4.12 NEW ENGLAND COASTAL BOUNDARY LAYER MODELING

Mark Žagar and Michael Tjernström*
Stockholm University, Stockholm, Sweden

Wayne Angevine
CIRES, University of Colorado, and NOAA Aeronomy Laboratory, Boulder, Colorado

1. INTRODUCTION

Coastal areas are among the most highly populated, with consequences for effects on health and on the ecosystem from emissions of different pollutants to the sea and the air. At the same time, the presence of the coastline itself poses problems in the understanding, monitoring and forecasting of transport and dispersion of pollutants in the atmosphere. The coastline constitutes a step-change in all surface parameters: surface roughness, temperature, terrain height etc. The responses in the lower atmosphere – the boundary layer – are many and diverse, but the most commonly known resulting circulation system is the sea breeze.

The sea-breeze is probably the most prototypical mesoscale circulation, and it was also one of the very first to ever be simulated in high-resolution numerical models (cf. e.g. Estoque 1961). With the development of more advanced models over the last several decades, the sea-breeze has been revisited many times (e.g. Colby 2004, Marshall et al. 2004). With all the efforts invested, one would think that we should know by now, almost all there is to know about this phenomenon. However, although the basic theoretical background well understood and is simple enough, the actual appearance of the sea breeze is complicated by its high sensitivity to real environmental complexities such as variations in coastline orientation, coastal terrain and differential heating of inland areas due to variations in land use.

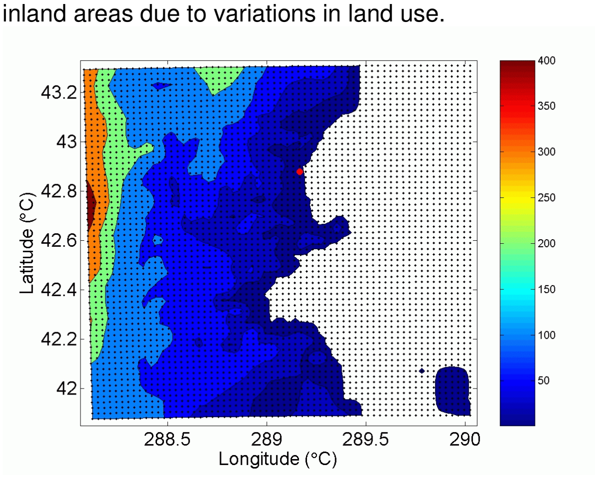

Figure 1. The NEAQS model domain, showing terrain heights in color shading, model grid points (black dots) and the target area for this study (red dot). The northeast corner of Cape Cod is visible in the lower right corner of the domain and Boston is situated in the bay south of the model center.

* ***Corresponding author address:*** **Michael Tjernström, Stockholm University, Department of Meteorology, SE-106 91 Stockholm, Sweden. Email:** mark@misu.su.se

The need to better understand this complex system partly arises from its large impact on transport and dispersion of airborne pollutants. When pollutants from coastal emissions are transported out over colder water, the increased static stability reduces mixing, maintaining high local concentration. If a sea breeze subsequently transports air in over land again, this can lead to high concentrations of pollutants at locations very far from the emission sources. The exact timing of mesoscale circulations with respect to emissions and to the time scales of chemical conversions is critical.

The New England Air Quality Study (NEAQS 2002) (e.g. Angevine et al. 2004a b, http://www.al.noaa.gov/neaqs for details) was conducted in July and August 2002. The background to NEAQS is the frequently exceeded regulatory standards for ozone along the coast of New Hampshire and Main, in spite of limited local emissions of pollutants. These are instead located farher south,

