

# Mesoscale weather forecasting in the classroom environment

Report on SIO209 Weather and pollution forecasting class  
Winter 2007

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## **Summary**

The graduate seminar class on numerical weather and pollution forecasting taught at Scripps Institution of Oceanography, University of California, San Diego (Scripps) is described. The goal of the class was to introduce students to operational mesoscale weather forecasting and physical and operational principles behind weather forecasting. To this end students used an easy-to-use graphical user interface developed by the Naval Research Laboratory for their mesoscale coupled atmosphere-ocean model COAMPS-OS. Students were able to relocate model grids to their region of interest, examine model output including meteograms, soundings, and prognostic and derived meteorological fields. Instructions centered on better understanding of model physics and structure including data assimilation, definition of mesoscale and discussion of representative examples of mesoscale flows, discussion of basics of model parameterization. Because of the diversity of the student population at Scripps, training material developed by the Cooperative Program for Operational Meteorology, Education, and Training (COMET) was extensively used, which allowed some of the basic instruction to be relegated to these modules.

## ***Introduction***

Scripps Institution of Oceanography at University of California has a very diverse student population engaged in research of oceans and atmosphere. Ongoing investigations include climate change, the interactions between the ocean and atmosphere, and waves and currents. Scripps's research ships are used in these investigations throughout the world's oceans. Other field projects involve studies of atmospheric properties of aerosols and clouds. More than 300 programs may be under way at any time, including studies of air-sea interaction, climate prediction, and the multidisciplinary aspects of global change and the environment. Our challenge was to design a modern weather and pollution forecasting class that would be relevant to the research of Scripps students.

In this paper we describe our attempt to provide instruction on numerical weather forecasting which would be at the same time modern and suitable to research needs of oceanography, climate, and atmospheric science students. There were some unique aspects of this seminar class, which included use of a semi-operational numerical weather model in real time. As Scripps students are working at the crossroads between oceanography and weather we wanted to emphasize coupled ocean-atmosphere weather forecasting. Constant engagement of students in various field projects dictated emphasis on mesoscale weather and ocean forecasting. Strong research driven interests provided additional impetus to develop curriculum around numerical mesoscale weather forecasting with semi-operational capabilities to relocate model grids to arbitrary regions of the world and run forecasts in real time. Finally, we wanted to provide instruction, which would go beyond a workshop on numerical model usage and provide basic understanding of the principles behind modern weather forecasting.

We begin by defining the class scope and its organization, including description of class instructions, choice of numerical weather model, our use of COMET modules, and use of wiki-type software for “web with edit button” application. We proceed to discuss our weather model choice, choice of graphical user interface (without which this class would have been much more difficult to realize), hardware requirements, issues related to security which are increasingly important even in the university environment, software and networking needs. Last, but not least we discuss student projects.

## ***Class scope and organization***

The class was structured in a rather loose way on the graphical user interface of the COAMPS-OS input requirements and discussion of the model output. It was apparent that not all facets of mesoscale weather modeling could be discussed in class composed of about 24 lectures. Initially we concentrated on discussion of the COAMPS-OS graphical user interface. Students were asked to bring laptop computers and they used the campus-wide wireless network while accessing the COAMPS-OS. The instruction given to the class was to select an arbitrary region on the globe and initiate a mesoscale weather forecast for that region. Due to the ease of use of the COAMPS-OS interface this task

was completed quickly. After this initial step the instructions concentrated on topics related to model setup. In particular we covered model grids and projections, vertical coordinate systems, introduction to mesoscale weather prediction, introductory concepts of data assimilation, sources of data and observations, concept of date-time group, and concept of warm and cold start. This set of classes was to provide basic concepts needed to understand the model setup and scope of problems solvable by numerical weather forecasting. We also used this time to acquaint students with the terminology and jargon used. Our next step was to understand model output. Again two hours of instruction were provided related to COAMPS-OS user interface, but this time concentrating on model output. We covered concepts of data formats such as GRIB and NetCDF, model options such as scheduling jobs, synoptic times, discussion of scheduler and job monitoring, as well as discussion of model graphical output such as meteograms, streamlines, and contour plots. This set of COAMPS-OS instructional classes was followed by in-depth discussions of several mesoscale weather forecasting applications. The choice of applications was limited and guided largely by student interest who, in our case, were a mix of oceanography, climate, and atmospheric sciences doctoral candidates. Some of our interests included interaction of wind with ocean surface, pollution transport and wind driven emissions, as well as properties of California stratocumulus. We also discuss applications of mesoscale weather forecasting to sailing non-stop around the World. This topic provided an opportunity to discuss optimal route selection and large scale weather systems pattern around the clipper route. Our original plan was to assist the Polish sailor Roman Paszke in his attempt to establish shortest time of passage around the world, but this project was eventually abandoned when his voyage was postponed.

Another guidance in choice of topics was the availability of COMET modules. We discussed gap winds, deep convection, and skew-T log-p diagrams, and maintenance and structure of the California stratocumulus. These subjects provided sufficient opportunity to discuss the remaining COAMPS-OS output, choice of prognostic and diagnostic variables on output and the data formats. This was also a time to formulate projects, which centered on COAMPS-OS. Students did some hands-on map drawing and one class was devoted to drawing skew-T log-p soundings. We purchased two inexpensive wireless weather stations from Oregon Scientific with software allowing data transfer to the internet, and established our own site on [www.weatherunderground.com](http://www.weatherunderground.com).

One of the advantages of the environment at Scripps Institution of Oceanography is expertise in diverse topics related to environmental sciences. Masao Kanamitsu discussed introductory material about data assimilation. This material centered on data assimilation and was complemented by his insight on historical development in numerical weather forecasting. In passing we discussed the role of Japanese scientists in development of weather models in the US, the NCEP reanalysis project, and he provided insight to the future of weather forecasting. On the other hand, one of the disadvantages of the diverse student population at Scripps Institution of Oceanography is their uneven atmospheric science preparation. We handled these discrepancies by grading the class on the basis of projects only. The projects were assigned according to each student's research interest. However, all projects involved COAMPS-OS runs, in the hope that this will steer students to acquire at least minimal skill in weather forecasting.

## ***Use of Wikispaces***

Class schedule, assignments and posting of class material were handled through wiki-type software, which is a driving mechanism behind now-popular Wikipedia. In essence our use of wiki software was similar to use of the web but with editing capabilities. This provided a collaborative aspect to the class and ability to enhance the content. Our choice was Wikispaces ([www.wikispaces.com](http://www.wikispaces.com)). This served as a convenient mechanism to exchange power point presentations, post relevant articles, share software, as well as post homework assignments and scheduling. Since the class involved student participation in the form of short talks, the Wikispaces served as convenient mechanism for information exchange. Use of wiki-type software also provides the ability to monitor history of changes, as well as being able to revert to previous versions in cases of inadvertent mistakes.

