High-Resolution Modeling of Atmospheric Dispersion and Turbulence Transport in the Coastal Marine Boundary Layer

A contribution to subproject CAPMAN

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Summary

Due to the highly variable conditions in the marine boundary layer close to a coastline, accounting for the atmospheric deposition of nitrous compounds to the coastal ocean requires high resolution modeling of both the dispersion processes in the atmosphere and the deposition. For the deposition, no global theory exist for deposition in the case of heterogeneous meteorological conditions, although a simplified theory was suggested by Geernaert (2000, personal communication). The aim of this project is partly to study the dispersion of atmospheric gases in highly complex conditions, through high-resolution modeling, and to device a parameterization of the atmospheric deposition for use in coarser scale models.

In this paper, we report on the initial attempts in these fields. High-resolution modeling of the dispersion of a passive tracer for the Kattegat using the US Navy Coupled Ocean/Atmosphere Mesoscale Prediction System - (COAMPS) model (Hodur 1997) illustrates the complexity of the flow in the strait between Sweden and Denmark. For summer conditions, the low-level flow in the strait favors a northerly or southerly flow even for background flow across the strait - a channeling effect due to the often stably stratified boundary layer over the water. Dispersion of a tracer that was continuously released at the surface over northern Jutland illustrates the fate of pollutants for a single day. The plume meanders strongly but remains unmixed and reaches the Swedish coast at different locations for different times of the day.

Highly simplified simulations with a very high-resolution model were utilized to study the variability in the turbulent fluxes close to the coast. Near-shore variations in surface momentum flux of the order of 50% compared to that far off shore were found. It was also found that the distance off-shore at which the surface fluxes approached the free undisturbed conditions are of the order of ~100 km, thus the Kattegat is not wide enough to ever be treated as an open ocean – coastal effects will influence deposition all over this water body.

Aim of the research

This study is part of the MEAD project. The over-all aim of this project is to model the conditions that are favorable for harmful algae blooms in the Kattegat sea between the west coast of Sweden and Denmark. The aims of the current project are:

1. Study dry deposition in horizontally inhomogeneous conditions, using field experiment data and high-resolution meteorological models.
2. Improve the understanding of the meteorological processes that govern extreme events of dry deposition of nutrients into the coastal marine ecosystem.
3. Develop dry deposition parameterizations suitable for inhomogeneous coastal environments in an operational meteorological model.
4. Parameterize wet deposition over the study area.

Activities during this year

This year has been devoted to address the first objective. The main tools utilized in this research are two atmospheric models, a high-resolution mesoscale research model (the MIUU model, Tjernström 1987; Enger 1990) and an operational modeling system, the COAMPS model (Hodur 1997). The latter also has the option of being used in research mode and includes an advection and dispersion algorithm for passive tracers. The situations simulated so far are idealized cases, i.e. controlled experiments.

The research model is a mesoscale model that may be used for idealized cases or for real cases characterized by relatively stationary meteorological conditions on the larger scale. This model is easy to run in one to three dimensions and for this first study, we have limited the calculations to two dimensions. The model is set up so that half of the model domain is ocean and the other half is land; one coastal zone is thus considered. The model was run for this setup for a number of background wind speeds and directions, with different temperature differences between the sea and the land and for different initial stability of the atmosphere. If the background wind speed is weak enough, sea-breeze circulations will arise. The main objective in this study is to see how the various background conditions change the turbulent transport to the ocean surface in the coastal zone. The flow is influenced by the change in surface roughness and temperature when crossing the coastline. Consequently, the turbulent transport, which controls the deposition, is influenced.