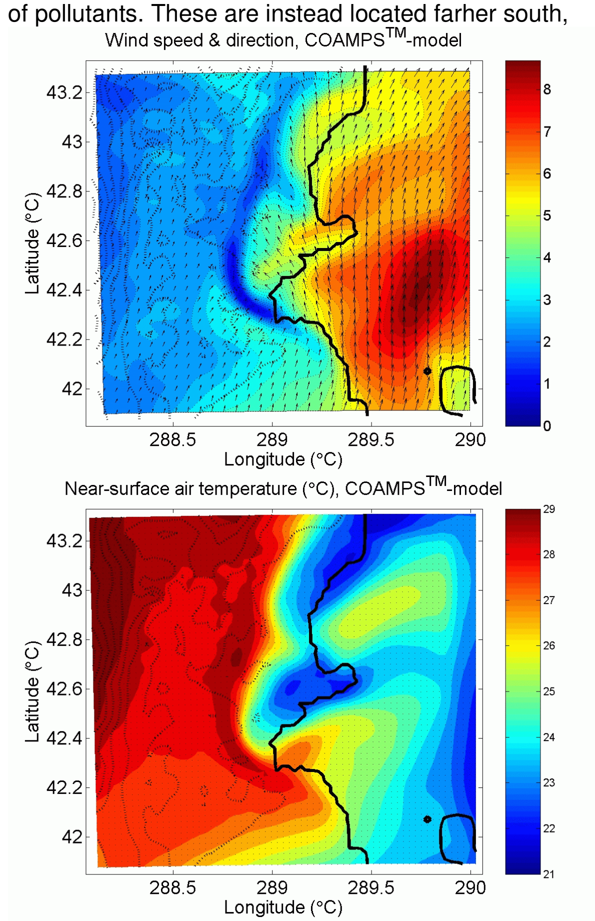

Figure 2. Simulated COAMPS™-model fields of (top) wind speed (shading) and direction (arrows, every other grid point) and (lower) 1 m potential temperature at 1600 local time on 14 August 2002.