## ***COMET modules***

During the class we used several modules developed by the Cooperative Program for Operational Meteorology, Education and Training. This program was established to promote a better understanding of mesoscale meteorology and looked like the logical choice for a class of our scope. Typically, the COMET presentation was played, and the instructor commented on the material. One advantage of COMET modules was that they help to establish common knowledge between students with diverse backgrounds, for example “definition of mesoscale” and “how mesoscale models works” were not discussed during the class but formed good off-class prerequisite material. The COMET module on introduction to data assimilation was a great source of information about applicability of data assimilation in operational weather forecasting. The modules “gap winds” and “flow interaction with topography” were used to illustrate examples of the type of the dynamical setting in which mesoscale models are needed.

## ***Hardware***

One of the class requirements was efficient access to a semi-operational mesoscale model for several student groups who, we envisioned, would run rather diverse forecasting scenarios. Thus, we wanted to provide an environment in which several student groups could work independently, have easy access to computer resources and which would provide secure but not restrictive access to computer resources. Such an environment was offered by the Center for Observations, Modeling, and Prediction at Scripps (COMPAS). The center was formed to address numerical modeling of physical processes in the ocean and atmosphere. For educational outreach one of the smaller COMPAS computing clusters was rebuilt to house the course. This LINUX cluster consisted of 32 two processor 1.0 GHz Pentium III with 512MB per CPU and front-end computer with 300 GB storage. The cluster was managed with the Rocks cluster software. Once

the cluster software was installed, there was typical local configuration, including installing the Portland Group Fortran compiler (version 6.2-5) and recompiling mpich (version 1.2.6-1) to work with it. The entire installation process took about a week on and off due to diagnosing the various hardware issues we were having and waiting for some assistance with the Rocks group to help discover the problems. Having finished the base cluster install, accounts and software were setup to allow the initial COAMPS install (described later), which took about an additional day after the base cluster install. After the COAMPS install, the only major cluster issue was losing one of our NFS disks about halfway through the class which happened to house the main COAMPS directory.

In summary, the project required modest computer resources composed of somewhat obsolete Intel processors. An important requirement was assignment of non-overlapping computing resources to different forecasting projects and ability to provide secure access to the cluster from the web server. The cluster was accessed mostly from within the Scripps Institution of oceanography network. However, several students were accessing the cluster externally using virtual pPrivate network software.

## **COAMPS-OS**

COAMPS-OS was selected as a tool to enhance the student's experience with weather forecasting. COAMPS-OS provides a simplified interface allowing novice programmers to set up and run a regional numerical weather prediction model. COAMPS-OS was developed by the Naval Research Laboratory to support high-resolution (2 to 10-km), short-term weather forecasting. Hodur (1997) and, more recently, Chen et al (2003) provide thorough descriptions of COAMPS including the numerics, grid characteristics, and physics used by the model. In addition to its atmospheric component, COAMPS-OS uses the Navy Coupled Ocean Data Assimilation (NCODA, Cummings 2005) system to generate lower boundary conditions of sea surface temperature and sea ice concentration to COAMPS. The lateral boundary conditions are provided from the Navy's global NWP model, NOGAPS (Hogan and Rosmond, 1991).

COAMPS-OS was an ideal application to support student interactions with numerical weather prediction models for a number of reasons. It provides a java-based, graphical user interface allowing students to quickly set up a location to run COAMPS without requiring the students to interact directly with the LINUX operating system or learn the intricacies of FORTRAN. The graphical user interface allows students, many without extensive backgrounds in atmospheric science, to focus their efforts on running and interpreting model output as opposed to spending time programming. In addition, COAMPS-OS provides a number of automated services including visualization and data management. With each forecast, it produces graphical output of common meteorological fields and user-selected GRIB fields that are automatically posted to a web site to view and/or download.

## ***The GODAE server***

The GODAE server at Navy's Fleet Numerical Modeling Operations Center in Monterey was used to provide access to real-time data stream, as well as global model data used as boundary conditions for the mesoscale model runs. The Navy Operational Global Atmospheric Prediction System (NOGAPS) fields provided by the server were used to force the regional COAMPS model. USGODAE data sets were available in their original format via HTTP and FTP (Sharfstein et al., 2006).

## ***Class Projects***

Class project centered on the use of mesoscale weather forecasting in real life applications. The main goal was hands on experience with COAMPS-OS model setup and its analysis. Most projects required current global model input data and ocean and atmospheric analysis. Two projects used historical data sets for analysis of mesoscale events. All datasets were accessed through the GODAE server. Current initial boundary conditions were automatically transferred to COMPAS cluster at Scripps. However, historical datasets were separately moved to the cluster and made available for student projects.

## ***Gulf of Tehuantepec Project***

Gap wind refers to ageostrophic flow driven by synoptic surface pressure differences, commonly accompanied by large temperature differences, across a low-level mountain gap (see Figure 1).

A shallow cold layer, on the high pressure side of the mountains, gets trapped by the surrounding mountains and channeled through the gap. Mountain gap winds occur throughout the world, for example in the Central American region the Panama, Papagayo and Gulf of Tehuantepec winds, in north America at the Columbia River Gorge in the border between Washington and Oregon, in Europe at the Strait of Gibraltar, among others (Steenburgh et al., 1998). In the Gulf of Tehuantepec, Mexico, mountain gap winds are more common during boreal winter months (Romero-Centeno et al., 2003) when cold weather systems move south into the Gulf of Mexico creating significant pressure differences across a mountain gap (the Tehuantepec Isthmus, also known as Chivela Pass), forcing an offshore wind jet over the Pacific Ocean which can extend for hundreds of kilometers. These wind events typically last for 2 to 3 days, and surface winds speeds reach up to 25 m/s (Trasviña et al., 1995).

