P3.22 NUMERICAL SIMULATION OF DIFFERENT COMPLEX TERRAIN FLOWS IN SOUTH-CENTRAL ALASKA: IMPLICATION FOR AIR POLLUTION TRANSPORT

Jeremy R. Krieger * and Jing Zhang
Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska

1. INTRODUCTION

Numerical simulations of the basic features of different flow fields in south-central Alaska are carried out in this study with a mesoscale regional model. South-central Alaska is an area characterized by extensive rugged mountain ranges and complex coastal topography. Over this highly complex terrain, a variety of different types of wind flows regularly occur, among them sea breezes, mountain valley nocturnal drainage flows, daytime upslope winds, gap winds, as well as downslope flows. In particular, we have chosen to focus our efforts on the Valdez basin. This basin consists of Port Valdez, a narrow inlet on the south-central coast of Alaska which opens into the broader Valdez Arm, and further into Prince William Sound. Port Valdez is ringed on all sides by steep mountains which help to isolate it from the general synoptic environment. Its only connection to the larger ocean is through a < 1 km-wide opening in its southwest corner, called the Valdez Narrows, a formation which can induce strong “gap” winds as air is forcibly channeled through. Moreover, the sharply rising mountains containing the basin can lead to the generation of strong downslope winds. The city of Valdez is located on the northeastern shore of the inlet, directly across from the Valdez Marine Terminal (VMT), which serves as the terminus of the Alaska oil pipeline. Oil tankers regularly come and go from the VMT, transporting oil from the North Slope of Alaska to ports all over the world. The VMT represents the primary source of air pollution in the basin, and due to the enclosed environment it is desirable to study the flow fields in this region.

We will present two case studies in this paper, detailing a typical summertime sea breeze situation and a more unusual downslope wind event. From the results of the simulations, we have been able to examine the features of the different flows which develop in this complex region and have a better understanding of the basic nature of air pollution transport in this area.

* *Corresponding author address:* Jeremy R. Krieger, Univ. of Alaska Fairbanks, Geophysical Institute, P.O. Box 757320, Fairbanks, AK 99775-7320; e-mail: jeremy@gi.alaska.edu

2. MODEL and CONFIGURATION

The Arctic MM5, developed by the Mesoscale Modeling and Applications Group at UAF based on the Penn State/NCAR mesoscale model MM5, is used to conduct the simulations in this study. The Arctic MM5 consists of the fifth-generation Penn State/NCAR mesoscale model (MM5), version 3.6, modified to incorporate a coupled thermodynamic sea-ice model (Zhang and Zhang 2001). Three one-way nested domains were set up as shown in Figure 1. The outer domain (D1), used to simulate the synoptic environment, is centered at 62 N latitude and 155 W longitude and has a horizontal coverage of 3700 km (east/west direction) × 3300 km (north/south direction) covering the entire Alaskan region, along with parts of Canada and Russia and a good part of the Arctic and northern Pacific Oceans. D1 has a grid resolution of 20 km and a total of 42 vertically stretched terrain-following sigma levels, which are closely spaced near the ground and more coarsely spaced with height to the model top at 50 hPa. The two inner domains (D2 and D3) have resolutions of 4 km and 1 km with dimensions of 51 by 61 and 45 by 65 points, respectively, and cover the south-central portion of Alaska east of the Kenai Peninsula, along with the whole of Prince William Sound (D2), and the Valdez region including Port Valdez, the Valdez Arm, and much of the enclosing mountain ranges (D3). In order to effectively simulate boundary layer winds which were the focus of this study, both inner domains have a very high resolution vertical structure consisting of 62 sigma levels, with a near-surface vertical resolution of ~ 15 m and the lowest half-sigma level having a height of ~ 8 m.

Physics parameterization schemes used include the MRF planetary boundary layer scheme (Hong and Pan 1996), NOAH land-surface model (Mitchell et al 2002), in which a thermodynamic sea ice model is coupled, modified CCM2 radiation scheme (Cassano et al. 2001), modified Reisner microphysics scheme without graupel (Cassano et al. 2001), and the Grell (1993) convective parameterization. The latter is used only on the outer domain D1; on the inner domains D2 and D3 the resolution is sufficient to resolve convection.

