1995

A case study of a coastally trapped disturbance during MABLES WC

Fernando J. Aluzzi
San Jose State University

Follow this and additional works at: https://scholarworks.sjsu.edu/etd_theses

Recommended Citation

Aluzzi, Fernando J., "A case study of a coastally trapped disturbance during MABLES WC" (1995).
Master's Theses. 970.

DOI: <https://doi.org/10.31979/etd.jbeq-yr4k>
https://scholarworks.sjsu.edu/etd_theses/970

This Thesis is brought to you for free and open access by the Master's Theses and Graduate Research at SJSU ScholarWorks. It has been accepted for inclusion in Master's Theses by an authorized administrator of SJSU ScholarWorks. For more information, please contact scholarworks@sjsu.edu.

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
313/761-4700 800/521-0600

A CASE STUDY
OF A
COASTALLY TRAPPED DISTURBANCE
DURING
MABLES WC

A Thesis
Presented to
The Faculty of the Department of Meteorology
San Jose State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Fernando J. Aluzzi

May, 1995

UMI Number: 1374561

UMI Microform 1374561

Copyright 1995, by UMI Company. All rights reserved.

**This microform edition is protected against unauthorized
copying under Title 17, United States Code.**

UMI

**300 North Zeeb Road
Ann Arbor, MI 48103**

APPROVED FOR THE DEPARTMENT OF METEOROLOGY

Wilson F. C. Bridger

Dr. A. F. C. Bridger

Peter F. Lester

Dr. Peter F. Lester

Doug M. Sinton

Dr. Doug M. Sinton

APPROVED FOR THE UNIVERSITY

Serena J. Stanford

© 1995

Fernando J. Aluzzi

ALL RIGHTS RESERVED

ABSTRACT

A CASE STUDY OF A COASTALLY TRAPPED DISTURBANCE DURING MABLES WC

by Fernando J. Aluzzi

Coastally trapped disturbances are a phenomenon common to mountainous coastal regions where subsidence inversions are common. In California these disturbances lift the elevated inversion, commonly in the form of a gravity current or a Kelvin wave, and propagate along the coastal boundary as a narrow wedge of stratus moving north along the coast. Changes in weather conditions at coastal stations brought on by the passage of a coastally trapped disturbance include an increase in surface pressure, a decrease in surface temperature, changes in wind direction and wind speed.

This study will use data obtained during MABLES WC (July 31 - August 17, 1978) to analyze whether changes in local weather conditions along the coast of California on Aug. 14, 1978 were the result of the passage of a coastally trapped disturbance. The features commonly present in coastally trapped disturbances were not evident in the data.

ACKNOWLEDGEMENTS

There are many people in the Meteorology department that I would like to thank for helping me complete this study. I would like to start by thanking Dr. Alison Bridger for taking on the arduous job of being my advisor. Thank you Donna Hurth for helping me with everything from A to Z. A special thanks goes to Dr. Peter Lester and Dr. Doug Sinton. Both of you always made time to answer my questions and helped guide me in the right direction. Also, I will always be grateful for the immeasurable number of times one of you assisted me in matters not related to this thesis or even to Meteorology.

To my fellow graduate students and friends who were always helpful, supportive, and put up with me in the grad room and up in the lab: Sheng, Jessie, Frank, Matt, Pambos, Isadora, Dennis, Annette, Greg, William, John, The Kahn man, Brother E., Andy, the Academy, and Maurice.

I would like to thank my mother for her always encouraging words and assistance throughout this process.

Finally, and definitely not least, to a very special someone, who has not only helped me with many different aspects of this project, but has been very patient and supportive. You helped inspire me to complete this project.

TABLE OF CONTENTS

	Page
ABSTRACT	iv
ACKNOWLEDGEMENTS	v
LIST OF FIGURES	viii
LIST OF TABLES	x
Chapter	
1. INTRODUCTION	1
1.1 Background	1
1.2 Literature Review	9
1.3 Purpose of Present Study	21
2. DATA	22
2.1 Data Source	22
2.2 Missing Data	26
3. SYNOPTIC DESCRIPTION	30
3.1 Upper Air/Surface Maps	30
3.2 Satellite Imagery	39
3.3 Application of a CTD Forecast Scheme	39

4.	ANALYSIS	44
4.1	Outline	44
4.2	Pressure	44
4.3	Temperature	49
4.4	Wind Direction	54
4.5	Wind Speed	54
4.6	Inversion Height	61
4.7	Pressure Gradient	64
4.8	Upper Air	69
5.	CONCLUSIONS	76
5.1	Discussion	76

LIST OF FIGURES

Figure		Page
1.1	A model of a Kelvin waveform resulting from a CTD (taken from RS90)	6
1.2	Pressure variations over several days from two different studies of California CTDs (taken from RS92)	8
2.1	Stations providing data for present study	23
2.2	Schematic diagram of Mt. Sutro Tower and outline of the west to east topography of San Francisco (from Lester 1979)	25
2.3	An example of a cubic spline approximation	29
3.1	500 mb charts at 0000 UTC from Aug. 1 - 16, 1978	31
3.2	Surface pressure charts at 0000 UTC from Aug. 1 - 17, 1978 . .	35
3.3	Visible satellite imagery for western North America from Aug. 13 - 17, 1978	40
4.1	The variation in surface pressure on the Acania	45
4.2	The variation in surface pressure on the Farallon Islands	46
4.3	The variation in pressure at Sutro Tower	47
4.4	The variation in surface temperature on the Acania	50
4.5	The variation in surface temperature on the Farallon Islands . .	51
4.6	The variation in temperature at levels 1 and 6 at Sutro tower	52
4.7	The variation in potential temperature at levels 1 and 6 at Sutro tower	53

4.7	The variation in potential temperature at levels 1 and 6 at Sutro tower	53
4.8	The variation in wind direction on the Acania	55
4.9	The variation in wind direction on the Farallon Islands	56
4.10	The variation in wind direction at Pt. Reyes	57
4.11	The variation in wind speed on the Acania	58
4.12	The variation in wind speed on the Farallon Islands	59
4.13	The variation in wind speed at Pt. Reyes	60
4.14	Variation in the height of the inversion base at OAK, MRY, and VBG	62
4.15	Calculated variation in the height of the inversion base on the Farallon Islands from SODAR measurements	65
4.16	Calculated variation in the height of the inversion base on the Acania from SODAR measurements	66
4.17	Variation in altimeter difference between MRY and SMX	67
4.18	Variation in 500, 700, 850, and 1000 mb heights at OAK	70
4.19	Variation in 500, 700, 850, and 1000 mb heights at VBG	71
4.20	The variation of 850 mb heights along the western U.S. coast from Aug. 11/0000 UTC to Aug. 16/1200 UTC	73
5.1	Variation in the height of the marine layer due to mean divergence field (taken from Simon 1977).	81

LIST OF TABLES

Figure		Page
2.1	A summary of splined data	27
3.1	The Felsh/Whitlach (FW) California stratus surge (or CTD) forecast scheme	42
5.1	A summary of expected and observed changes brought on by a CTD	77

CHAPTER 1 - INTRODUCTION

1.1 BACKGROUND

Off the coast of northern California during the summer months, predominantly northerly flow is occasionally interrupted by periods of southerly flow. Dorman (1987) reported six such surges of southerly flow during the summer of 1982, each lasting from two to four days. These southerly surges, which are marked by narrow tongues of stratus on satellite imagery, hug the western side of California's coastal mountains as they move northward. Therefore, in California these alongshore surges are commonly referred to as coastal stratus surges. Since stratus surges can unexpectedly bring visibility changes and aviation hazards, they present a problem for weather forecasters.

Stratus surges start their northward movement off the coast of southern or Baja California. The limit of northward progression is normally between the San Francisco Bay area and the Oregon border, but strong surges have been observed to reach British Columbia (Mass and Albright 1987, hereafter MA87). The horizontal width of a typical stratus surge varies: surges are narrowest at the leading or northernmost edge, and increase in width toward the southern end. For one surge event, Dorman (1987) estimated a width of 40 km near southern Oregon and 200 km near Point Conception. A typical horizontal scale along the direction of motion of a stratus surge is 1000 km (Reason and Steyn 90, hereafter RS90).