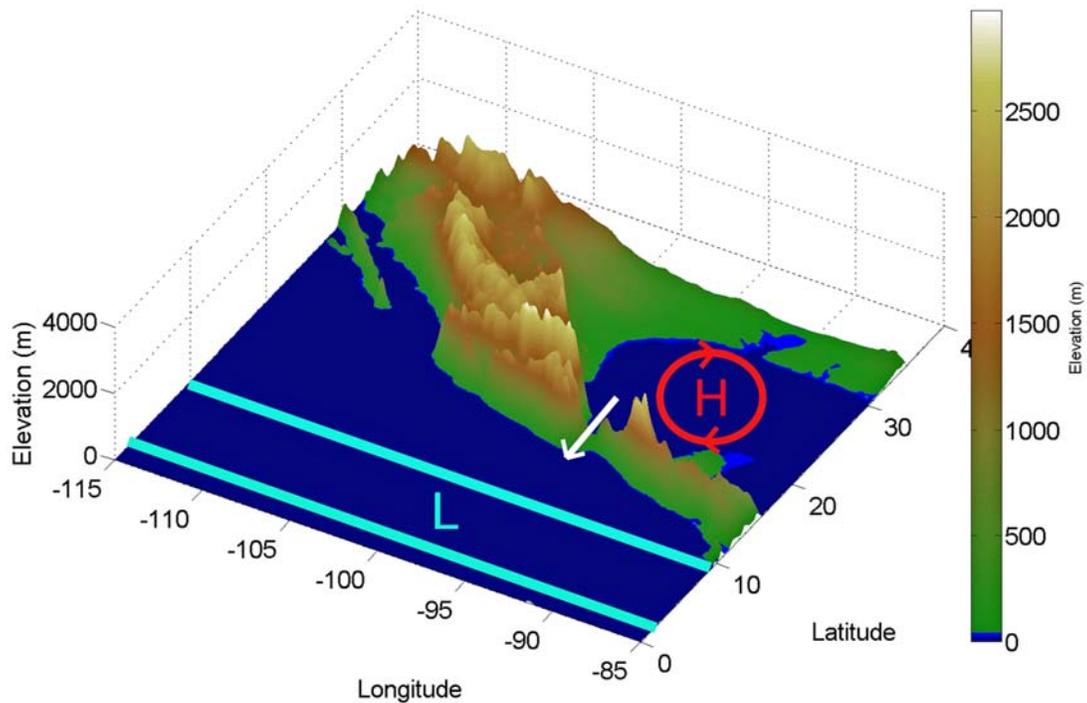


Figure 1. Schematic representation of mountain gap flow in the Gulf of Tehuantepec. Synoptic pressure differences across a low level mountain gap force a jet. The jet corresponds to ageostrophic flow, where the pressure gradient is balanced by surface friction.

Tehuantepec winds can have significant impacts on the ocean, which range from small scales, such as the generation of surface waves, increase in biological productivity due to upwelling and entraining of cold and nutrient rich subsurface waters, and aerosol production; to mesoscale processes such as eddy spin up, frontal genesis, and the Eastern Tropical Pacific circulation (Steenburgh et al., 1998; Martinez-Diaz-De-Leon et al., 1999; Kessler, 2006; Schultz et al., 1997). The predictability and frequency of occurrence of wind events over the Gulf of Tehuantepec make it an ideal location to study air-sea interaction processes. A recent experiment, the Gulf of Tehuantepec Experiment (GOTEX), was carried out in February 2004 to study the evolution of the marine-atmospheric and oceanic boundary layers, as well as the surface gravity waves in fetch-limited conditions. Meteorological and oceanographic measurements were collected on board the NSF/NCAR C-130 aircraft, covering large distances (up to 500 km) along the jet. Meteorological measurements, which include temperature, humidity, pressure, winds and turbulent fluxes, were collected at various altitudes above the mean sea level ranging between 30 to 1500 m. The surface waves underneath the aircraft were measured with LIDAR altimeters, temperature profiles in the upper ocean were obtained from airborne expendable bathythermographs (AXBT), and breaking waves were identified and recorded with two downward-looking video cameras.