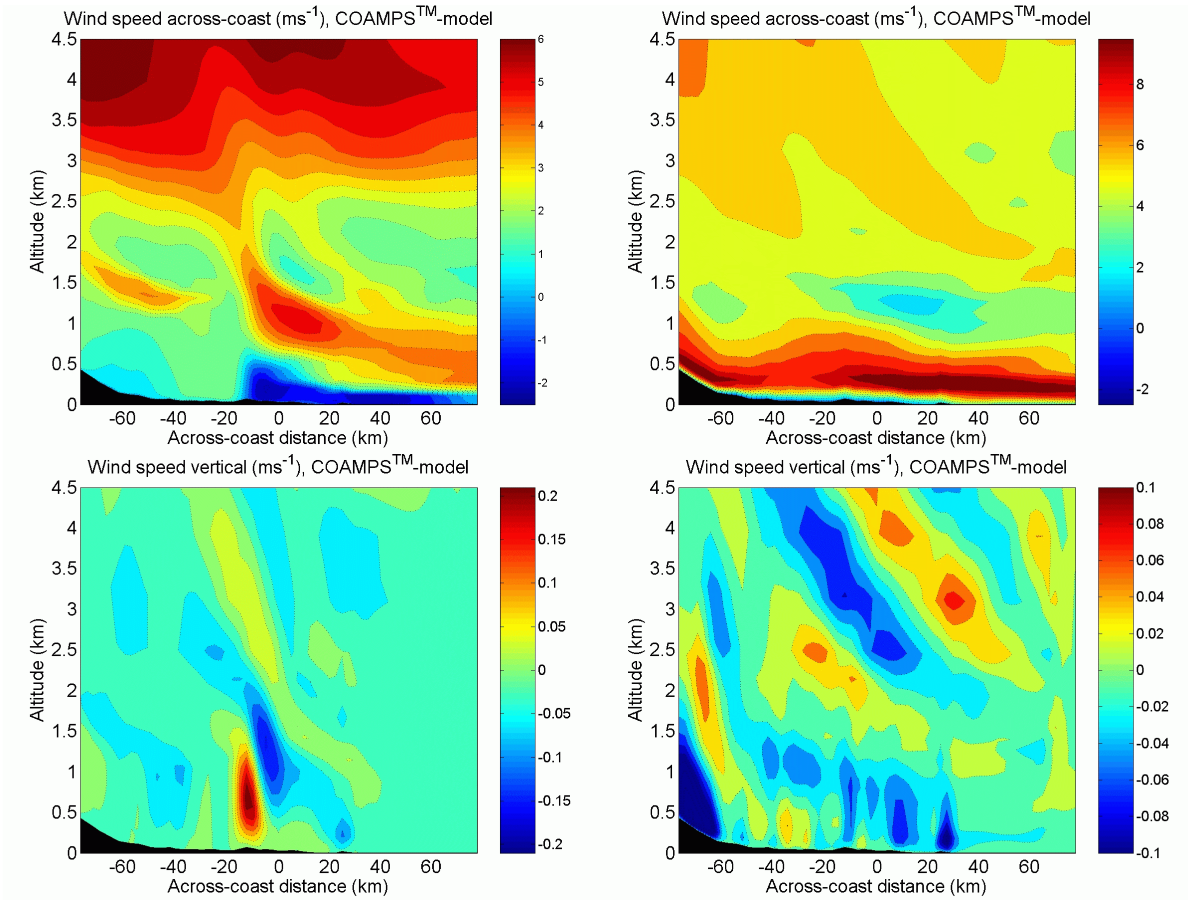

Figure 3. East-west cross-sections of (top) across-coast and (bottom) vertical wind speed (ms^{-1}) at (left) 16.00 local time 14 August, and (right) 02.00 local time the following night, through the location marked with a red dot in Figure 1.

e.g. along the Boston/New York metropolitan corridor and are often transported to these coasts across colder ocean water; a persistent pool of cold water typically exists offshore in the northern and eastern Gulf of Maine and the Bay of Fundy. As a result, high-pollution episodes here are often not related to stagnation periods, as in some other highly polluted coastal areas, for example Los Angeles in California or Athens in Greece.

2. METHOD

The aim of this study was to investigate effects of the sea breeze in this area and to attempt to isolate the effect of inherent sea breeze dynamics from the effects of local physiography, such as differential inland heating, local terrain and the interaction of the background flow with the complex local orientation of the coastline (see Figure 1). The strategy is to perform idealized 2-D model simulations using prescribed forcing based on an analysis of fully 3-D model results.

The 3-D model used here was the COAMPS™ model, developed at the Naval Research Laboratory in Monterey, California, (Hodur 1997). Real case simulations were performed with COAMPS™ for two pollution episodes (see Angevine et al. 2004b). The preliminary study discussed here focuses on an event in August 2002, starting on the 11th and persisting for four days (Figure 2-3). Initial conditions, background wind profile and surface temperatures were extracted from the fully 3-D COAMPS™ simulation and were used to drive 2-D simulations with the MIUU model (e.g. Enger 1990).

COAMPS™ was run with three consecutive grids, with a resolution of 2.5 km in the inner nest. The MIUU model utilize a stretched variable horizontal grid, with a ~ 3-km resolution at the coastline, employing 80 x 60 grid points over a 600 x 5 km^2 domain. Vertical resolution was comparatively high in both models. COAMPS™ had 40 levels, 13 below 1 km and 5 below 100 m, while the MIUU-model has a log-linear vertical coordinate with a 2-m resolution at the surface gradually degrading to ~ 100 m at the model top.

3. SOME 3-D COAMPS™ MODEL RESULTS

Results from COAMPS™ are illustrated in Figures 2-3. Figure 2 shows fields of near-surface wind speed and temperature at 16.00 local time on 14 August, when the sea breeze on this day is at its maximum. Two connected sea breeze systems are quite clear in both wind speed and temperature, with a front running in an arc from south of Boston to Portsmouth. The inland wind speeds are quite small, while to offshore winds are predominantly from south roughly along the coast. The background winds at only a few 100 m (not shown) are however directed off shore.