Along with the onset of a stratus layer, Dorman (1985, 1987) and MA87 observed

changes in pressure, wind direction, wind speed, temperature, and inversion height at individual stations. The arrival of cool, dense marine air behind stratus surges can induce pressure increases greater than 5 mb over several hours, along with sudden temperature drops of 10° to 15° C over a period of 1 hour (MA87). Stratus surges travel north in the form of a tongue of southerly winds, so a change in wind direction from northerly to southerly is usually observed as the leading edge of the surge passes. Increases in wind speed have not been observed as frequently as wind directional changes but are sometimes observed along with gusts at the leading edge of a surge. Stratus surges are confined below the base of the semi-permanent subsidence inversion found over the eastern Pacific Ocean during summer. The dense air associated with a surge causes an increase in the height of the inversion base at local stations (Dorman 1985). Surges are also confined horizontally over the immediate coastal area as they propagate parallel to the mountainous California coastline. Therefore, changes in pressure, temperature, and winds are most easily observed at coastal stations.

Coastal stratus surges observed along the California coast are similar to coastal phenomena observed in South Africa and Australia. All these alongshore surges have similar structures and have been referred to as coastally trapped disturbances (hereafter CTDs) since they are confined within a certain distance from the coast and below the base of an elevated inversion. An overview of CTDs in all three of these areas is given by RS90.

CTDs are also found in the ocean, and occur as higher density water currents propagate along coastlines as either Kelvin waves (Gill 1982) or gravity currents, the latter being better known as ocean currents (Reason and Steyn 1992, hereafter RS92). Oceanic CTDs are confined to the coastal region horizontally by a continental boundary and vertically by the oceanic surface. It had been speculated that under suitable conditions, coastal atmospheric phenomena similar to these oceanic disturbances could occur in the atmosphere (Gill 1977, RS92). The idea that oceanic and atmospheric CTDs are similar presumes two important points: the existence of a steep or mountainous coastal topography, and the presence of an elevated inversion. A barrier-like coastal boundary would confine the atmospheric CTDs to the immediate coastal environment in a similar manner to that done by an underwater coastal boundary. The presence of an elevated inversion would serve to confine the energy of atmospheric CTDs below the base of the inversion in the same way that the oceanic surface traps oceanic CTDs, in the vertical.

Rotational effects help confine CTDs to the coastal area and determine the horizontal extent of CTDs away from the coast. Maxworthy (1982) noted the important effect of the Earth's rotation as did Gill (1982): coastally trapped Kelvin waves always travel such that the Coriolis force is directed into the coastal mountains. Therefore California's CTD travel northward with the coastline on the right. Also due to rotational effects, the horizontal scale determining the width of CTDs is given by the Rossby radius

of deformation:

$$a = (g'H)^{1/2}/f, \quad g' = g\Delta\theta/\theta$$

where g' is reduced gravity, g is the acceleration of gravity, θ is the potential temperature of the marine layer, $\Delta\theta$ is the change in potential temperature across the inversion, f is the Coriolis parameter, and H is the height of the marine layer or inversion base. Laboratory studies by Maxworthy (1982) of Kelvin waves in rotating tank experiments verified the applicability of the Rossby radius in determining the horizontal extent of these waves from a lateral boundary. When modeling CTDs, approximating the coastal mountains by an infinitely long vertical barrier is justified when the radius of curvature of the coastline is much greater than the Rossby radius (RS92).

CTDs are frequently observed in California, South Africa, and southeastern Australia because these coastal areas are able to confine the energy of CTD both horizontally and vertically. Common to all three regions is a strong subsidence inversion capping a shallow marine layer. The strong potential temperature gradients with height in these regions confines the energy of CTDs below the base of the inversion (Gill 1977, Cook 1986). All three regions also have steep coastal mountain ranges which prevent energy from penetrating inland. The base of the inversion in each area is normally lower than the height of the coastal mountains which is vital for the coastal trapping of CTDs. CTDs are therefore common during the summer months when cool ocean currents and strong subsidence from the subtropical highs help maintain an elevated inversion. In

South Africa, CTDs form on the western side of the continent and dissipate upon reaching the eastern coast. Reason and Jury (1990) explain that this dissipation is due to the absence of both a strong inversion (warmer waters) and a coastal barrier (mountains turn inland) on the Indian Ocean side.

Although CTDs in different areas have many common features, some important differences between them should be noted. CTDs are all triggered by synoptic scale ridges and troughs interacting with the coastal topography (MA87, RS90), and these interactions result in spatial variations in the height of the marine layer which proceed to propagate along the coast. The method by which these interactions lead to the generation of CTDs is not fully understood though. Dorman (1985) states the possibility of blocking of the westerly synoptic flow by California's coastal mountains as being the main forcing mechanism. In both Australia and South Africa, CTDs are preceded by the passage of synoptic scale ridges, but the resulting CTDs differ between the two locations: Australian CTDs propagate as mesoscale ridges while South African CTDs propagate as mesoscale lows. The undulations in the marine layer trigger CTDs to move along a coastal barrier, and differing interpretations of the resulting form of the marine layer flow have arisen.

CTDs, especially in California, have had various interpretations since the flow of dense marine air can resemble a Kelvin wave, a gravity current, or even both simultaneously. Fig. 1.1 (from RS90) shows the structure of a coastally trapped Kelvin wave in the southern hemisphere. Kelvin waves trapped against a coastal barrier always

Fig. 1.1 - A model of a Kelvin waveform resulting from a CTD (taken from RS90).

travel with the coastal boundary on the left in the southern hemisphere. Fig. 1.1 shows the wave-like structure of the marine layer parallel to the coastline. Another feature of these waves is their exponential decay of both the inversion displacement and alongshore velocity with distance from the coast. The amplitude of CTDs and their alongshore velocity are therefore greatest at the coast. A coastally trapped gravity current would have similar features as a Kelvin wave with the exception of the wave like structure parallel to the coast.

The distinction between a CTD resembling a Kelvin wave and one resembling a gravity current is shown in Fig. 1.2. The figure shows the variation in surface pressure at individual stations from two different CTD studies in northern California. The left side of Fig.1.2 shows pressure variations from a Kelvin wave-like CTD at 4 different coastal stations, while the right side shows similar plots, at the same stations, from a study of a gravity current-like CTD. The vertical axis in each case indicates surface pressure while the horizontal axes indicates time. While both structures show increases in pressure with the passage of a CTD, this increase is more abrupt with a the passage of a Kelvin wave. The increase in pressure for the gravity current persists for a much longer time period than the maximum triggered by the Kelvin wave disturbance. Further complicating the distinction, CTDs can also have features of both types of disturbances. RS90 explain that the inclusion of nonlinear terms in models describing CTDs can initially result in a gravity current with a nonlinear Kelvin wave component moving through and ahead of

Figure 1.2 - Pressure variations over several days from two different studies of California CTDs (Taken from RS92)

the gravity current.

1.2 LITERATURE REVIEW

To more fully understand the phenomena of CTDs, a history of pertinent studies will now be presented. The first study of CTD in the atmosphere was that of Gill (1977), who discussed the propagation of coastal lows off South Africa, and classified these lows as coastally trapped Kelvin waves. The lows propagate southward along the western coast of the continent, around the Cape of Good Hope, and northward along the eastern coast. Coastal lows are observed throughout the year and appear at local stations about once every six days. The passage of these coastal lows brings changes in the pressure and wind fields, and in the height of the inversion. The passage of a coastal low at a station is characterized by a minimum in inversion height (which is opposite to the effect of a CTD in California), and a maximum in the inversion temperature gradient. The passage is then followed by a decrease in temperature, and an increase in dew point temperature due to the arrival of cool marine air. Gill claimed that the coastal topography was steep enough so that these coastal waves could be assumed to behave as their oceanic and laboratory counterparts. This led to the use of the Rossby radius to characterize the horizontal scale of the coastal phenomena, which Gill calculated at approximately 300 km.

Using a simple nonlinear forced Kelvin wave model, Gill was able to reproduce many of the observed features of the South African coastal lows. The interaction of

synoptic scale pressure systems with the coastal escarpment was assumed as the mechanism forcing the propagation of the coastal lows or Kelvin waves. Gill's model showed a time lag to exist between the minima in the inversion height and the surface pressure at a given location. The lag in the model, approximately 1 to 1 1/2 days, had the same sign as the observed lag but was longer than the observed lag of less than a day. Gill stated that this lag was due to non-linear effects and speculated that these non-linear effects caused lows to be the prominent disturbances observed, as opposed to highs.

