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Evaluation of COAMPS performance forecasting along coast wind events during a frontal passage

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MONTEREY, CALIFORNIA

THESIS

EVALUATION OF COAMPS FORECASTING PERFORMANCE OF ALONG COAST WIND EVENTS DURING FRONTAL PASSAGES

by

Carl Sim James

March 2005

Thesis Advisor:	Wendell A Nuss
Second Reader:	Rebecca Stone

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13. ABSTRACT (maximum 200 words)

Performance of high resolution mesoscale models has been in a continuous state of refinement since their inception. Mesoscale models have become quite skillful in forecasting synoptic scale events such as mid-latitude cyclones. However, atmospheric forcing becomes a much more complicated process when faced with the challenge of forecasting near topography along the coastline. Phenomena such as gap flows, blocked flow winds and low level stratification become important to predictability at these scales. The problem is further complicated by the dynamics of a frontal passage event. The skill of mesoscale models in predicting these winds is not as well developed.

This study examines several forecasts by the Coupled Ocean Atmospheric Mesoscale Prediction System (COAMPS) during frontal passage events for the Winter of 2003-2004. An attempt is made to characterize the predictability of the wind speed and direction both before and after frontal passage along the California coast. Synoptic forcing during this time is strong due to the effects of the mid-latitude cyclones propagate across the Pacific.

The study’s results indicate that the wind field predictability is subject to several consistent errors associated with the passage of fronts over topography. These errors arise due to difficulty in the model capturing weak thermal advection events and topographic wind funneling. The deficiencies in model representation of topography contributes to these errors.

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EVALUATION OF COAMPS PERFORMANCE FORECASTING ALONG COAST WIND EVENTS DURING A FRONTAL PASSAGE

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I. INTRODUCTION

A. MOTIVATION

In recent years national security needs have dictated numerous operations be conducted in and across the littoral areas of hostile and friendly nations alike. Thus, the littoral battlespace has been an area of increased focus for the U.S. Navy. Large scale blue water operations have decreased in probability, and but the littoral regions of the world have taken on increased importance. As a result, demand for precise mesoscale meteorological support for those areas has also increased.

This study could assist in improving those operational forecasts in two ways. First, its results could be used to develop training materials for future military forecasters. This purpose would best served by having it distributed to Navy forecast training centers for both commissioned and enlisted personnel alike. It could used to modify the NWP and mesoscale training modules training criteria of the forecaster ‘A’ and ‘C’ school curricula at Naval Technical Training Unit Keesler AFB. If the future forecasters are made aware of the limitations of their model forecasts, they can better compensate for them and give better decision making guidance to the warfighter.

Second, from a research standpoint, this study is also potentially useful. It will be forwarded to research institutions such as the Naval Research Laboratory Marine Science Division, Monterey, California. There its results can be expounded upon to improve the operational model’s ability to forecast the wind events examined in this study.

An accurate low-level wind forecast can be considered an integral part of a successful pre-planning phase for many littoral warfare activities. Often, organizations such as the Mission Support Center (MSC) in San Diego, California coordinates Naval Special Warfare (NSW) operations for the Navy Special Forces operates in the along coast environment.

An example of the improved forecasts that could result from applying this work in both a training and research environment could then be seen in the day to day operations of NSW. Fore example, it is frequently necessary for NSW teams to deploy small boat units close to the shore to insert personnel into a hostile environment. An accurate mesoscale winds forecast for the along coast mesoscale environment could mean the difference between a success or a failure in such operations.

Mesoscale Numerical Weather Prediction (NWP) models have become quite skillful at predicting the larger mesoscale features in the atmosphere. They provide a reasonably realistic depiction of small scale details to help forecasters do their work (Doyle, 1997). However, in certain circumstances they are less skillful in their predictions. The imperfect representation of coastal topography along the land-sea interface is a source of forecast error, even for mesoscale models, with their increased resolution. This is due to the fact that;1) the terrain data must be under-sampled to match the model grid; 2) we have an incomplete understanding of how winds interact with the topography at the smallest scales, and 3) initial conditions are typically determined using sets of observations that are very sparse compared to the model grid.

The purpose of this study is to determine how well COAMPS™ forecasts both pre and post frontal passage winds in the presence of the California coastal topography. When the forecast is in error, this study will examine why such errors occur to determine which mesoscale variabilities the model is not handling skillfully.

B. PREDICTABILITY

Predictability is the upper limit to forecast skill (Anthes et al. 1984). It is the upper limit because it is an inherent property of the atmosphere. The limit exists even with perfect model and perfect analysis. This study attempts to make the distinction between predictability and forecast skill. Since it is not possible to observe the atmosphere at all times through all scales, Anthes notes that there is an unavoidable loss of forecast skill with time. This loss in forecast skill is illustrated in Figure 1 (Kuypers, 2000)

The problem of predictability is further compounded by the fact that the small scale interactions in the lower level of the atmosphere are not completely understood or observed. The effects of variables such as heat and moisture fluxes in the boundary layer are emulated in models rather than directly simulated. That is to say while the actual process itself is not modeled the effects of the process are. These emulated processes, though occurring on small scales, can contribute to the decrease in forecast skill with time, due to the aggregate effects of their small errors. However, these small scale processes do not always have such an effect as to reduce forecast predictability. (COMET 2004)

Lorenz (1982) suggests that the lack of predictability in the behavior of the atmosphere is in due part to these processes that are not as well understood. He uses the term: predictability time limit. This is the amount of time between the best estimate of the atmosphere based on observations and an estimate of its state in a forecast, to the point at which the forecast looses all skill. After a forecast reaches this limit it is no better than guessing (Lorenz 1982). This predictability limit is strongly dependent upon the accuracy of the measure of the initial conditions. A model that initializes well stands a better chance of keeping skill longer into the forecast future. Some of the issues with long term predictability have been addressed with the use of ensemble forecasting for synoptic scale events.

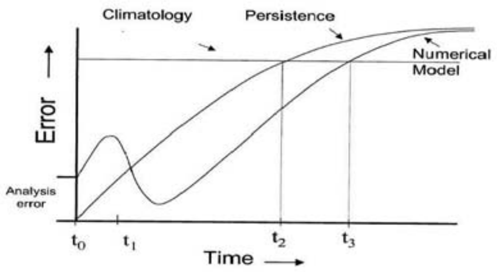

Figure 1. Theoretical model error growth (From: Kuypers 2000)

Kuypers (2000) provides us with graph (Figure 1) depicting the growth of error in NWP over time. It shows that the error in NWP starts small but grows rapidly due to the initial spin up of the model, which may operationally last from one to six hours. Eventually, these initial errors are dampened out as the model goes past its initial spin up and it adjusts to the assimilated data. After this spin-up, the limitation of the model's ability to represent the physics of the atmosphere becomes important and the error begins to grow again. This continues until the forecast error exceeds the predictability limit.

The specific issues of predictability vary greatly from case to case and area to area. In the case of the California coastline, the wind fields interacting with the topography can lead to orographic lifting, gap flows, and blocked flow regimes with a frontal passage The largest wind speed errors in the model wind fields were found to occur near the topography during the case of a landfalling front (Nuss and Miller 2001). These errors due to wind interacting with topography are examined in this thesis to help understand limitations in forecasting these events.

C. OBJECTIVES

There are three overarching objectives for this thesis. First, there will be a thorough analysis of the meteorological conditions that existed before, during, and after seven frontal passages across the California coast taken from the period of October 2003 to February 2004. This includes a synoptic scale analysis of the Eastern Pacific to analyze phenomena such as the jet stream placement, 500 millibar (500 MB) heights, and vorticity advection. The purpose of these upper air analyses is to determine the synoptic scale forcing that occurred during the frontal passages.

The lower levels will be used to analyze the position and timing of the surface front as it encroaches upon and passes over the coastline. This analysis will be done to track the speed and direction of pre and post frontal modeled and observed winds along the coast as they interact with the topography. The above analyses will also be compared to satellite imagery to determine their relative accuracy.

Second, a point by point verification of the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) performance along the coast will be performed. The model will be compared against its own analysis and against buoy observations at four key points along the California coast. This will be done to assess the model's performance in predicting along coast wind events near topography. These points were chosen for two reasons. Each possessed the most complete data set of buoy observations for the duration of each frontal passage, and together they represent a variety of different topographical orientations along the coast, thus providing an assessment of COAMPS' skill in many scenarios.

Third, the assessment of COAMPS performance in forecasting along coast wind events will be conducted. The assessment will be made by comparing the resultant frontal winds against several conceptual models for along coast wind flow. Specifically, the attention will be focused on the four areas where the verification of COAMPS performance took place and the key physical mechanisms to produce coastal wind effects. After these assessments then conclusions will be drawn detailing under what conditions COAMPS performed well in forecasting along coast winds and similarly under what conditions it did not do well.

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II. MODEL DESCRIPTION AND CLIMATOLOGICAL BACKGROUND

A. COAMPS MODEL DESCRIPTION

The COAMPS model is a 30-level nonhydrostatic mesoscale model being run operationally at a nominal grid spacing of 27 km by Fleet Numerical Meteorology and Oceanography Center (FNMOC). COAMPS is run operationally over a grid covering the mid-latitude East Pacific (EPAC) region out to 48 hours. Boundary conditions for COAMPS are taken from the Navy Operational Global Atmospheric Prediction System (NOGAPS) also run at FNMOC (Hodur, 1997). The model fields used in this study were taken from archived COAMPS data for the Winter of 2003-2004. It is the same data that the FNMOC users received in real time to assist in their forecasting.

The atmospheric portion of COAMPS includes a complete three-dimensional data assimilation system comprised of data quality control, analysis, initialization, and forecast model components. Features include a globally relocatable grid, user-defined grid resolutions and dimensions, nested grids, an option for idealized or real-time simulations, and code that allows for portability between mainframes and workstations. The nonhydrostatic atmospheric model includes predictive equations for the momentum, the non-dimensional pressure perturbation, the potential temperature, the turbulent kinetic energy, and the mixing ratios of water vapor, clouds, rain, ice, grauple, and snow, and contains advanced parameterizations for boundary layer processes, precipitation, and radiation. (COAMPS Home Page, 2005)

The model’s boundary conditions are passed from NOGAPS at every new forecast run. COAMPS then uses these data to give a forecast for up to forty-eight hours in six hour tau increments. The model is designed to be able to analyze and forecast events of terrain-induced circulations, coastal frontal systems, marine boundary layer dynamics, and land-sea interface effects. All of these come into play when analyzing the coastal wind phenomena that are the topic of this thesis.

B. CLIMATOLOGICAL BACKGROUND

Evaluating model performance for coastal wind events requires an understanding of both the synoptic and the mesoscale meteorological forcing in the Eastern Pacific and near the California Coast specifically. The meteorological forcing on these two scales, and the interactions between the two scales, are described below.

1. Wintertime California Synoptic Forcing

During the winter months the Sun moves southward over the equatorial regions towards the southern hemisphere's Tropic of Capricorn. The sun's area of maximum heating is entirely in the southern hemisphere and as a result the Polar Front Jet's mean position moves further southward over the United States, as its thermal gradient continues to strengthen. The Aleutian low continues to deepen and moves southward in the Gulf of Alaska. The semi permanent Eastern Pacific high off the coast of California continues to weaken and there is an increase in the frequency of extratropical storm tracks that transit over the west coast of the U.S. During the winter months the vertical thermal stratification off the California coast reduces in strength compared to the strong capping inversions found in the summer months (Dorman et al., 1995). The stratification that remains gets eliminated when the transient mid-latitude cyclones propagate across the Eastern Pacific and onto the California coast.

2. Wintertime California Mesoscale Topographic Forcing

During the winter months along the coast, the occurrence of a low-level inversion is not as pronounced. This is due to the fact that the semi-permanent East Pacific high has moved south, and taking its strong subsidence with it. In the area between Pt. Arena and San Francisco the capping inversion is still often present, but is frequently dissipated by the transient mid-latitude cyclones that destabilize the atmosphere. Areas of topography that jut out from the shore in a point (such as at Cape Mendocino) lay the backdrop for the mesoscale forcing that leads to low level coastal jets, and along coast wind intensification during a pre-frontal wind event. Moving further south in the area of Pt. Conception the inversion is not as well defined as in the summer but the atmosphere is usually stable. Santa Ana winds, directed offshore, occur from fall through spring resulting from the combined influence of the large high pressure system that develops over Colorado and Nevada and a low which develops to the West of Southern California. South of Pt. Conception in the Santa Barbara Channel region, the flow is typically dominated by diurnal variabilities. However, the strong synoptic scale forcing associated with a frontal passage can cause the winds to channel in a southerly direction through the gap between the California coast and the islands. (Dorman et. al. 1995).

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III. ANALYSIS PROCEDURES AND CONCEPTUAL WIND INTERACTION

This study began with the search for a sample of fronts associated with winter storms that affected the California coast, during the winter of 2003-2004. Once the cases were identified, an initial verification of the landfall was performed. Data fields for analysis were obtained from the archived COAMPS and NOGAPS model data stored at FNMOC in Gridded Binary (GRIB) format. The fields were then converted to the General Meteorological Package (GEMPAK) format and placed into the GEMPAK Analysis and Rendering Program (GARP) viewer. GEMPAK is a suite of application programs for the analysis, display, and diagnosis of meteorological data. GARP is the Graphic User Interface (GUI) for GEMPAK. The author then performed a tau by tau analysis of the forecast fields for each frontal passage.

A. ANALYSIS METHODS

1. Synoptic Analysis Methods

The synoptic scale evolution of each case was examined with the NOGAPS fields and their respective satellite imagery. Both the upper and lower level forcing was analyzed by using the GARP viewer to step through the movement of each of the cold fronts in six hour increments from the initial 00Z model run through six hours after frontal passage in the vicinity of the Santa Barbara Channel Islands. After this point the front was no longer interacting with the area of interest for this study. Analyzing the model fields in this way provided a familiarization with the time evolution of the synoptic scale forcing that resulted in the propagating mid-latitude cyclone interacting with the California coast.

2. Mesoscale Analysis Methods

A finer “point by point” form of analysis and verification was done to assess the modeled and observed terrain interactions with the wind field. The author used GARP to focus in on the coast of California, and selected four key points along the coast. Each point was chosen using the following criteria: 1) the point has a buoy from the National Climactic Data Center (NCDC), and 2) the point was located in an area where there is significant topography nearby. These criteria were chosen to ensure that there was both wind interaction with the topography by the model wind fields and that such interaction could be verified against the buoy observations that spanned the time series of each frontal case. The four points chosen were (going from North to South) were Cape Mendocino, Point Reyes, Point Sur, and Point Conception.

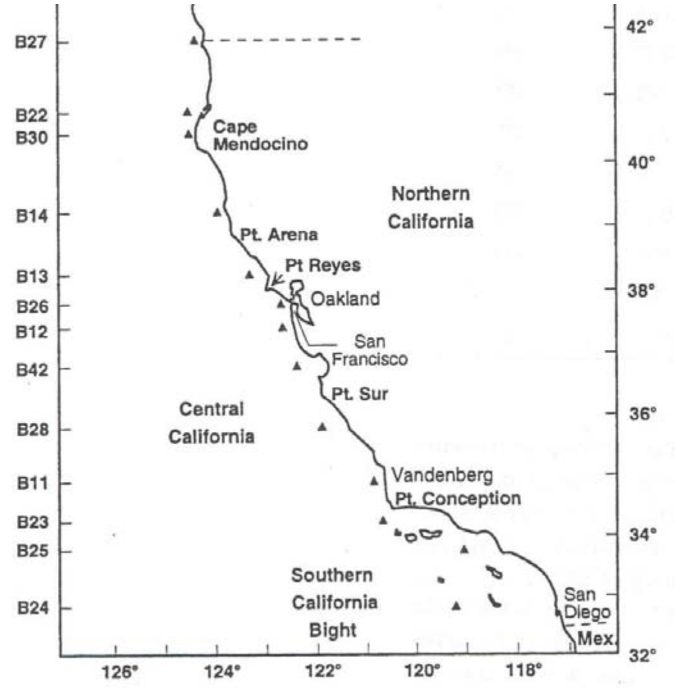


Figure 2. Chart showing locations of buoys in the NCDC system along the California coast (From: Dorman and Winant 1995)

Wind speed and direction changes were analyzed in six hour increments from the 00Z of the model run to six hours after the frontal passage. The wind speed and direction for both the model and the buoys were catalogued and compared. Time series plots were made from this data in the form of observation versus model graphs to easily highlight model performance issues. The plots were generated using MATLAB software.

The along coast mesoscale wind flow events were analyzed by comparing them to different idealized hypothesized low-level wind interactions depending on the particular area’s flow pattern and topography. These hypothesized interactions were used as a starting point to describe the along coast wind events. Variations from the hypothesized interaction conditions were observed in both the COAMPS model fields and the verifying buoy observations. These variations were used to characterize the evolution of the wind field interactions with the topography in the pre and post frontal passage stages of the time series.

B. CONCEPTUAL WIND INTERACTION

There are two main elements that define the interaction of wind with terrain for the landfalling storms in this study. The first is the synoptically forced low-level pre-frontal flow. The second is the mesoscale flow's response to the coastal topography.

1. Character of Low-level Flow

The low-level along coast flow may take on some unique characteristics in the presence of mountainous coastlines due to a few key factors. These factors can set the stage for a blocked flow wind event. First, the presence of low level along-coast winds is often associated with an approaching cold frontal boundary. The pre-frontal winds of the approaching cyclone come from the southwest as they make their trek through the warm sector of the cyclone. These southwesterly winds are potentially strong due to the presence of the cold front and the cyclone's north-south pressure gradient.