All simulations were initialized on the outer domain D1 by NCEP/NCAR reanalysis data, which has a resolution of 2.5° × 2.5°. The lateral boundaries of the outer domain were nudged at six-hourly intervals by reanalysis data as well. The sea ice model was initialized by data provided by the Marine Modeling and Analysis Branch of NCEP's Environmental Modeling Center, with a resolution of 0.5° × 0.5°.

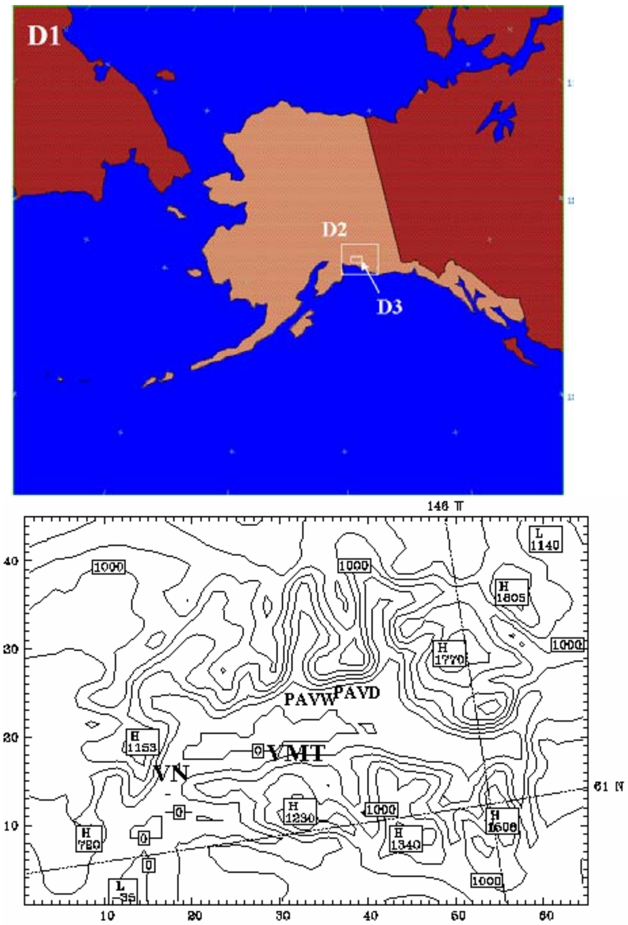

Figure 1 Domain configuration for the case studies - D1 has a resolution of 20 km, D2 4 km, and D3 1 km. A closeup of D3 is also given, with elevation contoured at intervals of 250 m. The Valdez basin, our focus in this study, is situated in the center of the small domain, and locations of the Valdez WSO (PAVW), Valdez Airport (PAVD), Valdez Marine Terminal (VMT), and Valdez Narrows (VN) are noted.

3. VERIFICATION DATA

Unfortunately, there exist only two surface stations in the Valdez domain, located very near to one another, and no upper-air observations in the Valdez basin, making verification of modeling results a challenge. The two surface stations are the Valdez Weather Service Office, located in the city of Valdez (labeled PAVW), and the Valdez Airport (PAVD), situated less than 5 km to the east of PAVW. Also labeled on the diagram are the Valdez Narrows in the southwest portion (VN), and the Valdez Marine Terminal (VMT), the major source of pollution in the basin.

4. CASE STUDIES

4.1 *Sea breeze*

For the first case study analyzing winds in the Valdez region, we chose to look at a typical sea breeze situation representative of much of the spring and summertime wind regime around Port Valdez. While this is not a very complex situation, its prevalence in the spring and summer months means that understanding it is nevertheless important for those who wish to analyze potential air pollution impacts in the region.

For this particular case, the outer domain D1 was initialized on 11 July 2003 at 18 UTC. Domain D2 was initialized six hours later (to allow for spin-up of domain D1) at 00 UTC 12 July, and the Valdez domain D3 six hours after that at 06 UTC. All domains were run out to 12 UTC 13 July, encompassing the July 12 diurnal cycle. This case was chosen due to the presence of a weak ridge over the area of interest and hence little synoptic forcing.

