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Mt. Sutro Tower, July 1979**

Mazur, Andreas, M.S.

San Jose State University, 1991

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WIND AND TEMPERATURE PROFILES THROUGH THE MARINE
INVERSION: MT. SUTRO TOWER, JULY 1979

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

Andreas Mazur, Capt, USAF

August, 1991

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ABSTRACT

WIND AND TEMPERATURE PROFILES THROUGH THE MARINE
INVERSION: MT. SUTRO TOWER, JULY 1979

by Andreas Mazur

In this study, wind and temperature profiles taken from sensors on Sutro Tower in San Francisco have been processed into a data set suitable for analysis on a personal computer. Mean and daily variations of the marine inversion were analyzed for July 1979, and compared to Miller (1976).

Many inversion characteristics were similar to those found by Miller (1976), however, the rotation in the hodograph of mean hourly wind vectors here was counter-clockwise, while Miller (1976) found clockwise. This difference has not been resolved.

A case study showed a correlation between inversion characteristics and changing synoptic conditions over approximately five days. Diurnal and shorter period oscillations in the wind and temperature fields were also observed. In contrast to Miller (1976), the location of the wind maximum was not observed to have a preferred location relative to the inversion base. Further study is recommended to reconcile differences between the results here and Miller (1976).

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God bless you and your family!

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than I in many respects. Praise God it's done! I love
you!

To my Lord, Jesus Christ: all glory and honor in this
effort is yours for providing me everyone and everything I
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Chapter 1. INTRODUCTION

1.0 Background

Semipermanent anticyclones are dominant features of the low level atmospheric circulations of subtropical oceans. Those high pressure cells have important effects on the weather across the oceans. They also play important roles in the transport of heat and moisture within the general circulation of the atmosphere (Palmen and Newton 1969; Schubert 1976; Randall et al. 1984).

On the eastern and southern sides of the subtropical anticyclones are found well defined temperature inversions based a few hundred meters to a few kilometers above the surface. The inversions are known as "trade wind" inversions over the low latitude regions of prevailing easterly winds, and "subsidence," or "marine," inversions elsewhere. These subsidence inversions extend for thousands of kilometers across the Atlantic from western Africa to Brazil, and across the Pacific from California to Hawaii (Neiburger et al. 1945, 1961; Kruger and Miller 1966; Palmen and Newton 1969; Albrecht et al. 1979).

One of the most often studied marine inversions is found along the west coast of the United States. In particular, the inversion along the California coast has received much attention from scientists. The general cause

of the inversion there (and along the subtropical west coasts of all continents) is well known. Located on the east side of the Pacific Subtropical High (Figure 1.1), California's prevailing coastal winds blow primarily from the north-northwest (NNW). The along shore winds are enhanced by the proximity of the California Heat Trough, a thermally induced low pressure region extending northwestward from the Sonoran-Mojave Deserts into the central California valleys (Gilliland 1980; Winant et al. 1988). The combined effects of the Pacific High and Thermal Trough cause maximum divergence in the low level winds offshore and along the California coast (Neiburger et al. 1945, 1961; Neiburger 1960; Simon 1977). Under these conditions, mass continuity leads to a coupling of the low level divergence with subsiding air aloft. The descending air is warm and dry, in sharp contrast to the cool, moist air of the surface marine layer (Neiburger et al. 1961; Edinger 1963; Brost et al. 1982a). The transition zone between the marine air and the subsiding air is the elevated marine inversion.

Schroeder et al. (1967) document the critical effects of the marine layer and the marine inversion on agriculture, native vegetation, urban development, recreation, shipping, fishing, transportation, and air pollution along the California Coast. For example, when

Figure 1.1 - Normal sea level pressures in July (after Nelburger et al. 1961).

the inversion is high, persistent low stratus may hamper aircraft operations; when the marine inversion is low, the cool, moist, marine air is absent and fire danger is high in the coastal mountains (Schroeder and Fosberg 1964; Mass et al. 1986).

Despite these and other important effects of the marine inversion, there have been few comprehensive investigations of the causes, structure, and variations of that phenomenon over the last 255 years; Neiburger et al. (1961) lists only Hadley in 1735, Byers in 1930, von Ficker in 1936, and Petterssen in 1936. Lilly (1968) inspired a major increase in the studies of the marine inversion with a paper which implied a strong connection between the global radiation budget, subtropical inversion maintenance, and subinversion cloudiness. Since then many numerical studies and observational experiments, especially in the eastern Pacific, have been performed to verify Lilly's hypotheses (e.g., Schubert 1976; Deardorff 1976, 1980, 1981; Kraus and Schaller 1978a,b; Albrecht et al. 1979; Cederwall 1980; Brost et al. 1982a,b; Albrecht et al. 1988; Albrecht and Barlow 1989; Kloesel and Albrecht 1989).

The increased attention to the marine inversion has also revealed a far more complicated inversion structure near the land-sea interface, i.e., along the west coast. Interactions with the land/sea breeze, topographical

effects, and upwelling cause a wide variety of spatial and temporal variations in the inversion, the marine layer, and the associated cloudiness. Such complications are manifested in a number of important mesoscale phenomena including gravity waves, hydraulic jumps, stratus surges, low level coastal jets, coastal eddies, and local inland intrusions of marine air (e.g., Edinger 1959, 1963, 1966; Williams 1966; Lovill and Miller 1968; Ahrens and Miller 1969; Lenschow 1970; Lile 1970; Edinger and Wurtele 1972; Holman 1978, 1980; Van Patten 1980a,b; Lester 1981, 1985; Brost et al. 1982a; Dorman 1985, 1987, 1988b; Mass et al. 1986; Lapworth 1987; MacArthur et al. 1987; Mass and Albright 1987, 1988; Winant et al. 1988; Felsch and Whitlatch 1990; Bridger et al. 1990).

Brost et al. (1982a), stated "although instrumented aircraft are very useful in a stratocumulus experiment, a vertical-probing capability such as a balloon or tall tower would provide very desirable complementary information." In an effort to understand the mesoscale phenomena more completely and to quantify their relationship with the marine inversion, Miller (1975) instrumented Mt. Sutro Television Tower in San Francisco to acquire continuous, detailed observations of the inversion. Collection and analysis of tower data were carried out as part of Project STABLE (Sutro Tower Atmospheric Boundary Layer Experiments)

during summers 1974-1976. STABLE began with the following objectives (Miller 1975):

- a. Determine the characteristics of the interface between the marine layer and the inversion layer;
- b. Determine the vertical gradients of temperature, moisture, wind, and pollutants across the interface;
- c. Study the development of waves and vertical fluxes across the interface;
- d. Study the composition of fog and aerosols on both sides of the interface.

After only a few detailed studies of STABLE data were accomplished (Miller 1976; Goodman and Miller 1977; Holman 1978; Van Patten 1980a,b) Miller realized a longer period of record and greater vertical resolution were needed to verify and enhance the observations and analyses (Lester 1985). Therefore, a second program of tower studies (STABLE, Phase II; Lester, 1981) was conducted from mid 1978 through April 1980 (STABLE, Phase II, also included the Marine Atmospheric Boundary Layer Experiments, West Coast [MABLES WC] field experiment; see Lester 1979, 1981).

Unfortunately Miller died in 1978. Since that time only a few analyses using tower data from the summer of 1978 have been accomplished (Goodman 1979; King 1980; Roope 1980; Erickson 1981; Lester 1981; MacArthur et al. 1987; Tredo 1987) and data from summer 1979 have yet to be analyzed.

1.1 Objectives

The purposes of this investigation are:

- 1) to prepare a quality assured data base of summer 1979 data, suitable for archiving for future analysis;
- 2) to expand and verify the earlier studies of the marine inversion structure and behavior (Miller 1976) with the analysis of summer 1979 Mt. Sutro Tower data.

1.2 Scope

Specifically, the 1979 Mt. Sutro Tower data will be analyzed in a manner identical to Miller (1976) to document and compare wind and temperature variations within the inversion. As background to the task, a review of the literature relevant to the west coast marine inversion is presented in Chapter 2. The tower, instrumentation, and the procedures for data acquisition, processing, and analysis are described in Chapter 3. Results and conclusions are detailed in Chapters 4 and 5, respectively.

Chapter 2. LITERATURE REVIEW

2.0 Introduction

Literature pertinent to the west coast marine inversion will be reviewed in this chapter. First will come a review of the inversion over the eastern Pacific Ocean (section 2.1). In section 2.1, research about the observed structure of the inversion on a large scale, and studies investigating the maintenance of the inversion will be examined. Following that, previous studies of the marine inversion along the west coast will be reviewed (section 2.2), with particular emphasis given to studies close to the San Francisco Bay Area (SFBA).

2.1 The Marine Inversion Over the Eastern Pacific Ocean

2.1.1 Observed Structure

The definitive observational study, thus far, of the marine inversion over the eastern Pacific Ocean is that of Neiburger et al. (1961). As such it forms the basis of this section. In that study, radiosonde data obtained during cruises of research vessels in the years 1949-1952 were presented, documenting many of the large scale patterns of the marine/inversion boundary layer over the ocean.

As mentioned in Chapter 1, the marine inversion over the eastern Pacific covers thousands of kilometers, from California to the Hawaiian islands and beyond (Neiburger et al. 1961).

The height of the inversion base, Z_i , increases from a minimum of about 400m near the California coast, rising westward to approximately 2000m ASL over Hawaii (Neiburger et al. 1961). Additionally, Z_i generally increases northwest and southward of California, but more gradually (Neiburger et al. 1961). Later studies near the equator, however, have shown little latitudinal or longitudinal variation in Z_i south of 15°N (Ramage et al. 1981; Firestone and Albrecht 1986; Kloesel and Albrecht 1989). Brost et al. (1982a) argued that north-south differences in Z_i were caused primarily by entrainment and mesoscale vertical motions; the latter effect reflecting the north-south variations in the length of periods during which air subsides on its generally southward track. An example of such a variation was documented by Simon (1977), in a study of mean cloudiness patterns. He postulated a summer Z_i minimum east of 125°W and north of 35°N , i.e., in the location of an observed mean cloudiness minimum and maximum of low level divergence.

The westward rate of increase of Z_i is greatest at the California coast (Neiburger et al. 1961; Brost et al.

1982a; Bridger et al. 1990). Neiburger et al. (1961) also observed that this rate of increase slows abruptly in the vicinity of 135°W . West of 135°W , Z_i continues increasing but much more slowly. Z_i is highest in winter and lowest during summer, with the inversion generally being weaker when Z_i is high, and stronger when Z_i is low (Neiburger et al. 1961).

Diurnally, the inversion base is observed to follow the same pattern over the open ocean as over coastal regions: high in the morning and low in the late afternoon/early evening (Neiburger et al. 1961). The diurnal pattern along the coast has been attributed to the sea breeze circulation, i.e., the land-sea temperature differences (Neiburger 1944; Edinger 1959; Johnson and O'Brien 1973; Miller 1976; Elliot and O'Brien 1977; Lester 1985). Neiburger et al. (1961) claimed, however, that similar patterns of Z_i behavior over the ocean could be induced by inversion base oscillations along the coast. The latter are discussed in greater detail in Section 2.2.

Synoptically, Neiburger et al. (1961) observed upper level troughs, surface fronts, or cyclonic disturbances of any kind weaken, raise, and frequently dissipate the marine inversion (see also Meitin and Stuart 1977; Gilliland 1980; Lester 1980; Bridger et al. 1990). The inversion also disappeared in the region of the Intertropical Convergence

Zone (ITCZ; Neiburger et al. 1961). Their observations supported the hypothesis of given by Dohrmann in 1937, in which he concluded convergence is the primary cause of inversion dissipation in the ITCZ (Neiburger et al. 1961).

Neiburger et al. (1961) observed that Z_i , relative to the lifting condensation level (LCL), was the primary controlling factor in the formation of clouds. When Z_i is below the LCL, low clouds will not form. When Z_i reaches or exceeds the LCL, stratus and/or stratocumulus forms. In the previously mentioned study by Simon (1977), the minimum in low cloud frequency near 125°W , west of the California coast, occurred when Z_i decreased to a level below the LCL as a result of strong low level divergence. Simon (1977) also noted that stratocumulus was generally found west of 125°W (over warmer sea surface temperatures), while stratus occurred eastward of that longitude over colder coastal waters (see also Bridger et al. 1990).

The mean temperature at Z_i observed by Neiburger et al. (1961) increased towards the south-southeast from the central California coast, rising from 10°C to 20°C at the tip of the Baja Peninsula. This was attributed to generally decreasing Z_i and increasing sea surface temperatures in that direction; i.e., because the water is warmer beneath the inversion, and the subsiding air has had

a longer time to subside, the temperature at Z_i is warmer along the Baja Peninsula than along the California coast. North and west of the central California coast the temperatures at Z_i generally decrease, controlled by the colder sea surface temperatures and higher inversion base. West of 135°W , where Z_i increases more slowly, the increasing sea surface temperatures more strongly influence the temperature at the inversion base, thus causing the temperatures at Z_i to begin increasing. Neiburger et al. (1961) also noted the potential temperature at Z_i increased continuously towards the west, from roughly 288K at the California coast to 304K west of Hawaii.

Neiburger et al. (1961) observed low level winds were divergent everywhere in the eastern Pacific, with maximum divergence found at the coast. They also found no clear relation between wind speeds and inversion base height over the ocean. On the basis of the frequent observations of light surface winds ($1-4\text{ms}^{-1}$), they concluded the characteristics of the inversion could not be explained in terms of cooling at the surface, combined with turbulent mixing. In contrast, over the eastern Pacific Simon (1977) observed mean summer wind speeds ranging $7-10\text{ms}^{-1}$ and found a distinct relationship between the variation of wind speeds along streamlines (i.e., divergence), and Z_i .

2.1.2 Inversion Maintenance

In an early study of the causes of the marine inversion along the west coast of the United States, Byers (1930) hypothesized that the inversion existed because of the presence of "an abnormally cold stratum at and immediately above the surface," while the warmer air above the inversion "is the normal condition....It is simply a case of the cool moist air making inroads into the warm air of the land."

Von Ficker, in a study of the south Atlantic trade wind inversion reported in 1936, was apparently the first to suggest the inversion was caused by subsidence in a subtropical anticyclone (Neiburger 1960). Based on further research (e.g., see Neiburger et al. 1961; Csanady 1974; Brost et al. 1982a) subtropical subsidence has been verified as a primary cause of the trade wind/marine inversion. However, other processes have also been identified as critical to the characteristics of the inversion. For example, Petterssen (1936) suggested turbulence within the marine layer and radiative heat loss from the stratus were the primary causes for maintaining the inversion in an elevated state.

In what Deardorff (1980) has described as a "pioneering theoretical paper," Lilly (1968) followed the ideas of

Petterssen (1936) and formulated an hypothesis "relating, explaining, and predicting features of a radiatively active turbulent cloud layer over the sea and under a strong subsidence inversion." Lilly's work showed radiant and latent heat energy exchanges at the tops of low clouds would lead to convective instability within the marine layer. Furthermore, this process was essential to the establishment of an elevated marine inversion. He focused on stratocumulus clouds primarily, but suggested that the theory should also "hold for the fog-, stratus- or stratocumulus-containing layer typically observed near the coast of California" as well as other continental west coasts in mid and lower latitudes.

One may...conjecture that the strong inversions typical of...coastal California and similar regions are necessarily maintained by a low cloud layer.... It would appear impossible for any observed combination of subsidence, convection, and shearing turbulence to produce sufficient amounts of kinetic energy to maintain a 15-20 degree inversion at a height of 500-1000 meters without a radiatively effective cloud cover. (Lilly 1968.)

Many subsequent researchers have followed Lilly's lead, modifying and using his model. For example, Schubert (1976), modified the parameterization of the types and amount of negative vertical motion (and hence, entrainment) from the inversion base/cloud tops, using the mean value between the maximum and minimum found by Lilly (1968). He

reported results which agreed with Lilly's--at least when clouds were present. Schubert also predicted the diurnal variation of solar radiation should produce significant diurnal variation of the marine layer depth/inversion base height, even over the ocean.

Deardorff (1976) modified Lilly's model further. Whereas Lilly (1968) and Schubert (1976) assumed the inversion was infinitesimally thin and all the radiative divergence, r , occurred within the inversion layer, Deardorff (1976) assumed only a fraction of r occurred within the inversion. The remainder, $1-r$, was assumed to occur in the upper regions of the marine layer, just beneath the inversion base. Positioning $1-r$ in the marine layer allowed turbulent entrainment of inversion layer air, thus cooling the lowest levels of the inversion. His goal was to explore the relative importance of cloud-top radiative cooling by itself (confining r to the inversion layer--Lilly's model) against a model containing both cloud-top radiative cooling and turbulent entrainment (locating $1-r$ in the marine layer). Deardorff also modified the entrainment closure parameterization, specifying the negative buoyancy flux to be -0.5 of the vertically integrated positive buoyancy flux throughout the marine layer instead of a mean between minima and maxima. This value was the same as Schubert's (1976) when $r=1$ or

when the level of minimum buoyancy flux occurred at the inversion base. Most of the experiments conducted by Schubert (1976) had minima of buoyancy flux at the surface or at the cloud base. Deardorff's (1976) results were similar to Lilly's (1968), but with enhanced turbulent energy exchanges and a cooling tendency in the top of the marine layer.

In another numerical experiment, Albrecht et al. (1979) also concluded radiative divergence (i.e., cooling) occurs in both the inversion layer and top of the marine layer. They used a simple predictive model (based on Betts 1973), which contained three layers: sub-cloud, cloud, and inversion. Convection and radiation were parameterized, while large scale divergence, sea surface temperatures, and surface wind speed were specified externally. Their goal was to explore how the externally specified parameters affected boundary layer structure and fluxes. Their experiments showed the marine layer depth depends strongly on large scale divergence, surface wind speed, sea surface temperatures, and radiation parameters (Albrecht 1979). Thus, they took the first step numerically to tie Lilly's ideas with the ideas of previous researchers (e.g. Byers, Petterssen, Neiburger, Edinger).