The COAMPS model can be run either operationally or for idealized cases, given a vertical sounding and the SST-fields as input. It also includes an option for advection and dispersion of a passive tracer, which was utilized here. A number of idealized sunny summer cases (August) were run, using climatological SST and low background wind speed from three different directions. The model was run with one nest, the outer domain covering most of Denmark and parts of southern Sweden and the inner domain covering the Danish and Swedish coasts with the Kattegat strait in between. The simulations were performed with an area source of an inert tracer at the surface, covering the northern tip of Jutland. These simulations reveal the complexity in the three-dimensional flow patterns that evolve over the area. It is clear that the ideal picture of a linear transport from Denmark over the water to Sweden is inadequate even for westerly winds.

Principal results

Figure 1 shows the momentum flux in the lowest km of idealized flows from the MIUU model, with winds from the land towards the sea, i.e. easterly background wind. The left panel shows a case with strong (10 ms^{-1}) flow; a turbulent boundary layer up to 500 m is seen over land. This boundary layer collapses when the air is advected over the colder water. The surface temperature difference here is 6 K between the land and the sea. *Figure 2* shows the momentum flux close to the ground normalized with the value over the open water far offshore. The turbulent momentum transport is much larger over land than over the water, due to the differences in stability. A more interesting aspect in this figure is that there is a reduction of the momentum transport by more than 50% in the coastal zone compared to the offshore value. Also interesting to notice is that this effect can be seen as far from the coast as 120 km. Since the strait between Sweden and Denmark is about 100 km wide, this means that undisturbed conditions over the water in Kattegat cannot be expected; the flow in the region will always be modified by the coasts.

In the right panel in *Figure 1*, the background wind direction is the same but the speed is reduced to 4 ms^{-1}. In this case a sea-breeze circulation develops, which changes the flow, and the momentum flux is reduced over land. Just at the coastline, however, there is a zone with enhanced fluxes. The reduction in the momentum flux over the water is in this case almost constant in a 40-km zone from the coast (see *Figure 2*, blue line).

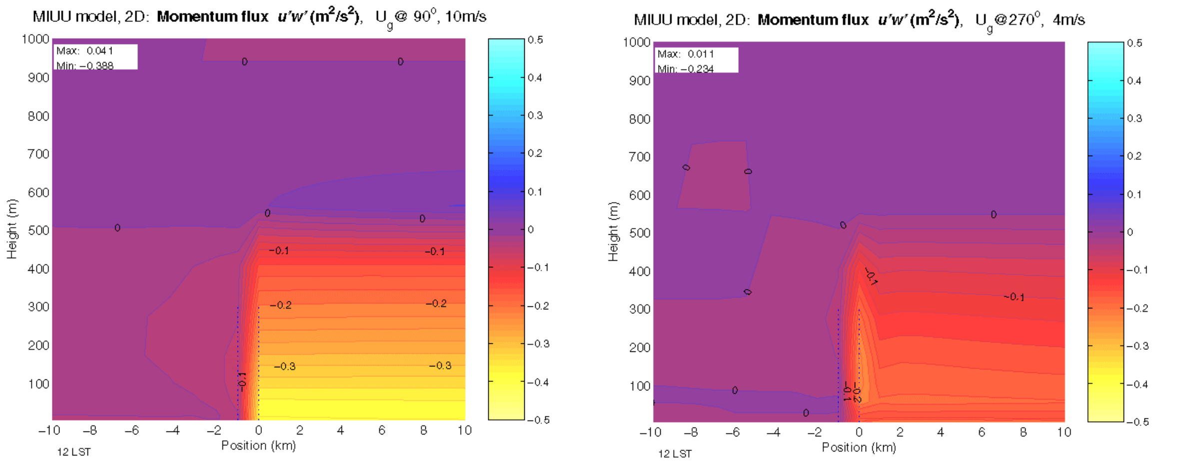

Figure 1. Vertical cross-section of the momentum flux for offshore flow at 10 ms^{-1} (left, compare the blue line in Figure 2) and 4 ms^{-1} (left, compare the red line in Figure 2).

