Observational Studies of the Marine Boundary Layer over an Upwelling Region

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ABSTRACT

The mesoscale structure of the lowest 1500 m of the atmosphere for the central Oregon coast region was investigated during August 1973, using meteorological and sea surface temperature data obtained primarily by an instrumented aircraft. Two types of aircraft flight patterns were utilized. The horizontal variability of wind velocity, air temperature, moisture and sea surface temperature are discussed from data collected during level flights at 150 m over the ocean. The vertical structure of temperature, mixing ratio and wind, extending from 50 km inland to 40 km seaward, is examined from a series of horizontal traverses and aircraft soundings made throughout the lowest 1500 m.

The mesoscale wind field over the upwelling region has a structure which depends, to a large extent, on the basic stratification and depth of the marine layer. On days with moderate to strong northerly winds, three separate patterns in the seaward variation of wind speed at 150 m above the surface were observed: a maximum along the coast which was the most frequently observed pattern; a maximum 10–30 km offshore oriented parallel to the coast; and otherwise a mostly uniform pattern. Those cases with a maximum offshore were characterized by a shallow marine layer with no significant inversion in the lowest 1500 m and a protrusion of relatively dry air (presumed subsidence from aloft) associated with the wind maximum; all other cases were characterized by either a deep marine layer or strong marine inversion.

Horizontal gradients in the ambient air temperature appear to reflect the sign of the sea surface temperature gradient to a height of only 150 m or less, as horizontal gradients in the air temperature at 150 m were typically quite small, 1°C (30 km)⁻¹, even on days when sea surface temperature gradients were as large as 5°C (30 km)⁻¹.

1. Introduction

As part of the Coastal Upwelling Experiment (CUE II) off the central Oregon coast during the summer of 1973, an extensive meteorological program was carried out. An overall objective of CUE II was to gain an increased understanding of the forces causing coastal upwelling and of the abundant life which exists in upwelling regions. It is estimated that over half the world's fish catch is from upwelling regions, most of which are located along the west coasts of continents.

The summer climate off the Pacific coast of the United States is dominated by the Pacific anticyclone. Intense daytime heating inland produces a large-scale gradient wind flow along the coast. The combination of this sustained northerly flow and the earth's normal rotation act to push the warm surface waters away from the coast. This water is replaced by colder subsurface waters, which are rich in nutrients that boost the natural food chain. A strong coastal thermal gradient results from the intense heating inland and cold surface waters, leading to the development of a sea breeze circulation. Johnson and O'Brien (1973) have investigated an Oregon sea breeze event for a case study in August 1972 from the coast to 60 km inland. The need for an expanded meteorological program was realized, as little was known about the seaward variation of the mesoscale wind field and marine boundary layer over an upwelling region.

Thus, our main purpose was to attempt to evaluate the character of the mesoscale wind field in the lowest 1500 m over the upwelling region off the central Oregon coast. To investigate the physical processes involved, the wind field is examined in relation to the atmospheric stability, marine layer depth, sea surface temperature and sea breeze circulation.

This study is based primarily on aircraft data, supplemented with rawinsonde, pibal, surface buoy, ship and land station data taken during CUE II. The region of study extends from approximately 40 km seaward to 50 km inland and about 100 km in the north–south direction. A total of 27 aircraft flights were made during August, with a majority of these at 150 m as the measurement of sea surface temperatures.
was a primary objective of CUE II. Aerial explorations on a much larger scale have been made off the coast of Somalia, another upwelling region, to investigate the cross-equatorial jet of the western Indian Ocean (Bunker, 1965; Findlater, 1972). Most of the previous studies have been in terms of the spatial and/or temporal variations of surface winds (Burt et al., 1972, 1973; Maeda and Kishimoto, 1970). In the following sections, a description of the meteorological program and a discussion of the mesoscale phenomena observed for several case studies are presented. Section 2 describes the various field observations during CUE II and includes the methods of data analyses. In Section 3 horizontal variations at 150 m in the wind, temperature and moisture are examined for an oceanic wind speed maximum and a coastal wind maximum. In Section 4 the vertical structure throughout the lowest 1500 m, extending from 40 km seaward to 50 km inland, is discussed for three different cases.