Simon (1977), however, pointed out that the height of the inversion base fluctuates dramatically and the

inversion has been observed to exist in an elevated state even when there is no stratus upstream. Because of these observations, he suggested radiant energy exchanges associated with cloudiness may not be a major factor in the maintenance of the elevated inversion--at least in some cases.

Cederwall (1980), used a one dimensional (stick) model to investigate the maintenance of inversions in the absence of a lower cloud layer. His results indicated long wave radiative flux divergence (i.e., cooling) was greatest where water vapor decreased most rapidly with height (i.e., the inversion layer), thus lending further credibility to Lilly's (1968) work, even in the absence of clouds. He also noted, however, that without clouds the radiative cooling was generally too weak, by itself, to support the energy exchanges necessary to elevated inversion. He suggested other processes (e.g., subgrid scale gravity waves or turbulence) were necessary in addition to radiative cooling.

Brost et al. (1982a,b) described results from an observational investigation undertaken in June 1976 (The Marine Stratocumulus Experiment--STRATEX). A basic goal of the experiment was to test the predictions of "Lilly-type" models and their underlying assumptions. The reported results were derived from airplane observations taken 13

and 17 June 1976, from stratocumulus-topped marine layers off the California coast, about 126°W , 35°N . They claimed "the mesoscale flow patterns and thermodynamic variations are, for the most part, successfully resolved" by the works of Lilly, Deardorff, Albrecht et al. and others.

One limitation in the models discussed above is they dealt with overcast or clear conditions. Those processes involved in the formation and dissipation of fractional marine stratocumulus cloud systems are still relatively unknown (Randall et al. 1984). The First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment (FIRE, Phase I) took place off the coast of southern California in June and July 1987. Focusing on marine stratocumulus clouds, the project was designed to collect an observational data base which would increase understanding about how stratocumulus clouds are generated, maintained, and dissipated (Albrecht et al. 1988). The knowledge gained would then be used to provide better parameterizations in large scale numerical models (Randall et al. 1984; Albrecht et al. 1988). FIRE, Phase I, involved four research aircraft, two research vessels, tethered balloons, radiosondes, RADAR, LIDAR, and SODAR units, as well as researchers from around the world (Albrecht et al. 1988). Early results support and extend

previous studies. For example, several studies confirm a complicated structure exists within the inversion, as observed by earlier research (e.g., Edinger 1963; Meitin and Stuart 1977). Well defined moist strata have been found within the inversion over large areas of ocean (Kloesel and Albrecht 1989). Often these moist strata are "capped" with another inversion (Edinger 1963; Albrecht and Barlow 1989; Kloesel 1989; Betts and Boers 1989). At least one study indicates that the inversion layer may, in places, act as a moisture source for the subinversion cloud layer (Hanson 1989). Note that previous studies (e.g., Edinger 1963; Johnson and O'Brien 1973) have found the top of the moist (marine) layer above Z_i . Minnis et al. (1989) reported diurnal cycles of Z_i with maxima in the late mornings and minima around sunset.

Based on the amount and types of equipment, the numbers of researchers involved in FIRE, Phase I, and the results published thus far, it is possible Neiburger et al. (1961) may be supplanted as the definitive observational study of the eastern Pacific Ocean.

2.2 Observed Structure of the Coastal Marine Inversion

As noted in Chapter 1, inversion structure and behavior are complicated in the vicinity of the coast. For example,

several studies have observed a lower inversion base over regions of cold (upwelling) water (e.g., Williams and DeMandel 1966; Miller 1968; Elliot and O'Brien 1977; Brost et al. 1982a), while others have found higher inversions over elevated terrain (e.g., Edinger 1959, 1963; Williams 1966; Williams and DeMandel 1966; Ahrens and Miller 1968; Uthe and Russell 1976; Goodman and Miller 1977).

Edinger (1959) presented evidence that convection from the land surface beneath the marine layer serves to increase the height of the base of the inversion. He argued that convection, when coupled with divergence and advection, could account for observed diurnal oscillations of the inversion base (i.e., high in the morning, low in the afternoon; see also Neiburger 1944; Neiburger et al. 1945; Ball 1960; Edinger 1963).

Neiburger et al. (1961), found mean Z_i to be about 400m ASL along the west coast of Oregon and California. They also observed the greatest temperature increases through the inversion to be located along the coast, averaging 10-12°C from bottom to top of the inversion. The average height of the top of the inversion along the coast was 800-1000m, being slightly higher in northern California, Oregon, and southern Washington. These values correspond with an average vertical temperature gradient of about 2°C/100m in this inversion.

During STABLE, Phase I, Miller (1976) observed mean Z_i to be 300m ASL at Mt. Sutro Tower in San Francisco (see also Miller 1975). The mean temperature gradient observed was $2.2^{\circ}\text{C}/100\text{m}$. Goodman and Miller (1977) observed the mean inversion top height to be 900m ASL at Mt. Sutro Tower.

Brick (1988), using data from MABLES WC (a field experiment of STABLE, Phase II, conducted roughly 200km west of San Francisco; see Lester 1979, 1985), observed mean Z_i roughly equal to Miller (1976), i.e., 300m ASL. The inversion base was also observed to slope downwards towards the coast, agreeing with findings of Neiburger et al. (1961) and Brost et al. (1982a).

Within 150km of the California coast, Neiburger et al. (1961) observed individual instances during afternoons of slopes as great as 1:60, descending eastwards, though mean slopes were roughly 1:700, descending towards the east. Inland, the direction and magnitude of the slope of Z_i depends to a large extent on the local topography. Edinger (1959, 1963) showed the marine layer in the Los Angeles vicinity rose, increased in thickness, and weakened inland over generally rising terrain. The inversion base topography in the SFBA has been shown to be dependent on both terrain and time of day. Because of the terrain, it forms a wave-like structure. The inversion is higher over

the coastal mountains, lower over San Francisco Bay, then higher again over the east bay hills (Williams and DeMandel 1966; Miller 1968; Lile 1970; Miller and Ahrens 1970; Goodman and Miller 1977; Russell and Uthe 1978; Lester 1985). Miller (1968) presented evidence which suggested that the amplitude and form of this topographically created wave in the inversion base varied diurnally. The trough over the bay is near the western shore at night, and shifts eastward across the water during the day with increasing amplitude. Because of these effects, local radiosonde observations of the inversion (e.g., Oakland) are often not representative of low level conditions elsewhere in the area (Lester 1985).

A primary cause of changes in slope of the inversion base and Z_i is the sea breeze. Because the sea breeze is a diurnal circulation, coastal Z_i changes exhibit pronounced diurnal oscillations. With the onset of the sea breeze, mass continuity requires the replacement of the air surging inland. As a result, the inversion base lowers and its eastwardly descending slope increases near the coast (Neiburger 1944, 1960; Russell and Uthe 1978; Bearsdley et al. 1987; Pinelli et al. 1990). Neiburger (1944, 1960) also identified convergence and divergence of the sea breeze circulation as the most important factor controlling the height of the inversion base (see also Neiburger et al.

1945; Edinger 1959, 1963; Miller and Ahrens 1969; Edinger and Wurtele 1972; Elliot and O'Brien 1977; Simon 1977; Albrecht 1979; Myrup et al. 1983; Glendening et al. 1986).

In addition to the effects of the sea breeze on Z_i , Neiburger (1944) showed that combined ocean and elevated terrain effects often produced much stronger coastal winds than a classical sea breeze circulation alone (see also Glendening et al. 1986; Stull 1988). Olsson et al. (1973) and Johnson and O'Brien (1973) documented similar sea breeze/mountain-valley events along the Oregon coast; Schroeder et al. (1967) did the same for central California.

Williams and DeMandel (1966) observed the sea breeze in the San Francisco Bay Area (SFBA) begin as a sudden surge in surface wind speed, which deepened with time (see also Johnson and O'Brien 1973). Lester (1985) reviewed evidence which shows that during typical summertime conditions in central/northern California, the coastal flow resembles a larger scale monsoon circulation upon which the sea breeze is superimposed. Thus, the coastal flow is characterized by persistent onshore winds which strengthen during the day and weaken at night (see also Simon 1977; Gilliland 1980). Beardsley et al. (1987), in an extensive two year study along coastal northern California, the Coastal Ocean Dynamics Experiment (CODE), also observed solenoidal

circulations they believed were not classical sea breeze situations. The circulations observed were thought to be driven primarily by stability changes inland, rather than density differences (i.e., temperature differences) between land and sea. The stability changes (less stable during the day, more stable at night) allowed a diurnal, cross coast shift of a low level jet core, from alongshore to slightly inshore, thus creating a semblance of a sea breeze.

A low level jet has been found frequently in the coastal boundary layer. Those found offshore tend to be northerly along the Oregon and north-central California coasts. For example, Elliot and O'Brien (1977) reported a northerly jet parallel to, and located 10-30km off the Oregon coast. Friehe and Winant (1982), Zemba and Friehe (1987), and Winant et al. (1988) observed northerly jets during CODE, at or near Z_i , with speeds to 30ms^{-1} . Brost et al. (1982a), in the Stratocumulus Experiments (STRATEX), conducted 200km W-WSW of San Francisco, observed low level northerly jets ranging in speeds from $12\text{-}20\text{ms}^{-1}$. These jets were generally below Z_i , with minima near or above Z_i . Bridger et al. (1990), using data from MABLES WC, observed northerly boundary layer wind maxima of $12\text{-}18\text{ms}^{-1}$ in both the marine layer (around $38^\circ\text{N } 125^\circ\text{W}$) and in the inversion layer (around 38°N

123.5°W). They also noted wind minima at approximately Z_i (see also Roope 1980; Brick 1988).

Gerber et al. (1989), observed low level jets above San Nicolas Island (SNI), approximately 100km WSW of Los Angeles. Maximum speeds were $8-13\text{ms}^{-1}$ from the west, located at or above Z_i . They found the jets over SNI were caused by an oscillation of the westerly wind interacting with sea surface temperature gradients, and with horizontal temperature gradients in the atmosphere, created by the sloping inversion base. Because the jets observed did not require land-sea temperature differences Gerber et al. suggested they could exist over oceans where similar temperature advection and gradients exist.

Over the coast (e.g., the SFBA) a jet-like structure is commonly tied into the sea breeze circulation, with a minimum speed found at Z_i , and local maxima in both the marine and inversion layers (Williams and DeMandel 1966; Miller 1968, 1976; Lester 1985). Coincident with the sea breeze, these wind maxima tend to occur during afternoon and evening hours. Wind directions in the SFBA, though dependent upon local terrain and synoptic conditions, tend to be WSW-W in the marine layer, backing to NW in the inversion (Miller 1976; Goodman and Miller 1977; Lester 1985).

Miller (1968) and others have hypothesized that

mesoscale temperature variation within the inversion layer (i.e., the thermal wind) was primarily responsible for the existence of the jet. However, more recent studies over the eastern Pacific and elsewhere support other models. For example, Chao (1985) argues that the prevailing coastal winds flow in response to the boundary layer pressure gradient generated by the inland Thermal Low and the offshore Pacific High. This pressure gradient is modified by spatial and temporal variations caused, e.g., by the local sea breeze and/or transient synoptic circulations such as upper level troughs. Thus, if far enough from land, an alongshore jet is more of a geostrophic phenomenon which forms as a result of the Coriolis torque on the onshore monsoonal flow (Bridger et al. 1990).

Chao (1985) also suggested coastal topography could play a large role in the creation of an alongshore jet. He theorized the coastal mountains of California (and other subtropical, continental west coasts) might act as a barrier, deflecting the zonal component of the horizontal flow, thus adding momentum in the meridional direction.

Although Miller did not find small scale, topographically caused changes in the inversion base slope to be clearly related to the jet structure (Lester 1985), near the coast the local pressure gradient force, caused by temperature differences between land-sea, may overwhelm the

Coriolis force, resulting in a more westerly jet (Beardsley et al. 1987). The thermal wind, which is often opposed to the jet because of the downward slope of the inversion towards the coast, will limit the jet to low levels, with frictional effects retarding wind speeds near the surface (Bridger et al. 1990). The thermal wind, and thus the low level jet, can be modified by variations in the slope of the inversion layer, especially near the coastal mountains (Miller 1968; Brost et al. 1982a; Lester 1985; Zemba and Friehe 1987; Gerber et al. 1989) or by changing sea surface temperatures, which, in turn, affect the east-west thermal gradient and, thus, the thermal wind (Brost et al. 1982a; Zemba and Friehe 1987).

Brost et al. (1982a), suggested that the speed of a N-NW geostrophic wind often may be greater below Z_i than at, or above it. Based on the thermal wind and a sloping inversion base, their calculations led to the expectation of a large decrease or "jump" (averaging approximately -6ms^{-1}) in N-NW geostrophic wind speed across the inversion base. However, their hypothesis does not explain the previously described minimum of wind speed often observed at Z_i in the SFBA. The occurrence of that feature led Miller and his colleagues into a long series of investigations to determine the role of smaller scale phenomena, such as gravity waves and turbulence, in the

maintenance of the wind maximum within the marine inversion (i.e., above the wind minimum at Z_i).

Williams and DeMandel (1966) explained the wind speed minimum observed at the inversion base in the SFBA by flux divergence of momentum due to continuous wave activity and turbulence near Z_i . As a consequence, they believed momentum was deposited in the jet above Z_i (see also Miller and Ahrens 1970). Miller (1968) hypothesized the strong wind shear observed in the inversion layer was responsible for the shorter, unstable, shearing gravity or Kelvin-Helmholtz waves within it (see also Gossard et al. 1970). Metcalf (1975), observed gravity waves in the marine inversion near San Diego, California, with lengths between 44m - 560m. He found nearly all the waves with these wavelengths were horizontally propagating in the inversion, often confined to thin sublayers within it. He noted the longer waves appeared preferentially oriented, whereas the shorter ones flowed in all directions (see also Atlas and Metcalf 1970; Holman 1978, 1980). Miller and Ahrens (1970), observed ozone maxima above Z_i in regions of turbulent/wave activity. Their analyses "suggested that the ozone 'injection' mechanism was related to some type of large-amplitude wave (i.e., a breaking gravity wave or hydraulic jump) which resulted in cross-inversion mixing" (Lester 1985; see also Lile 1970). Goodman and Miller

(1977) used fluorescent particle tracers to show conclusively that mass is exchanged both upwards and downwards across the marine inversion base (see also Goodman 1975, 1976, 1979; Lester 1981).

Miller (1976) suggested the observed cross inversion fluxes were caused by horizontal mixing induced by breaking gravity waves. These small amplitude waves would be generated by the sloping inversion base and the strong shears present within it. The waves would induce horizontal eddies which would then transfer mass from one layer to another. This effect would not be limited to terrain induced tilting of the inversion base, but could exist anywhere the inversion base slopes (Lester 1985; see also Edinger 1966; Edinger and Wurtele 1972; Brost et al. 1982a).

Holman (1978) examined the energy budget of turbulence from STABLE, Phase I data. She found turbulent bursts in layers within the inversion were caused by unstable, trapped gravity waves. In support of Miller's (1976) theory described above, she found an energy imbalance which could not be accounted for with strictly vertical exchange processes (e.g., very large amplitude breaking gravity waves or hydraulic jumps). She suggested a horizontal mixing process was required to compensate for the deficit (see also Browning et al. 1973; Readings et al. 1973).

Van Patten (1980a,b) created temperature and wind spectra for periods ranging from ten seconds to 90 days, using data from STABLE, Phase I. He found synoptic and diurnal peaks in the spectra, but also found peaks in periods between three and thirty minutes. Cross spectral analysis revealed the latter maxima were caused by gravity waves a few hundred meters in length. These waves moved through layers 20-40m thick.

MacArthur et al. (1987) conducted spectral analysis of a 30 minute turbulent episode at Mt. Sutro Tower from summer 1978 (STABLE, Phase II, MABLES WC). Their results revealed significant mixing within a 30m layer, likely caused by breaking gravity waves. Associated with the mixing was an increase in Z_i of 30m and lapse conditions below Z_i . Further analysis indicated the wind field was affected by the turbulent episode, rather than being a cause of it.

Confirmation of Miller's horizontal mixing hypothesis does not preclude the important occurrences of the truly vertical fluxes caused by hydraulic jumps or large amplitude, breaking gravity waves (Lester 1985). Miller (1976) documented one hydraulic jump over San Francisco Bay and Winant et al. (1988), deduced the presence of hydraulic jumps downwind of Pt. Arena, California, during CODE (see also Dorman 1988a). Large scale gravity waves have been

reported frequently as well. Edinger (1966) observed gravity waves in clouds upwind of Pt. Sal, California. Based on his calculations the marine layer more than doubled its depth (approximately 140-150m) in moving from trough through crest along a wavelength 1300-1700m. Edinger and Wurtele (1972) reported gravity waves, as well as longitudinal stratus rolls and cells off the south-central California coast.

Dorman (1985, 1987, 1988b) postulated gravity or Kelvin waves as the causes of the sporadic southerly surges of stratus and marine air which often progress northwards along the west coast (see also Edinger and Wurtele 1972; Gill 1977; Ahn and Gill 1981; Bannon 1981; Overland 1984; Reason and Steyn 1988). Mass and Albright (1987, 1988), however, reexamined the southerly surge case analyzed by Dorman (1985, 1988b). They argued that rather than a Kelvin wave, this particular event was "ageostrophic flow controlled by the synoptic alongshore pressure distribution, superposed on a geostrophic component associated with the pressure gradient normal to the coast." Mass et al. (1986) described southerly or onshore surges as "a relatively rapid transition from warm, dry continental air to cool, moist, marine air." During these surges the wind field reverses to include a dominant southerly component and Z_1 increases allowing the stratus

to move northwards along the coast. Frequently these events are accompanied by pressure falls at the leading edge of the surge, strong winds, temperature falls, and increased cloudiness (Mass et al. 1986; Felsch and Whitlatch 1990). Similar phenomena occur in mountainous, coastal regions elsewhere in the world, such as southeastern Australia and southern South Africa (Mass et al. 1986; Mass and Albright 1987; see for example, Colquhoun et al. 1985; Holland and Leslie 1986; Gill 1977). Most southerly surges begin with synoptic scale changes and are modulated by responses to the mesoscale topography of the west coast (Mass et al. 1986). The surges which affect the Pacific Northwest almost invariably begin between 1800-2200 PST, with May the month containing the most frequent strong surges ($>10^{\circ}\text{C}$ temperature drops; Mass et al. 1986).

