1B.2 Simulation of a North American Monsoon Gulf Surge Event

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1. INTRODUCTION

The North American Monsoon (NAM) is considered a “true” monsoon by nearly all authors (Adams and Comrie 1997). It has the typical characteristics of a monsoon, a seasonal wind reversal, and areas receiving a significant portion of their annual precipitation during the NAM (Adams and Comrie 1997; Johnson et al. 2007). Higgins et al. (1999) show a mean onset date starting in early June around 15^{o}N progressing northward into Arizona by mid July. Retreat of the NAM then begins to occur in late September and progresses back down the Mexican coast into October (Vera et al. 2006).

Moisture is provided to the NAM through the Gulf of Mexico (GoM) and Gulf of California (GoC). It is generally believed that the GoM provides upper-level moisture to the NAM through E to SE mid to upper level flow into the NAM region (Adams and Comrie 1997). The GoC provides moisture through the nocturnal low level jet (LLJ), gulf surge events, sea/land breezes and the mountain circulation around the Sierra Madre Occidental (SMO) (Hales 1972; Brenner 1974; Douglas et al. 1993; Adams and Comrie 1997; Berbery 2001; Fawcett et al. 2002; Vera et al. 2006). Gulf surge events are critical transient events in the NAM region because they have been linked to precipitation anomalies during the NAM (Gochis et al. 2004; Higgins et al. 2004) and possibly severe weather in Arizona (Maddox et al. 1995).

The North American Monsoon Experiment (NAME) took place from 1 June- 30 September 2004. This field experiment produced an unprecedented number of observations of the core NAM region during the monsoon season. Two strong surge events (as defined by the criteria of Higgins et al. 2004), one on 12-14 July and the other 22-24 July, occurred during the NAME. The 12-14 July event was the subject of an in-depth observational analysis by Rogers and Johnson (2007), RJ2007 hereafter. Figure 1 shows the NAME region along with important geographical features, locations and cross section lines used later.

On 12 July 2004 at 12 UTC an upper level inverted trough (IV) was centered just west of the SMO. During the next 36 hours the IV moved slowly to the NW and weakened. Also at 12 UTC 12 July a tropical depression was positioned at 14.6 N and 105.5 W. This depression strengthened into tropical storm Blas by 18 UTC and tracked NW through 00 UTC 14 July. The circulation of Blas influenced the GoC on 13-14 July. Besides these two features of note, extensive convection formed several clusters along the entire SMO from about 21 UTC 12 July through 09 UTC 13 July. Convection formed again along nearly the entire SMO during late afternoon/evening of 13 July.

This work examines this surge event using WRF and compares the simulation to the observational analysis of RJ2007. Furthermore, the model simulation provides the opportunity to perform a detailed analysis of the surge event parlayed with a strong understanding of the short comings and strong points of the simulation from observational comparisons.

2. MODEL SETUP

The Weather Research and Forecasting (WRF) Advanced Research WRF (ARW) version 3.1.1 was used for the simulation. The model was configured with one domain with a horizontal resolution of 4 km, shown in Figure 1. A stretched vertical grid having 55 levels with more levels near the surface was used. The domain encompasses the entire GoC and SMO along with the Baja Peninsula. This allows for explicit simulation of convection along the entire SMO and GoC. The Yonsei University (YSU) PBL scheme (Hong et al. 2006), Monin-Obukhov surface layer and Noah land surface model were used for surface through boundary layer parameterizations. The single moment version of the Thompson et al. (2004) scheme was used for the microphysics parameterization.

Initial and boundary conditions were supplied by 6-hourly GFS analysis and the model was run from 06 UTC 11 July to 00 UTC 14 July 2004. Analysis will start at 06 UTC 12 July, giving the model 24 hours of spin-up time to generate appropriate mesoscale circulations not captured by the GFS analysis. After the 24 hour spin-up a check of the large-scale patterns revealed the model was capturing the important features well.

3. SIMULATED SURGE DESCRIPTION

The simulated surge event began in the south-central GoC on the evening of 12 July (not shown). The initial surge event seemed to be triggered by

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afternoon/evening convection along the SMO. This convection developed a cold pool along the coastal plain near and just north of Los Mochis by 0130 UTC 13 July. Note, the locations of the three ISS sites (Los Mochis, Kino Bay and Puerto Penasco) are shown in Figure 1. The main thrust of the cold pool was to the W through NW with a background flow in the GoC from the SE at around 4-6 m s^{-1}. The cold outflow progressively moved over the GoC and was deflected more toward the NW, along the GoC, with the Peninsular Ranges acting as a western barrier.

Between 02-08 UTC, convection continued to propagate to the NW along the coastal plain, producing a continual inland cold pool (not shown). By 0900 the convection had nearly dissipated and nearly all surface signature of the cold pool dissipated by 10 UTC. It is interesting to note that throughout this time period the cold pool is nearly confined to within the coastal plain, there is essentially no near surface (first sigma level, ~41 m) potential temperature perturbation over the GoC. During this phase it appears that the cold outflow from the convection continually builds a perturbation feature over the GoC while being modified in the near surface layer.

By 07 UTC, this feature was quite prominent as can be seen in Figure 2. Figure 2 displays the third sigma level (216 m AGL) wind vectors and first sigma level (41 m) surface potential temperature. From this, one can see the lack of a negative potential temperature signature associated with the initial surge feature over the GoC. A prominent cool anomaly appears only over the coastal plain associated with the convective outflow. Again it appears the convective outflow was deflected to the NW by the background flow and Peninsular Ranges. Over the course of 3-6 hours, the Coriolis force should have had some impact on deflecting the outflow to the NW as well.

The surge appears to be some type of solitary Kelvin wave as it moves through the northern GoC, which will be explored in more detail in section 5. While the surge is propagating through the northern GoC it is enhanced by the GoC LLJ. The GoC LLJ maximizes from around 06 to 16 UTC (Douglas et al 1998), which coincides with the arrival of the initial surge in the northern GoC. By 14 UTC the surge front has propagated through Yuma, AZ (not shown). The initial surge decays as it spreads out into southern Arizona. Throughout the rest of the GoC, SE flow is evident, primarily from the influence of tropical storm Blas, located near 113^{o}W, 19^{o}N (Fig. 2).

The boundary layer deepens and cools as the surge passes sites in the northern GoC. Along the northern GoC coast and southern Arizona it is also associated with an increase in moisture. Figure 3 shows a time series from the grid point nearest Yuma, AZ, while Figure 4 shows a sounding from before and after surge passage at the same grid point (12 and 15 UTC). The time series shows a sharp increase in dew point temperature around 02 UTC and again at 13-15 UTC. The increase around 02 UTC is associated with convective outflow from the evening convection along the northern SMO, while the increase in dew point from 13-15 UTC is associated with the surge event. Modeled dew points remain slightly elevated and surface temperatures suppressed throughout the remainder of 13 July. Also, a 6 mb pressure rise occurs at Yuma beginning after surge passage (around 13 UTC) with no noticeable temperature decrease.