Ahn and Gill (1981) also presented a model to simulate the generation of the CTDs found off South Africa. Their model differed from that of Gill's (1977) by not including nonlinear effects, and by including explicit representation of the incident synoptic scale wave. The model generated two coastally moving waves, a northward and a southward propagating disturbance, with the latter wave being much stronger than the former. Ahn and Gill explained that since the southward propagating disturbance moved in the same direction as a coastally trapped Kelvin wave, its response to the synoptic scale forcing should be larger. The speed of the southward moving disturbance was altered by the existence of the northward moving model wave. The model was linear and was unable to simulate the results of Gill (1977) which showed that lows would be more prominent than highs as the generated disturbance. Ahn and Gill noted that the meridional slope of the escarpment had a significant effect on the results and might have accounted for the observed deviance of the generated wave from a Kelvin wave.

Bannon (1981) extended the work of Gill on South African CTDs by using two linear models to look at the synoptic-scale forcing of coastal lows. Bannon used both an equatorial beta-plane model and a two layer f-plane model to simulate the coastal lows. Bannon had observed that a coastal low in this region is accompanied by an inland low adjacent to it and that the two lows propagate together around the coastline. Both lows show a similar structure by being most intense at the coast and decreasing with distance from the coast. Bannon's two layer model reproduced these double waves and Bannon noted their similarity to double Kelvin waves. As with the other studies mentioned, Bannon confirmed that the width of the disturbances was slightly less than the Rossby radius of deformation. Bannon's results did confirm Gill's (1977) conclusion that non-linear terms are the cause of lows being more prominently generated than synoptic highs. Bannon also mentioned other reasons for this, one being that synoptic highs, which always precede the onset of a coastal low, increase subsidence and the strength of the inversion, making it easier for the inversion to contain the response to the forcing at the coast.

Reason and Jury (1990) summarized the work done by the aforementioned authors on South African coastal lows. They used a model to verify the similarity of the coastal lows to internal Kelvin waves. Reason and Jury also found close agreement between observed speeds of coastal lows to theoretical Kelvin wave speeds. They stated that the observation of coastal lows easily propagating around the sharp bend in the South

African coastline was consistent with both forced and unforced Kelvin waves. Reason and Jury also noted the climatological importance of the South African lows: lows occur all year round, as opposed to California and Australia where CTDs are only observed during the summer.

Reason and Jury were the first to explain why the South African CTD form as mesoscale lows instead of mesoscale ridges (ridges are observed off the California and Australian coasts). They observed that the coastal lows are always preceded by a synoptic anticyclone moving eastward and slightly south of the southern tip of the African continent. Reason and Jury observed that offshore flow, along the western coast of South Africa and at the inversion level due to the migrating anticyclone, always preceded the passage of a low. This offshore flow descends down the coastal mountains and warms adiabatically. Model results showed that with the assumption of conservation of potential vorticity of the descending offshore flow, a region of cyclonic vorticity is generated in the marine layer. Reason and Jury explained that this vorticity pattern, along with falling pressures due to the lower density of the offshore flow, results in a coastal low.

Holland and Leslie (1986) studied a common coastally trapped phenomenon in southeast Australia. The disturbance observed was similar in nature to those observed in California but was triggered differently. Holland and Leslie observed an easterly moving synoptic scale ridge approach the Great Dividing Range in southeastern Australia. This

anti-cyclone forced marine air onshore into the dividing range. A mesoscale ridge then formed on the southern tip of the dividing range and was ducted around to its eastern side. The resulting flow propagated northward along the coast and the eastern side of the Dividing Range.

Consistent with other CTDs, Holland and Leslie observed a maximum amplitude at the coast with exponential decay out to sea. The horizontal extent was observed as less than 500 km, in agreement with the Rossby radius. Holland and Leslie observed sudden pressure rises of up to 10 mb with the passage of the observed disturbance. They modeled the Australian disturbance and analyzed it as having both Kelvin wave and gravity current type characteristics.

The first study of a California stratus surge was done by Dorman (1985). He interpreted one surge event as a Kelvin wave similar to that noted by Gill (1977). Dorman observed a lifting of the marine layer/inversion following the eastward passage of a synoptic disturbance over California's coastal mountains. According to Dorman, the forced lifting of the inversion caused an internal solitary Kelvin wave to progress northward in geostrophic balance, as the pressure gradient force normal to the coastal mountains equaled the Coriolis force produced by the southerly flow. The observed marine layer disturbance (or wave) was highest at the coast and decreased offshore, similar to the structure of the Kelvin wave observed by Gill (1977). Dorman used a model based on Gill (1982) and found good agreement between his results and those of

Gill (1977). An important difference between these two studies though is that the southern California disturbance appeared as a ridge of high pressure as opposed to a coastal low. Also, the coastal low Kelvin wave observed by Gill traveled around the Cape of Good Hope quite easily, while the Kelvin wave observed by Dorman was unable to move beyond any sharp bend in the coastline.

Dorman raised some unexpected questions about the propagation of CTDs along the California coastline. The first question concerned the observed decrease in wave amplitude as it moved north. The second question was why the wave progression was observed to stop at the sharp coastal bend at Cape Mendocino where two coastal eddies formed as a result: one off Point Arena and a smaller one off Cape Mendocino. Dorman's last question dealt with the dynamics causing the observed eddies to form as a result of the cessation in wave propagation. Some of these issues were later resolved by Reason and Steyn (1987, 1992).

Dorman (1987) noted that during the summer of 1982, northerly winds along the California coastal region were interrupted by a total of six coastal stratus surges. One of these events is the same disturbance analyzed as a Kelvin wave by Dorman (1985). Dorman interpreted four of the five remaining events as gravity current phenomena. An important reason for the gravity current classification was the fact that the surges did not progress up the coast at a steady pace. A gravity current requires a constant input of denser air in order to flow (Simpson 1987) so fluctuations in the synoptic scale forcing

near southern California might account for the variations in propagation speed. On the other hand, the speed of a Kelvin wave would be more consistent despite any changes in the initial forcing mechanism. Dorman explained that the passage of a synoptic scale trough over southern California caused convergence in the marine layer, initiating one of the surge events. This led to a deeper marine layer which acted as the mass reservoir that caused a gravity current to flow northward. Dorman observed that the marine layer in southern California remained lifted throughout the surge period of three days. As the gravity current moved northward, Dorman observed that this elevated (and level) marine layer extended all the way up to the southern Oregon coast. Dorman cited the absence of perturbations in the inversion base (other than the main one) in forming his gravity current hypothesis.

MA87 examined two cases of along shore surges of coastal stratus, one being the same case studied by Dorman (1985). MA87 did not explain these events as being caused by coastal blocking but rather as simple ageostrophic flow due to a readjustment of the synoptic scale pressure gradient. They observed the same surface pressure gradient as Dorman (1985): higher surface pressure to the south due to a synoptically lifted inversion, and lower surface pressure to the north associated with a lower inversion and a shifting of the normal synoptic pressure pattern. According to MA87, the observed alongshore flow was simply a readjustment of the mass field (i.e., ageostrophic flow) from higher to lower pressure.

MA87 claimed that southerly geostrophic balance was impossible alongshore within the Rossby radius, but that geostrophic balance was possible for opposing northerly flow with the across shore pressure gradient (higher pressure offshore, lower pressure onshore). The resulting flow was therefore a superimposition of oppositely directed ageostrophic and geostrophic flows. Variations in the strength of the southerly surges were observed by MA87, weaker during the day and stronger at night. This was explained by the variation in the opposing northerly geostrophic flow, which strengthens during the day as inland heating strengthens the across shore pressure gradient.

MA87 disagreed with previous interpretations of California and South African CTDs as Kelvin waves. MA87 noticed many of the characteristics of gravity currents in the observed wind and pressure fields, along with a lack of perturbations in those fields. These gravity current characteristics consisted of: gradual changes in the observed parameters, as opposed to abrupt changes associated with Kelvin waves; agreement with the theoretically calculated gravity current speed; and confinement of the observed disturbance to the lowest 150 mb of the troposphere. MA87 stated that the observed CTD did not start out as a gravity current, but that the CTD was simply due to ageostrophic adjustment of the alongshore pressure gradient, and that with time the CTD resembled a coastally trapped gravity current. Although MA87 did notice the existence of perturbations on the inversion interface, these were interpreted as gravity waves. Such waves moving ahead of and atop a gravity current were shown by Simpson (1987) to be

common phenomena.