2. Field observations

Meteorological data were collected from a variety of sources, including aircraft, rawinsondes, pibal, buoys, ships, and coastal land stations. Aircraft measurements provided the bulk of the data for investigating the atmospheric boundary layer over the upwelling region. A summary listing of data collected during CUE II has been compiled by Pillsbury and O'Brien (1973).

a. Aircraft observations

During August 1973, the NCAR Queen Air aircraft participated in CUE II off the central Oregon coast. The aircraft was equipped with a remote infrared thermometer for measuring sea surface temperatures and instruments for measuring meteorological parameters such as wind velocity, air temperature, dew-point temperature, pressure and liquid water content. A Doppler navigation system was used in measuring wind velocities.

Two types of flight patterns were carried out. During Type I, the aircraft flew tracks at 150 m above the ocean to measure sea surface temperatures in addition to obtaining meteorological data. The grid area extended 30–40 km off-shore and approximately 75 km north-south. Fig. 1 shows a typical flight pattern. Occasionally, changes were made due to fog or the need to pass over a ship to obtain a reference sea surface temperature measure for the aircraft’s calibration. A report on the preparation of sea surface temperature maps from CUE II is given by O’Brien et al. (1974). Meteorological aircraft soundings were made at points A, B, C and D.

![Fig. 1. Map of central Oregon coast showing the aircraft flight pattern and meteorological observing stations during CUE II.](image-url)
indicated by triangles in Fig. 1. During each vertical sounding, the aircraft made a spiral descent from 1500 to 150 m over the ocean or to 450 m over land.

During Type II flights (Fig. 2), the aircraft collected meteorological data by flying horizontal traverses at altitudes of 300 to 1500 m in steps of 300 m from approximately 50 km inland to 40 km seaward. Aircraft soundings were made over the same locations as in Type I flights. In addition to Type I and II flights, there were two special flights. On 4 August a flight collected data off the Washington coast for Skylab mission 0841, and on 18 August a flight was made 132 km seaward along the buoy line.

All meteorological and infrared measured sea surface temperature data were recorded on magnetic tape with the NCAR Aircraft Recording Instrumentation System during the flights and processed later by the NCAR Aircraft and Computer Facilities. From a continuous record, the wind data were read and plotted in half-minute intervals for Type I and 1 min intervals for Type II along each flight leg. Each minute corresponds to approximately 4.5 km. All Doppler winds were utilized except those during spiral descents, sharp turns and other times when the Doppler gave unreliable winds, e.g., when the ocean surface was relatively calm the Doppler system would often go into memory. A summary on the accuracy of Doppler winds and data errors is given at the end of this section.

b. Pibal and rawinsonde observations

During the latter part of August, an observational program was conducted to gain additional meteorological data. Rawinsondes were launched every 6 h at 0500, 1100, 1700 and 2300 PDT on 18–19, 22–23 and 26–27 August at Cape Kiwanda and Salem. Pibals were launched every 2 h for the same periods at stations indicated in Fig. 1, and twice daily at Cape Kiwanda from 9 to 30 August and at Newport from 1 to 31 August. Transpondersondes released on a few days from the ship R/V Cayuse were tracked from near Cape Kiwanda. These data are used here mainly to supplement the aircraft data.

c. Surface observations

Surface meteorological data were collected from offshore buoys, ships and numerous land stations. Wind velocity, air temperature and sea surface temperature were recorded at nine buoys extending out to 150 km along the Sand Lake buoy line. Ships participating in CUE II were NOAA Ship Oceanographer, R/V Thomas G. Thompson (University of Washington) and R/V's Cayuse and Yaquna (Oregon State University). Routine meteorological observations were taken by the ships in addition to their oceanographic observations. A total of 27 surface stations from the coast to approximately 60 km inland also provided meteorological data.

d. Comments on data errors and the accuracy of Doppler winds

Two main types of errors were observed in the aircraft data: 1) FM radio interference and 2) Doppler wind errors.