Figure 4 shows that the low level cooling associated with the surge maximizes around 950 mb, with around a 5 K decrease in temperature. However, surface temperatures remain essentially unchanged. Slight cooling extends up to approximately 800 mb with moistening up to 900 mb. The maximum moistening also occurs around 950 mb in the simulation with up to a 9 K increase in dew point temperature. The low level winds increase up to around 900 mb, with southerly flow around 10 m s^{-1} after surge passage.

4. COMPARISONS TO OBSERVATIONS

It is worthwhile to compare model simulations with observations to determine the performance of the simulations. In this case the observations of the NAME experiment and in particular, the work done by RJ2007 will be used to compare to the model simulation. Comparisons of surface observations and wind profiles at the three ISS sites were performed as well as qualitative comparisons of reflectivity to that of the NAME radar network (see Lang et al. 2007 for details of the radar network).

At Los Mochis (LM) (not shown), the model was slightly dry (bias of 1 K) and slightly cool (bias of 0.8 K).The model underpredicts the MSLP rise early on the 13th and is too dry as well. Examination of the wind profile shows that the simulated wind surge has easterly winds rather than southeasterlies. The simulation also does not catch the increased southeasterly flow from 06-10 UTC. This suggests the simulation is not properly simulating the initial surge at Los Mochis. Further investigation is needed to understand why this is happening.

Figure 5 gives the modeled and observed surface traces and wind profiles at Kino Bay (KB) from 06 UTC 12 July through 00 UTC 14 July. Again the model has a dry bias, 2.8 K for this site. From the surface trace one can see a significant drop in dew point after sunrise indicating dry air mixing down from aloft. Examination of actual soundings (not shown) indicates that boundary layer (BL) moisture in the model is too low above the surface and the modeled BL is too deep, which contributes to the dry bias. This most likely goes back to the GFS initial conditions, which don't properly resolve the GoC, its moisture field and depth as compared to the North American Model 12 km analysis fields (not shown). Unfortunately, the GFS is needed for to initialize the simulation due to the required southern extent of the domain being south of the North American Model boundary.

The diurnal cycle of temperature is represented in by the simulation quite well, with nearly correct timing and amplitude. The diurnal cycle of pressure is also well simulated with the largest discrepancies coming after 10 UTC on 13 July. The simulation does capture the initial

MSLP increase with the surge between 06-10 UTC. However, it then has a brief rapid decrease in MSLP near 10-12 UTC, which then lead to a low bias in MSLP the rest of the day. This short rapid drop in surface pressure and dew point around is related to a downward intrusion of warm dry air just to the west of KB on the trailing edge of the cold pool. This type of intrusion event is possible in this region (Martin and Johnson 2008) due to the shallow depth of the moist marine layer, but was not observed in this case. This event seemed to warm and dry the boundary layer too much, which led to a warmer, dryer BL and lower MSLP values from around 10 UTC on. This suggests that the model does not fully capture the evolution of the surge event at KB properly, allowing for too much downward mixing of warm dry air.

The wind profile at KB was simulated reasonably well. The wind maximum around 06-10 UTC 13 July was captured by the model as well as the slightly elevated flow from 20-03 UTC 12-13 July. However, the simulated flow was too weak from 10 UTC through 18 UTC 13 July. The modeled wind maxima were also too shallow during the 20-03 UTC and 06-10 UTC 12-13 July peak time periods. This again seems to link back to improper boundary layer development in the model.

Finally, Figure 6 displays the same information as Figure 5, except for Puerto Penasco (PP). Again the model has a dry bias, 2.3 K, with a fairly small cool bias (0.6 K). The timing of the diurnal cycle appears to be quite good from the temperature trace with the model underestimating the high on 12 July and overestimating it on 13 July. There is a consistent bias of about 2 mb in the MSLP between the model and observations at PP. Once again, dew point temperatures drop too much in the simulation after sunrise on 13 July indicating too shallow of a moist layer in the model simulation. This is again confirmed by examination of model and observed soundings at PP.

The modeled wind profile agrees quite well with the observed profile at PP. The surge timing and maximum velocity are captured nearly correctly by the simulation. The simulation struggles to simulate the duration of high wind speeds and produces a surge event that is about 500-1000 m too shallow. The inversion depth at PP is observed and modeled to be around 950 mb at 06 UTC 13 July and 900 mb at 18 UTC. However, the model does not develop a strong enough inversion at and just above 900 mb and has essentially no mixed layer below 900 mb.

Overall the simulation compares favorably to the observations at the three ISS sites and in general comparisons to the synoptic setting, convective timing and placement, and surge evolution. The simulation captures most of the convection on 12-13 July and produces a surge feature that moves along the GoC, reaching the northern GoC near the peak of the GoC LLJ. TS Blas is also captured in the simulation with reasonable track timing and placement.

5. SURGE DYNAMICS

In the early stages, the initial surge is primarily a gravity current. Figure 7 shows a sounding from near Los Mochis at 0230 and 0330 UTC 13 July. Note the strongest cooling in the lowest 100 mb along with an increase in surface-900 mb winds from ~5 m s^{-1} to ~12.5 m s^{-1} and a decrease in near surface moisture. There is also an associated mean sea level pressure increase with the passage of the gravity current of ~1.2 mb. The initial gravity current generates a bore which can be seen in Figure 8. This figure is a cross-section taken at 04 UTC 13 July along the line denoted as CS1 in Figure 1. Potential temperature is contoured with horizontal wind magnitude shaded in Figure 8.

From Figure 8, one can see the surface cold pool and higher near surface winds associated with the cold pool and a separate leading feature. This leading feature is the bore, which has only one undulation at this point in the simulation. The bore has little to no surface reflection in potential temperature and is associated with a distinct local maximum in horizontal wind speed which is in phase with the potential temperature perturbation. There is also a distinct vertical velocity couplet associated with the bore having upward vertical motion on the leading edge and downward motion on the trailing edge (not shown). The bore propagates away from the gravity current with significant loss in amplitude in time. This is most likely due to the model improperly simulating the 875-800 mb lapse rate. An actual sounding taken from Kino Bay at 06 UTC 13 July shows a lapse rate near dry adiabatic in this layer, which would help inhibit vertical propagation of energy from the bore feature (Crook 1986). This is not represented in the model, as can be seen in Figure 7. The modeled vertical velocity couplet associated with the bore extends through 5 km with some vertical tilt, which is possibly another indication that there is vertical energy loss.

A second undulation propagates ahead of the initial cold pool beginning around 0430, with less amplitude than the first undulation (not shown). The initial bore undulation dissipates around 0530 UTC along with the initial cold pool. Another cold pool intrudes into the CS plane around 04 UTC, nearly overtakes the original cold pool around 0530 UTC and is mostly modified by 07 UTC. At this point the surge feature appears to have a consolidated dome of cool air moving NW along the GoC. It is important to note here that the surface/near surface potential temperature anomalies in the cool dome are only around 1 K, the largest potential temperature anomalies were elevated above the surface through the rest of the event (similar to Douglas and Leal 2003).

Figure 9 is a cross-section of horizontal wind speed (shaded) and potential temperature (contours) along CS2 (see Figure 1) at 07 UTC 13 July. From this figure one can see that the 302 K contour is located around 150 m AGL pre-surge, around 500 m at the peak and around 280 m after the wind maximum passes. The 302 K contour stays elevated near this level through 14 UTC, when SE flow throughout the GoC begins to transport more cool air along the GoC which causes further lifting of this isentrope. It appears the maximum winds are in-phase with the maximum vertical displacement of isentropes. Time series analysis of a point near 28.2 N, 112.3 W indicates the maximum wind speed is in-phase with the largest Dp/Dt values as well. These facts suggest that the feature moving through the northern GoC after 07 UTC is a solitary Kelvin wave (Ralph et al. 2000).