Figure 2 shows a time series of observed surface wind speed and direction for the Valdez city station (PAVW), along with the corresponding values from the lowest model level (~ 8 m) of the 1 km domain, taken from the closest grid point. The observed sea breeze starts to pick up at ~ 18 UTC (~ 9 am, LST) and peaks at ~ 8 m/s from the west at 02 UTC (~ 5pm, LST). The model captures the timing of the cycle and direction of the surface wind reasonably well. Unlike others who have found MM5 to produce a too-strong sea breeze (Soler et al., 2003; Hong, 2001), however, in our case the magnitude of the peak is too small, being just over 3 m/s. PAVD (not shown) has a similar pattern as that for PAVW, but with a decreased amplitude for both observations and model data due to its increased distance from the coastline and more eastward location, resulting in a smaller sea breeze effect.

A possible explanation for this discrepancy could lie in the model's topographical resolution. As shown in Figure 3, the sea breeze enters the basin through the Narrows, its acceleration driven by its forced channeling through the gap.

Unfortunately, it is possible that even with the 30" topography available (roughly 1 km resolution) that the opening is not sufficiently resolved in order to allow the incoming breeze to be accelerated to a sufficient speed. This in turn may result in the peak winds not penetrating far enough into the basin, causing the magnitudes at the far end (where PAVW is located) to be too small. Supporting this idea is a similar time series shown in Figure 4, this time of a grid point located two points to the west and two to the south from that in the Figure 2. Here, the timing, direction, and now magnitude of the observed wind are all replicated quite well.

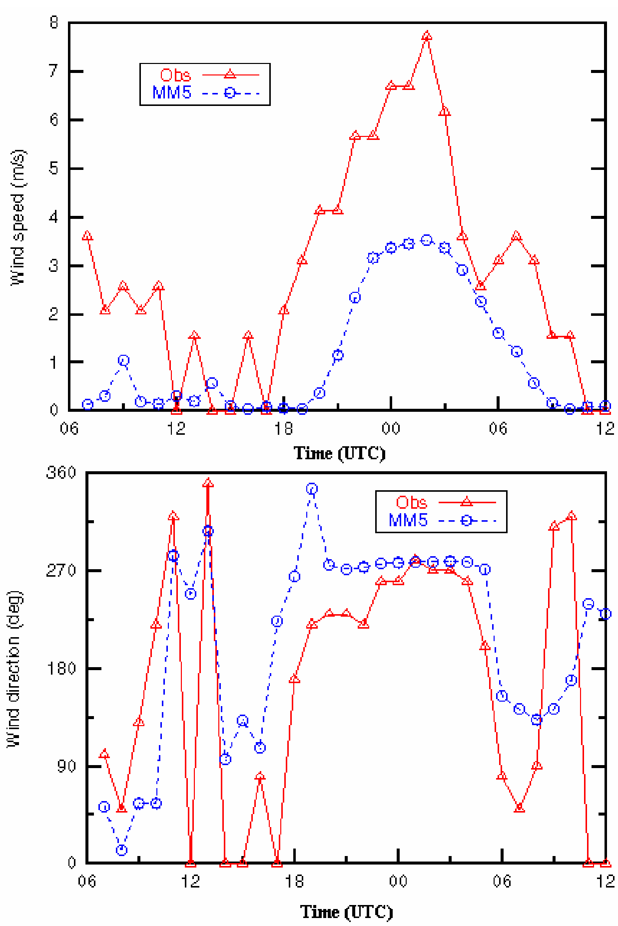

Figure 2 Surface wind speed (top) and direction (bottom), observed at PAVW (solid red, triangles) and from the closest grid point in MM5 (dashed blue, circles) from 07 UTC 12 July through 12 UTC 13 July.

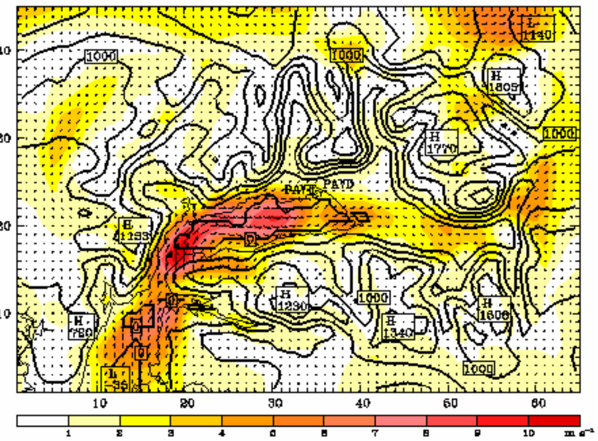

Figure 3 Near-surface wind speeds (colors) and vectors at 01 UTC 13 July for domain D3, near the time of maximum modeled wind speed in Valdez (PAVW). The sea breeze is sharply accelerated through the Narrows as it enters the basin.