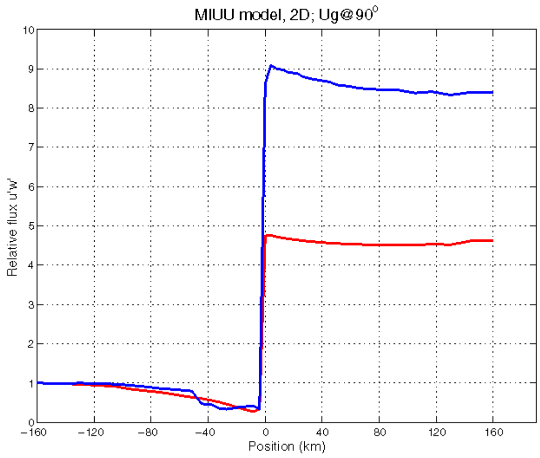

Figure 2. Normalized (by its offshore value for each case) momentum flux for two idealized simulations where the background wind was offshore at 10 (red) and 4 (blue) ms^{-1} (see Figure 1)

A conclusion from this idealized study is that although the turbulence parameterization in the mesoscale model assumes horizontal homogeneity close to the surface at each grid-point, the effects of the sudden changes at the coastline are still substantial. The momentum flux is used as a proxy for deposition here, representing the turbulent transport, as the deposition flux itself is related to the momentum flux. In addition, the amount of matter deposited to the surface is highly dependent on the concentrations in the air.

Figure 3 shows a sequence of horizontal cross sections for the inner grid of a COAMPS simulation using climatological SST, about 16°C while the inland temperatures reach about 25°C at maximum with a realistic diurnal cycle. The background wind is here from NW at a speed of 4 ms^{-1}. The arrows in these panels show the wind field close to the ground and the colors represent the concentrations of the inert tracer, emitted over land in the upper left corner with a constant emission rate. The panels show results from 6 am to 9 pm local time (note that the scale on the colorbar varies).

High concentrations (at 6 am and 9 pm) indicate that the tracer is confined to a relatively shallow layer due to stably stratified conditions, initially over both land and sea. During the day, the plume of the tracer can be followed out over the water in Kattegat. The effect of the island, Læsø, where a local convective boundary layer develops during the day, can clearly be seen in the concentration field at noon. Here the tracer is mixed through a deeper layer, thus the low-level concentrations are reduced. The transport during the day is mainly towards the SE, but the wind field shows large complexity with a sea breeze developing along the Danish coast.

