Analysis of the Monterey Bay Sea Breeze

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Operational Oceanography
OC3570

1. Introduction

Understanding the sea breeze is important because of who and what it affects: fire weather, air pollution, aviation, military operations, agriculture, recreation, urban development, shipping, and transportation (Banta, 1995). It is one of the most studied atmospheric phenomena due to the heavy concentration of the world's population along the coastline of oceans (Banta et al, 1993).

The purpose of this project was to collect, compare, and analyze data from the summer cruise. The cruise was a special opportunity to incorporate data from various sources, including aircraft, ship, and surface stations.

One must know that the sea breeze along the coast of Monterey Bay differs from that in areas where many other studies have been conducted because of the strong marine inversion at the coast and offshore (Banta et al, 1993). Other key features unique to this area are the coastal mountain ranges and hot interior valleys (Banta et al, 1993). Studies previously performed in Monterey Bay sea breeze illustrate the importance of the statements above. The literature provides better insight into evolution, growth, and spatial and temporal variability, and examines the sea breeze to a greater extent that this project allows.

The present study focuses on three days: July 25, 26, and 27. The ship's position and rawinsonde launches provide the best information to compare with other instrumentation. Past observational studies, which have relied on radiosondes, surface-station measurements, and/or radar, have produced only limited data on the vertical structure of the sea breeze (Intrieri et al, 1990). Because rawinsondes only provide single-location data, important details on the evolution and growth of the sea breeze remain unknown for this study. (Intrieri et al, 1990). In this paper the main areas of study and instrumentation used will be described, along with results and conclusions, and any recommendations for future projects.

2. Background

In order to understand the results and conclusions of this project, an overview of the sea breeze will be presented. The basic forcing mechanism driving sea breeze circulations is the development of a coastal thermal gradient to which the wind responds. A horizontal temperature gradient develops due to the differential radiative properties of the water and land surfaces. This temperature gradient will produce a pressure gradient. The warm air over land tends to lower the surface pressure relative to the unchanged, or cooler boundary layer air over the water. Thus, an onshore- directed pressure gradient arises to which the air must respond by accelerating toward the coastline (MR4240, 2003). Sea breezes typically form and begin their flow inland during the mid- to late-morning hours, when the daytime temperature gradient between land and ocean is fairly strong. The sea breeze circulation intensifies as solar heating reaches its maximum. Afternoon is the most active time of day for this circulation, as sea breeze penetration reaches a maximum and winds are strongest. The results of the cruise study will be consistent with this background information.

3. Data and Methods

Meteorological data was collected during the oceanographic cruise on the Research Vessel Point Sur during the period of 21July 2003 to 28 July 2003. This project focuses on the information obtained on 25-27 July, when the R/V Point Sur was in the Monterey Bay. See figure 1. Additionally, surface-station measurements were acquired for those days. Data used in this study consists of height, wind direction, wind speed, position, time, air temperature, relative humidity, dew point, and sea surface temperature. Ship-collected measurements were collected using Pt. Sur's Science Data Acquisition System, which is referred to as the SAIL data. The cruise meteorological data consisted of hourly observations and rawinsonde launches at approximately 18Z and 23Z, as instructed by Professor Nuss. Surface-station measurements include: the NPS 915 MHz Profiler located at Fort Ord, positioned at 51 meters; station MRY (Monterey) located at 67 meters at 36.59^{o} N, 121.84^{o} W, and station SNS (Salinas) positioned at 25 meters at 36.66^{o} N, 121.61^{o} W. See figure 2.

4. Data Analysis

The computer software program MATLAB was used to ingest the data from the various sources and produce plots that were used for the analysis. Many of the data files had bad values, so NaN was manually entered at these points to eliminate a plotting error. The rawinsonde data had to be converted into a .mat file with the help of loadsnd.d3.m, a program provided by Professor Guest. The figures generated from the rawinsonde data uses the following parameters: height, temperature, dew point, wind speed, and wind direction. Each balloon went to a certain height, but since the sea breeze is a lower level phenomenon, the parameters were plotted up to 2000 meters. The rawinsonde graphs also illustrate the up-down direction.

The SAIL data consists of time, wind speed and direction, temperature, relative humidity, and sea surface temperature. Dew point was calculated by td.m, a program provided by Professor Guest, and was plotted against time along with sea surface temperature and air temperature. Surface-station data was plotted using time, wind speed and direction, temperature, and dew point. Dr. Nuss, NPS Department of Meteorology, provided me with all of the surface station data from July 25-27. Because Dr. Nuss uses numerous surface sites for his own analysis, I had to manually extract SNS and MRY from all the files. Each file contained the numerous stations with its hourly observation. The hourly observations were extracted for both SNS and MRY to create a plot for each day.

Procedures for analyzing the characteristics of the Monterey Bay sea breeze were plotting and "eyeballing" specific changes in the different parameters. The variables for each data source were compared for each day, and these results will be discussed in further detail. The plots containing time show the variables in local time. Please refer to the power point if there are marks missing on the pictures contained in the appendix.

5. Results and Discussion

A. 25 July (Refer to Appendix A for figures)

To begin, the rawinsonde launch at 2345Z (1545 PDT) was marked on all corresponding plots. This corresponds to approximately 206.975 on the graphs. The sonde data shows westerly, northwesterly flow until approximately 1000 meters with the highest wind speeds of 9 meters per second occurring at 500 meters. The ship's sensor indicates an air temperature of about 14.2 degrees Celsius, which is verified with the temperature reading obtained from the rawinsonde. The ship's sensor also specifies a westerly, northwesterly wind of about 3.5 meters per second. Keep in mind that the ship's sensor was about 13 meters above sea surface. Station MRY is depicting a wind speed of about 6 meters per second with decreasing winds as time progresses. It also shows that the flow is from the west, northwest at the time of the launch. MRY is showing a temperature of about 18 C, with decreasing temperatures as time progresses. Salinas is indicating a wind speed of about 7.5 meters per second of northwesterly wind. Salinas is showing a temperature of 18.5 degrees Celsius with decreasing temperatures observed in the next few hours.

The Ft. Ord profiler displays time increasing from right to left. The 25 July plot runs from 00Z to 2330Z. Since the launch took place at 2345Z, both the 25 and 26 July plots were looked at to verify conditions. At the time of launch, the profiler shows flow from the west up to about 900 meters with speeds of about 5 meters per second. The surface temperature as indicated by the profiler is approximately 15 degrees Celsius. Interestingly, a study by Banta observed two different sea breeze layers occurring on the same day. A shallow sea breeze began between 0900 and 1000 (PDT) but remained less than 300 meters deep. After 1200, the flow between 300 meters and 1000 meters reversed and began to flow onshore. The lower-level shear that had existed atop the shallower sea breeze at 300 meters disappeared as the deeper sea breeze absorbed the shallower sea breeze (Banta, 1995). This can be seen on the Ft. Ord profiler data. The onset of onshore flow begins at about 1000 PDT, up to about 400 meters. The shallow layer was absorbed around 1600 PDT, after the reported time in the previous study.

In review, the rawinsonde data shows onshore flow at the lower levels with a southerly flow aloft, with the max wind speed occurring at 500 meters on the up route. The ship's sensor displays onshore flow with wind speeds fluctuating between 2 and 4 meters per second after the rawinsonde launch, and reports a change in direction of winds from southerly to westerly around 1330-1500 PDT. This is the onset of the sea breeze.

The shift in direction is accompanied by a decrease in winds, and lasts for a few hours. The measured air temperature from the ship shows a decrease around the same time that there was a shift in winds. An increase in wind speed lags the wind shift. Should there be a decrease in wind speed at the time of wind shift if this is a sea breeze? This question will be further addressed later in the report. MRY shows a reversal of winds at about the same time as the ship's data, with a lag in the increase of wind speed, which is consistent with the ship. Once the winds are out of the west, the air temperature begins to decrease. The sea breeze cannot be deduced from the data on 25 July at Salinas. The winds are from the west to north throughout the day.

B. 26 July (Refer to Appendix B for figures)

Once again, the rawinsonde launch at 1758Z (1058 PDT) and 2341Z (1641 PDT) was marked on all corresponding plots. This corresponds to approximately 207.73 and 207.97 respectively, on the graphs. The first rawinsonde shows a very shallow layer of westerly flow up to about 300 meters, with a wind max of 5.5 meters per second happening at 100 meters. The second rawinsonde indicates westerly to northwesterly flow occurring up to approximately 800 meters, with a wind max of about 7 meters per second at 250 meters. SAIL indicates an increase in wind speeds around 1000 PDT. This increase in wind speed lags the change in wind direction, which occurs just a little earlier. The westerly winds last throughout the rest of the day. The shift in direction is accompanied by a rise in air temperature according to the SAIL data. MRY shows an increase in wind speeds about the same time the ship does. The increase lasts for several hours. There is some indication of onshore flow early in the morning , but better indication of the afternoon sea breeze 1500. The afternoon onshore flow is associated with a decrease in temperature. Salinas indicates a wind shift to westerly early in the morning, and remaining westerly throughout the day. Similar to the ship, the wind speed increase lags the change in direction. It is hard to deduce a true sea breeze with this data, as illustrated in the previous day at Salinas.

The profiler data exhibits a very shallow layer of westerly flow up to about 300 meters beginning at 1100 PDT and lasting only a few hours. The shallow layer seems to be absorbed by a much deeper sea breeze around 1400 PDT. This layer reaches about 850 meters. This characteristic of the sea breeze is fairly consistent with the previous day. In review, the rawinsonde data is comparable to the profiler data in that it displays both the shallow and deep layers of onshore flow. The ship's sensors indicate that the onshore flow begins early in the morning and persists throughout most of the day. An increase in wind speed lags the change to onshore flow, and an increase in air temperature occurs after the wind shift. MRY shows some indication of the shallow onshore flow observed in the profiler, and clearly depicts the afternoon sea breeze. SNS, however, shows the wind shift occurring only once, and is early in the morning.

C. 27 July (Refer to Appendix C for figures)

Finally, for the last day both rawinsondes were marked accordingly. These took place at 1802Z and 1648Z, or 208.75 and 208.96 respectively on the plots. There is implication of shallow westerly flow, up to about 550 meters on the first launch. On the second launch, a much deeper layer of westerly flow remains up to 1000 meters. The wind speed has increased since the earlier launch. The ship data shows that the westerly flow began at 1000 PDT, which ironically corresponds to the time of the first balloon launch. It also features an associated wind speed increase. Station MRY gives clear indication of an afternoon sea breeze. Here, the wind direction fluctuates so much in the morning that it is hard to deduce the shallow layer of onshore flow that was present in the morning rawinsonde launch. MRY displays a short rise in temperature and then decreases the rest of the evening. The data at the Salinas station reports westerly flow in the morning with a few hours of northerly flow. There is clear evidence of the afternoon onshore flow, which began a little earlier than in Monterey. It is associated with an increased wind speed.

The profiler shows small evidence of the shallow morning westerly flow. It reports this flow up to about 300 meters, whereas the rawinsonde expressed the westerly flow up to 550 meters. It depicts onshore flow occurring at 1200 PDT and persisting for several hours. The level rises to 800 meters. In review, the rawinsonde data supports Banta's findings of the two different sea breeze layers occurring on the same day. The SAIL data does not contain evidence of this, but displays an early change of wind direction and increase in speed that lasts throughout most of the day. The surface station data in Salinas exhibits onshore winds earlier than Monterey, which lasts much longer.

6. Remarks/Conclusion

Because rawinsondes give only single location data, it is important to incorporate more sources into the project. However, there is a downside to surface stations. They do not measure in the vertical so the depth of the sea breeze could not be measured at these locations. Only the profiler and rawinsonde are capable of illustrating the depth of the onshore flow. Despite having five sources of data (profiler, two surface stations, rawinsondes, and ship), the characteristics of the Monterey Bay sea breeze were hard to trace because of the lack measurement sources described above. Also, because the topography of the California coast is highly complex, it is not surprising that the sea breeze in Monterey Bay is also complex (Banta, 1995). With the data presented here, it is hard to infer the spatial scale. Had there been access to surface stations deeper into the Salinas Valley, there may have been evidence of the presence, or lack of, a sea breeze further inland. The most fascinating result of this study was the presence of two layers of onshore flow, as proved in previous research. It was stated earlier that a decrease in wind speeds occurred with the wind shift in some instances. Banta (1995) discovered that as the deep sea breeze absorbed the earlier shallow sea breeze layer, it produced an elevated wind speed maximum and was accompanied by a deceleration of flow at the surface. This would explain the reported wind decrease on the ship sensor.