RS90 discussed all the aforementioned CTDs. They showed the fundamental dynamics in each case to be governed by the hydrostatic and semi-geostrophic equations. After simplification of the equations by scale analysis, RS90 showed that the alongshore velocity of a coastally trapped disturbance would be in approximate geostrophic balance with the across shore pressure gradient. The across shore flow was shown to not be in geostrophic balance with the alongshore pressure gradient. RS90 assumed that the across shore velocity could be neglected everywhere since blocking by the coastal mountains was assumed as the generating mechanism behind CTDs. Neglecting nonlinear terms in the equations, RS90 then found two possible solutions resulting from different boundary conditions: a Kelvin wave solution, and a gravity current solution. RS90 went on to assume that the zonal or across shore flow could only be neglected at the coast since this was more realistic than neglecting it everywhere within the width of a CTD. They also included forcing at the coast by the synoptic scale flow. The revised equations led to important results about the type of coastal disturbance that would result from synoptic forcing.

RS90 showed that for both the linear and nonlinear cases, synoptic forcing leading to initially onshore flow would result in the formation of a mesoscale ridge. They observed that onshore flow is initially forced in the California and Australian CTD cases. RS90 explained that convergence of marine air due to the onshore flow causes ascending

vertical motions that result in the formation of a mesoscale ridge or an increase in the inversion base height for both California and Australia (recall that Reason and Jury (1990) had previously explained the opposite effect of coastal lows forming due to offshore flow preceding the passage of CTDs in South Africa).

RS90 used observations from Dorman (1985, 1987), Holland and Leslie (1986), and Reason and Jury (1990) to estimate the Rossby (Ro) and Froude (Fr) numbers for California, Australia, and South Africa. The initial blocking by the coastal mountains is strong when $Fr < 1$. The persistence of this coastal blocking is indicated by the value of Ro/Fr . When $Ro/Fr < 1$, blocking will not persist and quasi-geostrophic theory becomes valid in describing the dynamics of a coastally trapped flow. RS90 calculated values of 1.3 and 0.21 for Ro and Fr respectively for a California case, leading to a value of 6.19 for Ro/Fr . These values were much higher than the values calculated for the South African and Australian cases. Therefore, RS90 concluded that the dynamics of the California CTD would not be quasi-geostrophic, and that blocking of the incident flow by the coastal topography would persist longer compared to other areas. This explained why CTD would exhibit more complex and nonlinear forms in California. Rossby and Froude numbers for CTD in the South Africa region were calculated as 0.1 and 0.33, respectively, and according to RS90, this would explain the consistent, semi-geostrophic nature of the South African coastal low.

RS92 expanded the work of RS90 by developing a more general theory of CTDs

in California and Australia. To explain the different interpretations of the coastal surges by Dorman (1985, 1987) and MA87, RS92 cited an insufficient resolution in the observations and a lack of a suitable theoretical framework. RS92 focused on a solution of the latter problem. A nonlinear theory was developed that included the possibility of both Kelvin waves and gravity currents, and also explained other features of coastal ridges which had not been explained by previous studies.

RS92 showed all previous and conflicting explanations of California's CTD to be viable and to fit into their more general theoretical framework. For example, Dorman (1985) had labeled one event as a solitary Kelvin wave, an interpretation which was later disputed by MA87 as being unreasonable. MA87 explained that a Kelvin wave could not have resulted in this case if the propagation was controlled by changes on the synoptic scale. RS92 explained that both interpretations were correct. Their theory showed MA87 to be correct if the Kelvin wave was specified as a linear Kelvin wave. They continued to explain that a nonlinear Kelvin wave could result from synoptic forcing, and that this wave could propagate as either a nonlinear solitary Kelvin wave or a shock Kelvin wave (which appears similar to a gravity current). According to RS92, a shock Kelvin wave would develop if alongshore winds existed near the leading edge of the disturbance, while a nonlinear solitary Kelvin wave would result if across shore winds preceded the flow. RS92 applied their model to CTDs previously studied by Holland and Leslie (1986), Dorman (1985, 1987), and MA87. They found observed propagation speeds and time

scales of CTDs to agree with those predicted by their model.

RS92 incorporated nonlinear and dispersive effects into their theoretical framework to explain the California and Australian CTDs. This, along with the results of Reason and Steyn (1988), allowed them to explain the occasional inability of surges to propagate past convex bends in the coastal topography (as observed by Dorman (1985) and Holland and Leslie (1986)). The explanation involves a linear theory of Kelvin wave diffraction, and states that for a convex bend in the coastline a critical angle for the bend determines whether or not a wave will propagate past the bend. The decaying amplitude of CTD was also modeled by the incorporation of dissipative effects which simulated gaps in the coastal mountains, and again an agreement was found between the model and observations.

Felsch and Whitlach (1993, hereafter FW) devised a forecast scheme to predict the onset of stratus surges along the central California coast. They looked for synoptic patterns prior to stratus surges similar to those observed by Dorman (1985, 1987) and Mass and Albright (1986): ridging off the Pacific Northwest and troughing over the southern California coast. FW also mentioned the westward movement of the California heat trough (an axis of low pressure arising from diabatic heating and normally found aligned along the central valley) prior to a surge as being a common occurrence prior to a stratus surge. The forecast scheme was structured as a simple decision tree, and initialized by observations from satellite imagery of the coastal area. Two important

parameters used in addition to the satellite observations were measurements of the Oakland 850 mb temperature and the San Francisco to Santa Maria pressure gradient, both at 0000 UTC. The Oakland measurement was used to indicate the strength of the inversion, temperatures lower than 9.8°C indicating a weak inversion and a low surge probability. A San Francisco to Santa Maria pressure gradient of less than -0.2 mb (negative values indicate a higher pressure at Santa Maria) showed a strong correlation to the onset of a stratus surge. The methods of the forecast model resulted in a 74% accuracy when applied to actual surge events, and were 80% accurate when used to predict non-surge events. FW also observed that all the surges studied began during the nighttime hours which is consistent with the explanation of MA87 that surges are strongest during the nighttime hours.

1.3 PURPOSE OF PRESENT STUDY

This study will analyze the possible onset of a CTD in California on August 14, 1978. Observations from stations will be analyzed to document the passage of the surge. The analysis will include hourly changes in pressure, temperature, and wind parameters. Upper air soundings and SODAR data will be used to evaluate changes in the height of the subsidence inversion at individual stations. This study will focus on coastal stations and those close enough to the coast to document a stratus surge passage. The primary data source is the MABLES WC field experiments which ran from July 31 to August 17, 1978.

CHAPTER 2 - DATA

2.1 DATA SOURCE

The primary data source for this study is the Marine Atmospheric Boundary Layer Experiments West Coast (MABLES WC, henceforth MABLES). MABLES ran from July 31 to August 17, 1978 and its main purpose was to gather data at a mesoscale resolution relating to the elevated inversion and associated marine layer found off the coast of northern California during the summer months. Stations providing data for this study, both within and outside of the MABLES study area, are shown in Fig. 2.1. Details of MABLES are given in Lester (1979).

MABLES comprised three observational networks: a primary, secondary, and tertiary network. The primary network consisted of various types of meteorological observations from various sources set up specifically for MABLES. The secondary network consisted of conventional surface and upper air stations. The tertiary network was comprised of automatic surface stations along with voluntary observers. The data and observations from MABLES which were chosen for use in this study comes from stations potentially able to verify the possible onset of a stratus surge or CTD: specifically coastal stations and those within a few kilometers, either inland or offshore, from the coast.

Data used in this study from the primary network was provided by automated instrumentation on Mt. Sutro tower, surface observations and SODAR measurements

Figure 2.1 - Stations providing data for present study

from both the Farallon Islands and the Research Vessel Acania (henceforth Acania), and rawinsonde data at Monterey. The Acania was not stationary as it traveled along the dashed line indicated in Fig. 2.1 through the MABLES period, but it did remain close to the eastern end of this line during the possible surge period. Figure 2.2 shows a schematic diagram of Mt. Sutro tower, which is located in the city of San Francisco. The base of Sutro tower is located at a height of 254.2 m above sea level. Data from Sutro tower was taken at 6 different levels: 259, 298, 341, 388, 432, and 472 meters above sea level. On the average, the lowest two levels are usually within the marine layer while the upper 4 levels are normally above the base of the elevated inversion (Miller 1975). Data from the secondary network used here includes: Oakland (OAK) rawinsonde data, and surface weather observations at the San Francisco International (SFO) airport. Tertiary network data used consists of wind observations at Pt. Reyes.