As the surge moves north it is disrupted somewhat by the islands around 28-29.5 north that nearly span the entire GoC. This makes cross-section interpretation more difficult in this region. The surge also enters the area of the climatological maximum of the GoC LLJ. Nevertheless, the Kelvin wave maintains its shape quite well. Figure 10 is a cross-section along CS3 from 11 UTC. The rise in the 302 K surface is still present along the wave with strong winds near its peak displacement height. It appears that the strongest winds are leading the largest upward perturbation in the 302 K surface at this time. This may be due to the GoC LLJ superimposing itself on the surge event, or because of the island disruption.

Figure 11 shows the surface trace of wind magnitude and MSLP from the grid point nearest PP. Focusing on the time period from 06-14 UTC 13 July, one can see that the maximum wind speed is associated with the maximum Dp/Dt around 12 UTC. Also, examination of the inversion top height at PP shows a maximum between 12-14 UTC. Lastly, Figure 12 displays two cross-gulf cross sections along AC1 (see Figure 1) at 11 UTC and 14 UTC of the same fields as all other CSs, with terrain shaded in black. It is evident that the potential temperature perturbations are deepest on the eastern side of the GoC and decay with westward extent. The maximum winds are located near the maximum height of the cool air dome at 11 UTC and slightly displaced to the west at 14 UTC. This may be due to the GoC LLJ influence. Figures 11 and 12 lend additional support to the hypothesis that this surge is possibly a solitary Kelvin wave. This surge evolution from gravity current to solitary Kelvin wave agrees very well with the proposed surge evolution in RJ2007 based on their observational analysis. This also fits into the discussion by Zehnder (2004) as one of the possible mechanisms causing gulf surge events.

6. CONCLUSIONS

The 12-14 July 2004 gulf surge event during the NAME was simulated using version 3.1.1 of the ARW core of WRF. The simulation was performed on a 4-km horizontal resolution grid with 55 vertical levels and covered the entire GoC, SMO, Baja peninsula and portions of the Pacific Ocean, SW U.S. and south to 16°N. This allowed the simulation to capture TS Blas, convection along the SMO and the complete surge event as it propagated up the GoC.

Comparisons to observations show that the model represents the timing and amplitude of the diurnal cycle of temperature fairly well at KB and PP. However, it has too shallow of a moist layer, resulting in a dry bias throughout a majority of the simulation at inland points. This probably stems from the GFS initial conditions being too dry and not properly resolving the moist marine layer over the GoC. The MSLP features are simulated for the most part at LM and KB, with the most disagreement at LM and KB. A constant high bias of 2 mb was seen at PP.

The wind field associated with the surge was simulated quite well at KB and PP. The timing of the initial wind increase and wind maximum were in good agreement with the observations. The depth of the surge event was too shallow by 500-1000 m at both sites and the duration of the high winds was too short in the simulation. It appears that these issues may stem from the improper development of the marine boundary layer and inversion layer in the central and northern GoC.

Convection along the SMO from around 21 UTC 12 July through 08 UTC 13 July seems to play a role in initiating the initial surge event. An initial gravity current begins to propagate off the SMO and is deflected to the NW by the background flow and Peninsular ranges initially. Two undulations of a bore feature are seen to have propagated ahead of the initial gravity current between 0330 and 0530 UTC 13 July. These initial undulations lose amplitude with time due to vertical energy propagation. As the convection continues to the NW, additional cool air is fed into the consolidating surge. By 07 UTC the surge appears to have become a solitary Kelvin wave with the maximum winds in-phase with the maximum Dp/Dt and maximum perturbation height of the feature. The simulated surge moves up the GoC, passes PP between 10-15 UTC 13 July, and moves into southern Arizona, having the characteristics of a solitary Kelvin wave.

7. ACKNOWLEDGMENTS

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Figures

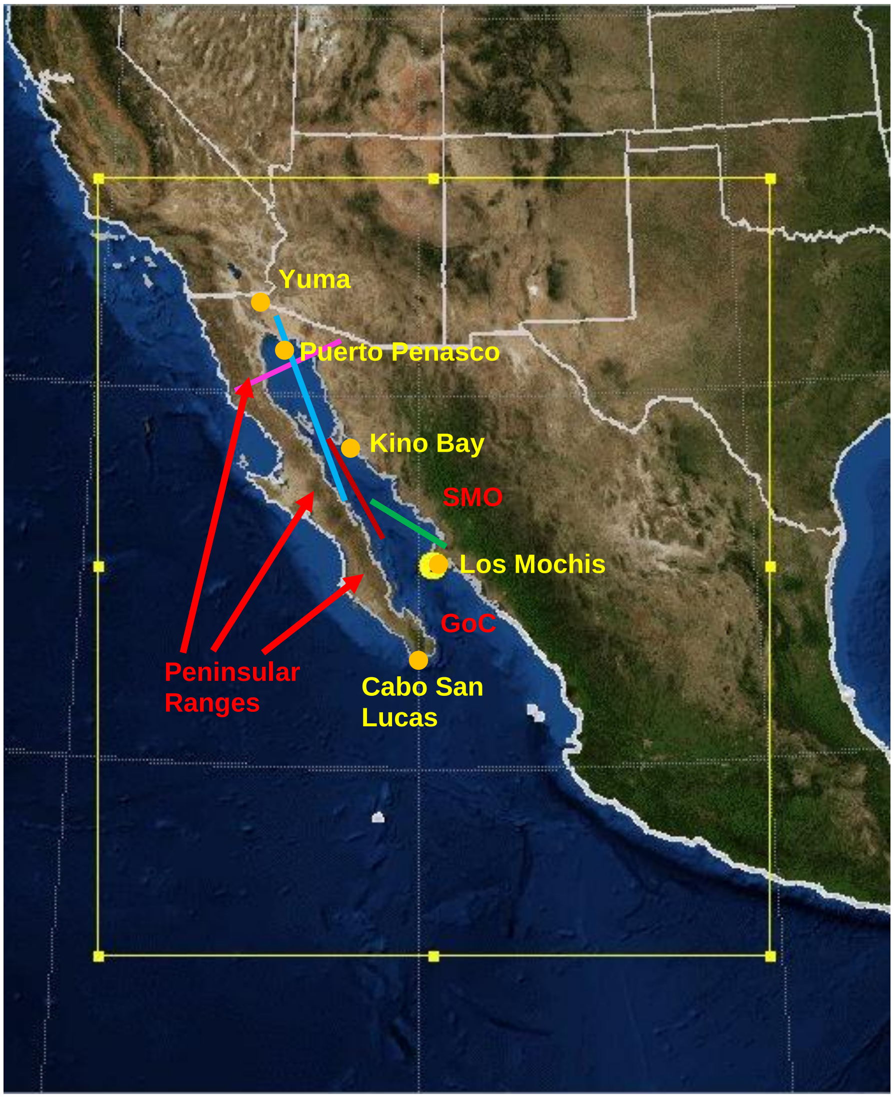

Figure 1. The simulation domain is shown with the yellow box; the SMO, Peninsular Ranges and GoC are highlighted in red, important geographical sites are highlighted with orange dots and yellow text. Cross-section one (CS1) is highlighted in green, cross-section two (CS2) is highlighted in dark red, cross-section 3 (CS3) is highlighted in light blue and across the GoC cross-section one (AC1) is highlighted in light pink.