Sea breezes pose forecast challenges in the coastal environment, thus it is critical to the meteorologist to understand the characteristics unique to the area. The forecast has effects on aviation, military operations, and others that were mentioned in the beginning of this report. Here are some important ingredients relative to the sea breeze that are vital to the forecaster (http://meted.ucar.edu/mesoprim/seabreeze):

- amount of heating: crucial to the development of any sea breeze
- distribution of heating: determines the details of the sea breeze, dependent on environmental conditions
- synoptic-scale flow: can vary the sea breeze winds

It is important to use all available forecasting tools when dealing with sea breezes.

7. Recommendations

Recommendations for future sea breeze studies include more rawinsonde launches. This may help show more of a diurnal cycle, and the presence of a land breeze in the bay. Surface station data scattered throughout the peninsula and deep into the Salinas Valley would aid in identifying how far the sea breeze actually penetrates inland.

Incorporating aircraft data would be a useful remote sensing tool to verify the ground observations and provide a wider range of data. Observational gaps could be filled with the use of surface lidar. Its capability would aid in capturing the vertical and horizontal structure of the sea breeze.

References

1) Banta, R.M., L.D. Oliver, D.H. Levinson, 1993: Monterey Bay Sea-Breeze As Observed by Pulsed Doppler Lidar. *J. of Atmospheric Sciences,* **50,** 3959-3982.

2) Banta, R.M., 1995: Sea Breezes Shallow and Deep on the California Coast. *Monthly Weather Review,* **123**, 3614-3622.

3) Intrieri, J.M., C.G. Little, W.J. Shaw, R.M. Banta, P.A. Durkee, R.M. Hardesty, 1990: The Land/Sea Breeze Experiment (LASBEX). *Bulletin of the American Meteorological Society,* **71,** 656-664.

4) MR4240 Coastal Meteorology course notes

5) MATLAB program provided by P. Guest

6) http://meted.ucar.edu/mesoprim/seabreeze : Sea breeze tutorial

SURFACE STATIONS – Figure 1

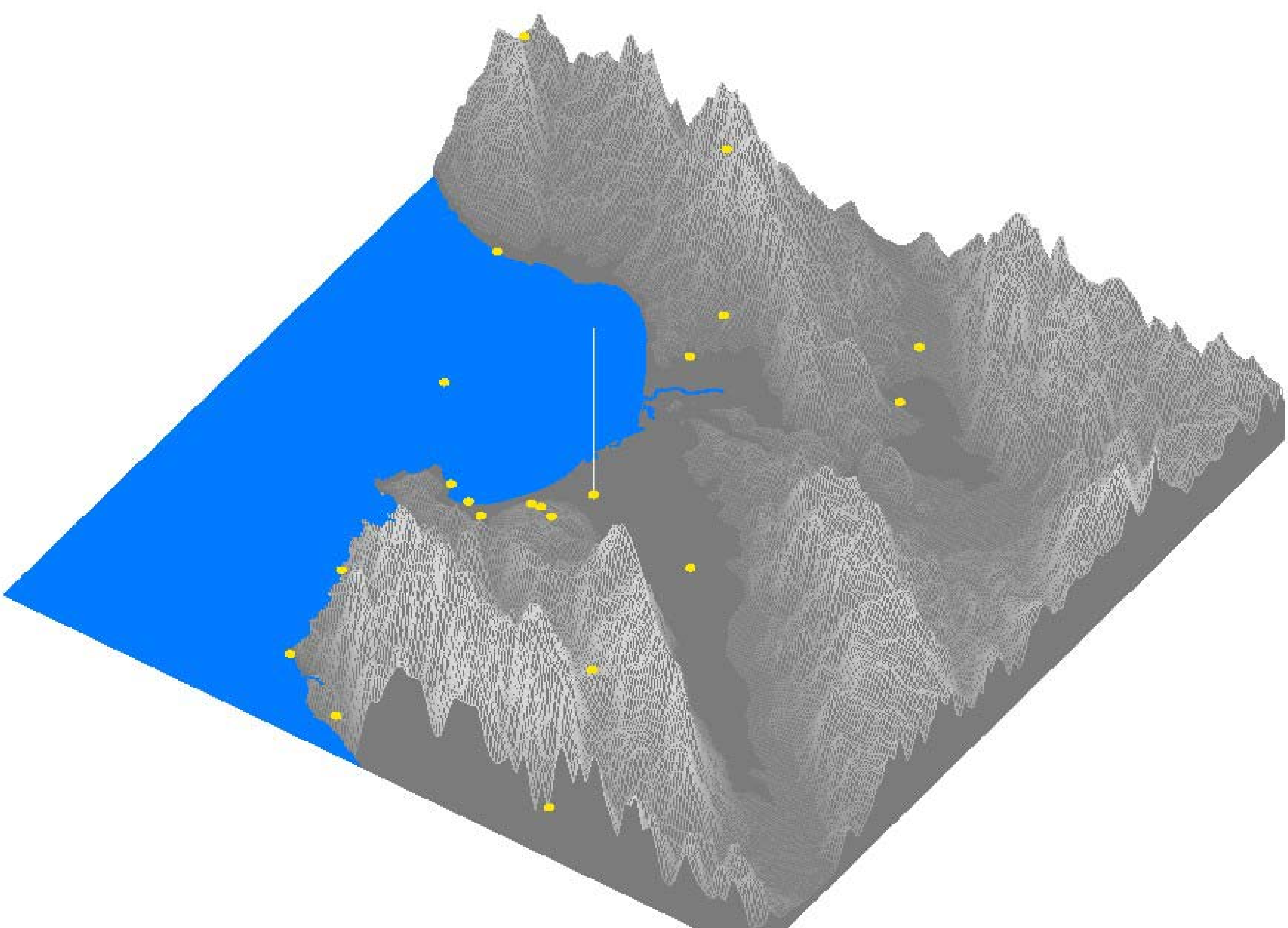
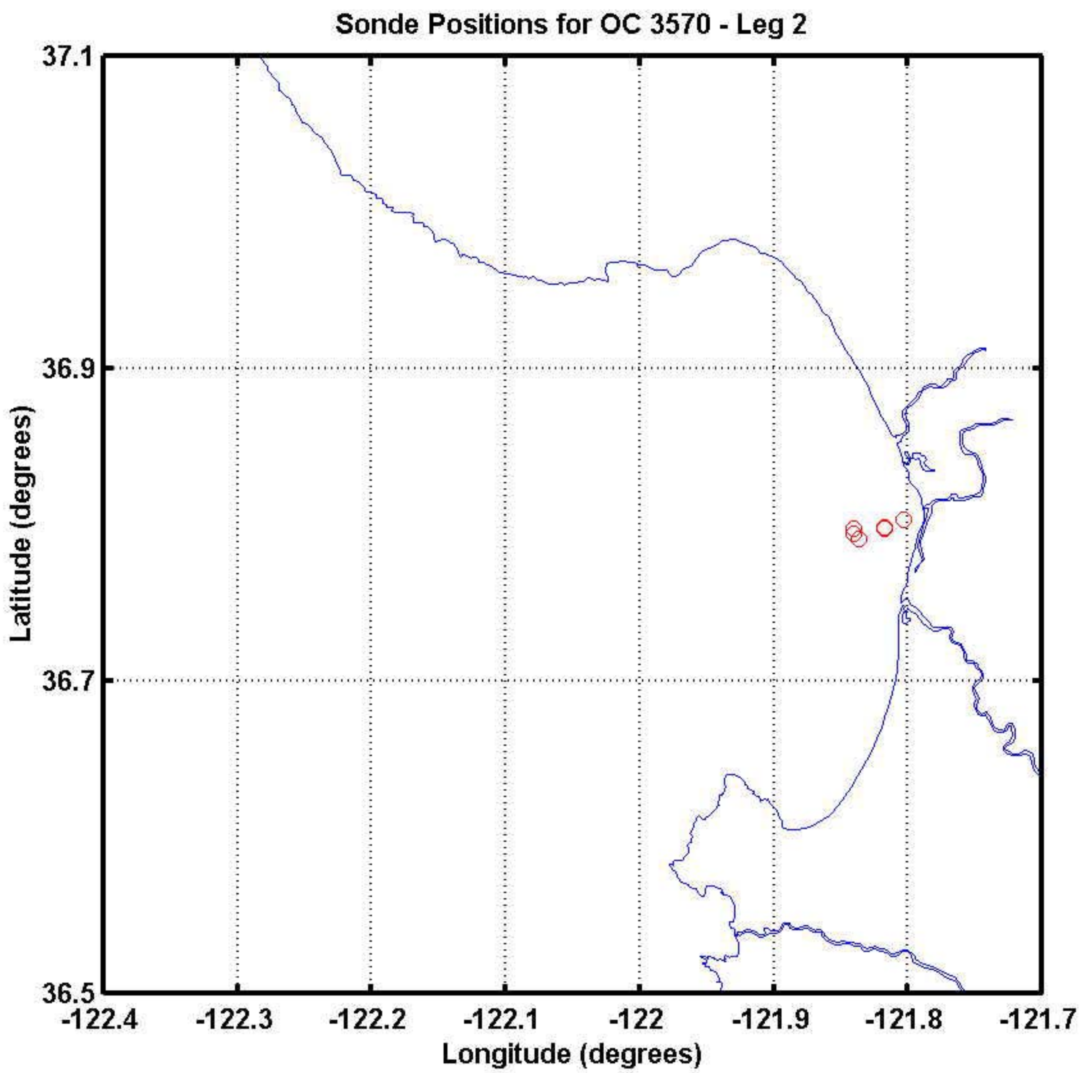
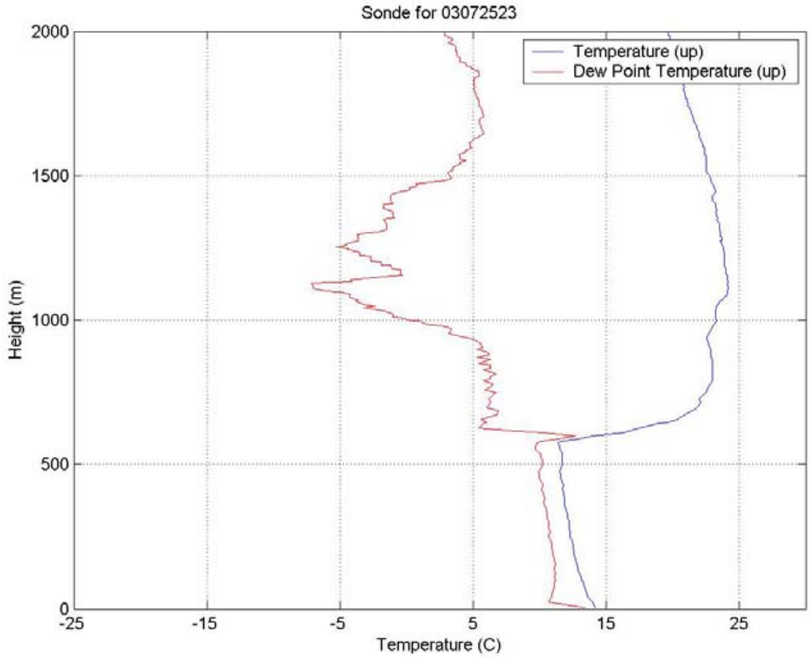


Figure 2



Sonde Positions for OC 3570 - Leg 2
37.1
36.9
36.7
36.5
Latitude (degrees)
-122.4
-122.3
-122.2
-122.1
-122
-121.9
-121.8
-121.7
Longitude (degrees)

