A Study of the Variability of the Coastal Marine Atmospheric Boundary Layer

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LONG TERM GOALS

The long term goals are: 1/ To understand the impact of complex coastal terrain and/or coastline orientation on the structure of the coastal marine atmospheric boundary layer (MABL); 2/ To study the effect on the atmospheric forcing of the coastal ocean, by the the local flow induced by the coastal terrain, including possible feedback mechanisms.; 3/ To understand the internal turbulence structure of marine stratocumulus and how the presence of such clouds interact with the coastal flow.

OBJECTIVES

Different processes influence the coastal meteorology on different space and time scales. The interaction between coastal baroclinicity, background (synoptic scale) flow, coastal terrain and coastline geometry are believed to be important. The coastal baroclinicity is important for the diurnal cycle of the coastal jet, but also generates cross-shore flow in gaps where the terrain height is lower. If the terrain is higher than the top of the PBL depth, the flow becomes semi-bounded and geostrophic adjustment is impaired. If the flow is super-critical, information on changes in the pressure field caused by the geometry of the coast cannot propagate upstream. The flow responds with expansion fans and hydraulic jumps to such changes. The strength and direction of the background flow determine to some degree the location and strength of such mesoscale flows. Marine stratocumulus are important in that they enhance turbulent mixing and thus deepens the PBL. This affects coastal jets, since they are driven by the slope of the capping inversion. The interaction between the jet and changes in the coastal terrain may also modify the coastal MABL so that the cloud field is perturbed.The spatial variability of the flow generates horizontal gradients in the momentum transfer to the ocean. This result in up- and downwelling of cold water, changing the sea surface temperature (SST). The new SST distribution may, or may not, feed back to the atmospheric flow. The non-linear interaction between all these processes is responsible for the observed complexity of coastal flows, and our objective is to determine their relative importance.

APPROACH

The study of complex, coupled and non-linear flows in atmospheric turbulent boundary layers requires several different tools. Adequate observations are a cornerstone, but due to the vast range in scales and the interaction between these scales, often involved in atmospheric flows, it is seldom possible to completely resolve any particular flow phenomena by measurements alone. Much insight on the nature of atmospheric flows can be gained from numerical rather than field experiments. All the terms that are solved for in a model also lend themselves to analysis, often in three dimensions and without severe

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restrictions in time. However, all models also have limitations, due to various assumptions inherent in the model formulations and to imperfect parameterizations; different models are best suited for different problems. To achieve the most insight from a field experiment requires a careful mix of analyzing field experiment data and simulations of that data with an appropriate model. Some processes can be studied in more detail in a model and also be isolated in model output, e.g. budgets for different processes can be calculated. Sensitivity and parameter studies – “what if” experiments – can be performed. Such results are very difficult to obtain from field experiment data alone.

In this research we focus on i) small- (meso-γ-) scale processes, ii) turbulence structure and iii) marine stratocumulus. This requires a model with detailed description of these processes. We have thus implemented a high-resolution mesoscale model with higher-order turbulence and sub-grid scale cloud closures, as a tool to analyze field experiment data. The data are taken both from the Coastal-Waves 1996 experiment and from similar experiments in the Baltic Sea. The approach is to use field data to keep the simulations realistic. Cases from the field data are simulated using as simple initial and boundary conditions as possible. After a reasonable correspondence between the model and the field data is achieved, the model output is analyzed in terms of processes and budgets that are more easily extracted from the three-dimensional time-continuous model output than from sporadic or local measurements. Also simulations are performed with such changes to the the initial and boundary conditions that can reveal controlling factors. For each simulation, momentum budgets and the surface forcing on the ocean can be calculated as well as other parameters relevant to the flow, e.g. the local Froude number, vorticity or divergence. Finally, a large number of generic simulations can be performed to quantify the likely occurrence of a particular process.

WORK COMPLETED

The main activity during 1998 continued to focus on the analysis of data from the Coastal-Waves field experiment, that took place during June 1996 along the central and northern California coast. Two preliminary model studied were completed, focusing on the Pt Sur and the Cape Mendocino areas, respectively. The studies were performed with model resolutions of O(km), for cases with supercritical flow. In addition, the study for Cape Mendocino was extended with a large number of sensitivity simulations, where the SST and the terrain as well as background flow and initial conditions were varied. Simultaneous analysis of the experimental data is ongoing and results from both measurements and model simulations has been presented at several international conferences.