Felsch and Whitlatch (1990) compiled a climatology of surge events for the central California coast. They too observed all surge events started during the night. Above the boundary layer, they found surges began under one of two circumstances: a cutoff low at 500mb over southern California, creating convergence and increasing Z_i there, or ridging extending NE-SW at 850mb over northern California, intensifying the divergence and decreasing Z_i in the north. These effects must increase the mesoscale pressure gradient alongshore (higher in the south) relative

to the macroscale gradient created by the Pacific High and Thermal Low. At night radiative cooling decreases the land-sea temperature differences diminishing the macroscale pressure gradient and allowing the oppositely directed mesoscale gradient to dominate the horizontal flow.

Often the southerly surges will "pause" at topographical protrusions from the coast (e.g., Cape Mendocino or Pt. Reyes). Frequently a "coastal eddy" will be created at this point (Dorman 1987). Eddies do not, however, require southerly surges to form (Lester 1981; Bosart 1983; Wakimoto 1987). A previous study has shown eddies will be found somewhere along the California coast more than 50% of the time between May and August (Lester 1981). In the Pt. Reyes region, north of the SFBA, eddies were observed 24% of the time. Key features associated with non-surge eddy generation are passage of an upper level ridge, and an increase in the pressure gradient between Pacific High and Thermal Low (Wakimoto 1987). The resulting increase in wind speeds flowing generally southward around projections of the coastline (e.g., Pt. Conception) creates a cyclonic circulation in the lee of the protrusion, such as the Catalina Eddy in the Los Angeles Basin (Bosart 1983; Wakimoto 1987). Eddies induce variations in the slope and height of the inversion base and thus can modify cross inversion fluxes, horizontal wind

velocities, and cloud amounts (Roope 1980; Erickson 1981; Lester 1981; Wakimoto 1987; Bridger et al. 1990). Roope (1980) observed an eddy approximately 30km in diameter south of Pt. Reyes, during MABLES WC. It was revealed by the strong horizontal wind shear accompanying it. Additionally, the eddy was characterized by the NW wind maximum along its western edge. Erickson (1981) analyzed the spatial and temporal variations of Z_i over the SFBA during MABLES WC, simultaneously with the discovery of the eddy at Pt. Reyes (Roope 1980). He noted a distinct trough in Z_i extending from Pt. Reyes southwards, almost to the Monterey Peninsula. Interestingly, the Catalina Eddy has been observed to increase Z_i (Bosart 1983; Wakimoto 1987).

When Z_i increases, the likelihood of clouds increases, along with the ability for the cool moist air to move inland. When Z_i decreases, cloudiness decreases, and the marine air becomes coastally bound. Synoptically, the approach of upper level troughs and surface fronts increases Z_i , sometimes destroying the inversion completely. In contrast, upper level ridging causes a decrease in Z_i (Neiburger et al. 1961; Meitin and Stuart 1977; Gilliland 1980; Lester 1980, 1981; Pinelli et al. 1990; Felsch and Whitlatch 1990).

Because Z_i is linked closely to both, transient,

synoptic scale features, and the lives of millions of people inhabiting the Pacific coastal regions of North America, a clearer understanding of wind and temperature behavior will only help operational weather forecasting. By "stepping back" from the turbulence, waves, and fluxes, to reexamine and verify previous conclusions about the slightly larger scale structures, it is hoped this study will provide additional insight into the behaviors mentioned, and provide data for future researchers to do the same.

Chapter 3. PROCEDURES

3.0 General

The tower, instrumentation, data acquisition, data processing, and analysis are described in this chapter. It is important to note at the outset that because of the long period between the collection of the original data and the completion of the present study (12 years), about 1/3 of the summer 1979 data could not be recovered. Despite careful documentation of observational procedures in a number of publications, theses, reports, and logs (e.g., DeHay 1974; Miller 1975, 1976; Goodman and Miller 1977; Lester 1979, 1980, 1981; Holman 1980; Van Patten 1980; MacArthur et al. 1987), questions about the veracity of some of the remaining data arose during quality assurance and subsequent analysis. These problems and the details of the final quality assured data sample are presented in the following pages.

3.1 Site Description

Mt. Sutro Tower is located near the center of San Francisco, California (Figure 3.1). It is about 5km from the Pacific Coast, on a hill 254m above sea level (ASL). The tower is a television transmission tower (Figure 3.2)

Figure 3.1 - Topographic map of the area around Mt. Sutro Tower.

Figure 3.2 - Aerial photograph of Mt. Sutro Tower,
looking west.

which rises 298m above ground level (AGL). The topmost 65m consists only of antennae; thus, the highest level on which instruments may be installed is 233m AGL (487m ASL). Compared to mean inversion base heights in the SFBA (e.g., 300m ASL; Miller 1976), Mt. Sutro Tower often extends through the inversion base well into the marine inversion. As noted by Miller (1975):

Typically, the bottom third of the tower is enshrouded in fog while the upper two-thirds is in the boundary layer of warm dry air that lies above the marine air during at least six months each year.

The terrain in the immediate vicinity consists of low hills which slope gently to sea level in all directions except southward (DeHay 1974). The tower is not precisely on the highest part of Mt. Sutro. Mt. Sutro summit is 480m northwest of the tower and rises to 277m ASL (24m higher than the tower base). A schematic east-west cross section through the tower and surroundings is shown in Figure 3.3a.

During summer 1979, when the observations discussed in this study were taken, a stand of eucalyptus trees surrounded the site on three sides: north, west, and south (Figure 3.2). The trees extended 13-14m above the tower base and came within approximately 30m of the tower at their closest point (DeHay 1974). More details about the tower and site is given by DeHay (1974).

Figure 3.3 - Mt. Sutro Tower:

(a) Schematic diagram.

(b) West-east cross topographic cross section.

3.2 Meteorological Instrumentation

During STABLE Phase II, the tower instruments consisted of sensors to measure horizontal and vertical wind, dry- and wet-bulb temperature, and pressure. Descriptions of instrument types, manufacturers, response times, and accuracies are given in Table 3.1. Complete instrument packages were mounted on booms at the six levels originally used in Phase I (Figure 3.3b; Table 3.2, Levels labelled 1-6) and dry-bulb temperature sensors alone were installed at three intermediate levels used in 1975 (Levels 1.5, 2.5, and 3.5, Table 3.2).

Important Phase II improvements in the tower sensors included the addition of dry-bulb thermistors (T) at three more intermediate levels (Levels 4.5, 5.5, and 6.5; Figure 3.3b; Table 3.2), and the modification of all dry- and wet-bulb thermistors to half tolerance.

The instrument booms were attached to the westernmost leg of the tower for maximum exposure to the prevailing west-northwest (WNW) flow. The instrument packages on the booms had pendulums attached to monitor the deviation of the boom orientation from the horizontal. The booms at levels 2-6 could also be raised and lowered for servicing. After the wind probes were installed, the booms were purposely aligned a few degrees from the horizontal to

<u>PARAMETERS</u>	<u>INSTRUMENTS</u>	<u>RESPONSE CHARACTERISTICS</u>
Wind west (u) north (v) vertical (w)	Anemometer: R.M. Young Co. Model 2182: Propellor Blades: 4 Diameter: 19cm Pitch: 30cm Polystyrene	Range (all angles): 0-70km hr ⁻¹ Threshold: 0.5-0.7km hr ⁻¹ Distance constant: 0.8m
Temperature (T)	Thermistor: Yellow Springs Instrument Co. Model YSI 705X Urethane coated	Range: -5 to 45°C Accuracy: ±0.075°C Time constant: 0.6s
Wet-Bulb Temperature (T _w)	Thermistor: Yellow Springs Instrument Co. Model YSI 700X	Range: -5 to 45°C Accuracy: ±0.075°C Time constant: 1.4s (without muslin wick)
Pressure (P)	Transducer: Rosemount Model: 12 1201 A2G8BD	Range: 677 to 1084mb Accuracy: Not given Time constant: 25x10 ⁻⁶ s

TABLE 3.1 - Mt. Sutro Tower instrumentation
during STABLE, Phase II.

LEVEL	HEIGHT (m AGL)	HEIGHT (m ASL)	PARAMETERS
6.5	232.4	486.6	T
6.0	218.1	472.3	T, T _w , P _u , V, W
5.5	197.9	452.1	T
5.0	177.4	431.6	T, T _w , P _u , V, W
4.5	154.0	408.2	T
4.0	134.1	388.3	T, T _w , P _u , V, W
3.5	110.9	365.1	T
3.0	86.9	341.1	T, T _w , P _u , V, W
2.5	65.6	319.8	T
2.0	43.4	297.6	T, T _w , P _u , V, W
1.5	24.2	278.4	T
1.0	4.9	259.1	T, T _w , P _u , V, W

Table 3.2 - Sensors at each level during STABLE, Phase II.

overcome problems associated with the starting threshold for the vertical velocity probe. The angular deviation from the vertical, as measured by the pendulums, was used by the HP9825A calculator in the Data Acquisition System (see Section 3.3 below) to correct the horizontal wind and vertical velocity measurements (Miller 1975; Lester 1981).

3.3 Data Acquisition

The primary features of the Mt. Sutro Tower Data Acquisition System (DAS) have been described in detail by DeHay (1974) and by Lester (1981). What follows is a review of Phase II improvements which are pertinent to the current study.

Probably the most important Phase II DAS improvement consisted of major changes to the analog-to-digital (A/D) signal converters. Originally (Phase I), these had been located near the instrument packages at the ends of the booms to suppress problems with radio frequency (RF) noise from the tower antennae. For Phase II, the A/D converters at the ends of the booms were removed. The analog signals were sent via shielded cable to a single, improved, A/D converter housed at the base of the tower (Lester 1985).

Figure 3.4 presents a simplified schematic of the improved DAS. Note the "16 Channels of Instrumentation" at

Figure 3.4 - Schematic flow diagram of the data acquisition system.

levels 1-6 included extra channels for the intermediate temperature levels (1.5, 2.5,...,6.5; see Table 3.2). The central piece of hardware in the DAS was the Hewlett-Packard 3052. It included a data scanner, clock, calculator, and digital voltmeter (DVM). The HP 9825A calculator acted as the controller. The DAS was capable of scanning 125 channels per second, measuring 3-1/2 digits to 0.1mv, had a 100 (expandable to 180) channel capacity with greater than 120db of common mode rejection ratio. The upgraded DAS performed well. The system down time was greatly reduced over Phase I performance (Lester 1981).

Data acquisition schedules for all portions of STABLE, Phase II, i.e., including MABLES WC, have been documented by Lester (1979, 1981). Between June 1978, and March 1980, most of the data were sampled at a "slow scan" rate of one per 5 minutes. Between June and October 1978, approximately 125 two hour fast scan (one per 3 seconds) blocks were sampled, some in support of MABLES WC (Lester 1979; MacArthur et al. 1987). The current study, however, uses data taken during June - September 1979, all of which were sampled at a rate of one per 5 minutes.

3.4 Data Processing

The processing of Mt. Sutro Tower data from summer 1979

was performed to identify usable information, to correct systematic errors (biases), and to prepare the data for subsequent analysis. In addition, extra steps in the processing of the tower data were necessary at the outset because of two practical problems. First, the original data had been stored on 7-track magnetic tapes since 1980, while 9-track had become the industry standard. Therefore, before anything else could be done, the old tapes had to be converted to 9-track. Secondly, the formats of the raw data tapes varied considerably; these had to be standardized and data merged to facilitate further data processing.

Subsequent data processing procedures consisted of the six tasks that are shown in Figure 3.5 in a simple flow diagram. A brief discussion of each task follows.

3.4.1 Tape Conversion; Data Set Selection

All 7-track data tape labels were compared to the data inventory and tape log notebooks kept during summer 1979. Observational period covered, observational scan rate, number of files, and block and record lengths of each file on each tape were verified. At this step it was discovered the raw data tape holding the 1-15 August 1979 observations was accidentally destroyed in 1980. Also, problems with

Figure 3.5 - Data processing flow diagram for this study.

several of the data tapes occurred during the tape conversion process. The conversions of tapes with data from 8-28 June, and both 8-22 and 26-28 September, were unsuccessful. The final data set consisted of data for two separate periods (54 days total) from summer 1979: 1-31 July and 16 August-7 September (hereafter identified as "Jul79" and "AugSep79", respectively).

3.4.2 Data Merge

Having established the raw data set in a series of disk files, the next step consisted of merging the files into one chronological file, i.e., by day and by hour. This required the examination of each data file to determine the block size and record length, since they varied from tape to tape. Seven separate computer programs were required to read the variable data files and, finally, to write the data to disk in a single file with a standardized format. In addition, missing data and any unrecognizable data were identified with a standard missing data flag.

3.4.3 Gross Error Detection and Elimination

In this step obviously bad data were identified and eliminated. Additionally, any questionable data were flagged for further checking.

Wind, vertical velocity, and temperature data were identified as bad if they exceeded a predetermined, large threshold, i.e.,

$$|u|, |v| \geq 50\text{ms}^{-1} \quad (3.1)$$

$$|w| \geq 10\text{ms}^{-1} \quad (3.2)$$

$$T \leq 0^{\circ}\text{C} \quad (3.3)$$

$$T \geq 36^{\circ}\text{C} \quad (3.4)$$

Wet bulb temperatures and pressure were handled slightly differently. In any case where $T_w > T$, T_w was replaced with the missing data flag. Pressures were checked by verifying that the pressure at the level above was less than the pressure at the current level; if not, both were set to the missing data flag.

After checking for extreme values, a "buddy check" was carried out by intercomparing monthly frequency distributions of all parameters at all levels. Although this is a somewhat subjective exercise, it is useful in the identification of erroneous (extreme) variances and instrument drift. If the monthly frequency distribution of a parameter at a particular level indicated a problem, then daily frequency distributions of that parameter were examined. The systematic examination of those distributions allowed individual days with bad data to be identified.

As an example, Table 3.3 shows the frequency

NUMBER OF OBSERVATIONS OF INDIVIDUAL TEMPERATURES AT
TOWER LEVELS:

T	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5
≤0:	1937	2	461	1	0	3	0	0	0	0	0	0
1:	1695	0	234	0	0	3	0	0	0	0	0	0
2:	1276	0	193	0	0	0	0	0	0	0	0	1
3:	1380	0	192	0	0	0	0	0	0	0	0	0
4:	755	0	173	0	5	0	0	0	0	0	0	0
5:	459	0	174	0	129	0	0	0	1	0	0	0
6:	256	0	190	1	379	0	9	0	0	38	0	0
7:	142	0	202	0	436	3	130	70	0	280	127	1
8:	101	59	298	1	835	156	267	347	186	313	154	1
9:	51	856	534	312	712	611	403	549	339	503	300	148
10:	10	1707	474	1022	1148	1024	515	880	635	567	595	307
11:	1	2105	741	1489	1124	1377	777	921	630	632	518	451
12:	0	1394	654	1688	816	1190	699	743	735	519	483	456
13:	0	734	343	1235	499	678	525	573	584	463	565	429
14:	0	474	312	684	387	451	420	445	594	388	557	477
15:	0	390	235	427	342	375	377	386	403	356	360	513
16:	0	272	214	267	243	294	340	312	369	293	238	482
17:	0	159	215	181	168	190	252	211	255	273	229	435
18:	0	152	211	111	152	181	198	229	310	279	286	363
19:	0	114	171	137	151	182	205	228	280	316	331	298
20:	0	92	194	151	165	210	229	280	301	329	363	300
21:	0	58	219	153	199	178	255	266	341	327	411	331
22:	0	81	287	173	181	231	271	316	281	335	308	362
23:	0	66	294	160	194	253	299	329	370	407	316	369
24:	0	44	252	134	139	262	306	387	446	460	475	424
25:	0	7	209	94	126	284	283	329	472	451	632	514
26:	0	3	164	72	100	257	232	318	394	362	565	491
27:	0	2	101	56	64	173	192	256	328	346	335	509
28:	0	0	65	31	41	87	174	213	273	263	317	406
29:	0	0	54	21	22	54	57	110	163	139	195	331
30:	0	0	53	17	12	30	43	46	75	73	117	197
31:	0	0	56	4	10	15	21	25	18	58	6	95
32:	0	0	42	0	5	6	12	7	0	11	0	72
33:	0	0	34	0	0	0	1	0	0	0	0	17
34:	0	0	24	0	0	0	0	0	0	0	1	0
35:	0	0	17	0	0	1	0	0	0	0	0	1
36:	0	0	18	0	0	1	0	0	0	0	0	1
≥37:	721	13	455	10	0	15	1292	4	1	2	0	0
MSSNG:	0	0	25	152	0	9	0	4	0	1	0	2

TABLE 3.3 - Temperature distribution
during July 1979.

distribution of temperature for July 1979. Temperature observations from Level 1.0 were exceptionally low during most of the month. Level 2.0 observations spanned an excessive range, falling to $\leq 0^{\circ}\text{C}$ 461 times, and rising to $>36^{\circ}\text{C}$ 455 times. Level 3.0 also appeared to have a cold bias. The latter problem was emphasized by the frequent occurrence of an unrealistic superadiabatic lapse rate between Levels 2.5 and 3.0. Also, the Level 4.0 sensor had many data with observations $>36^{\circ}\text{C}$. A further examination of daily frequency distributions for Level 4.0 during July revealed the monthly warm bias was caused by problems on 1-5 July. This particular finding was also verified by logs of tower/instrument status kept throughout STABLE, Phase II, i.e., the Level 4.0 T-sensor was logged as inoperative during 1-5 July.

Finally, averages and variances for each parameter were computed as a function of tower level and hour of the day. The means and variances were then examined for unusually large values compared to surrounding hours/levels. Suspect parameters, dates, and levels were noted for more detailed evaluation during subsequent data processing and analysis.