The sea breezes are the strongest in the bays north and south of Cape Ann. The east-west cross-sections in Figure 3 are taken across the northern bay at the location indicated in Figure 1. The depth of the sea breeze circulation is ~500 – 600 m deep and only penetrates ~ 15 km in the east-west direction (top left). The structure of the sea breeze front resembles a gravity current, and the convergence zone, as it runs into the offshore background flow, triggers a gravity wave (lower left). The offshore branch of the circulation is thus a pronounced part of a standing wave rather than a weak return flow. There also seems to be a second weaker gravity wave that may be connected to the terrain farther inland, interacting with the westerly flow aloft. At night, the pattern is completely different. Instead of a weak night breeze, expected if the inland temperature had become sufficiently cool, there is a strong offshore flow in the boundary layer and a down-slope flow branch farthest to the west. The low-level wave pattern is gone but the wave aloft, possibly associated with the terrain to the west is pronounced.

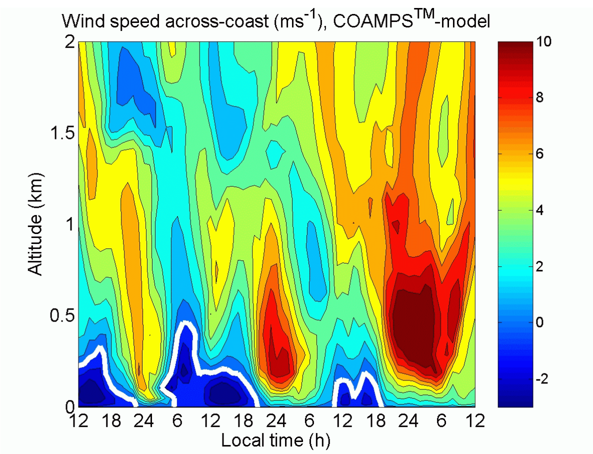

Figure 4. Time-height cross-section of across-coast wind speed from COAMPS™ at the location of the red dot in Figure 1. The white line is the zero isoline.

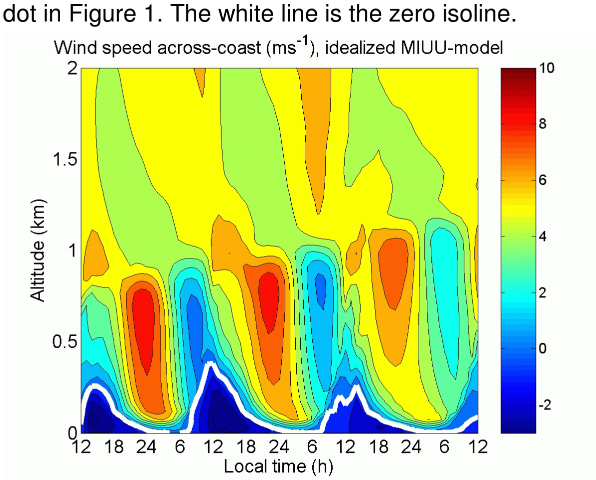

Figure 5. Same as Figure 4, but for the MIUU model.

Figure 4 shows cross-coast flow at the location of the red dot in Figure 1 as a function of time. There is variability on many scales, some of which that would not be expected to be captured in an idealized model. Some more general features are worth noticing. The strongest winds occur not in the sea breeze but at night, with wind speeds of ~ 6 – 10 ms^{-1}. The sea breeze circulations are ~ 400 – 500 m deep at this location and lasts about half the day, from 06.00 to 18.00 local time. One question of interest is what is causing the strong offshore flow during the night. One possibility is an inertial oscillation triggered when the sea breeze collapses. Another is that it is tied in with the gently sloping terrain to the west.