Second, the amount of warm air advection (WAA) also plays a role in determining the character of the low-level flow. If there is significant WAA over the water between the approaching cold front and the steep coastal topography, then the vertical temperature gradient from the sea surface to the lower levels of the atmosphere can become quite sharp. This sharp contrast of the warm air over the cooler water provides a very stably stratified low level atmosphere. The WAA ahead of a cold front is generally quite strong so this gradient is a fairly common occurrence in the case of an advancing cold front.

Finally, the presence of significant mountainous coastal topography that butts up against the coast line is also a factor. This topography provides a boundary that the pre-frontal winds in the warm sector can get blocked by. These pre-frontal winds then get trapped between the two constraints of the approaching frontal boundary and the mountainous coastal topography.

Taking all three factors into account at once, there is a potential for the cross coast flow to become blocked and turn in an along coast fashion flowing from south to north.

The pre-frontal flow can become trapped between the approaching frontal boundary and the mountainous topography. Also, the stability of the atmosphere provided by significant pre-frontal WAA prevents the flow from propagating over the mountain tops. The result when these conditions exist together is an intense along-coast blocked flow wind event.

The three factors that give rise to blocked flow will be assessed in this study by analyzing the COAMPS model forecast wind and temperature fields at both 850MB and the surface. The 00Z run of each case study will be analyzed forecast tau by forecast tau (six hour increments) from the initialization of the model (00Z) through six hours after frontal passage in the vicinity of the Santa Barbara Channel Islands. After this, the front will have passed through the area of the study. The 850MB level was chosen as the upper limit of the mesoscale analysis because above this level the winds are flowing over the tops of the coastal mountains and no longer have the potential to be blocked. The forecast model wind speed and direction fields at each six hour increment will then be verified against the NBDC buoys that are collocated with each of the four aforementioned points of interest. (Cape Mendocino, Point Reyes, Point Sur, Point Conception)

2. Coastal Response to Blocked Flow

When the three factors that give rise to blocked flow events are present along the coast the end result can be a low-level barrier jet event or a split flow event. Though the conditions for their formation are similar, there are some key differences between the two flow types.

The low-level barrier jet occurs when the winds that become blocked between the coastal topography and the encroaching frontal boundary have significant WAA ahead of the frontal boundary and above the 850MB level (providing low-level stratification). As the pre-frontal winds make their way around from the southwest they become accelerated by the intensity of the along coast south to north pressure gradient provided by the synoptic low pressure system. This pressure gradient tends to become more tightly packed as the cold frontal boundary comes closer to the coast. This can lead to along coast winds as high as thirty-five to forty knots in the cases of this study. The timescale of this event is rather short as it only lasts until the front has made landfall on the coast.

This event is also characterized by fronts where the associated low pressure center makes landfall just north of an abrupt change in coastal topography, such as a point or cape where there is sufficiently high coastal mountains to complete the blocked flow scenario.

South of the area where the low pressure center makes land fall, the potential exists for a split flow event. Here the southwesterly synoptic scale flow moves onshore against the steep coastal mountain topography. This causes the mass of the onshore flow to become 'piled up' along the shoreline. The along shore pressure perturbation that results becomes superimposed upon the synoptic scale pressure field for the split flow blocking scenarios. The WAA in this region is significantly lower than further north ahead of the synoptic low pressure system. Therefore, the vertical temperature gradient between the sea and the lower levels of the atmosphere is not as sharp. As a result the stability of the atmosphere in these lower levels is not as great. Thus, the potential for flow blocking is not as great. If the flow is blocked then it will flow north and south down the coast. This flow is not very intense compared to the flow further north because it does not have the benefit of the tightly packed along shore pressure gradient ahead of the front.

In order to mathematically describe the flow interaction with topography, it is necessary to consider the energetics of air being lifted over a barrier.. The dimensionless quantity that governs this behavior is the Froude number. The Froude number in this application is defined as:

$$F_R \equiv \frac{V}{Nh}$$

Where V is the velocity of the flow and Nh is the work required to lift an air parcel to the height h. The quantity h is the height of the coastal topography and N is the Brunt-Vaisala frequency. If the Froude number is less than 1 then kinetic energy is not sufficient to overcome the work required to lift the parcel over the mountain. This situation corresponds to the flow being blocked. If the Froude number is greater than 1, then the kinetic energy is more than adequate to lift the air over the barrier and the flow is not blocked. For this study it is appropriate to take the h value from the model terrain height rather than actual terrain height. This is because the model terrain height will reflect why the model has a blocked flow event in its wind fields or not. The same could be said of the use of model temperature values when calculating WAA.

With the weaker flow and weaker WAA in the southern portion of the region, it is possible that the onshore synoptic flow may not become blocked at all. In this case it will continue to flow over the mountain tops in a southwesterly synoptic fashion.

IV. SYNOPTIC AND MESOSCALE CASE BY CASE ANALYSIS

As previously mentioned, six cases of landfalling fronts were chosen to examine in this study. Of those fronts, three occurred in December and three in November. In general, the December cases were stronger fronts that produced a clearer coastal interaction, consequently there are described first in the following sections.

A. 5-7 DECEMBER 2003

1. Synoptic Analysis

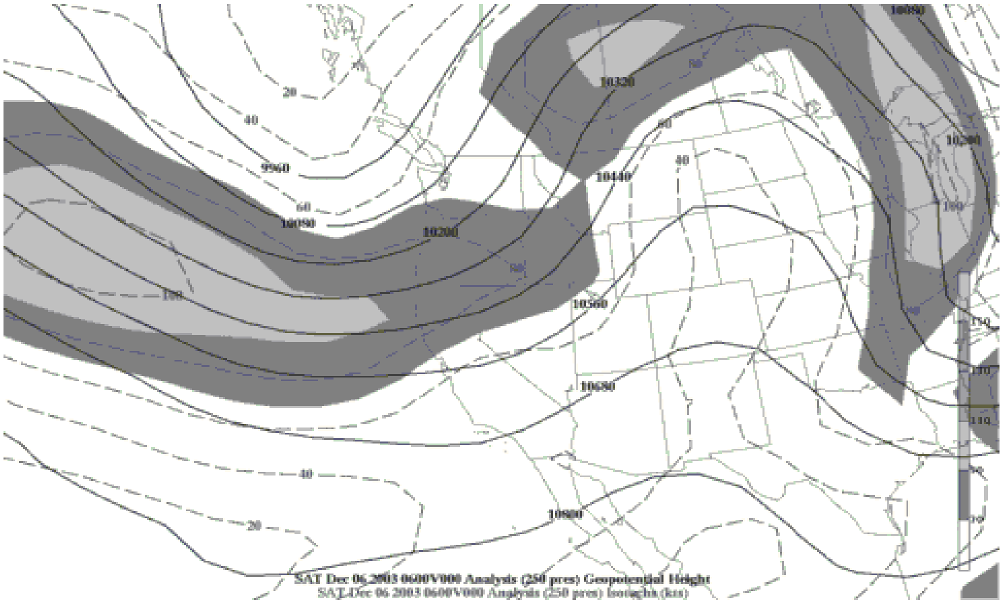


Figure 3. Analysis of 250MB Heights/Isotachs for 06Z 6 DEC 03

The 250 MB heights and Isotachs at 06 Z 6 DEC 03 (figure 3) shows jet streak in the mid-Pacific is beginning to accelerate through the trough. This causes the trough to dig in a bit, and bring to bear the left front quadrant of the jet streak on top of a surface low off the coast of British Columbia which intensifies it. Throughout the evolution of this case, the jet maintains this pattern of progressing to the east while staying in the northern portion of the Western U.S.

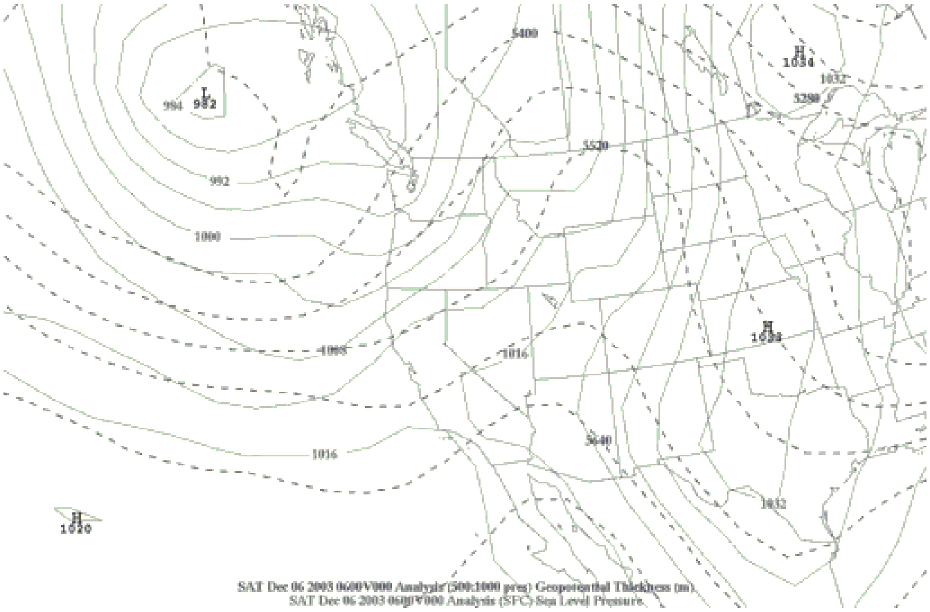


Figure 4. Analysis of SLP and thickness for 06Z 06 DEC 03

On the surface, we see the cyclone off the British Columbia coast produces a front that moves from the northwest to the southeast toward the California coast (Figure 4). The front continues this approach toward the coast as it approaches from a 45 degree angle (northwesterly). The pre-frontal winds begin interacting with the topography by 00Z on 6 DEC 03. This is illustrated in Figure 5 where the 850MB winds and theta show the beginning of the progress of this case study's front toward the coast of Northern California.

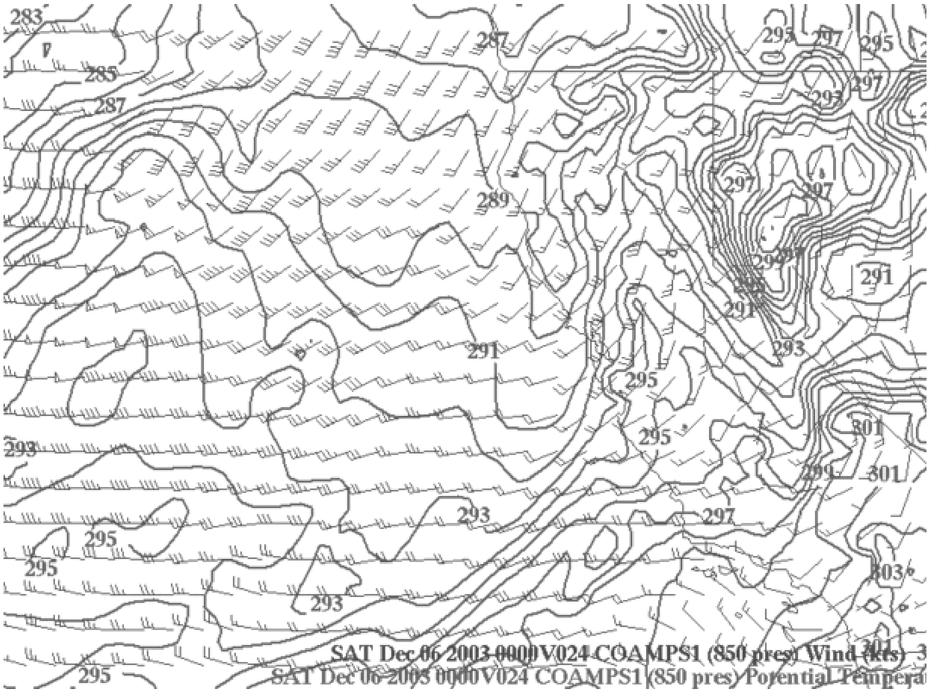


Figure 5. 00Z 06 DEC 03 850MB Theta and Wind forecast

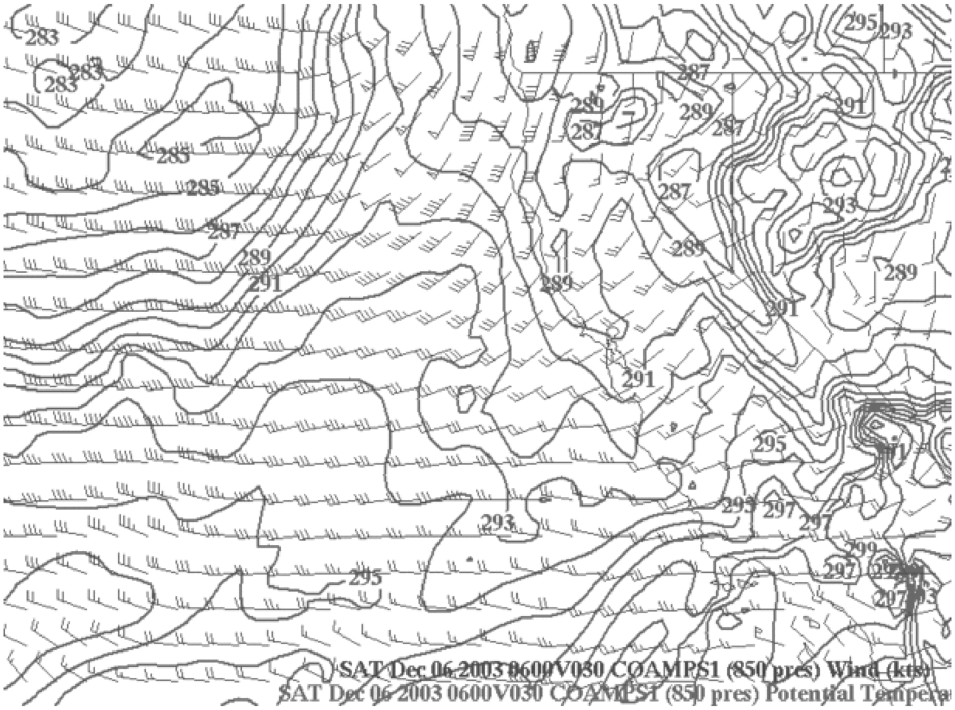


Figure 6. 06Z 06 DEC 03 850MB Theta and Wind forecast

By 06Z on 6 DEC, the WAA ahead of the front has helped to propagate the front to the point where the winds are affecting the California coast(Figure 6). The pre-frontal 850MB winds are seen along the coast to be at a maximum at Cape Mendocino. This flow pattern is potentially conducive for of a low level barrier jet event. This pattern is also reflected on the surface. By the next tau increment, the front has passed over Cape Mendocino and the winds have shifted around in a westerly fashion after the frontal passage (Figure 7). However, the front itself continues to propagate southeasterly affecting the flow further south along the coast.

