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OC 3570
Cruise Project

Central California Circulation Study

1. Introduction

Central California is the location of various unique low-level circulations. There are several factors that contribute to this uniqueness: 1) large body of water on the windward coast (Pacific Ocean) with a large heat capacity, 2) complex coastal topography, 3) large central valley and 4) extremely high eastern valley topography (Sierra Nevada Range). Data for this circulation study was collected from 28 January to 04 February 2002 and included global and regional model data as well as surface and vertical atmospheric profiles from the Pt. Sur Research vessel. The first several sections of this paper will cover an interesting low-level feature that developed early in the study period. The final sections will address diurnal variations in the region followed by a conclusion.

2. Low-level Feature Synoptic Analysis

The 28th of January produced a very interesting vortex just south of San Francisco Bay at 12Z. The feature can best be described as an extremely low-level weak low that brought minor amounts of rain to the central coast. This event was captured extremely well by the eta1 and MM5 models, which traditionally have problems forecasting land falling circulations particularly ones this shallow. The circulation was limited to only a 2 millibar (mb) depression in the sea level surface pressure (SLP) and confined to the lower 250 mb of the atmosphere. The event occurred in the cold air behind a strong cold front that passed through the area the day before.

The 80 km eta1 300 mb trough was directly overhead with the convergent portion of the jet maximum (left entrance region) over the development area. Convergence aloft tends to inhibit upward development at the surface, therefore the 300 mb jet dynamics did not contribute to low-level positive vorticity development. The eta1 500mb trough looked equally as harmless with little evidence of a significant short-wave trough and normal values of absolute vorticity advection. Continuing down to 700mb level the only significant feature visible on the MM5 or eta1 models was slight ridging on the windward side of the Sierra Nevada range. Finally at 850mb the low pressure system could be detected by a small cold trough at 12Z over the development area. The surface synoptic picture for that period displayed the presence of a strong East Pacific High pressure to the west, moderate low pressure system (1006 mb) to the east of the Sierra Nevada's and a weak low developing in the Pacific Northwest. The East Pacific High contains a ridge of high pressure extending into Southern California. The western portion of the country on the 28th was bathed in an unusually cold Gulf of Alaska air mass that was bringing unusually cold temperatures to Central California. Look to slides 3-7 for graphical representation in attached PowerPoint presentation.

3. Major factors contributing to Low formation

There were three major factors which contributed to the low pressure development: 1) Low-level coastal shear set up by topography and Synoptic situation, 2) weak 500 mb positive vorticity and 3) Air-Sea temperature difference. Several small very low-level cyclonic circulations developed all along the California coast this day and will also be discussed briefly at the end of this section.

The synoptic situation from 00Z to 18Z had a weak west-northwesterly flow from the East Pacific High. All but the very lowest level air passed over the coastal range and into the central valley. The flow was weak (low kinetic energy) and the air was fairly stable allowing the Sierra Range to block flow below 700 mb.

Flow Blocking Equation

$$F_r = U^2/h^2 N^2$$

F_r - Froude Number or Hill Number
U - horizontal wind magnitude
N - Brunt-Vaisala Frequency (Stability Parameter)
h - height of topographic barrier

The wind component is extremely low (5 to 10 knot winds at low levels). The stability, represented by N, is high in the boundary layer due to night-time radiational cooling causing increased temperatures with height below 2000 meters. The Sierra Nevada range provided an extremely high barrier (h). The combination of these factors led to a F_r less than 1. The Froude Number can be best described as the ratio of KE to APE, therefore a ratio less than 1 indicates flow blocking.

This flow allowed for mass to accumulate in the southern portions of the central valley increasing pressure a few millibars. The northern portions of the valley were under relatively lower pressure which set up a pressure gradient along the central valley. The low pressure system on the east side of the Sierras had little to no effect on the central valley flow which is shielded by the Sierra range. Winds were still weak and skies clear in the central valley setting up maximum radiational cooling conditions. The situation begins to favor low-level shear near the coast at 09Z (1 am local). Air flows north-northwest out of the central valley due to the pressure gradient intensified by cold air drainage flowing out of the central valley through coastal passes. Northwesterlies over the ocean allow for low-level positive vorticity to develop along the Central California coast. Vertical cross section of the atmosphere using the 12 km MM5 model (37.5 N 123 W and 37.5 N 120 W) from 1000 mb to 500 mb confirms strong positive vorticity in the lower 250 mb at 12Z. By 15Z the vorticity has dissipated dramatically due to interaction of the coastal topography. See slides 9-11 on PowerPoint presentation.

