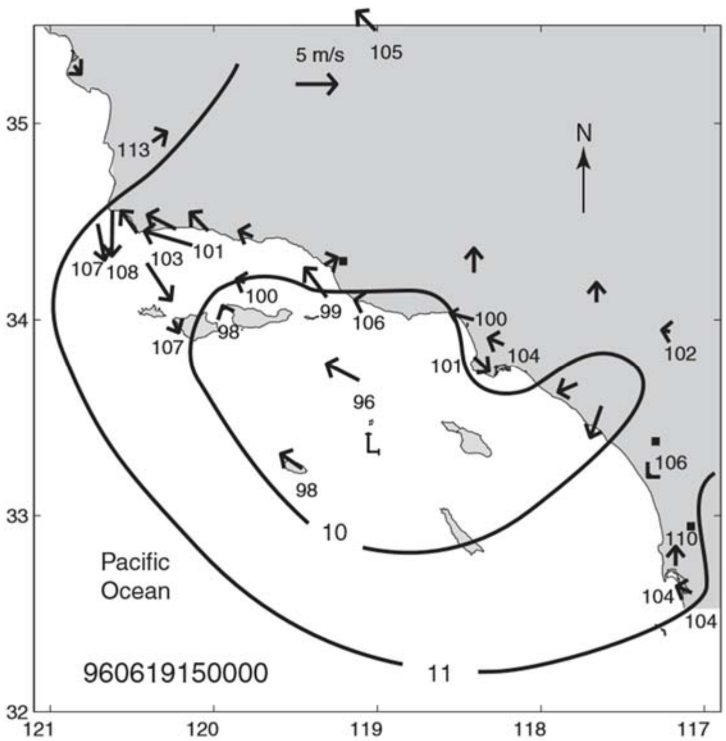

Figure 20. Sea-level pressure and surface station wind vectors for 1500 UCT 19 June 1996. Isobars are in hPa minus 1000. Station values are in hPa minus 1000 times 10. A large low-pressure over the bight is centered between B25 and San Nicolas Island. The pressure in the Santa Barbara Channel is higher and increases toward the west, although the winds are from the east at the land stations from WCAM (Fig. 1a, # 7) to PCON (Fig. 1a, # 2), as well as B53 (Fig. 1a, # 9) and platform GAIL (Fig. 1a, # 12). Around this time, the stratus cloud layer surges westward along the Santa Barbara Channel.

There are three important aspects about this pressure and wind analysis. First, the increased observations around the Santa Barbara Channel clearly show no indication of the semi-permanent Santa Barbara Channel pressure minimum moving south to the central portion of the SCB near B25 to form the center of the mature stage of the eddy in direct conflict with prior hypotheses and numerical models (Table 1). Second, a new feature missed in M&A89 and all previous numerical models (Table 1) has been identified, namely, an eastside Santa Ana low that forms and expands westward to become the mature eddy center. And third, the stratus and surge in the Santa Barbara channel appear to be moving against the surface pressure gradient, suggesting dynamics other than simple lee lows or ageostrophic advection down a gradient.

The sea-level pressure gradient should be forcing the low level winds and serve as an indicator of upper level processes. Unlike earlier authors, we break the San Diego-Santa Barbara coastline into two sections: SDGO-B45 and B45-HOND, substituting HOND for Santa Barbara, for which the sea-level pressure was not available. Consistent with earlier publications (pressures posted in M&A89's Figure 24), Fig. 21 shows that the majority of the pressure difference between SDGO and HOND is in the southern portion of the bight, contradicting the implication (M&A89) that the San Diego-Santa Barbara pressure gradient is quasi-uniform along the coast. Moreover, the B45-HOND pressure difference is routinely weakly negative (HOND lower pressure) in the early morning and positive in the afternoon so that both 18 and 19 June are not distinguished from the other, non-eddy formation days.

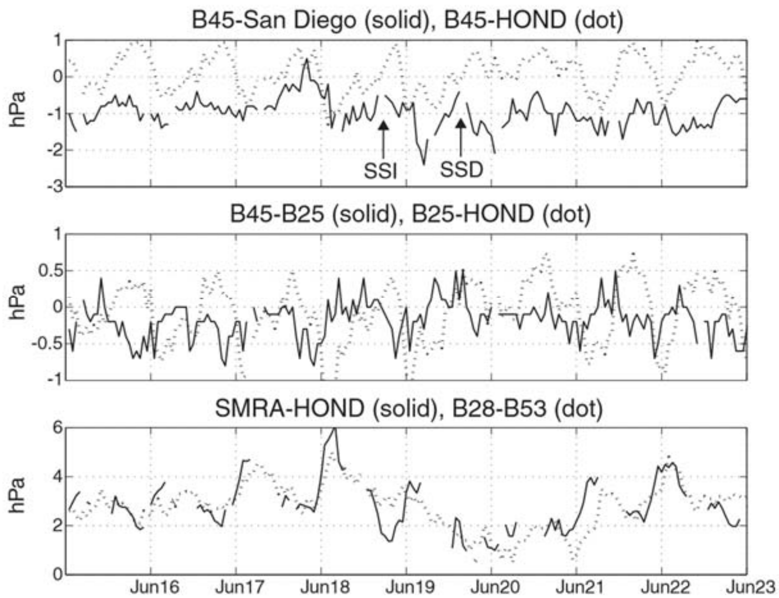

Figure 21. Time-series of surface station pressure differences along the coast in June 1996. Most of the pressure difference between San Diego and the Santa Barbara Channel occurs between B45 and San Diego (SDGO), while the difference between B45 and HOND is often weak or reversed. B45 is # 16, SDGO is # 19, HOND is # 5, B25 is # 14, SMRA (Santa Maria) is # 1, B53 is # 9 in Fig. 1a. B28 is to the north of Fig. 1a. Stations are listed in Table 2a.

Cross-shore pressure differences are difficult to interpret but are shown in Fig. 21 for comparison with earlier analysis (M&A89 Figure 24b). Both the B45-B25 (56 km apart) and B25-HOND (121 km apart) pressure differences are erratic, close to the range of instrument error, and weakly oscillating diurnally about zero. The pressure differences on the night of 18/19 June is indistinguishable from other non-eddy days.