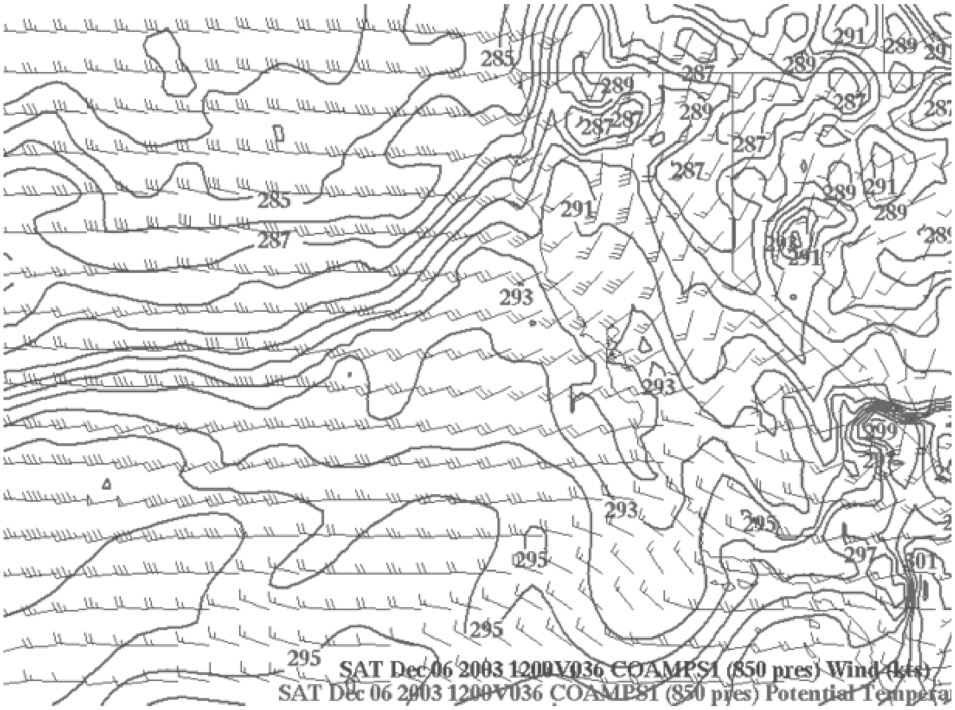


Figure 7. 12Z 06 DEC 03 850MB Theta and Wind forecast

3. Mesoscale Analysis

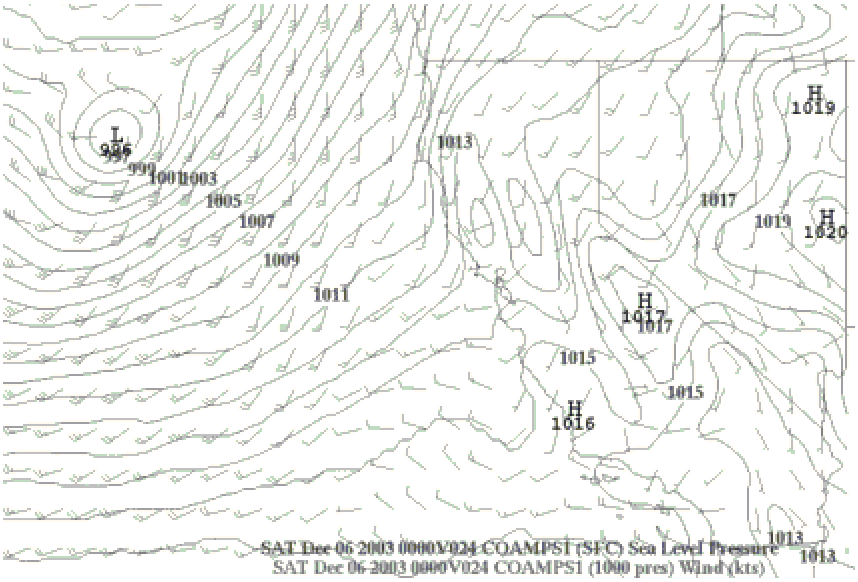


Figure 8. Surface analysis of Pressure and Model Winds 00Z 6 DEC 03

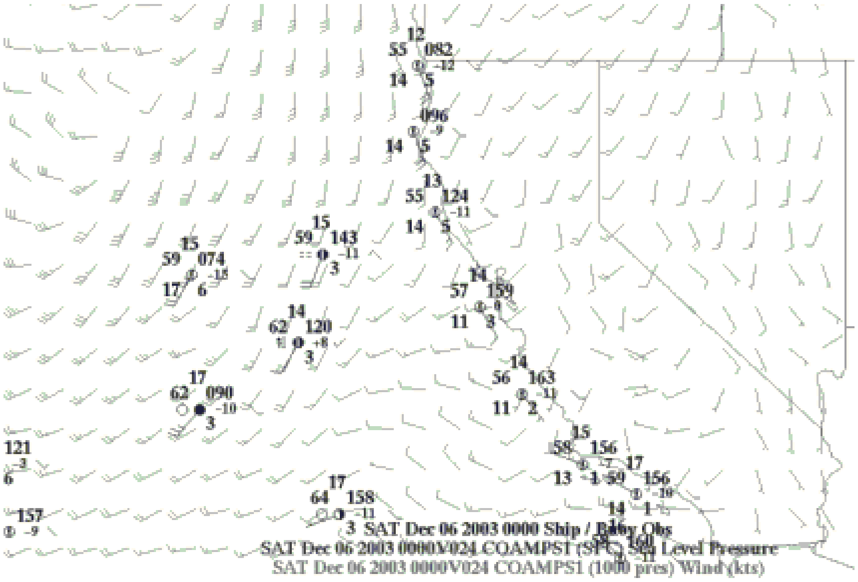


Figure 9. Surface analysis of Model Winds and Buoy Verification 00Z 6 DEC 03

The front in this case makes a steady southeasterly trek toward the coast, first making its winds felt near the Cape Mendocino area. The model has a good handle on the synoptic scale forcing and this supports the accuracy of the mesoscale forecast in the early portion of the time evolution. At tau 24, the front produces its maximum along shore pressure gradient at Cape Mendocino (Figure 8). At this time, an error in the model forecast of the along coast low level barrier jet begins to reveal itself. The forecast wind speed and direction grows as the speed holds at 20 knots with a direction between 182 and 184 degrees(Figure 10). However, the verifying buoy observations show the flow to be faster and the wind direction to be from 160 to 165 degrees. The wind speed trend continues to increase over the next six hours in the tau 30 forecast. The buoy observations confirm the increasing trend, but the model continues to lag behind the wind speed increase, which may be due to it failing to account for the coastal effect of the Cape's topography even though the model winds seem to capture the wind direction very well.

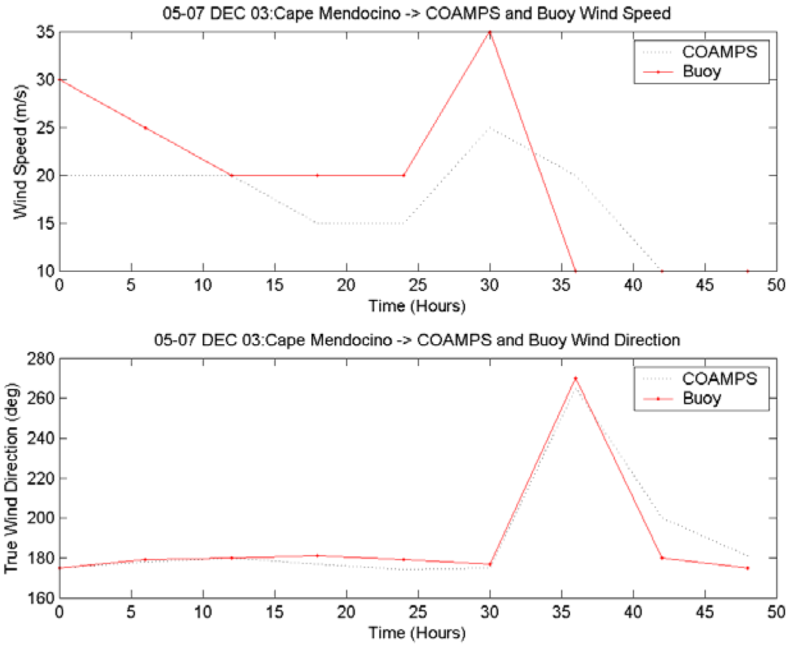


Figure 10. Cape Mendocino Model v. Buoy Time Series 5-7 DEC 03

The rapidly intensifying winds and steady along coast flow confirmed by the buoy are consistent with low level barrier jet phenomena as the time series indicates. However, the model has not simulated this process in a timely manner. As Figure 10 shows, the model forecast lags behind the observations by about 4 to 6 hours starting at tau 24 and catching up by tau 30. The wind speed observations do not catch up before the frontal passage over Cape Mendocino and the winds shift around. After the frontal passage, both the model wind speed and direction are in good agreement with the buoy.

What caused the COAMPS forecast to lag behind the buoy observations? The model failed to recognize two features of the wind. First, the model missed the extent to which the presence of the steep topography at Cape Mendocino would block the flow and turn it to a more south easterly fashion than the synoptic flow. Second, it could not keep up with the rapidly increasing along coast pressure gradient as the front makes its way toward the shore, which is evident in wind speed differences shown in Figure 10.

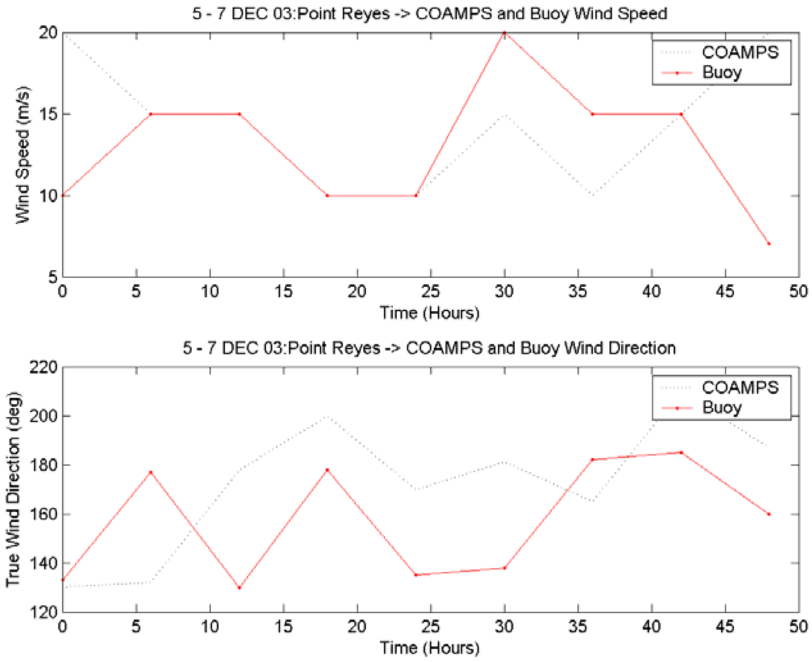


Figure 11. Point Reyes Model v. Buoy Time Series 5-7 DEC 03

Southward at the next point of interest at Point Reyes, a similar pattern plays out, but the along coast pressure gradient is not as pronounced only 4MB is observed compared to 8MB over an equivalent distance, and therefore the wind speeds are also not as fast. This is due to the fact that the pressure gradient this far south of the land fall of the front is not as tight. For the first portion of the time series, the along coast wind speeds from the model are a steady 10 knots up until the frontal passage at which time they are accelerate slightly to 15 knots. The buoy observations show a frontal passage by tau 36 in this region according to the wind shift. The along coast winds stay at 15 knots but the model lags slightly behind in the forecast. The model winds hold steady at 20 knots throughout the remainder of the time series.

This is the same set of forcing that occurs in the Cape Mendocino area and the model makes the same error in this location that it did further north. The model tended to under forecast the wind speeds occurring just ahead of the front in the cyclones warm sector. However, the difference is not as pronounced until just ahead of the front (tau 24 forecast) due to the fact that the synoptic scale along coast pressure gradient forcing is not as strong as it is further north. The wind direction showed a more distinct difference at Point Reyes then at Cape Mendocino. The buoy winds are southeasterly while the model winds stay southerly. The difference is probably due to the lower coastal topography at Point Reyes. These errors in the model winds are due to the model not accounting for the amount of blocking that the along shore topography is capable of, and failing to keep up with the rapidly changing flow due to the steep pressure gradient ahead of the front as it comes on shore.

Further south the synoptic forcing of the front is less prevalent and the wind pattern along the coast follows a split flow interaction. The onshore flow becomes more westerly further south on the California coast. The result of this flow is the formation of a pressure perturbation on the coast between Point Sur and Point Conception. The mass of the air piles up along the coast at this point and then the wind flows both north and south along the coast. The end result is a relaxed yet persistent along shore pressure gradient that produces an along coast blocked flow wind event. The southern branch of this flow goes past Point Conception and is funneled as a light gap flow through the Santa Barbara Channel Islands near the Southern California Bight region. This flow is modeled fairly well in situations of strong synoptic forcing. The differences in observed wind speed are no more than 5 knots in either the north or south direction. Upon entry into the Santa Barbara Channel Islands the flow is funneled at a near constant 10 knots due to the properties of the gap flow for the duration of the forecast period. This is consistent with the model forecast.

B. 13-15 DECEMBER 2003

1. Synoptic Analysis

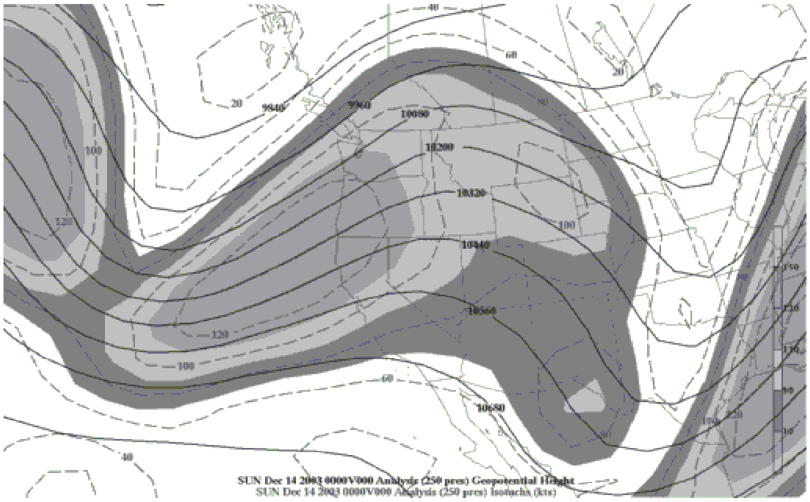


Figure 12. Analysis of 250MB Heights/Isotachs for 12Z 14 NOV 03

In this case, the 250MB height and isotachs analysis at 12Z 14 NOV 03 (Figure 12) shows that the PFJ starts with a zonal flow, but over the course of the evolution of the event, it becomes quite meridional. By 18Z on 14 DEC 03 the left front quadrant of the jet is poised over the surface cyclone, providing upward vertical motion and intensifying it. Through thermal gradient tightening it is strengthening the frontal boundaries, which then modify the flow along the coast.

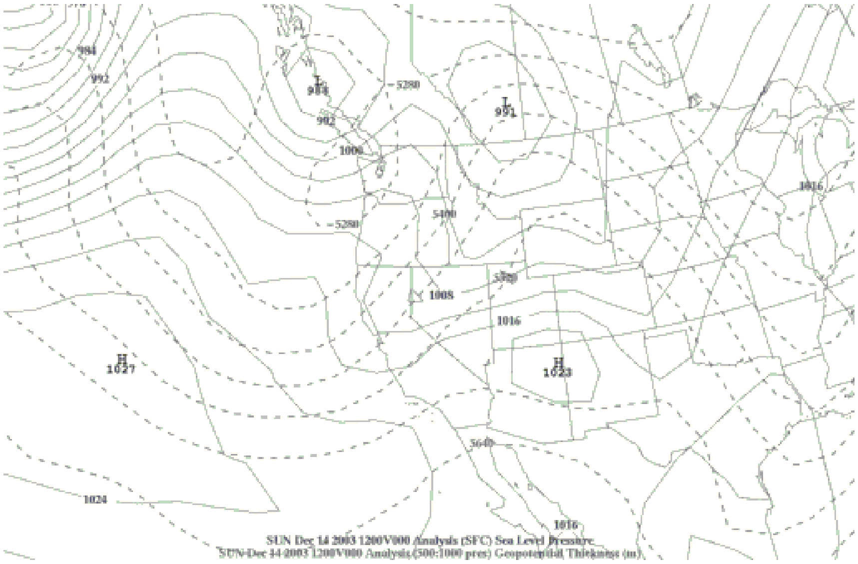


Figure 13. Analysis of SLP and thickness for 12Z 14 DEC 03

At 12Z 14 DEC 03 in the surface analysis we see the cyclone has propagated in from the west to the British Columbia coast. The low has deepened as it moves toward the coast, and its phase speed remains steady as it tracks across the ocean.

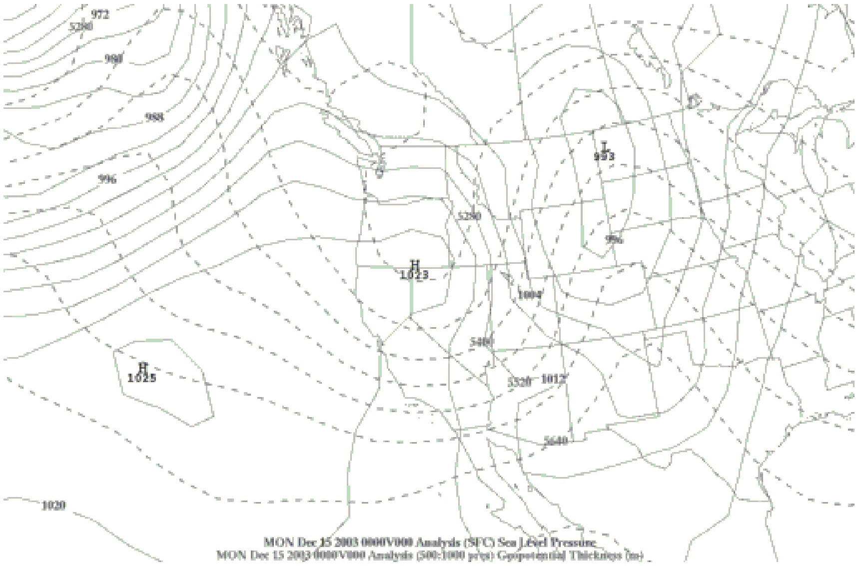


Figure 14. Analysis of SLP and thickness for 12Z 14 DEC 03

We see in Figure 14 the continuing trend of the northwestern most low to propagate and deepen, as it moves into the Gulf of Alaska the front that impacted the California coast has moved inland over the Great Barrier. Looking at the 850 MB forecast of the frontal position at 06Z 14 DEC 03 in Figure 15, we can see how this front orients itself in a coast parallel fashion as it begins to make landfall. In addition, the winds tend to be oriented more coast parallel especially over Northern California. This pattern continues as the front comes on shore over the next 6 hours as shown in Figure 16. The winds to the south of Point Reyes tend to be more cross coast, which intersect with the coastal mountains more. This is in contrast to the angle at which the 5-7 DEC 03 front made its approach at a 45 degree angle. The model captures the movement of the oncoming front well, and this aids the forecast on the mesoscale.