Low-level shear near the coast apparently was not enough to develop a low pressure system since several shallow circulations were present on the MM5 model outputs along the central coast. Examining 500 mb vorticity anomalies and vertical vorticity displayed a very weak positive vorticity maximum which was just enough energy to intensify a low level circulation. Stronger and equally weak vorticity maximums were present throughout the domain of interest. Why did the low form on this local vorticity maximum? The reason is the other vorticity maximums where not aligned with the low-level shear near the coast. See slide 13 in PowerPoint presentation.

The final contributing factor to development of the low were the presence of cold polar air over relatively warmer ocean water. The air over the water was already moderately unstable due to the air-ocean temperature difference and moisture gradient. Low-level vorticity further enhances this air-sea temperature difference by rearranging the mass field near the coast where maximum cyclonic shear was occurring. Typically in mid-latitude weather systems the wind adjusts to the mass field attempting to reach geostrophic balance. In this case the low-level shear set up a cyclonic circulation and the mass field adjusted causing a cold trough to develop in the lower 150 mb. The presence of a cold trough increased air-sea temperature difference and decreased stability. See slide 14 on PowerPoint presentation.

The final topic on this section addresses the multiple cyclonic circulations that developed along the coast on this day, from just north of San Francisco Bay to Pt. Sur. Low-level shear near the coast certainly helped develop these vortexes but why did they occur predominately south of San Francisco Bay and Monterey Bay? It was due to large valleys linked to the Central Valley. San Francisco is linked to the Santa Clara and Sacramento River valleys that provide nearly unimpeded flow from the San Juaquin Valley. Monterey Bay with its half moon shape surrounded by the Santa Cruz and coastal mountains already provides a good basin for low-level circulations. The Salinas valley also links the central valley flow that further enhances these circulations.

4. Diurnal Circulations on the Central Coast

When diurnal circulation is mentioned concerning the California coast those most familiar with the area think summer sea breeze immediately. Naturally that should be the first thought since strong inland thermal conditions and cold upwelled coastal waters produce tremendous sea breeze circulations. During this circulation study period Central California actually experienced a fairly strong land breeze event. These events where stronger some days more than others but usually present everyday at least to 0900 local time before flow returned to the general synoptic flow. Why did a significant land breeze regime set up during this time? The 27th of January brought with it cold Gulf of Alaska air as well as weak synoptic forcing. This established strong radiational cooling conditions over land. The coastal waters are generally warmer this time of year due to lack of coastal upwelling. The combination of these factors set up thermal gradients along the coast.

5. Results from Data Collection

The purpose of this section is to examine the extent and vertical influence of the land breeze circulation over the ocean as well as some estimates to the circulation strength. This is where data from the Pt. Sur paid dividends. Some data analyzed was from the MM5 12 km and WOCSS 1 km models but mainly to point out the weaknesses of these models in diurnal prediction. Primary case study concentration will be the evening of the 1st and morning of 2nd February (00Z 02 to 18Z 02 Feb.). The 2nd of February was chosen due to timing of rawinsonde launches and surface data quality.

Beginning at 00Z 02 Feb (4pm local), the temperatures over the water were in the low to mid 50's (close to sea surface temperature) and the temperatures over land where in the mid 50's. Winds were 15 to 20 knots in the Bay from the west-northwest consistent with the back ground synoptic flow. Inland winds were 5 to 10 knots from the same direction. These observations make sense because there was no thermal gradient between the ocean and land, therefore the only forcing is the background synoptic flow.

Advancing to 03Z (7pm local), the sun has been set for a couple of hours and the land is beginning to cool. Inland temperatures have dropped to the mid 40's while temperatures on the Bay remain in the low 50's. Wind direction over the water remained out of the north-northwest at 10 knots while over land winds are light and variable.