A model study of the first Astex Lagrangian experiment was also concluded. To deal with details in the interaction between the sea surface and the MABL, and between turbulence and radiation in the clouds, we implemented new state-of-the-art schemes for the surface fluxes and for radiation. A scheme for simulations of drizzle was also implemented.

RESULTS

The data analysis from the Coastal Waves experiment has been supplemented by data from the Monterey Shiptracks Experiment, MAST, and then provide an opportunity to study the boundary layer response in a wide range of distances from the coast. It is found that the response to details in the coastline geometry is confined to the emediate coastal zone, 10-50km, but that the distance within which the presence of the coast affects the bulk structure of the PBL is larger, O(100km). Close to the coast, the PBL is often stable, due to the upwelling of cold water to the ocean surface. Even so, the turbulence is often significant and this is due to mechanical production by strong wind shear conditions associated with the coastal jet. The turbulence structure is very far from the classical homogeneous steady-state PBL, although the conditions are fairly steady and the homogeneous fetch can be substantial. This causes most simplified turbulence schemes to fail, particularly when the static stability is positive. The scale imposed on the PBL by the strong inversion, which is modulated by e.g. expansion-fan dynamics, perturbs the PBL and furthermore, interplay between gravity waves and turbulence is an important component in both the TKE budget and in the mean momentum budget.

In most cases, the jet originate as a consequence of the synoptic conditions, and it is thus different in structure and location depending on those conditions. The jets are strongly affected by the coastal geometry. Close to the coast, at points or capes, there is often a superimposed wind speed maximum and wind speed maxima of the order of 25-30 ms^{-1} were not uncommon. Offshore, the PBL is slightly unstable and in equilibrium with the surface forcing. However, coherent PBL structures or decoupled marine stratocumulus clouds can alter these conditions. Closer to the coast, the PBL depth slopes continuously down towards the coast, however, in the presence of marine stratocumulus, the PBL depth is in general increased, and the reduction in PBL depth then occur more abruptly and closer to the coast.

Model studies of two cases of high-speed flow has been concluded for the locations around Pt Sur and Cape Mendocino, respectively. Analyzed in terms of the Froude number, the flow becomes supercritical within O(100km) from the local coast, due to the continuous slope of the inversion and the subsequent increase in wind speed. At Pt Sur, the wind speed decreases and part of the flow is blocked and diverted into Monterey Bay. At Cape Mendocino, with local terrain at the cape more perpendicular to the flow, similar blocking forces a lee-wave that collapses the PBL downstream, into Shelter Cove. The flow is strongly ageostrophic as it passes the points or capes, within 10-20km from the coast. The local ageostrophic acceleration at such locations balances the mesoscale pressure forcing and both these terms are more than an order of magnitude larger than any other term in the momentum budget. Upstream the flow is semi-geostrophic; geostrophic in the cross-shore direction while the alongshore flow is more complex. In a zone closest to the coast, the pressure forcing is balanced by the ageostrophic acceleration, due to changes in coastline geometry. Further off-shore, but still within a Rossby radius, there is a balance between the pressure forcing and the turbulent friction.