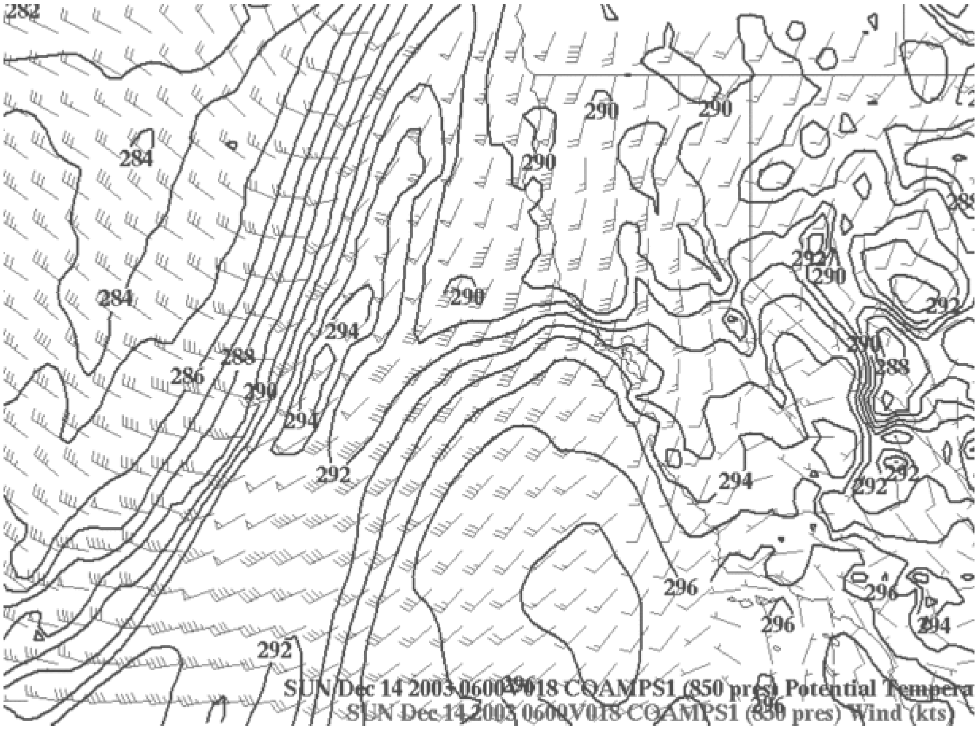


Figure 15. Analysis of 850MB Theta and Winds 06Z 14 DEC 03

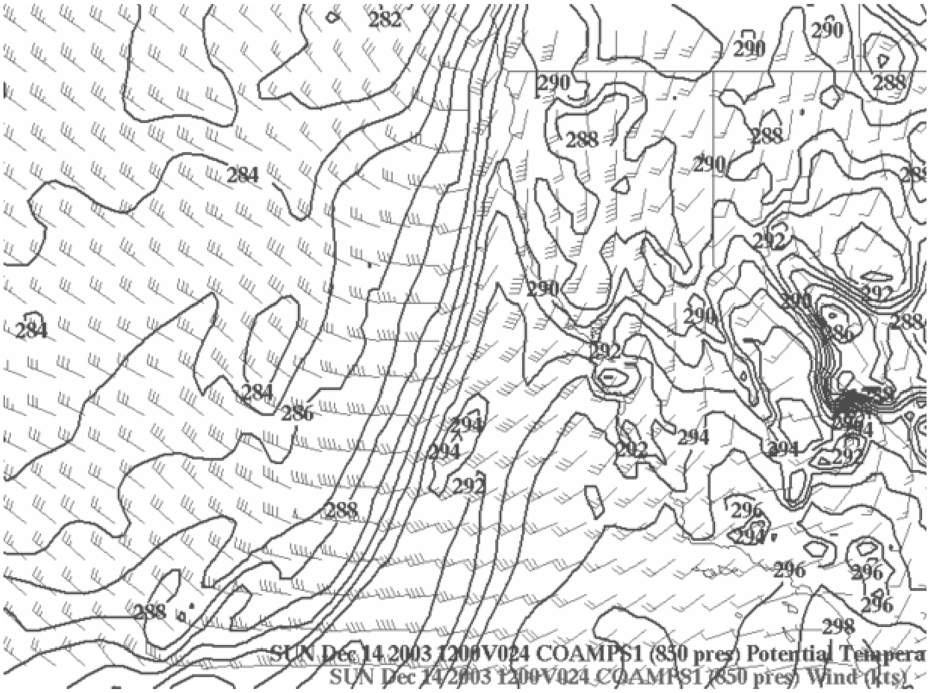


Figure 16. Analysis of 850MB Theta and Winds 12Z 14 DEC 03

2. Mesoscale Analysis

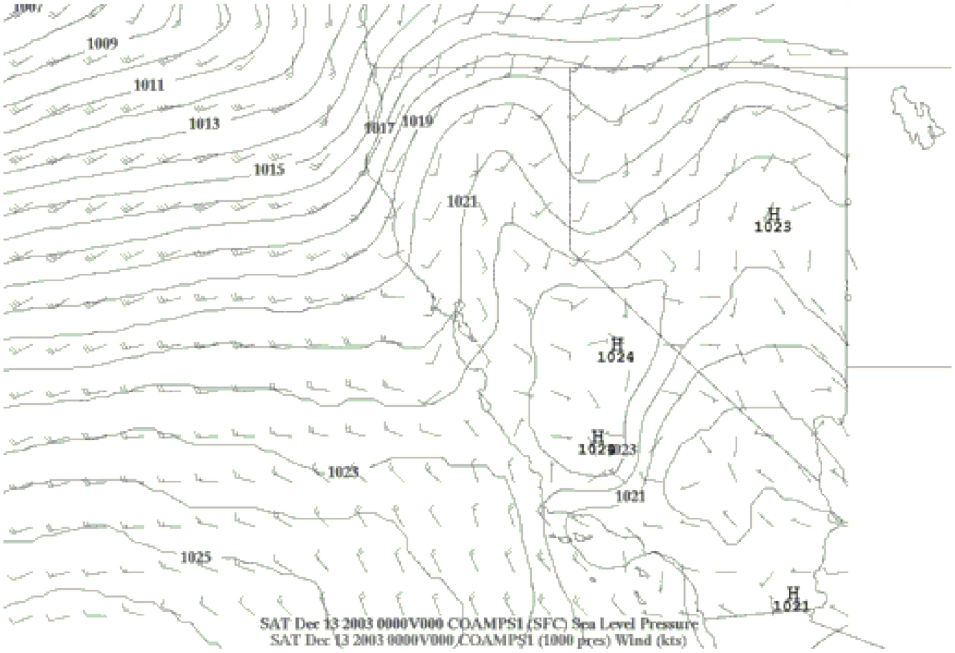


Figure 17. Surface analysis of Pressure and Model Winds 00Z 13 DEC 03

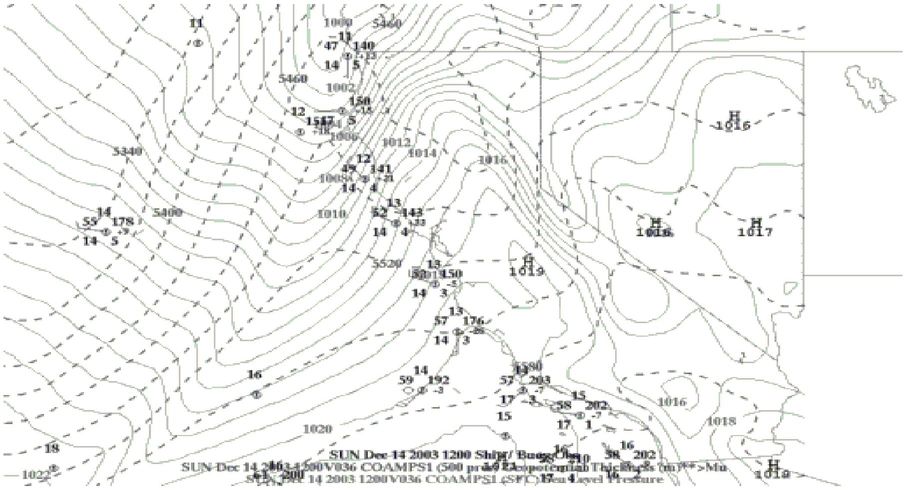


Figure 18. Surface analysis of Buoy Observations and Model Winds 12Z 14 DEC 03

This case displays what occurs along the coast during a synoptic low that has a faster pace as it encroaches up on the California coast. Figure 17 shows the model analysis for 00Z 13 DEC 03 with a weak warm front over the coast and the cold front well offshore. Within 24-30 hours, the cold front interacts with the California coast. This front also takes on a slightly different character as it is approaches from a nearly coast parallel fashion, unlike the 5-7 DEC 03 case where the front was approaching from a 45 degree angle. This changes the character of the along shore pressure gradient such that the brunt of the tightest packing is observed near Point Reyes when the front moves south (Figure 18) and not at Cape Mendocino as in the 5-7 DEC 03 case. The evolution of the time series plays out in a similar manner at Point Reyes that played out at Cape Mendocino in the earlier case. The pre-frontal south westerly flow at Point Reyes is just starting to respond to this forcing at 00Z on 13 DEC. It does so by beginning to shift around to a more coast parallel fashion and speed up with the approach of the front. The time series of the Point Reyes area of interest for this case (Figure 19) shows a similar trend for the wind direction as the 5-7 DEC 03 case. Starting from tau 15 continuing through tau 35 the model wind direction takes on a synoptic southerly flow. However, the buoy wind direction for the same time shows a more coast parallel southeasterly flow. COAMPS wind speeds for the same period of time (12 to 30 hour forecast) also are shown to be lagging behind their corresponding buoy observations in this pre-frontal flow.

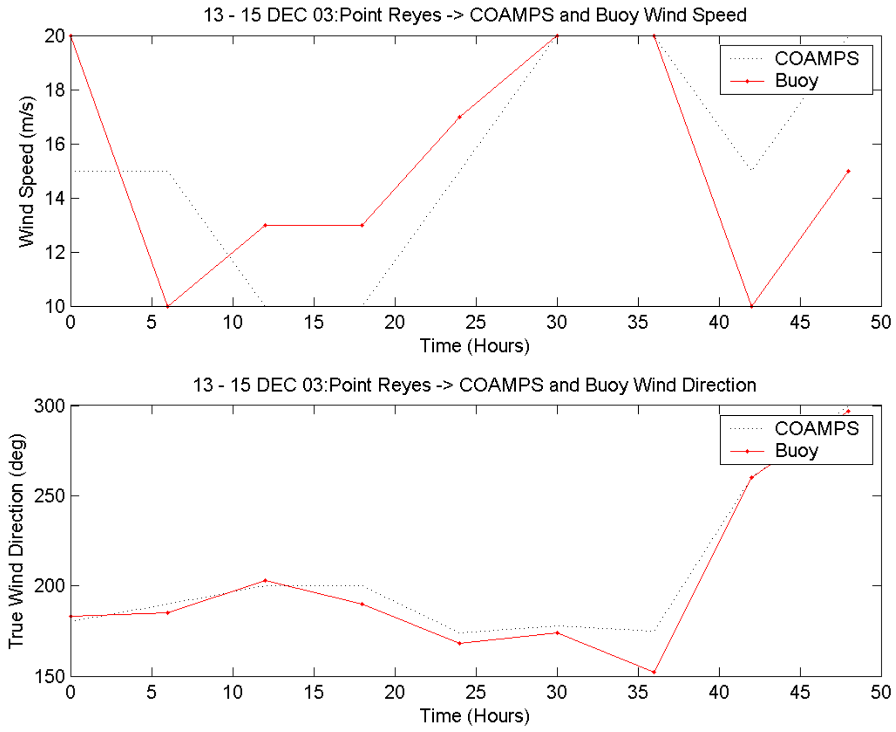


Figure 19. Point Reyes Model v. Buoy Time Series 13-15 DEC 03

This is typical of the COAMPS coastal wind response during these events for the December cases of this study. It is slow to bring the along coast winds up to speed and slow to bring them back down after the front has passed. WAA at the surface ahead of the front is also not as strong as that which may be occurring in the atmosphere. If the model's WAA was as properly represented as it is in the atmosphere, then the model would likely be more adept at accurately reflecting these conditions. The weaker WAA leads to a slower propagation pace for the front and an along coast pressure gradient that is not quite as tight as the 5-7 DEC 03 case. Other reasons for the discrepancy in the model forecast are the same as for the 5-7 DEC 03 case. The model topography does not reflect its real world counterpart well enough to properly catch the amount it modifies the direction of the flow. Consequently, the model does not keep up with the rapid intensification of the along shore pressure gradient as the front propagates toward landfall. The errors in this case are not as dramatic as the previous December case because the pressure gradient for this front overall is not as tight. By tau 35, the front has passed over the Point Reyes area of interest and the winds have shifted around to the west.

In the vicinity of Cape Mendocino the front moves inland over Oregon and the front approaches straight from the west. The result is 850MB flow parallel to the mountains ahead of the front (Figure 16) which would not produce a pronounced blocking effect. Consequently, the buoy and model winds were rather similar at Cape Mendocino, driven mainly by the synoptic scale.

In the vicinity of Point Sur, the model's synoptic flow is onshore in nature. In the case of the first frontal passage, the mass of the wind piles up along the shore and forms a small high pressure perturbation at this point on the shore. As in the 5- 7 DEC 03 case, the flow becomes blocked and takes on a split flow character. This effect occurs further south than in the 5-7 DEC 03 case because the front makes landfall south of Cape Mendocino, and the along shore pressure gradient was not as tight as the 5-7 DEC 03 case. With this pressure perturbation further south, the gradient from Point Conception through the Santa Barbara Channel Islands is tighter, results in greater wind speeds being funneled through the islands. The wind speed kicks up to a steady 15 knots during the last portion of the time series from 06Z 14 DEC 03 to 00Z 15 DEC 03. After this the front passes beyond all of our regions of interest.

C. 19-21 DECEMBER 2003

1. Synoptic Analysis

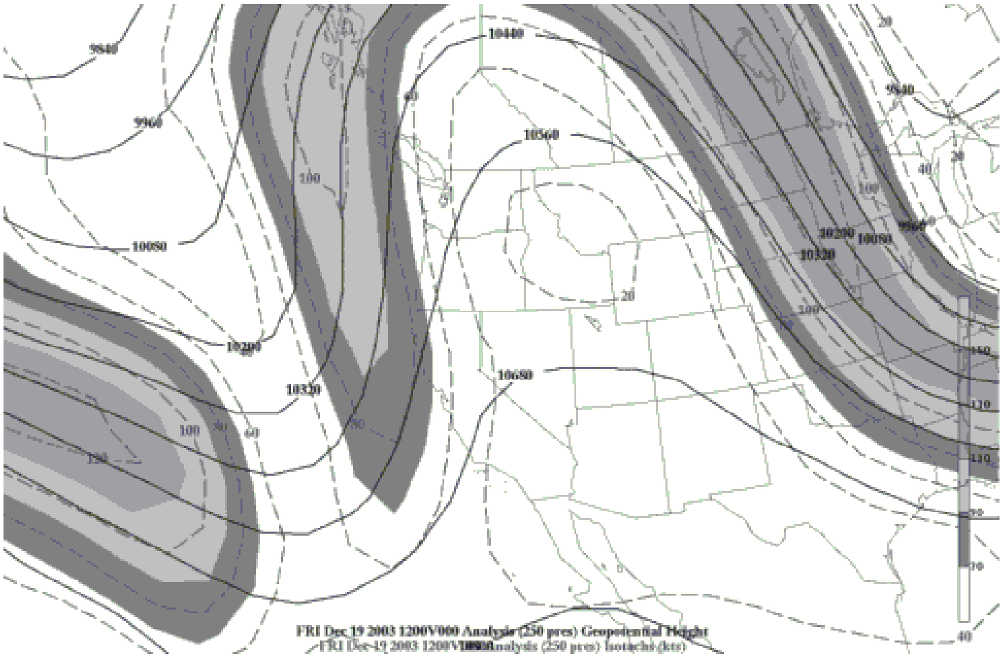


Figure 20. Analysis of 250MB Heights/Isotachs for 12Z 19 DEC 03

The 250MB height and isotach analysis (Figure 20) indicate that upper level flow for this event is largely meridional. The jet streak is seen exiting the trough in Figure 20 and its right rear quadrant over the surface cyclone in this case. There is another streak seen to the west of it that also propagates through by the end of the evolution of this case at 18Z 21 DEC 03. The jet provides upper level divergence over the time shown in Figure 21, Later when the second jet streak reaches the same approximate area, the surface front remains under an area of jet divergence.

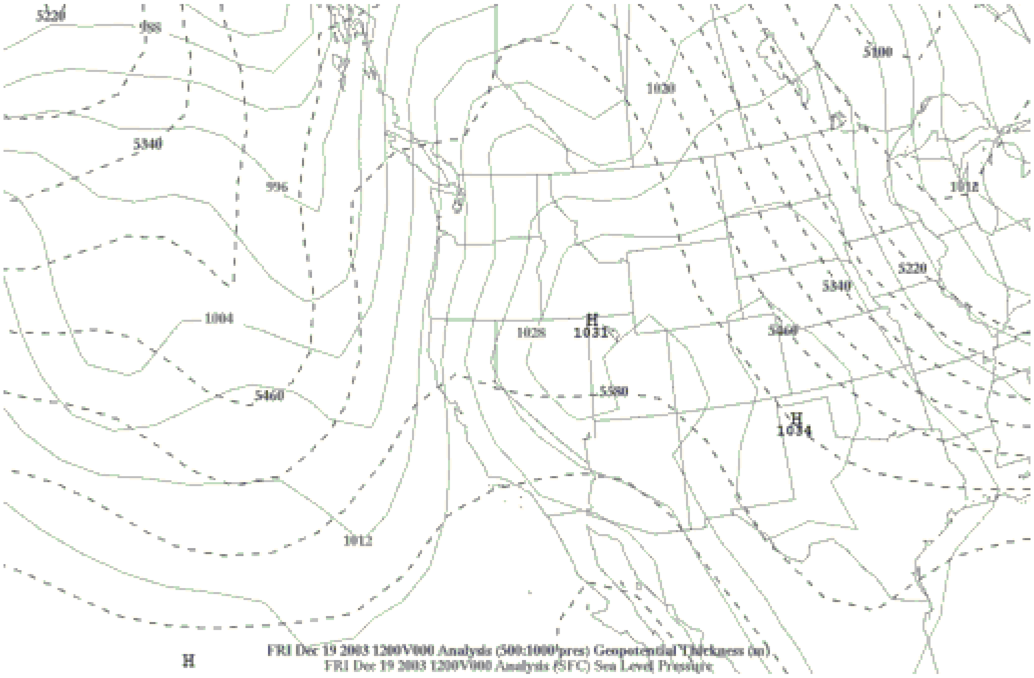


Figure 21. Analysis of SLP and thickness for 12Z 19 DEC 03

The surface synoptic picture for 12Z 19 DEC 03 (Figure 21) shows the front approaching the coast in a nearly north-south orientation. The WAA ahead of the cold front is assisting in the propagation across the coast. As was noted in Figure 20, the jet streak is also positioned above this advection; the circulation of the jet, tightens the horizontal thermal gradient and intensifies the surface front This pre-frontal WAA and frontal circulation are the primary features that interact with the coastal topography in this event.