Data from outside the MABLES WC study area includes rawinsonde measurements taken twice daily at 00 and 12 UTC at the following locations: San Diego (SAN) and Vandenburg (VBG), CA; Medford (MFR) and Salem (SLE), OR; Quillayute (UIL), WA; and Port Hardy (YZT), British Columbia. Surface weather observations at Santa Maria (SMX), CA were also used.

Most of the data used in this study comes directly from hourly measurements taken during MABLES. The only exception to this was the upper air data, which was taken twice daily and three times daily at Monterey (MRY) on Aug. 14 and 15. Upper air

Figure 2.2 - Schematic diagram of Mt. Sutro tower and outline of the west to east topography of San Francisco (taken from Lester 1979).

data was used to indirectly calculate the height of the marine layer; using the measured values of the 1000, 850, 700, and 500 mb heights from radiosonde/rawinsonde data and integrating hydrostatically, the height of the inversion base was then estimated.

2.2 MISSING DATA

All of the MABLES data sets used contain missing data points. In some cases the number of missing data points was greater than 25% of the total (missing + actual) number of points, while the remaining data sets had approximately 5% or less of the total data points missing. The former data sets were left as is and are displayed graphically with "*" symbols. For the latter data sets, a cubic spline approximation program was written to interpolate the missing data points. Table 2.1 shows the data sets to which the cubic spline approximation was applied. As an example, the first line of the table shows that both Sutro tower pressure and temperature data had two gaps of missing data points within a 315 point domain. The first gap spans 11 missing points and the second gap covers 7 missing points.

A cubic spline approximation interpolates the value of a function at any desired point in the domain while maintaining continuity of both the first and second derivatives of that function. The cubic spline method therefore avoids interpolation of missing data points by simply oscillating back and forth across the actual value, a problem inherent in other higher order interpolation schemes. One limitation of the spline method (or any

SITE	DATA	DOMAIN SIZE (# OF POINTS)	SIZE OF GAPS
Sutro Tower:	pressure, temp.	315	11, 7
Sutro Tower:	winds (u & v)	152	7
Farallons	pressure	142	1, 1
Farallons	temperature	142	1
Acania	pressure	180	4, 1, 1, 2, 1
Acania	temperature	180	1, 2, 1
Acania	winds (u & v)	180	1, 1, 1, 2, 2, 1

Table 2.1 - A summary of splined data

other interpolation scheme) is its inability to detect any wave smaller than the size of the gap it is interpolating.

Fig. 2.3 shows an example of a cubic spline fit. A continuous interval of 100 data points was chosen from Sutro tower (level 2) temperatures and is shown in the top graph of Fig. 2.3. After the removal of 5 arbitrary points from the center of the domain (points # 48 through 52), the cubic spline program was used to approximate the missing points. The size of this gap (5 % of the total number) was chosen since it is similar in size to the gaps shown in Table 2.1. The results are shown at the bottom of Fig. 2.3. The splined curve has a smoother curvature than the actual curve. Also, the position of the interpolated maximum occurs slightly sooner than the actual maximum. Overall, the routine looks good.

Figure 2.3 - An example of a cubic spline approximation

CHAPTER 3 - SYNOPTIC DESCRIPTION

3.1 UPPER AIR/SURFACE MAPS

The synoptic situation during the first 10 days of August, 1978 was typical of California during summer as an upper level anticyclone persisted over or near California (Lester 1979). During the last few days of the study period, atypical conditions occurred as two upper level troughs passed through the study area. It is between the passing of these two troughs that a CTD possibly progressed along the California coastline.

Fig. 3.1 shows the 500 mb charts and Fig. 3.2 shows the surface pressure charts throughout the MABLES study period. In the beginning of the period, the area was dominated by an anticyclone at 500 mb, centered just off the coast to the west of the SFBA. It slowly drifted eastward during the first 5 days of August but retreated westward while continuing to dominate the Pacific states until August 10. Throughout most of this period, the California heat trough was well defined. The axis of the heat trough was not as well defined and readjusted itself on the 9th and 10th as a weak upper level trough passed well north of the study area.

On the 11th of August the upper level high moved southeast and 500 mb heights began to fall as a trough at the 500 mb level approached California from the northwest. The anticyclone that had dominated the region for the previous eleven days continued to move eastward. The axis of this first upper level trough to pass over the SFBA did so a few hours after 0000 UTC on the 13th. Heights at 500 mb then began to slowly rise on

Figure 3.1 - 500 mb for charts at 00 UTC during MABLES, August 1 - 4, 1978.

Figure 3.1(cont.) - 500 mb for charts at 00 UTC during MABLES, Aug. 5 - 8, 1978.

Figure 3.1(cont.) - 500 mb for charts at 00 UTC during MABLES, Aug. 9 - 12, 1978.

Figure 3.1(cont.) - 500 mb for charts at 00 UTC during MABLES, Aug. 13 - 16, 1978.

Figure 3.2 - Surface pressure charts at 00 UTC during MABLES, August 1- 4, 1978.

Figure 3.2 (cont.) - Surface pressure charts at 00 UTC during MABLES, Aug. 5 - 8, 1978.

Figure 3.2 (cont.) - Surface pressure charts at 00 UTC during MABLES, Aug. 9 - 13, 1978.

Figure 3.2 (cont.) - Surface pressure charts at 00 UTC during MABLES, Aug. 14 - 17, 1978.

the 14th and through the 15th before the passage of a second upper trough over the study area during the 16th.

3.2 SATELLITE IMAGERY

Visible satellite imagery between August 13 and 16, 1978 is shown in Fig. 3.3 at 00 UTC. The black square on each image outlines the MABLES study area. Fig. 3.3 shows that by 00 UTC on the 14th, the coastal area was completely clear of any stratus clouds northward from Point Conception. The propagation of CTD along California's coastline is only evident on days which follow coastally clear days such as the 14th. On the 15th, a wedge shaped stratus layer was present adjacent to central California and extended northward into the MABLES study area. The stratus layer on the 15th was clearly narrower near the northern edge and increased in width (or distance from the coast) toward the south, a feature common to CTD. Inspection of the satellite imagery therefore prompted investigation of the return of coastal stratus by Aug. 15 as a possible CTD.

3.3 APPLICATION OF A CTD FORECAST SCHEME

FW devised a forecast scheme to predict the onset of a coastal stratus surge or CTD along the California coast. Their forecast procedure will be applied to the MABLES data to see if a stratus surge would have been predicted between Aug. 14 0000

Aug. 13 0000 UTC

Aug. 14 0000 UTC

Figure 3.3 - Visible satellite imagery for western North America from Aug. 13 - 14, 1978.

Aug. 5 0001 UTC

Aug. 16 0000 UTC

Figure 3.3 (cont.) - Visible satellite imagery for western North America from Aug. 15 - 16, 1978.

CALIFORNIA CTD FORECAST CRITERION	MET BY PRESENT STUDY?
STRATUS FREE ZONE ADJACENT TO CENTRAL CALIFORNIA	YES
NO CUMULUS WEST OF THE STRATUS FREE ZONE	YES
STRATUS FREE ZONE MUST END NORTH OF MEXICAN BORDER	YES
OAKLAND'S 850 MB TEMPERATURE GREATER THAN 9.8 °C	YES
SANTA MARIA SFC. PRESSURE HIGHER THAN SAN FRANCISCO SFC. PRESSURE BY AT LEAST 0.2 MB	NO

Table 3.1 - Elements involved in the FW California stratus surge (or CTD) forecast scheme

UTC and Aug. 15 0000 UTC.

The forecast scheme of FW is in a flowchart form and requires that all criteria be met to forecast a CTD. There are 5 criteria as shown in Table 3.1, of which the first three are subjective and the last two objective. The first three are subjective as they involve inspection of visible satellite imagery. They are as follows: 1) a stratus free zone at least 120 nautical miles (nm) alongshore and 60 nm offshore must exist adjacent to central California; 2) A second zone, adjacent to and west of the stratus free zone and extending close to 250 nm offshore, must be free of any cold air cumulus clouds; and 3) the stratus zone must not extend south of the Mexican border. Fig 3.3 shows that all three of these criteria were met on August 14, 00 UTC.