The larger scale pressure gradient across the Santa Ynez Mountain ranges is represented by pressure differences between two pairs of surface stations in Fig. 21. One is between the Santa Maria airport (SMRA, Fig. 1a # 1) and Hondo Platform (HOND, Fig. 1a # 5) that are 68 km apart. The other is between buoy B28, off the central California coast (north of Fig. 1a), and buoy B53 (Fig. 1a # 9) in the mid-Santa Barbara Channel that are 244 km apart. A weak increase above the normal positive 2 - 3 hPa on 17 June, sharply peaks early 18 June, and is coincident with a short wave trough passage. The B45-San Diego and the B45-HOND pressure differences in Fig. 21 are near average for 16 - 19 June, so that the SMRA-HOND pressure difference does not indicate a special deepening of the Santa Barbara Channel low but rather the synoptic-scale tendency for increased subsidence over the entire SCB. This interpretation is consistent with the general increase in land surface-temperatures over Southern California and the lack of significant and persistent cross-ridge winds above the Santa Ynez Mountains or the surface stations on the western slope and the northern coast of the Santa Barbara Channel .

5. Catalina Eddy Case of 1 August 1996

The high points of a second Catalina Eddy on 1 - 7 August 1996 are presented to show that an eddy can exist without any easterly winds or clouds in the Santa Barbara Channel. This eddy began at 1500 UTC 1 August and ended at 0200 UTC 6 August, according to the M&A89 criteria for southerly winds at San Diego (Fig. 22 – SSD vector marks start). Satellite images confirm the presence of a cyclonic eddy in the central portion of the SCB exclusive of the Santa Barbara Channel. At 1615 UTC 1 August 1996, a cyclonic and anticyclonic circulation in the cloud layer was centered in the eastern Bight (Fig. 23). A Santa Catalina Eddy has formed with a cloud-free Santa Barbara Channel, similar to that in Wakamoto (1987).

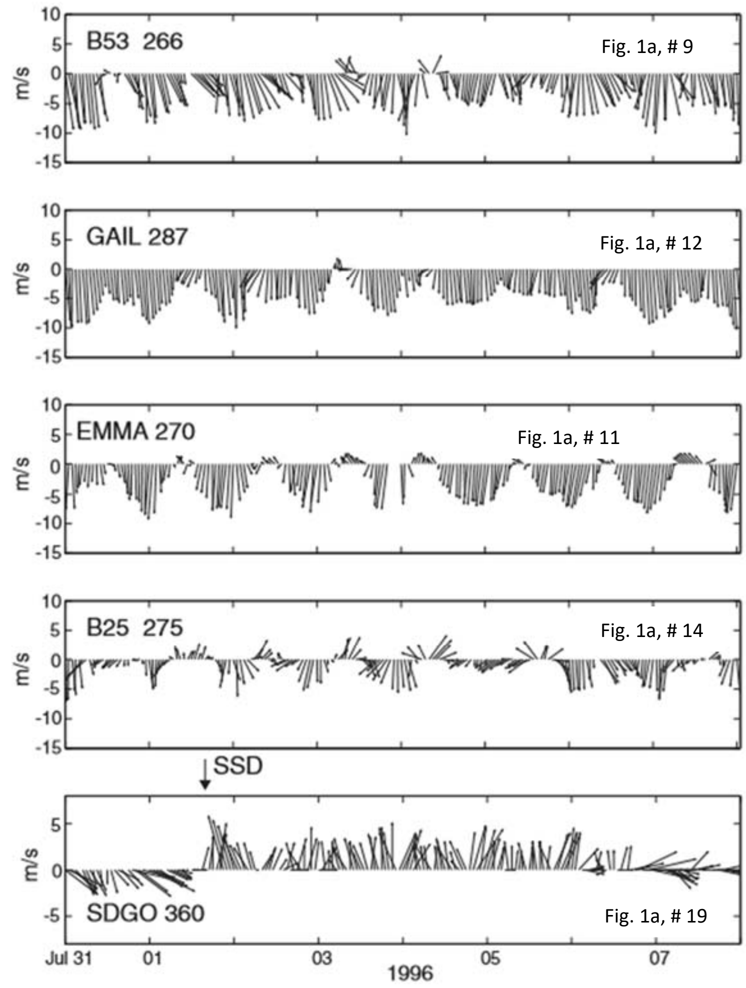

Figure 22. Surface winds at San Diego, B25 and two stations on the eastern end of the Santa Barbara Channel. Winds are rotated in the direction of maximum variation, which is in degrees and posted next to the station name. Although the eddy began at 1500 UTC 1 August according to the M&A criteria (arrow labeled SSD), only brief easterly winds occurred around sunrise in the Santa Barbara Channel more than a day later and no significant, organized easterly wind surge occurred.

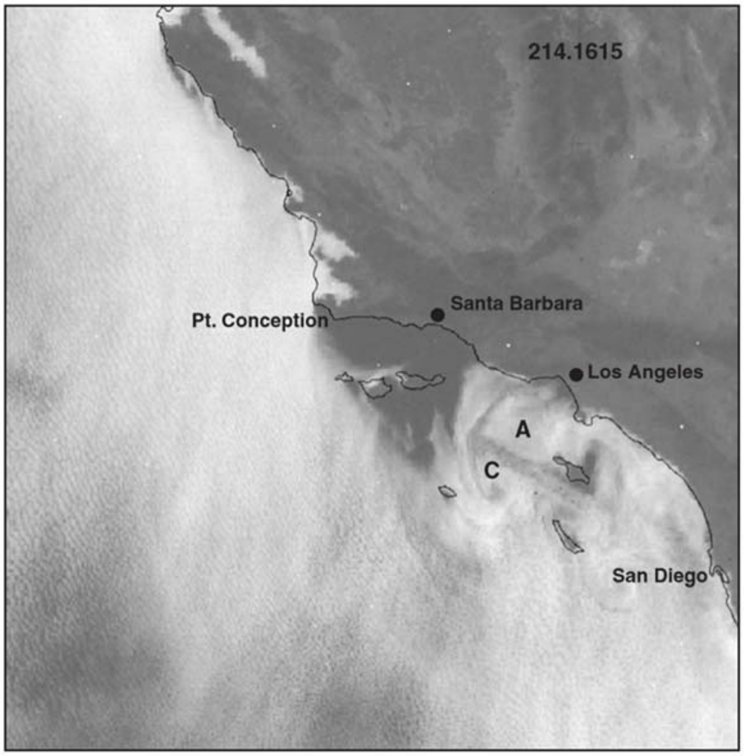

Figure 23. Stationary satellite visible image for 1615 UTC 1 Aug 1996. An eddy is apparent in the SE portion of the bight that does not extend to the Santa Barbara Channel. A cyclonic eddy may be seen in the cloud structure at "C" and an anticyclonic eddy at "A".