Early in the field operations it was determined that
the FM radio influences the data signal during voice transmissions. For this reason the radio usage was noted in the observer's flight log. Interference usually appeared in the form of spikes, and affected temperature, dew point temperature and sea surface temperature readings. Usually, the interference occurred for less than 2 min (9 km). Linear interpolation was employed to estimate the data in areas of interference.

Although no experiments were carried out in this project to determine the accuracy of the Doppler winds, extensive aircraft calibrations and intercomparison studies have been conducted by the National Hail Research Experiment (NHRE) group and others. Duchon et al. (1972) gave a concise summary of this program, while a more intensive discussion was provided in NHRE (1972). Information on the instrumentation and characteristics of the Queen Air aircraft is available (Burris et al., 1973). Foote and Fankhauser (1973) discuss the accuracy of Doppler winds measured by the Queen Air in comparison with an inertial navigation system. For wind speeds of at least 5 m s⁻¹, mean value differences were less than 1 m s⁻¹ in speed and 10° in direction. For higher wind speeds these differences decreased. A cross-spectral analysis comparing Doppler winds with inertial winds indicates there is no significant correlation for scales <3-4 km.

During Type I flights, a slight shift in the magnitude and direction of Doppler winds was noted between north-south and east-west legs. However, wind data were consistent along flight legs of the same (or exact opposite) aircraft heading, as no shifts were apparent. Relative changes in speed and direction along each leg agreed with relative changes along other legs. Over the upwelling region, observed variations in wind speed were greater, for the most part, along E-W flight legs. For this reason absolute values along E-W legs were taken as standard, while relative changes along other legs were utilized to provide greater continuity over the study area.

3. The horizontal distribution of moisture, temperature and wind

In this section we present a summary of aircraft wind data for August 1973 and describe the mesoscale synoptic situation for three separate days with Type I flights. Table 1 lists all of the aircraft flights and the range of observed wind speeds and directions. From a total of 27 flights (Type I and II) 12 were utilized
### Table 1. Summary of Queen Air aircraft flights and winds observed over the upwelling region during CUE II in August 1973