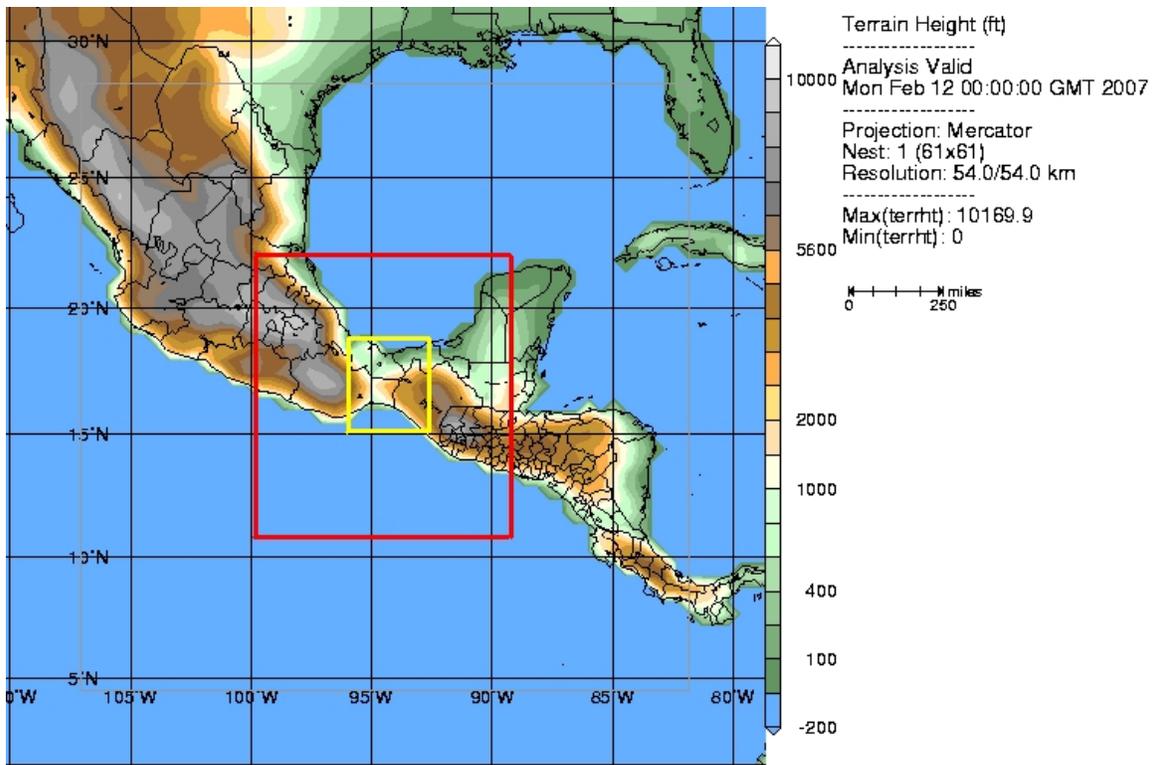
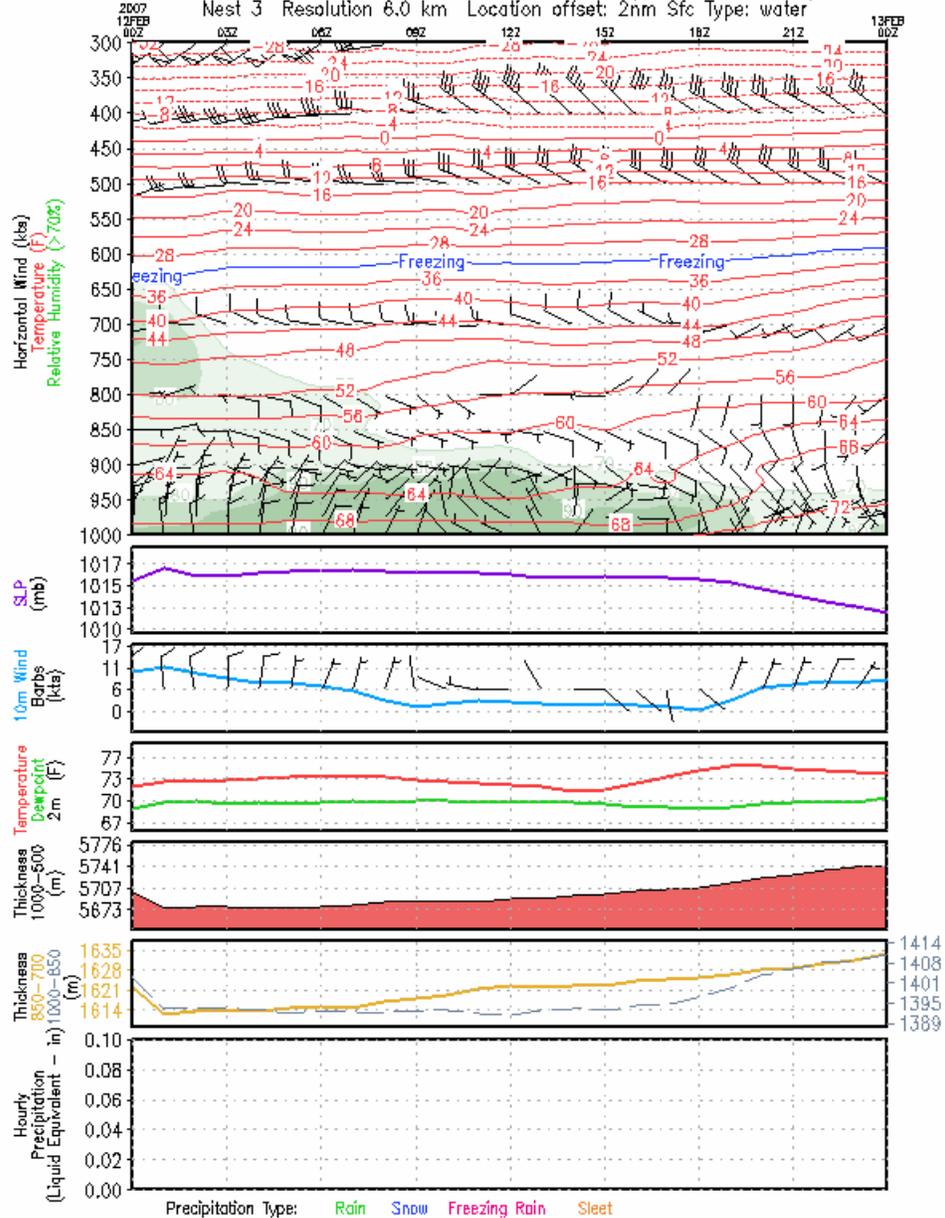


Figure 2. Domain used for COAMPS forecasting around the Gulf of Tehuantepec. The largest and coarser grid corresponds to the entire area shown, the middle and finer grid are marked in red and yellow, respectively. The spatial resolutions used are 54, 18 and 6 km.

During the class COAMPS was set up to run routinely over the Gulf of Tehuantepec producing hourly forecasts once per day. The nested configuration used is shown on Figure 2. The largest and coarsest grid had resolution of 54 km, the middle grid 18 km and the smaller grid had 6 km. Figure 3 shows two sample meteograms from the 24hr forecast for Feb 12th, 2007, the top (bottom) panel corresponds to a location on the northern (southern) side of Chivela Pass. A shallow northerly jet can be observed on the exit of the mountain pass, with a maximum vertical thickness of about 200 mb. The pressure difference across the mountain gap is greatest early in the day (between 00:00 and 03:00Z) with a maximum of about 3mb. The maximum wind speed attained at the exit of the gap is about 13kts. Figure 4 shows an example of the typical surface jet structure produced by COAMPS, the forecast time corresponded to 02:00 UTC, Feb 12th, 2007. The panel on the top shows surface wind streamlines and the right panel shows surface temperature, wind flags and pressure contours. The maximum winds are located over the ocean, reaching speeds of up to 20-30 knots, differing from the traditional funnel theory, which would predict maximum wind speeds at the center of the gap. The additional acceleration over the ocean near the exit of the flow may be attributed to the frictional change experienced by the flow going from land to ocean; the development of the boundary layer in offshore winds was previously by Taylor and Lee (1984). At the head of the Gulf the flow is strongest and narrowest, with a mean orientation due south. The jet extends for several hundreds of kilometers over the Pacific Ocean, expanding and weakening, while turning anticyclonically. The veering of wind-jet due west is due the

Coriolis acceleration (Bourassa et al., 1999) as gradual adjustment of the flow towards geostrophic balance, slowly turning parallel to pressure contours (see figure 4, left panel). Significant temperature differences between the Gulf of Mexico and The Gulf of Tehuantepec can be observed on Figure 4 (bottom panel), the surge of cold air can be identified as a tongue of cold air emerging from Chivela Pass, similar cold air tongue patterns had been observed in the numerical work by Steenburgh et al. 1998. Recent numerical investigations by Gabersek and Durran (2006) showed that significant contributions to the pressure difference across an idealized mountain gap were due to upstream blockage of the flow, on the high pressure side of the gap, as the flow turns towards the mountains due to surface friction. The surface streamlines shown on Figure 4, top panel, are consistent with Gabersek and Durran (2006) showing upstream blockage on the northern side of the gap.