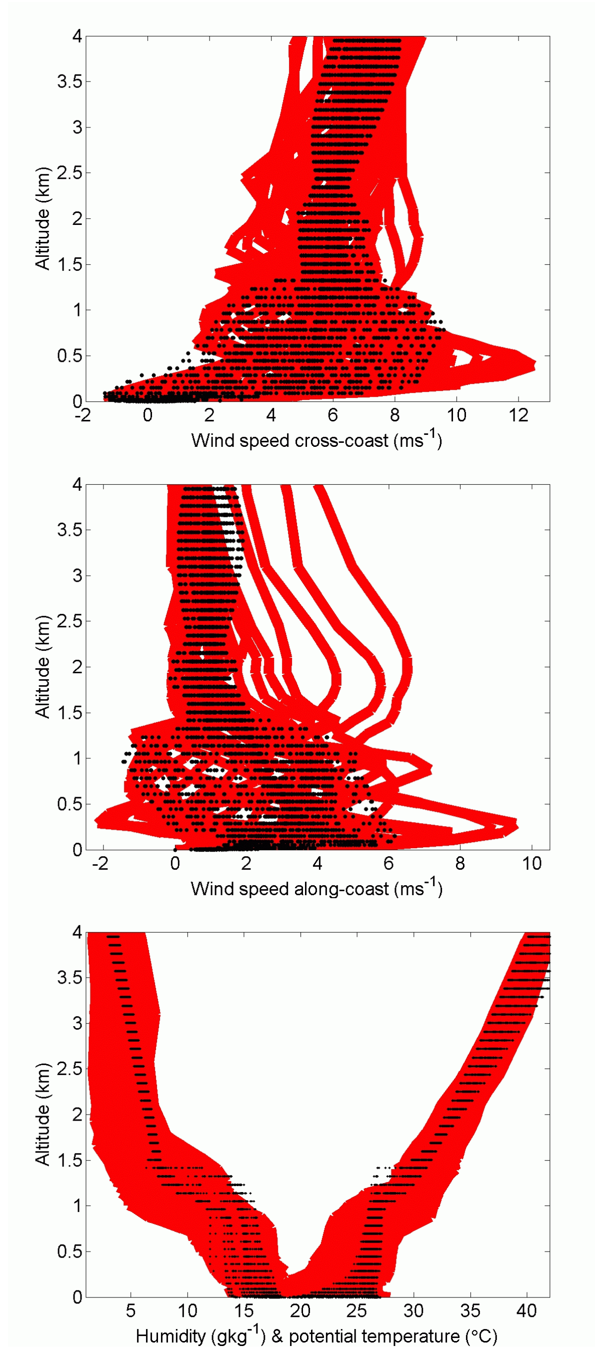

Figure 6. Comparison of wind speed (u – top, v – middle, ms^{-1}), and potential temperature (ºC) and humidity (gkg^{-1}) profiles from COAMPS™ (red) and MIUU (black).

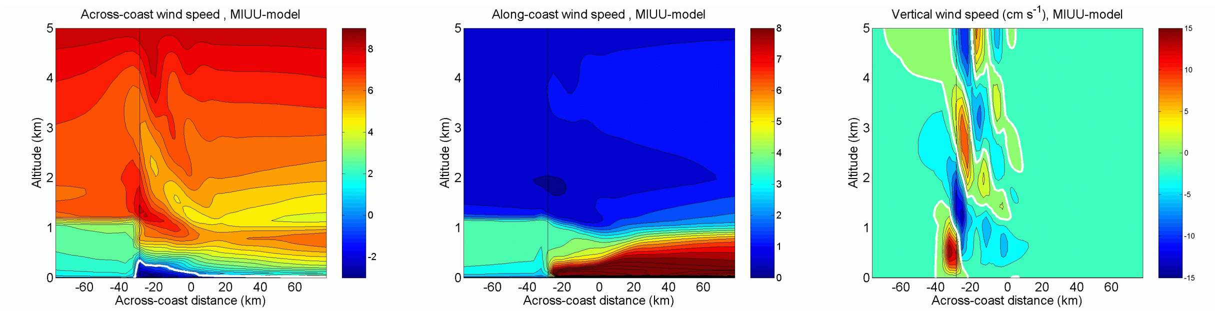

Figure 7. Across-coast cross-sections of (left) across-coast, (middle) along-coast and (right) vertical wind speed