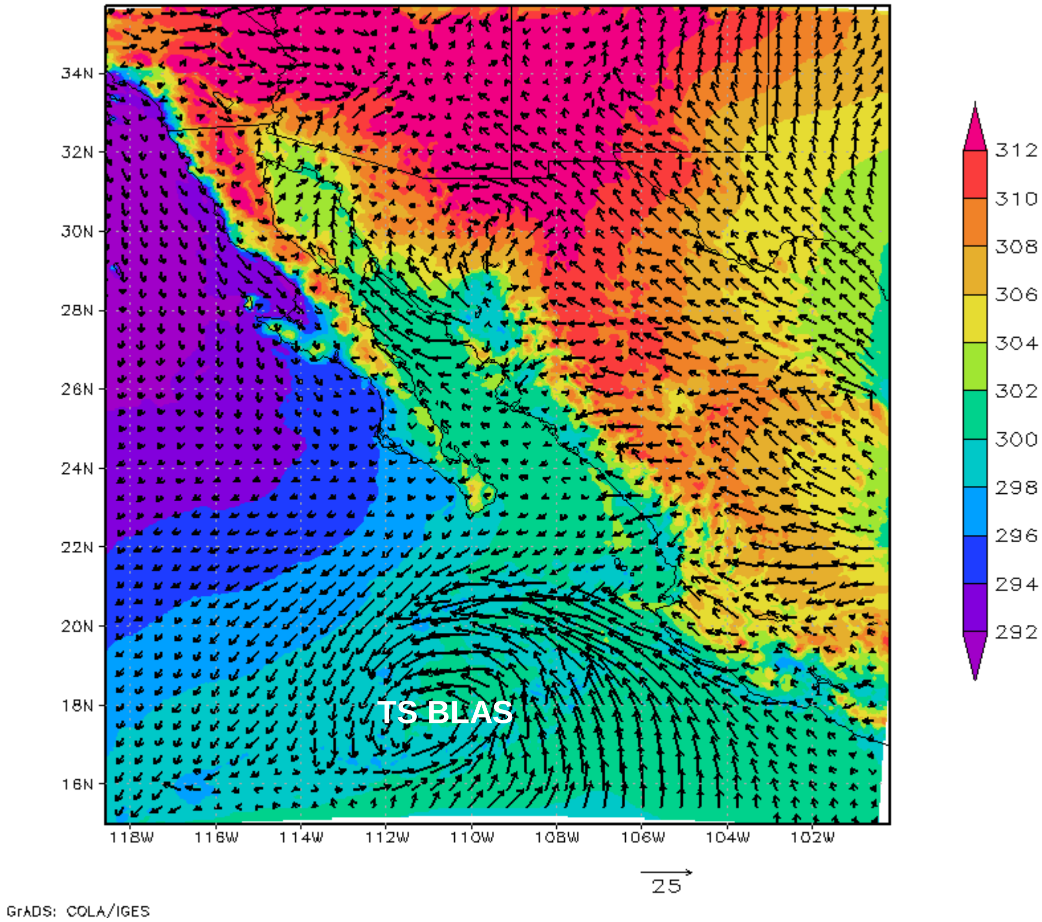

Figure 2. First sigma level (~41 m) potential temperature and third sigma level (~216 m) wind vectors are shown here at 0700 UTC 13 July.

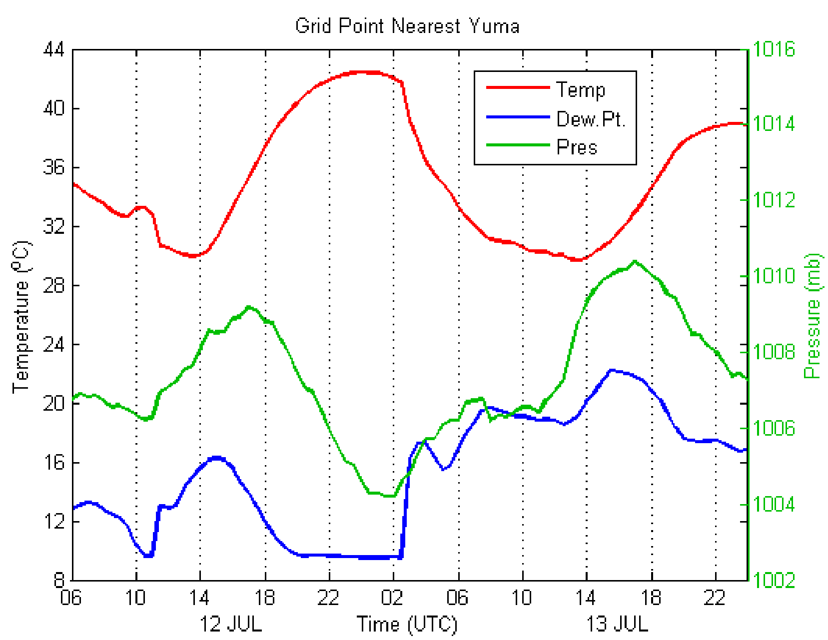

Figure 3. Simulated surface trace from Yuma, AZ from 06 UTC 12 July through 00 UTC 14 July.