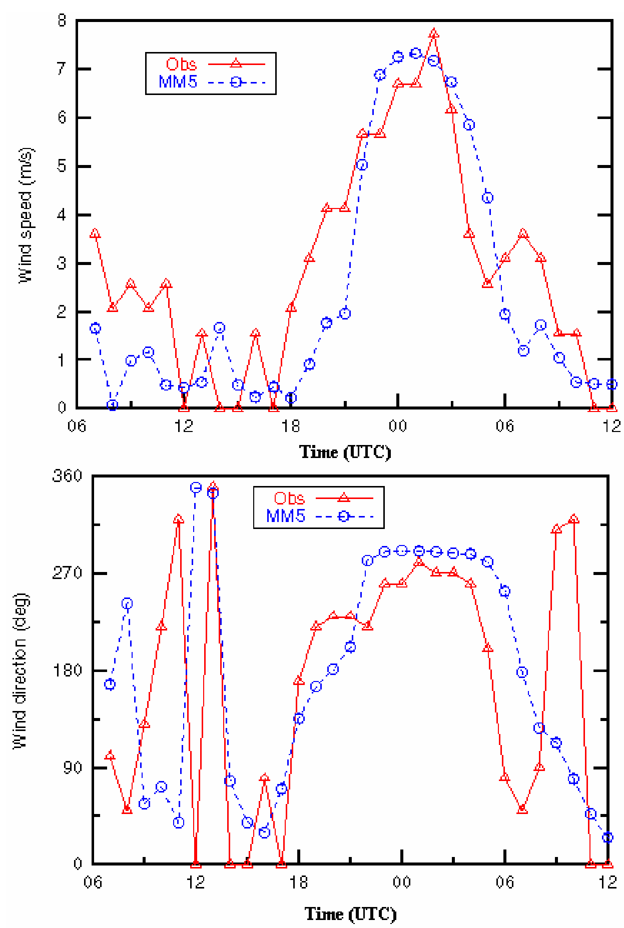

Figure 4 Same as Fig. 2, but for a model grid point two points to the west and two to the south of PAVW

Another possible source of error is that the location of the station in the model's grid space may be slightly different from reality, due to rounding in the official latitude and longitude of the station. This region has very sharp topographical gradients, and a difference of a grid point or two can make a substantial difference in the wind profile.

From an air pollution standpoint, it can easily be seen that in the case of a sea breeze, near-surface winds would tend to direct any pollutants from the VMT toward the south and east, away from the population center to the north. The only potential impact on the city would be from exhaust from shipping traffic passing through the inlet. Figure 5 shows the trajectory of several air parcels released in the Narrows during midday, at a height of ~ 25 m, from 20 UTC until 22 UTC, as calculated by the RIP software package (Stoelinga, 2003). Under these conditions, the parcel is advected into the urban area within one to two hours, though this is likely a very minor effect.

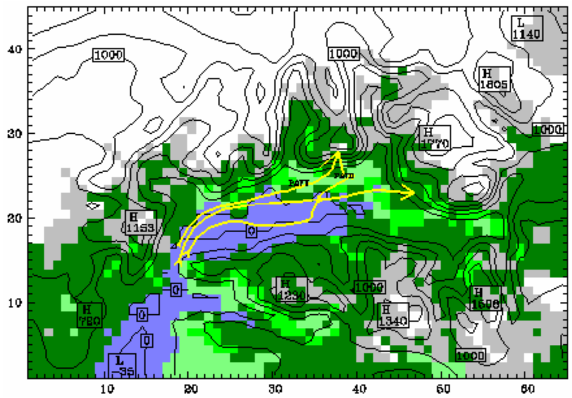

Figure 5 Trajectories (yellow arrows) calculated from 20 to 22 UTC 12 July originating from points near the entrance to Port Valdez at a height of ~25 m. Colors represent land use (greens are vegetation, gray is sparsely vegetated land, white is permanent ice, and blue is water) and elevation is contoured in increments of 250 m. Parcels released from the Narrows in midday are quickly advected over the city of Valdez (PAVW) and the population centers to the northeast.