3.4.4 Wind Correction for Tower Effects

Ballanti, (1976), simultaneously with STABLE, Phase I,

conducted detailed wind tunnel analyses of the effects the tower would have on in situ wind measurements. On the basis of that study, he

- 1) concluded that the tower has a significant effect on wind measurements, especially downwind;
- 2) derived correction factors based on tower level and direction of wind flow, using a 1:75 scale model in a wind tunnel;
- 3) Suggested Miller's (1976) results be reanalyzed using his corrections, and that his corrections be used in future studies;
- 4) Suggested a study be undertaken to determine the tower effects on vertical velocity observations.

On the basis of Ballanti's (1976) findings, u and v data for Jul79 and AugSep79 were modified, using the matrix of correction values derived from his study (Table 3.4). Assuming the observed direction was correct, the actual wind speed (V_a) for each observed direction was determined as a function of the observed wind speed (V_o) and the correction factor (K) from Table 3.4, i.e.,

$$V_a = V_o / K \quad (3.5)$$

As would be expected, the greatest corrections were for easterly winds because of tower blockage. The observed easterly winds were reduced to as little as 35% of the actual value at Level 1.0. However, because winds were prevailing westerly, most correction factors were in the range 0.90 to 1.10; with typical speeds (10ms^{-1}) the most

WIND DIRECTION (degrees)	TOWER LEVELS: <u>1.0</u>	<u>2.0</u>	<u>3.0</u>	<u>4.0</u>	<u>5.0</u>	<u>6.0</u>
10	1.20	1.15	1.07	1.02	1.10	.97
20	1.24	1.19	1.11	1.02	1.06	1.00
30	1.28	1.24	1.13	1.04	1.06	1.00
40	1.27	1.27	1.17	1.05	1.06	1.00
50	1.08	1.26	1.15	1.05	1.06	.98
60	.90	1.04	.98	.90	.81	.77
70	.43	.70	.50	.65	.52	.72
80	.41	.60	.42	.42	.41	.55
90	.35	.70	.36	.37	.41	.51
100	.38	.54	.42	.41	.60	.57
110	.53	.82	.46	.59	.71	.80
120	.62	1.12	.63	.88	.99	.92
130	1.28	1.36	.94	.99	1.01	.95
140	1.30	1.36	1.22	1.04	1.02	1.02
150	1.27	1.29	1.18	1.04	1.06	.95
160	1.25	1.16	1.10	1.00	1.00	.94
170	1.22	1.16	1.08	1.01	1.05	.92
180	1.11	1.08	1.08	.97	1.02	.93
190	1.07	1.10	1.08	.96	1.02	.93
200	1.04	1.12	1.07	.96	1.00	.93
210	1.03	1.07	1.04	.95	1.00	.91
220	.96	1.00	1.03	.96	.99	.90
230	.94	.93	1.02	.92	1.00	.95
240	.92	.93	.95	.89	1.00	.95
250	.93	.86	.92	.89	.98	.96
260	.85	.86	.88	.93	.98	.97
270	.80	.83	.87	.92	.97	.98
280	.79	.85	.87	.95	.98	.99
290	.92	.94	.90	.95	.97	1.00
300	1.07	.96	.93	.96	.99	.99
310	1.08	1.00	.93	.96	.96	1.03
320	1.13	1.04	.98	.97	.98	.96
330	1.10	1.04	1.00	1.00	1.04	.95
340	1.11	1.08	1.04	.97	1.00	.95
350	1.17	1.08	1.05	.99	1.01	.97
360	1.23	1.10	1.05	1.02	1.00	.97

Table 3.4 - Wind correction matrix derived from Ballanti (1976).

frequent corrections were of the order $\pm 1\text{ms}^{-1}$.

3.4.5 Temperature Bias Removal

As noted in Section 3.4.3, Level 3.0 temperatures showed a cold bias. An attempt was made to estimate an average bias as the difference between the monthly average of T at Level 3.0 and the average of a linearly interpolated value between Levels 2.5 and 3.5. The difference for Jul79 was -1.5°C , while for AugSep79 it was -1.9°C . A similar exercise was accomplished for Level 5.5. Results showed that Level 5.5 also had cold biases which were -0.6°C during Jul79, and -0.5°C during AugSep79. In addition to the biases, the computations revealed an apparent drift in both temperature elements. Since it was not possible to determine the rate of drift of either the Level 3.0 or the Level 5.5 sensors, those data were subsequently eliminated from the final data base.

3.4.6 Wet Bulb Temperature Data Elimination

An ongoing and unsolved problem for STABLE, Phase I and II, was the rapid drying out of the wet-bulb water reservoirs above the inversion base. Without corroborating, independent cloud observations, zero

wet-bulb depressions were often ambiguous; i.e., they were not necessarily related to saturated conditions (Lester 1981). Since there were no such independent observations in 1979 at Mt. Sutro, wet-bulb temperature data were not included in the final data base for later analysis.

3.4.7 Hourly Averages

As a final step in the data processing, hourly averages were calculated for every parameter at each hour and day within the data base; i.e.,

$$x_h = \frac{1}{12} \sum_{i=1}^{12} x_i \quad (3.6)$$

where: h is the hour in question (1-24);
 i are the individual 5-minute observations
from the preceding hour.

The averaged data were placed into separate disk files for each meteorological parameter. Separate, daily, disk files were also created for quality assured 5-minute tower observations of all variables. The hourly averaged files and the 5-minute daily data files were then downloaded from mainframe to diskette to facilitate analysis on personal computers. Table 3.5 shows, for each observed variable, the approximate percentage of hourly averaged data available for subsequent analysis.

	JUNE	JULY	AUGUST	SEPTEMBER
Notes:	1,2,6	2,3,4,5,6	3,6,7,8,9,10	3,6,11,12,13
	T: 4%	T: 78%	T: 39%	T: 25%
	u: 4%	u: 97%	u: 52%	u: 36%
	v: 4%	v: 97%	v: 52%	v: 36%
	w: 4%	w: 97%	w: 52%	w: 36%
	P: 4%	P: 83%	P: 44%	P: 32%

Notes:

- 1 - For period 1-28 Jun, tape to tape (7 to 9 track) transfer unsuccessful.
- 2 - From 29 Jun to 5 Jul, Level 4.0 out of service for all variables.
- 3 - Level 1.0 T-sensor had extreme cold bias during period.
- 4 - During 6-31 Jul, Level 2.0 T-sensor fluctuated wildly (e.g., varied from <0 to >40°C).
- 5 - On 30-31 Jul, Levels 1.5-3.5, inclusive, T-sensors provided bad data.
- 6 - Level 6.0 P-sensor very erratic during entire period (e.g., pressures often > Level 5.0).
- 7 - Level 6.5 T-sensor had extreme cold bias during period.
- 8 - For 1-15 Aug 79, original data tape destroyed in 1980. Data unavailable to this study.
- 9 - During 16-24 Aug, Level 3.5 T-sensor provided incorrect data.
- 10 - During 20-31 Aug, Level 4.0 T-sensor data bad.
- 11 - During 1-8 Sep, Level 4.0 T-sensor data bad.
- 12 - Level 2.0 T-sensor bad for entire period.
- 13 - For period 8-22 Sep 79, and 26-30 Sep 79, the tape to tape (7 to 9-track) transfer was unsuccessful.

TABLE 3.5 - Summer 1979 data set.

3.5 Data Analysis

In order to "expand and verify" STABLE, Phase I observations with summer 1979 observations from Phase II, the work of Miller (1976) was used as a guide. Miller's (1976) analyses can be divided into three distinct parts:

- 1) Climatology: Monthly distributions of hourly averaged data.
- 2) Case Studies: Day-to-day variations of hourly averaged data under specific synoptic conditions.
- 3) Turbulence: turbulent fluxes and profiles based on data gathered at 3-second intervals.

To ease comparison with Miller (1976), identical analyses were performed during this study, to be presented in identical formats, wherever possible.

There are three major differences between the data base available in this study (summer 1979) and that used by Miller (1976):

- 1) The 1979 data sample consisted of only 54 days, whereas Miller (1976) used 90 days. Miller (1976) stated the small amount of valid data is attributed to "the extremely harsh environment of Sutro Tower. There is frequent fog composed of droplets formed on sea salt; very rapid, large magnitude temperature changes; and high-energy emissions from dozens of radio and TV antennas that tend to saturate all electronic devices..." (see also Lester 1981).
- 2) The combination of data for 16-31 August and 1-7 September into one period of study (AugSep79) precluded an exact comparison with any of Miller's (1976) August or September analyses. For this reason, and because of some ambiguities in the temperature data, the AugSep79

results are presented with a brief description in Appendix A. Chapter 4 (Results), therefore, concentrates on the analyses from July 1979.

3) Turbulence data (3-second samples) were not available in summer 1979. A study of some of those higher frequency data from STABLE, Phase II, summer 1978 (MABLES WC) has been accomplished by MacArthur, et al (1987).

3.5.1 Climatology

The climatological parts of Miller's (1976) work and the current study were designed to quantify inversion strength, height, and wind profiles, and their diurnal variations. The specific climatological analyses performed in the current study to accomplish these aims are listed with Miller's (1976) analyses in Table 3.6. Note that additional analyses (items a,b,f,h,j,k in Table 3.6), not done by Miller (1976), were carried out to "expand" the STABLE, Phase I results. Whereas Miller's (1976) height-time section analyses were performed by hand, several commercial software packages were used to produce those analyses and the other figures in the current study. These included IBM GKS Graphics, Computer Associates' DISSPLA Graphics package, Software Publishing Corporation's HARVARD GRAPHICS, and Golden Software's SURFER graphics package.

MILLER (1976) ANALYSES

CURRENT STUDY ANALYSES

a. No equivalent.	a. July inversion base mean heights by hour (Fig. 4.1).
b. No equivalent.	b. July Sutro Tower/Oakland inversion base heights at 1600 PST (Fig. 4.2).
c. July mean temperature profiles at selected hours (Fig. 1a).	c. July mean temperature profiles at selected hours (Fig. 4.3).
d. July mean temperature curves by tower level (Fig. 2a).	d. July mean temperature curves by tower level (Fig. 4.4).
e. July mean temperature height-time section (Fig. 2b).	e. July mean temperature height-time section (Fig. 4.5).
f. No equivalent.	f. July mean temperatures by number of levels above/below the inversion base (Fig. 4.6).
g. July hodographs of mean diurnal wind variation (Fig. 5a,b).	g. July hodographs of mean diurnal wind variation (Fig. 4.7).
h. No equivalent.	h. July mean wind profiles at selected hours (Fig. 4.8).
i. July mean wind curves by tower level (Fig. 6b).	i. July mean wind curves by tower level (Fig. 4.9).
j. No equivalent.	j. July mean wind direction/speed height-time section (Fig. 4.10).
k. No equivalent.	k. July mean u- and v-component height-time section (Fig. 4.11).
l. July mean vertical velocity profiles at selected hours (Fig. 3a).	l. July mean vertical velocity profiles at selected hours (Fig. 4.12).

TABLE 3.6 - Analyses performed by Miller (1976) and in this study. Note that figure numbers for Miller (1976) are from his study.

3.5.2 Case Study

The extended case study analysis was designed to document the behavior of the inversion and the associated wind profiles during a period (19-26 Jul 79) when there was a variety of typical summer synoptic changes. These included the passages of weak upper level troughs and ridges (e.g., see Gilliland 1980). Conventional weather map analyses and satellite images are used to describe and document synoptic circulations and cloud features. Twenty-four hour height-time sections have been constructed to show the response of the inversion to those features.

Six different computers were utilized in the data analysis described here. These include the SJSU Cyber 170 mainframe, an Air Force Global Weather Central Sperry 1172 mainframe, an AT & T PC-6300, and several SJSU personal computers, including IBM PC-XT, IBM PC-AT, and ELTECH 386.

Chapter 4. RESULTS

4.0 General

The analyses of the Mt. Sutro Tower data described in the previous chapter are presented here. Where possible, they are presented in the order of Miller's (1976) analyses of STABLE Phase I (1974-1975) observations (see Tables 3.7 and 3.8).

Mean properties of the marine inversion are considered first (section 4.1), followed by a case study analysis illustrating typical day-to-day variations of the temperature and wind structure of the inversion (section 4.2).

4.1 Climatology

4.1.1 Temperature

4.1.1.1 Diurnal Variations of Inversion Structure

Figure 4.1 shows the mean, diurnal cycle of Z_i as recorded on the tower. Z_i reached its minimum at approximately 1600 PST in Jul79, and its maximum at 0600-0700 PST. These results agree with Miller's (1976) observations of the occurrence of Z_i minima at 1600-1800 PST and maxima at 0200-0600 PST (he did not provide any more Z_i specific information than that). Many other investigators have observed the same diurnal pattern in Z_i movement; i.e., high during morning, low during afternoon/evening (e.g., Neiburger 1944; Edinger 1959; Russell 1976; Simon 1977).

The location of Z_i was determined using a computer algorithm which searched for specified positive temperature gradients between adjacent tower levels, beginning at the bottom and working to the top of the tower. The algorithm reported all simultaneous occurrences of the specified gradient or greater. In those instances where some doubt existed as to where Z_i was located, daily height-time sections of hourly averaged temperatures were examined, and a subjective judgement made to settle the matter.

Figure 4.1 - Jul79
inversion base mean heights.

Figure 4.2 - Inversion Base Heights at
Sutro Tower/Oakland--1600 PST July 1979.

Mean Z_i for Jul79 was approximately 390m ASL (roughly Level 4.0). Miller (1976) and Miller and Goodman (1977), for their periods of observation, reported mean Z_i of 300m ASL (Level 2.0). During Jul79, Z_i is significantly higher than during summers 1974 and 1975. However, Neiburger et al. (1961), reported mean Z_i of 414m ASL at Oakland (see Figure 3.1) for July, based on 566 soundings available to their study. Van Patten (1980a,b), using tower data from summer 1976, reported mean Z_i of 378m ASL, so the average for Jul79 is not unusual.

Miller (1976) reported that the mean diurnal change in Z_i during summers 1974 and 1975 was approximately 120m. In contrast, the magnitude of the mean diurnal change in Z_i was 100m in Jul79. According to Neiburger (1960), Blake, in 1928, reported mean diurnal fluctuations in Z_i at San Diego of 102m, and King (1980), using summer 1978 tower data, observed 100m mean diurnal changes in Z_i .

Figure 4.2 is a comparison of Z_i as seen at 1600 PST by the instruments on Mt. Sutro Tower and the Oakland radiosonde (Miller 1976 did not provide corresponding information). There is good agreement in the phase of movement of Z_i , although the amplitudes often show large differences. This result is in agreement with previous studies which have shown that the inversion is generally higher over higher terrain (e.g., Edinger 1959; Williams

and DeMandel 1966; Miller 1968; Goodman and Miller 1977; Russell and Uthe 1978; Erickson 1981). In the SFBA, Williams and DeMandel (1966), Miller (1968, 1975, 1976), and others have shown that not only is the inversion lower over the Bay (as represented by the Oakland soundings; Figure 4.1) and higher over the hills (e.g., at Mt. Sutro), but also that height changes at both locations are well correlated. The only exception to this (as noted in Figure 4.2) is when the inversion base is very high and/or weak. Miller (1976) stated the amplitude at Mt. Sutro Tower is approximately half that seen in the Oakland radiosonde.

4.1.1.2 Temperature Profiles

Figure 4.3 shows the mean vertical profiles of temperature at four selected hours during Jul79. Note Levels 1.0, 2.0, 3.0, and 5.5 were removed from the final Jul79 data set (see Chapter 3). The profiles are very similar to Miller's (1976) results for July 1974, i.e., rapid heating at all levels between 0600 and 1200 PST, and rapid cooling between 0000 and 0600 PST. The most distinctive difference is found at 1200 PST, where July 1974 had a positive, slightly superadiabatic, lapse rate between Levels 1.0 and 2.0. The lapse rate during Jul79 was everywhere negative. This difference between July 1974

Figure 4.3 - Jul79 mean temperature profiles at selected hours.

Figure 4.4 - Jul79 mean temperature curves by tower level.

and Jul79 may be attributable to the inoperative T-sensor at Level 1.0 during summer 1979.

4.1.1.3 Mean Diurnal Temperature Variations by Level

Figure 4.4 shows the mean diurnal temperature curves for each available level during Jul79. In comparison to Miller (1976), Jul79 was warmer than July 1975, with greater diurnal variability in the temperature range, especially in the higher (drier) tower levels. The higher and upper middle levels (4.0 - 6.5), almost always in the inversion layer, had diurnal ranges of 4-5°C, whereas the lower levels (1.5 and 2.5) which were almost always within the marine air, varied diurnally less than 2°C. These results agree with Miller's (1976) observations of a maximum diurnal variation at Level 6.0 of 4°C, and a minimum at Level 2.0 of 2°C during July 1975.

July 1975 maximum mean temperatures occurred between 1500 and 1600 PST. Jul79 maximum mean temperatures occurred between 1600 and 2000 PST, and depended on the level; the higher levels reached their maxima earliest. In July 1975 the upper levels were last to reach their mean maxima. A feature which was quite distinct in Miller (1976) was a pronounced local maxima in temperatures at 2100-2200 PST. This maxima occurred at Levels 4.0-6.0

during July 1975, but is absent from the Jul79 analysis.

Jul79 mean temperatures exceeded 20°C at levels 5.0 - 6.5 (430m-490m ASL), with Level 6.5 reaching 22°C and Level 6.0 achieving 21°C. Mean July 1975 temperatures never reached 20°C; Level 6.0 only climbed above 19°C and Level 5.0 reached 18°C. Comparing the middle levels (including 3.0, 3.5, 4.0, and 4.5) July 1975 mean temperatures climbed to 16°C at Levels 3.0 and 4.0. During Jul79 Levels 4.0 and 4.5 reached 19°C; Level 3.5 only got to 16°C. Lower down on the tower, July 1975 Level 2.0 was very similar to Jul79 Level 2.5.