4. RESULTS FROM 2-D MIUU MODEL RUNS

Figure 5 shows the same type of cross-section as in Figure 4, but for the MIUU model. Here, all the forcing is now prescribed from COAMPS^{TM} results. Moreover, the inland surface temperature was set homogeneous. As the model is 2-dimensional it represents an idealized sea breeze at an infinitely long straight coast without terrain. There are differences, in particular during the night, in the cross-coast wind between COAMPS^{TM} and MIUU, as expected. Still, the basic features agree well and as is illustrated in Figure 6, there is more correspondence than discrepancy between the two models. Thus, much of the dynamics even in a complex environment are captured in the simplified 2-D concept.

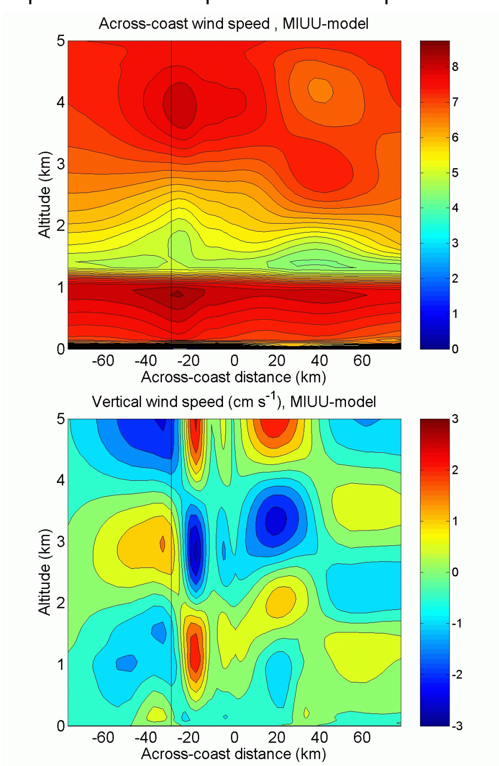

Figure 8. Same as Figure 7, but only for the horizontal wind components and at the time corresponding to the night in Figure 3.

Figure 7 shows three wind-speed components during the same sea breeze event as in Figures 2-3, but from the 2-D simulation. The across-coast wind speed component (left) is rather similar to that in Figure 3, only the standing wave now tilts consistently downstream. The wave is clearer in vertical wind speed (right), propagating all the way to the model top at 5 km. The vertical wavelength is ~ 2 km. The wave is quite clearly triggered by the convergence zone at the sea breeze front. The low-level along-coast wind is strong from south, as in the 3-D run, while the background flow is mainly directed offshore, as in the real-case 3-D simulation.