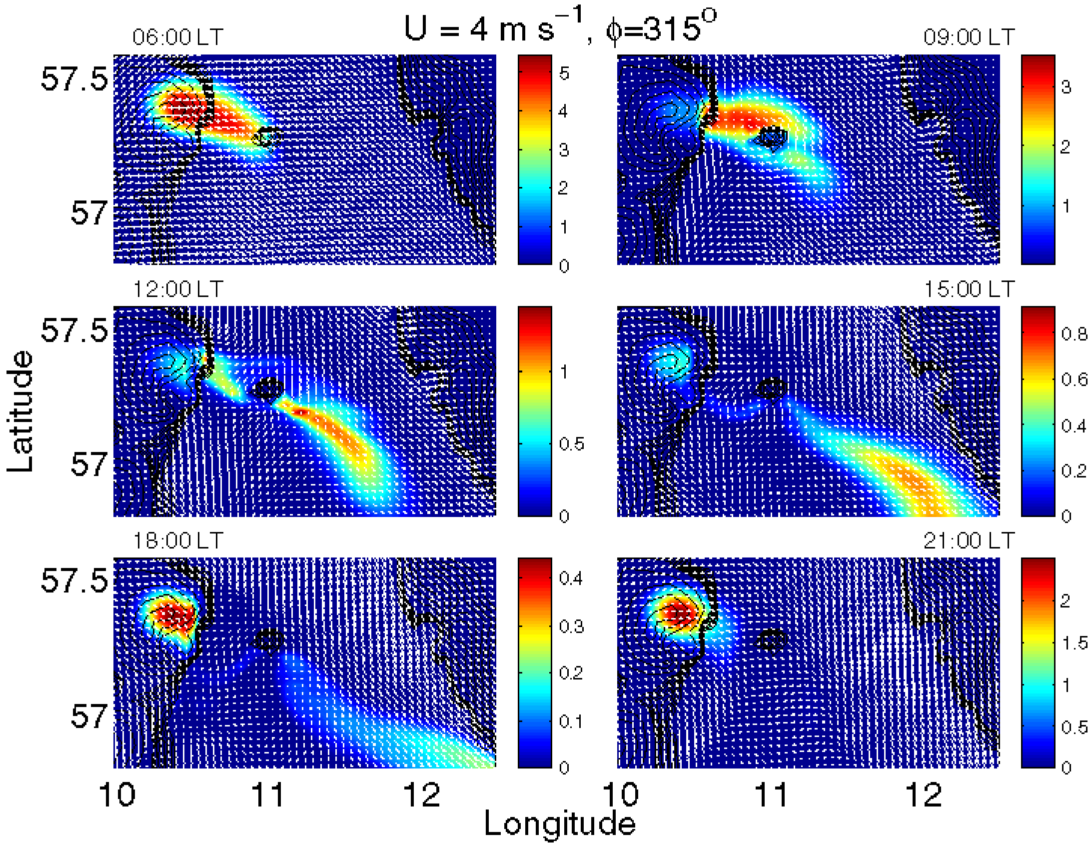

Figure 3. Horizontal cross-section across the Kattegat of wind speed (arrows) and tracer concentration (color scale) for an inert tracer continuously released at a constant rate at an area source over the northern tip of Jutland.

If the background wind is instead from the East (*Figure 4*), the plume of the tracer is instead trapped in a flow along the Danish coast by a local circulation. Some of the matter is then rapidly transported towards the south presumably in a coastal low-level jet, a local wind maximum close to the ground. No tracer can be found at the Swedish coast in this case.

Main conclusions

The simplified mesoscale simulations with just one straight coastline illustrates three things. Firstly, the turbulent fluxes at the coastline immediately on the offshore side are affected by the step-change in surface conditions. In this particular case, there was a reduction in the momentum flux by a factor of 20. Secondly, while comparing the near-coast turbulent fluxes by those far offshore representing open water conditions, there was a factor of 2 difference. The coastal fluxes gradually adjusted to the open-water conditions but the distance over which this occurs is of the order of 100 km, thus in a strait like the Kattegat the whole area will be influenced by the coastlines regardless of wind direction. Finally, if the background offshore flow is sufficiently weak a local breeze circulation will develop that further perturbs the fluxes. In this case, there will also be a mesoscale transport in that there is a substantial vertical wind in the sea-breeze front. The latter transport is not included in coarser models.

The COAMPS simulations show that the wind field over this region, with the two coastlines and the island of Læsø, is quite complex and that mesoscale phenomena such as sea breezes and low level jets are common. There appears from this limited experiment to be a tendency for the low-level flow over the Kattegat to be either northerly or southerly, trapped in the strait. The tracer emitted from one side cannot be expected to be found in a simple plume over the water. The concentration close to the surface, i.e. the material that is subject to deposition, varies quite substantial with time and space over both land and sea, due to the different stability in the atmosphere at different locations. Complex deposition patterns are thus expected to be found in the region.