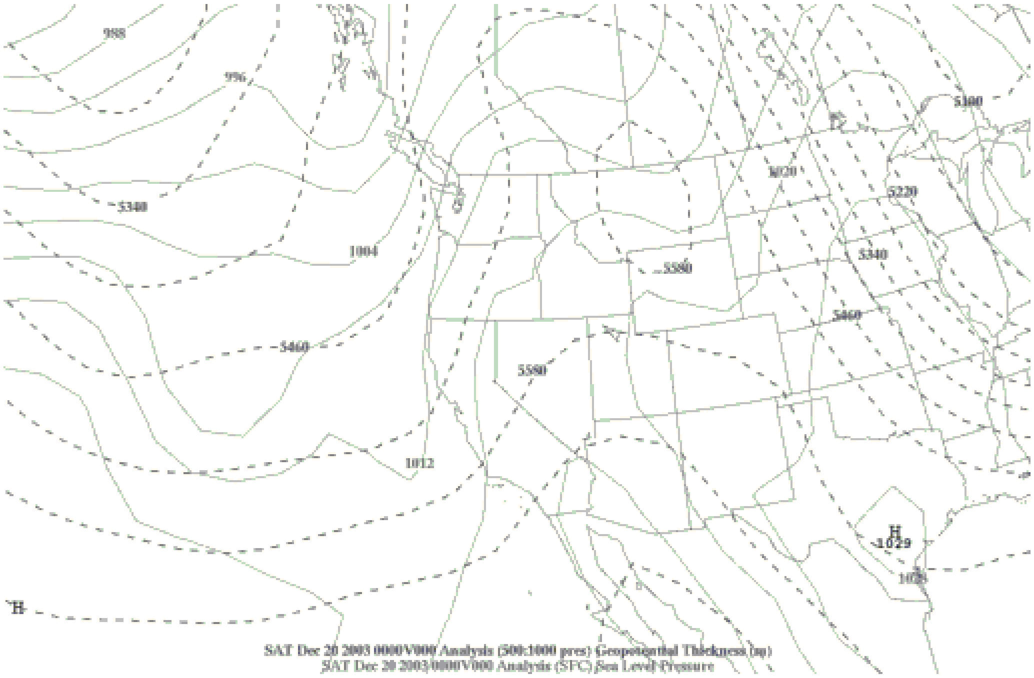


Figure 22. Analysis of SLP and thickness for 00Z 20 DEC 03

Twelve hours later the synoptic analysis at 00Z 20 DEC 03 (Figure 22) shows the progression of the surface front as it is crossing over the California coast and weakening. This is the point at which the winds become post frontal and begin to shift around west. The influence of the topography on the flow by the end of the event is different as it shifts to a more summertime pattern once the ridge behind the low settles in.

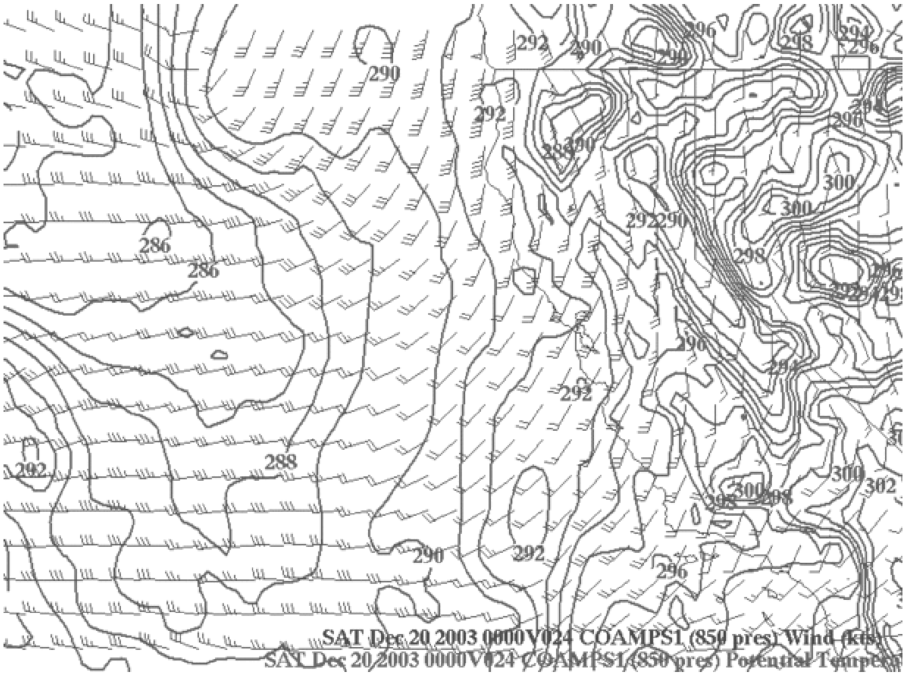


Figure 23. 850MB Theta Winds Analysis 00Z 20 DEC 03

The 850MB analysis for 00Z on 20 DEC 03 (Figure 23) shows this front's nature as it propagates across the coast with its associated theta gradient concentrated in the Northern portion of California. The winds ahead of the front at Cape Mendocino are southerly (coast parallel) and approaching upwards of 50 knots at this level. The model has initialized well in the synoptic analysis and has placed the front where it should be according to the surface observations at this time.

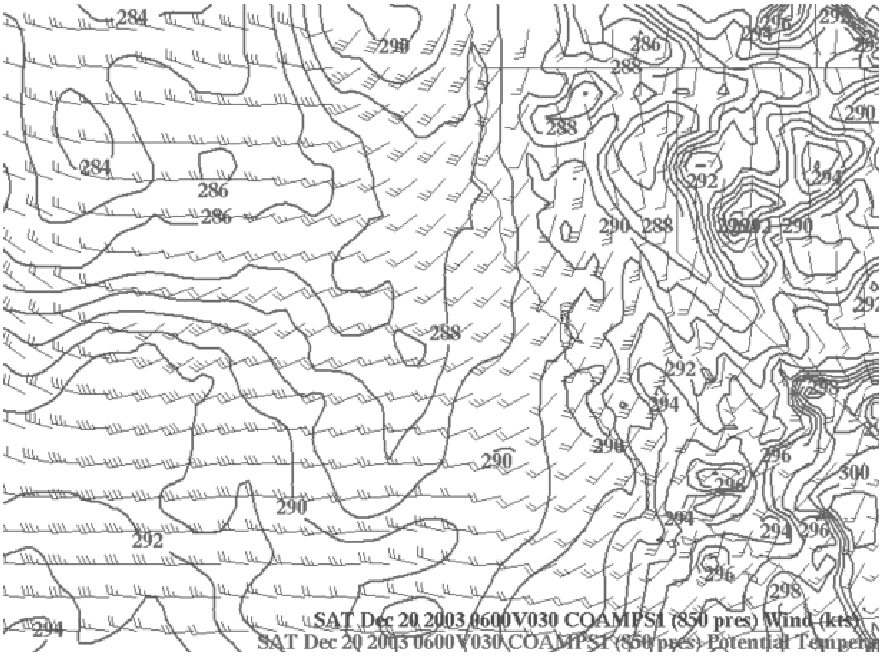


Figure 24. 850MB Theta Winds Analysis 06Z 20 DEC 03

Six hours later the surface front has made landfall and the theta gradient weakens as the front moves inland (Figure 24). The winds across the coast are southwesterly behind the front, which is inland over central California and is oriented in a northwest to southeast direction. This orientation differs from the previous cases in that the front rotates into the coast from a west to southwest direction.

2. Mesoscale Analysis

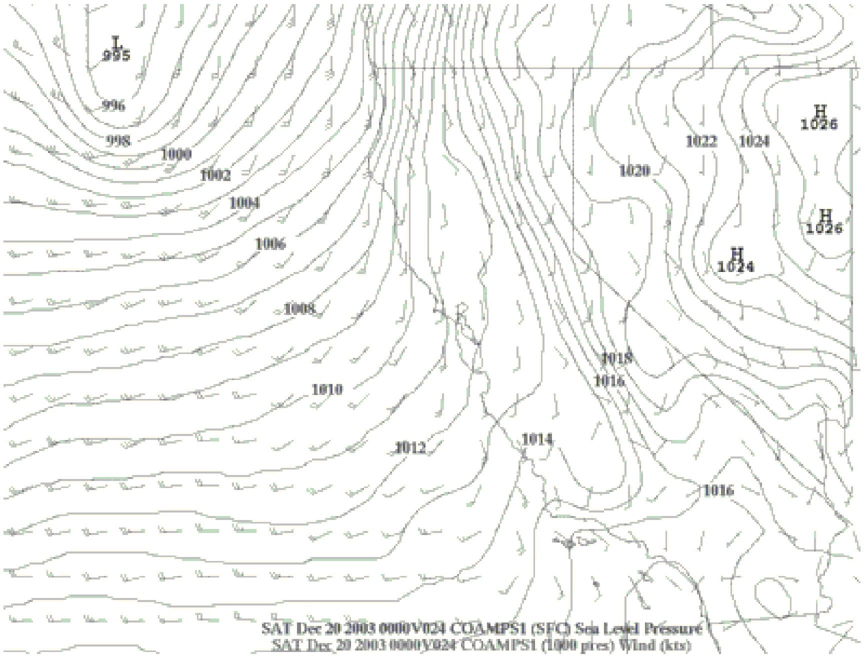


Figure 25. Surface Winds and Pressure 00Z 20 DEC 03

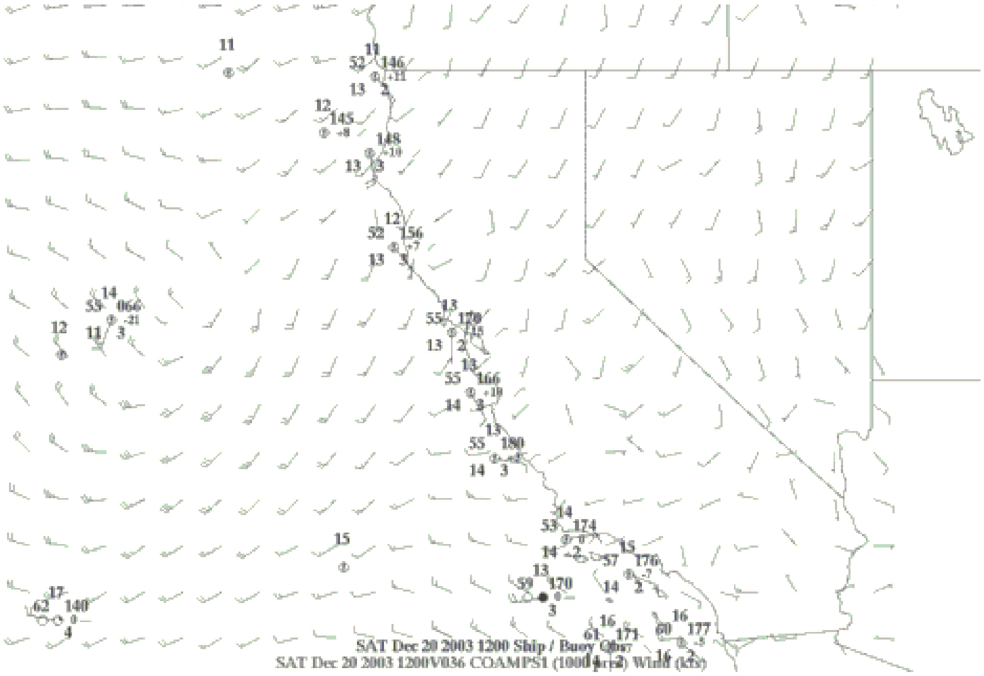


Figure 26. Surface winds and buoy observations 12Z 20 DEC 03

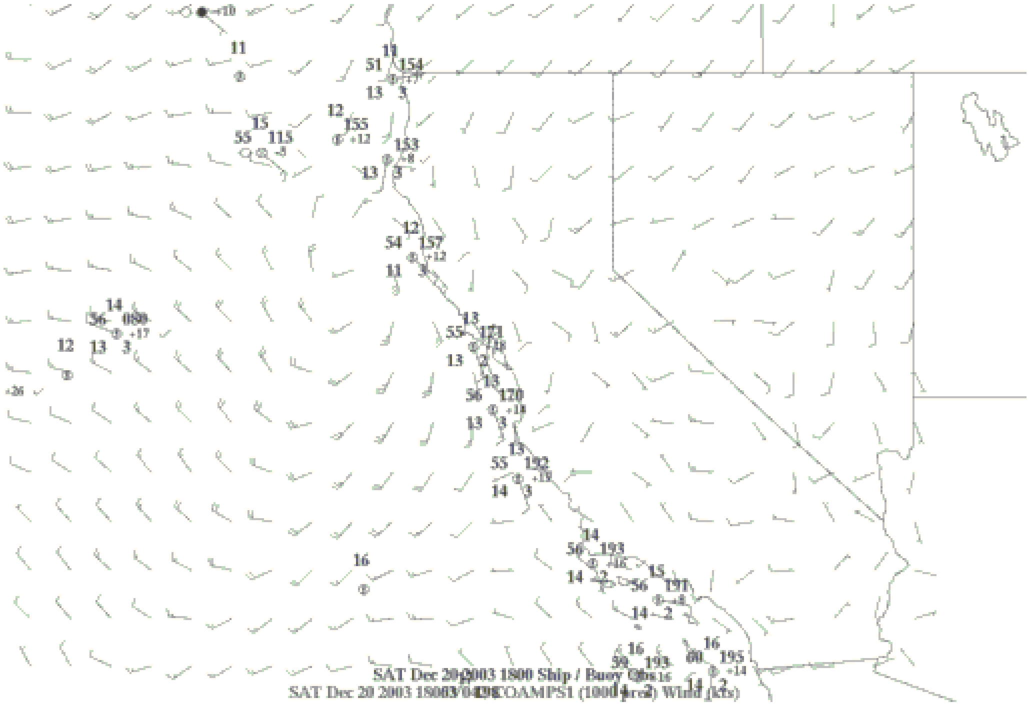
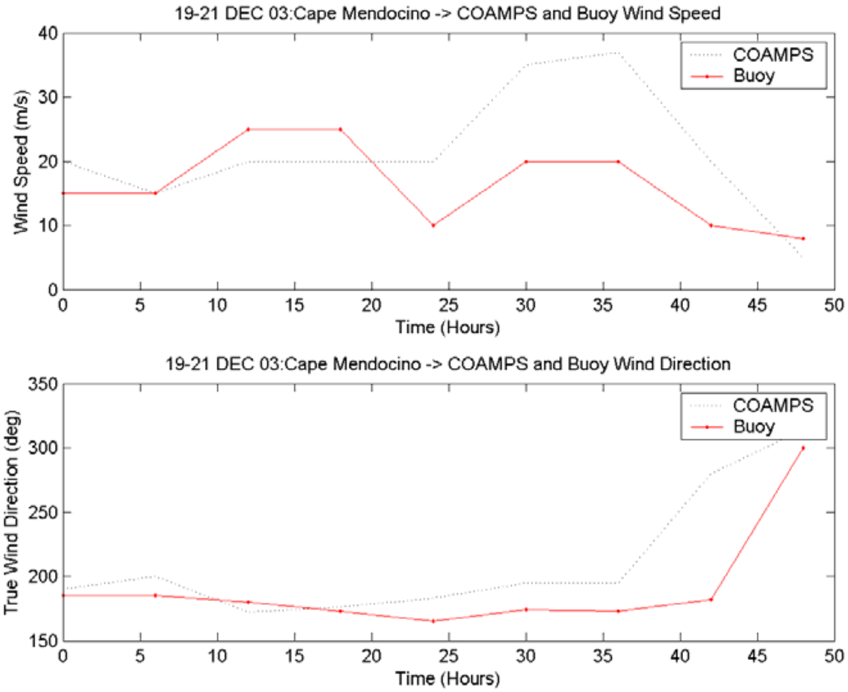


Figure 27. Surface Winds and Buoy observations 18Z 20 DEC 03

The synoptic low associated with the front shown in Figure 25, skirts the Northern portion of the COAMPS area to eventually make landfall in Southern Canada. Its interaction with our points of interest on the coast of California is limited to Cape Mendocino. The mesoscale forecast winds near the cape are similar to the synoptic scale and are southwesterly at 06Z 20 DEC 03 (Figure 26). However, the verifying buoy winds at that time are considerably more along coast in direction. The offshore observation does suggest that the model is moving the front onshore too quickly, which should produce a stronger coastal response in the model than is seen. This suggests that the model winds are not properly responding to the stratification along the coast to capture the blocked flow. This is also representative of our results from the previous two December cases. In this case, it occurs only for Cape Mendocino.

Figure 27 shows the front as it swings into the coast south of Cape Mendocino. The model winds and buoy winds both show southeasterly along coast flow, which is more nearly front parallel than earlier. This suggests that when the frontal forcing dominates over the coastal effects, the model does rather well.