Upon passage of these subjective criteria, two objective screening criteria must be met in order for the FW forecast scheme to predict a California CTD. The objective screening criteria developed by FW are as follows: 1) The 0000 UTC upper air data on the day in question must show OAK's 850 mb temperature to be higher than 9.8°C ; and 2) the 0000 UTC pressure difference between SFO and SMX must be less than -0.2 mb (a negative value meaning the pressure at SFO must be lower than at SMX). Inspection of 0000 UTC data for Aug. 14 showed the OAK 850 mb temperature to be 15°C and the SFO-SMX pressure difference to be 0.0 mb. The second of these criteria was therefore not met and FW would not have predicted a stratus surge to occur on Aug. 14.

CHAPTER 4 - ANALYSIS

4.1 OUTLINE

Observations will now be discussed to evaluate the possible passage of a CTD along the central California coast on August 14, 1978. The analysis will include hourly changes in pressure, temperature, and wind parameters. The following changes will be looked for at individual stations: a sustained (several hours or longer) increase in surface pressure and decrease in surface temperature, along with a wind shift to southerly and changes in wind speed. Upper air soundings and SODAR data will be used to evaluate changes in the height of the subsidence inversion at individual stations since CTDs tend to lift the base of the elevated inversion as they propagate. Variations in the height of the 850 mb surface along the entire west coast of the U.S., along with the surface pressure gradient along the California coast, will also be presented to investigate the possibility of a reversal in the normal surface pressure gradient along the coastline.

4.2 PRESSURE

The variation in pressure measured on the Acania, at the Farallon Islands, and at Sutro tower throughout the MABLES period is shown in Figs 4.1, 4.2, and 4.3 respectively. Note that the vertical axis has been reversed for the Sutro Tower graph. During the period Aug. 3 - 8, the pressure profile did not vary greatly from day to day. Some noticeable features on all three figures includes a general minimum during the

Figure 4.1 - The variation in surface pressure on the Acania

Figure 4.2 - The variation in surface pressure on the Farallon Islands

Figure 4.3 - The variation in pressure at Sutro tower

period 9-11 Aug., followed by a sharp rise and maximum on the 13th, and a second but smaller maximum on the 16th. The minima observed on the 9th-11th occur while surface fronts passed well to the north of the SFBA. A readjustment of the California heat trough resulting in a trough extending into the area from the northeast can be seen on the surface maps for these days in Fig. 3.2. On the 13th, both the Farallons and the Acania along with all 6 levels at Sutro Tower, show a well defined maximum in pressure. This maximum appears similar to that associated with a Kelvin wave type CTD, but occurs too early to be due to the arrival of a CTD on the 14th. This maximum does coincide with the passage of the first upper level trough (Aug.13) through the SFBA during the MABLES period.

The trough passage on Aug. 13 explains the existence of the pressure maximum. An upper level trough can advect cooler air which will lower the thickness between the 500 mb and 1000 mb layers. Under hydrostatic situations, the pressure at the surface will then increase. Trough passage at upper levels can also lift and weaken the inversion. An increase in inversion height above the lifting condensation level enhances the formation of stratus clouds and deepens the marine layer. Surface pressure can then increase at a given station under the influence of the cool, dense marine air. A surface pressure maximum is therefore observed during the passage of the upper level trough.

On the possible stratus surge day of the 14th, no significant pressure increase is observed at any of the three stations. What does occur on the 14th is a return to the

pressure signature seen early in the period, after which another but smaller (compared to the maximum on the 13th) maximum occurs on the 16th. This second maximum is concurrent with the passage of a second upper level trough and associated surface front. Trough passage again causes an increase in surface pressure similar to that seen on the 13th.

4.3 TEMPERATURE

When looking for evidence of a CTD, one would expect to see a sudden decrease in surface temperature which remains for at least several hours. Hourly temperature variations from both the Acania and Farallons, which are shown in Figs. 4.4 and 4.5, show a lack of a persistent decrease in temperature on the possible surge day of Aug. 14th. A sudden and sharp drop does exist on this day, but this minimum is very short in duration. As the minimum on the 14th is similar to other temperature minima throughout the period, it is unlikely to be due to a CTD.

Temperature and potential temperature profiles for Sutro tower are shown in Figs. 4.6 and 4.7 (only levels 1 and 6 are shown for clarity). These figures show all 6 levels of Sutro Tower to be under the inversion base (or within the marine layer) from approximately Aug. 12/1200 UTC until 0000 UTC on the 14th. Fig. 4.6 shows all tower levels to be within a quasi-isothermal layer while Fig. 4.7 shows all levels to be in a quasi-neutral stable layer during this time. This layer is deep since all 6 levels are under

Figure 4.4 - The variation in surface temperature on the Acania

Figure 4.5 - The variation in surface temperature on the Farallon Islands

Figure 4.6 - The variation in temperature at Sutro tower at levels 1 and 6

Figure 4.7 - The variation in potential temperature at levels 1 and 6 of Sutro tower

its influence (see Fig. 2.2), and it also coincides with the passage of the upper level trough on the 13th and associated surface pressure maximum discussed earlier. These two features are temperature signatures that could signal the onset of a CTD but occur too early to indicate a CTD during the latter hours of the 14th.

4.4 WIND DIRECTION

A northward propagating CTD off the California coast would bring with it a reversal in wind direction at coastal stations. In the SFBA, this would mean a reversal from the predominantly northerly winds to southerly or southeasterly. Wind direction profiles throughout the MABLES period on the Acania, on the Farallons, and at Pt. Reyes are shown in Figs. 4.8, 4.9, and 4.10, respectively. The possible stratus surge day of Aug. 14 does show a reversal to southerly winds during the middle of the day. The reversal is brief and might be easily explained as being due to non CTD phenomena since there are other occurrences of southerly winds throughout the MABLES period both on the Acania and at Pt. Reyes. Occurrence of southerly winds on the Farallons is almost non-existent as only one hourly report on the 14th showed southerlies present.

4.5 WIND SPEED

Wind speed variations are shown in Figs. 4.11, 4.12, and 4.13. All four stations show stronger than average winds speeds at the beginning of the 14th with a sudden drop

Figure 4.8 - The variation in wind direction on the Acania

Figure 4.9 - The variation in wind direction on the Farallon Islands

Figure 4.10 - The variation in wind direction at Pt. Reyes

Figure 4.11 - The variation in wind speed on the Acania

Figure 4.12 - The variation in wind speed on the Farallon Islands

Figure 4.13 - The variation in wind speed at Pt Reyes

around 1000 UTC. The best example of this is on the Acania: winds peaked at 22 knots at 0400 UTC and dropped to 2 knots just eight hours later. This minimum in wind speed observed at the 3 stations late in 14th occurs at the same time as the aforementioned change in wind direction to southerly. A drop in observed wind speed could result from a coastal stratus surge, as Dorman (1985) found strong northerlies replaced by weak southerlies with the passage of a CTD. This would agree with the results found here if a coastally trapped disturbance was present on the 14th. Alternatively, MA87 found wind speed increases in California following the passage of a strong CTD.

4.6 INVERSION HEIGHT

CTDs along the California coast propagate northward as mesoscale ridges which tend to lift the elevated inversion along their path. The propagation of a CTD would therefore be indicated by a maximum in inversion height at coastal stations with the southernmost stations observing a lifted inversion before stations further north.

Inversion base heights for VBG, MRY, and OAK were estimated for days with available data. The results are shown in Fig. 4.14. At OAK, a maximum clearly occurs at 00 UTC on the 13th, and a maximum at MRY occurs but 18 hours later. A weak inversion height maximum also occurs on the 13th at VBG and remains until 00 UTC on the 14th. Also evident is the lower amplitude in the VBG maximum when compared to both OAK and MRY.

Figure 4.14 - Variation in the height of the inversion base at OAK, MRY, and VBG

There are several arguments against attributing the maxima in inversion height to the passage of a CTD. First, OAK's maximum at 00 UTC on the 13th occurs too early to be due to a CTD on the 14th. The occurrence of this maximum coincides with the passage of an upper level trough and maximum in surface pressure discussed in section 4.2 and can therefore be explained as simple lifting of the inversion due to the trough passage. Another reason against the CTD explanation is the approximate simultaneous occurrence of all three maxima. MRY's maxima even occurs later than OAK's, opposite to the effect expected from the passage of a CTD. One would also expect a CTD to lift the inversion to an equal or greater extent at the southernmost station (VBG) when compared to the two stations further north, which clearly did not occur.