<table>
<thead>
<tr>
<th>Date</th>
<th>Flight</th>
<th>Type</th>
<th>Starting time (PDT)</th>
<th>Wind speed (m s⁻¹)</th>
<th>Wind direction</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug 1</td>
<td>1*</td>
<td>II</td>
<td>1038</td>
<td>8-12</td>
<td>NNE-NNW</td>
<td>Fog offshore.</td>
</tr>
<tr>
<td>2</td>
<td>No flight-fog</td>
<td></td>
<td>1305</td>
<td>8-13</td>
<td>NNE-NNW</td>
<td>Largest wind speeds from coast to 30 km seaward.</td>
</tr>
<tr>
<td>3</td>
<td>2*</td>
<td>I</td>
<td>0842</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>Special support Sky Lab I</td>
<td>1104</td>
<td>2-10</td>
<td>NNE-NNW</td>
<td>Approaching front; rain, clouds NW part of study area.</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>I</td>
<td>0904</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>No flight-fog</td>
<td></td>
<td>0855</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>II</td>
<td>0855</td>
<td>—</td>
<td>—</td>
<td>Short flight due to Doppler in memory over flat ocean.</td>
</tr>
<tr>
<td>8, 9, 10, 11</td>
<td>No flights-scheduled down</td>
<td></td>
<td>0955</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>13</td>
<td>7</td>
<td>II</td>
<td>1332</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>14</td>
<td>8*</td>
<td>II</td>
<td>1257</td>
<td>6-8.5</td>
<td>N-NNW</td>
<td>Wind speed decreases seaward.</td>
</tr>
<tr>
<td>15</td>
<td>9*</td>
<td>I</td>
<td>1002</td>
<td>3-6</td>
<td>NNE-N</td>
<td>—</td>
</tr>
<tr>
<td>16</td>
<td>No flight</td>
<td></td>
<td>1021</td>
<td>2-4</td>
<td>NE-NNW</td>
<td>Areas of flat ocean. Doppler occasionally goes into memory.</td>
</tr>
<tr>
<td>17</td>
<td>10</td>
<td>I</td>
<td>1021</td>
<td>2-4</td>
<td>NE-NNW</td>
<td>Wind speed maximum 10-20 km offshore. Sharp horizontal moisture gradient offshore.</td>
</tr>
<tr>
<td>18</td>
<td>11*</td>
<td>I</td>
<td>0853</td>
<td>1.5-5.5</td>
<td>NNE-NNW</td>
<td>Wind speed maximum 20-30 km offshore. Sharp horizontal moisture gradient offshore.</td>
</tr>
<tr>
<td>19</td>
<td>12*</td>
<td>Special</td>
<td>1327</td>
<td>4-7.5</td>
<td>NNE-NNW</td>
<td>Wind speed maximum 20-30 km offshore. Sharp horizontal moisture gradient offshore.</td>
</tr>
<tr>
<td>20</td>
<td>13</td>
<td>II</td>
<td>0909</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>21</td>
<td>14*</td>
<td>I</td>
<td>1332</td>
<td>2-5</td>
<td>N-NNW</td>
<td>—</td>
</tr>
<tr>
<td>22</td>
<td>15*</td>
<td>I</td>
<td>1230</td>
<td>2-5</td>
<td>NNE-NNW</td>
<td>Wind speed decreases seaward.</td>
</tr>
<tr>
<td>23</td>
<td>16</td>
<td>I</td>
<td>1122</td>
<td>Light and variable</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>24</td>
<td>17</td>
<td>I</td>
<td>0857</td>
<td>Light and variable</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>25</td>
<td>18</td>
<td>II</td>
<td>1338</td>
<td>Light and variable</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>26</td>
<td>19</td>
<td>I</td>
<td>0858</td>
<td>1-4</td>
<td>S-WSW</td>
<td>—</td>
</tr>
<tr>
<td>27</td>
<td>20</td>
<td>II</td>
<td>1319</td>
<td>1-6</td>
<td>S-SW</td>
<td>—</td>
</tr>
<tr>
<td>28</td>
<td>21*</td>
<td>I</td>
<td>1221</td>
<td>3-6.5</td>
<td>NNW-NNW</td>
<td>Wind speed maximum 15-20 km offshore. Sharp horizontal moisture gradient offshore.</td>
</tr>
<tr>
<td>29</td>
<td>22*</td>
<td>I</td>
<td>0908</td>
<td>2-6</td>
<td>NE-NNW</td>
<td>Wind speed decreases seaward. Doppler occasionally in memory over ocean.</td>
</tr>
<tr>
<td>23</td>
<td>23*</td>
<td>II</td>
<td>1549</td>
<td>3-7</td>
<td>N-NW</td>
<td>Doppler occasionally in memory over ocean.</td>
</tr>
<tr>
<td>24</td>
<td>24</td>
<td>I</td>
<td>0855</td>
<td>Light and variable</td>
<td>—</td>
<td>Flat ocean. Doppler frequently in memory.</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>II</td>
<td>1554</td>
<td>Light and variable</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>26</td>
<td>26</td>
<td>I</td>
<td>0854</td>
<td>2-5</td>
<td>NE-NNW</td>
<td>Largest wind speeds in southern half of study area.</td>
</tr>
<tr>
<td>27</td>
<td>27*</td>
<td>I</td>
<td>0904</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

* Indicates those flights utilized in studying the mesoscale wind field.

For studying the mesoscale wind field. Out of these 12, three had a wind speed maximum offshore, five showed a decrease of wind speed seaward and four had no pronounced changes in wind speed. The other 15 cases were not utilized for one or more of the following reasons: 1) light and variable winds; 2) an unfavorable
A brief description of the overall wind pattern for each low-level flight is included with the comments in Table 1. Temperature and dew-point temperature fields for Type I flights were very uniform in most cases with only 1-2°C change over the entire study area. Largest horizontal dew-point temperature gradients were primarily found in regions of offshore wind speed maximum. We examine three cases in describing the horizontal distribution at 150 m above the sea surface.