Appendix A


Sonde for 03072523
Temperature (up)
Dew Point Temperature (up)
Height (m)
Temperature (C)
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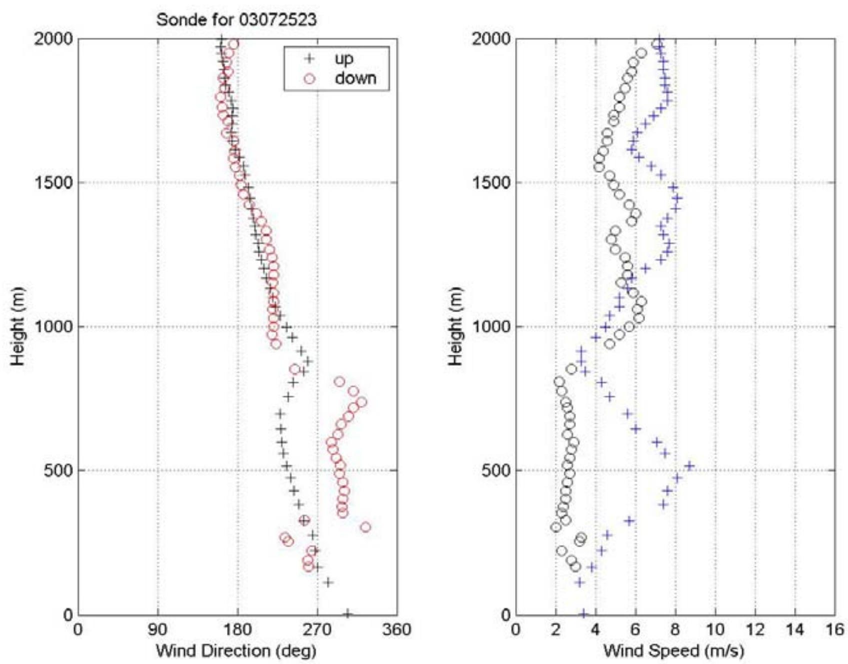
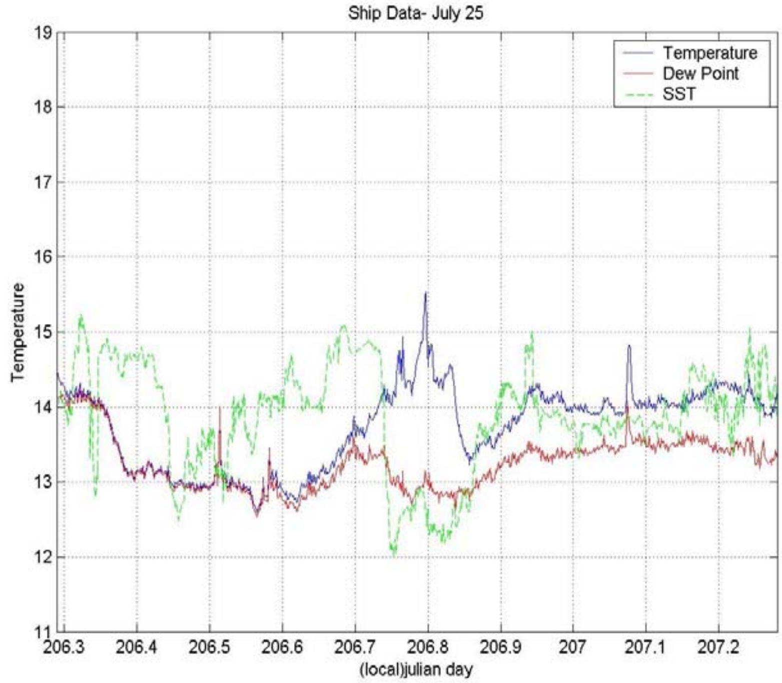
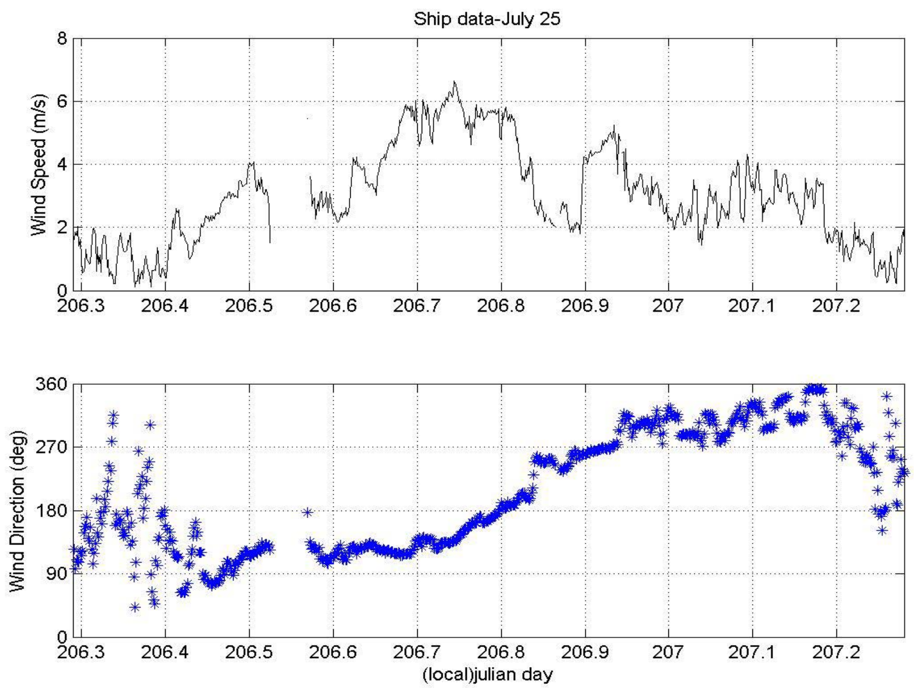
1500
1000
500
0
-25
-15
-5
5
15
25


Sonde for 03072523
up
down
Height (m)
Wind Direction (deg)
0
90
180
270
360
Wind Speed (m/s)
0
2
4
6
8
10
12
14
16
2000
1500
1000
500
0


Ship Data- July 25
Temperature
Dew Point
SST
Temperature
(local)julian day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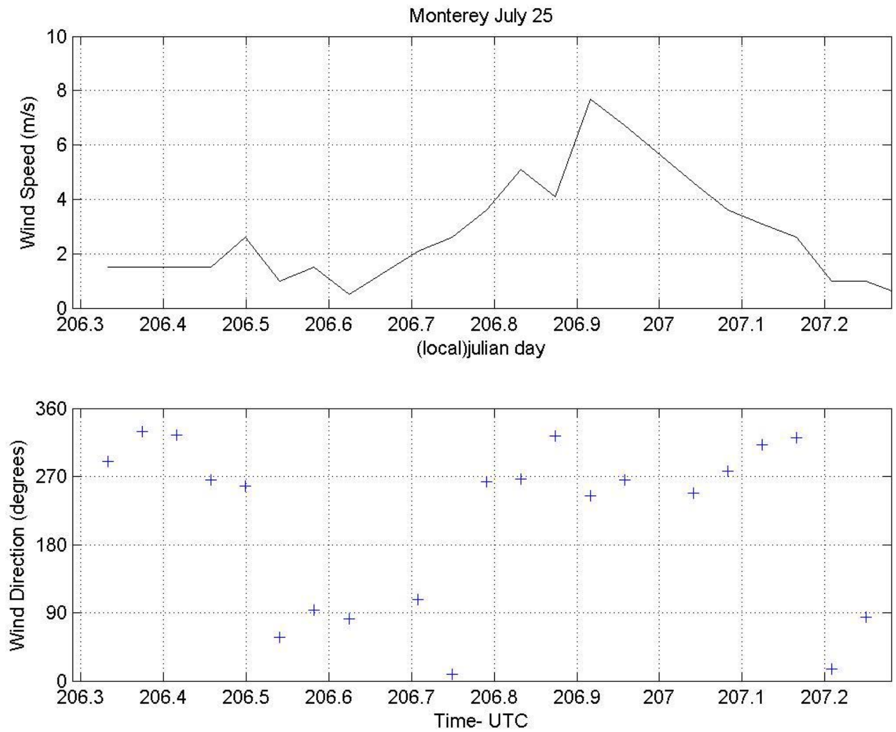
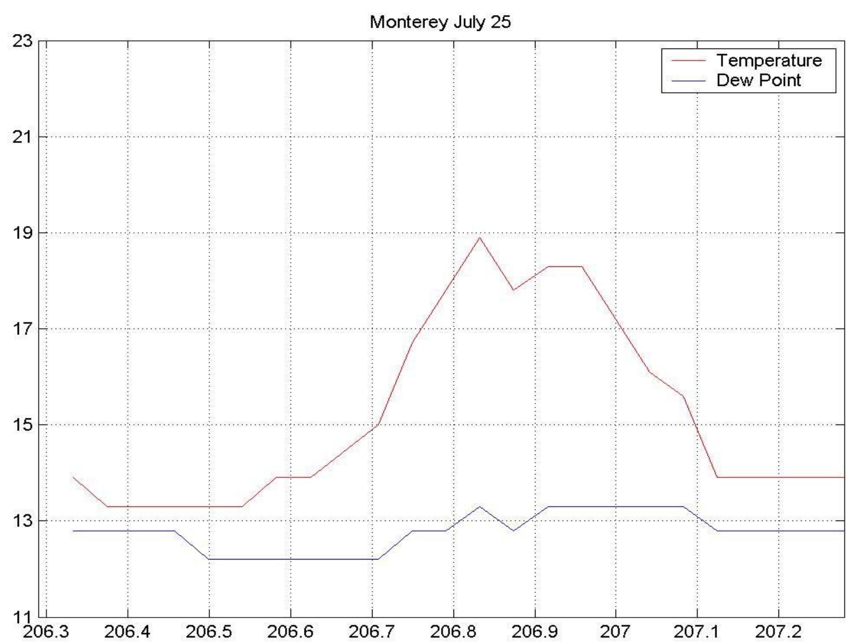
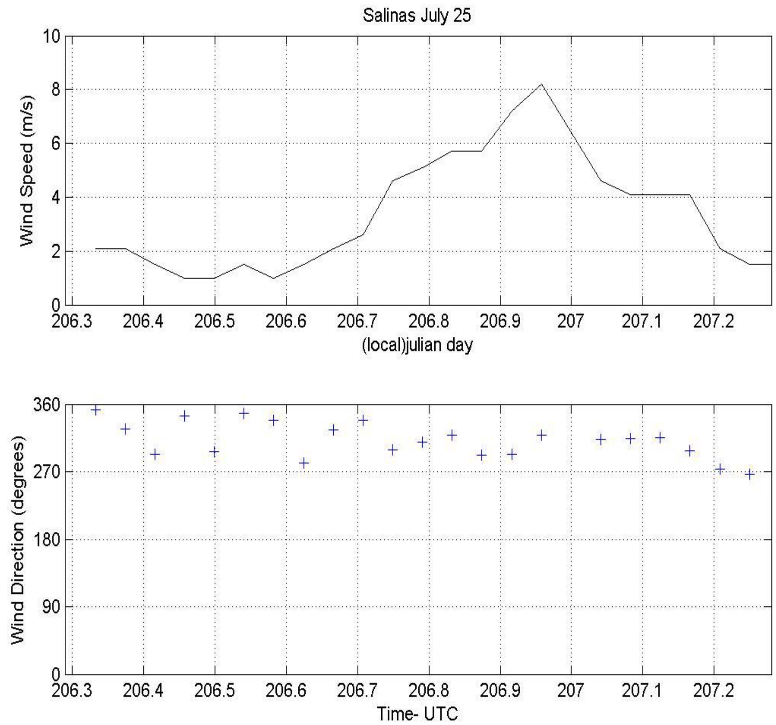
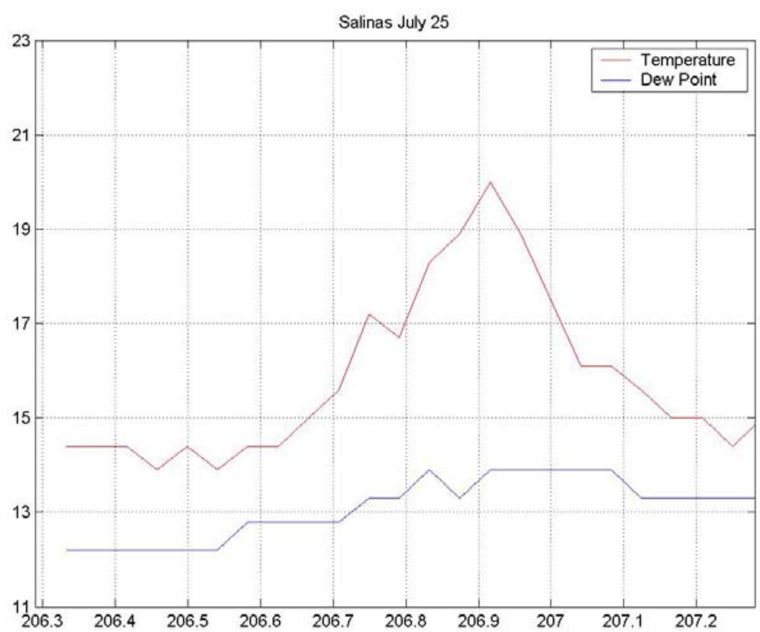
Wind Speed (m/s)
Wind Direction (deg)
(local)julian day