COAMPS® Forecast Meteogram for 00Z12FEB2007  
 COATZACOALCOS 18.17N 94.41W (18.15,-94.42)  
 Nest 3 Resolution 6.0 km Location offset: 2nm Sfc Type: water



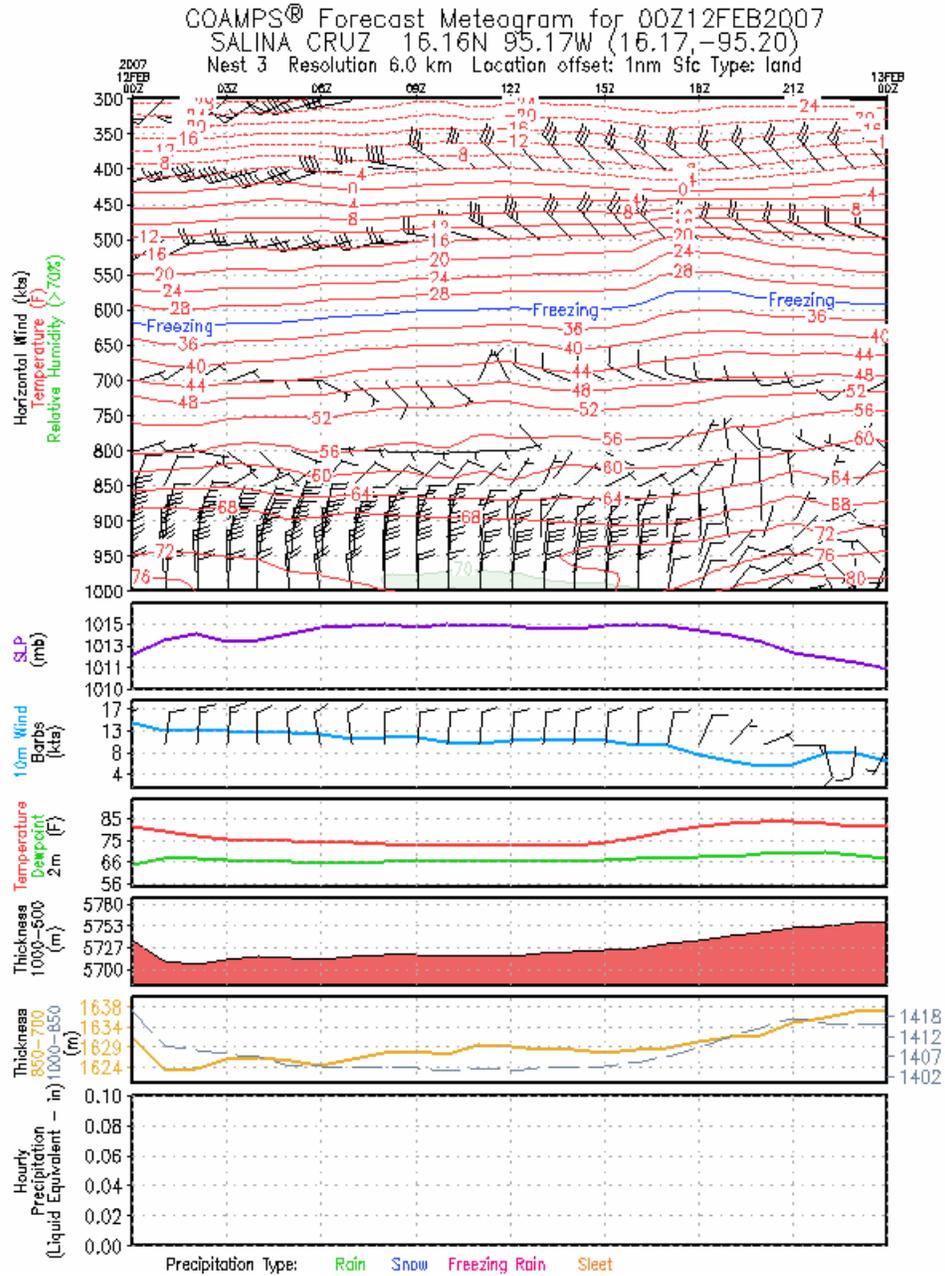
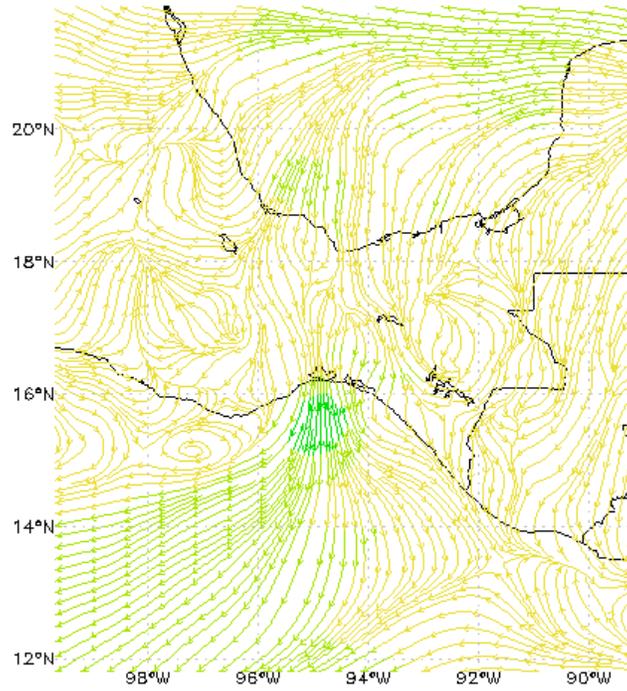


Figure 3. Meteograms for the Feb. 12th, 2007, COAMPS forecast. The top (bottom) panel is located on the entrance (exit) of the mountain gap.