On 25 August, a distinct low-level wind speed maximum was observed from 15-20 km offshore, oriented almost parallel to the coast line (Fig. 3). When viewed with respect to absolute vorticity, the wind speed maximum is probably significant enough to be termed a "jet." The width scale of this offshore jet is 20-30 km. Bunker (1965) observed a larger scale "jet" (order of 100 km) with a speed of 25 m s⁻¹ from 100-200 km off the coast of Somalia, which is another coastal upwelling region. In the southern half of the study area, the isogon pattern (Fig. 4) indicates confluence ahead of the speed maximum and divergence associated with the minimum. Near the ocean surface, there is no evidence of an offshore maximum based upon an investigation of buoy and ship winds for 25 August.

Figs. 5 and 6 show the synoptic pattern for the Pacific coast at the surface and 850 mb for 1700 PDT 25 August. With the large high-pressure system over the eastern Pacific Ocean and the thermal trough extending northward from California, the synoptic pattern here is quite typical for the Pacific coast during August. Thus, there is no evidence of any large-scale features which can be associated with the mesoscale wind maximum offshore.

The dew-point temperature field (Fig. 7) reveals a distinct minimum at 10-15 km offshore, which corresponds approximately to the east side of the jet axis. The 150 m temperature field is quite uniform with only 1.5°C range over the study area. From aircraft soundings, the vertical structure shows an inversion (2°C 100 m⁻¹) near 960 mb at 40 km seaward which weakens at the coast and disappears inland. Stronger
the aircraft flew at 150 to 132 km seaward, made a
sounding to 1500 m and returned at 150 m along the
same path. Profiles of the meteorological and sea
surface temperature data are shown in Fig. 9. The
synoptic-scale pattern for 1700 PDT 18 August is
similar to that of 25 August (Fig. 5). At the surface
a large anticyclone is centered near 145°W, 50°N. As
on 25 August, a wind speed maximum appears from
15–30 km seaward on both the outbound and inbound
flight, but it is somewhat weaker and discontinuous
on the outbound flights.

Associated with the wind maximum is evidence of
subsidence as shown by the dramatic drop in dew-point
temperature and slight increase in air temperature. In
1.2 h the area of subsidence has not propagated toward
the coast. One possible explanation is the orographic
effect of the coastal mountains, preventing the subsi-
dence from moving any closer than about 10 km
offshore.

The sea surface temperature ranges from 8°C at the
coast to 15°C seaward. The largest gradient is within
10 km of the coast. Due to several days of sustained
northerlies prior to 18 August, which increased the
inversions (5°–10°C 100 m⁻¹) are more typical during
an upwelling regime. A marine layer (>6–7 g kg⁻³)
extends up to the base of the weak inversion.

The sea surface temperature pattern for 25 August
(Fig. 8) shows the isotherms generally aligned NE
to SW, with coldest water near the coast in the southern
half of the study area. Since strong southerly winds
occurred on 23 and 24 August, the sea surface tempera-
tures on 25 August are warmer than normal. Holladay
and O'Brien (1975) discuss the mesoscale variability
of sea surface temperatures during CUE II. The sea
surface temperature pattern for other cases will be
examined and compared with the 25 August pattern
in an effort to determine if there is a direct relation
between the sea surface temperature pattern and the
occurrence of wind speed maximum offshore.

b. Evidence of subsidence offshore

During the early afternoon on 18 August, the NCAR
aircraft made a special flight to examine the variability
of sea surface temperatures, winds and other parameters
seaward from the coastal upwelling zone. After making
routine soundings inland and at the coast, the aircraft
headed north to the Sand Lake buoy line. From here,
c. A coastal wind speed maximum

During the afternoon flight of 14 August, the aircraft recorded NNW winds of 8–9 m s⁻¹ near the coast, decreasing seaward to 6 m s⁻¹. The only major difference in the synoptic-scale pattern from 25 August (Fig. 5) is the northward extension of the thermal low and an intensification of the coastal thermal gradient. Thus, surface wind speeds are greater than on our previous case studies, reaching a maximum of 10 m s⁻¹ by 1800 PDT.