19-21 DEC 03:Cape Mendocino -> COAMPS and Buoy Wind Speed

19-21 DEC 03:Cape Mendocino -> COAMPS and Buoy Wind Direction

Figure 28. Point Reyes Model v. Buoy Time Series 19-21 DEC 03

The time series plot for Cape Mendocino reflects some similar trends in the direction error found for the previous cases. However, the wind speed error is opposite to that seen in the previous cases. In this case, the model wind speeds are higher than the buoy winds suggesting that the model front may be too strong. The model wind speed and direction at tau 20 begins to diverge significantly from the verifying buoy winds. Again, the model winds respond more to the southwest synoptic flow pattern and do not reflect the blocked along coast flow that the buoy verifies to be from a southeasterly direction. There is also evidence to suggest that the model moves the front through too quickly as the model winds begin to shift around to the west several hours before the buoy winds reflect this change. By the end of the time series the model and buoy winds are again in good agreement when the frontal forcing is on top of the buoys as noted above.

Further down the coast between Point Conception and Point Sur we again see the effects of blocked flow. The southwesterly winds flow up against the coast and get blocked flowing south in between the coast and the Santa Barbara Channel Islands.

However in this case, the model has stronger winds than the buoy observations. This may be a reflection of the model front being too strong.

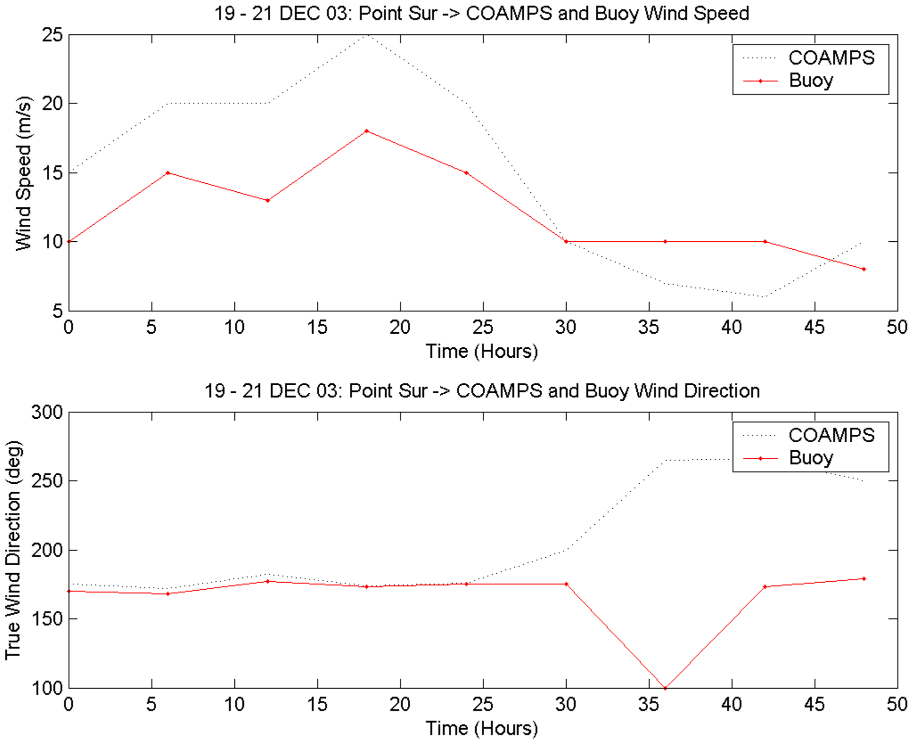


Figure 29. Point Sur Model v. Buoy Time Series 19-21 DEC 03

As the time series for Point Sur (Figure 29) shows, late in the forecast period the buoy winds shift around to between 150 and 120 degrees. This is indicative of blocked flow going north up the coast toward the Monterey Bay. However, the model flow at this time shows a southwesterly flow component consistent with onshore flow that has not been blocked by the topography. This error for the flow is likely due to the model's inability to capture the WAA properly during the later portion of the forecast period. The weak WAA was enough to stratify the lower levels such that the flow would be blocked, however the model did not capture this and the flow was going over the mountains in its wind fields.

D. 7-9 NOVEMBER 2003

1. Synoptic Analysis

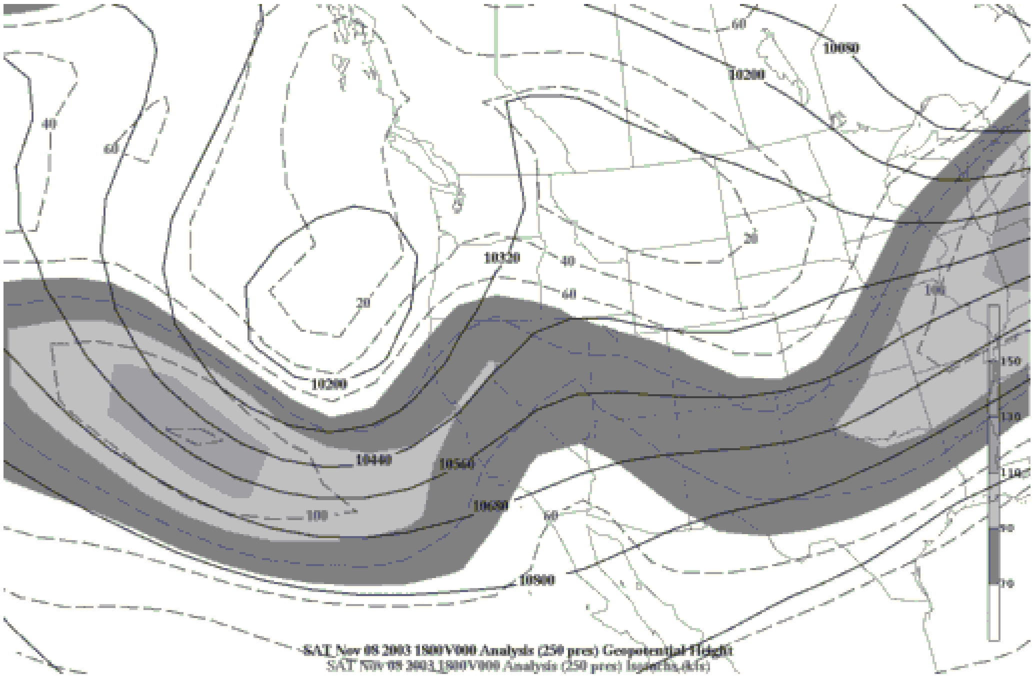


Figure 30. Analysis of 250MB Heights/Isotachs for 18Z 8 NOV 03

Our first look at the synoptic conditions for the 7-9 NOV 03 case shows the Polar Front Jet (PFJ) at 18Z on 8 NOV 2003 (Figure 30). This position of the jet is the result of it moving more south and its flow becoming more zonal over the time from 00Z. The left front quadrant of the jet streak is propagating toward the northeast. There the divergent quadrant begins to help develop the surface cyclone of interest due to increased upward vertical motion. The jet streak stays in the base of the trough to assist in propagating the surface cyclone over the coast. The speed at which the jet streak propagates through a trough helps to determine how much the surface cyclone will intensification will occur within a cyclone. If the divergent quadrant lingers in the area over a surface cyclone the intensification will be more pronounced than if it propagates through quickly. In this case, the jet propagated rather slowly to help maintain a distinct low center through the event.

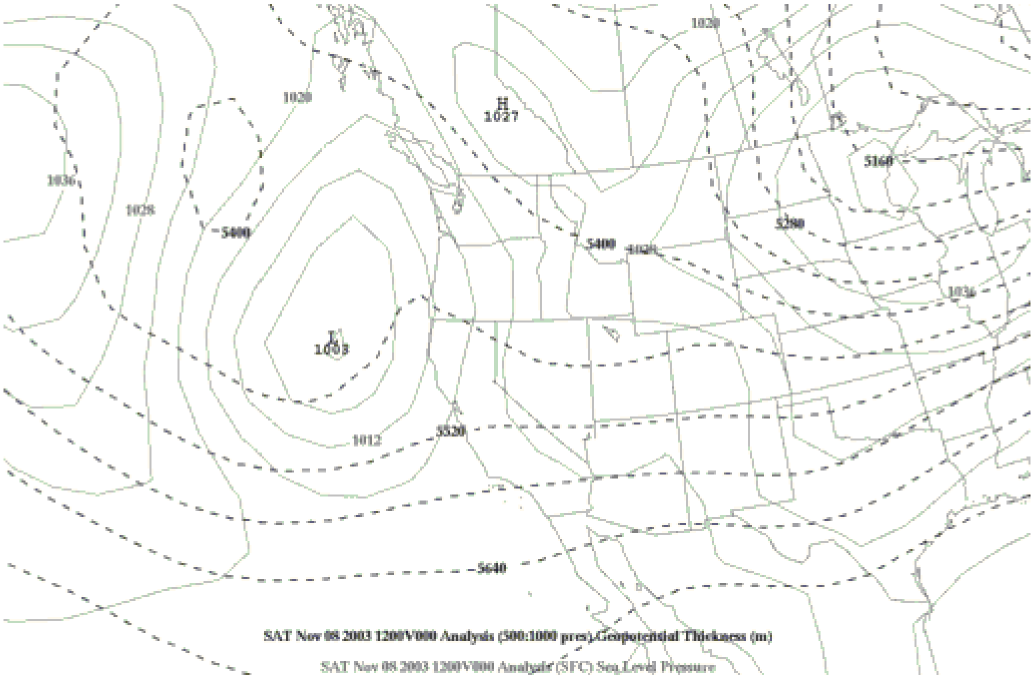


Figure 31. Analysis of SLP and thickness for 12Z 8 NOV 03

On the surface, the 250MB upper level synoptic forcing is reflected as a surface low off the Northern California coast (Figure 31). The jet streak to the south (Figure 3) moved northeast and developed this low over the previous 12 hours. By 06Z 9 NOV 03 (Figure 32) the surface low has moved slightly north easterly and the trailing cold front is rotating into the California coast. Pre-frontal winds are readily felt along the California Coast by this time. The low does not deepen any further after 06Z 9 NOV 03 and eventually begins to fill before it moves onshore, after 12Z 9 NOV 03.

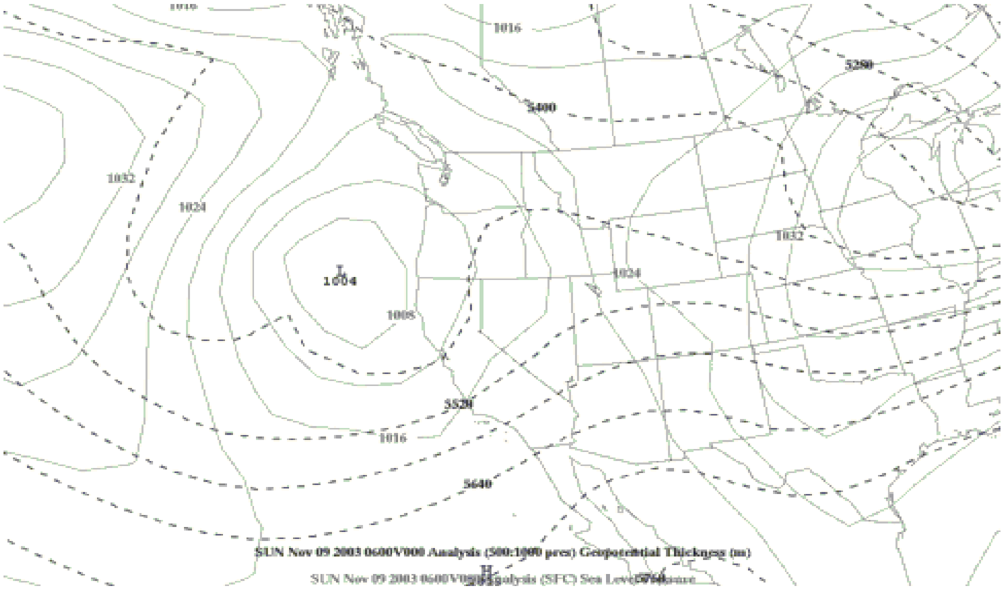


Figure 32. Analysis of SLP and thickness for 06Z 9 NOV 03

Between 06Z and 18Z on 9 NOV 03 the surface cyclone continues to steadily propagate to the southeast. Since it is not moving quickly, the effects of its large scale southwesterly flow along the coast to the south of the flow also linger longer than other faster propagating storms. The cyclone continues to spin just offshore throughout the rest of the event until it fills. The effect of the cyclone loitering in this manner is that it makes its forcing a factor in the mesoscale for a longer period of time, but no more intense due to the fact it has stopped deepening. By 9 NOV 03 18Z it has filled 4MB and ceases to be a closed circulation.

2. Mesoscale Analysis

This case for early November illustrates what happens when a synoptic low pressure system meanders in a somewhat quasi-stationary fashion before its associated frontal boundary comes ashore. As the front does not definitively make a rapid trek across the coastline, the model wind field interaction with the topography varies throughout the period. The model never gets a solid position on the synoptic low or its associated frontal boundaries, which is evident by the poor agreement between the offshore buoy observations and the model in Figure 33. The effect of the meander of the low center is the speeding up and subsequent slowing down of the winds as it shifts position back and forth toward the coast. This continues until the frontal boundary makes its way across the coast line around 12Z 9 NOV 03. The aggregate effect of this misplaced front is that the model inaccurately forecasts all the mesoscale along coast wind effects. Since the synoptic pressure features are misplaced, their mesoscale influence is also misforecast.

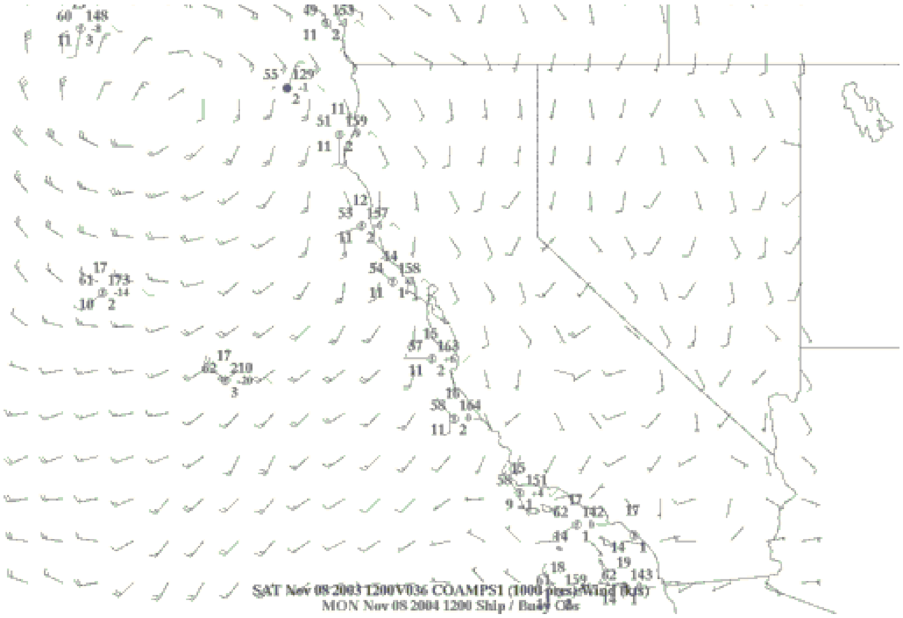


Figure 33. Winds and Buoy Observations 12Z 8 NOV 03

At 12Z on 8 NOV 03 (Figure 33), the front in the model begins to make its way across the coast toward the Cape Mendocino area of interest. This is the point in the time series at which the low pressure center begins to make its way toward the coast after a period of quasi-stationary meandering in the Eastern Pacific. The along coast winds in the model at the Cape show a 20 knot flow where the corresponding buoy observation shows only a 10 knot flow. Both agree with a steady wind direction from the south at this time.

At the Point Reyes, location the along coast flow is still under the influence of the synoptic scale southwest forcing. Both the model winds and the buoy observation (not plotted) are in agreement at this tau (Figure 33). Further down the coast at Point Sur, the flow is also reflective of this broad synoptic swath of air being guided cyclonically around the low. Both the flow and the low level WAA are weak in this area. The Froude numbers generated by this onshore flow are well below 1 so there is slight flow blocking as the winds travel south along the coast, but at a slogging pace of 5 to 10 knots.

Further south still in the Point Conception area, the frontal boundary is not playing a significant role in the wind flow regime. It is too far away from the central low pressure and the frontal boundary. The flow is weak and variable being controlled by the northernmost boundary of the East Pacific High.

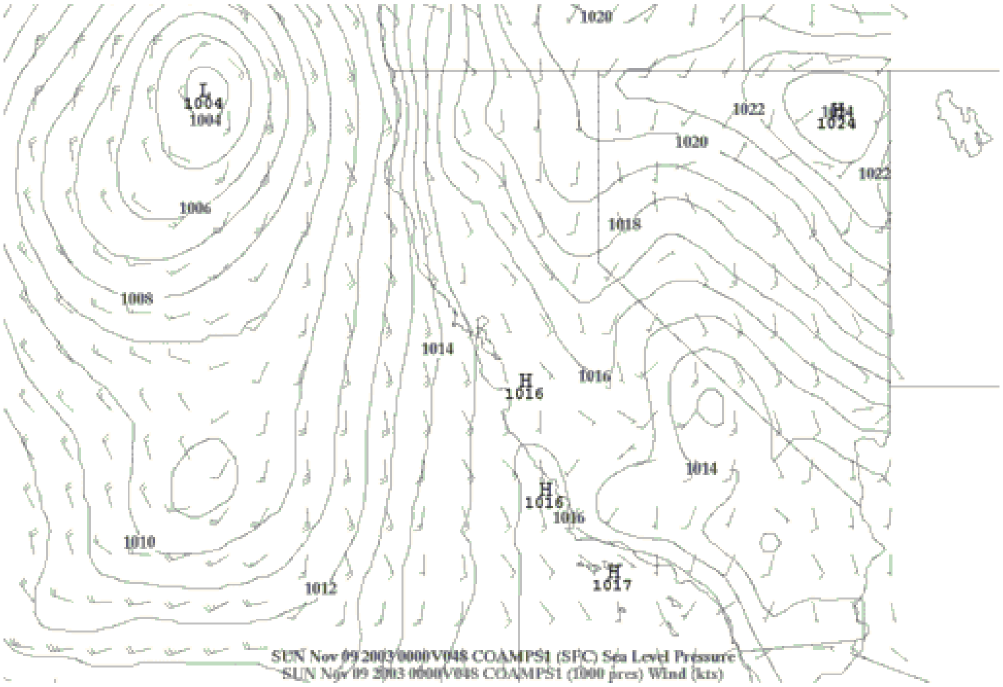


Figure 34. Model Winds and Pressure 00Z 9 NOV 03

By the end of this case's time series at 00Z 9 NOV 03, the frontal forcing in the model is at a maximum affecting the along coast winds (Figure 34). The model shows rather strong south easterly flow along the coast. This flow is parallel to the front, which positioned offshore and parallel to the coast in the model. However, as seen in Figure 35 the verifying buoy observations for the model forecast in this case show large differences in both the coastal and offshore winds. The buoy observations all along the coast of California show flow that is indicative of a weak onshore flow. Such flow "piles up" air mass along the mountainous coast and should split both north and south along coast when the flow is blocked. However, the buoys suggest that the flow is not blocked in this case and that the model has very poorly forecast this event in its later stages. Consequently little can be said about how the coastal interaction is handled by the model at tau 48, when its overall synoptic forecast is so far off.