4.2 *Downslope wind*

For our second case study, we have simulated a strong downslope wind event which impacted the Valdez basin from 13-17 September 2003. During this time period, a developing low pressure system formed in the Gulf of Alaska, traveling to the northeast until stalling near the Alaskan panhandle before finally tracking southward along the coast as it weakened. The presence of a stationary high pressure center over central Alaska resulted in a tight, persistent northwest-southeast pressure gradient over the Valdez region, a situation favorable for the development of strong north-to-northeasterly winds. Valdez sits at the foot of the Chugach mountain range to its north, and so under such synoptic conditions a strong downslope wind penetrates into the basin. Figure 6 shows the sea-level pressure field from the NCEP reanalysis near the time of maximum observed wind in Valdez.

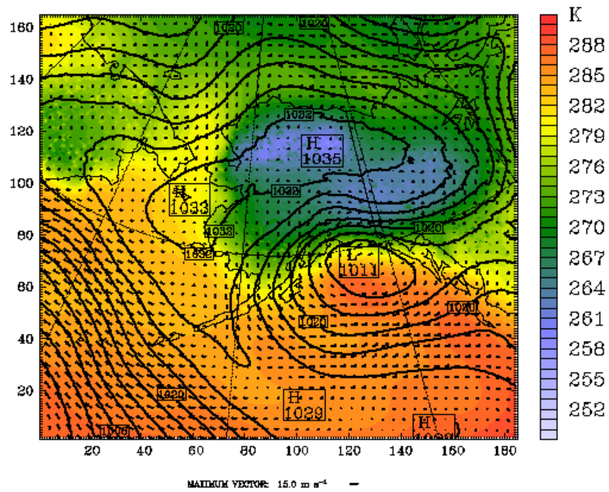

Figure 6 NCEP reanalysis surface temperature (K) (colors), wind field (vectors) and sea level pressure (mb) (contour) at 18 UTC 14 Sep.

For this case, domain D1 was initialized at 00 UTC 13 Sep, D2 at 03 UTC, and D3 at 06 UTC. All domains were run through 00 UTC 17 Sep.

As before, the surface observation and lowest half-sigma level winds for PAVW are plotted in Figure 7, along with those from PAVD in Figure 8. Again, modeled wind speeds from the closest grid points indicated errors associated with being situated too close to the mountains (i.e. excessively strong downslope flow), so the figures instead show data from one gridpoint to the south of each station. For both stations, the overall timing of the beginning and ending of the event are very well represented, as are the magnitude of the peak winds.

For PAVD, wind direction shows generally good agreement, capturing the overall northeasterly flow along with the short-term wind shifts around 09 UTC Sep 14 and 03 UTC Sep 15, with the largest deviations occurring near the start and finish of the period during times of low wind speeds, when observed direction is less reliable. Speeds for PAVD are a bit too weak early and too strong late in the period.

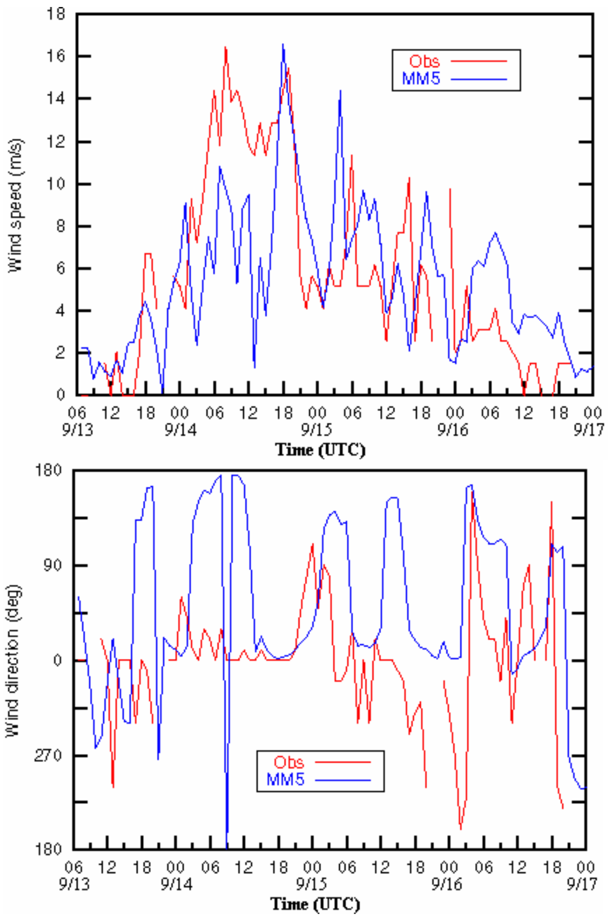

Figure 7 Observed (red) and modeled (blue) wind speed and direction for PAVW for the downslope wind event.