There was no significant from the north, cross-crest flow above Santa Barbara (Goleta radar profiler, GOL, Fig. 1a, # 8) in the three days before the eddy event. Instead, the strongest 600-1200 m flow was mostly from the south around 0000 UTC (Fig. 24). The weak, from the north winds at 200 - 600 m was a routinely occurring, thermally caused, feature appearing for several hours around sunrise. On the other hand, the strong flow from the north below 1500 m on 30.5 July-2 August at Vandenberg (Fig. 25) was unrepresentative of that in the Santa Ynez Mountain lee 75 km to the east as shown by the Goleta radar profiler.

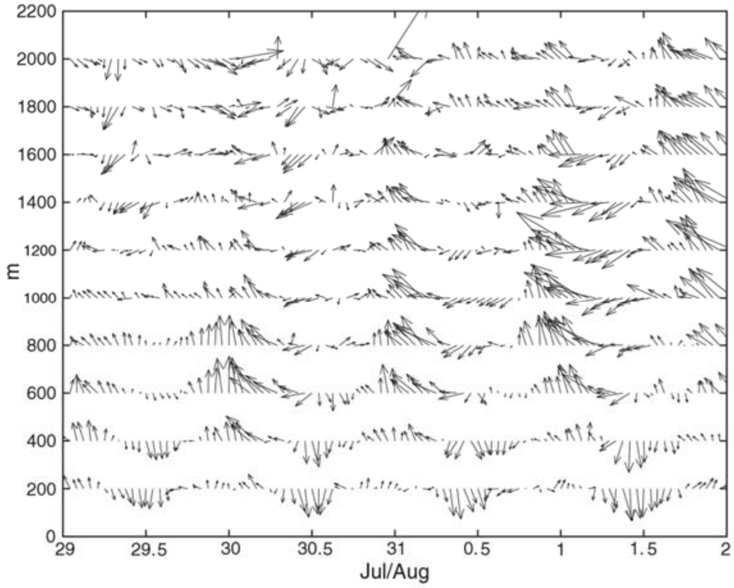

Figure 24. Goleta (GOL, Fig. 1a, # 8, at Santa Barbara airport) radar profiler winds, July-August, 1996. A vector with the length of 0-200 m distance along the vertical axis has a speed of 10 m/s.

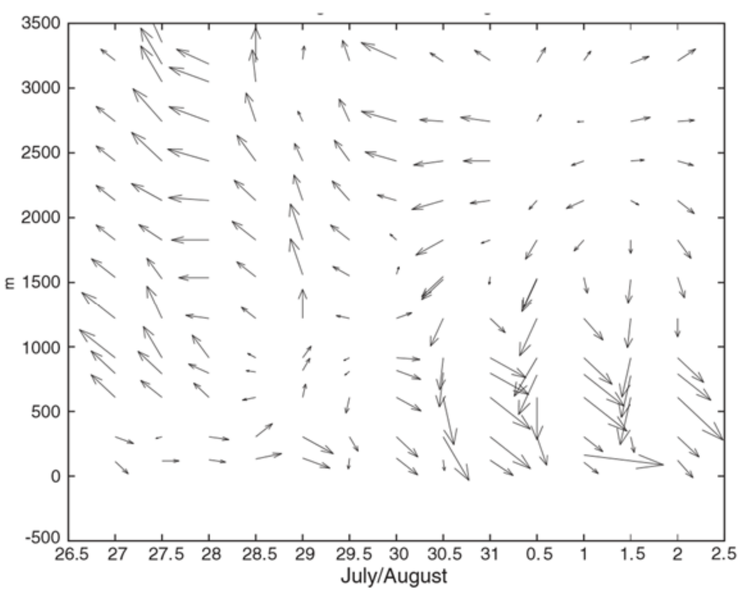

Figure 25. Vandenberg (VBG, Fig. 1a, # A) RAOB winds July/August 1996. A vector with the length of the 0-500 m distance along the vertical axis has a speed of 10 m/s. These winds correlate poorly to those at Goleta.

Analyses of pressure and winds on 1500 UTC 1 Aug 1996 confirmed that there was a broad, weak low-pressure centered in the eastern SCB near Catalina Island that was separated from a weaker low-pressure in the Santa Barbara Channel by a ridge of weak high pressure (Fig. 26). This was consistent with a Catalina Eddy circulation being exclusive of the Santa Barbara Channel area. Again, there is no evidence in the sea-level pressure analysis (others not shown) that the Santa Barbara Channel low formed and moved to the south to form the center of the mature eddy. On the contrary, there is evidence that the Santa Anna centered low expanded and moved westward to become the center of the Catalina Eddy.

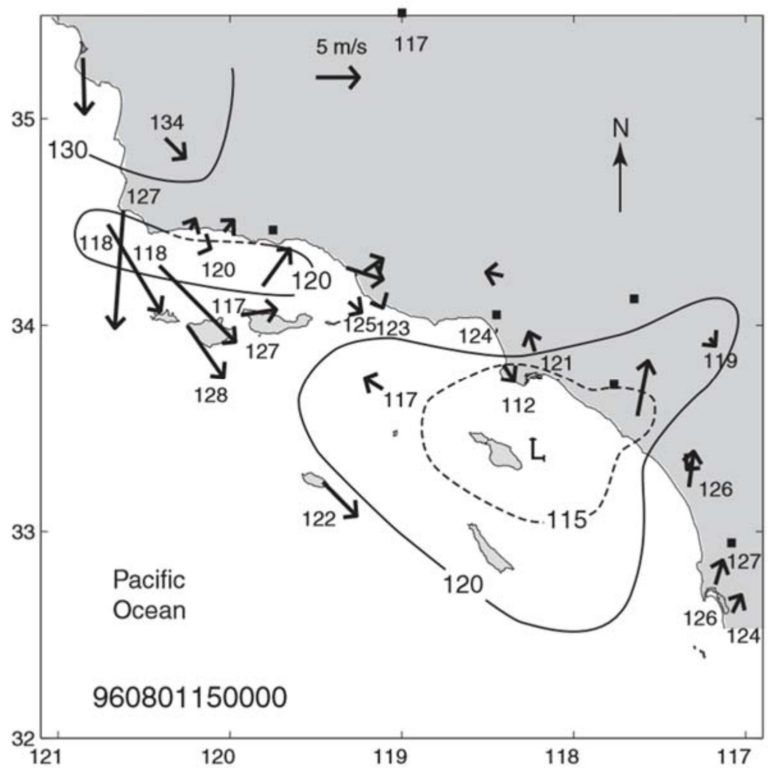

Figure 26. Sea-level pressure and surface station winds for 1500 UCT 1 Aug 1996. A large low-pressure over the bight is centered near Santa Catalina Island and separated from a weaker low to the NW in the Santa Barbara Channel by a weak-pressure ridge. This is coincident near the time of the initiation of southerly winds at San Diego.