Observations at 06Z (10pm local) have already indicated a reverse in wind direction for land station toward the Bay. Temperatures over land have decrease to the lower 40's while Bay temperatures remain unchanged. Winds over the water remain unchanged as well, but winds in Salinas are calm.

The 09Z (1am local) observations indicate temperatures over land have dropped into the upper 30's while NOAA buoy 42 still maintained 50° F 55 km offshore. Winds at the outer buoy were still at 10 knots but direction was now out of the north. Winds over land are unchanged.

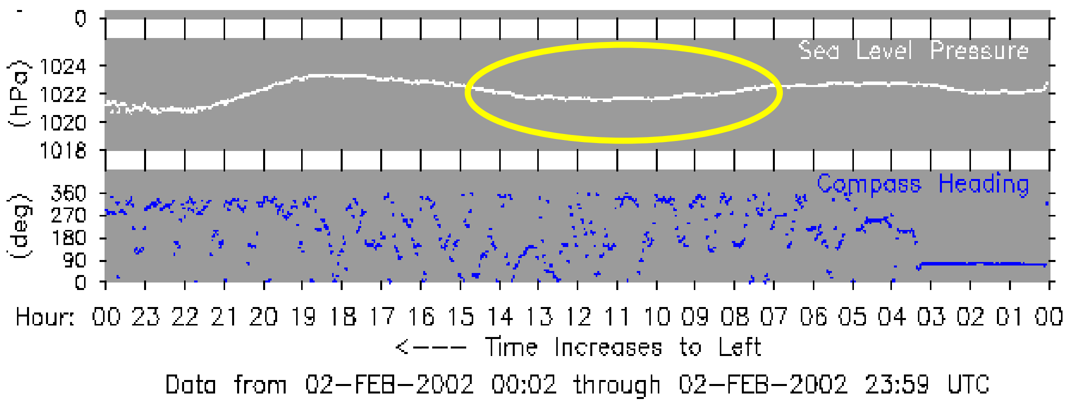
The time is now 4am (12Z) and coastal land temperature have dropped to the low to mid 30's with winds offshore at 5 knots. NOAA buoy 42 winds have dropped to 5 knots still out of the north. Winds on the Pt. Sur were also offshore at 5 knots but what was interesting was that temperatures onboard have dropped to 40° F indicating that cold air advected off land had made it out over the water to approximately 14 km.

The 15Z observations indicate offshore winds at NOAA buoy 42 have turned to offshore flow at 10 knots. This should be an indication of the extent of the land breeze circulation, approximately 55 km offshore. The temperature at the far buoy was not influenced much (only a drop from 52 to 48 degrees F).

Conditions at 18Z (10 am local) showed inland temperatures in the mid to upper 40's. Winds at Salinas were still offshore at 10 knots. The NOAA buoy 42 still reports 50° F and winds out of the northeast at 10 knots indicating a weakening in the offshore flow influence.

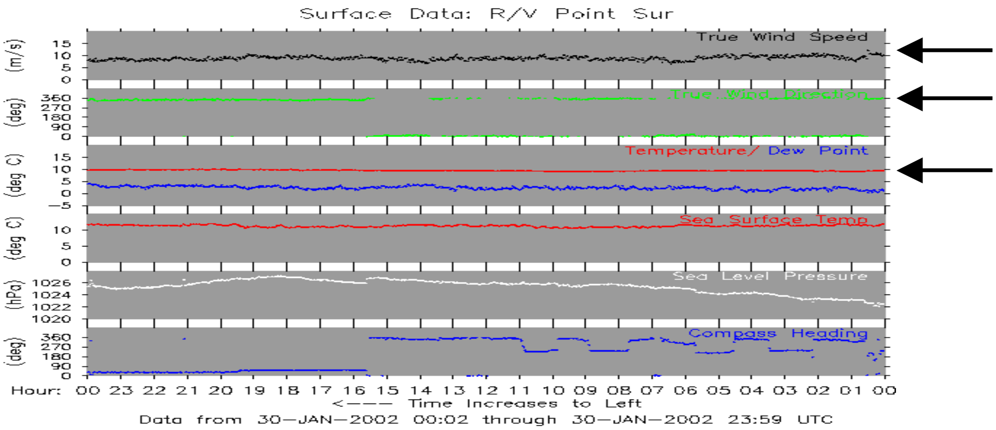
The 21Z (1 am) observation indicates that flow was completely onshore again for the over water observations. Winds were calm in Salinas and onshore at 10 knots in Monterey. Inland temperatures had risen to the mid 50's, which indicates the thermal gradient between land and sea has disappeared. See slide series 20-28