Monterey July 25
Wind Speed (m/s)
10
8
6
4
2
0
206.3 206.4 206.5 206.6 206.7 206.8 206.9 207 207.1 207.2
(local)julian day
Wind Direction (degrees)
360
270
180
90
0
206.3 206.4 206.5 206.6 206.7 206.8 206.9 207 207.1 207.2
Time- UTC


Monterey July 25
Temperature
Dew Point
23
21
19
17
15
13
11
206.3 206.4 206.5 206.6 206.7 206.8 206.9 207 207.1 207.2


Salinas July 25
Wind Speed (m/s)
0
2
4
6
8
10
206.3
206.4
206.5
206.6
206.7
206.8
206.9
207
207.1
207.2
(local)julian day
Wind Direction (degrees)
0
90
180
270
360
Time- UTC


Salinas July 25
Temperature
Dew Point
11
13
15
17
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23
206.3
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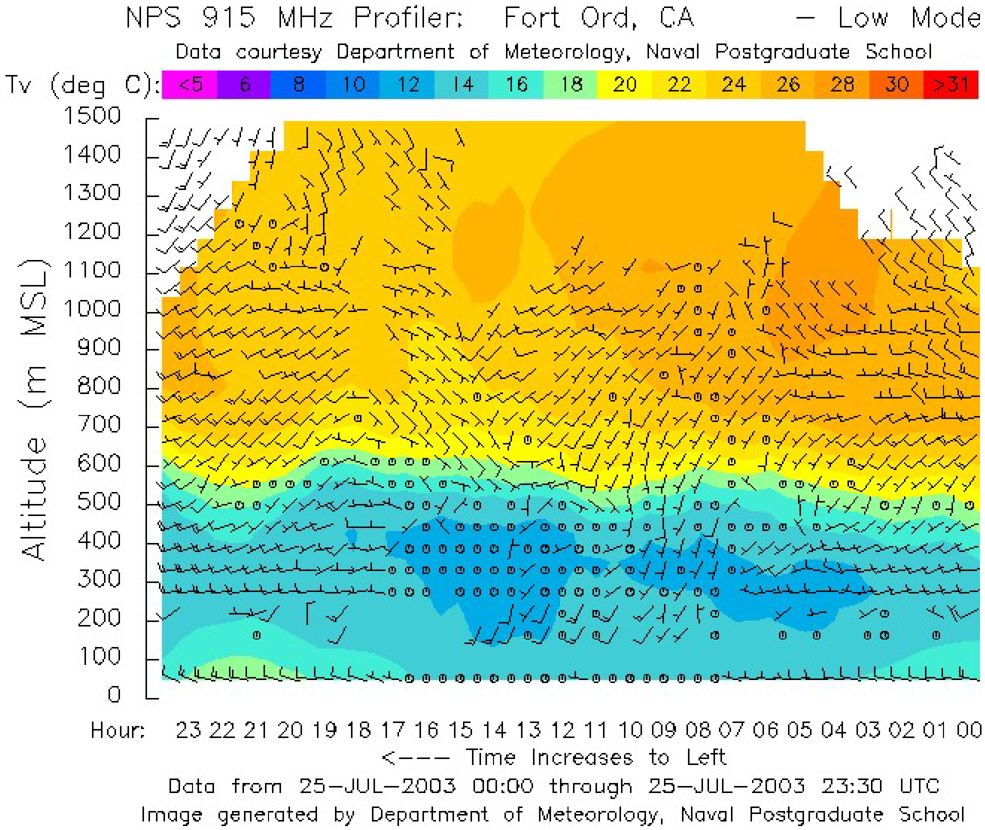
207
207.1
207.2


NPS 915 MHz Profiler: Fort Ord, CA — Low Mode
Data courtesy Department of Meteorology, Naval Postgraduate School
Tv (deg C): <5 6 8 10 12 14 16 18 20 22 24 26 28 30 >31
Altitude (m MSL)
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Hour: 23 22 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00
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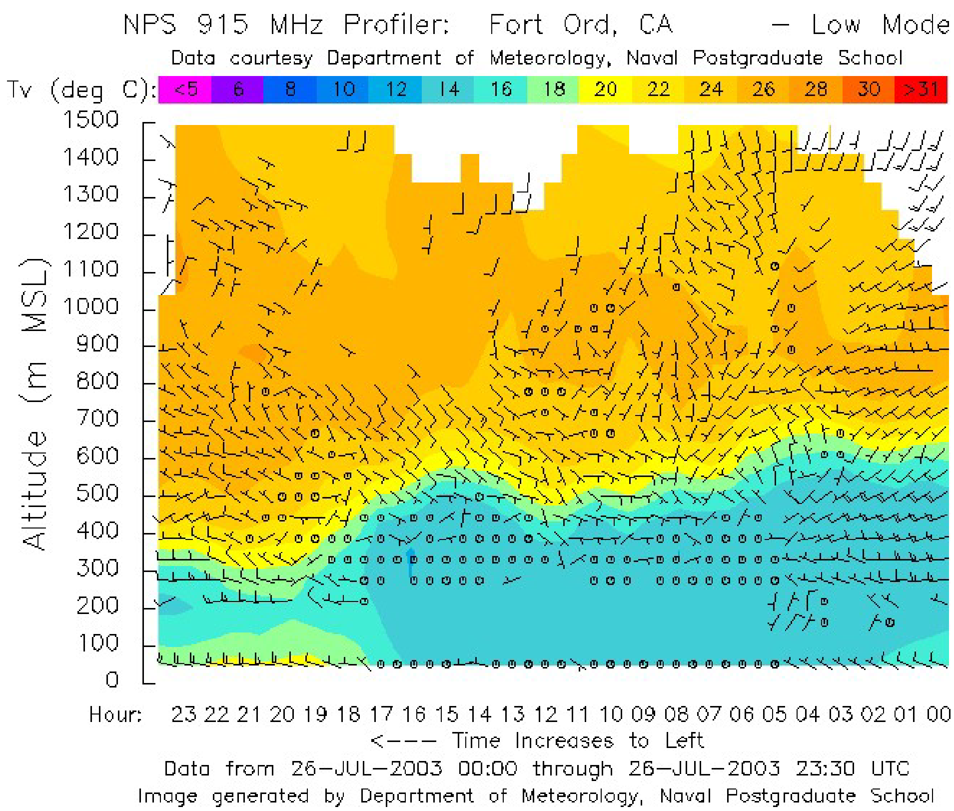
Image generated by Department of Meteorology, Naval Postgraduate School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Data courtesy Department of Meteorology, Naval Postgraduate School
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Altitude (m MSL)
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Hour: 23 22 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00
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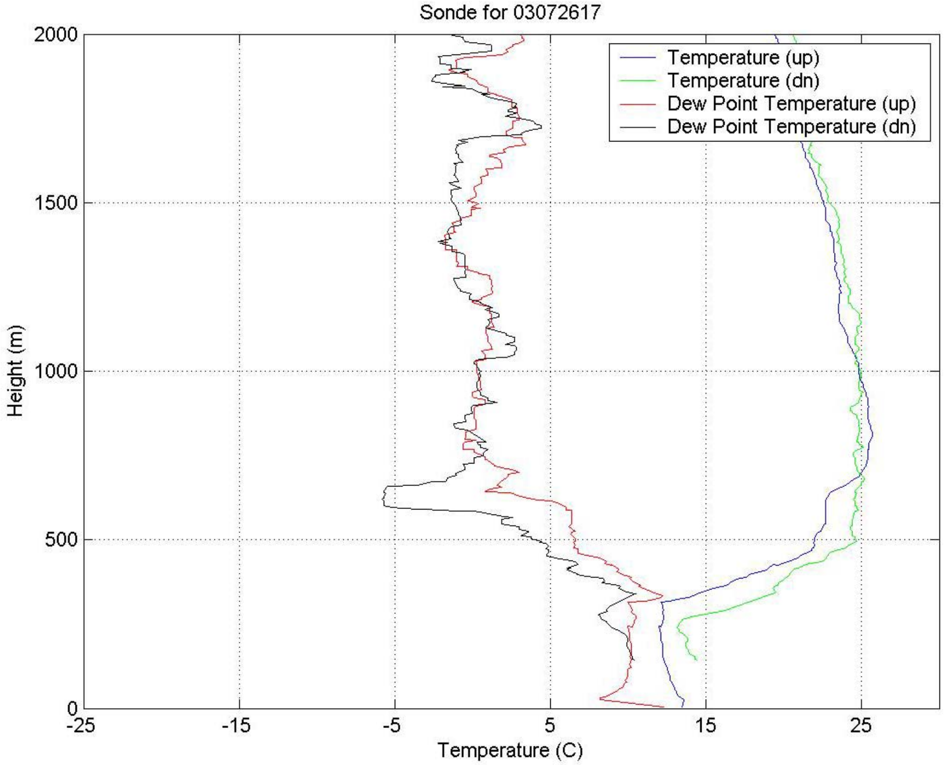
Image generated by Department of Meteorology, Naval Postgraduate School

Appendix B



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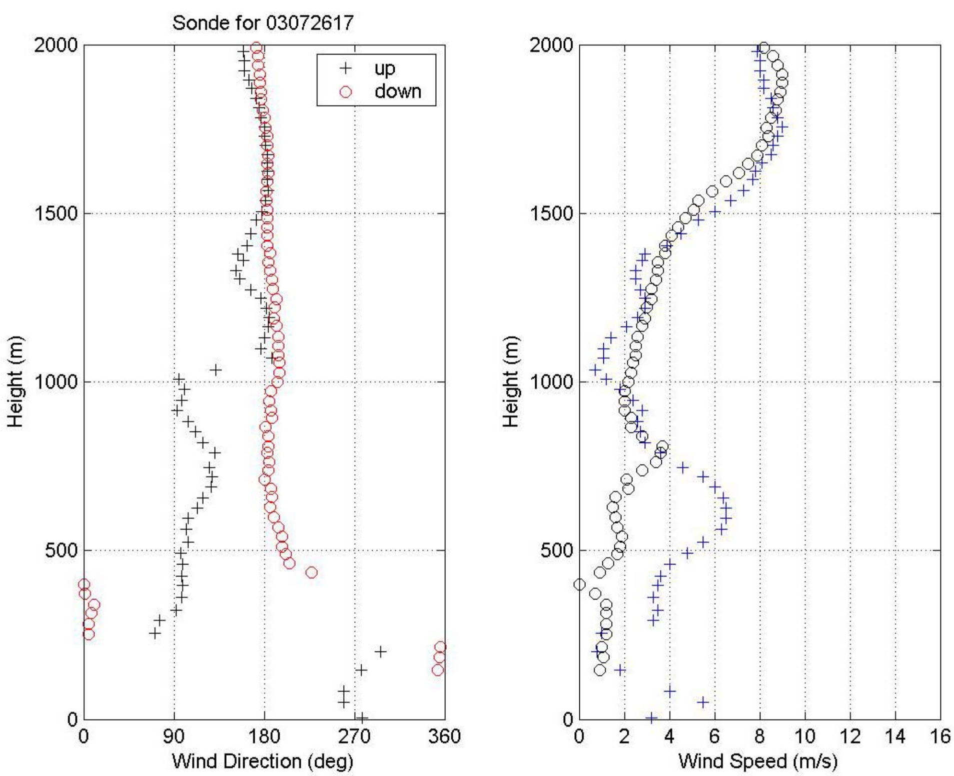
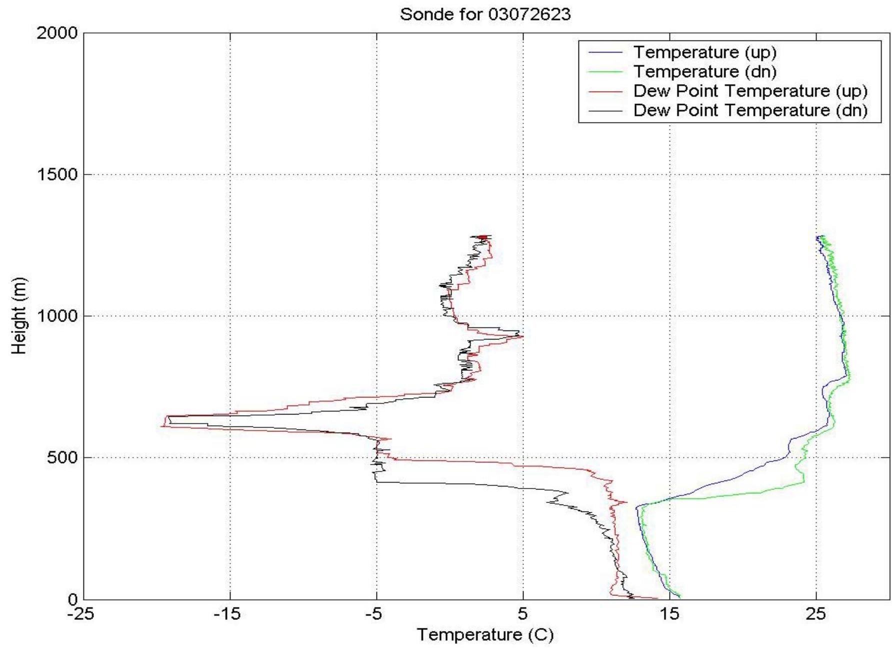
Temperature (up)
Temperature (dn)
Dew Point Temperature (up)
Dew Point Temperature (dn)
Height (m)
Temperature (C)