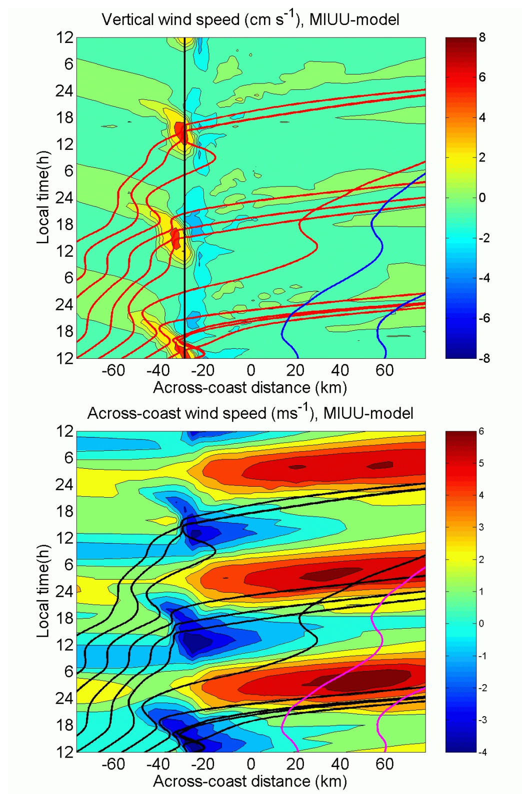

Figure 9. Time – cross-coast cross-section of vertical (top) and across-coast (bottom) wind speed at ~ 200 m. Solid lines are trajectories, see the text for a discussion.

At night (Figure 8) the wave pattern is collapsing and is and oriented horizontally; the waves are propagating away from the coastline in both directions (also see Figure 10). No wave pattern appears aloft. The strong offshore flow in the boundary layer is deeper in the MIUU model than in COAMPS^{TM} and the wind speed maxImum also at a higher altitude and is somewhat weaker. This may be connected to the absence of the nigh-time

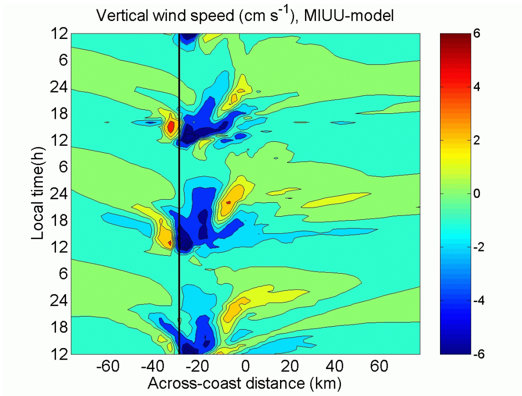

Figure 10. Same as top panel in Figure 9, but at 700 m.

weaker terrain-triggered wave in the idealized MIUU simulation. But, consistent with COAMPS™, the strongest cross-coast flow occurs in the boundary layer and at night.

The gravity wave triggered by the sea breeze has the structure of a standing wave, but as the sea breeze front evolves and moves, this causes propagating modes to be excited. In Figure 9 (top panel), the convergence zone of the fronts is shown as regions of up-winds corresponding to the front. As the sea breeze collapses the convergence propagates against the wind while the almost entirely wave free region corresponds to the areas of strong offshore flow during the night. The different modes of the waves are clearer at higher altitude (Figure 10). The main propagation inland is still at the collapse of the sea breeze, but offshore propagation occurs at several phase speeds, repeatedly each day.

All these vertical motions obviously must affect the transport processes at the coastline. The solid lines in Figure 9 represents several trajectories started at different distances from the coast, from 120 km inland to 80 km offshore, at 10 m on 19.00 local time, August 11. Figure 11 also illustrates these trajectories. All but one of those twelve that started inland are eventually caught in the updraft of the sea breeze front, lofted and propagated offshore at an increased speed. All those released offshore remain close to the surface and crosses those from inland after ~ 2 - 3 days. Note the blue trajectory in Figure 11, that actually crosses the coast before becoming swept up by the sea breeze, taken inland, lofted and advected off shore again. The green trajectory in Figure 11 is the only trajectory here making it across the coast during the night, and is not lofted.