Speeds at PAVW, on the other hand, are modeled reasonably well, with the overall pattern well-simulated. However, there are a few periods, most notably from around 03 to 13 UTC Sep 14 (~ 6 pm to 4 am LST), along with shorter periods on Sep 15, when the modeled wind, rather than being a downslope wind from the north, instead shifts to an off-ocean, southeast-to-southerly flow. Since the VMT lies on the south shore of Port Valdez, accurately modeling wind from this direction is particularly important.

For a clue as to an explanation for this unobserved wind shift, it is helpful to look at a north-south cross-section through the city of Valdez, shown in Figure 9. From this diagram, it can be seen that the strong downslope winds, warmed via compressional heating, are forced aloft shortly after reaching the floor of the basin due to buoyancy created by the temperature difference between the warm downslope wind and the colder boundary-layer air over the water. This rising air induces a return flow in the lower levels (not unlike a sea breeze circulation), resulting in a more southerly wind along the surface. This

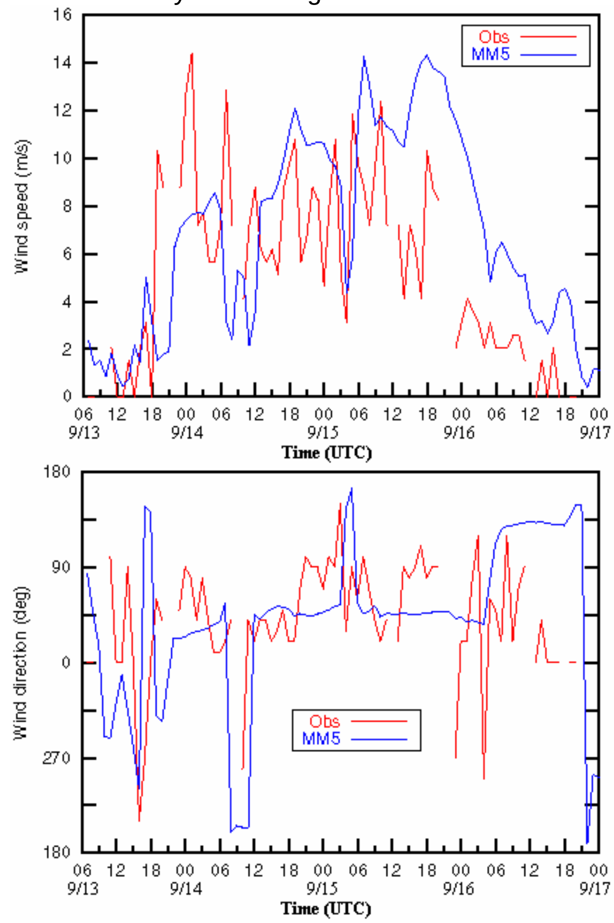

Figure 8 As in Fig. 7, for station PAVD.

phenomenon is naturally strengthened during the nocturnal hours, as the marine boundary layer cools and enhances the effect, suggesting why the significant directional differences at PAVW are seen primarily at night.

Accurately modeling the position of the convergence line between downslope and off-ocean flow is thus paramount in being able to correctly represent the winds observed in Valdez. For this case, since there is no observational evidence of such a southerly flow, it is very possible that the magnitude of the downslope wind is simply too small. This could cause the convergence line to be located too far to the north, with the southerly return flow penetrating too far inland, particularly at night. If a weak downslope wind is the culprit, extending the 1 km Valdez domain farther to the north in order to better resolve the northern mountain range should result in more accurately represented winds over the floor of the basin. Another potential source of error is in the misrepresentation of the sea surface temperature in the basin. If this were too cold, it might erroneously exacerbate the temperature gradient between the warm downslope wind and the cooler air over the ocean, resulting in exaggerated buoyancy and excessive lifting of the downward flow, causing the southerly, off-ocean flow to be increased as well.