There is some evidence supporting the passage of a CTD between Aug.14 00 UTC and Aug.15 00 UTC, which is the appropriate time period indicated by the satellite imagery. The maximum in inversion base heights observed at VBG on the 13th does remain until the 14th. At the same time the inversion base height at both OAK and MRY falls sharply at 00 UTC on the 14th. These conditions, a higher than normal inversion base at VBG with lower inversion heights further north, agree with observed conditions for the formation of CTDs. This abnormal height difference does occur around 12 hours before the observed wind shift to southerly at Pt. Reyes and on the Acania mentioned earlier. Dorman (1985) found a lifted inversion at VBG due to a CTD occurring approximately 24 hours before a lifted inversion at OAK. If a CTD did propagate along

California on the 14th, it would have been very weak and limited in northerly extent. The reason is that additional maxima at MRY and OAK should have occurred late during the 14th or early on the 15th. Clearly this did not occur: instead the inversion base at both stations dropped to very low levels.

Further information on the height of the inversion base were obtained from SODAR instrumentation on the Acacia and Farallons Islands. Details of the SODAR observations taken during MABLES are given in King (1980). Figures 4.15 and 4.16 show these variations. Complete measurements of the inversion height during the period were not possible due to bad data, noise, and ground based sheared layers. This is most evident with the SODAR measurements on the Farallons where data for most of the hours on the 13th are missing. Both SODAR figures are inconclusive as to the passage of a CTD on the 14th.

4.7 PRESSURE GRADIENT

The triggering of a CTD along California is due to synoptic disturbances which lift the inversion near southern California and reverse the normal surface pressure gradient along the coast. Both Dorman (1985) and MA87 found the normal pattern of higher pressure in northern California with lower pressure in southern California reversed during the passage of CTD's along California's coastline. This is also the reason for FW's criterion of SMX's sea level pressure being at least 0.2 mb higher than that at SFO to

Figure 4.15 - Calculated variation in the height of the inversion base on the Acania from SODAR measurements

Figure 4.16 - Calculated variation in the height of the inversion base on the Farallon Islands from SODAR measurements.

Figure 4.17 - Variation in altimeter difference between MRY and SMX

forecast the occurrence of a California CTD.

Figure 4.17 shows the altimeter difference between MRY and SMX. Altimeter readings are used as a substitute for sea level pressure due to the unavailability of sea level pressure measurements at these locations. Higher altimeter readings at SMX are indicated by negative values. The 14th of August did show the occurrence of higher altimeter readings at SMX which would indicate the proper pressure gradient for the occurrence of a CTD on this day. Most of the negative values on this day have a magnitude of -0.02 " Hg. This converts to 0.7 mb which is greater than the minimum value of 0.2 mb required by the FW scheme of forecasting CTD's in California. Dorman (1985) found a pressure difference maximum close to 1 mb over a horizontal distance similar to that between MRY and SMX. It is inconclusive whether our measured altimeter difference is great enough to trigger the northward movement of a CTD. Also, there is error involved in the use of the altimeter readings and converting this number to a pressure in millibars. The approximate length of time this altimeter difference reaches -0.2 " Hg is close to 10 hours which is similar to the length of time observed by Dorman (1985) of a greater pressure near southern California.

4.8 UPPER AIR

Figures 4.18 and 4.19 show the variation in the heights of the 1000, 850, 700, and 500 mb levels for OAK and VBG. A higher than normal 1000 mb height is evident on the 13th and 14th at both locations, and results from a deepening of the marine layer due to the upper level trough passage. The lowering of the upper levels between the 13th and 14th is due to the same upper level trough. The maxima in 1000 mb heights occurs too early to be the result of a CTD. Even though these maxima do extend into the possible CTD day of the 14th at both locations, the maximum at VBG would be expected to occur earlier than the maximum at OAK. Instead, the two maxima occur around the same time. These maxima during the 13th and 14th do show higher 1000 mb heights (or surface pressure) at VBG which would help support the theory of a CTD passage. The difference in 1000 mb heights was never greater than 10 gpm on these two days. Therefore only a very weak (if any) CTD would be suggested by Figs. 4.18 and 4.19.

A common upper level synoptic condition for the propagation of a CTD along the California coast is higher than normal heights in the Pacific northwest and lower than normal heights in southern California. In a case study of a very strong CTD, MA87 (their Fig. 17) not only show a deviance from normal, but also a reversal in the alongshore 850 mb height gradient extending from San Diego to Port Hardy on Vancouver Island, i.e., higher than normal 850 mb heights in the northwest and lower than normal 850 mb heights near southern California. A similar figure to the one

Figure 4.18 - Variation in 500, 700, 850, and 1000 mb heights at OAK

Figure 4.19 - Variation in 500, 700, 850, and 1000 mb heights at VBG

presented by MA87 is shown in Fig. 4.20.

Figure 4.20 shows the height of the 850 mb surface along the coast as it would appear looking east: San Diego is on the extreme right (SAN) and Port Hardy, Vancouver Island (YZT) on the extreme left. The stations in between are Quillayute, Washington (UIL); Salem (SLE) and Medford (MFR), Oregon. Only the variation between the Aug. 11 00 UTC and Aug. 16 12 UTC is shown. The typical or normal height gradient appears on most of the plots shown: higher 850 heights to the south and lower heights to the north. On the possible CTD day of Aug. 14 there is a deviation from the normal gradient: heights have risen slightly in Oregon and Washington while staying the same in California. This would constitute support for the presence of a CTD on this day, although the change is not very large in magnitude.

Figure 4.20 - The variation of 850 mb heights along the western U.S. coast from Aug. 11/00 UTC to Aug. 12/12 UTC

Figure 4.20 (cont.) - The variation of 850 mb heights along the western U.S. coast from Aug. 13/00 UTC to Aug. 14/12 UTC

Figure 4.20 (cont.) - The variation of 850 mb heights along the western U.S. coast from Aug. 15/00 UTC to Aug. 16/12 UTC

CHAPTER 5 - CONCLUSIONS

5.1 DISCUSSION

Data from the MABLES WC study period of July 31 - August 17 has been examined to determine if the reappearance of stratus in the SFBA during August 14, 1978 was due to a coastally trapped disturbance (CTD, a northward propagation of stratus along the coastline from southern California to northern California). Visible satellite imagery showed a stratus free region on August 14 0000 UTC, followed by the appearance of a wedge-shaped area of stratus 24 hours later extending from Pt. Concepcion to just north of the SFBA.

Previous studies of CTD's along California's coastline have shown certain properties to be common in most of these disturbances (Dorman 1985, MA87, FW). These properties are listed in Table 5.1. Also shown in Table 5.1 is a summary of the results of the present study.

Investigation of the surface pressure variation at three locations through the study period failed to show the expected surface pressure maximum on August 14. Surface temperatures did show a sudden drop at three locations, but this minimum was brief and would therefore not suggest the existence of a CTD. CTD's along California's coastline normally result in a shift in wind direction from northerly to southerly. There is evidence of such a wind shift late during Aug. 14, but again this wind shift was very brief.

PARAMETER	EXPECTED COASTAL OBSERVATIONS	OBSERVATION IN PRESENT STUDY
SURFACE PRESSURE	SUSTAINED INCREASE	BRIEF INCREASE AT WRONG TIME
SURFACE TEMPERATURE	SUSTAINED DECREASE	BRIEF DECREASE, MAY BE ATTRIBUTABLE TO DIURNAL CYCLE
WIND DIRECTION	SHIFT TO SOUTHERLY	SHIFT TO SOUTHERLY, SOUTHEASTERLY
WIND SPEED	VARIES: WEAK OR STRONG SOUTHERLIES	WEAK SOUTHERLIES
INVERSION HEIGHT	A MAXIMUM WHICH MOVES NORTHWARD	LIFTED INVERSION AT WRONG TIME & NOT PROPAGATING NORTH
SURFACE PRESSURE GRADIENT	FROM SOUTH TO NORTH	PROPER GRADIENT OBSERVED (USING ALTIMETER DIFFERENCE)

Table 5.1 - A summary of expected and observed changes brought on by a possible CTD.