Three days before and during the first two days of this event, there are no significant easterly winds at sea level in the Santa Barbara Channel. In fact, winds are persistently from the west at B54 (Fig. 1a, # 3), B53 (Fig. 1a, #9), platform Gail (GAIL, Fig. 1a, # 12), and the Santa Cruz Island station (CRUZ, Fig. 1a, # 10), showing that easterly surface winds and clouds in the Santa Barbara Channel are not required for a Catalina Eddy.

6. Synoptic Evolution accompanying the 19 June 1996 Catalina Eddy

M&A89 describe a synoptic evolution accompanying the initiation of Catalina eddies. A crucial aspect is the development of low-level cross mountain flow over the Santa Ynez Mountains that sets up lee troughing to spawn a surge of air from the north over the sea that initiates the eddy. This is associated with an upper-level ridge building into the West Coast. However, the evolution of the 19 June 1996 eddy did not occur with cross mountain flow over the Santa Ynez Mountains. In addition, the synoptic scale evolution around June 19 suggests a rather different mechanism that lead to the development of this Catalina eddy. Prior to the development of the Catalina eddy, an upper-level trough crossed into northern California and the Pacific Northwest (Fig. 27a). There was an anticyclone over northwestern Mexico extending across the Baja California to San Diego on the NW edge. During the next 48 hours, this upper-level ridge amplified, extended over the SW United States and included Southern California as shown in Figs. 27b and 27c. The amplification of this upper-level anticyclone is associated with warming over northwestern Mexico and Southern California in the mid and lower levels between 0000 UTC 18 June and 0000 UTC 19 June. The air column below 400 hPa warmed during this time as shown in Fig. 28 which presents the San Diego sounding for these two days. This warming occurred while the 500 hPa height remained constant which resulted in a decrease in surface pressure over the San Diego area. The development of the surface low pressure centered in the eastern SCB at 2100 UTC 18 June (Fig. 16) is consistent with this sequence of events. As the 500 hPa anticyclone strengthened, the flow below 500 hPa turns more southwesterly above San Diego by 0000UTC 19 June (Fig. 28). By 0000UTC 20 June, the upper-level trough axis had moved inland (Fig. 27c). The NE expansion of movement of the 500 hPa anticyclone over Mexico was associated with a strengthened southerly flow off the west coast of Mexico which is shown in the Guadalupe Island sounding (Fig. 29). The evolution of the synoptic flow over the Bight region can be summarized as an amplifying 500 hPa ridge over San Diego that then propagates inland as the eddy becomes firmly established as shown in Fig. 19.

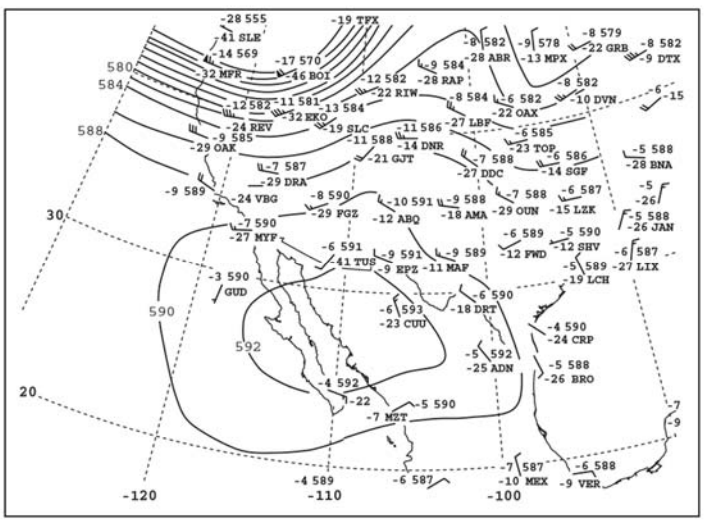

Figure 27a. 500 hPa geopotential height analysis and data for 0000 UTC 18 June .

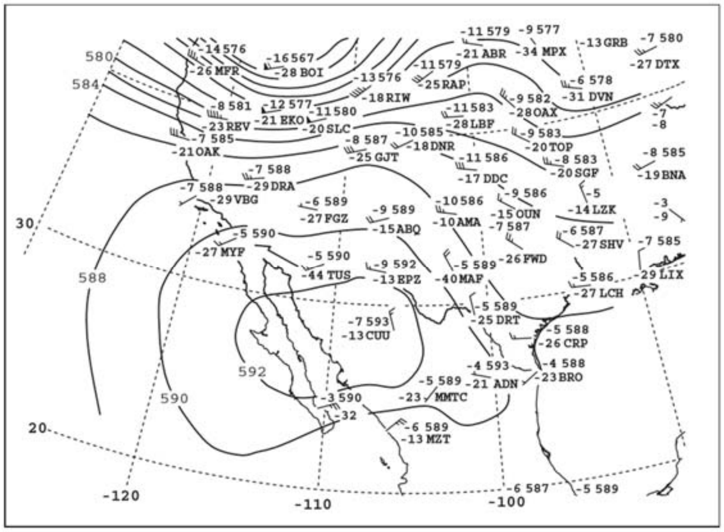

Figure 27b. 500 hPa geopotential height analysis and data for 0000 UTC 19 June 1996.