The observations over land reported a 1.8 mb increase on average for SLP over night. These results make sense, as the land starts to cool cold air begins to pool toward the valleys (where most observations are located) which increased SLP as the air becomes more dense. The observations at the outer buoy indicate 1.1 mb decrease in SLP overnight. These observations also make sense, mass from the mid-levels was transported to the low-levels over land and mass in the surrounding mid-levels moved in to replace it. Since water has a high heat capacity, surface temperatures are relatively higher over the water which means low and mid-level thickness is higher (hypsometric approximation). Air from the mid-levels over the ocean move in to replace mass removed from the mid-levels over land setting up a land breeze circulation with a relative high over land and relative low over water. The Pt. Sur 10 meter observations show this drop in surface pressure over the water on 02 Feb (See below SLP from 07Z to 15Z (11pm to 7am local).



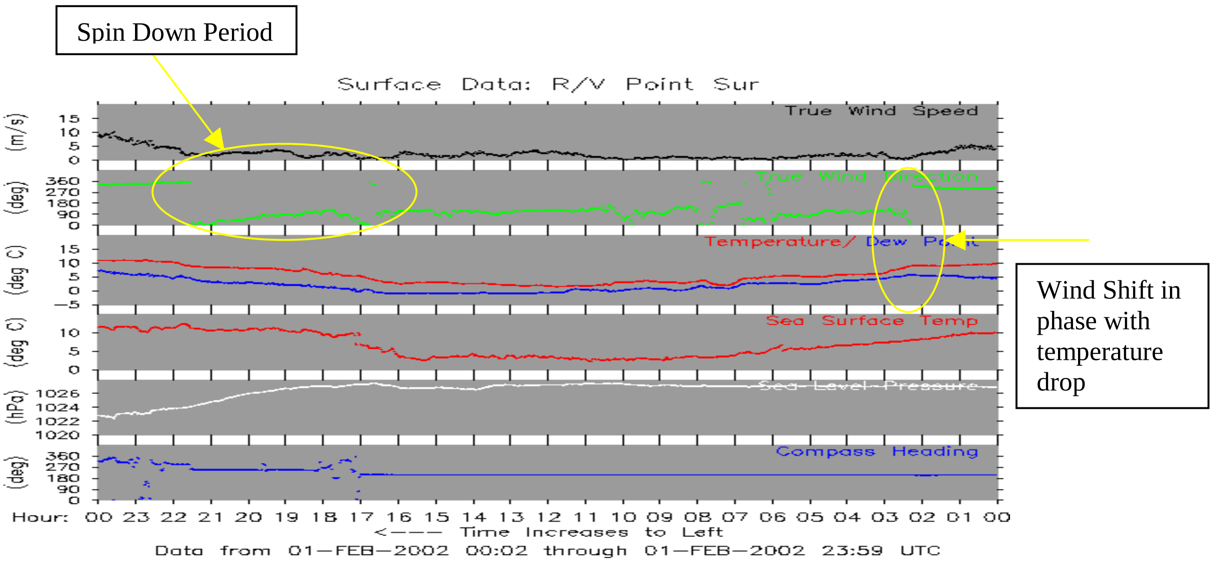
The results from other days are harder to interpret. The 02 Feb case study was not chosen because of its easily identifiable characteristics but because it had the best data coverage. Data from the first leg was not usable for diurnal variations because the Pt. Sur was to far offshore. Data from 04 Feb was fairly straight forward since the vessel was close to land or inport and produced results consistent with coastal observation sites (lower pressure during day due to heating and higher at night due to cooling). The results from Feb. 1st and 3rd were difficult to examine due likely to vessel spatial change.