Sonde for 03072617
up
down
Height (m)
Wind Direction (deg)
Height (m)
Wind Speed (m/s)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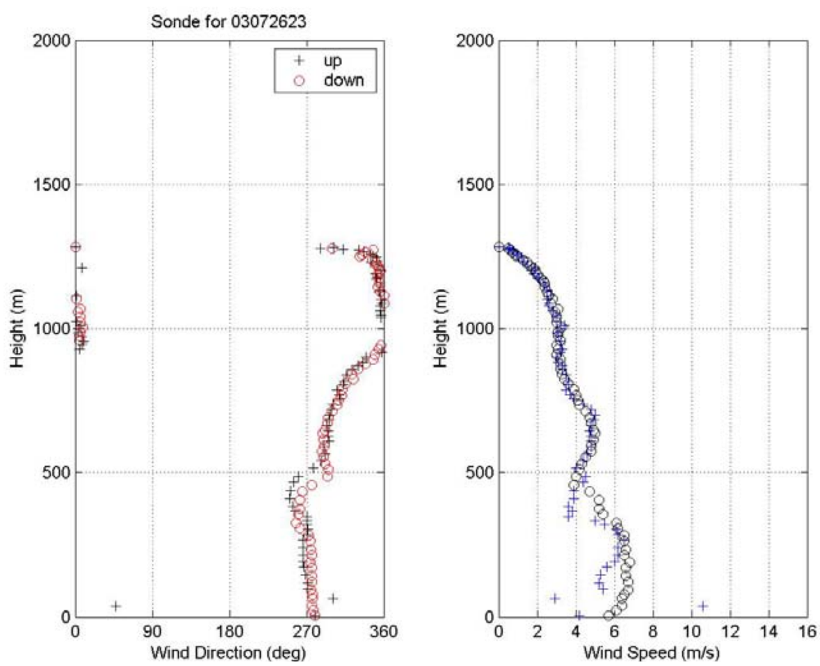
Temperature (dn)
Dew Point Temperature (up)
Dew Point Temperature (dn)
Height (m)
Temperature (C)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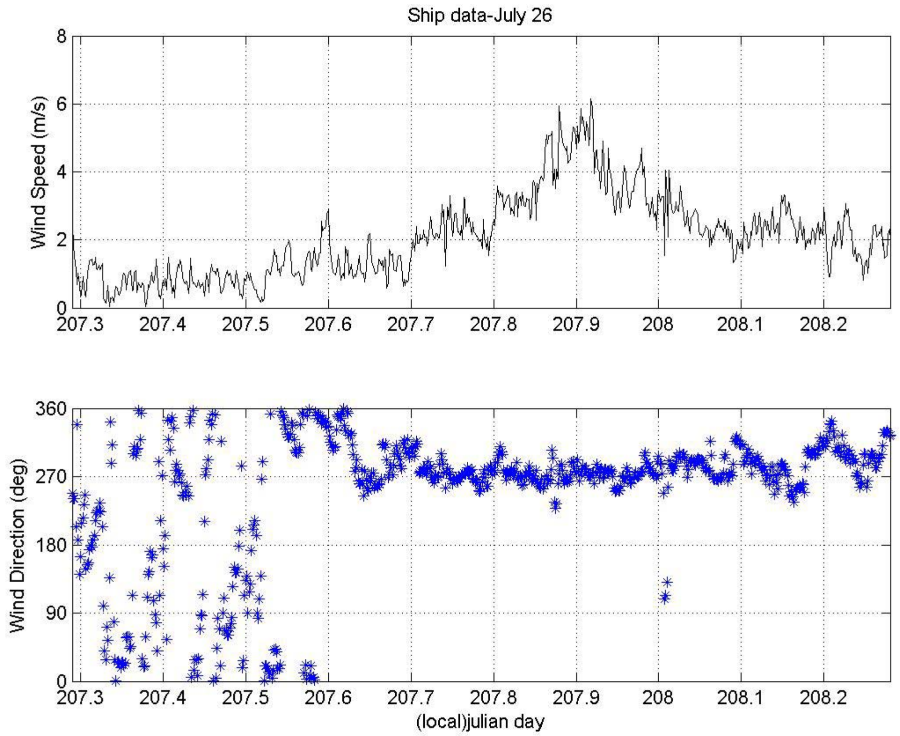
up
down
Height (m)
Wind Direction (deg)
Wind Speed (m/s)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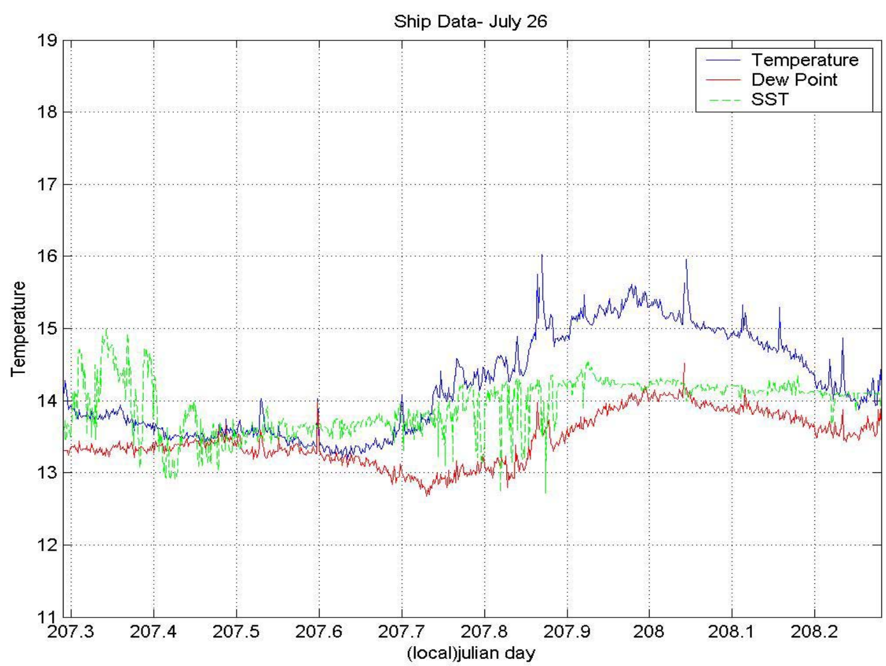
Wind Direction (deg)
(local)julian day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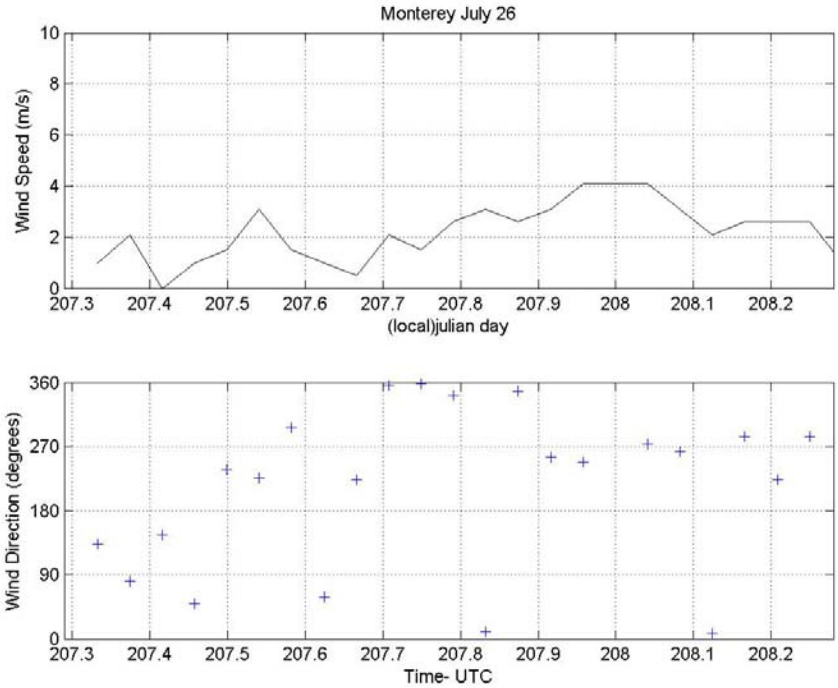
Dew Point
SST
Temperature
(local)julian day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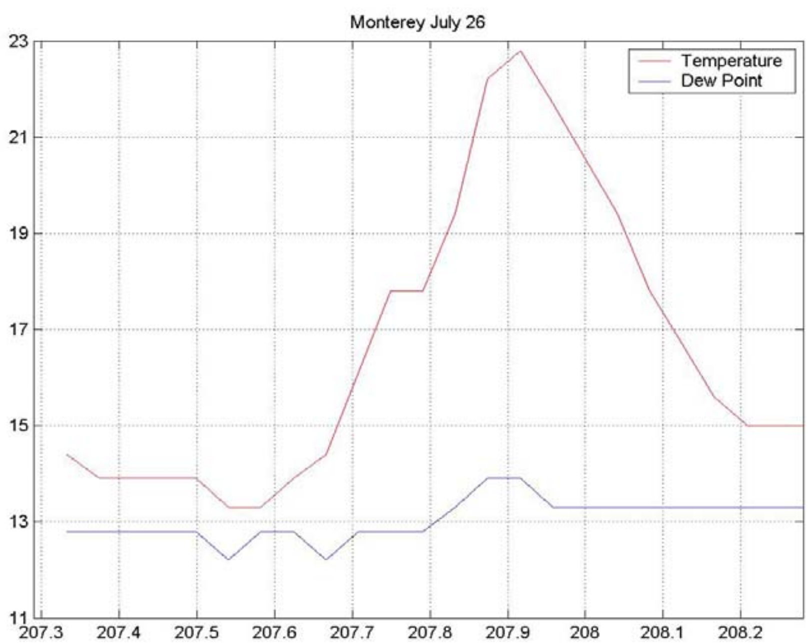
Wind Direction (degrees)
Time- UTC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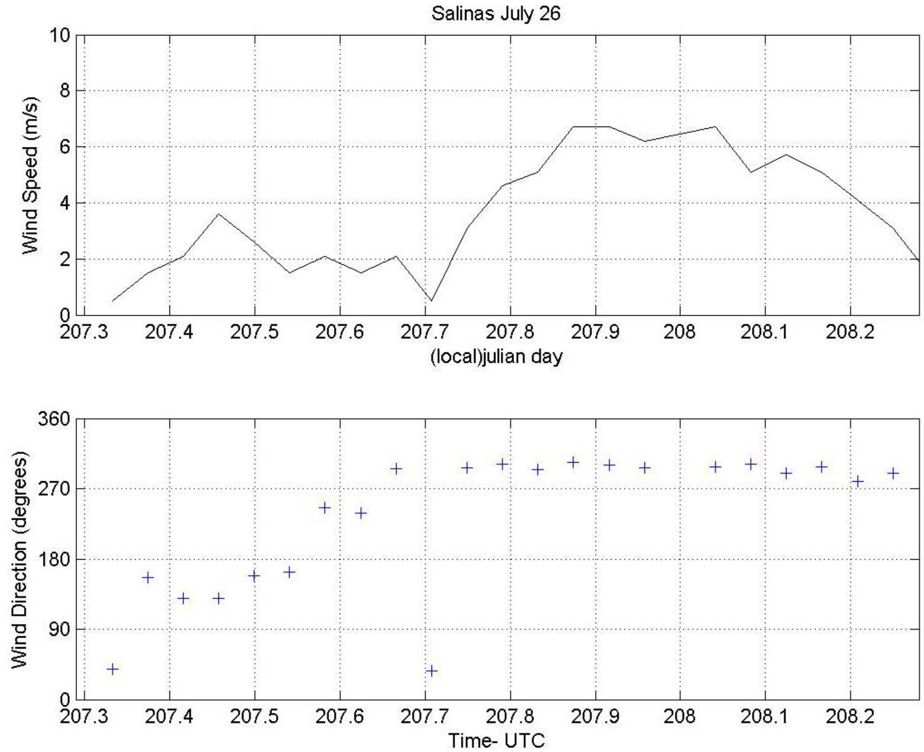
Temperature
Dew Point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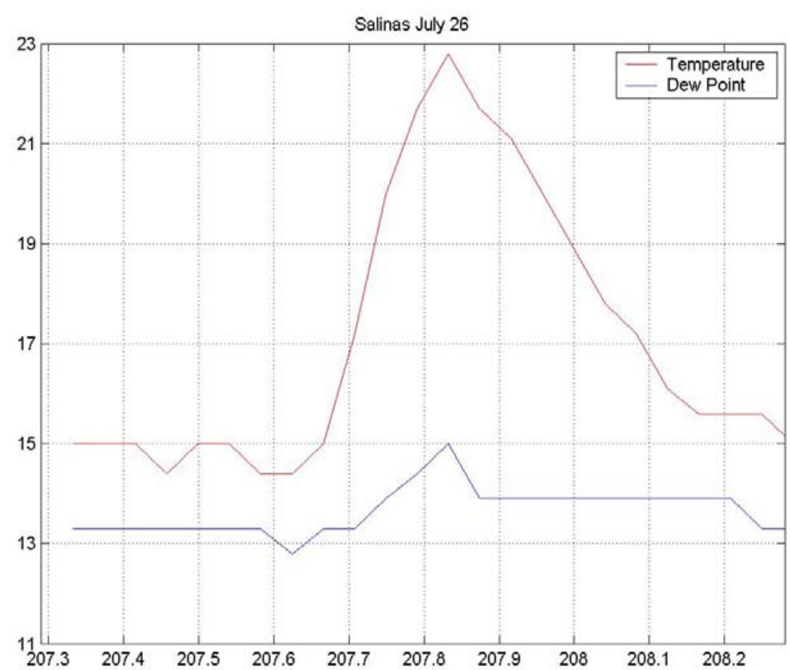
Wind Speed (m/s)
(local)julian day
Wind Direction (degrees)
Time- UTC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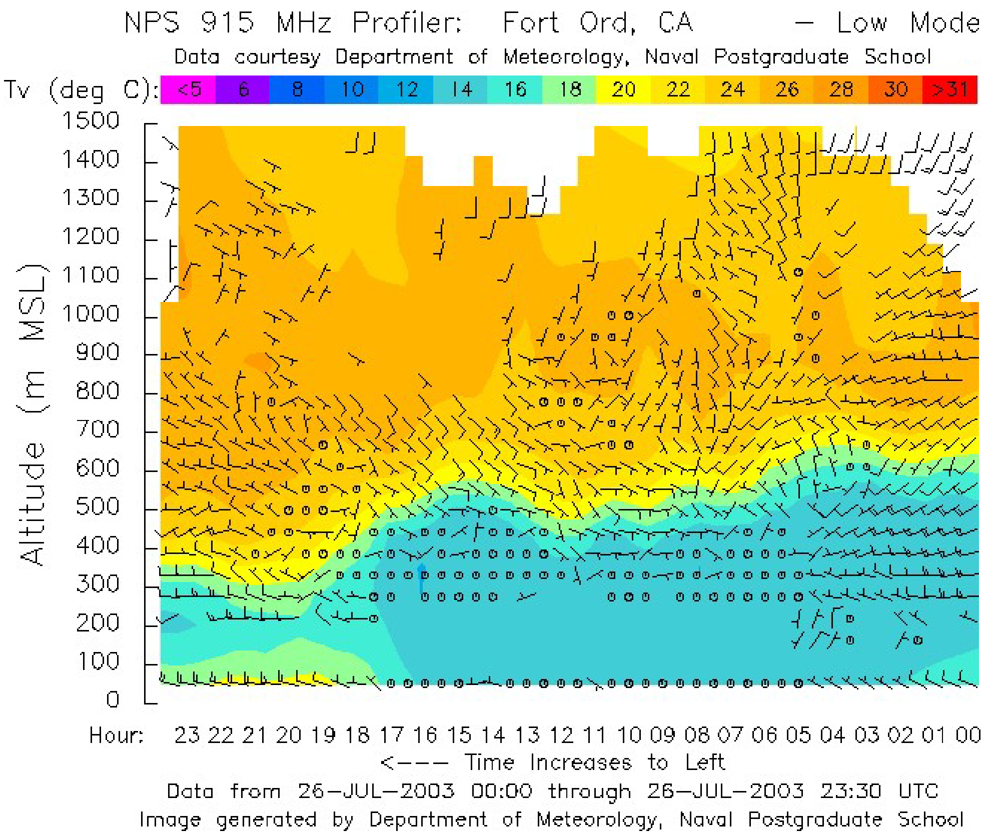
