A STUDY OF THE VARIABILITY OF THE COASTAL MARINE ATMOSPHERIC BOUNDARY LAYER

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Award # Grant No N00014-96-1-0002

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); 3/ To study the effect on the atmospheric forcing of the coastal ocean, from the impact on the local flow induced by the coastal terrain, including possible feedback mechanisms. 2/ To understand the internal turbulence structure of marine stratocumulus and how the presence of such clouds interact with the coastal flow.

OBJECTIVES

Many different processes influence the coastal meteorology on different scales. The interaction between coastal baroclinicity, background 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 about changes in the pressure field as a consequence of the coastline geometry 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 often involved in atmospheric flows and the interaction between the scales, it is often impossible to completely resolve any particular flow phenomena. 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 restrictions in time. All models have limitations due to the various assumptions inherent in the model formulations and parametrizations; different models are best suited for different problems. To achieve the most insight from a field experiment requires a mix of analyzing field experiment data and simulations with an appropriate model. Some processes can be studied in more detail in a model and also be isolated. Budgets for different processes can be calculated. Sensitivity and parameter studies Ð Òwhat ifÓ experiments Ð can be performed. Such results are very difficult to obtain from field experiment data alone.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**

4. TITLE AND SUBTITLE **A Study of the Variability of the Coastal Marine Atmospheric Boundary Layer**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Uppsala University,Department of Meteorology,Box 516,S-751 20 Uppsala, Sweden,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

In this research we focus on i) small 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 a higher-order turbulence closure and a sub-grid scale cloud module, as a tool to analyze field experiment data, taken both from the 1996 Coastal-Waves 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 with as simple initial and boundary conditions as possible. After a reasonable correspondence between the model and the field data is achieved, model simulations are performed with such changes to the initial and boundary conditions that 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 1997 was focused 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. 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 for the Blekinge coast in the Baltic sea was concluded. This study was based on one well documented case of the diurnal variation of a flow past an almost 90 degree turn in the coastline. The study was organized, starting with a simulation of the actual case. The following parts focused on the sensitivity of the flow to the surface forcing and on variations in background flow.

A generic model study of coastal flow along the central California coast was also concluded. Detailed simulations of the coastal MABL were conducted for eight different background flow directions. Spatial as well as temporal structure was examined. The relevant physic was examined, as well as momentum budgets and the forcing of the coastal ocean.

A model study of the sensitivity of Bura-type flows in the Adriatic sea to conditions in the coastal boundary layer was concluded. Two dimensional simulation studies of several generic cases were conducted for different ambient and boundary layer conditions.

A tentative 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 immediate coastal zone, 10-50km, but that the distance within which the presence of the coast affects the over-all 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. 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 conducted 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.

The Swedish study at the Baltic coast show that even quite moderate coastal terrain, O(100-200m), can trap the coastal flow, provided that thermal stability in the marine PBL is sufficiently large. Diurnal development along a coast with a significant bend in the coastline is significantly more complex than along a semi-straight coastline. If the night-time flow becomes blocked, a diurnal coastal jet may form along one coastline, as determined by the background flow direction. This jet will impede the formation of a sea breeze on a perpendicular coastline downstream, when this turns away from the jet flow. The result is a formation of a meso-eddy at the bend and a stationary sea breeze front along the perpendicular coast. In the sea breeze convergence zone the flux of heat and water becomes significant.

Along the California coast, jets occur for practically all background flow directions. With background flow from NW over N to E, the jet is northwesterly and for background flow from S, SW and W, it is southeasterly. For background flow from SE, the local flow is transient. For the northwesterly jet, the PBL structure is sensitive to the background flow direction. As the background flow turns more offshore, the coastal PBL depth decrease and the Froude number increase. The jet from southeast, in contrast, varies much less with background flow direction. Both flows are semi-geostrophic; the across-shore momentum is geostrophic while in the alongshore momentum, there is a balance between the pressure forcing and the turbulent drag. This holds true for large distances from the coast (O(100km)), while significant ageostrophy in both components become important within ~10-50km from the local coast. The variability in the momentum balance terms is much larger along than across the coast. The upwelling potential is significant only for the northwesterly jet and only when the background flow is from a sector from northwest to north. The magnitude of the upwelling potential is a function of local wind speed, but the localization is dependent on coastline orientation. Maxima occur downstream of points and capes, when the wind speed maximum detach from the coast. Details in the boundary layer structure often associated to coastal wind reversals were found also in non-transitory flows and appear to be inherent to the wind direction in relation to the coast.

The Bura study show, in contrast to what is predicted by linear theory and simple Rossby number consideration, that wave-breaking of a hydrostatic mountain wave is affected by the rotation of the Earth. Favorable synoptic conditions for a Bura to happen can be canceled by unfavorable MABL conditions and conversely, a Bura may happen even in unfavorable synoptic conditions, if the coastal MABL conditions are favorable. A propagating hydraulic jump can thus be present as a result both of the appropriate background flow, but also due to a favorable SST-land temperature difference. For a given background flow, the offshore propagation of the Bura front is a function of land/sea surface temperature difference. For a strong Bura flow, the Bura is not a local wind Ð it will propagate more than 150km to the Italian coast.

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 day-time, 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.

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.

TRANSITIONS N/A

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 SIO.

REFERENCES

Information on this effort can be found at Òhttp://drizzle met.uu.se/MMDG/index htmlÓ