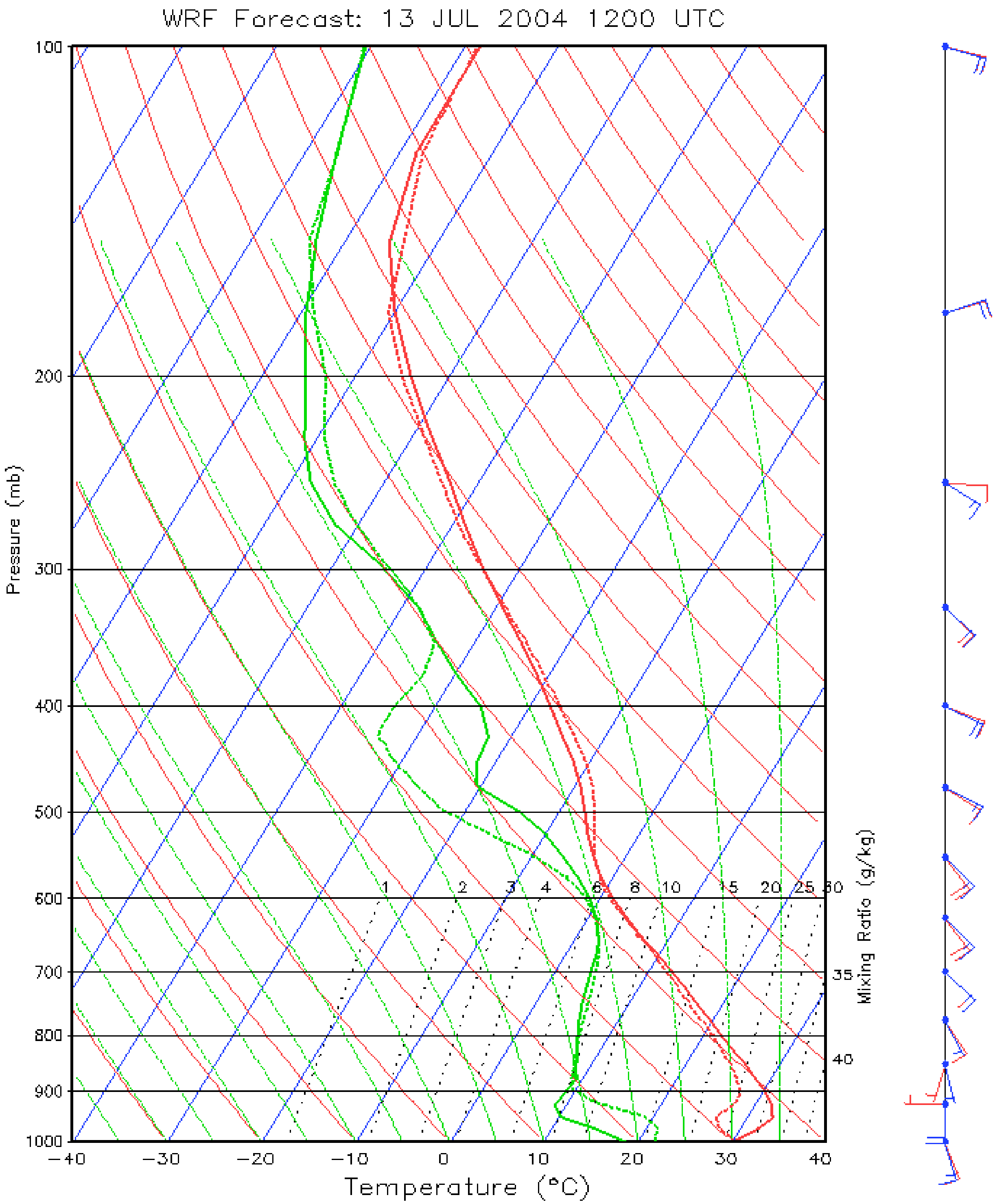

Figure 4. Soundings from the grid point nearest Yuma, AZ from 12 UTC and 15 UTC 13 July. The solid lines represent 12 UTC while the dotted lines represent 15 UTC. The red wind barbs are from 12 UTC and the blue from 15 UTC.

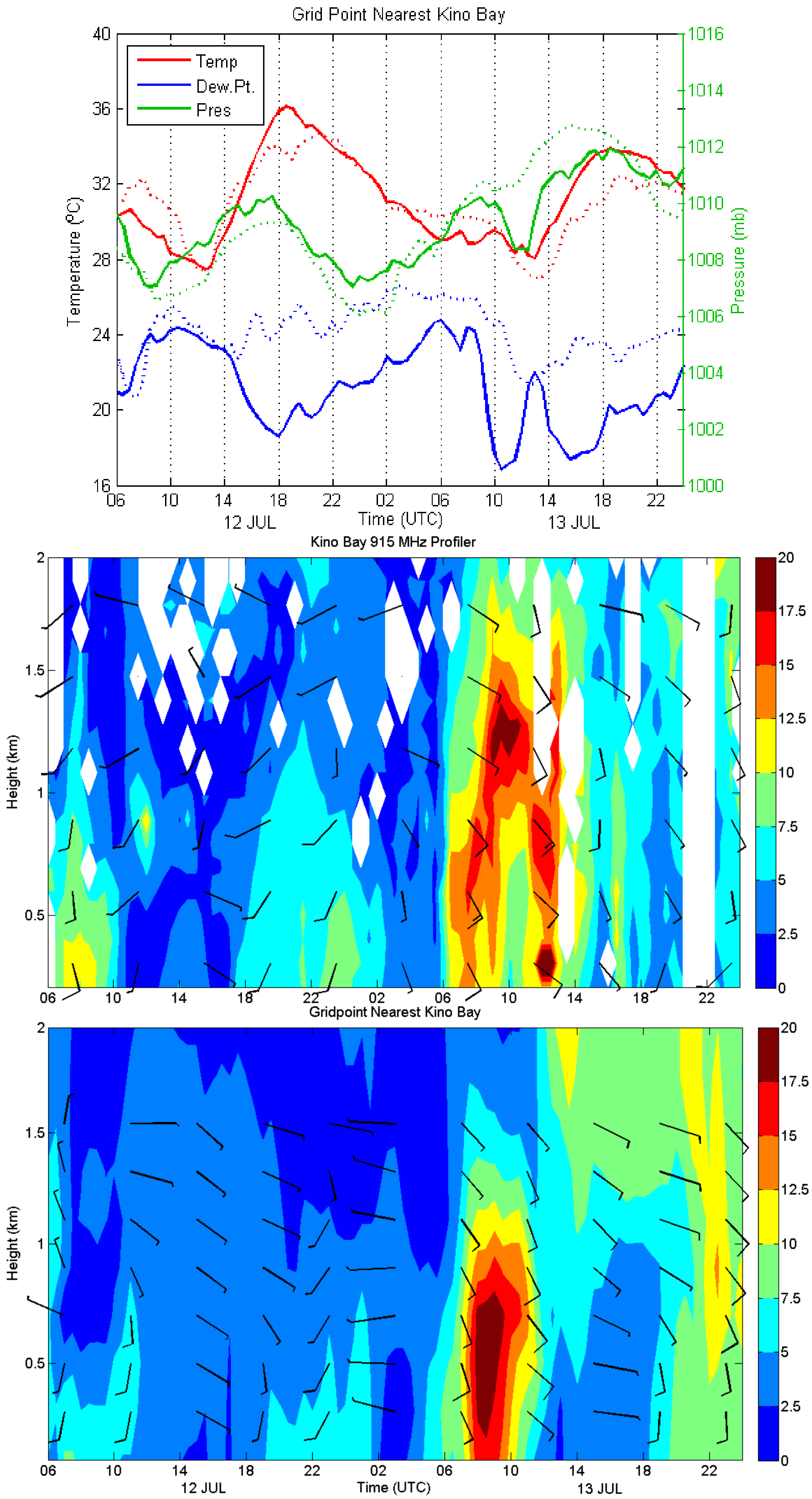

Figure 5. Top panel is surface trace of temperature, dew point and sea level pressure. Model fields are solid, observed fields are dotted. Middle and bottom panel are observed and modeled time series of winds from ~200 m to 2 km. All plots are for the ISS site at Kino Bay and time is the same as Figure 3.