5. SUMMARY

This study has analyzed the wind field features of a typical summertime sea breeze and an unusual downslope wind event and their relation to air pollution problems over the topographically complex Valdez basin by means of numerical modeling with the Arctic MM5. The analysis reveals that the model captures the timing of the cycle and direction of the sea breeze reasonably well, though the magnitude of the peak is too small. One possible reason for the weaker modeled sea breeze could be the model's topographical resolution. The sea breeze enters the basin through the Narrows (<1km), which isn't sufficiently resolved in the model, and thus the incoming breeze cannot be accelerated to a sufficient speed. As for the relation between sea breezes and air pollution within the basin, this case study shows that the sea breeze would direct any pollutants from the VMT toward the south and east, away from the population center to the north.

As for the downslope wind event, the timing of the beginning and the ending of the strong winds have been successfully simulated by the model. Modeled wind direction and magnitude of the peak winds show generally good agreement with the observations as well. There are a few periods, however, when winds are modeled as southerly flows rather than the observed downslope wind from the north, which may result from either a too-cold ocean surface temperature or a too-weak downslope wind. From an air pollution standpoint, accurately modeling wind from the south is particularly important since the VMT lies on the south shore of Port Valdez. This remains a significant challenge for wind field simulations over this highly complex terrain.

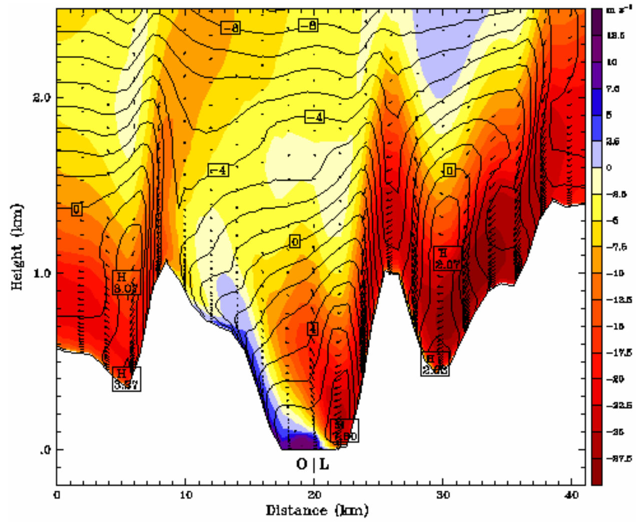

Figure 9 S-N cross-section through PAVW in the Valdez domain (D3) at 07 UTC Sep 14. Colors are model v-component wind (m/s), with warm colors representing northerly, cool representing southerly flow. Solid contours are of temperature (C), every 1 degree. The "O|L" designation signifies the ocean/land boundary on the basin floor.

6. REFERENCES

Cassano, J. J., J. E. Box, D. H. Bromwich, L. Li, and K. Steffen, 2001: Evaluation of polar MM5 simulations of Greenland's atmospheric circulation. J. Geophys. Res., **106**, 33 867 – 33 890.

Grell, G., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev.,* **121**, 764-787.

Hong, J-S, 2001: The evaluation of the high-resolution model forecasts over Taiwan during GIMEX. Int. Conf. on Mesoscale Meteorology and Typhoon in East Asia, Taipei, Taiwan.

Hong, S.Y., and H.-L., Pan, Nonlocal boundary layer vertical diffusion in a medium-range forecast model, *Mon. Wea. Rev*., **124**, 2322-2339, 1996.

Mitchell, K., et al, 2002: Reducing near-surface cool/moist biases over snowpack and early spring wet soils in NCEP ETA model forecasts via land surface model upgrades, Preprints, 16th Conference on hydrology, Amer. Met. Soc., January 2002, Orlando, FL.

Soler, M.R., et al, 2003: Analyzing the basic features of different complex terrain flows by means of a Doppler Sodar and a numerical model: Some implications for air pollution problems, *Meteorol. Atmos. Phys.*, **85**, 141-154.

Stoelinga, M.T., 2003: A User's Guide to RIP Version 4: A program for visualizing mesoscale model output (*http://www.mmm.ucar.edu/mm5/documents/ripug_v4.html*)

Zhang, X., and J. Zhang, 2001: Heat and freshwater budgets and pathways in the Arctic Mediterranean in a coupled ocean/sea-ice model, *J. Oceanography*, **57**, 207-237.

Acknowledgments

This work was supported by funding from the University Partnership for Operational Support.