Temperature
Dew Point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Data courtesy Department of Meteorology, Naval Postgraduate School
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Altitude (m MSL)
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Hour: 23 22 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00
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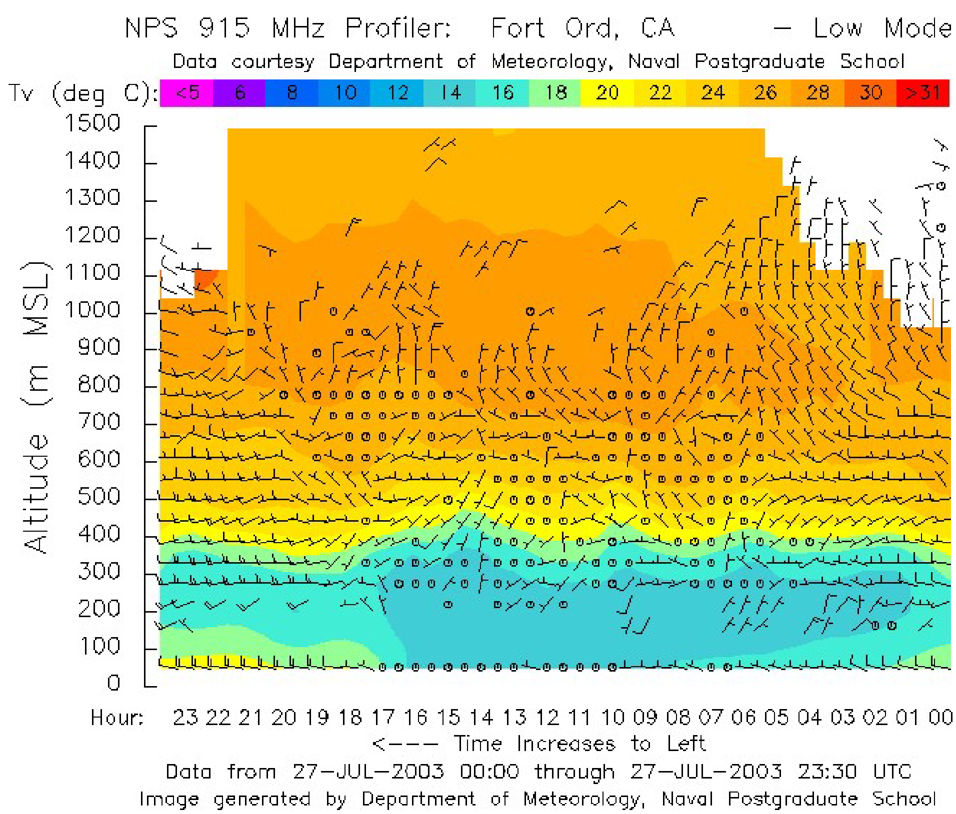
Data from 26-JUL-2003 00:00 through 26-JUL-2003 23:30 UTC
Image generated by Department of Meteorology, Naval Postgraduate School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Data courtesy Department of Meteorology, Naval Postgraduate School
Tv (deg C): <5 6 8 10 12 14 16 18 20 22 24 26 28 30 >31
Altitude (m MSL)
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Hour: 23 22 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00
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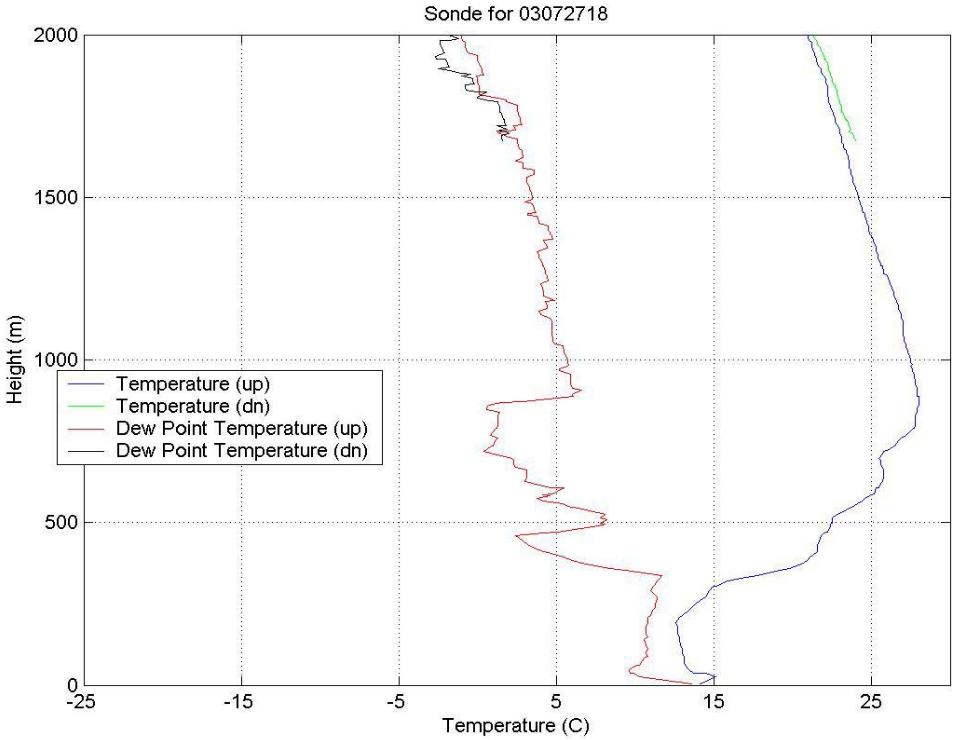
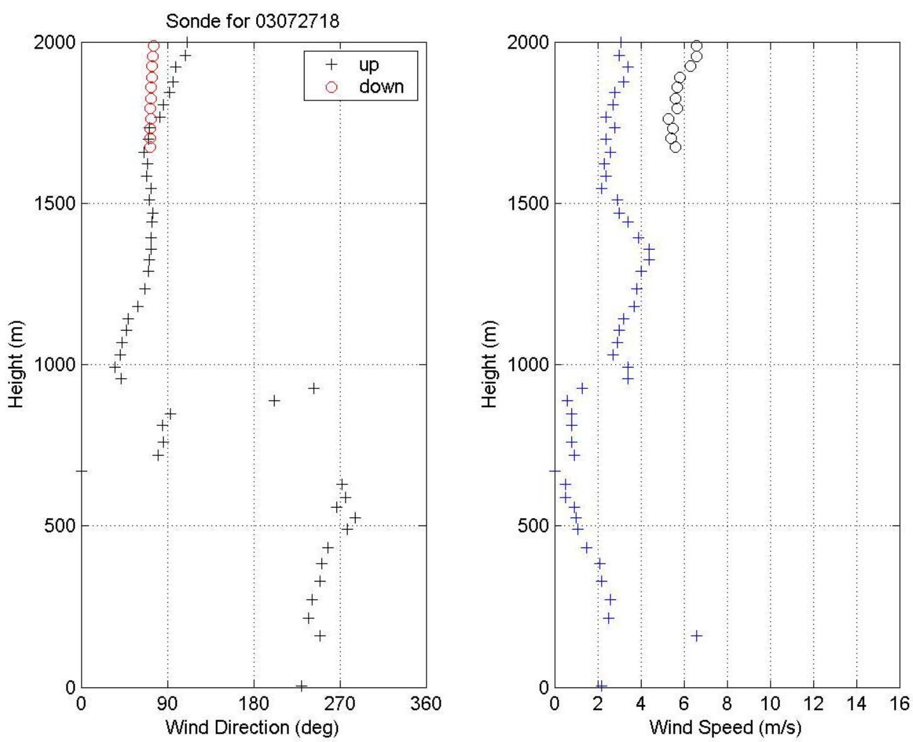
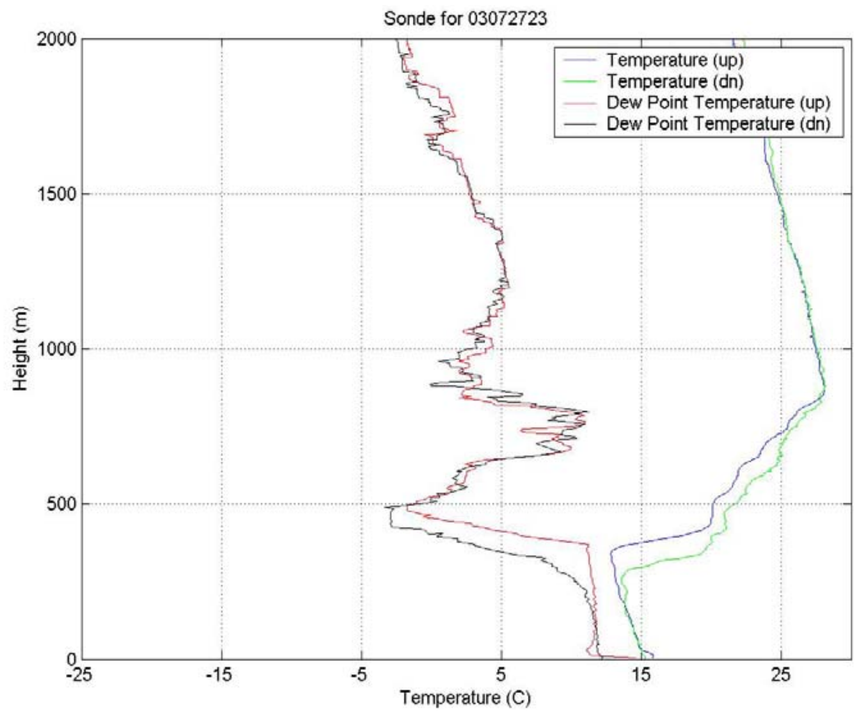
Data from 27-JUL-2003 00:00 through 27-JUL-2003 23:30 UTC
Image generated by Department of Meteorology, Naval Postgraduate School