5. DISCUSSION

The most commonly occurring and best understood mesoscale circulation, the sea breeze, is investigated from the point of view of its effects on local transport and dispersion of atmospheric pollutants. The study uses idealized 2-D simulations based on fully 3-D simulations with a nested model, for a case from the NEAQS 2002 field experiment. A significant result is the quite strong nighttime offshore flow, consistently occurring in both the real-case 3-D COAMPS™ simulation and the

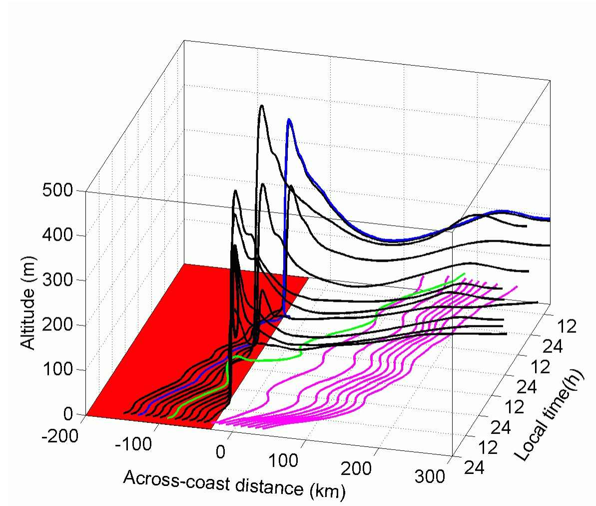

Figure 11. 3-D plot of across-coast and vertical position of several trajectories as a function of time. Red indicates land.

idealized 2-D MIUU-model simulation. It is, however, weaker in the latter. We hypothesize that the primary cause is an inertial oscillation that is triggered as the blocking of the offshore background flow by the sea breeze collapses in the evening. In the 3-D simulation, with terrain, there is also a weak gravity-wave pattern induced by the quite moderate terrain farther west. Interaction with this wave system may be one reason that the offshore flow is shallower in the 3-D simulation and thus more intense. The 3-D model results also indicated a shallow down-slope flow over the terrain to the west that may have contributed to the nighttime offshore flow. This was not present in the 2-D simulation as this did not include any terrain.

The sea breeze is associated with an in principle standing gravity wave at the sea breeze front, triggered by the boundary layer convergence. However, as the front moves, so does the "standing" wave and it spawns different propagating modes offshore as it goes along. As the sea breeze collapses, the "standing" wave collapses and its components are propagated away from the coast, both inland and offshore.

The transport of boundary-layer trajectories from inland sources in the 2-D simulation is dominated by lofting. Of the twelve trajectories, released inland at the start of the simulation at different locations from ~ 120 km to the coast, only one is not lofted by a sea breeze. One (blue line) is propagated offshore, but picked up by the sea breeze, re-circulated and then lofted. This picture would off course be different with a continuously released tracer. Any near-coast but offshore concentration continuously accumulated during the night would be re-circulated during the day. The different depths of the sea breeze at different times of day will contribute to the dispersion of the air pollution, as the lofting will lift the plume to different heights possibly with slightly different wind directions.

References

Estoque, M. A., 1961: A theoretical investigation of the see breeze. *Quart. J. Roy. Met. Soc.*, **87**, 136 – 146.

Colby Jr, F. P., 2004: Simulation of the New England sea breeze: The effect of grid spacing. *Wea. Forecast.*, **19**, 277 – 285.

Marchall, C. H., R. A. Pielke Sr., L. T. Stayaert and D. A. Willard, 2004: The impact of anthopogenic land-cover change on the Florida sea breezes and warm season sensible weather. *Mon. Wea. Rev.*, 132, 28 - 52

Angevine, W. M. and coauthors, 2004a: Coastal boundary layer influence on pollutant transport in New England. *J. Appl. Meteorol.*, In press.

Angevine, W. M., M. Zagar, M. Tjernström, C. J. Senff and A. B. White, 2004b: Coastal boundary layer transport of urban pollution in New England, 16th Symposium of boundary layers and turbulence, Portland, Maine, This issue.

Hodur, R. M., 1997: The Naval Research Laboratory's coupled ocean/atmosphere mesoscale prediction system (COAMPS). *Mon. Wea. Rev.*, **125**, 1414 – 1430.

Enger, L., 1990: Simulation of dispersion in moderately complex terrain - Part A. The fluid dynamic model. *Atmos. Environ.*, **24A**, 2431-2446.