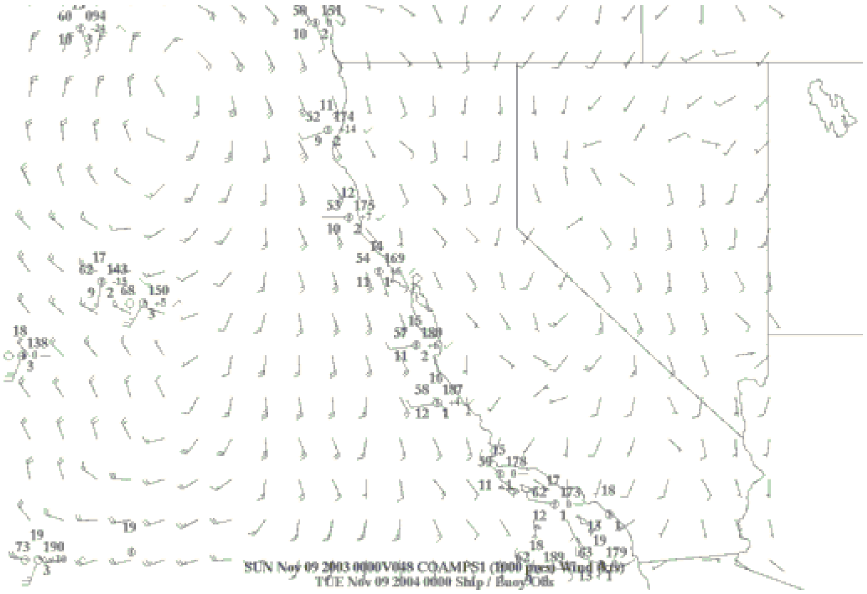


Figure 35. Model Winds and Buoy Observations 00Z 9 NOV 03

E. 14-15 NOVEMBER 2003

1. Synoptic Analysis

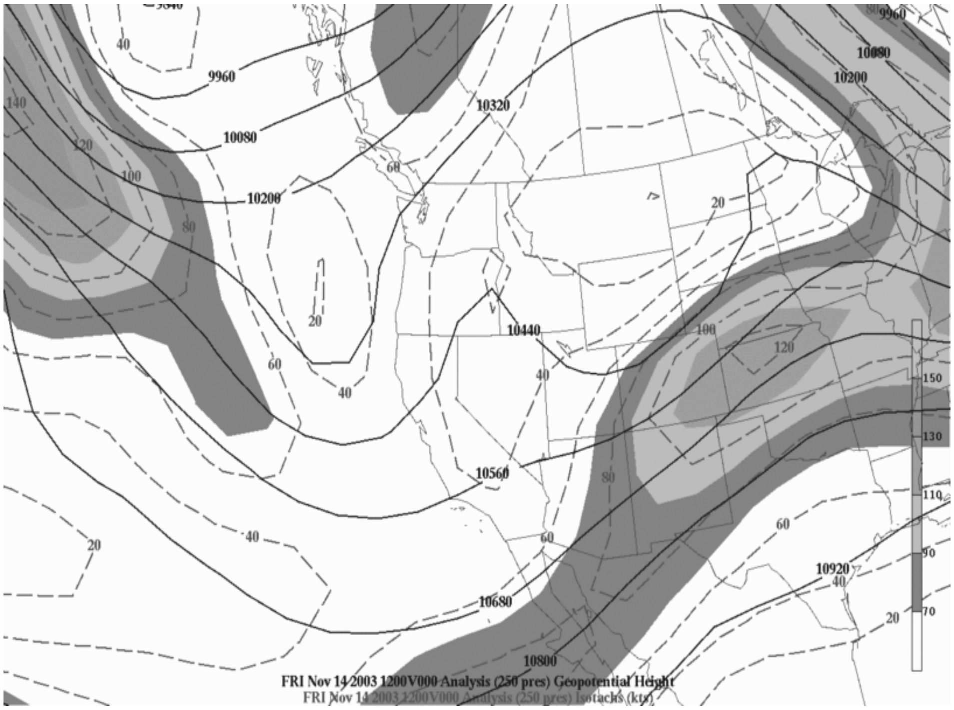


Figure 36. Analysis of 250MB Heights/Isotachs for 12Z 14 NOV 03

The position of the PFJ in Figure 36 shows the characteristic forcing at 250MB that sets the stage for this case. The jet's flow is broken into two branches one in the southeast and the other in the northwest pattern of the trough. Throughout the event, the jet streak to the northwest propagates to the southeast. Since the jet streak travels quickly through the trough aloft, it does not provide much additional forcing to intensify the surface cyclone. The cyclone in this case is weak compared to the other cases and propagates quickly through the areas of interest. Like the previous case, the frontal position gets misplaced from the initialization and beyond.

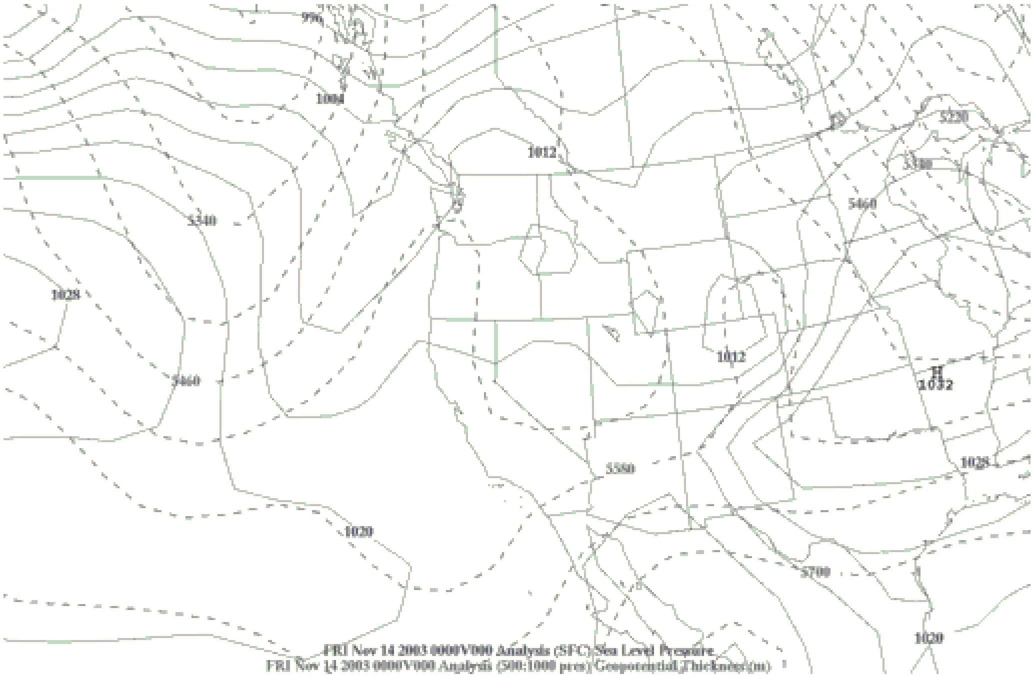


Figure 37. Analysis of SLP and thickness for 00Z 14 NOV 03

At the surface (Figure 37), we see the weak synoptic forcing offered by this cyclone. The center of circulation for the low is well northwest of the California coast at 00Z 14 NOV 03. Effectively the coast is seeing the effects from the southern end of the weak cold frontal boundary as the cyclone propagates eastward. Figure 38 shows the front continuing to weaken as it approaches the coast at 12Z 14 NOV 03. The combined synoptic effects of the jet streak moving quickly through and the synoptic scale low pressure system positioned north of California combine to make the forcing for this case unusually weak compared to the other cases.

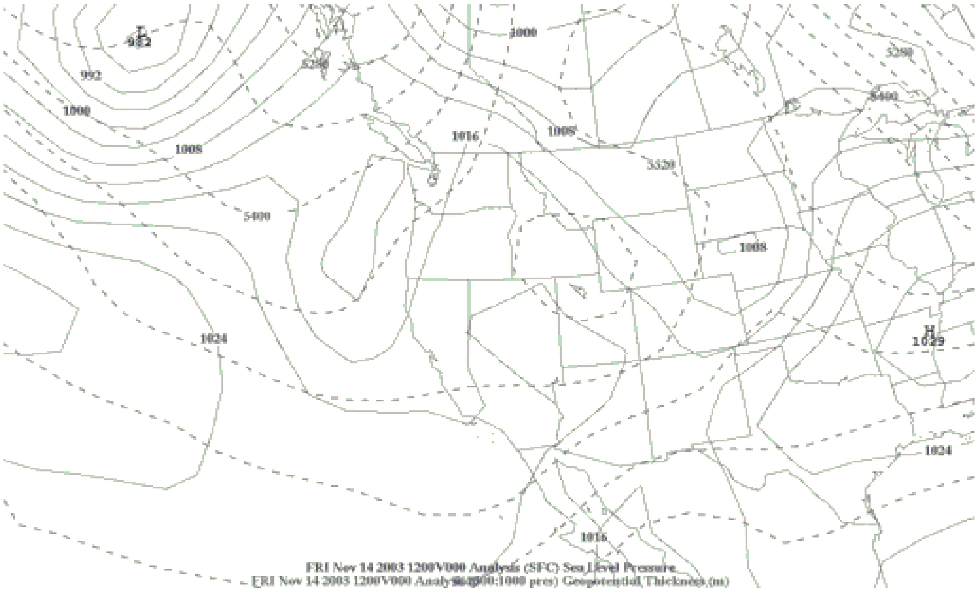


Figure 38. Analysis of SLP and thickness for 12Z 14 NOV 03

2. Mesoscale Analysis

The 13-15 NOV 03 case is characterized by a weak north south frontal boundary and no real low pressure system as the front makes land fall at 12Z 15 NOV 03 (Figure 39). The model has a great deal of trouble properly placing this system and it propagates too slowly in the model. This incorrectly forecast synoptic low causes the mesoscale features to be misplaced as well. This is best exemplified in this case by the model winds and buoy observation at 18Z shown in Figure 40. The flow at the buoys is northerly all the way down the coast. This is indicative of the high pressure system behind a low that has already propagated through. The model in this case did not move the front fast enough through the area of interest, and consequently the model winds in Figure 40 are still southerly over much of the California coast. As a result of this poor synoptic forecast, the mesoscale features were also improperly forecast.

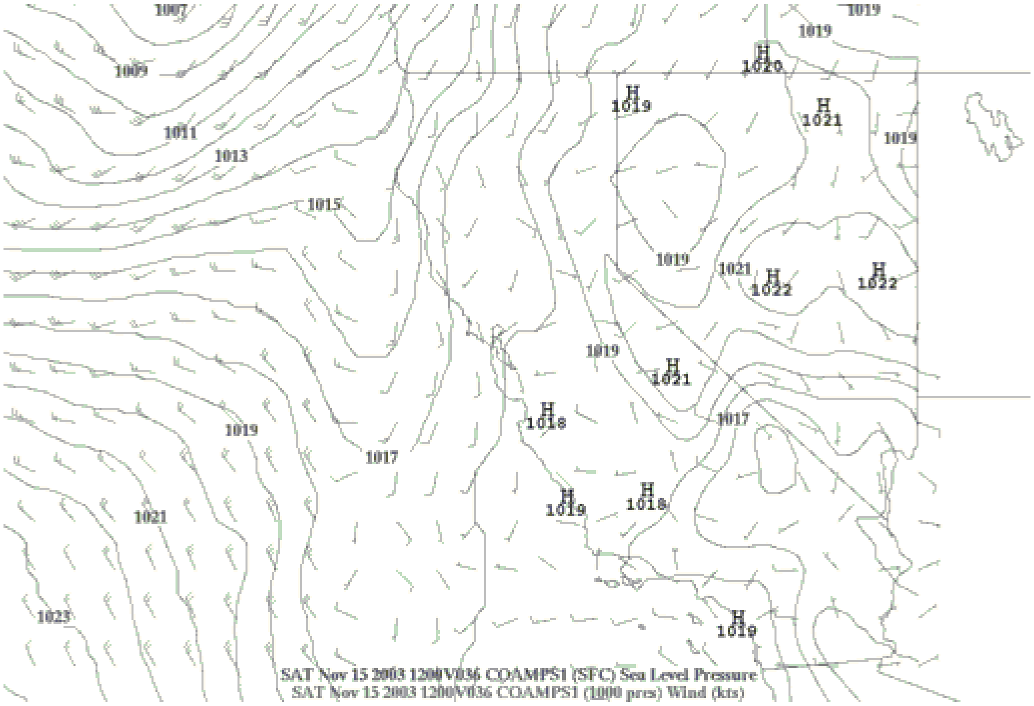


Figure 39. Model Winds and Pressure 12Z 15 NOV 03

The model forecasts for 12Z and beyond on 15 NOV 03 show rather weak coastal winds as the front and weak pressure trough cross the coast. The buoy winds are generally stronger and from the opposite direction due to the poor model forecast of the frontal passage. Again, little can be definitively concluded about the coastal interaction in this case.

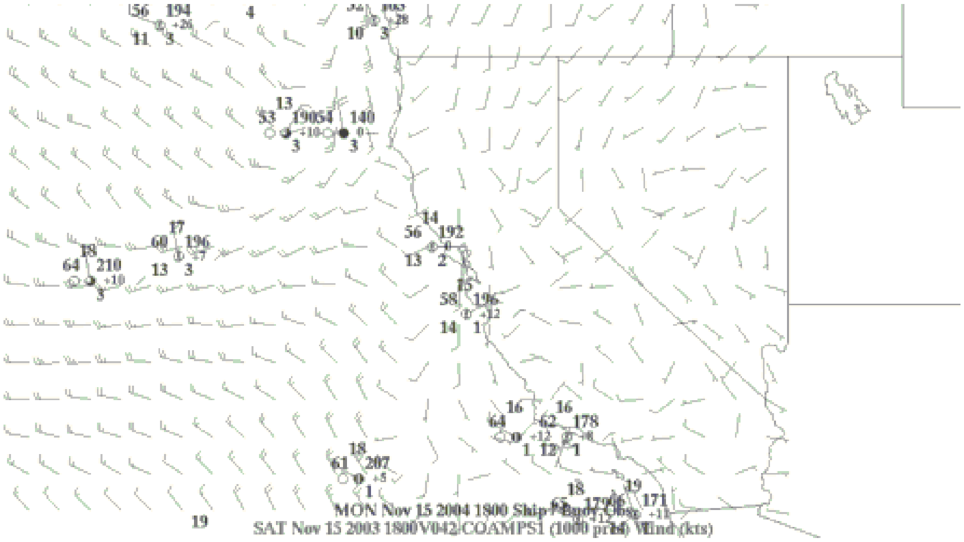


Figure 40. Model Winds and Buoy Observations 18Z 15 NOV 03

F. 18-20 NOVEMBER 2003

1. Synoptic Analysis

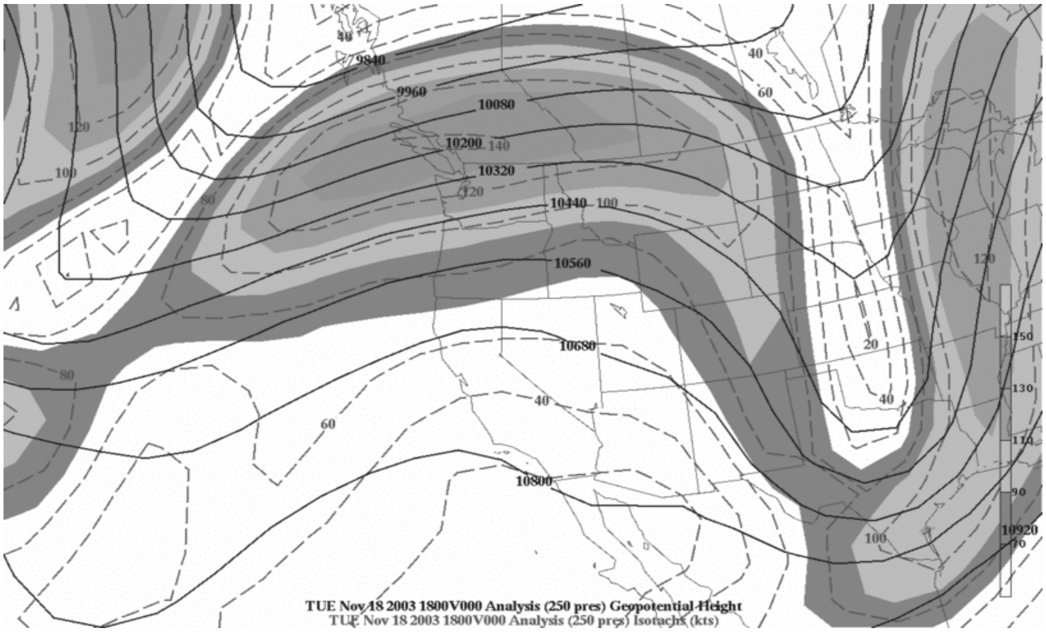


Figure 41. Analysis of 250MB Heights/Isotachs for 12Z 14 NOV 03

The 250MB height and Isotachs for 18Z 18 NOV 03 (figure 41) show the jet streak is just north of the California coast. The right rear quadrant of the jet is influencing the low pressure system and front that are moving toward the western coast of North America. The flow of the jet in this case is zonal for most of the time series. By 06Z on 20 NOV 03, the large jet streak has assumed a northeast to southwest orientation as the trough offshore moved to the southeast. When aligned in this manner it assists in the deepening of the surface low and its frontal boundaries, thereby enhancing the fronts and their interactions with the topography as the front makes landfall. This case provides the strongest frontal boundaries of the November cases.