In sensitivity studies, several important factors were varied: 1/ Surface forcing, where simulations were carried out with and without a realistic SST forcing, without terrain at the cape and without the cape; 2/ Internal structure, where simulations were performed altering the strength of the capping inversion and the background flow; 3/ Cloud forcing, where simulations were performed with increased initial humidity to impose clouds of varying thickness. In general it was found that the expansion fan dynamics was a very dominant factor. Even with substantial changes in forcing or initial conditions it was impossible to force the flow to become entirely sub-critical. From the runs with altered surface forcing it was concluded that the realistic SST, with substantially cooler temperatures along the coast, had a minor impact on the flow. This means that the atmosphere-ocean interaction is one-way only. Cases with substantial upwelling favorable conditions, strong winds, generate this cool SST, but is at the same time insensitive to the SST depression,since they are so strongly controlled by the expansion-fan dynamics. It was also found that the local terrain at Cape Mendocino, located across the flow with a hight comparable to the boundary-layer depth, had a significant impact on the downstream conditions in that they generate a deep lee-wave that is responsible for the observed collapse of the boundary layer in Shelter Cove to the south of Cape Mendocino. Finally, the expansion fan remained, although with a different shape, also when the entire cape was removed, indicating that the smooth curvature of the mountains and the coast is sufficient to trigger this dynamics. In the tests with altered internal structure an interesting feedback was observed. With a weaker inversion, the Froude number is expected to increase, and *vice versa*. In the model runs this does not happen, instead the Froude number is almost unchanged. This is due to increased or decreased entrainment at the inversion causing a deeper or more shallow PBL. The change in depth almost exactly compensates for the change in inversion strength. A weaker inversion facilitates the entrainment of warm and dry air into the boundary layer. Finally, even when the background flow speed is reduced by 50%, the expansion fan remains. Although the upstream flow becomes sub-critical, the acceleration at the cape is sufficient to generate Froude numbers larger than unity. In the final set of tests, where initial humidity was increased to generate clouds, it was found that no amount of reasonable initial cloud cover was sufficient for clouds to remain throughout the day in question. No clouds were observed on this day. The presence of the clouds significantly alter the PBL structure, but after the clouds dissipate it only takes a few hours for the flow to adjust to the coast and become very similar to the control run.

The most important result from the Astex study illustrates clearly the importance of a adequate description of the drizzle processes. Even a fairly simple parameterization brings the maximum cloud water down by a factor of two, to within a good agreement with the measurements. Furthermore, over a ~2 day simulation it has a significant impact on the gross PBL moisture budget, bringing the sub-cloud humidity down by O(1) gkg^{-1}. The cloud layer is most turbulent during the night, however, in-cloud turbulence is constantly higher than sub-cloud turbulence and the cloud layer is completely or partly decoupled most of the daytime, in particular as the PBL deepens towards the end of the Lagrangian and becomes more convective. The deepening of the PBL and transformation of the stratocumulus to trade cumulus is critically dependent on three factors the drizzle, the synoptic scale subsidence and the increasing sea surface temperature. It was impossible to reproduce the observed transition while neglecting any of these factors in the model. Neglecting drizzle enhances the radiative cooling, and thus the entrainment, and lead to a significantly more rapid deepening. Neglecting subsidence also enhances the deepening, through the removal of a counteracting vertical advection. The primary driving mechanism, however, is the heat input from the sea surface. While removing the increase in sea surface temperature, the remaining development is just a diurnal cycle, with only a marginal increase in PBL depth, regardless of the two other processes. A significant over-prediction of near-surface humidity, also when using a state-of-the-art scheme for the atmosphere-ocean interaction, indicates a problem with the parameterization of the gas exchange at the ocean surface.

IMPACT

Many naval activities are affected by the meteorology in coastal zone. Strong and variable winds as well as turbulence and low clouds affect naval air operations and flight safety as well as naval activity on the surface. Amphibious activities are very sensitive to local winds and high sea. The coastal PBL structure in general and interaction between coastal meteorology and marine stratocumulus in particular is very important for the use of different optical sensors both for detection and for naval target acquisition. Understanding of the coastal MABL structure is an important piece in choosing weapons combinations and tactics for all naval air operations. The fact that the Froude-number pattern around Cape Mendocino appears self-similar in many sensitivity runs with quite significant changes in the forcing can possibly be used for wind speed forecasts based on simulations with coarser models, using representative upstream values of wind speed and PBL depth.

RELATED PROJECTS

This project runs in parallel with a Swedish project by the same name. Collaboration also excise with Baltex, the European contribution to Gewex, and with ASTEX and the Gewex Cloud System Study. Our group is also actively collaborating with Dr Dave Rogers and Dr Clive Dorman at Scripps Institute of Oceanography and with Dr Darko Koracin at the Desert Research Institute in Reno.

PUBLICATIONS

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