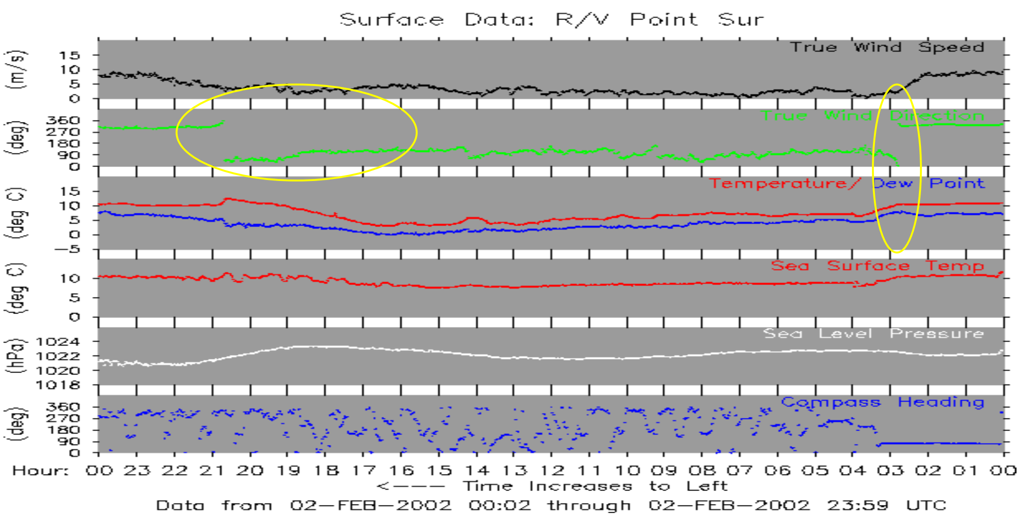
The 1st leg results should be free of large variations in temperature and wind due to the vessels distance from land and looking at the plots below its easy to see that is true (Plots are from 29th and 30th of January).



The results from the second leg, which were only 10 to 14 km offshore, displayed much larger temperature and wind variations. The interesting part was that data from the second leg each day displayed a diurnal signature in temperature and wind suggesting that the Pt. Sur environmental conditions were under the influence of a land breeze everyday. Everyday of the results displays winds onshore from approximately 21Z to 03Z and winds offshore during the remainder of the day.

The temperature plots also changed in phase with the wind shifts. Sharp temperature decrease occurs at 03Z at which time wind shift to offshore. The afternoon temperatures stop increasing at 21Z when wind shifts back to onshore. These results seem reasonable since offshore flow was associated with cold air coming off land, hence sharp temperature drop at 03Z. The afternoon temperature signature is harder to explain. The thermal gradient disappeared at 18Z but winds did not fully shift until 21Z. It’s likely that momentum spin down of the offshore land breeze fueled the offshore flow until early afternoon when friction dissipated the offshore momentum. See plots below for diurnal cycles in temperature and wind, for Feb 1-4.


Spin Down Period
Wind Shift in phase with temperature drop
Surface Data: R/V Point Sur
True Wind Speed
True Wind Direction
Temperature/ Dew Point
Sea Surface Temp
Sea Level Pressure
Compass Heading
(m/s)
(deg)
(deg C)
(hPa)
Hour: 00 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 01-FEB-2002 00:02 through 01-FEB-2002 23:59 UTC