NRL COAMPS-OS<sup>®</sup> Tehuantepec3 18.0km  
Valid Time: 02:00Z 12 2007 FEB Forecast: 02:00  
Base Time: 00:00Z 12 FEB 2007



10m Winds (kts) 

NRL COAMPS-OS<sup>®</sup> Tehuantepec3 18.0km  
 Valid Time: 02:00Z 12 2007 FEB Forecast: 02:00  
 Base Time: 00:00Z 12 FEB 2007

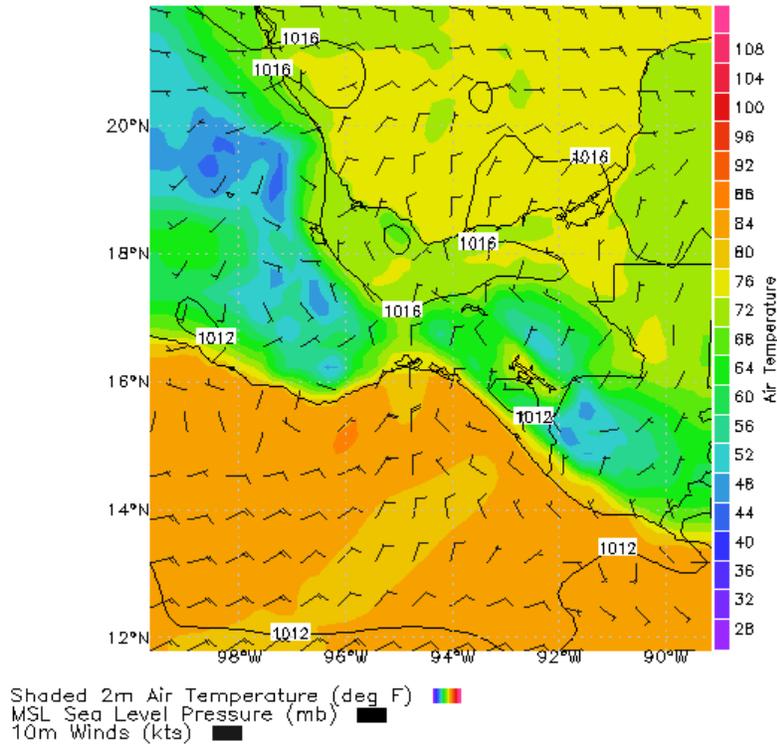


Figure 4. Top (Bottom) panel COAMPS surface wind (10m) streamlines (SST, surface pressure and wind flags) for Feb 12 at 3:00Z. By this time the jet had already been blowing for 2 full days. The maximum surface velocities predicted by COAMPS for this period are about 20 to 30 knots.

### R/V Revelle Project

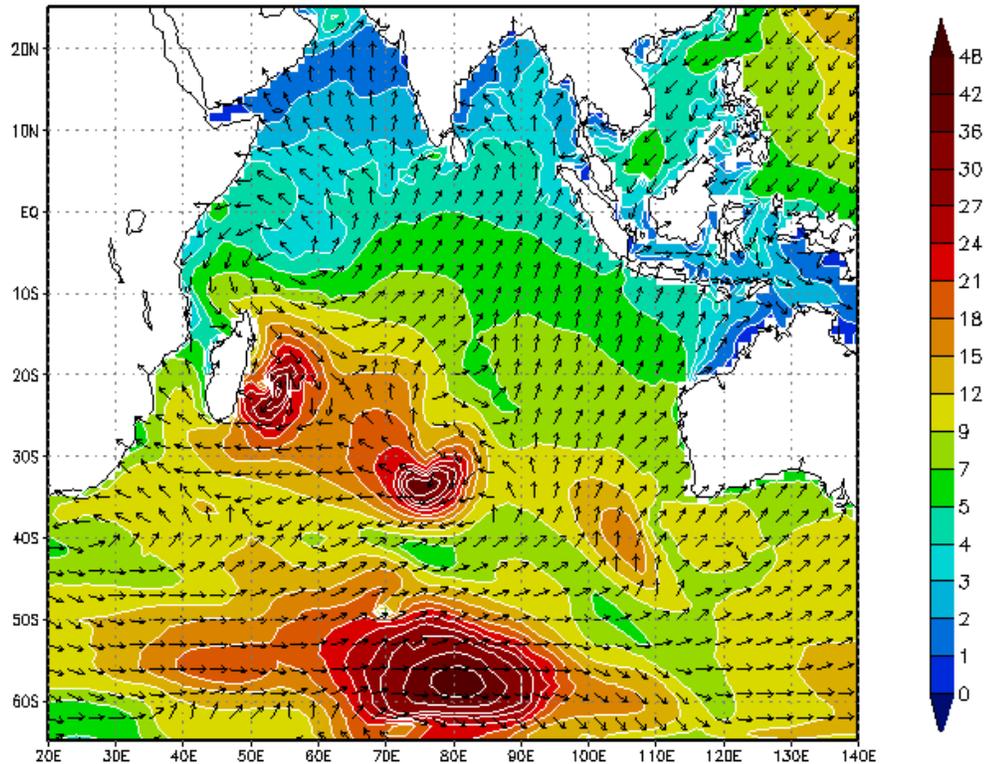
The unique nature of research at Scripps means that it is not uncommon to have students or faculty leaving during a term to travel to remote areas of the world. Since these regions may be not just at sea, but also outside of standard shipping lanes, accurate weather forecasts can be difficult to obtain. This was the case during our class when one of the students left for a six week cruise on the Research Vessel Revelle, which undertook an oceanographic survey that started in Dunedin, New Zealand in early February and ended in Fremantle, Australia in mid-March. The course was initially southwestward to about 65S, westward along the coast of Antarctica and then generally north-northeast through the Southern Indian Ocean. The path took it through the latitudes known notoriously as the “Roaring 40’s” and “Furious 50’s, where strong storms and high seas are relatively common.



Figure 5. The R/V Revelle, seen as it nears an iceberg near 65S

Forecasting for a ship at sea involves not just accurately forecasting the weather and sea state, but also, owing to the relatively low bandwidth available on the ship, choosing what to communicate graphically, what to communicate textually, and what to leave out. Strict bandwidth limits meant that it would be impossible for the ocean-going student to access the vast amount of model data available on the World Wide Web (WWW) or to have it transmitted to her. For this reason model data needed to be “cherry-picked” to provide the most useful information while not overloading the limited bandwidth of the ship. Since this was a class exercise it was important not to interfere with the active research that is taking place on board the ship, so we limited the attachments that we emailed to the ship to about 100 kilobytes. Initially we had some problems setting up the Revelle model in the COAMPS GUI, so that the first model data we sent was output from the GFS model. Additionally, we included output of the FNMOC’s Wave Watch 3 model, showing significant wave height and direction.

WW3\_GLOBAL Wave Height [ft] and Direction for 24FEB2007 00Z  
Valid 28FEB2007 00Z Forecast Hour 96



GRADS: COLA/IGES

2007-02-24-06:19

Figure 6. Wave Watch 3 forecast sent to R/V Revelle, showing area of forecast waves exceeding 25 feet through which the ship was scheduled to travel.