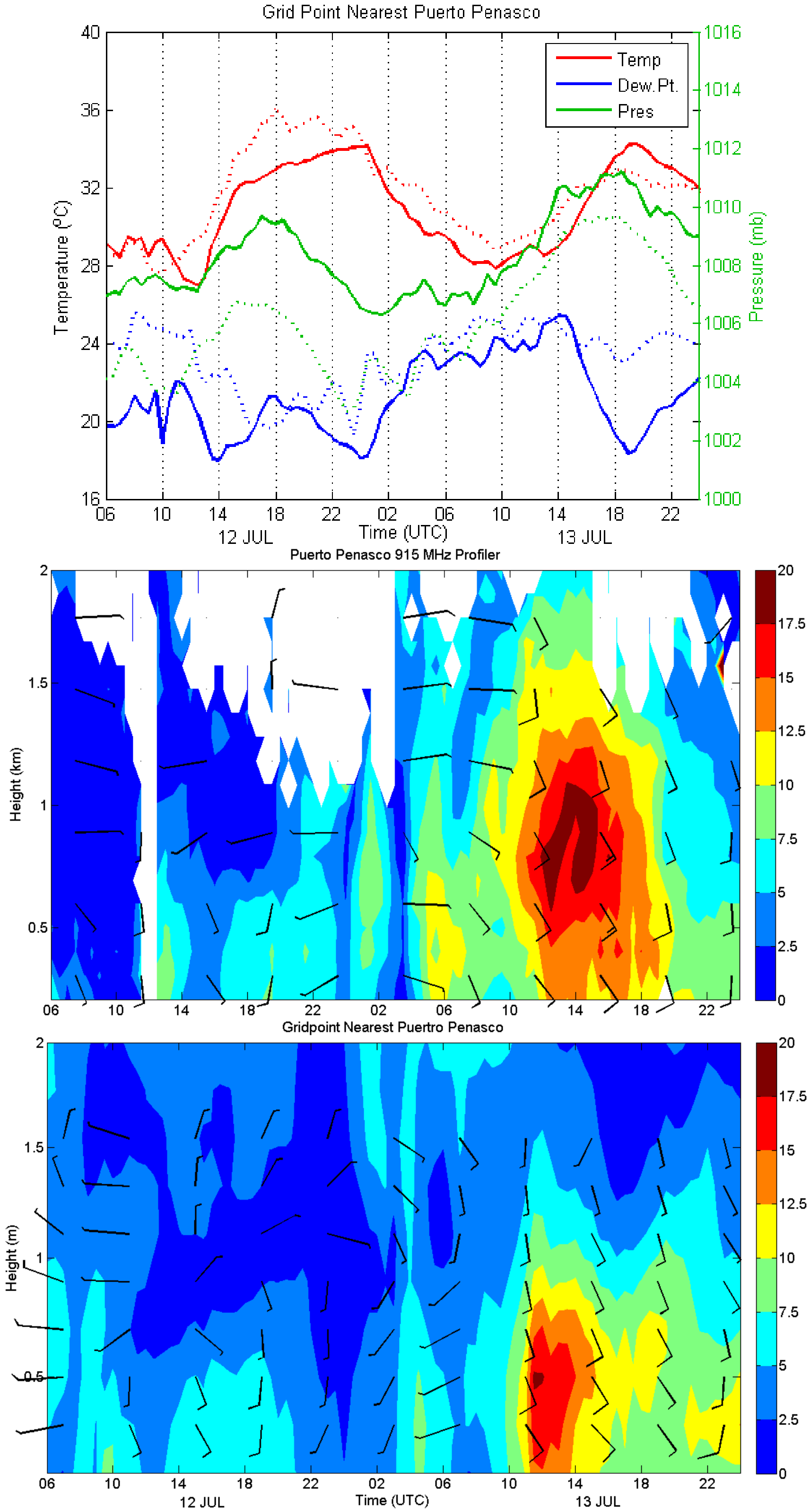

Figure 6. Same as Figure 5, except for the ISS site at Puerto Penasco.

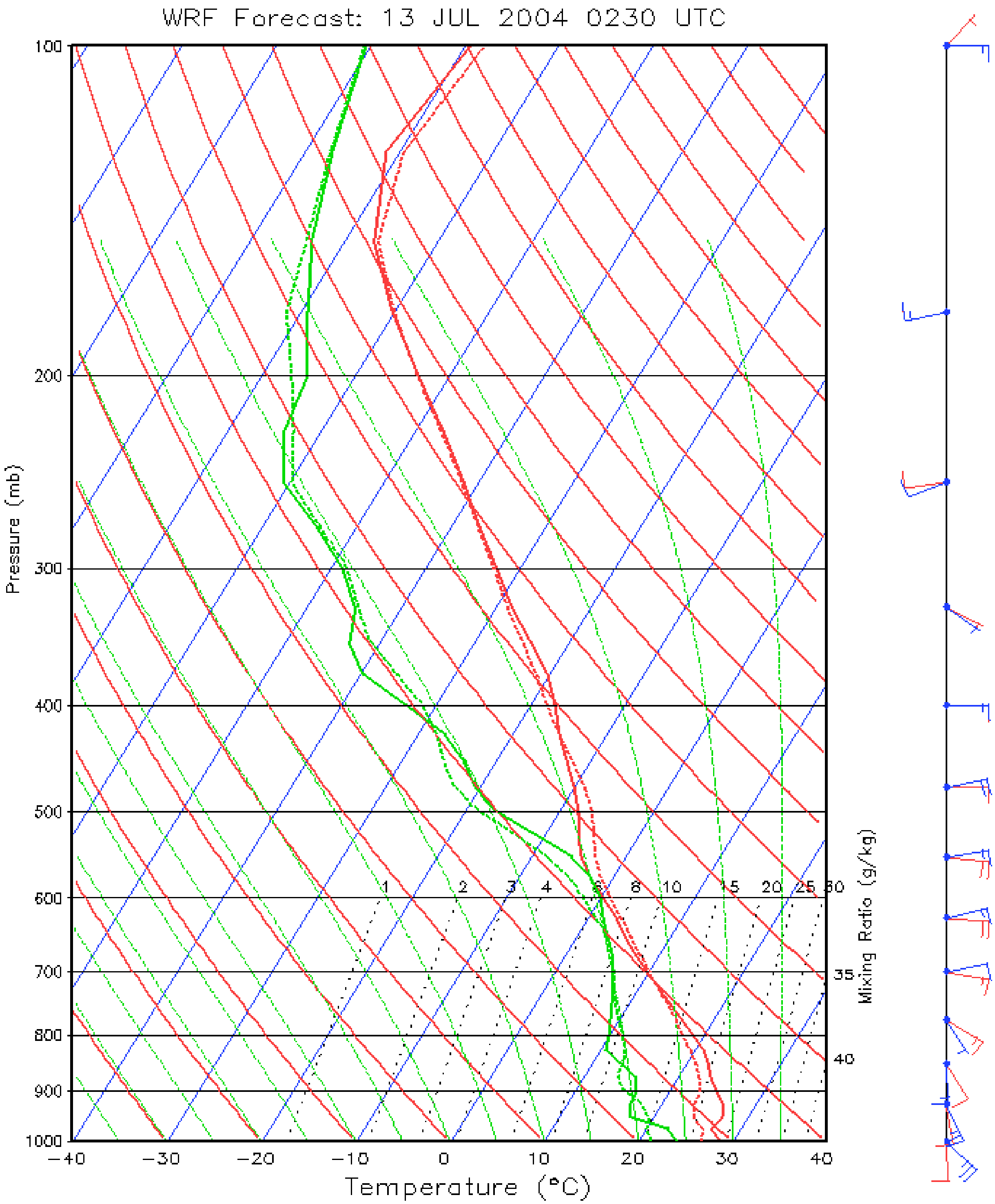

Figure 7. Model soundings from 0230 and 0330 UTC 13 July at 109.7^{o}W and 26.8^{o}N. The coloring scheme is the same as in Figure 4.