4.1.1.4 Temperature Height-Time Sections

Figure 4.5 shows the mean isotherm patterns for Jul79. Miller (1976) presented results for July 1975. The location of the inversion base in Figure 4.5 is vague because of the averaging process. Similar to Miller's (1976) results, mean temperatures increase continuously from the lowest tower levels through the highest at all hours. Also evident in both Miller (1976) and the current study is the diurnal oscillation of Z_i , with higher Z_i in the morning and lower Z_i in the afternoon. A phase difference does exist between the July 1975 and Jul79 Z_i oscillations, however. On the average, Z_i reached its

Figure 4.5 - Jul79 mean temperature ($^{\circ}\text{C}$)
height-time section.

lowest point earlier in the afternoon during July 1975, and closer to evening in Jul79. Comparing figures, it appears that gradients were generally stronger at the middle and upper tower levels during Jul79 for most of the day. Possible reversals occurred in the late evening and early morning hours in the upper tower levels, where it appears that July 1975 had slightly stronger gradients. In the lower levels, July 1975 had stronger gradients. Without Level 1.0 during Jul79, however, it is somewhat of an improper comparison.

4.1.1.5 Diurnal Temperature Variations Relative to Z_i

In order to show more detail of the temperature profile with respect to Z_i (to compensate for the smearing of Z_i in Figure 4.5), Figures 4.6a and b show the diurnal variations of temperatures at levels relative to Z_i (heavier, solid line). Miller (1976) gave no corresponding information or figure, though Goodman and Miller (1977) provide similar information in a different format. As would be expected, the temperature at levels above Z_i (Figure 4.6a) and below (Figure 4.6b) Z_i are warmer than at Z_i . The well mixed layer shows only small temperature differences between levels while the inversion layer displays large increases as the number of levels

Figure 4.6 - Jul79 mean temperatures by number of levels:

Levels Above Z_1

— 5th Lvl Above Z_1	-+- 4th Lvl Above Z_1	* 3rd Lvl Above Z_1
-o- 2nd Lvl Above Z_1	-x- 1st Lvl Above Z_1	—•— Inversion Base (Z_1)

Levels Below Z_1

— 5th Lvl Below Z_1	-+- 4th Lvl Below Z_1	* 3rd Lvl Below Z_1
-o- 2nd Lvl Below Z_1	-x- 1st Lvl Below Z_1	—•— Inversion Base (Z_1)

(b) Below Z_1

above Z_i increases. Also, as shown in Figure 4.4, the diurnal variation of temperature is significantly greater in the drier inversion air.

4.1.1.6 Lapse Rates

In Table 4.1 the mean and instantaneously most extreme vertical lapse rates (standardized to $^{\circ}\text{C}/100\text{m}$) between tower levels are listed. Miller (1976) reported a mean lapse rate above Level 2.0 of $2.2^{\circ}\text{C}/100\text{m}$. During Jul79, the average lapse rate above Level 2.0 was 3.6°C . The large gradient between Levels 4.0 and 5.0 during Jul79 is indicative, perhaps, of mean Z_i , which corresponds well to mean Z_i shown in Figure 4.1. The largest vertical temperature difference observed between Levels 1.5 and 6.5 was 21°C .

As mentioned, Table 4.1 also lists extreme lapse rates observed on the tower during Jul79. Note that though all values are listed with units of " $^{\circ}\text{C}/100\text{m}$," the actual vertical distances over which these measurements were taken were much less, varying from approximately 13 meters to 25 meters. The strongest positive gradients ranged from 60°C - $70^{\circ}\text{C}/100\text{m}$. These compare well with the strongest positive gradient Miller (1976) observed of $12^{\circ}\text{C}/20\text{m}$ ($60^{\circ}\text{C}/100\text{m}$). Although tower Levels 3.0 and 5.5 were

<u>LEVELS</u>	<u>HEIGHTS (m ASL)</u>	<u>MEAN T-GRADIENTS</u>	<u>EXTREME T-GRADIENTS</u>	
			<u>OBSVD VALUE</u>	<u>DATE/TIME (dd/hhmm)</u>
1.0-1.5	259.1 - 278.4	n/a	n/a	n/a
1.5-2.0	278.4 - 297.6	+3.2	n/a	n/a
2.0-2.5	297.6 - 319.8	+3.2	+40.3	13/2000
2.5-3.0	319.8 - 341.1	+0.6	+70.5	19/1845
3.0-3.5	341.1 - 365.1	+2.5	+68.4	19/2300
3.5-4.0	365.1 - 388.3	+1.3	+50.7	19/1620
4.0-4.5	388.3 - 408.2	+5.0	+66.2	17/1110
4.5-5.0	408.2 - 431.6	+5.4	+57.0	19/1255
5.0-5.5	431.6 - 452.1	-1.2	+63.1	19/0500
5.5-6.0	452.1 - 472.3	+4.8	+57.3	19/0700
6.0-6.5	472.3 - 486.6	+11.2	+53.0	01/1950

TABLE 4.1 - Mean and extreme July 1979
vertical temperature gradients.

removed from the final quality assured data set because of suspected cold biases, extreme lapse rate data for these levels are included in Table 4.1. The lapse rates in Table 4.1 were calculated from the original ("uncorrected") observations at Levels 3.0 and 5.5 (see Chapter 3).

4.1.2 Wind

4.1.2.1 Hodographs

Figures 4.7a and b show hodographs illustrating the mean diurnal variation of the wind for Jul79. In comparison, Miller (1976) found "the marked elliptical [wind] oscillation is clockwise at every level, with the major axis having a 110° - 290° orientation...." In contrast, while the analyses presented in Figures 4.7a and b show similarly oriented elliptical hodographs, the rotation is counterclockwise (CCW). The significance of the CCW rotation in this study is unclear, as is the reason for the difference compared to Miller (1976). Atkinson (1981; among others) makes clear that clockwise (CW) rotation is expected in the northern hemisphere because of frictional effects and the Coriolis force.

It must be mentioned, however, that CCW rotation has been observed in earlier studies in and near the SFBA. For example, Miller (1968) reported counterclockwise rotation at San Francisco International Airport, among other locations. Fosberg and Schroeder (1966) showed both clockwise and counterclockwise rotation in a study performed just north of the SFBA. Because the oppositely directed hodographs were circumstantial evidence of a data problem, specifically in the v-component, much effort was

Figure 4.7 - Jul79 hodographs of mean diurnal wind variation:

(b) Levels 1.0, 3.0, 5.0

expended checking data and algorithms to determine if errors exist in the current study. None has been found. Even if an error has been made, it cannot be said conclusively that it exists in STABLE, Phase I (Miller 1976), or STABLE, Phase II (the current study).

4.1.2.2 Mean Wind Profiles

Figures 4.8a and b present mean wind profiles at selected hours from Jul79. Two figures were provided here to more clearly delineate the periods/rate of increasing wind speeds (Figure 4.8a) and the periods/rate of decreasing wind speeds (Figure 4.8b). Note that minimum wind speeds (in the hours selected) occurred near 0900 PST, and they increased to maximum speeds near 1800 PST, i.e., a period of nine hours. In contrast, the winds required 15 hours to decrease in speeds back to the values around 0900 PST. (Note, the minimum mean wind speeds actually occurred about 0800 PST and the maximum at 1800-1900 PST, so the results from Figures 4.8 are reasonably accurate.) The maximum wind speed at all hours shown in Figures 4.8 occurred near Level 3.0. The increase in speed between Levels 1.0 and 2.0 at all hours is striking. Surface effects, including friction and the 14m eucalyptus trees (see Chapter 3), account for most of the decrease at Level

Figure 4.8 - Jul79 mean wind profiles
at selected hours:

(a) increasing wind speeds

(b) decreasing wind speeds

1.0 (located six meters AGL).

Miller (1976) presented a similar, single figure detailing selected mean winds only from 25-30 June 1974. As in this study, his results also showed maximum winds near 1800 PST, but the minimum occurred near 0600 PST, providing a balanced 12 hour period of both increasing and decreasing wind speeds. Most of the speed maxima at different hours occurred near Level 4.0 in the June 1974 period, though 2100 PST showed a Level 3.0 maximum, and 0900 PST showed a Level 5.0 maximum. Miller's (1976) results, however, were not modified using Ballanti's (1976) correction factors, as were the winds in this study.

4.1.2.3 Mean Diurnal Wind Curves

Mean diurnal curves of wind speeds for each tower level are given in Figure 4.9. The curves in Figure 4.9 show maximum speeds occurred near Level 3.0 (342m ASL) during Jul79. Miller (1976) provided a similar figure for July 1975. He observed maximum wind speeds on Level 4.0 during July 1975.

Miller's (1976) results show that Levels 2.0 - 6.0 had wind speeds within about 1ms^{-1} of each other, while Level 1.0 had speeds $2-4\text{ms}^{-1}$ less than any other level. In the current study wind speeds were generally less at levels 2.0

Figure 4.9 - Jul79 mean wind curves by tower level.

- 6.0 at all hours of the day during Jul79, than during July 1975. Speeds at Level 1.0, however, were similar between the two periods in the mornings, with slightly higher speeds during Jul79 in the afternoons. The latter result may be partly caused by the application of Ballanti's (1976) wind speed correction factors (see Chapter 3), which generally increased slightly the observed speeds at Level 1.0.

Miller's (1976) speeds do not reflect the corrections calculated by Ballanti (1976). Prior to applying Ballanti's correction factors to the data in the current study, the greatest wind speeds were found near Level 5.0 during Jul79. Ballanti (1976) noted that without correction, a wind speed maximum observed near Levels 4.0 - 5.0 could be tower induced. The actual speed maximum would be between Levels 3.0 and 4.0. The results in the current study appear to support that hypothesis.

Diurnally, from Figure 4.9 it can be seen the winds began increasing at all levels around 0800-0900 PST. The rate of increase at Levels 1.0 and 2.0 remained fairly constant throughout the day. The rates of increase for the other levels, however, shows an increase around 1200-1300 PST, which is about the time the sea breeze typically begins. This result disagrees with Williams and DeMandel (1966; among others) who observed the sea breeze begin in

the surface winds and move upwards. They observed the sea breeze at a coastal station, however. Mt. Sutro Tower is 5km from the coast. The increased frictional effects from the intervening city, as well as the eucalyptus trees, could account for the sea breeze arriving first at levels above 1.0.

4.1.2.4 Mean Wind Height-Time Sections

Figure 4.10 shows a height-time section of the mean monthly wind speeds and directions for Jul79. Figures 4.11a and b show the corresponding Jul79 average u- and v-component analyses. In these figures the jet shows up clearly (in the u-component rather than the v-component). Miller (1976) did not provide corresponding figures. Clear also is the mean diurnal pattern of the wind, especially the speeds. There existed during Jul79 a minimum in mean speed in the morning, with a maximum in the late afternoon and early evening. Maximum mean vertical wind shear occurred beneath the afternoon wind maximum, close to the mean Z_i . Shears increased downwards from about $3.2 \times 10^{-2} \text{s}^{-1}$ immediately below the maximum, to about $6.3 \times 10^{-2} \text{s}^{-1}$ between Levels 1.0 and 2.0. This generally agrees with Miller (1976) who found maximum vertical wind shears usually between Levels 2.0 and 4.0, near mean Z_i .

Figure 4.10 - Jul79 mean wind direction (degs--dashed lines) and speed (ms^{-1} --solid lines) height-time section.

Figure 4.11 - Jul79 mean wind (m s^{-1}) height-time sections:
 (a) U-component (b) V-component

Miller (1976) did not provide mean values of shear, though the results above are in agreement with values given in some of Miller's (1976) case studies. As seen in Figure 4.10, wind speeds were also generally higher in the mid-tower levels (3.0-4.0) than above or below them. Wind directions were closer to NW below mean monthly Z_i and more westerly above. The mean wind maximum was located above mean Z_i .

Given the diurnal nature of the wind maximum observed (high during night/morning, low during afternoon/evening) at the tower, one possible cause is the sea breeze. As seen here, and as other studies have found (e.g., Edinger 1959; Glendening et al. 1986), sea breeze effects extend through Z_i well into the inversion layer. However, Johnson and O'Brien (1973) observed a sea breeze along the central Oregon coast which was confined to the marine layer. It is unclear whether the "jets" observed over the SFBA in this study and by Williams and DeMandel (1966) and Miller (1976) are related to the "jets" observed offshore along the California coast in other studies (e.g., Brost et al. 1982; Beardsley et al. 1987; Bridger et al. 1990). Beardsley et al. (1987) suggested they may be manifestations of the same feature, though Bridger et al. (1990) found that the offshore jet was stronger and more frequent during the mornings, whereas the wind maxima in

the current study occur more frequently during the afternoons (see also Williams and DeMandel 1966; Miller 1968, 1976). Bridger et al. (1990) noted the core of the offshore jet they observed was located between their study area (123°W and 125°W , west of San Francisco) and the California coast (see also Brick 1988).

4.1.3 Vertical Velocity

Lester (1981) noted "the most serious difficulty encountered in the data analysis has been the isolation of the tower effect on vertical velocities." Compounding the problem with vertical velocities is the terrain surrounding the tower site. Mt. Sutro Summit lies 480m northwest of the tower and is 23m higher than the base of the tower. Any northwesterly winds would likely have terrain induced vertical velocities unrepresentative of the mean values. In addition, the fact the tower is located on a hill would likely introduce errors or biases in the vertical velocities.

Figure 4.12 shows the vertical velocities for Jul79. Miller (1976) provided a similar figure showing mean vertical velocities for July 1974. If the vertical velocities at different levels are at all affected by Z_i , then the "group phase" of all selected hours in Figure 4.12 (similarly in Miller's [1976] figure) is most likely tower induced.

Because of the uncertainties surrounding the vertical velocities, the remaining analyses performed may be found in Appendix B.

Figure 4.12 - Jul79 mean vertical velocity profiles at selected hours.

4.2 Case Study: 19-25 Jul 79

4.2.0 Introduction

Miller (1976) considered a number of "case studies" from the summers of 1974 and 1975. However, his analyses dealt primarily with gravity wave and turbulence characteristics. He gave minimal consideration to the effects of synoptic influences on the inversion. For example, he showed height-time sections (based on hourly averaged data) for only one period (10-14 June 1974).

The responsiveness of the marine inversion to transient synoptic disturbances has been known for many years (e.g., Byers 1930). In a comprehensive study of the California Heat Trough (CHT), Gilliland (1980) documented a quasi-periodic (3-6 day) oscillation in the sea level pressure field over California during summer. He showed that the oscillation, which manifests itself as changes in the intensity and movement of the CHT axis, was related to the approach and passage of weak synoptic scale disturbances. He stated:

as an upper trough approaches from the west, the CHT axis moves inland....The [marine] inversion rises and weakens and the marine air and stratus penetrate... into the Central Valley....When an upper ridge influences the area, the CHT axis moves coastward.... The coastal inversion lowers and intensifies and the marine layer and stratus become shallow with insignificant inland penetration....

Although these influences on the marine inversion are well known, their details are not, because of the lack of fine scale observations of the inversion structure. Mt. Sutro Tower data offer a solution to that problem.

Data from the week of 19-25 Jul 79 contain an example of a typical oscillation, as identified by Gilliland (1980). In the following sections, day-by-day changes in the marine inversion at Mt. Sutro Tower are documented for that week.

4.2.1 Overview

The synoptic conditions during 19-25 Jul 79 can be divided into two distinct time periods: 20-21 Jul, when weak cyclonic disturbances at 500mb moved across the area; and 23-24 Jul, when a weak 500mb ridge moved through. The 19th, 22nd, and 25th were "transition" days.

Figure 4.13 shows the heights of the inversion base (Z_i) as measured at 0400 and 1600 PST (12 and 00 UTC, respectively), by instruments on the tower and by the Oakland radiosonde. The behavior of the inversion shown in the diagram is similar to other studies (e.g., Lester 1979). There exists a positive correlation in the phase of the Z_i records at the tower and Oakland, although there are differences in the amplitudes. For example, on 21-22

Figure 4.13 - Inversion base heights: Sutro Tower/Oakland at 0400/1600 PST -- 18 Jul to 26 Jul 79.

Jul Z_i is generally high at the tower and Oakland, while on 23-24 Jul Z_i was lower. An exception occurred at Oakland at 1600 PST on the 24th. This is possibly due to the destruction of a very low marine inversion by radiational heating in the afternoon, and subsequent identification of a spurious, secondary stable layer aloft as the "marine" inversion.

4.2.2 19-22 Jul 79: Predominantly Cyclonic Flow Aloft

4.2.2.1 19 Jul 79

By 1600 PST on 19 Jul 79, 500mb heights had fallen 50 to 80m along the California coast as a weak trough moved into eastern Oregon and northeastern California. At the same time a cyclonic disturbance moved northward from Mexico forming a closed low over northern Baja California (Figure 4.14a). The ridge over Nevada was retreating eastward ahead of the latter two features. A rapidly moving shortwave trough in the Gulf of Alaska was also approaching the region.

At the surface the CHT was intense and well established. It extended northward to the California/Oregon border with its axis slightly coastward of its mean position, tightening the onshore pressure gradient everywhere except the northern California coastal area where a slight offshore gradient existed (Figure 4.14b). Temperatures in the central valley of California were well over 100°F. Stratus covered most of the coast, although some clearing occurred from south-central to southern California (Figure 4.14c).

At Mt. Sutro Tower (Figure 4.15), a well defined, very intense inversion, with vertical temperature gradients frequently exceeding 60°C/100m, dominated the temperature

field on 19 Jul 79. The diurnal movement exhibited this day was fairly typical, with maximum Z_i reached between 0600-0800 PST, and the minimum at 1900 PST. However, in contrast with normal behavior (Figure 4.1), Z_i did not increase during the evening much above the afternoon minimum. This was likely caused by the weak upper level ridging (i.e., enhanced subsidence) following the upper into Oregon and northeastern California. The average Z_i was 390m ASL, very close to the mean Jul79 value (Figure 4.1).

The "step-like" descent of the inversion during the late morning and afternoon (Figure 4.15a) was observed frequently during summer 1979. Commonly the inversion would "plunge" 40m or more in an hour or two, remain at that elevation for 2-4 hours, then descend again. Step-like ascents of Z_i were also observed, but generally were not as sudden. These "steps" may be indications of some mesoscale feature (e.g., gravity waves), but it is also possible they are caused by aliasing. In the latter case, artificial steps could be created in a steadily descending/ascending inversion when the inversion layer has dimensions less than the distance between T-sensors on the tower (20-40m).