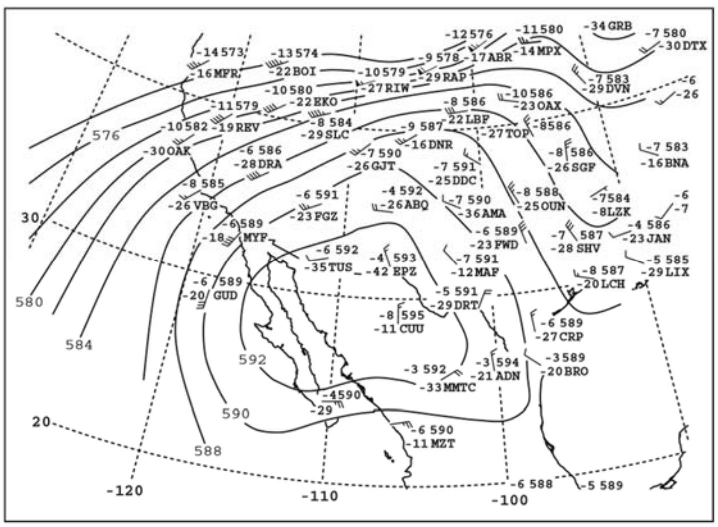

Figure 27c. 500 hPa June geopotential height analysis and data for 0000 UTC 20 June 1996.

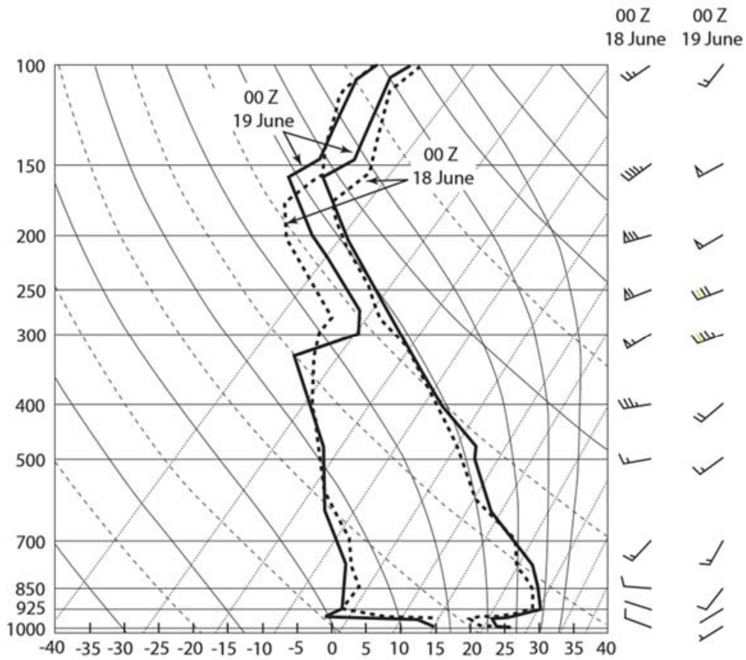

Figure 28. San Diego (SAN, Fig. 1a, # B) RAOB soundings for 0000 UTC on 18 and 19 June 1996.

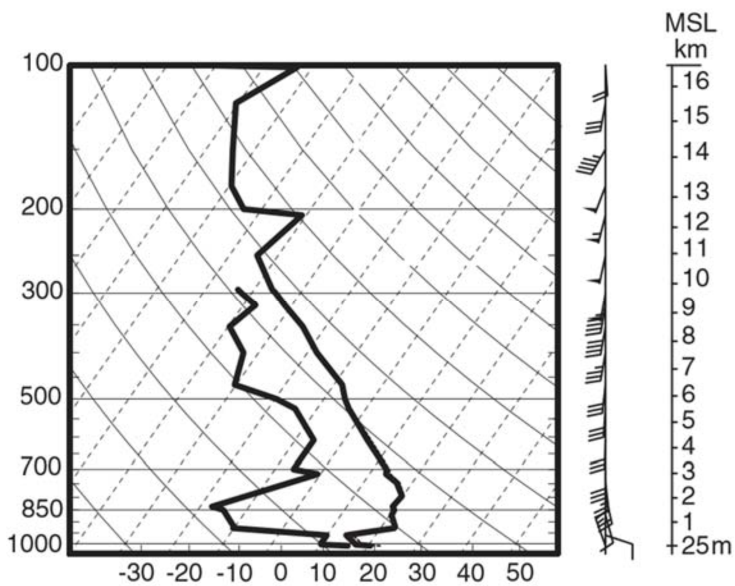

Figure 29. Guadalupe Island RAOB sounding for 0000 UTC 19 June 1996. This station is approximately 230 km S of San Diego and 240 km west of Baja California.

The upper-level synoptic evolution described above is consistent with the evolution of the surface pressure depicted in Figs. 16-20. As the upper-level ridge amplified over the Bight region and San Diego, the surface low just north of San Diego developed and shifted westward as stronger warming occurred just offshore. This period of warming aloft corresponds to the time period when the inversion base was lowering and the inversion top was warming (Fig. 9) as well as in the San Diego sounding (Fig. 28). The initiation of the eddy around 0000UTC 19 June corresponded to the lowest inversion and greatest 1000-500 hPa thickness at San Diego. As the 500 hPa ridge axis moved inland over night between 0000 and 1200 UTC 19 June, the 500 hPa anticyclone expanded over the SW United States. This was followed by a weakening of the large-scale subsidence over the SCB which was coincident with the rise in the inversion. This deepening of the marine layer probably encourages the eddy to develop as vortex stretching occurs in the marine layer. The critical aspect for the formation of this eddy was the thermal warming over the SCB and not cross mountain flow over the Santa Ynez mountains that generated lee troughing.

7. Discussion

7a. General Event Characteristics of 1996

Ten events occurred May through September 1996 that repeat the essential structures in the two cases presented here. The event start and end times are defined according to the M&A89 criteria based upon the San Diego (SDGO) winds (Table 5) and are confirmed by a mesoscale cyclonic cloud formation filling most of the SCB in satellite visual images. However, it was found that the SDGO southerly winds began 12 - 24 hours *before* the M&A89 defined start times in all but two of the cases. Seven of the ten began in the early afternoon of the day before, as in the 19 June 1996 case presented here. The San Diego southerly winds for a majority of Catalina eddies start the afternoon before the closed eddy formation and usually well before the M&A89 criteria.

Table 5. Event characteristics.