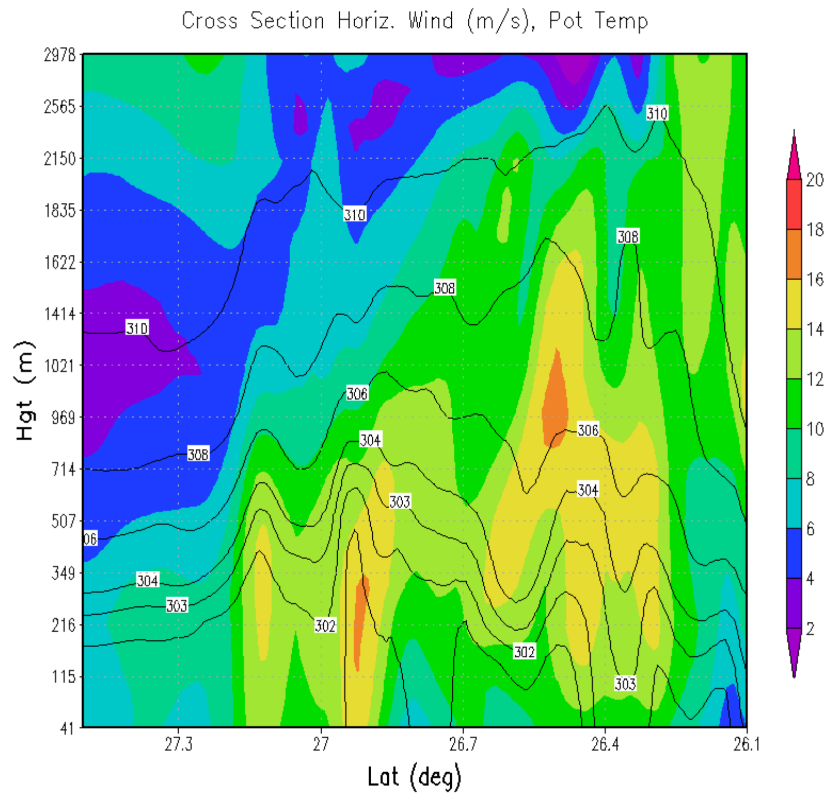

Figure 8. Cross-section along CS1 from 04 UTC 13 July displaying horizontal wind magnitude (shaded) and potential temperature (contours).

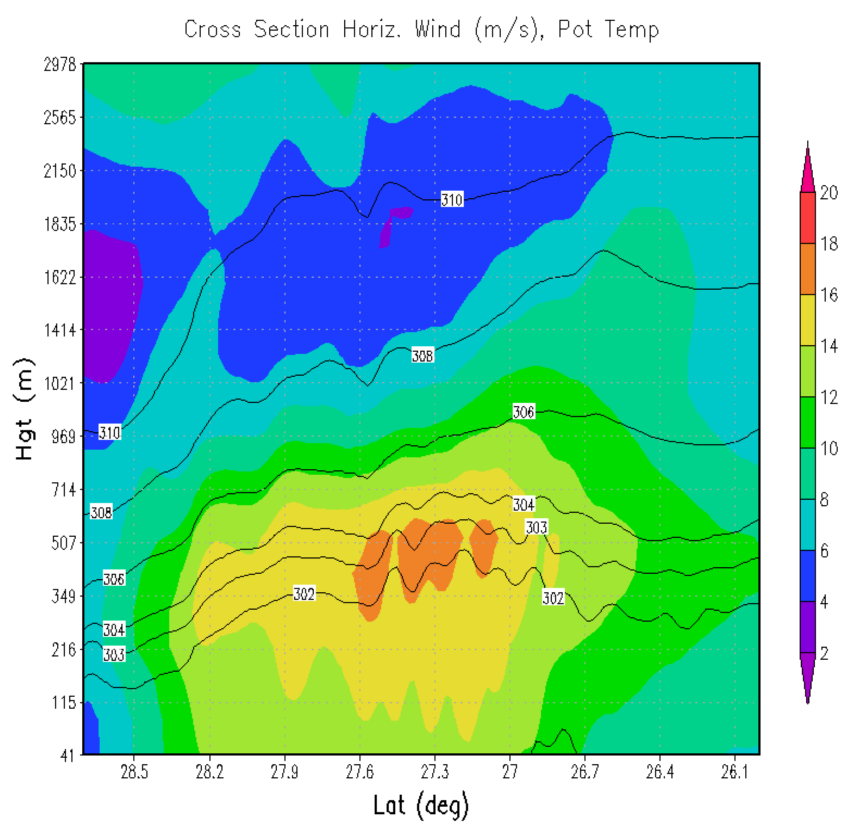

Figure 9. Cross-section along CS2 from 07 UTC 13 July. Fields displayed are the same as Figure 8.

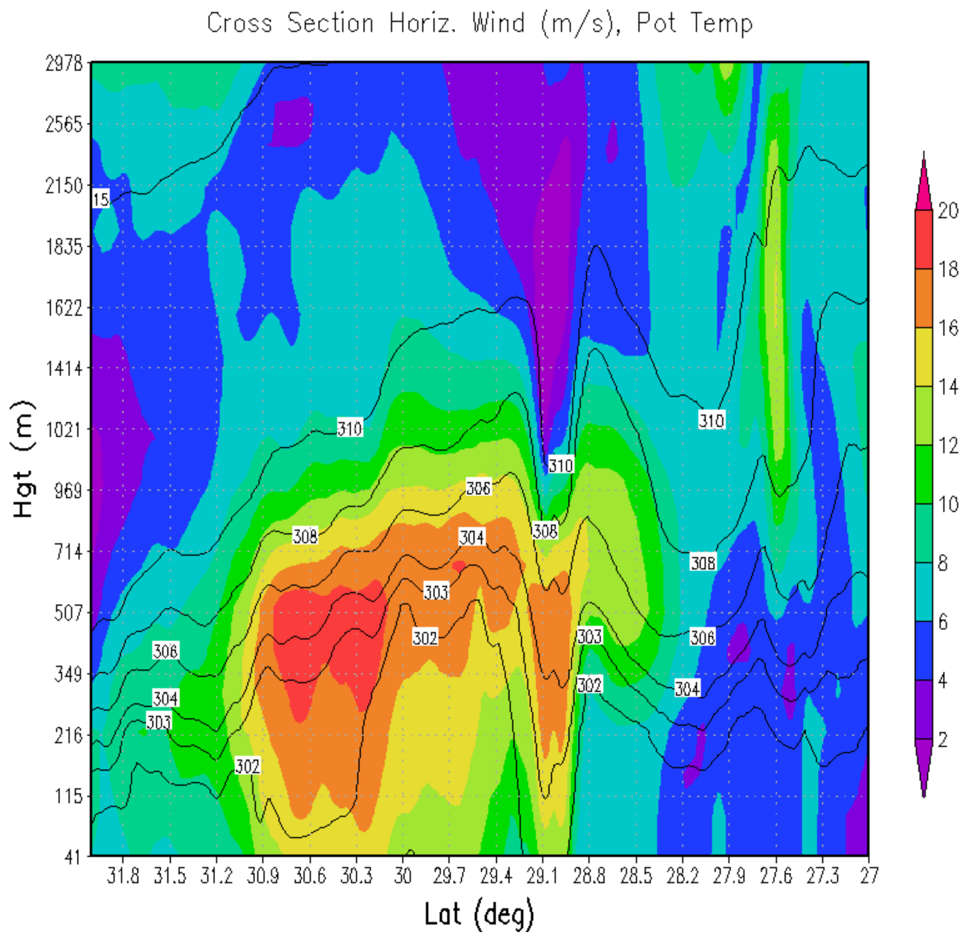

Figure 10. Cross-section along CS3 at 11 UTC 13 July. Fields displayed are the same as Figure 8.