Temperatures below Z_i were cool ($9-13^{\circ}\text{C}$), i.e., below the corresponding Jul79 means (Figure 4.5), and

cooler than climatological means ($10-14^{\circ}\text{C}$) reported by Miller (1976). In contrast, temperatures above Z_i reached almost 30°C , much warmer than Jul79 or climatological averages ($14-21^{\circ}\text{C}$; Miller 1976).

Figure 4.15b shows steady NNW winds below Z_i , at approximately $5-7\text{ms}^{-1}$, decreasing rapidly to $2-3\text{ms}^{-1}$ at Level 1.0. These speeds were close to the Jul79 means (Figure 4.10), although the directions were more northerly. According to Miller (1976) the climatological winds are generally WSW-W below the Z_i .

Speeds above Z_i were less than below it. Early in the day the winds above Z_i were WNW at 4ms^{-1} . Between 0400 and 0700 PST they veered to NNE and increased to 9ms^{-1} . The winds above Z_i continued from the NNE (offshore), diminished to $<2\text{ms}^{-1}$ in the evening, and then backed to N-NNW between 2200 and 2400 PST. Above Z_i the winds were quite different than both mean Jul79 winds in this study and those given by Goodman and Miller (1977), which are more westerly.

Significant changes in the large scale wind field were also noted about 0400 PST (1200 UTC). The National Weather Service (NWS) surface analysis for that time (not shown), indicates that the CHT axis had already extended offshore in northern California, likely in response to the transient ridge moving through the area. This change is also

associated with the development of more northerly low level flow. However, the cause of the oscillation of the wind speed at higher tower levels (period of about 12 hours), evident in Figure 4.15b, is not clear. That oscillation contrasts with the mean Jul79 diurnal wind variation (Figure 4.10).

Figure 4.14 - 19 Jul 79; 1600 PST (20/00 UTC) NWS
analyses: (a) 500mb heights (dam)/temperatures (°C)
(b) Surface (mb) (c) Satellite image

Figure 4.15 - 19 Jul 79 height-time sections:
 (a) Temperature ($^{\circ}\text{C}$) (b) Wind direction (degs)/speed (ms^{-1})
 (dashed line/solid line)

4.2.2.2 20 Jul 79

Figure 4.23 presents the synoptic analyses and satellite image for 1600 PST, 20 Jul 79. Heights and temperatures fell at 500mb (-4°C and -40m at Oakland) as the trough previously in the Gulf of Alaska reached the coast in the Pacific Northwest, and the low previously over northern Baja moved over the interior valleys of California (Figure 4.16a).

The surface analysis over California shows a weakened CHT (Figure 4.16b). The pressure increases are associated (hydrostatically) with widespread cooling, especially in southeastern California. Cloudiness spread northward with the diffuse upper level cyclonic disturbance moving from the south (Figure 4.16c). Temperatures at Las Vegas, for example, fell 27°F (15°C) in the previous 24 hours. Along the coast the onshore pressure gradient remained strong with the approach of the cold front and associated shortwave aloft. The satellite image (Figure 4.16c) shows that the stratus had disappeared from some areas along the west coast (e.g., southern California and north of the SFBA).

On the 20th, the inversion was much less intense than on the 19th (Figure 4.17a); vertical temperature gradients averaged $20^{\circ}\text{C}/100\text{m}$. Temperatures below Z_i were similar

to those 24 hours earlier; however, temperatures above cooled dramatically ($8-10^{\circ}\text{C}$) during the night and morning hours. Z_i was lowest from 0000 to 0200 PST. Thereafter it increased rapidly until 0800 PST, reaching about 410m ASL (Level 4.5), where it remained until 1900 PST. At that time it rose again above Level 6.5. Mean values of Z_i for this day were 410m ASL, higher than the Jul79 mean (Figure 4.1), and much higher than climatological averages (300m ASL, Miller 1976; Goodman and Miller 1977).

In addition to the expected deepening marine layer associated with the increased, large scale, cyclonic activity aloft (Gilliland 1980), shorter period changes were also noted. Z_i rose in two "steps": between 0200 and 0800 PST (a distance of about 70m); then again between 1900 and 2100 PST (about 80m).

Early in the day, winds below Z_i were 5ms^{-1} from the NNW, then backed slightly to NW (Figure 4.17b). Beginning about 0600 PST speeds increased. Maximum speeds below Z_i attained $9-10\text{ms}^{-1}$ between 1600 and 2000 PST, then diminished to 6ms^{-1} by 2400 PST. Above Z_i winds were NNW-N all day, eventually reaching speeds of $>15\text{ms}^{-1}$ at Level 6.0 (470m ASL) around 1700 PST.

Figure 4.16 - 20 Jul 79; 1600 PST (21/00 UTC) NWS
analyses: (a) 500mb heights (dam)/temperatures (°C)
(b) Surface (mb) (c) Satellite image

Figure 4.17 - 20 Jul 79 height-time sections:
 (a) Temperature ($^{\circ}\text{C}$) (b) Wind direction (degs)/speed (ms^{-1})
 (dashed lines/solid lines)

4.2.2.3 21 Jul 79

Synoptic conditions at 500mb for the 21st are shown in Figure 4.18a. The short wave trough on the Pacific Northwest coast on 20 Jul moved into central Washington and Oregon. That trough and the low over the central valley are indistinguishable by this day. They appear as a single trough extending southward through Washington, Oregon, Nevada, and across the coast in central California. The Oakland 500mb height did not change from 24 hours earlier; however, heights rose during the previous 12 hours and the temperature increased 4°C at 500mb. Also, 500mb winds had increased to 20 knots from the north.

At the surface (Figure 4.18b) the CHT continued to fill as cool air moved into the central valley where temperatures fell 15°F into the low 80s. The onshore pressure gradient along the California coast remained strong, especially north of the SFBA.

Figure 4.18c, the satellite image for 1600 PST, 21 Jul 79, shows the stratus had retreated from the Pacific coast everywhere except in central California, continuing the trend noted 24 hours previously. The general retreat of the clouds corresponds well with expected cloud behavior accompanying the passage of a shortwave, and the shift of the winds to northerly (offshore), at 500mb (Gilliland

1980).

At Sutro Tower the notable inversion base behavior was the descent of a weak inversion below the top of the tower after 1200 PST (Figure 4.19a). Two apparent "steps" are noted at 0300 and 1000 PST. The descending inversion was much weaker on this day than on 20 Jul 79 (Figure 4.17a). The average vertical temperature gradient in the lowest layers of the inversion was $5\text{--}6^{\circ}\text{C}/100\text{m}$. This gradient increased as Z_i descended (again, in steps) during the evening hours. Temperatures below Z_i warmed slightly over the previous two days, reaching $14\text{--}15^{\circ}\text{C}$, while the $17\text{--}19^{\circ}\text{C}$ temperatures above Z_i were much cooler than 19 Jul (Figure 4.15a), and slightly cooler than 20 Jul (Figure 4.17a).

Winds below Z_i remained NW-N until evening when Z_i decreased (Figure 4.19b). At that time directions backed towards the west. Speeds below Z_i varied, with a series of peaks and lulls at approximately three hour intervals until 1400 PST. The earliest peak (0200-0300 PST) displayed maximum speeds of 14ms^{-1} from the NNW at Level 6.0, and was associated with an equally brief descent in Z_i . A similar process occurred at 1000 PST. Such a correlation of wind speed increases with inversion descents is expected from mass conservation. After 1200 PST winds again increased to a relatively broad afternoon maximum of

$5-6\text{ms}^{-1}$ as the inversion descended during the afternoon and evening. As Z_i descended during this period, the winds shifted and decreased in speed. Directions backed from 340° at 1600 PST to 210° by 2100 PST, and 180° by 2400 PST.

Figure 4.18 - 21 Jul 79; 1600 PST (22/00 UTC) NWS
analyses: (a) 500mb heights (dam)/temperatures ($^{\circ}\text{C}$)
(b) Surface (mb) (c) Satellite image

Figure 4.19 - 21 Jul 79 height-time sections:
 (a) Temperature ($^{\circ}\text{C}$) (b) Wind direction (degs)/speed (m s^{-1})
 (dashed lines/solid lines)

4.2.2.4 22 Jul 79

This day was a transition period between the dominant cyclonic flow aloft over 20 and 21 Jul, and the anticyclonic circulations of the next couple of days. By the afternoon of 22 Jul 79 (Figure 4.20a) the 500mb trough over Nevada had moved eastward and a trailing shortwave ridge brought rising heights and temperatures to the northwest coast of California. The Sonoran High intensified in the southwest. Over the SFBA 500mb heights rose 20-40m, and 500mb winds decreased to 5-15 knots from the west.

At the surface (Figure 4.20b) pressures fell and temperatures rose as the CHT intensified, especially in southern California. In the north, despite the increase of inland valley temperatures to near 100°F, the onshore pressure gradient was somewhat weaker than the previous day (at least as analyzed by NWS).

The satellite image for 1545 PST on this day (Figure 4.20c) differs from that on 21 Jul in the extensive clearing of clouds inland. It also shows that the stratus had moved back along the coast in the SFBA.

As seen in Figure 4.21a, the marine inversion was near the ground during the morning of 22 Jul 79, probably partially masked by a surface radiation inversion.

Vertical temperature gradients were weak, only $3^{\circ}\text{C}/100\text{m}$. Beginning at 0800 PST, the inversion rose about 60m in 2-3 hours. In the same time span, what appears to be another inversion layer ($T > 20^{\circ}\text{C}$) began to descend from above the tower at the rate of approximately $-3 \times 10^{-3} \text{ms}^{-1}$. The lower inversion remained around Level 2.5 (320m ASL) until 1700 PST, when the higher inversion layer merged with it. The base of the deeper, stronger (combined) inversion layer then descended about 20m to Level 2.0, where it remained for five hours. Z_i then rose 20-40m between 2100 and 2300 PST.

Figure 4.21a shows that temperatures above Z_i increased nearly 10°C over those observed on 21 Jul 79 (Figure 4.19a). Below Z_i temperatures were $12-14^{\circ}\text{C}$, similar to marine layer temperatures observed on the previous two days.

A period of unusual cooling occurred beneath the inversion between 0800 and 1000 PST. The cooling (from 15°C to 12°C) occurred in conjunction with the rising Z_i and shifting, increasing winds. Winds prior to the cooling were $<2 \text{ms}^{-1}$ and easterly; simultaneously with it they veered rapidly to westerly, increasing in speed to $3-4 \text{ms}^{-1}$ (Figure 4.21b).

Before the brief cooling event noted above, winds were light and variable across the tower during the morning

hours. When the lower inversion rose and the upper inversion descended after 0800 PST, directions turned to WNW below the lowest Z_i , and W-SW above it. Wind speeds generally increased at the same time. By 1900 PST, a well defined maximum with speeds exceeding 9ms^{-1} existed over the lower two thirds of the tower. The maximum was centered on Level 3.0, i.e., above Z_i .

Figure 4.20 - 22 Jul 79; 1600 PST (23/00 UTC) NWS
analyses: (a) 500mb heights (dam)/temperatures (°C)
(b) Surface (mb) (c) Satellite image

Figure 4.21 - 22 Jul 79 height-time sections:
 (a) Temperature ($^{\circ}\text{C}$) (b) Wind direction (degs)/speed (ms^{-1})
 (dashed lines/solid lines)

4.2.3 23-25 Jul 79: Predominantly Anticyclonic Flow Aloft

4.2.3.1 23 Jul 79

At 1600 PST on 23 Jul 79, transient systems at 500mb continued to move from the Gulf of Alaska across Oregon and Washington, and from the south over California. While cyclonic disturbances moving along these tracks were in phase during the previous two days, on this day a more rapidly moving shortwave trough approached the Pacific Northwest coast, while a more slowly moving ridge persisted over California (Figure 4.22a).

Figure 4.22b, the surface analysis for the same time, shows a better defined CHT than the previous two days. It extended northward through inland California almost to the Oregon border, its axis again shifted westward of its mean position. Surface pressures fell over most of the area during the previous 24 hours. The satellite image (Figure 4.22c) shows continued inland clearing, while stratus remains along the central California coast.

Figure 4.23 shows the analyses of the tower observations for this day. Z_i (as indicated by the 13°C isotherm) initially rose from about 340m ASL (Level 3.0), reaching 370m ASL by 0500 PST. At 0800 PST, the inversion fell rapidly; however, similar to 22 Jul, another intense inversion layer descended from above the tower

simultaneously. The lower inversion base descended to or below Level 1.5 (about 280m ASL) between 1200 and 1500 PST. The upper inversion layer merged into the lower at the same time, once again creating a deeper, more intense inversion. Vertical temperature gradients increased from $10^{\circ}\text{C}/100\text{m}$ in the morning to more than $30^{\circ}\text{C}/100\text{m}$ in the evening. Associated with the descent of the inversion layer, temperatures above Z_i continued the increasing trend established with inversion layer descents on the previous two days (Figures 4.19a and 4.21a). Temperatures at Level 6.5 exceeded 29°C , comparable to the first day of this case study, 19 Jul 79 (Figure 4.15a).

The wind field (Figure 4.23b) was organized similarly to that of 22 Jul 79 (Figure 4.21b). In the morning, prior to the inversion descent, the winds within the marine layer were NW at $4\text{--}5\text{ms}^{-1}$. Above Z_i the winds were $<2\text{ms}^{-1}$, with variable, southerly to southeasterly directions. The winds above Level 2.0 veered to westerly around 1000 PST, with the rapid descent of Z_i . Similar to 22 Jul, a well developed westerly maximum became established around Level 3.0 with speeds $7\text{--}8\text{ms}^{-1}$. The winds below Z_i remained NW, backing to W in the inversion layer. As speeds began to diminish around 2100 PST the winds above the inversion base began to back towards SW.

Figure 4.23 - 23 Jul 79 height-time sections:
 (a) Temperature ($^{\circ}\text{C}$) (b) Wind direction (degs)/speed (ms^{-1})
 (dashed lines/solid lines)

4.2.3.2 24 Jul 79

The shortwave at 500mb moved very rapidly across the Pacific Northwest during the preceding 24 hours. As shown in Figure 4.24a, it was over the Washington/Idaho border at 1600 PST, on the 24th. In the meantime, another wave disturbance moved from the Gulf of Alaska to the Washington coast. Over California, ridging from the south dominated and the southwestern winds at Oakland increased to 25 knots.

The CHT at the surface further intensified and extended well into Washington (Figure 4.24b). As is frequently the case when under the influence of a ridge aloft, it remained shifted coastward in California, with very warm temperatures ($>100^{\circ}\text{F}$) in the interior of the state.

The satellite image (Figure 4.24c) shows that the stratus increased along much of the Pacific coast, especially in southern California. Inland areas remained relatively clear, with some convection occurring over the southern Sierra Nevada. Also, the remnants of Hurricane Dolores merged with the stratus field well off southern California (see also Figures 4.24b, 4.26b).

The inversion base remained low during the day (Figure 4.25a), fluctuating slightly above and below the base of

the tower until about 2100 PST, when it began to rise rapidly.

Vertical temperature gradients were about the same during the morning and evening, roughly $20^{\circ}\text{C}/100\text{m}$. Temperatures below Z_i during the morning were approximately 12°C ; during the evening they cooled to as low as 10°C , temperatures not observed since 19 and 20 Jul 79 (Figures 4.15a and 4.17a). Temperatures above Z_i were $4\text{--}5^{\circ}\text{C}$ warmer in the morning than 24 hours earlier. However, in the afternoon they were slightly cooler than the previous day (Figure 4.23a).

The winds (Figure 4.25b) displayed more of a "normal" diurnal variation (Figure 4.10). Early in the day they were SSW in the upper tower levels, and NW-N in the lower and mid levels. Eventually, around 0800 PST, the winds at all levels began shifting towards the WSW and increasing in speed. An evening maximum developed with speeds of 11ms^{-1} centered on Level 4.0 (390m ASL). The wind maximum in Figure 4.25b is temporally "broader" than typical afternoon maxima; i.e., it persisted to some extent until almost 0600 PST the next day (25 Jul 79).

4.2.3.3 25 Jul 79

By 1600 PST, 25 Jul 79, data at 500mb showed a trough approaching the California coast (Figure 4.26a). Heights above Oakland fell 20m, and the height gradient increased, causing the southwesterly winds to increase to 30 knots. A lobe of the upper ridge to the south moved inland, over the high deserts of Mexico, Arizona, and New Mexico, while another portion remained well to the southwest, off the Baja coast.

Surface data for this day (Figure 4.26b) shows the thermal trough continued at the same intensity and position. The coastal onshore pressure gradient had increased, although temperatures in the central valley had cooled slightly in the north.

The satellite image (Figure 4.26c) shows continued stratus along the California coast, with a broader, deeper cloud free region off the northern California and Oregon coasts, centered on 125°W (see Simon 1977). Additionally, inland areas continued clear, but with convective activity increasing east of the Sierra Nevada.

In a pattern similar to that of 20 Jul 79 (Figure 4.17a), Z_1 ascended throughout the day in response to the approach of the upper level trough. The vertical temperature gradient averaged about 20°C/100m in the

lower levels of the inversion. Temperatures beneath Z_i were 10-12°C, cooler than any other case study day, except 19 Jul 79 (see Figure 4.15a). Temperatures above Z_i reached 26-27°C.

Winds below the inversion were NW all day. Speeds generally increased, from 4-5ms⁻¹ in the morning, to a maximum of 10ms⁻¹ at 1900 PST, centered on Level 4.0 (390m ASL); i.e., below Z_i . In contrast, the previous evening maximum was also centered on Level 4.0, although it was above Z_i from the WSW (Figure 4.24b). Above Z_i wind directions remained WSW until 0600 PST above Z_i . However, with increasing Z_i , winds above the inversion began to veer towards NW around 0700 PST. They remained that way the rest of the day, with speeds approximately 5ms⁻¹.