1	2	3	4	5	6	7	8	9	10	11	12	13
1	05/13/1500	05/14/1100	Y-E	Y	Y	Y	Y	N	N	N	N	CO
2	05/23/1500	05/25/0400	Y-A	Y	Y	Y	N	N	N	N	Y	N
3	06/07/0800	06/11/2000	Y-A	Y	Y	Y	Y-W	Y-W	Y	N	N	OC
4	06/19/1500	06/21/0200	Y-A	Y	Y	Y	Y-S	Y	N	N	N	S
5	06/23/1200	06/24/1300	N	Y	Y	Y	Y-S	Y-S	Y	N	N	CO
6	07/14/0731	07/15/0150	Y-A	Y	Y	Y	N	N	N	N	N	CC
7	07/25/1100	07/26/0600	Y-A	Y	Y	Y	Y-W	N	N	Y-W	N	CC
8	08/01/1500	08/06/0200	N	Y	Y	Y	N	N	N	N	N	CC
9	08/18/1200	08/19/1453	Y-A	Y	Y	M	N	N	Y	N	Y-W*	OC
10	09/14/1653	09/07/0119	Y-A	Y	Y	Y	N	N	N	N	Y-S	UN

W=Weak, S=Strong, M=Marginal, *=Brief weak offshore at WCAM only.

Key
1. Event Number.
2. M&A Defined Event Start.
3. M&A Defined Event End.
4. SDGO general south winds start afternoon (A) or early evening (E) 12-24 hrs before M&A.
5. SDGO-B45 ~50% > B45-HONDO pressure difference for 24 hours before M&A start.
6. B45-HONDO pressure difference weak, + and -, diurnal trend goes through zero in 24 hours.
7. B28-B53 pressure difference weaker or equal to that on previous four days.
8. GAIL E wind component > 1m/s.
9. B53 E wind component > 1 m/s.
10. CRUZ S or E winds component > 1 m/s.
11. SB Coast temperature anomalous high, > surrounding 8 days, or 10°C > Buoy 53.
12. SB Coast offshore wind component > 2 m/s within 12 hours of wind surge.
13. Marine Clouds:
    - S- Cloud surge westward along Santa Barbara coast after sunrise.
    - N- No Bight overcast.
    - CO- Bight clear day before, overcast at sunrise, no cloud surge.
    - CC- Bight clear day before, California coast overcast at sunrise.
    - OC- Overcast California Coast & Bight day before and start day.
    - UN- Unusual summer cloud type, more unstable.

None of the ten 1996 Catalina Eddy cases listed in Table 5 had significant cross-ridge, northerly Santa Ynez Mountain ridge winds detected by the Goleta (Santa Barbara area) radar profiler that could be suggestive of significant lee-side, down slope flow. For at least 48 hours before all event initiations, and during the formation phase, the winds above the Santa Ynez Mountain ridge were mostly from an easterly or SE direction and at low speeds.

Significant northerly surface winds were not found at the network of surface stations on the Santa Barbara coast and west slope of the Santa Ynez Mountains before and during the formation stage of any Catalina Eddy in 1996. In nine of the 10 cases, there were no strong, persistent northerly winds greater than 2 m s^{-1} at Santa Barbara Channel surface stations during the four days preceding or during the event. Significant lee-side effects over the Santa Barbara Channel are unusual anytime (Dorman and Winant 2000) and specifically during the formation stage of eddies.

The pressure difference between B45-HONDO remained weak for all of events. This difference had a clear diurnal trend cycling from about -0.5 in the morning and +0.5 in the afternoon of the day before the defined start in all events. This fact is inconsistent with thesis of an eddy forming due to Santa Ynez lee troughing, the leading edge moving to the south along the western side of the Bight, then easterly to San Diego, and then moving northward along the coast from San Diego to past Los Angeles.

In the Santa Barbara Channel, easterly winds at GAIL, B53 and easterly or southerly winds at CRUZ during the eddy formation stage are not required and not found for five of the events. They did occur briefly for five of the events at GAIL and, during three of these five, were also found, weak and of short duration, at B53 and CRUZ. The 1 Aug 1996 case without easterly winds in the Santa Barbara Channel is routine. And, easterly winds existing along the Santa Barbara Channel at least halfway toward the western mouth occurs in only a small minority of cases.

Most events (five out of seven) experienced marine layer thinning at San Diego in the first 24 hours of the event. One of these five had a sharp marine layer thickness increase at the start, while another had only a weak upward trend.

Although no two events were completely alike, an attempt was made to characterize the cloud field. In only the 19 June 1996 case was the SCB clear the day before, followed by an early morning cloud surge to the west in the Santa Barbara Channel which formed short-lived "hook" clouds that did not extend far beyond Point Conception. On seven cases, the SCB experienced an overcast marine stratus cloud in place by first light, which is consistent with quasi-uniform, bight-wide development. In some cases, the marine stratus cloud overcast developed at night over a large section of the California coast including the bight. For two cases, the bight was overcast the day before, and in one case had no significant overcast at all. Cloud surges in the Santa Barbara Channel and transitory cyclonic cloud hooks at the formation stage are not typical of the Catalina Eddy.

7b. Comparison to Numerical Models

Four numerical model based investigation of the Catalina Eddy (U&R93, UHR&V95, TB&R97, DL&M01, Table 1) conflict significantly with the observations presented in this paper in that they include cross coast, sea level flow at Santa Barbara and a single low pressure in the SCB that is in the Santa Barbara channel. We focus on those that we can clearly check with the limited analysis presented in these publications. All five have northerly, cross ridge flow over the Santa Ynez Mountains, a single, sea-level low pressure in the Santa Barbara Channel, and little change or increases in the marine layer depth at San Diego, none of which fit the observations used to characterize the 1996 events. The absence of an upstream sounding in the San Joaquin Valley to sample the lower level flow and stability structure might be a contributing factor to the models' failure to reproduce the observed conditions. Another factor is that the model resolution and boundary layer coefficients may not adequately represent the marine layer or the boundary layer physics over the complex Southern California topography. The latter required a special gravity wave resolving model to handle transcritical marine layer dynamics (Rogerson 1998).