The problems with the COAMPS model were quickly fixed and we were able to set up a model domain centered on the Revelle with two grid resolutions: 61 x 61 gridpoints with 54 kilometer resolution and 46 x 46 gridpoints with 18 kilometer resolution. It would have been easy to include a higher resolution domain, but it was not deemed necessary since the ship was well out to sea so that there were no topographic features that would introduce small-scale perturbations. The larger domain produced output at 3 hour intervals out to 72 hours, while the higher resolution grid generated hourly output out to 48 hours. In contrast to most forecasting applications, the ship would move so that every few days the model would need to be re-centered on the new ship location.

The student that was onboard the ship was interested these forecasts professionally because her research involves coupled ocean-atmosphere models, but also because the weather and sea state was a prime contributor to her comfort (or lack thereof) while working on the ship. She was able to show the forecast data that she received to the ship's captain, who was interested in comparing it with his own sources of meteorological forecasts. Of course it was not the intention of the class forecasts for the ship to replace the primary system, but instead to be a "real-world" application of forecasting techniques that were being learned in the class.

NRL COAMPS-OS<sup>®</sup> Revelle1 54.0km  
 Valid Time: 00:00Z 05 2007 MAR Forecast: 72:00  
 Base Time: 00:00Z 02 MAR 2007

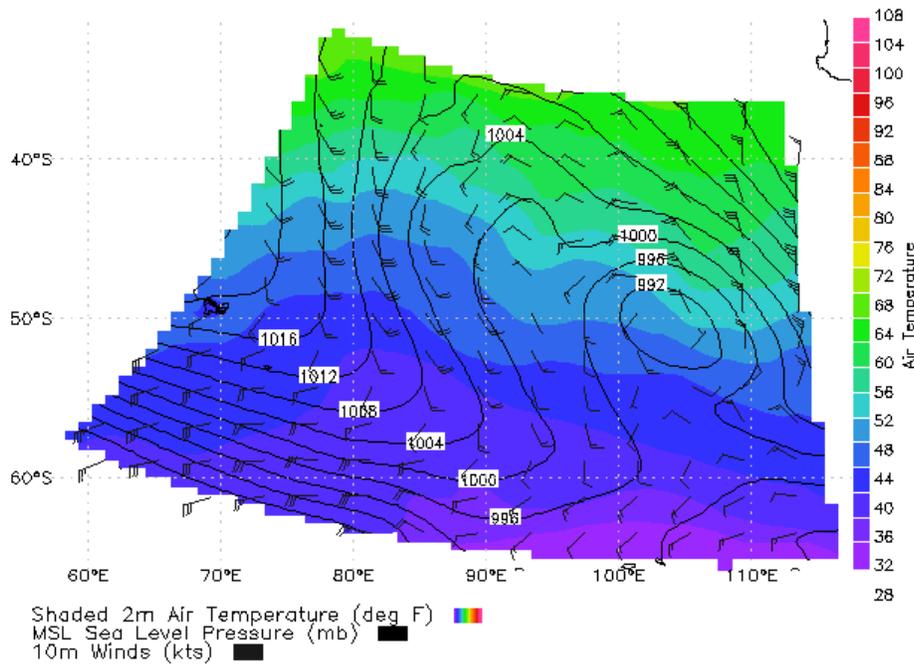


Figure 7. COAMPS output approximately centered on Revelle’s position, showing intense low pressure area the ship was skirting to the west

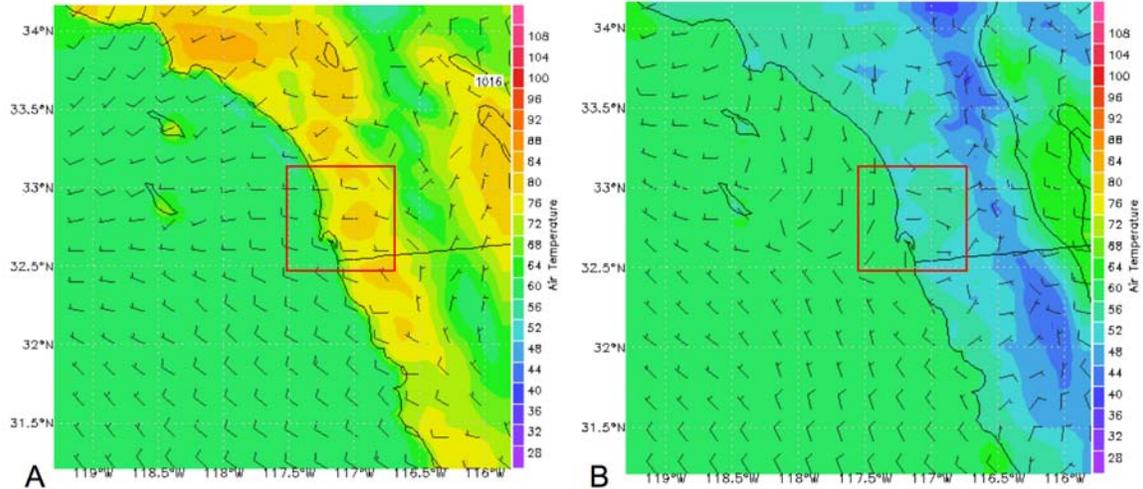
### **San Diego Sea Breeze**

One of the projects was to see how well COAMPS was capturing sea-breeze development by comparing model runs to local observations. Local observations were made using an Oregon Scientific WMR-100 weather station, with continuous online updates on wunderground.com using Ambient Weather’s Virtual Weather Station 13.1 for data acquisition. We mounted the weather station on the roof of Nierenberg Hall on the Scripps Institution of Oceanography campus.

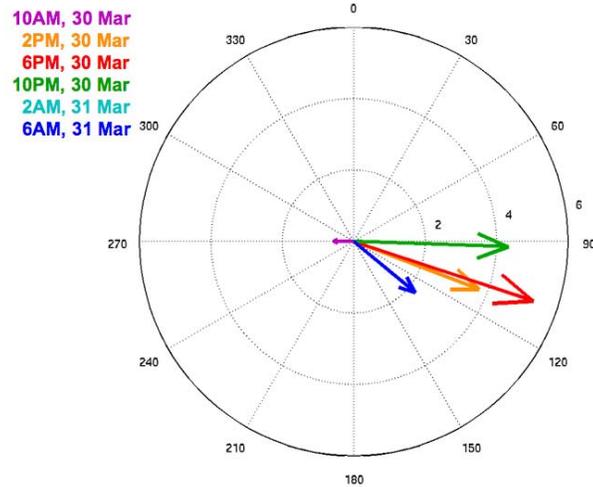
The model run had 3 nested grids centered around San Diego (32.7N, 117.5W), of 61x61 points with grid resolutions of 54 m, 18 m and 6 km. We analyzed the inner grid output. The outer grids were used to provide boundary conditions. The forecast model was run for 48 hours, assimilating new data every 12 hours and saving output on an hourly basis. The total running time was 4.9 hours, and total output files were 3 Gb. The forecast was reset every other day for 4 weeks, which allowed us to get a range of weather conditions.