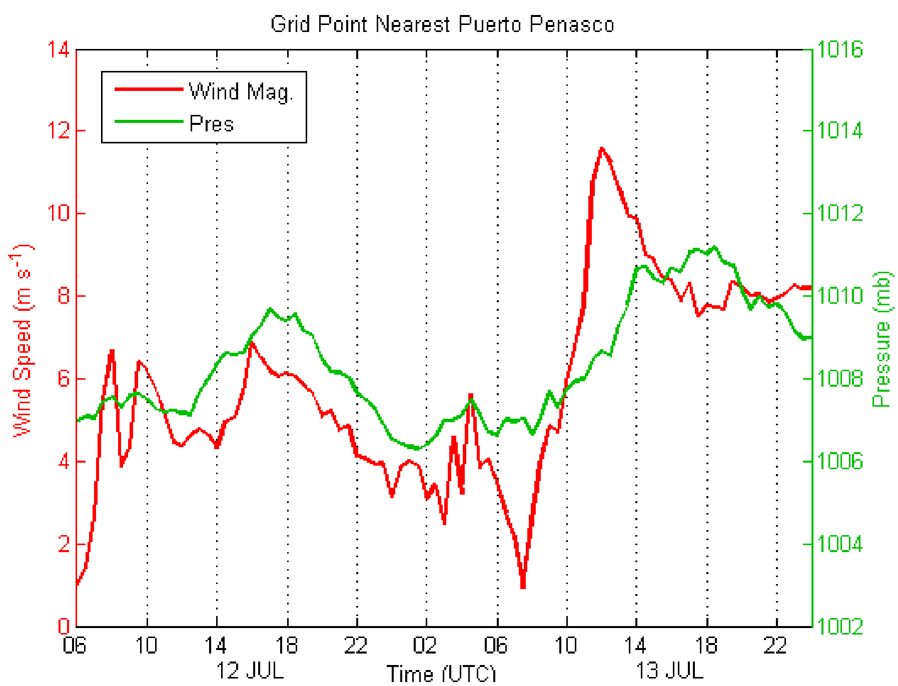

Figure 11. Simulated surface trace of wind magnitude and MSLP at the grid point nearest Puerto Penasco (PP).

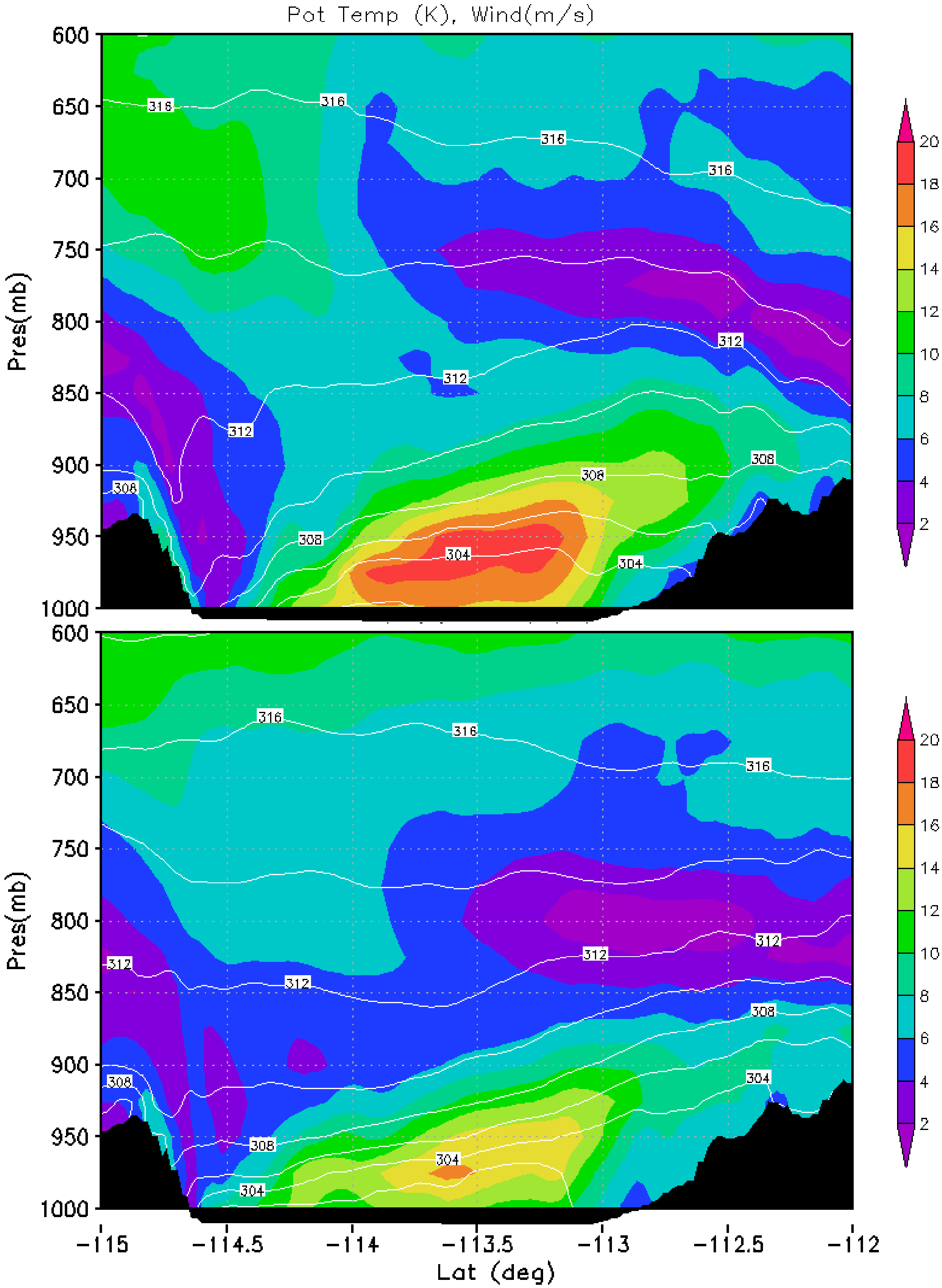

Figure 12. Across the GoC CSs from 11 UTC and 14 UTC 13 July along AC1. Fields displayed are the same as Figure 8. Note these CSs use pressure as the vertical coordinate and the surface and below is shaded in black.