A sharp marine inversion (Fig. 10) occurs near 950 mb. The 150 m dew-point temperature and temperature fields are very homogeneous, varying less than 1°C over the study area. Sea surface temperatures (Fig. 11) are very cold near the coast and increase rapidly seaward. The effect of the colder, coastal water on the atmospheric stability can be seen by comparing the two temperature soundings in Fig. 10. Unlike the offshore speed maximum of 18 and 25 August, the coastal speed maximum does not appear to be associated with a region of subsidence. Thus, we speculate that when the marine inversion is well developed, the presumed subsidence aloft does not penetrate to the extent required to provide the momentum necessary for a wind speed maximum offshore.

d. Summary of other Type I flights

In six other cases examined with moderate to strong northerlies, four had coastal wind speed maximum, one had stronger wind speeds in the southern half of the study area, and one revealed no pronounced variations in wind speed. The sea surface temperatures were generally coldest near the coast, with strongest gradients mainly within the nearest 20 km of the coast. As noted in the previous case studies, horizontal tem-
perature gradients at or above 150 m do not necessarily have the same sign as sea surface temperature gradients (see Figs. 10 and 11). The horizontal dew-point temperature fields were, for the most part, very homogeneous.

4. The vertical structure of moisture, temperature and wind

In this section we discuss the vertical structure of the mixing ratio, temperature and wind from data obtained during Type II flights. Three typical cases are considered: 1) a deep marine layer over the ocean with no significant inversion in the lowest 1500 m; 2) a shallow marine layer over the ocean also with no inversion; 3) a strong, low-level marine inversion. By "marine layer over the ocean," we mean the lower, relatively moist layer extending up to where a sharp gradient in the mixing ratio occurs. Typically, we found the mixing ratio at this level to be about 6–7 g kg⁻¹.

a. A deep marine layer over the ocean

The synoptic-scale pattern for 1700 PDT 26 August showed a weak surface front 200–300 km east of the central Oregon coast. The front appeared to have very little effect on the coastal pressure pattern and weather; coastal winds remained NNW throughout the frontal passage.

The cross section of temperature for late afternoon 26 August (Fig. 12) shows no significant inversions for
the lowest 1500 m, except for an inversion base seaward near 1500 m. In the cross section of mixing ratio (Fig. 13), a broad tongue of relatively dry air is observed over the coastal region; seaward, the marine layer deepens considerably. The corresponding wind field (Fig. 14) reveals horizontal diffuence over the coastal region.

**Fig. 13.** Cross section of mixing ratio (g kg⁻¹) for the period 1600–1830 PDT 26 August 1973.

**Fig. 14.** Solid vectors represent horizontal winds measured by the NCAR aircraft utilizing a Doppler navigation system. Time (PDT) is indicated along each flight leg. Dashed vectors represent pibal (or rawinsonde) winds for either 1615 PDT or 1815 PDT, whichever is closest to the aircraft flight time. M designates Doppler in memory; V, light and variable winds. Wind vectors relate to scale at lower right. In addition, three surface observations are plotted.
region on almost every flight leg. The winds lying offshore have a slight easterly component between 500 and 1200 m, while the winds lying onshore have a westerly component at every level. Although the aircraft made no measurements on vertical velocity, the combination of drier air in the moisture field and horizontal divergence in the wind field imply evidence of subsidence.

The sea breeze circulation from the coast inland is apparent from aircraft and pibal winds. The return flow of the sea breeze circulation appears as a minimum in the westerly component at approximately 1300–1500 m. Pibal winds show an increase in the westerly component again above 1500 m. By this time of day (1600–1800 PDT), the sea breeze circulation is usually well developed and extends eastward into Willamette Valley (50 km inland), as is the case here. With the return flow of the sea breeze circulation aloft and the strong westerly component in the lower levels over land, it appears that the presumed subsidence over the coastal region is associated with the seaward end of the sea breeze circulation.

b. A shallow marine layer over the ocean

Here we present a case, shown in Fig. 15, where a tongue of drier air (presumed subsidence) extended almost down to the sea surface. The seaward marine layer has lowered by approximately 600 m from 26 August to 27 August, due to an increase in large-scale subsidence aloft. The synoptic-scale pattern for 27 August shows an extension of the Pacific High inland at the surface and the strengthening of the westerly flow aloft, accompanied with a reduction in coastal pressure and thermal gradients. Northerly winds reached 5 m s\(^{-1}\) during the afternoon. The lapse rate was approximately 0.7°C (100 m)\(^{-1}\), both inland and seaward up to an inversion near 1500 m.