Surface Data: R/V Point Sur
True Wind Speed
True Wind Direction
Temperature/ Dew Point
Sea Surface Temp
Sea Level Pressure
Compass Heading
(m/s)
(deg)
(deg C)
(hPa)
Hour: 00 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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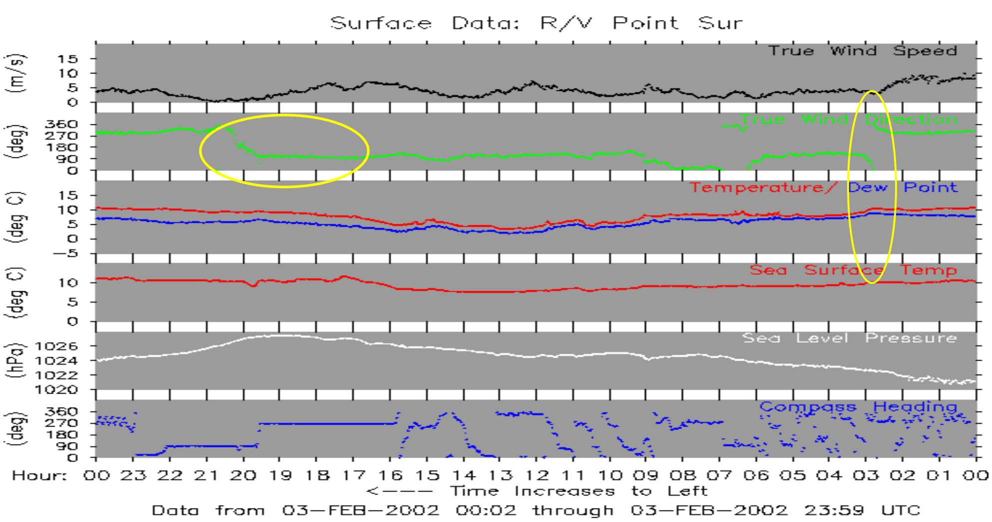
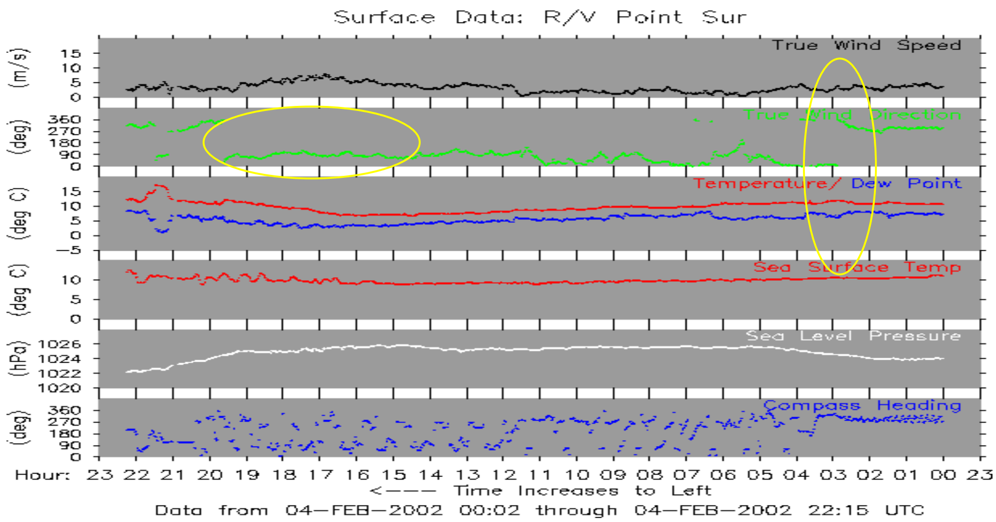
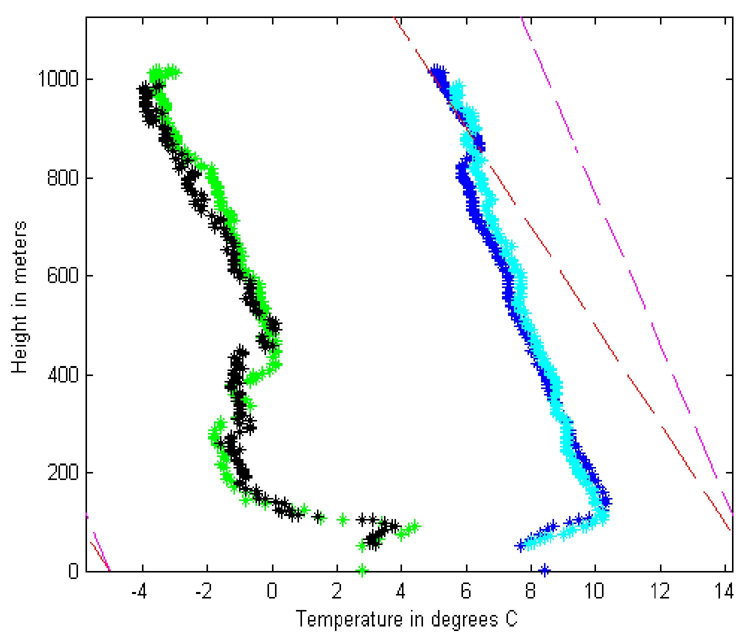
Data from 02-FEB-2002 00:02 through 02-FEB-2002 23:59 UTC