Figure 4.27 - 25 Jul 79 height-time sections:
 (a) Temperature ($^{\circ}\text{C}$) (b) Wind direction (degs)/speed (m s^{-1})
 (dashed lines/solid lines)

4.2.4 Discussion

Table 4.2 gives a summary of some of the pertinent data from each day during the case study. Several time scales of motion have been identified by the movement of the inversion during the week. In agreement with Gilliland (1980) the synoptic period of about five days was found, as the inversion began to rise on 20 Jul, descended between 22 and 24 Jul, and then started rising again on 25 Jul. The inversion displayed a well defined behavior during the synoptic changes: rising and weakening with the approach and passage of upper level cyclonic features (as on 20 and 21 Jul); falling and intensifying with anticyclonic activity aloft (as on 23 and 24 Jul).

Because of the masking influences of the synoptic changes the diurnal cycle (large Z_i in the morning, small Z_i in the afternoon) was not represented well in the days selected. The 19th and 23rd displayed the greatest similarities to mean diurnal Z_i patterns (Figure 4.1).

Embedded within the larger scale variations of Z_i appeared to be changes over periods of 24 hours which were not related to the diurnal radiation cycle. Specifically, during the descent of the anticyclonic phase of the case study, the inversion descended in three, distinct events, separated by approximately 24 hours.

(dd)	OAKLAND INVERSION BASE: hour/ z_i (PST/m ASL)	DAILY TOWER MEAN z_i (m ASL)	DAILY TOWER MEAN T_g (°C/100m)	TEMPERATURES as f (Z) :		DAILY WIND MAXIMA DATA						ABOVE/ BELOW z_i (A/B)
				$Z > Z_i$	$Z < Z_i$	TIME (hr PST)	Z (m ASL)	dd (dir)	ff (ms ⁻¹)			
19	04 / 450 16 / 110	390	35	23-28	9-13	1000	470	NE	9		A	
20	04 / 90 16 / 100	410	20	16-25	10-14	0300 1700	470 470	N NNW	10 15		A A	
21	04 / 400 16 / 420	430	7	15-20	11-15	0300 1800	470 390	NNW NW	14 6		B B	
22	04 / 115 16 / 118	300	10	16-27	11-15	1900	340	W	9		A	
23	04 / 116 16 / 75	300	18	20-29	11-16	1800	340	W	8		A	
24	04 / 96 16 / 760	270	20	20-28	11-17	2100	390	W	11		A	
25	04 / 88 16 / 92	390	25	14-27	10-13	1900	390	NW	10		B	

TABLE 4.2 - Case study summary.

Significant inversion features were also identified on time scales shorter than diurnal. For example, a series of local wind maxima and minima occurred on 21 Jul at intervals of 2-3 hours (Figure 4.19b). From the NWS surface analyses it appears these events occurred sometime after frontal passage in the SFBA. Another example is the step-like ascents and descents of the inversion. These occurred most often with a time scale of four hours or less. As noted, one possible explanation for these features is that they are caused by an aliasing problem attributable to a thin, vertically moving inversion layer across fixed sensors. Another possible reason for some of the events could be the onset of the sea breeze. Williams and DeMandel (1966) observed the sea breeze begin as a surge at ground level, then progress vertically. Mass conservation would require decreasing Z_i to compensate for the suddenly increased divergence in the marine layer. Still another possibility is gravity wave activity. Miller (1976), Holman (1978), and MacArthur et al. (1987) have all documented the ubiquitous nature of these features in the SFBA. MacArthur et al. (1987) saw the inversion rise 30m in a period of less than an hour in conjunction with a gravity wave. Another feature in the analyses which may be attributable to wave activity are the brief increases and decreases in the inversion layer which center on one level

(e.g., 0800 and 1900 PST, 19 Jul; Figure 4.15a). Because this study used hourly averaged data the smallest feature resolvable temporally will have a period of two hours. Thus, only the larger gravity waves would appear directly in the analyses, and the shorter period gravity waves would be aliased.

The mean Z_i observed over the course of the week was about 360m ASL. This was less than the mean for Jul79 (390m ASL), but closer to the mean of 300m ASL from previous studies (e.g., Miller 1976). During the case study the average temperature gradient in the 50m above Z_i was approximately $19^{\circ}\text{C}/100\text{m}$. This is a very high value compared with the Jul79 mean (Table 4.1).

On three days (21-23 Jul 79) the upper tower level temperature structure was intensified by successive "surges" of warmer air descending during the afternoons. When the descending layers reached extremely stable layers which were simultaneously rising from below, the gradients within the combined layer increased and the lowest inversion base descended further. During these surges a dramatic (often $>10^{\circ}\text{C}/24$ hours) increase in temperatures occurred above the lowest inversion base. Such surges occurred while high pressure was building over the Pacific coast. The synoptic data, however, were not adequate to identify specific details which may have been related to

each of the three discrete warming periods.

The winds at Level 1.0 were relatively unaffected by synoptic influences. Speeds at Level 1.0 showed a consistent diurnal cycle, varying from $1\text{--}2\text{ms}^{-1}$ during nights and early mornings, then increasing slightly in the afternoons to $3\text{--}4\text{ms}^{-1}$. These low values most likely reflect frictional effects as well as the sheltering influence of the surrounding trees (see Chapter 3).

At higher levels, wind maxima showed wide variations. Whereas the mean Jul79 wind field (Figure 4.10a) shows a single WNW wind maximum during the period 1600–1900 PST, centered about 360m ASL near the inversion base, more than one wind maximum occurred on some days. Six of the nine distinct wind maxima observed during the case study occurred around 1600–1900 PST, or were centered about 360m ASL, or both. Of these six, four occurred above Z_i , and two below. Three of the maxima were westerly, two NW, and one NNW.

When Z_i was high the wind maxima tended to occur high in the marine layer. When Z_i was low, they were located within the inversion.

The winds below Z_i were always W-N, mostly NW. This does not quite agree with Miller (1976) who reported mean winds beneath the inversion from WSW-WNW. The Jul79 mean was WNW below the Z_i .

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The first objective of this study was to organize and quality check a portion of the vast meteorological data set collected from Mt. Sutro Tower during Project STABLE. These data were converted from 7-track magnetic tape to 9-track magnetic tape, reformatted into sequential access files, and stored on minicomputer diskettes. The observations of eight meteorological parameters (T , T_w , P , u , v , w , dd , and ff) were gross error checked. Temperatures and winds were further examined for internal consistency to eliminate as much obviously bad data as possible. Winds were modified for tower effects on the basis of Ballanti's (1976) study. Hourly averages for each parameter were then calculated and stored in the same sequential format as that of the reformatted 5-minute data. The resulting files are not so large that the sequential access format drastically slows processing time. In fact, the files are small enough to be manipulated in almost any desktop computer environment. Thus, a convenient, quality assured data set, including the raw data, for July 1979 and 16 August to 8 September 1979, is available for future analysis.

The second objective was to analyze portions of the

data set to expand and verify the observations and conclusions reached by Miller (1976) and other researchers concerning the structure and behavior of the marine inversion. This study specifically focused on mean fields of temperatures and horizontal winds for July 1979. In addition, a case study from that month was presented to illustrate synoptic influences on the marine inversion.

The climatological portion of the study revealed July average pattern which were similar to Miller (1976), with only a few exceptions. The average height of the inversion base was 390m (ASL) during July 1979, somewhat higher than the 300m (ASL) mean height found by Miller (1976) and Goodman and Miller (1977). Mean temperatures for July 1979 at all tower levels (Figure 4.5), were 1-2°C warmer than those presented by Miller (1976) for July 1975. Mean vertical temperature gradients in the inversion, i.e., above Level 2.0, were 3.6°C/100m in July 1979, while Miller (1976) observed corresponding mean gradients of 2.2°C/100m. Observed extreme vertical temperature gradients were similar in both studies, i.e., 60-70°C/100m in the lowest part of the inversion layer.

The mean diurnal variation of Z_i for July 1979 showed a rising inversion during the night and early morning, and falling in the afternoon, in agreement with Miller (1976) and many others (e.g., Neiburger 1944;

Edinger 1959, 1963; Elliot and O'Brien 1977; Myrup et al. 1983; Glendening et al. 1986). Also in agreement with Miller (1976), the diurnal variation of mean temperatures was greatest at Level 6.0 ($>4^{\circ}\text{C}$) and least at Level 2.0 ($<2^{\circ}\text{C}$).

A marked mean diurnal variation of the wind speeds showed generally light winds in the early to mid morning hours and strongest winds between 1800 and 1900 PST. The latter "jet-like" feature was centered on Level 3.0 (340m ASL) on the tower. This is lower than Miller's (1976) afternoon jet and is at least partially the result of the application of the Ballanti (1976) corrections for the effect of the tower on the winds.

Mean winds during July 1979 were NW-W on the lower levels, backing towards WNW-WSW at the upper levels. Miller (1976) observed the opposite conditions in the mean, that is, the winds veered with increasing height. Other studies (e.g., Beardsley et al. 1987) have observed backing with height in the mean coastal winds north of the SFBA.

One of the most significant deviations from Miller (1976) was the observed reversal of the direction of rotation of the wind vector at all levels; i.e., Miller (1976) found clockwise rotation, while this study found counterclockwise. The two most obvious explanations of this are: (i) an error in the sign of the v-component of

the wind, either in this study or in Miller's (1976); or
(ii) different meteorological conditions between the years
of study (1974-1975 versus 1979).

The case study revealed several time scales of disturbances on the marine inversion, ranging from four hours or less, to about five days. The latter time scale agrees with the characteristics of synoptic scale influences observed by Gilliland (1980) in his studies of the CHT. The shorter time scales of inversion disturbances are related to mesoscale features, which are not resolved in conventional surface or 500mb analyses. These features were also observed by Van Patten (1980a,b) in his spectral analyses of inversion variations at Sutro Tower in 1976, and are caused, in many cases, by gravity waves.

The case study illustrated the wide differences between the mean and the day-to-day structure of the inversion. During the case study Z_i was observed to rise above the top of the tower and descend beneath the lowest observational level. The hourly averaged vertical temperature gradients through the lowest 50m of the inversion were observed to vary dramatically, from as little as $3^{\circ}\text{C}/100\text{m}$ to as much as $30^{\circ}\text{C}/100\text{m}$. The strongest vertical gradients were generally observed with falling or low inversions, while the weakest were associated with rising or high inversion layers. This

observation was also made by Miller (1976) and others (e.g., Neiburger 1944; Edinger 1959).

The maximum descent and ascent rates of the inversion layer were on the order of 0.5cm s^{-1} during the case study. Ignoring other factors (e.g., advection), these values are about equal to the vertical motions necessary to cause the observed temperature changes at any given level in the vicinity of the inversion base.

Miller (1976) hypothesized the sloping inversion base is the primary factor in the formation of a "jet-like" wind maxima. In contrast, the winds during the case study were a function of the height of the inversion, as well as the time of day, and the synoptic conditions. "Jet-like" wind maxima were observed during mornings and afternoons, with occasionally both in the same day. When the inversion was high the wind maxima were observed high in the marine layer. When the inversion was low, the maxima were observed within that stable layer. A westerly, afternoon maximum was the most common event, evidently caused by the sea breeze circulation.

5.2 Recommendations

The question concerning the correct diurnal rotation of the wind at the tower needs to be answered. Is it

clockwise, as observed by Miller (1976), or counter-clockwise, as observed in this study? A single, recording anemometer mounted on the tower would answer this question.

The 5-minute observations from July 1979 used in this study could profitably be analyzed for wave activity on resolvable temporal scales ranging from 10 minutes to 60 days. Miller (1976), Holman (1978), and Van Patten (1980a) have observed gravity waves within these time scales at the tower. Further study would help clarify the nature of the step-like descents and ascents of the inversion observed here.

Analysis of wet-bulb temperature, pressure, and vertical velocity from this data set should also be considered. Short term pressure variations should provide evidence of gravity wave propagation.

Wet-bulb temperatures should be analyzed in combination with stratus observations recovered from other sources for July 1979, as well as temperature and wind data from the tower. This information should provide greater insight regarding the role of clouds in the maintenance of the inversion.

A numerical simulation of the flow over the local terrain should help in understanding the observed vertical velocity profiles at the tower and their relationship to inversion maintenance.

Further research is needed to understand the interaction of the sea breeze wind maximum observed at Mt. Sutro Tower and the offshore jet (e.g., Brost et al. 1982a; Beardsley et al. 1987; Bridger et al. 1990).

Work is also needed to better understand the interactions between the wind maxima and the marine inversion. Neither Miller's (1976) hypothesis that gravity waves play a major role in establishing the "jet" in the inversion nor the contention of Bridger et al. (1990) that the "jet" is primarily a result of boundary layer land-sea temperature differences, simply modified by the inversion, have been verified.

Finally, it should be emphasized that only a fraction of the data set made available from this study has been examined in detail. It is hoped that the data base produced in this study will be used to explore the marine and inversion layers more fully.

REFERENCES

- Ahn, N.N., and A.E. Gill, 1981: Generation of coastal lows by synoptic-scale waves. Quart. J. Roy. Meteor. Soc., 107, 521-530.
- Ahrens, D., and A. Miller, 1969: Variations of the temperature inversion over the San Francisco Bay Area. Report, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 51 pp.
- Albrecht, B.A., 1979: A model of the thermodynamic structure of the trade-wind boundary layer: Part II. Applications. J. Atmos. Sci., 36, 90-98.
- _____, A.K. Betts, W.H. Schubert, S.K. Cox, 1979: A model of the thermodynamic structure of the trade-wind boundary layer: Part I. theoretical formulation and Sensitivity Tests. J. Atmos. Sci., 36, 73-89.
- _____, R. Penc, and W.H. Schubert, 1985: An observational study of cloud-topped mixed layers. J. Atmos. Sci., 42, 800-822.
- _____, D.A. Randall, and S. Nicholls, 1988: Observations of marine stratocumulus clouds during FIRE. Bull. Amer. Meteor. Soc., 69, 618-626.
- _____, and R.W. Barlow, 1989: Large-scale variability in marine stratocumulus clouds defined from simultaneous aircraft and satellite measurements. Fire Science Results, Proceedings of NASA Conference, July 10-14, 1989, Monterey, California, 9-13.
- Atkinson, B.W., 1981: Meso-scale Atmospheric Circulations. Academic Press, Inc., 495 pp.
- Atlas, D., and J.I. Metcalf, 1970: The amplitude and energy of breaking Kelvin-Helmholtz waves and turbulence. Technical Report #19, Laboratory for Atmospheric Probing, Department of Geophysical Sciences, The University of Chicago, and Illinois Institute of Technology, Department of Electrical Engineering, 29 pp.
- Ball, F.K., 1960: Control of inversion height by surface heating. Quart. J. Roy. Meteor. Soc., 86, 483-494.

- Ballanti, D., 1976: A wind tunnel investigation of wind measurement errors on Mt. Sutro Tower. M.S. thesis, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 51 pp.
- 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.
- Beardsley, R.C., C.E. Dorman, C.A. Friehe, L.K. Rosenfeld, and C.D. Winant, 1987: Local atmospheric forcing during the Coastal Ocean Dynamics Experiment: 1. A description of the marine boundary layer and atmospheric conditions over a northern California upwelling region. J. Geophys. Res., 92, 1467-1488.
- Betts, A.K., 1973: Non-precipitating cumulus convection and its parameterization. Quart. J. Roy. Meteor. Soc., 86, 178-196.
- _____, and R. Boers, 1989: A cloudiness transition in a marine boundary layer. Fire Science Results, Proceedings of NASA Conference, July 10-14, 1989, Monterey, California, 203-207.
- Bosart, L.F., 1983: Analysis of a Catalina Eddy event. Mon. Wea. Rev., 111, 1619-1633.
- Brick, W.C., 1988: Aircraft observations of the marine inversion during MABLES WC: Data processing and preliminary analysis. M.S. thesis, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 108 pp.
- Bridger, A.F.C., W.C. Brick, and P.F. Lester, 1990: The structure of the marine inversion layer off the central California coast: Mesoscale Conditions. Mon. Wea. Rev., to be published.
- Brost, R.A., D.H. Lenschow, and J.C. Wyngaard, 1982a: Marine stratocumulus layers. Part I: Mean conditions. J. Atmos. Sci., 39, 800-817.
- _____, J.C. Wyngaard, and D.H. Lenschow, 1982b: Marine stratocumulus layers. Part II: Turbulence budgets. J. Atmos. Sci., 39, 818-836.

- Browning, K.A., J.R. Starr, and A.J. Whyman, 1973: The structure of an inversion above a convective boundary layer as observed using high-power pulsed Doppler radar. Bound.-Layer Meteor., 4, 91-111.
- Byers, H.R., 1930: Summer sea fogs of the central California coast. University of California Publications in Geography, 3, 291-338.
- Cederwall, R.T., 1980: Effect of long wave radiative cooling on west coast subsidence inversions under cloudless conditions. M.S. thesis, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 66 pp.
- Chao, S.Y., 1985: Coastal jets in the lower atmosphere. J. Phys. Ocean., 15, 361-371.
- Colquhoun, J.R., D.J. Shepherd, C.E. Coulman, R.K. Smith, and K. McInnes, 1985: The southerly buster of southeastern Australia: an orographically forced cold front. Mon. Wea. Rev., 113, 2090-2107.
- Csanady, G.T., 1974: Equilibrium theory of the planetary boundary layer with an inversion lid. Bound.-Layer Meteor., 6, 63-79.
- Deardorff, J.W., 1976: On the entrainment rate of a stratocumulus mixed layer. Quart. J. Roy. Meteor. Soc., 102, 563-582.
- , 1980: Stratocumulus-capped mixed layers derived from a three-dimensional model. Bound.-Layer Meteor., 18, 495-527.
- , 1981: On the distribution of mean radiative cooling at the top of a stratocumulus-capped mixed layer. Quart. J. Roy. Meteor. Soc., 107, 191-202.
- DeHay, W., 1974: Sutro Tower atmospheric boundary layer experiments. User's manual. Report, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 46 pp.
- Dorman, C.E., 1985: Evidence of Kelvin waves in California's marine layer and related eddy generation. Mon. Wea. Rev., 113, 827-839.