With a smooth ocean surface, aircraft winds over the ocean were unreliable, as the Doppler system often went into memory. From the coast inland, pibal and aircraft winds indicate a low-level westerly component flow and a return flow of the sea breeze circulation between 1000–1500 m. As on 26 August, the relatively dry air in the lowest 600 m over the coastal region appears to be associated with the seaward end of the sea breeze circulation (Fig. 15).

The deep protrusion of presumed subsidence penetrated the 150 m level at approximately 10–15 km seaward. We suggest that similar occurrences produced the offshore subsidence bands, and the corresponding offshore wind speed maximum, observed during the afternoons of 18 August (Fig. 9) and 25 August (Fig. 7). Near the coast it is speculated that upslope winds counteract the subsidence. Sea surface temperatures for 27 August are coldest near the coast (11°C), increase rapidly to 14°C at 8 km seaward and to 16°C near 30 km seaward. Apparently, the strongest subsidence is not located directly over the coldest water.

c. A strong marine inversion

The synoptic-scale pattern for 1700 PDT 1 August shows a large anticyclone over the eastern Pacific
centered near 140°W, 40°N and extending northeastward to the Oregon-Washington coast. The sea level coastal pressure pattern is similar to that of 25 August (Fig. 5); however, the east-west pressure gradient is stronger and the thermal gradient more intense. Consequently maximum coastal wind speeds at the surface are approximately 12 m s⁻¹ on 1 August as compared to 8 m s⁻¹ on 25 August. Sea surfaces temperatures are less than 9°C near the coast and increase to 14°C at 40 km seaward. A sharp inversion, 5°C (100 m)⁻¹ exists near 500 m and disappears inland, and the top of the marine layer coincides approximately with the base of the inversion. A tongue of drier air (10–15 km in width) above the coastal region extends down to the inversion top. Inland the sea breeze circulation has developed. However, the presumed subsidence over the coastal region does not penetrate the strong marine inversion. The vertical structure here is very similar to that of 3, 14 and 15 August, which are also characterized by strong low-level marine inversions. The 150 m aircraft winds for these days reveal a decrease of wind speed seaward. Thus, we conclude that on days with strong inversions or deep marine layers, subsidence from aloft cannot penetrate to the extent necessary to provide momentum for an offshore low-level wind speed maximum.

5. Summary and conclusions

The case studies presented are believed to exhibit the majority of mesoscale features existing in the atmosphere over an upwelling regime for the Oregon coast region. The most outstanding features observed were the wind maximum offshore and the tongue of relatively dry air over the coastal region. Some important characteristics of the mesoscale wind field and the atmospheric boundary layer over the upwelling region, with respect to the stratification, depth of the marine layer, sea surface temperature, and sea breeze circulation, are:

1) The mesoscale wind field has a structure which depends on the basic stratification and the depth of the marine layer. Those days with a wind speed maximum offshore at 150 m are characterized by a shallow marine layer, a weak inversion (if any) and a protrusion of relatively dry air (presumed subsidence from aloft) associated with the speed maximum. Those days with a wind speed maximum along the coast are characterized by either a deep marine layer or strong inversion, preventing coastal subsidence from penetrating down to 150 m.

2) The wind maximum observed offshore is a mesoscale phenomenon, with a width scale of 20–30 km, occurring from 10–30 km seaward. From an investigation of surface buoy and ship winds, there is no evidence of the offshore maximum extending down to the sea surface.

3) A narrow region of subsidence over the coastal oceanic region appears to be associated with the seaward end of the sea breeze circulation and is perhaps a major mechanism in the maintenance of the wind speed maximum offshore.

4) Horizontal temperature gradients at 150 m over the upwelling zone are usually very small in contrast to sea surface temperature gradients which are often as large as 5°C (30 km)⁻¹. Above 150 m the horizontal air temperature gradient is often the opposite sign of the sea surface temperature gradient.

It is hoped that the results of this analysis will give some insight into the understanding of the mesoscale structure of the atmosphere during a coastal upwelling regime and stimulate some ideas for future research on this problem.

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