Observations of CTD-induced changes in wind speed have shown a range of possibilities, with weaker CTD's bringing weak southerlies (Dorman 1985), and stronger CTD's resulting in strong and gusting southerlies (MA87). There is evidence of a drop in wind speed between Aug. 14 1200 UTC and Aug. 15 0000 UTC. While CTD's raise the height of the marine layer and overlying inversion base, observed lifting of the inversion during the study period occurs too early to be attributable to a CTD, and can instead be explained by the passage of an upper level trough which can also lift the inversion. Finally, as CTD's progress northward along the coast, the lifting of the inversion would be observed to occur at VBG before it does at OAK. This was not observed in our case study as the previously mentioned maximum in inversion height occurred at approximately the same time at the two locations.

While the pressure and temperature profiles in the SFBA do not convincingly support the passage of a CTD on Aug. 14, there is evidence of a weak surge-like phenomenon on this day. The wind direction and speed variations do show a brief shift during the proper time. There is also evidence of a lifted inversion at VBG around Aug. 14 0000 UTC while the OAK inversion base had dropped back down to its pre-maximum level. Also, there was an observed change in surface pressure gradient between MRY and SMX during the latter hours of Aug. 14. This surface pressure gradient change might however have occurred several hours too late to be associated with a CTD.

The effects of synoptic scale disturbances on the meteorology of southern

California that would be required to generate a CTD did not occur during the MABLES study period. Dorman (1985), MA87, and FW93 found that synoptic situations where southern California is affected by an upper level trough (but not northern California) are conducive to the formation of CTD's. An unstable ridge over the Pacific northwest would be such an example. Such situations lift the inversion in the south which increases the surface pressure in southern California without doing so further north. The resulting surface pressure gradient triggers the northward propagation of CTD's. During the MABLES period this scenario did not occur. Instead the axis of the upper level troughs that did pass over California on Aug. 13 and 16 were oriented along a meridional line. This orientation caused the inversion to be lifted in both the northern and southern regions of the state at approximately the same time. With such a north-south trough axis, it would be expected that northern California see the trough axis slightly before southern California. This could explain why the height of the inversion base at VBG was observed to remain higher than normal on the 14th of August after the inversion base height at OAK had already returned to near normal levels. We conclude that this was not a classic example of a CTD.

One question that remains is why a wedge of stratus did reappear along the central California coast on Aug. 15 0000 UTC after being absent 24 hours earlier. There are several processes which can help bring about the formation of summertime stratus off the coast of California. Simon (1977) did a climatological study of the two types of low

clouds present off the coast of California (stratus adjacent to the coast and stratocumulus further west) during the summer of 1975. One important (in its relevance to the present study) conclusion by Simon (1977) was that the occurrence of stratus appeared to be related to the height of the inversion base. This concept was discussed in Chapter 4: a higher inversion base is conducive to the formation of stratus as air within the marine layer is able to rise above the lifting condensation level. This could possibly explain the disappearance of stratus along the coast on Aug. 14 0000 UTC after the existence of patchy stratus on Aug. 13 since the height of the inversion reached a maximum on the 13th and had dropped significantly by 0000 UTC on the 14th. A problem arises though in using the height of the inversion to explain the existence of the stratus wedge at 0000 UTC on the 15th: the height of the inversion dropped not only from the 13th to 14th but continued to do so until Aug. 15 0000 UTC.

As shown in Fig. 5.1, Simon (1977) separated the area adjacent to the coast into three zones. The zone closest to the coast (zone 3) is an area of convergence of the climatologically westerly surface winds in this region during the summer months. Simon (1977) describes zone 3 as a region with approximately constant dew points (with distance from the coast) where the inversion slopes upward toward the coast due to the convergence of surface winds (based on the continuity equation : $(1/u) \partial u / \partial x = - (1/h) \partial h / \partial x$). Zone 3 is the region where cooler upwelled water associated with northern and central California's coastal region is located. The wedge shaped region of stratus seen

Figure 5.1 - Variation in height of marine layer due to mean divergence field (taken from Simon (1977))

on the visible satellite imagery on Aug. 15 0000 UTC lies within zone 3. Therefore, another possible reason for the formation of the stratus wedge by the 15th would be an increase in convergence of westerly winds at the coast during the 14th. The wind direction profiles at two coastal stations do show the occurrence of south southeasterly winds from approximately Aug. 14 1200 UTC until 12 hours later. This might have caused an increase in convergence of surface winds immediately off the coast. South southeasterly winds during Aug. 14th may have also brought about an increase in dew points along the central coast. It should be noted that the northernmost tip of the wedge of stratus on the Aug.. 15 0000 UTC barely extended past the SFBA. Therefore the available data for the present study is inconclusive for a complete explanation of the formation of stratus along the central coast.

REFERENCES

- Anh, N. N., and A. E. Gill, 1981: Generation of coastal lows by synoptic-scale waves. *Quart. J. Roy. Meteor. Soc.*, 107, 521-530.
- Bannon, P. R., 1981: Synoptic-scale forcing of coastal lows: Forced double Kelvin waves in the atmosphere. *Quart. J. Roy. Meteor. Soc.*, 107, 313-327.
- Gill, A. E., 1977: Coastally trapped waves in the atmosphere. *Quart. J. Roy. Meteor. Soc.*, 103, 431-440.
- Gill, A. E., 1982: *Atmosphere-Ocean Dynamics*. Academic Press, 662 pp.
- Dorman, C. E., 1985: Evidence of Kelvin waves in California's marine layer and related eddy generation. *Mon. Wea. Rev.*, 113, 827-839.
- Dorman, C. E., 1987: Possible role of gravity currents in Northern California's coastal summer wind reversals. *J. Geophys. Res.*, 92, 1467-1488.
- Dorman, C. E., 1988: Comments on "Coastal southerlies and alongshore surges of the west coast of North America: Evidence of mesoscale topographically trapped response to synoptic forcing." *Mon. Wea. Rev.*, 116, 2401-2406.
- Felsch, P., and W. Whitlach, 1993: Stratus surge prediction along the central California coast. *Wea. Forecasting*, 8, 204-213.
- King, C. W., 1980: SODAR observations of the marine boundary layer during MABLES WC. Preprints Second Conf. on Coastal Meteorology, Los Angeles, American Meteorological Society, 258 - 261.
- Lester, P. F., 1979: Marine atmospheric boundary layer experiments, west coast (MABLES WC), July 31 - August 17, 1978: Experiments description. Department of Meteorology, San Jose State University, San Jose, California, 95192, 104 pp.
- Mass, C. F., and M. D. Albright, 1987: Coastal southerlies and alongshore surges of the west coast of North America: Evidence of mesoscale topographically trapped response to synoptic forcing. *Mon. Wea. Rev.*, 115, 1707-1738.
- Mass, C. F., and M. D. Albright, 1988: Reply. *Mon. Wea. Rev.*, 116, 2407-2410.

- Maxworthy, T., 1983: Experiments on solitary internal Kelvin waves. *J. Fluid Mech.*, 129, 365-383.
- Miller, A., 1975: Project STABLE. *Bull. Amer. Meteor. Soc.*, 56, 52 - 55.
- Reason, C. J. C., and D. G. Steyn, 1988: Comment on "Diffraction of solitary Kelvin waves at Cape Mendocino." *Mon. Wea. Rev.*, 116, 804-805.
- Reason, C. J. C., and M. R. Jury, 1990: On the generation and propagation of the southern African coastal low. *Quart. J. Roy. Meteor. Soc.*, 116, 1133-1151.
- Reason, C. J. C., and D. G. Steyn, 1990: Coastally trapped disturbances in the lower atmosphere: Dynamic commonalities and geographic diversity. *Prog. in Phys. Geogr.*, 14(2), 178-198.
- Reason, C. J. C., and D. G. Steyn, 1992: The dynamics of coastally trapped mesoscale ridges in the lower atmosphere. *J. Atmos. Sci.*, 49, 1677-1692.
- Simon, R. L., 1977: The summertime stratus over the offshore waters of California. *Mon. Wea. Rev.*, 105, 1310-1314.
- Simpson, J. E., 1987: *Gravity Currents in the Environment and the Laboratory*. Ellis Horwood, 244 pp.