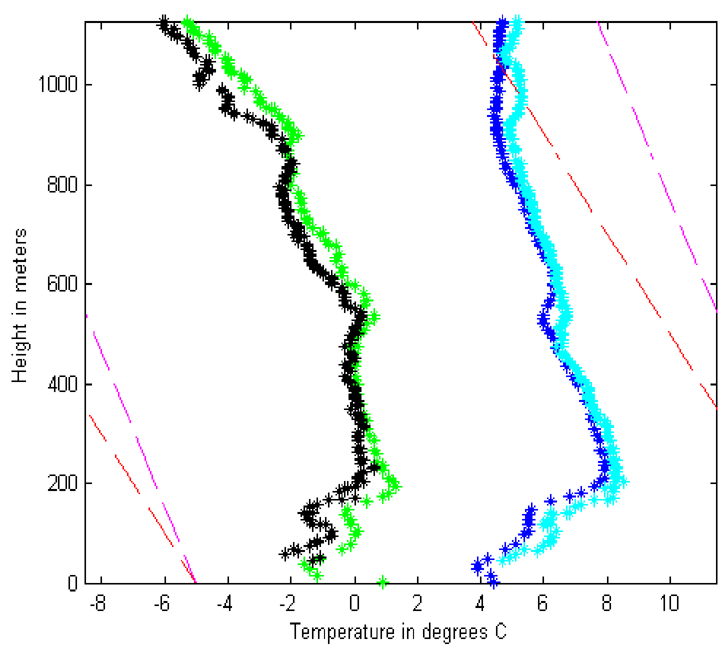

Surface Data: R/V Point Sur
True Wind Speed
True Wind Direction
Temperature/ Dew Point
Sea Surface Temp
Sea Level Pressure
Compass Heading
(m/s)
(deg)
(deg C)
(hPa)
Hour: 00 23 22 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00
<--- Time Increases to Left
Data from 03-FEB-2002 00:02 through 03-FEB-2002 23:59 UTC



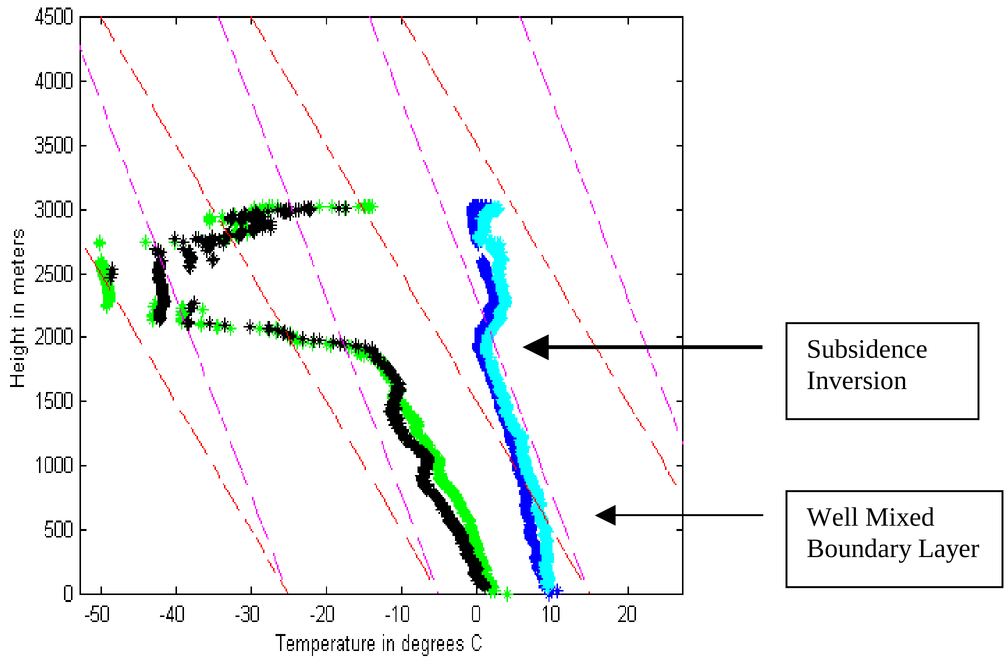
Rawinsonde data from the 2nd also displayed some interesting data. The 04Z (8pm local 01 Feb.) radiosonde showed low-level cold air advecting into the vicinity of Pt. Sur but the flow was extremely shallow. The inversion only extended up to 100 meters with offshore winds below representing cold air advection off land and onshore winds above represented the synoptic background (See radiosonde plot below).