7c. An Alternative Hypothesis

An alternative hypothesis is proposed for the basis for starting the Catalina Eddy. This combines the surface layer, lower atmosphere and mid-level synoptic variations. Consider the SCB between the Channel Islands and San Diego. The mean daily surface marine layer circulation over the SCB is cyclonic during all seasons. The surface flow past the western end of the Channel Islands moves south and eastward covering the SCB with half of a cyclonic gyre. During the daytime, the flow continues from the west across the coastal plane and inland. At night, winds are weak and variable in direction in the eastern 1/3 of the Bight. During the extended summer season, between Dana Point and San Diego, the mean flow during the latter part of the day has a partial southerly component, contributing to the cyclonic circulation aspect of the SCB circulation.

The mean SCB surface layer is capped by a stable lower atmosphere all year round which suppresses surface layer convection over water. The greatest stability and the strongest air temperature base capping the surface air is in the late spring through early fall. Weak synoptic scale variation causes this layer to modulate in height and strength. Mean clouds in the Bight and surrounding areas are stratus in this surface layer with the greatest cloud cover in the early morning and the least in the afternoon. Weak synoptic scale variation over ~ 10 days lifts and lowers this layer, increasing and decreasing stratus over the SCB while not eliminating the stable layer capping the surface marine layer. The SCB on the north side of the Channel Islands has a thinner marine layer and less stratus cover than the remained of the SCB.

The edge of the Bight is a concave shore curve extending from Pt Conception to San Diego that is backed by coastal mountains. This area is dominated by thermally driven sea-mountain breeze. During the day there is an onshore, up slope flow, and an elevated return cross shore flow above the marine layer. The concave shore mountain around the eastern bight focuses the return flow and subsidence in the overwater center. This is strongest along the San Diego to Dana Point portion with the toe of its western facing slope near the coast. In contrast is the greater Los Angeles area with its low coastal plain (topography) extending ~ 100 km to the east. This allows marine air flow to extend farther east while portions are pulled up the daytime heating of the slope of the surrounding mountain barrier surrounding the entire floor. The Santa Barbara Channel area on the north side of the Bight has its own thermal system somewhat isolated by the Channel Islands from the main SCB system.

Modest synoptic cyclonic features such as a weak summer trough passage or the relaxation of anticyclonic conditions that do not eliminate the stable layer capping the surface layer, combine with the surface layer vorticity to cause a distinctive cyclonic eddy circulation and stratus cover over the Bight. These start with winds from the south along the eastern side from San Diego to Dana Point.

Due to variations in the synoptic structure, there are a range of responses. Smaller and weaker scale cause a cyclonic eddy and stratus over the Bight south of the Channel Island. Broader and stronger events cause a similar eddy that does not affect the wind field in the western portion of the Santa Barbara Channel, but cause a stratus over cast over the entire Bight from Pt Conception to past San Diego. More infrequently, perhaps once every 2 or 3 years, the result creates a leading cloud edge and wind reversal that moves from southern Orange Country, poleward along the coast to Pt Conception.

There are several advantages to this hypothesis. A major one is that the first and most robust signal for the presence of a Catalina Eddy is southerly winds along the San Diego coast. It is consistent with satellite images that show a Catalina Eddy cloud cover forming at night that can include or not the Santa Barbara Channel area. Another is that a range of synoptic scale cyclonic trends that do not eliminate the stability over the marine layer in the Bight cause a range of eddy structure and clouds. This recognizes the semi-independent role of the Santa Barbara Channel from the main SCB which has its own wind and pressure system. Another is that no wind flow across the SB coastline or Channel is necessary which is not observed in the Santa Barbara radar profiler, the Santa Barbara Coast surface stations nor the channel buoys for the vast majority of Catalina Eddies.

9. Conclusions

An observational analysis of Southern California's Catalina Eddy based upon the greatly expanded surface and radar profiler data available in the mid-1990's reveals new features that challenge previously accepted assumptions. Hourly-averaged radar profiler data at Santa Barbara in the immediate, central lee of the Santa Ynez/San Rafael mountains fail to show anything that could be characterized as significant northerly, cross-ridge flow before or during a Catalina Eddy. Rather, the Santa Barbara (Goleta) radar profiler shows weak winds from other directions. These observations directly conflict with earlier analyses and numerical models that require extended lee flow for an eddy to form.

An expanded set of hourly automated surface stations located on the lee slope of the Santa Ynez Mountains, the Santa Barbara Coast, NDBC weather buoys, and the Channel Islands, show that significant northerly, down-slope, cross-coast flow on the southern slope of the Santa Ynez Mountains is rare, and did not occur before or during any of the Catalina eddies identified in 1996. This is contrary to previous publications, which did not take advantage of this data set.

The expanded surface network in the greater Santa Barbara Channel area with others in the SCB confirm the existence of a semi-permanent, low-pressure in the Santa Barbara Channel. The collective stations reveal a low forming on the eastern side of the SCB at Santa Ana during initiation of Catalina eddies. This low expands westward to become the center of the mature eddy. This is contrary to earlier hypotheses.

Radar profilers at San Diego and Los Angeles show marine layer air thinning in the formation stage of the 19 June 1996 Catalina eddy, and in five other 1996 cases examined here. This directly conflicts with the hypothesis that “cold air damming” against the topography behind the San Diego coastline is an essential element of eddy formation.

Analysis of a 1 August 1996 event shows eddy cyclonic circulation can exist south and east of the Channel Islands and exclusive of the Santa Barbara Channel. For this case, as most of 1996 cases, there are no significant winds from the east over the Santa Barbara Channel and no wind or cloud surge in the formation stage.

In the light of the more extensive surface and upper-air observations available, the dynamical cause of the Catalina Eddy in the SCB is re-examined. The hypothesis that lee-side effects of, or northerly winds over the Santa Ynez Mountain range is found to fail on several counts when closely compared with a 19 June 1996 event, a 1 August 1996 event, and eight other 1996 events.

A competing hypothesis for the initiation of an eddy is proposed. This combines the mean, semi-permanent, cyclonic flow of the atmospheric marine layer over the SCB with a weak increase in cyclonic or decrease in anticyclonic mid-level flow over the Bight that does not eliminate the stable layer capping the atmospheric marine layer. This explanation satisfies satellite images, the upper air stations and a dense surface station network over the entire Bight.

Acknowledgments. This study was supported by the Minerals Management Service of the U.S. Department of Interior under cooperative agreement 14-35-0001-30571. The authors are grateful for Dick Lind and Larry Riddle for capturing and saving data, much of which would have been otherwise lost. The Santa Barbara, San Diego and Ventura Air Pollution Control Districts, Pacific Gas and Electric, Southern California Edison and NOAA/ERL Boulder supplied crucial observations.