The first example shows standard San Diego weather on March 30, 2007. Offshore wind is westerly and rather weak (around 5 knots), turning to northerly flow inland. The sea

breeze begins in the morning and reaches its maximum in the early afternoon (Figure 8a where 22UTC is 2pm local time) when the land-ocean contrast is highest. Wind turns from being northerly to being westerly. When night falls a land breeze forms, and the winds turns to an easterly direction (Figure 8b).

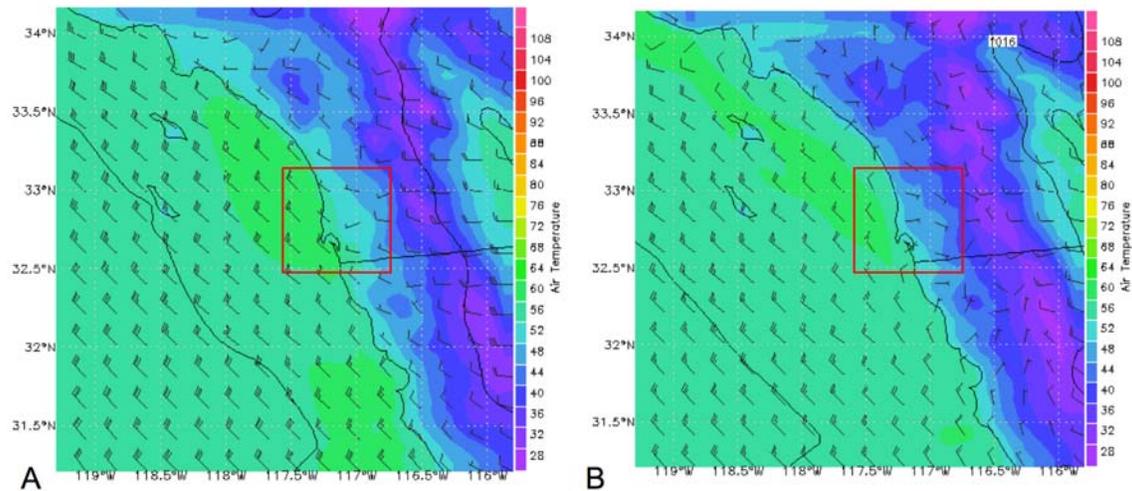


**Figure 8.** Output for COAMPS\_OS model run on March 30, 2007. San Diego is at the center of the red box. Contours are sea level pressure, shaded colors are 2 m air temperature, and arrows are 10 m winds. **A:** 22:00 UTC, 14:00 local time, forecast time: 22hrs. Temperature difference between land and ocean triggers a westerly breeze of 5 knots. **B:** 07:00 UTC March 31, 23:00 March 30 local time, forecast time 31 hrs. Cooler temperatures on land trigger a weak easterly land breeze inland, but it does not extend offshore.

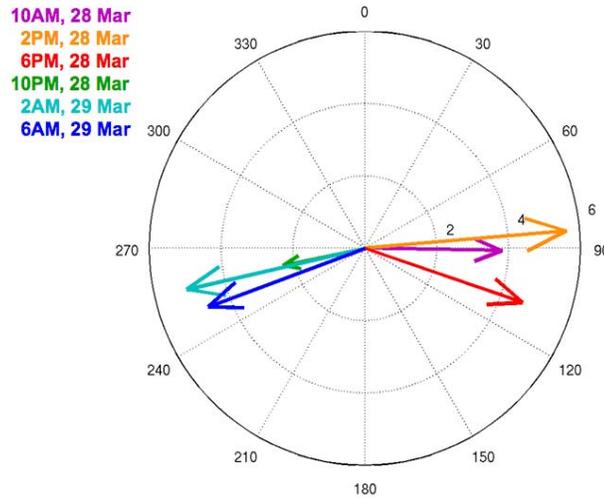


**Figure 9.** The diurnal wind pattern at the SIO weather station from the morning of March 30<sup>th</sup>, to the morning of the 31<sup>st</sup>. Arrows designate wind direction and strength, while orange, red, and purple designate daytime readings, and blue, green and cyan colors designate nighttime readings. Note the general absence of a land breeze at this coastal site (the 2am reading showed no measurable wind).

The land breeze is much weaker and the signal is more topographically influenced, but still noticeable inland. Figure 9 shows the weather station observations averaged over one hour each, at 4-hourly intervals from the approximate onset of onshore flow, extending 24 hours forward. The observations agree well with COAMPS, with weak winds dominated by a persistent westerly flow and an extremely weak land breeze forming at night. Note that at 2am the sensor was reading zero wind, and it is only in mid to late morning that a measurable easterly flow picks up. However, this is somewhat late in the morning for a land breeze and its value is so small that it may instead be due to micrometeorological influences.



**Figure 10.** Output for COAMPS\_OS model run on March 28, 2007. San Diego is at the center of the red box. Contours are sea level pressure, shaded colors are 2 m air temperature, and arrows are 10 m winds. **A:** 6:00 UTC, 22:00 March 27 local time, forecast time: 6hrs. There is a strong offshore north-westerly wind of 30 knots. The night land breeze is failing to set up. **B:** 12:00UTC, 4:00 local time, forecast time 12 hrs. Offshore wind has weakened and land breeze is clearly noticeable: wind on land turned easterly.



**Figure 11.** Same as Figure 10 except starting March 28<sup>th</sup>. Note the marked sea/land breeze cycle.

In the second example, there is a sustained northwesterly wind offshore (30 knots), which weakens the land/sea breeze cycle (Figure 10a). However, a westerly breeze is clearly visible in the observations (Figure 11), possibly due to the geography of the region. When the dominant wind weakens to less than 20 knots, the land breeze is able to appear and the wind direction on the coast is clearly easterly (figure 10b). On the following day, despite a very weak land-sea contrast, the land breeze is able to set in and the wind on land is clearly easterly. The observations generally agree better with the inland estimates of COAMPS. This may simply be a consequence of the averaging scale, causing coastal wind estimates to be skewed by the consistent northwesterly flow offshore. The land/sea breeze cycle is astonishingly clear in the measurements, showing a strong land breeze that reaches its maximum shortly before daybreak.

## ***Acknowledgements***

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