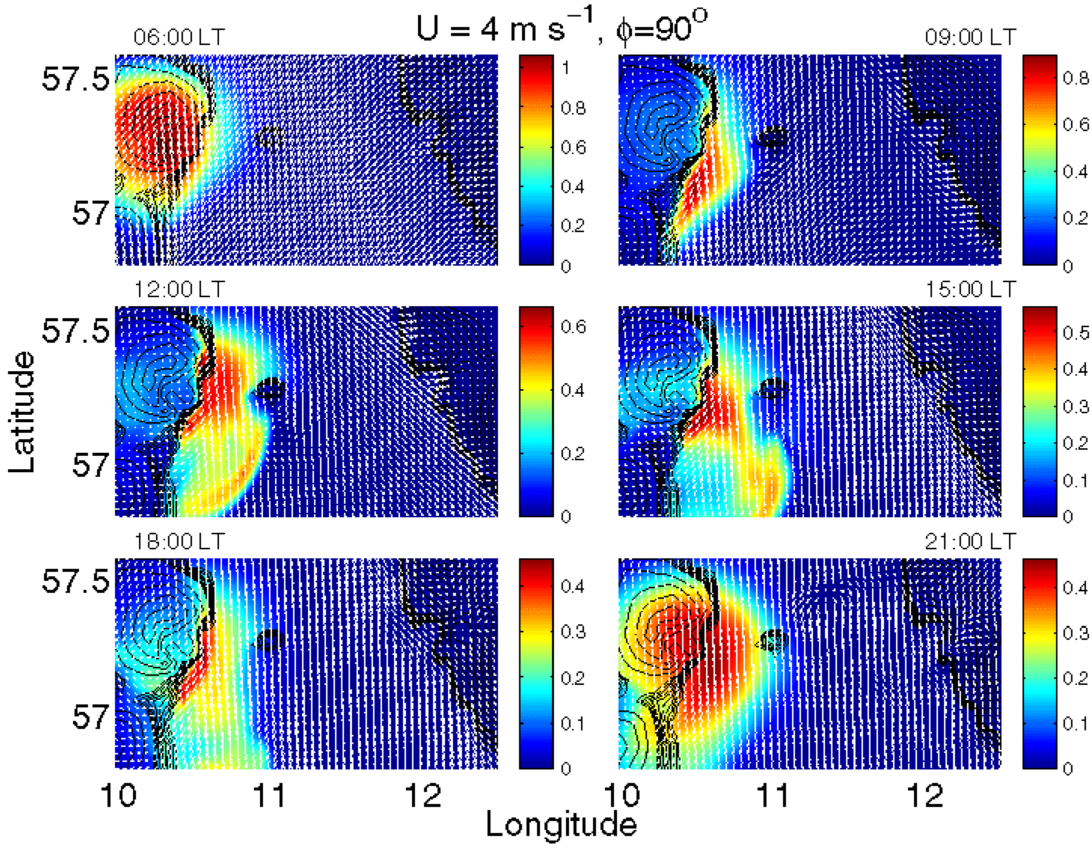

Figure 4. Same as Figure 3, but for easterly flow.

Aim for the coming year

The work with two-dimensional idealized simulations of one coastline is ongoing. A large number of cases will be run with varied input parameters (wind speed and direction, stability and land-sea temperature difference) to create a model database. This will be analyzed with respect to momentum fluxes in the coastal zone and its relation to the various input parameters. Tracer calculations will be implemented in the research model along with a deposition parameterization. At first this needs to be formulated in a standard way, using a deposition velocity related to the momentum flux.

Furthermore, we plan to investigate how much the assumption of homogeneity in the turbulence parameterization influences the results. A new boundary condition for the turbulence, without the assumption of homogeneity for the prognostic turbulent kinetic energy equation will be tested. New formulations for the boundary condition for the other prognostic variables (e.g. wind, temperature, humidity, tracer etc.) then have to be developed. The MEAD project includes two intensive field campaigns, one in 2000 and one in 2001. We will select appropriate episodes from these and run the MIUU mesoscale model so that the new parameterizations of the boundary conditions can be tested in controlled situation.

From the retrospective study of algae blooms, which is also part of the MEAD project, we will run detailed high-resolution simulations over several days for episodes with observed algae blooms, using the COAMPS model. The aim is to attempt to identify the atmospheric preconditioning for these blooms.

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