References

Blier, W., 1998: The Sundowner winds of Santa Barbara, California, *Wea. and Forecasting*, 13, 702-716.

Bosart, L.F., 1983: Analysis of a California Catalina eddy event, *Mon. Wea. Rev.*, 111, 1619-1633.

Burk, S. D. , T. Haack and R. M. Samelson, 1998: Mesoscale simulation of supercritical, subcritical and transcritical flow along coastal topography, *J. Atmos. Sci*., 56, 2780-2795.

Burk, S. D. and T. Haack, 2000:The dynamics of wave clouds upwind of coastal topography, *Mon. Wea. Rev*., 128, 1438-1455.

Clark, J. H. E. and S. R. Dembeck, 1991: The Catalina Eddy event of July 1987: A coastally trapped mesoscale response to synoptic forecasting, *Mon. Wea. Rev*., 119, 1714-1735.

Clark, J. H. E., 1994: The role of Kelvin waves in evolution of the Catalina Eddy, *Mon. Wea. Rev*., 122, 838-850.

Davis, C., S. Low-Nam, and C. Mass, 2000: Dynamics of a Catalina Eddy revealed by numerical simulation, *Mon. Wea. Rev*., 128, 2885-2904.

Dorman, C.E., 1995a: Evidence of Kelvin waves in California's marine layer and related eddy generation, *Mon. Wea. Rev*., 113, 827-839.

Dorman, C. E., 1985b: Hydraulic control of the northern California marine layer (abstract), *EOS, Transactions of the American Geophysical Union*, 66, 914.

Dorman, C. E., T. Holt, D. P. Rogers, and K. Edwards, 2000: Large-scale structure of the June - July 1996 marine boundary layer along California and Oregon, *Mon. Wea. Rev*., 128, 1632-1652.

Dorman, C.E., D. P. Rogers, W. Nuss and W. T. Thompson, 1999: Adjustment of the summer marine boundary layer around Point Sur, California, *Mon. Wea. Rev*., 127, 2143-2159.

Dorman, C. E. and C. D. Winant, 1995:Buoy observations of the atmosphere along the west coast of the United States, 1981-1990, *J. Geophys. Res*., 100, 16029-16044.

Dorman, C.E., C.D. Winant, 2000: The marine layer in and around the Santa Barbara Channel, *Mon. Wea. Rev.,* 128, 261-282.

Douglas, S. G. and R. C Kessler, 1991: Analysis of mesoscale airflow patterns in the south-central coast air basin during the SCCCAMP 1985 intensive measurement periods, *J. Appl. Meteor*., 30, 607-631.

Haack, T and S. D. Burk, 2001: Supercritical flow interaction within the Cape Blanco-Cape Mendocino orographic complex, *Mon. Wea. Rev.,* 129, 688-708.

Kessler, R. C. and S. G. Douglas, 1991: Numerical study of mesoscale eddy development over the Santa Barbara Channel, *J. Appl. Meteor*., 30, 633-651.

Koračin, D. and C.E. Dorman, 2001: Marine atmospheric boundary layer divergence and clouds along California in June 1996, *Mon. Wea. Rev.,* 129, 2040-2056.

Mass, C.F. and M.D. Albright, 1989: Origin of the Catalina Eddy, *Mon. Wea. Rev*., 117, 2406-2436.

Neiburger, M., D. S. Johnson and C. W. Chien, 1961:Studies of the structure of the atmosphere over the eastern Pacific Ocean in the summer, in *The Inversion Over the Eastern North Pacific Ocean,* pp 1-94, University of California Press, Berkeley.

Nuss, W.A, J. Bane, W. Thompson, C. Dorman, M. Ralph, R. Rotunno, J. Klemp, W. Skamarock, R. Samelson, A. Rogerson, C. Reason, and P. Jackson, 2000: Coastally trapped wind reversals: a new level of understanding from the experiment on coastally trapped disturbances, *Bull. Amer. Meteor. Soc.,* 81, 719-743.

Rogers, D., C. E. Dorman, K. A. Edwards, I. M. Brooks, W. K. Melville, S. D. Burk, W. T. Thompson, T. Holt, L. M. Ström, M. Tjernström, B. Grisogono, J. M. Bane, W. A. Nuss, B. M. Morley, and A. J. Schanot, 1998: Highlights of coastal waves 1996. *Bull. Amer. Meteor. Soc.*, 7, 1307-1326.

Rogerson, A.M., 1998: Transcritical flows in the coastal marine atmospheric boundary layer, *J. Atmos. Sci*., 56, 2761-2779.

Rosenthal, J., 1968: A Catalina Eddy, *Mon. Wea. Rev.*, 96, 742-743.

Ryan, G, 1996: Down-slope winds of Santa Barbara, California, *NOAA Tech. Mem., NWSR WR-240*, NEXRAD, National Weather Service, 520 North Elevar Street, Oxnard, CA. 93030, 44 pp..

Skamarock, W.C., R. Rotunno and J. B. Klemp, 2000: Dynamical models of coastally trapped disturbances and Catalina eddies, (abstract), *AMS Conf. Colorado*.

Thompson, W. T., S. D. Burk, and J. Rosenthal, 1997: An investigation of the Catalina Eddy, *Mon. Wea. Rev*., 125, 1135-1146.

Tjernström, M. and B. Grisogono, 2000: Simulations of supercritical flow around points and capes in a coastal atmosphere, *J. Atmos. Sci*., **57**, 108-135.

Ueyoshi, K. and J. O. Roads, 1993: Simulation and prediction of the Catalina Eddy, *Mon. Wea. Rev*., 121, 2975-3000.

Ulrickson, B. L., J.S. Hoffmaster, J. Robinson and D. Vimont, 1995: A numerical modeling study of the Catalina Eddy, *Mon. Wea. Rev*., 123, 1364-1373.

Wakimoto, R. M., 1987: The Catalina Eddy and its effects on pollution over southern California, *Mon. Wea. Rev*., 115, 837-855.

Winant, C. D., C. E. Dorman, C. A. Friehe, and R. C. Beardsley, 1988: The marine layer off northern California: an example of supercritical channel flow. *J. Atmos. Sci*., 45, 3588-3605.