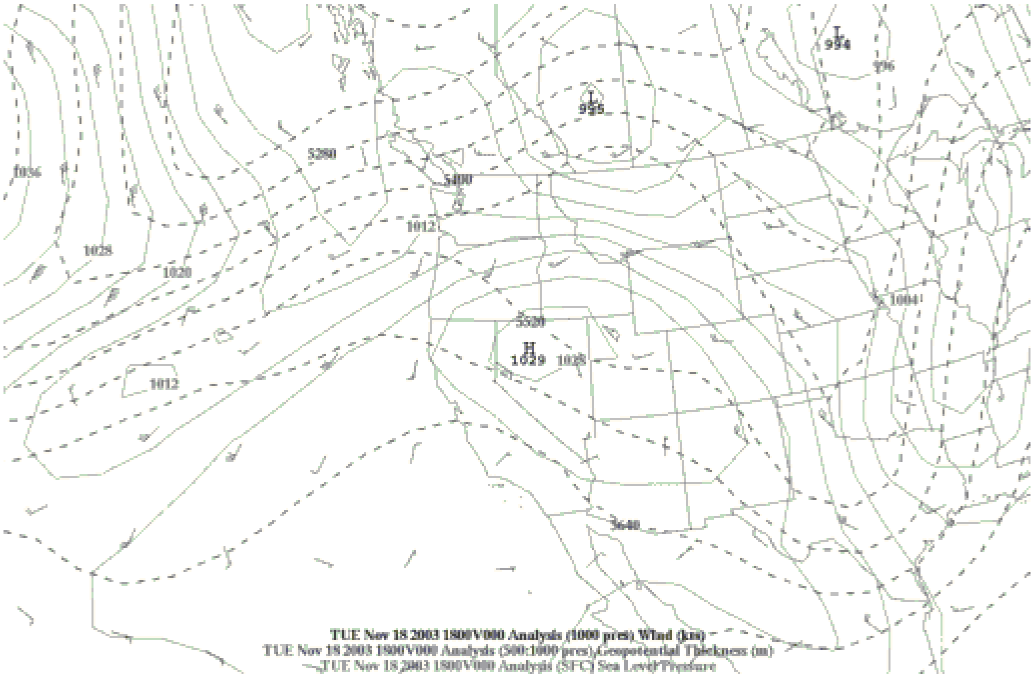


Figure 42. Analysis of SLP and thickness for 18Z 18 NOV 03

The surface cyclone is to the north of the California coast and its frontal boundary is descending upon the coast from the northwest (Figure 42). The warm air advection (WAA) ahead of the front is not as strong as the December cases, but it is present, and covers a large area. At upper levels, the trough behind this surface advection provides a weak baroclinic structure. To the south, the anti-cyclonic rotation around the high over the desert southwest dominates provides a persistent offshore flow over south central California.

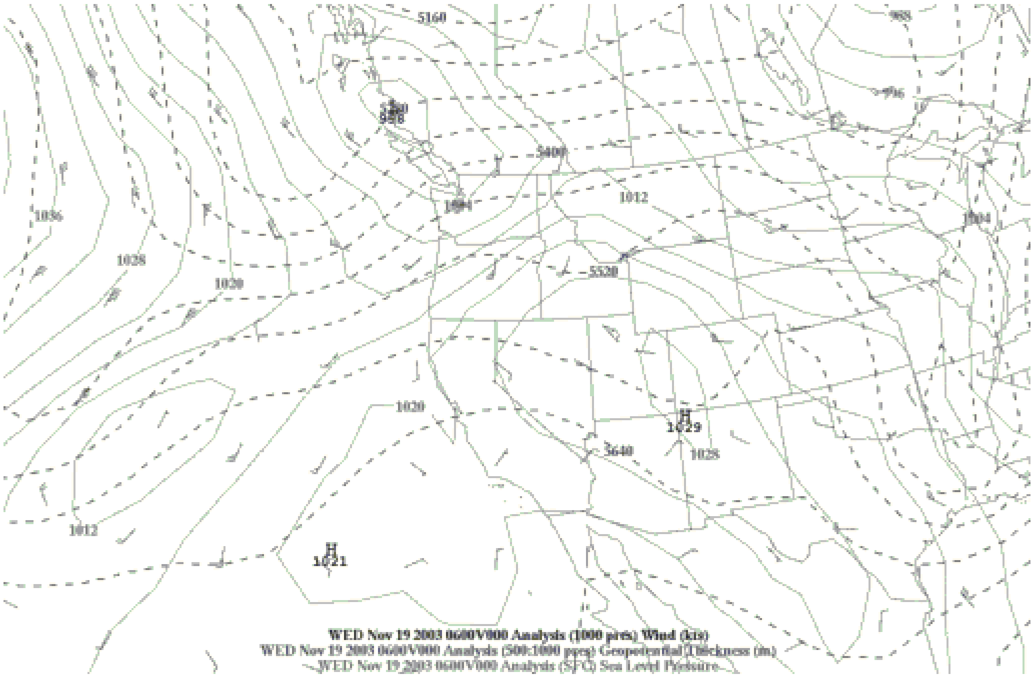
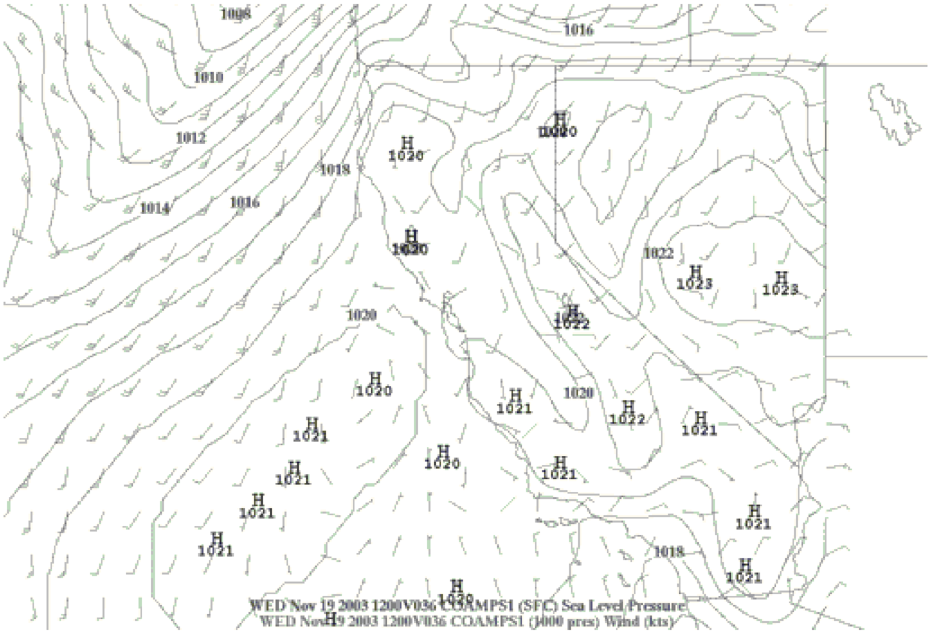


Figure 43. Analysis of SLP and thickness for 06Z 19 NOV 03

By 06Z on 19 NOV 03 (Figure 43), the front had advanced near the coast in Northern California. This is the beginning of the frontal winds affecting the coast. By 18Z on 20 NOV 03 the cyclonic flow ahead of the front is making its presence felt along the coast as far south as south San Francisco Bay. In the mesoscale, as the front moves closer to the coast a persistent along shore flow in both north and south directions occurs along the coast throughout most of the forecast period.

2. Mesoscale Analysis

The mesoscale flow develops due to two large synoptic scale features. The first is the large scale synoptic flow associated with the low pressure system and associated front approaching the coast from the northwest. The second is the large high pressure in the southeastern pacific that retreats southward as the low propagates across the coast to make land fall just north of the Cape Mendocino area of interest. The combined effects of their opposite rotational flows provide for constant along coast wind forcing in both directions throughout the duration of this case.



WED Nov 19 2003 1200V036 COAMPS1 (SFC) Sea Level Pressure
WED Nov 19 2003 1200V036 COAMPS1 (1000 pres) Wind (kts)

Figure 44. Winds and Pressure Winds 12Z 19 NOV 03

At 12Z 19 NOV 03 (Figure 44), the set up for possible blocked flow winds is evident in the model fields with southwesterly wind beginning to occur over the California coast. However, as the buoys show in Figure 45, the model has improperly placed the synoptic features. The verifying buoy observations at this time show a northerly flow all the way down the coast at each point of interest; this is consistent with a mesoscale wind flow around the high pressure system behind the surface low. However, the model has moved the surface front along too slowly, and the result is model winds still from the south which again shows a poor forecast on both the mesoscale and the synoptic scale.

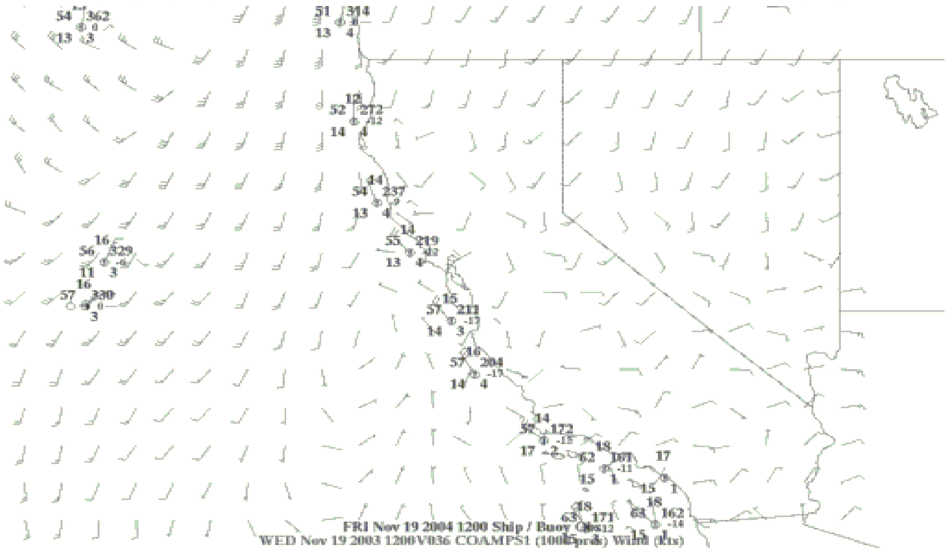


Figure 45. Winds and Buoy Observations 12Z 19 NOV 03

In this case, as well as the other November cases show, the COAMPS model forecasts for weak cold fronts were often be substantially in error due to timing and intensity differences. These larger-scale forecast errors prevent making any assessment of the manner in which COAMPS handles the coastal interaction. The model wind fields tend to show coastal signatures similar to the stronger, more accurately forecast events from December. Given the character of the model errors for the coastal winds in December, it is certainly likely that weaker fronts may show similar tendencies to underforecast the pre-frontal flow blocking and coastal wind direction.

V. RESULTS AND RECCOMENDATIONS

A. RESULTS

This study set out to examine COAMPS forecasts both pre and post frontal winds in the presence of the California coastal topography. Hypothesized models of wind interaction with coastal topography were used in an attempt to explain the unique mesoscale wind regimes that result from these interactions. When the coastal wind forecast was found to be in error when compared against the verifying buoy observations, an investigation was made to look at why the model failed to properly capture these events.

Generally speaking, the model performed better than the author believed it would when beginning the study. This line of thinking was influenced by the author's previous professional experience with COAMPS. However, there are some specific deficiencies and strengths in model performance that were noted during the analysis. Some of these model tendencies are best illustrated within the context of the conceptual models used to explain the wind flow. The others are explained within the context of how the COAMPS model itself processes its simulated atmosphere and represents the real world topography.

1. December Case Issues

The common forecast problem encountered during the December cases was the forecast lag encountered when the cold frontal boundary was close to the coast and about to make landfall. As the along coast pressure gradient increased with the encroaching cold frontal boundary, the winds along the coast would shift and increase in speed in line with the hypothesized interaction outlined in chapter three. However, it was observed that the model would have the tendency to not adjust for this wind acceleration or reorientation of the wind in a purely along coast fashion as quickly as the buoys observed. For most cases the winds in the model would still be responding to the southwesterly synoptic flow between 185 and 200 degrees, while the buoys showed southeasterly along shore flow.

With these incorrect forecast events in mind, the question becomes why did the model fail to accurately depict this coastal interaction? The first likely answer lies in the way the topography is modeled. The COAMPS model uses the Digital Terrain Elevation Data (DTED) data base to represent its terrain. This terrain database is a high resolution (100 Meter) terrain database, but it is not a perfect representation of the actual complex coastal topography of California. Also, DTED must be re-sampled to fit the model grid spacing, resulting in even more "approximated terrain" height values. The COAMPS uses a silhouette terrain method that preserves the terrain height better than would averaging, but some of the slope of the model terrain is more gradual than reality. As in most mesoscale models, there is no subgrid roughness parameter. These discrepancies between the model representation of the terrain at 27 kilometers and the actual terrain could be the cause of error. If the terrain is seen by the model as too 'smooth' compared to reality, then the model might have the flow go over a mountain top where in reality the low-level stratification would block the flow to turn the flow north or south for a steeper mountain slope.

A second possible source of error is that, in these areas far from the central low pressure forcing of the front, the strong warm air advection is not adequately captured. If the model's thermal advection is too weak then it would tend to slow propagation and reduce stratification ahead of the front. This reduced stratification could affect the model wind field forecast. The inaccurately forecast stratification could cause the model to not properly capture whether the flow should be blocked, or be allowed to propagate over the mountain tops.

The reason why the model does not perform as well in the blocked flow case is likely a combination of both factors of topographic resolution and temperature advection forecasting. Further study is required to determine which is more important in contributing to the model error along the coast. A more accurate WAA forecast and better data assimilation/observational availability could be helpful in this case.

2. November Case Issues

The November fronts also suffered a common difficulty. That is the initial synoptic position of the low pressure center and their fronts were not accurately placed at the analysis time, or subsequent forecast times. Since this was the case, it became impossible to discern the along coast wind events conceptualized in this study. The solution for this issue lies with continued improvement in data assimilation and/or improved observation networks.

B. RECOMENDATIONS FOR FURTHER STUDY

The sample of wintertime frontal passages investigated in this study represents many varied conditions that can occur when the wind and topography of the California coast interact. Many of the initial findings of this study could be expanded upon with the following approaches.

First and foremost, a larger sample size is recommended to be able to acquire some meaningful statistics on the individual wind events at different points along the coast. With such data, statistics could be analyzed to obtain model biases for the wind field. This information could then be expanded to be published as model tendencies to aid operational users to better utilize the tools that the model brings to aid in the challenge of forecasting mesoscale meteorological phenomena.

Second, the COAMPS data evaluated in this study had a resolution of 27 kilometers. This was the operational resolution that FNMOC was running at the time of these frontal events. It would be advantageous to see how an increased resolution version of the COAMPS model (such as 1 to 3 kilometers) could improve the forecasts of the finer scale wind events. Also, it would also be of use to see how increasing the update speed of the data assimilation cycle would assist in forecast improvement and eliminate the forecast lag. The data update cycle used in the Rapid Update Cycle (RUC) run by the National Centers for Environmental Prediction (NCEP) model is an example of a faster update cycle that could alleviate some of the issues found in this study.

Third, running the fields with an improved higher resolution topography database would be worthwhile in assessing what effect that would have on the model's performance in the cases where the blocked flow events were not properly modeled. This study showed that interaction with the mountainous terrain played a significant role in determining whether the wind flow was going to propagate over the mountain tops or be turned to an along coast flow. Thus, it is imperative to model the topography as closely as possible to achieve a realistic forecast.

Finally, it is worth noting that this study would also be helpful to perform in other areas of the world. The western coast of the United States is an area where there is abundant observational data to help forecasters compensate for expected model errors. Study in other regions would help Department of Defense (DoD) forecasters generalize these results into useful forecast aids for areas new to them or with a much less complete observational data record.

Upstream of the coast, is a data sparse regime over the Pacific Ocean. A better observing network or a better data assimilation system over the large data sparse regions could help alleviate some of the issues the model has placing mid-latitude cyclones and their frontal boundaries. With such improved systems, the initial synoptic scale model forecasts could be made better, this could aid the issue the November cases in this study had with placement of the synoptic scale features. However, it would likely not correct all of the mesoscale responses. This is due to the fact that the model grid resolution is still at 27 kilometers, and the observations are interpolated to those values. The small scale along coast wind interactions are well within those 27 kilometer limits and as such would not benefit from those interpolated observations in many cases.

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