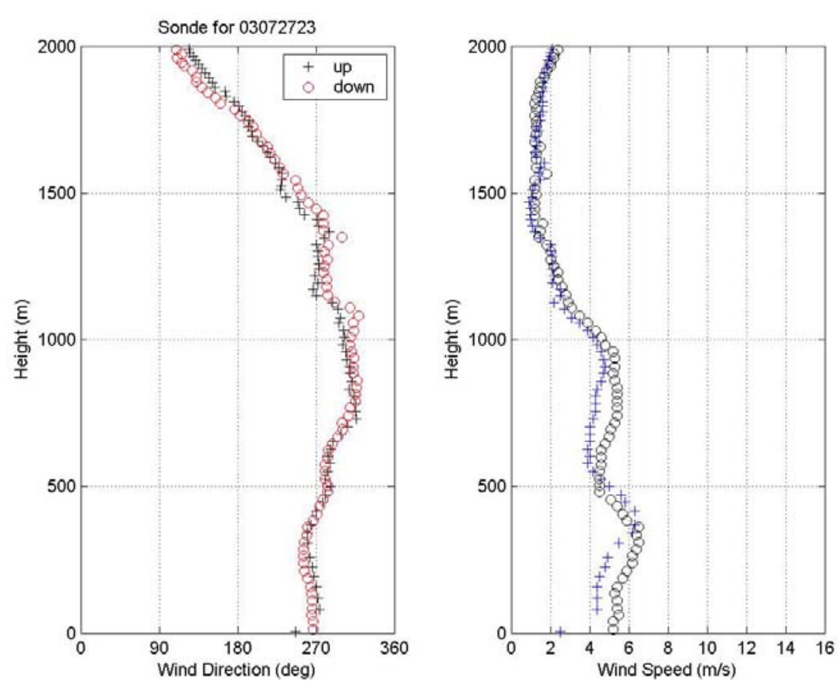
Appendix C


Sonde for 03072718
Height (m)
Temperature (C)
Temperature (up)
Temperature (dn)
Dew Point Temperature (up)
Dew Point Temperature (dn)

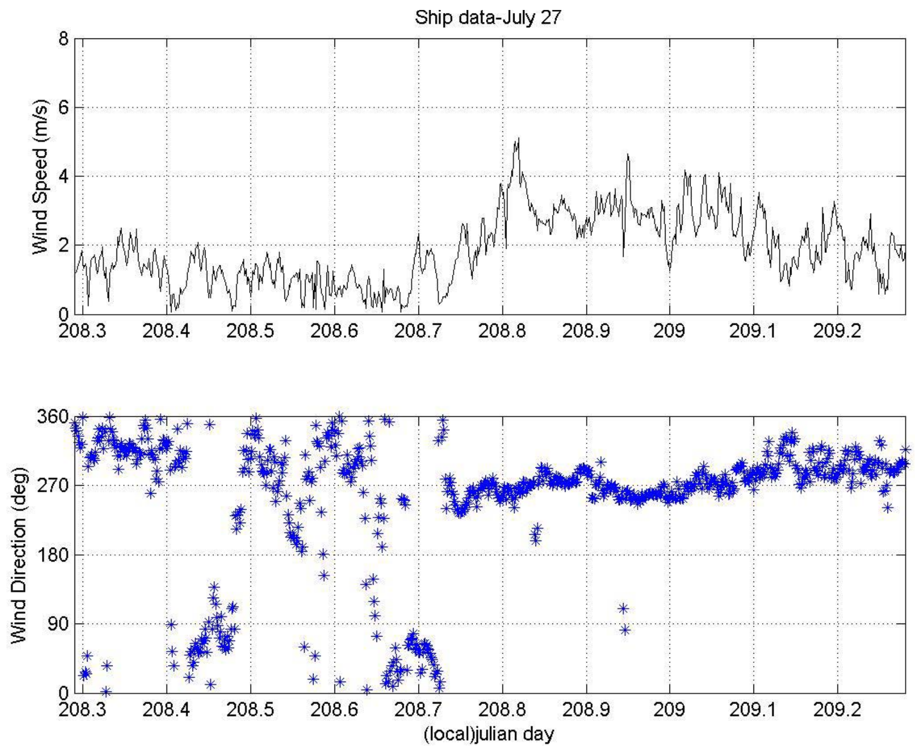

Sonde for 03072718
Height (m)
Wind Direction (deg)
up
down
Height (m)
Wind Speed (m/s)

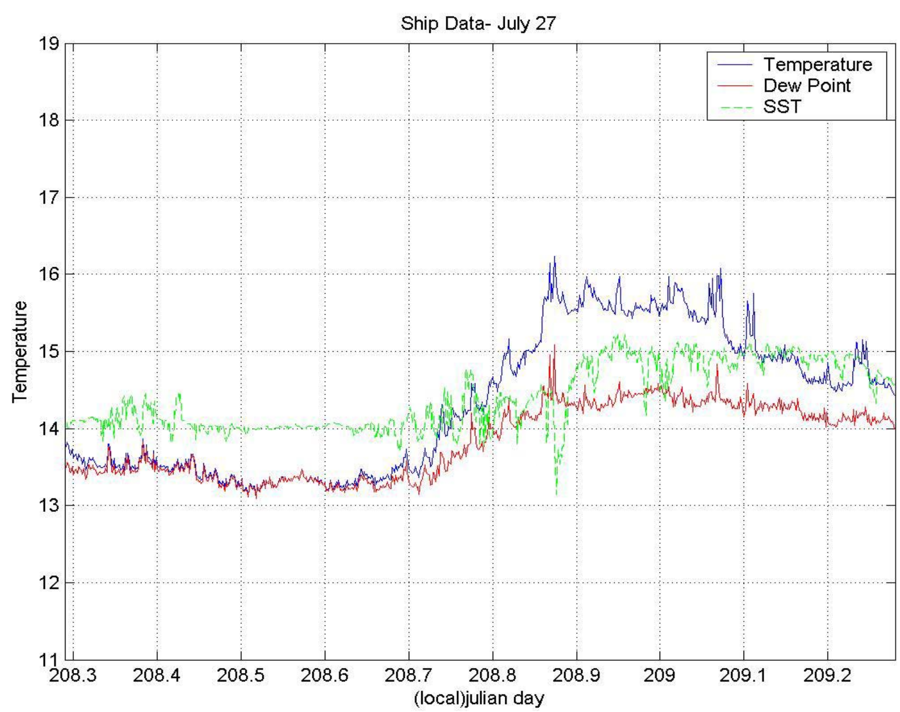


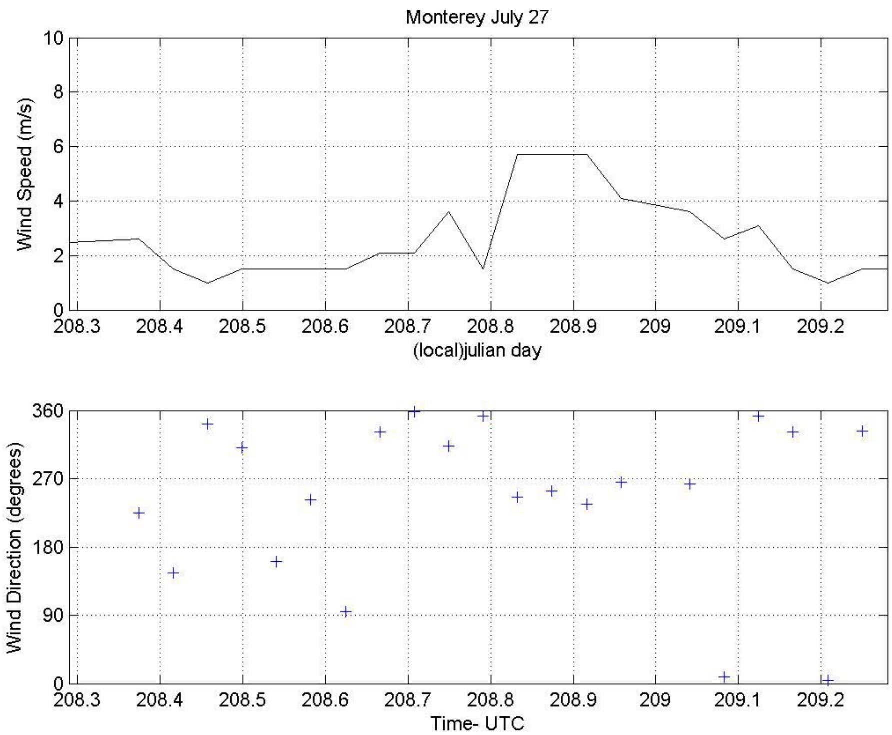
Sonde for 03072723
Temperature (up)
Temperature (dn)
Dew Point Temperature (up)
Dew Point Temperature (dn)
Height (m)
Temperature (C)