- _____, 1987: Possible role of gravity currents in northern California's coastal summer wind reversals. J. Geophys. Res., 92, 1497-1506.
- _____, 1988a: Forecasting west coast high speed summer wind maximums. Preprints, 4th Conference Meteorology and Oceanography of the Coastal Zone, February 3-5, 1988, Anaheim, California, American Meteorological Society, 95-96.
- _____, 1988b: 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.
- Edinger, J.G., 1959: Changes in the depth of the marine layer over the Los Angeles Basin. J. Meteor., 16, 219-226.
- _____, 1963: Modifications of the marine layer over coastal southern California. J. Appl. Meteor., 2, 706-712.
- _____, 1966: Wave clouds in the marine layer upwind of Pt. Sal, California. J. Appl. Meteor., 5, 804-809.
- _____, and M.G. Wurtele, 1972: Interpretation of some phenomena observed in southern California stratus. Mon. Wea. Rev., 100, 389-398.
- Elliot, D.L. and J.J. O'Brien, 1977: Observational studies of the marine boundary layer over an upwelling region. Mon. Wea. Rev., 105, 86-98.
- Erickson, N.A., 1981: Variations of the topography of the marine inversion over the central California coast. B.S. thesis, Department of Meteorology, San Jose State University, San Jose, California, 95192-0104, 26 pp.
- Felsch, P., and W. Whitlatch, 1990: Stratus surge prediction along the central California coast. NOAA Tech Memo NWS WR-209, 17 pp.
- Firestone, J.K., and B.A. Albrecht, 1986: The structure of the atmospheric boundary layer in the central Equatorial Pacific during January and February of FGGE. Mon. Wea. Rev., 114, 2219-2231.

- Fosberg, M.A., and M.J. Schroeder, 1966: Marine air penetration in central California. J. Appl. Meteor., 5, 573-589.
- Friehe, C.A., and C.D. Winant, 1982: Observations of wind and sea surface temperature structure off of the northern California coast. Preprints, 1st International Conference on Meteorology and Air/Sea Interaction of the Coastal Zone, The Hague, The Netherlands, American Meteorological Society, 209-214.
- Gerber, H., S. Chang, and T. Holt, 1989: Evolution of a marine boundary-layer jet. J. Atmos. Sci., 46, 1312-1326.
- Gill, A.E., 1977: Coastally trapped waves in the atmosphere. Quart. J. Roy. Meteor. Soc., 103, 431-440.
- Gilliland, R.P., 1980: The structure and behavior of the California Heat Trough. M.S. thesis, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 79 pp.
- Glendening, J.W., B.L. Ulrickson, and J.A. Businger, 1986: Mesoscale variability of boundary layer properties in the Los Angeles Basin. Mon. Wea. Rev., 114, 2537-2549.
- Goodman, J., 1975: The microstructure of California coastal fog and stratus. Report 75-02, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 61 pp.
- , 1976: The microstructure of California coastal fog and stratus. Report 76-09, Department of Meteorology, San Jose State University, San Jose, California, 35 pp.
- , 1979: The microstructure of California coastal fog and stratus. Report, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 29 pp.
- , and A. Miller, 1977: Mass transport across a temperature inversion. J. Geophys. Res., 82, 3463-3471.

- Gossard, E.E., J.H. Richter, and D. Atlas, 1970: Internal waves in the atmosphere from high-resolution radar measurements. J. Geophys. Res., 75, 3523-3536.
- Hanson, H.P., 1989: July 16, 1987 revisited: Lessons for modelers. Fire Science Results, Proceedings of NASA Conference, July 10-14, 1989, Monterey, California, 45-49.
- Holland, G.J., and L.M. Leslie, 1986: Ducted coastal ridging over S.E. Australia. Quart. J. Roy. Meteor. Soc., 112, 731-748.
- Holman, H.Y., 1978: Turbulent kinetic energy in an elevated temperature inversion. M.S. thesis, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 66 pp.
- _____, 1980: The budget of turbulent kinetic energy in the elevated temperature inversion. Preprints, 2nd Conference on Coastal Meteorology, Los Angeles, California, American Meteorological Society, 266-267.
- Johnson, A., Jr., and J.J. O'Brien, 1973: A study of an Oregon sea breeze event. J. Appl. Meteor., 12, 1267-1283.
- King, C.W., 1980: Sodar observations of the marine boundary layer during MABLES WC. Preprints, 2nd Conference on Coastal Meteorology, Los Angeles, California, American Meteorological Society, 258-261.
- Kloesel, K.A., 1989: The above-inversion moisture structure observed during FIRE. Fire Science Results, Proceedings of NASA Conference, July 10-14, 1989, Monterey, California, 63-65.
- _____, and B.A. Albrecht, 1989: Low-level inversions over the Tropical Pacific--Thermodynamic structure of the boundary layer and the above-inversion moisture structure. Mon. Wea. Rev., 117, 87-101.
- Kraus, H., and E. Schaller, 1978a: Steady-state characteristics of inversions capping a well-mixed planetary boundary layer. Bound.-Layer Meteor., 14, 83-104.

- _____, and _____, 1978b: A note on the closure in Lilly-type inversion models. Tellus, 30, 284-288.
- Kruger, P., and A. Miller, 1966: Transport of radioactivity in rain and air across the trade wind inversion at Hawaii. J. Geophys. Res., 17, 4243-4255.
- Lapworth, A.J., 1987: Wind profiles through boundary-layer capping inversions. Bound.-Layer Meteor., 39, 333-378.
- Lenschow, D.H., 1970: Airplane measurements of planetary boundary layer structure. J. Appl. Meteor., 9, 874-884.
- Lester, P.F., 1979: Marine Atmospheric Boundary Layer Experiments, West Coast (MABLES WC), July 31-August 17, 1978, Experiment Description. Report, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 57 pp.
- _____, 1980: Marine Atmospheric Boundary Layer Experiments, West Coast (MABLES WC). Preprints, 2nd Conference on Coastal Meteorology, Los Angeles, California, American Meteorological Society, 247-250.
- _____, 1981: Mass and energy transport by internal gravity waves. Report, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 36 pp.
- _____, 1985: Studies of the marine inversion over the San Francisco Bay Area . . . A summary of the work of Albert Miller, 1961-1978. Bull. Amer. Meteor. Soc., 66, 1396-1402.
- Lile, R.C., 1970: Tetroon-derived eddy viscosity in the region of the elevated west coast temperature inversion. Report #1, Mesoscale Circulation Modeling Project, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 36 pp.
- Lilly, D.K., 1968: Models of cloud-topped mixed layers under a strong inversion. Quart. J. Roy. Meteor. Soc., 94, 292-309.

- Lovill, J.E., and A. Miller, 1968: The vertical distribution of ozone over the San Francisco Bay Area. J. Geophys. Res., 73, 5073-5079.
- MacArthur, R.S., R.T. Cederwall, and P.F. Lester, 1987: A turbulent episode associated with gravity waves within the west coast marine temperature inversion. Paper presented at the 6th Conference on Atmospheric and Oceanic Waves and Stability, American Meteorological Society, 25-28 August 1987, Seattle, Washington.
- Mass, C.F., M.D. Albright, and D.J. Brees, 1986: The onshore surge of marine air into the Pacific Northwest: A coastal region of complex terrain. Mon. Wea. Rev., 114, 2602-2627.
- _____, 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.
- _____, and _____, 1988: Reply. Mon. Wea. Rev., 116, 2407-2410.
- Meitin, R.J., and D.W. Stuart, 1977: The structure of the marine inversion in northwest Oregon during 26-30 August 1973. Mon. Wea. Rev., 105, 748-761.
- Metcalf, J.I., 1975: Gravity waves in a low-level inversion. J. Atmos. Sci., 32, 351-361.
- Miller, A., 1968: Wind profiles in west coast temperature inversions. Report #4, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 57 pp.
- _____, 1975: Project STABLE. Bull. Amer. Meteor. Soc., 56, 52-55.
- _____, 1976: Wave properties in the west coast temperature inversion. Report 76-01, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 95 pp.

- _____, and D. Ahrens, 1970: Ozone within and below the west coast temperature inversion. Tellus, 22, 328-339.
- Minnis, P., D.F. Young, R. Davies, M. Blaskovic, B.A. Albrecht, 1989: Stratocumulus cloud height variations determined from surface and satellite observations. Fire Science Results, Proceedings of NASA Conference, July 10-14, 1989, Monterey, California, 33-37.
- Morgan, T., and R.D. Bornstein, 1977: Inversion climatology at San Jose, California. Mon. Wea. Rev., 105, 653-656.
- Myrup, L.O., D.L. Morgan, and R.L. Boomer, 1983: Summertime three-dimensional wind field above Sacramento, California. J. Climate Appl. Meteor., 22, 256-265.
- Neiburger, M., 1944: Temperature changes during formation and dissipation of west coast stratus. J. Meteor., 1, 29-41.
- _____, 1960: The relation of air mass structure to the field of motion over the eastern north Pacific Ocean in summer. Tellus, 12, 31-39.
- _____, C.G.P. Beer, and L.B. Leopold, 1945: The California stratus investigation. Report, U.S. Department of Commerce, Weather Bureau, Washington D.C., 84 pp.
- _____, D.S. Johnson, and C.W. Chien, 1961: Studies of the structure of the atmosphere over the eastern Pacific Ocean in summer; I. The inversion over the eastern north Pacific Ocean. University of California Publications in Meteorology, 1, 94 pp.
- Olsson, L.E., W.P. Elliot, and S.I. Hsu, 1973: Marine air penetration in western Oregon: An observational study. Mon. Wea. Rev., 101, 356-362.
- Overland, J.E., 1984: Scale analysis of marine winds in straits and along mountainous coasts. Mon. Wea. Rev., 112, 2530-2534.
- Palmen, E., and C.W. Newton, 1969: Atmospheric Circulation Systems. Academic Press, Inc., 603 pp.

- Petterssen, S., 1936: On the causes and forecasting of the California fog. J. Aero. Sci., 3, 305-309.
- Pinelli, M., P.F. Lester, and S. King, 1990: A summary of SODAR observations of stable layers below 1000m at San Jose for May - August, 1985. Report, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 25 pp.
- Ramage, C.S., S.J.S. Khalsa, and B.N. Meisner, 1981: The central Pacific near-equatorial convergence zone. J. Geophys. Res., 86, 6580-6598.
- Randall, D.A., J.A. Coakley, Jr., C.W. Fairall, R.A. Kropfli, and D.H. Lenschow, 1984: Outlook for research on subtropical marine stratiform clouds. Bull. Amer. Meteor. Soc., 65, 1290-1301.
- Readings, C.J., E. Golton, and K.A. Browning, 1973: Fine-scale structure and mixing within an inversion. Bound.-Layer Meteor., 4, 275-287.
- 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.
- Roope, G.W., 1980: Aircraft observations of the marine inversion during MABLES WC. Preprints, 2nd Conference on Coastal Meteorology, Los Angeles, California, American Meteorological Society, 254-257.
- Russell, P.B., 1976: Marine boundary layer behavior measured by a network of SODARS (acoustic radars) in the San Francisco Bay Area. Paper presented at the Navy Workshop on Remote Sensing of the Marine Boundary Layer, 9-11 August, 1976, Vail, Colorado.
- _____, and E.E. Uthe, 1978: Regional patterns of mixing depth and stability: SODAR network measurements for input to air quality models. Bull. Amer. Meteor. Soc., 59, 1275-1287.
- Schroeder, M.J., and M.A. Fosberg, 1964: Structure of the sea breeze front in central California. 44th Annual Meeting of the American Meteorological Society, Los Angeles, California, 29-31.

- _____, _____, O.P. Cramer, and C.A. O'Dell, 1967: Marine air invasion of the Pacific coast: A problem analysis. Bull. Amer. Meteor. Soc., 48, 802-808.
- Schubert, W.H., 1976: Experiments with Lilly's cloud-topped mixed layer model. J. Atmos. Sci., 33, 435-446.
- Simon, R.L., 1977: The summertime stratus over the offshore waters of California. Mon. Wea. Rev., 105, 1310-1314.
- Smith, R.K., M.J. Coughlan, and J.L. Lopez, 1986: Southerly nocturnal wind surges and bores in northeastern Australia. Mon. Wea. Rev., 114, 1501-1518.
- Stull, R.B., 1988: An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, 666 pp.
- Tredo, D.C., 1987: Application of a diagnostic boundary layer model to the San Francisco Bay Area. M.S. thesis, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 119 pp.
- Uthe, E.E., and P.B. Russell, 1976: Acoustic sounder network observations during an air pollution incident in the San Francisco Bay Area. Paper presented at Fall Annual Meeting, American Geophysical Union, 6-9 December 1976, San Francisco, California.
- Van Patten, B.D., 1980a: Spectra of wind and temperature near the marine inversion in San Francisco. M.S. thesis, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 60 pp.
- _____, 1980b: Long term spectra of wind and temperature in the vicinity of the marine inversion. Preprints, 2nd Conference on Coastal Meteorology, Los Angeles, California, American Meteorological Society, 262-265.
- Wakimoto, R.M., 1987: The Catalina Eddy and its effect on pollution over southern California. Mon. Wea. Rev., 115, 837-855.

- Williams, W.A., 1966: Wind and temperature variations in the vicinity of the marine inversion over the San Francisco Bay Area. M.S. thesis, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 52 pp.
- _____, and R.E. DeMandel, 1966: Land-sea boundary effects on small-scale circulations. Progress Report #2, Department of Meteorology, San Jose State University, San Jose, California 95192-0104, 97 pp.
- Winant, C.D., C.E. Dorman, C.A. Friehe, and R.C. Beardsley, 1988: The marine layer off northern California: An example of supercritical flow. J. Atmos. Sci., 45, 3588-3605.
- Zemba, J., and C.A. Friehe, 1987: The marine atmospheric boundary layer jet in the Coastal Ocean Dynamics Experiment. J. Geophys. Res., 92, 1489-1496.

Appendix A. AUGSEP79

AugSep79 data (16 August - 8 September 1979) has been placed in an appendix because of uncertainty surrounding the temperature data. Temperature figures from the period (Figures A.1-A.3) show an isothermal layer beginning around Level 3.0 and extending up to Level 6.0 (Figure A.1). Note that Levels 1.0, 3.0, 3.5, 4.0, 5.5, and 6.5 have been eliminated from the final AugSep79 data base because of errors in the data (Figure A.2).

The AugSep79 wind data (Figures A.4-A.8) has the same degree of confidence placed on it as was placed on that of Jul79; i.e., it is "good" data. As observed in the Jul79 data, the AugSep79 data (Figures A.4) also show the counterclockwise rotation of the mean diurnal wind vector, opposite to that found in Miller (1976). The mean wind profiles at selected hours (Figures A.5) show similar patterns of increasing and decreasing speeds to those observed during Jul79, with the maximum speeds found at Level 4.0 (390m ASL). Additionally, they give some indication of a relative wind speed minimum at Level 5.0 (452m ASL). The AugSep79 wind data (Figures A.6-A.8) also shows the afternoon, westerly wind maxima found by Miller (1976) and others, and observed during Jul79 in this study.

Figure A.1 - AugSep79 mean temperature profiles at selected hours.

Figure A.2 - AugSep79 mean temperature curves by tower level.

Figure A.3 - AugSep79 mean temperature ($^{\circ}\text{C}$)
height-time section.

Figure A.4 - AugSep79 hodographs of mean diurnal wind variation:

Figure A.5 - AugSep79 mean wind profiles
at selected hours:

Figure A.6 - AugSep79 mean wind curves by tower level.

Figure A.7 - AugSep79 mean wind direction (deg--dashed lines) and speed (ms^{-1} --solid lines) height-time section.

Figure A.8 - AugSep79 mean wind (ms^{-1}) height-time sections:
 (a) U-component (b) V-component

Appendix B. VERTICAL VELOCITY

Vertical velocity data for Jul79, AugSep79, and the case study period are presented in a series of 24 hour height-time sections. The values observed are most likely heavily influenced by tower effects and local topography, as they are orders of magnitudes larger than vertical velocities calculated from Z_i descent and ascent rates. If this is true, the data in this appendix may be relatively useless, as presented, because the actual, synoptic scale vertical velocities would almost always be masked by local effects. A more profitable study would consist of examining the vertical velocity changes relative to wind directions.

Figure B.1 - Mean vertical velocity (cm s^{-1}) height-time sections:
 (a) Jul79 (b) AugSep79

Figure B.2 - Vertical velocity (cm s^{-1}) height-time sections:
 (a) 19 Jul 79 (b) 20 Jul 79

Figure B.3 - Vertical velocity (cm s^{-1}) height-time sections:
 (a) 21 Jul 79 (b) 22 Jul 79

Figure B.4 - Vertical velocity (cm s^{-1}) height-time sections:
 (a) 23 Jul 79 (b) 24 Jul 79

Figure B.5 - 25 Jul 79 vertical velocity (cm s⁻¹)
height-time section.

Appendix C. CASE STUDY U- AND V-COMPONENTS

U- and v-component 24 hour height-time sections are presented in this appendix. They are presented more for completeness than for any additional information which may be gleaned from them. However, they do serve to clarify wind directions in those instances of rapidly changing conditions, e.g., during easterly wind regimes and the transitions to and from those regimes. Be aware of algorithm quirks (e.g., Figure C.3b) in which "noodling" around data points is particularly obvious.

Figure C.1 - 19 Jul 79 wind (ms^{-1}) height-time sections:
 (a) U-component (b) V-component

Figure C.2 - 20 Jul 79 wind (m s^{-1}) height-time sections:
 (a) U-component (b) V-component

Figure C.3 - 21 Jul 79 wind (ms^{-1}) height-time sections:
(a) U-component (b) V-component

Figure C.4 - 22 Jul 79 wind (m s^{-1}) height-time sections:
 (a) U-component (b) V-component

Figure C.5 - 23 Jul 79 wind (m s^{-1}) height-time sections:
 (a) U-component (b) V-component

Figure C.6 - 24 Jul 79 wind (m s^{-1}) height-time sections:
 (a) U-component (b) V-component

Figure C.7 - 25 Jul 79 wind (ms^{-1}) height-time sections:
(a) U-component (b) V-component