Another vertical sounding was available at 1530Z (7:30am local) that should represent the maximum in the land breeze phase of the diurnal cycle. The results showed a deepening and strengthening in the inversion. The low-level cold air is now extended all the way up to 210 meters with a 10 or 20 meters shallow layer near the surface slightly modified by ocean heat flux. The coldest temperatures where recorded at about 25 meters at 4° C. The winds are offshore all the way up to 1800 meters, backing slightly to the north as you ascend. Above 1800 meters the dew points drop dramatically and the temperature increases indicating subsidence from the East Pacific High (See plot below of the 1530Z sounding).



The final radiosonde of the day was launched at 1825Z (10:25am local) and produced the expected well mixed lower atmosphere. A steady lapse rate exist from the surface to 1800 meters where the subsidence inversion begins. No indication of cold air being advected in the offshore flow even though flow is still offshore. It was late enough in the morning that solar insolation on land has warmed inland temperatures. Inland and Monterey Bay temperatures begin to equalize destroying the land breeze, but winds were still offshore against the weak synoptic flow. This offshore flow present at 1025 local time was likely due to momentum spin down of the circulation (See plot below for 1825Z vertical sonding).



6. Conclusions

The OC3570 class cruise occurred during calm conditions under high pressure, but there still managed to be interesting weather. This says a lot about the complexity and variability in Central California weather. Almost any day can be studied and something new can be learned. The first few sections addressed the development of an unusual low-level low pressure vortex which was captured extremely well by the atmospheric models. This was due in part to the major forcing being synoptically driven and the ability of mesoscale models to capture Sierra Nevada range topography accurately. This case showed the great potential for low-level shearing at or near the Central Coast. The only question mark for this case is the role coastal topography played in generating the circulations. The MM5 model at 12 km still misses moderately sized valleys that have shown to be significant, particularly in the Monterey Bay circulations.

Diurnal variations, on the other hand, are not represented in the modesl well. The thermodynamics seem to be fairly accurate, evident by low error between surface observations and model temperatures. Land/Sea breeze circulations can be approximated by the equation below.

Sea/Land Breeze Equation

$$U_{max} = \frac{k\ g\ \Delta\theta_{max}\ Z_I}{\theta_o\ (k^2 + \Omega^2)}$$

(Perturbation land breeze wind speed)

k - Drag Coefficient
g - Gravitation Constant
$\Delta\theta_{max}$ - Maximum delta Potential Temperature across coast
Z_I - Vertical extent of circulation (usually 700mb or 3000m)
θ_o - Mean Potential Temperature of circulation layer
Ω - Earth's angular rotation rate (radians/sec)

The reason models do not handle these circulations well are model topography does not resolve narrow valleys and peaks. The reason topography is so vitally important is the flow of cold air off higher elevations collects in the valley until deep enough to flow over the lowest sill (lowest elevation). The $\Delta\theta_{max}$ term is underestimated by the model due to the weak thermal gradient represented near the valley outflow at the coast. The model treats the coastal range as fairly continuous with no relief at the Salinas valley which is a major outflow for cold air at night in the Monterey Bay area. The $\Delta\theta_{max}$ can be as high as 10° K in these areas as opposed to 5° K according to the mesoscale models. This difference in $\Delta\theta_{max}$ can result in wind difference in the 2 to 5 ms^{-1} range. This is where data from the Pt. Sur paid off since this platform could observe actual winds and temperatures in the data sparse Monterey Bay. What is interesting about Monterey Bay is its half moon shape with significant coastal topography traps outflowing cold air from the Santa Clara and Salinas valleys creating a fairly significant localized land breeze in these two areas.

Reference

Nuss, W. A., Coastal Meteorology Course Notes for MR4240, pg. 11-19 and pg. 21-30.