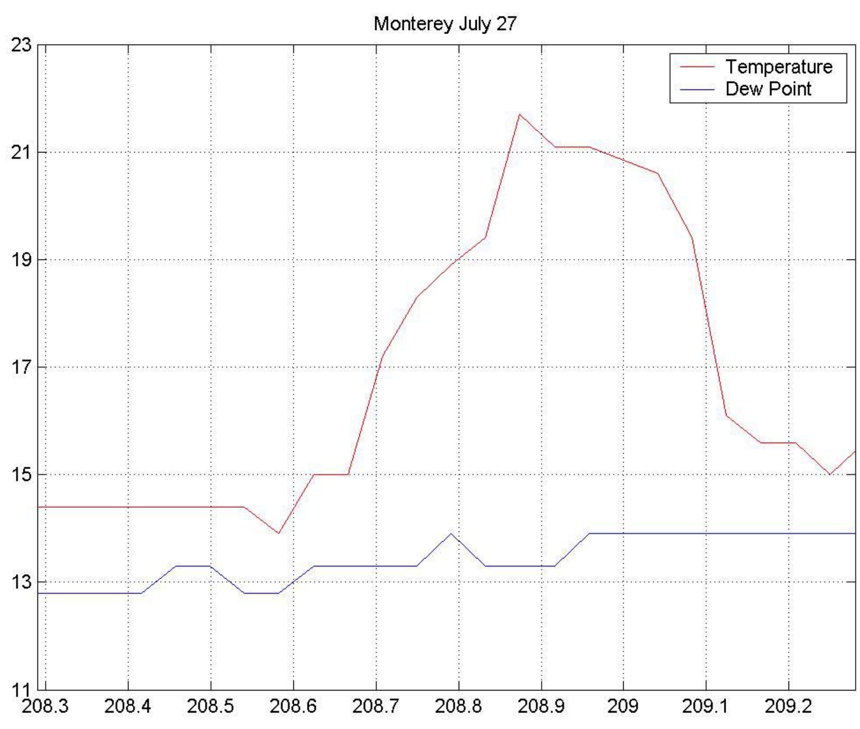


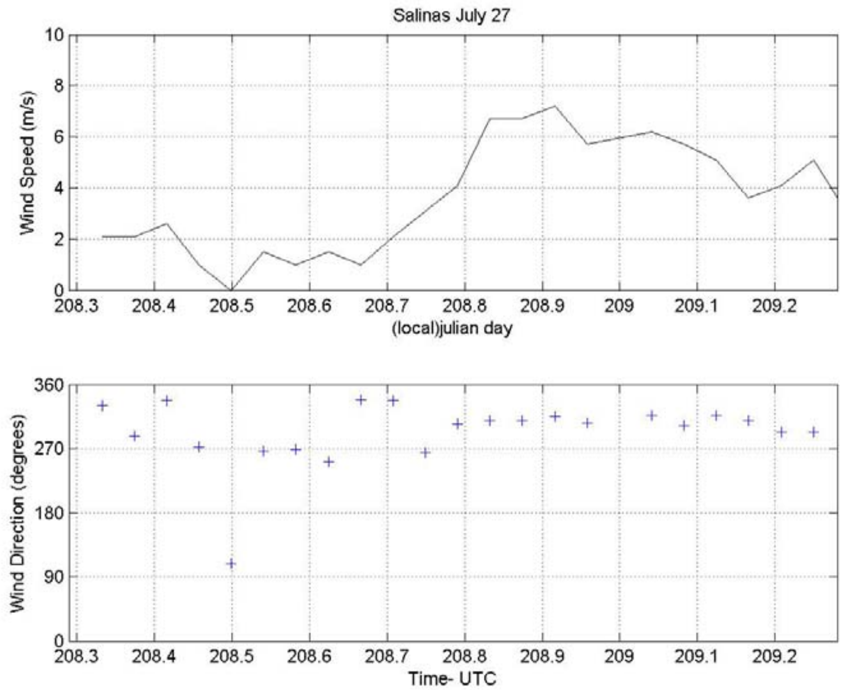
Sonde for 03072723
up
down
Height (m)
Wind Direction (deg)
Wind Speed (m/s)

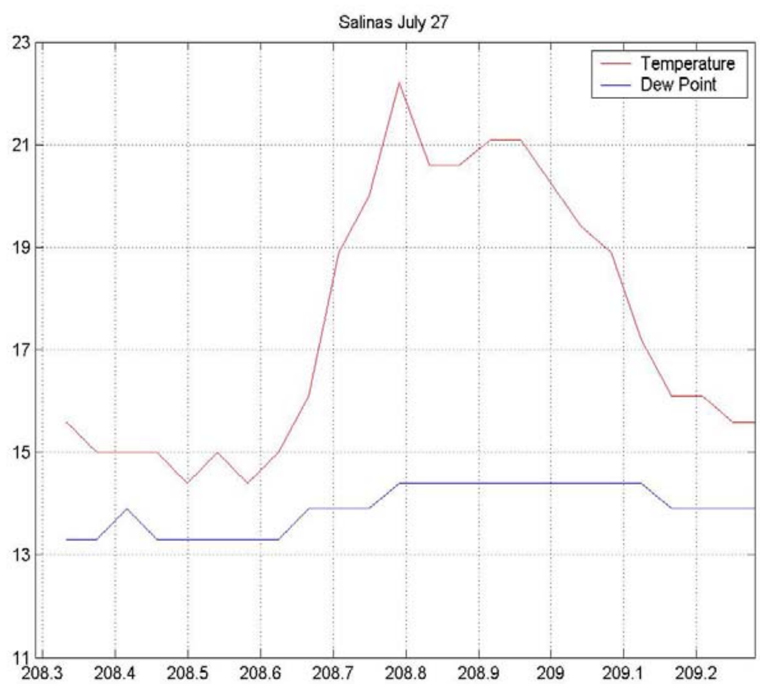

Ship data-July 27
Wind Speed (m/s)
Wind Direction (deg)
(local)julian day

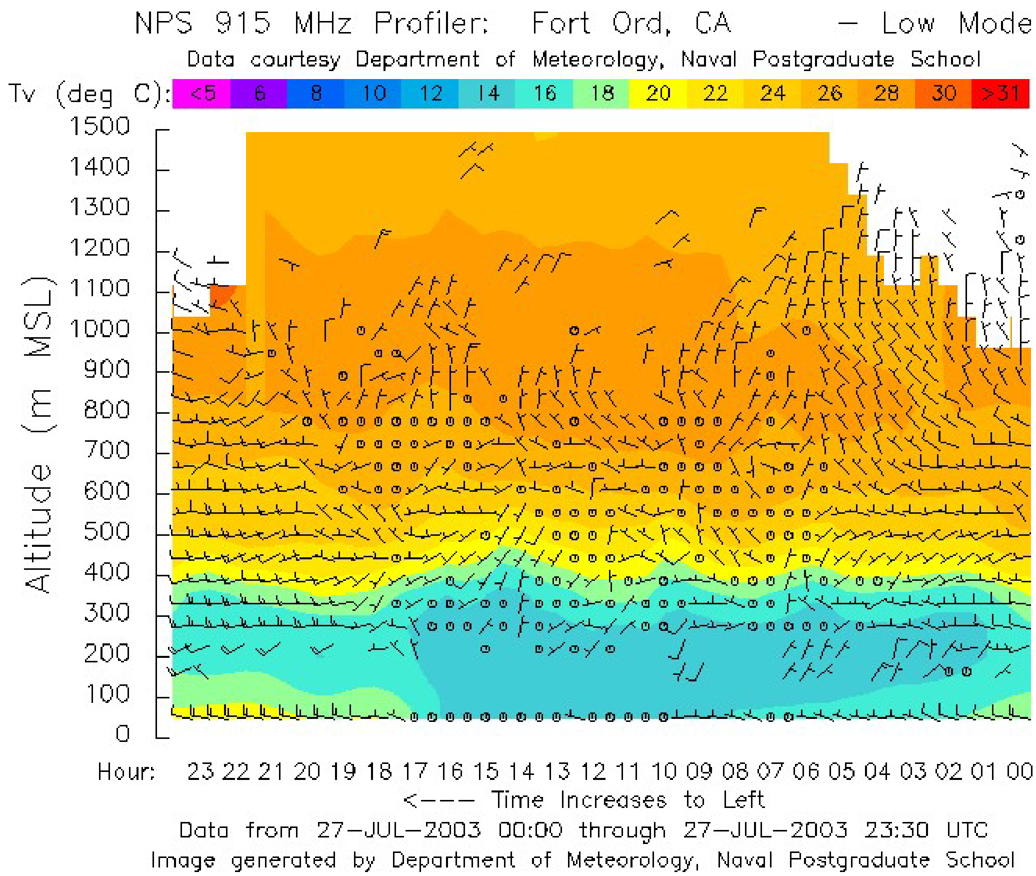

Ship Data- July 27
Temperature
Dew Point
SST
Temperature
(local)julian day

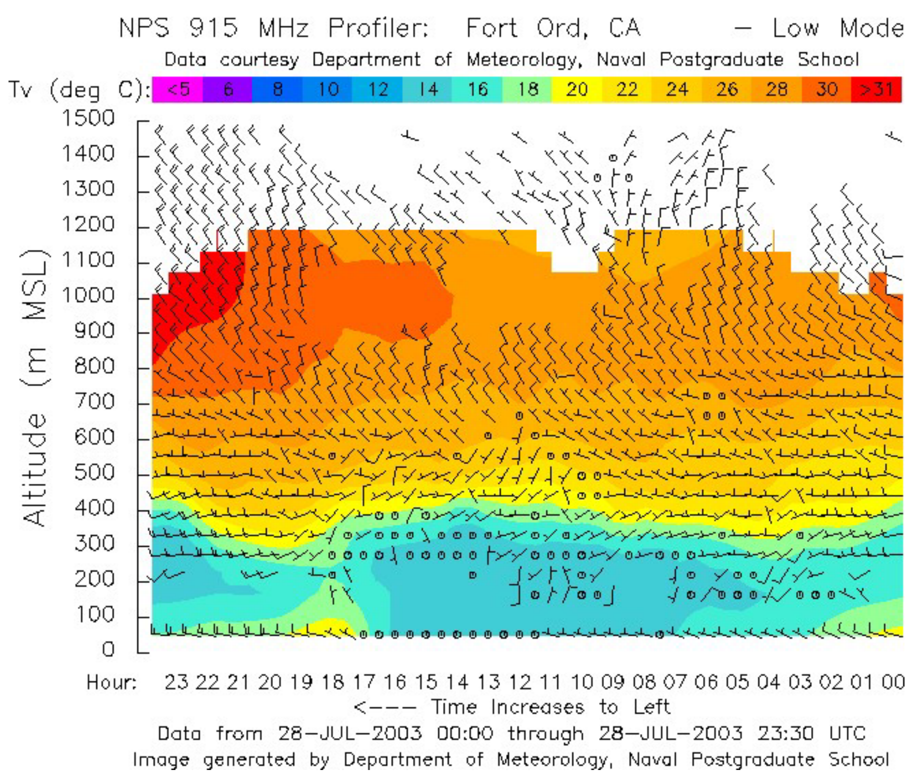

Monterey July 27
Wind Speed (m/s)
10
8
6
4
2
0
208.3
208.4
208.5
208.6
208.7
208.8
208.9
209
209.1
209.2
(local)julian day
Wind Direction (degrees)
360
270
180
90
0
208.3
208.4
208.5
208.6
208.7
208.8
208.9
209
209.1
209.2
Time- UTC


Monterey July 27
Temperature
Dew Point
23
21
19
17
15
13
11
208.3
208.4
208.5
208.6
208.7
208.8
208.9
209
209.1
209.2


Salinas July 27
Wind Speed (m/s)
(local)julian day
Wind Direction (degrees)
Time- UTC
10
8
6
4
2
0
360
270
180
90
0
208.3
208.4
208.5
208.6
208.7
208.8
208.9
209
209.1
209.2


Salinas July 27
Temperature
Dew Point
23
21
19
17
15
13
11
208.3
208.4
208.5
208.6
208.7
208.8
208.9
209
209.1
209.2


NPS 915 MHz Profiler: Fort Ord, CA — Low Mode
Data courtesy Department of Meteorology, Naval Postgraduate School
Tv (deg C): <5 6 8 10 12 14 16 18 20 22 24 26 28 30 >31
Altitude (m MSL)
1500 1400 1300 1200 1100 1000 900 800 700 600 500 400 300 200 100 0
Hour: 23 22 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00
<--- Time Increases to Left
Data from 27-JUL-2003 00:00 through 27-JUL-2003 23:30 UTC
Image generated by Department of Meteorology, Naval Postgraduate School


NPS 915 MHz Profiler: Fort Ord, CA — Low Mode
Data courtesy Department of Meteorology, Naval Postgraduate School
Tv (deg C): <5 6 8 10 12 14 16 18 20 22 24 26 28 30 >31
Altitude (m MSL)
1500 1400 1300 1200 1100 1000 900 800 700 600 500 400 300 200 100 0
Hour: 23 22 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00
<--- Time Increases to Left
Data from 28-JUL-2003 00:00 through 28-JUL-2003 23:30 UTC
Image generated by Department of Meteorology, Naval Postgraduate School