EXPLORING THE ROLE OF WAVE DRAG IN THE STABLE STRATIFIED OCEANIC AND ATMOSPHERIC BOTTOM BOUNDARY LAYER IN THE CNRS-TOULOUSE (CNRM-GAME) LARGE STRATIFIED WATER FLUME

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This paper reports on a laboratory experiment in the CNRM-GAME (Toulouse) stratified water flume of a stably stratified boundary layer, in order to quantify the momentum transfer due to orographically induced gravity waves by gently undulating hills in a boundary layer flow. In a stratified fluid, a surface corrugation is towed with different speeds to cover a range of Froude numbers. PIV measurements are used to quantify the flow field which is divided in a mean flow, a wave component and turbulent component. In addition wave drag divergence over the boundary layer is investigated. The experimental results aim to improve formulations for turbulent heat and momentum transfer for use in numerical weather prediction, climate models and ocean models

1. INTRODUCTION

Understanding the stably stratified oceanic and atmospheric boundary layer is especially important for numerous environmental issues as for instance air quality (Neu, 1995), fog forecasting (Uematsu et al, 2007), wind energy engineering (Smith, 2010; Storm, 2009), climate and ocean modelling (Sigmond, Kushner, Scinocca, 2007; Karlsson et al, 2008; Killworth & Edwards, 1999; Ott, Barth, Erofeev, 2004). It is also of interest in the fields of marine ecology and biology (Gaylord et al, 2004).

Despite previous research efforts, current understanding of the Stable Boundary Layer (SBL) in the atmosphere is rather poor and progress in the field slow (Beljaars & Holtslag, 1991; Cuxart, Holtslag, Beare et al, 2006; Holtslag, 2006). In addition, Numerical Weather Prediction (NWP) models still have a long way to go in correctly incorporating the SBL. Another hurdle towards better understanding of the SBL is the multiplicity of small-scale processes which may occur at the same time (Mahrt, 2007). Typically, polar winter climate is estimated 6K too warm and nocturnal winds are overestimated. Also, NWP models needs more drag than can be explained from turbulence field observations. Hence, it is desirable to study possibly overlooked physical processes, as orographically induced wave drag, suggested firstly in (Chimonas & Nappo, 1989) or (Teixeira & Grisogono, 2008).

Recent oceanic research has similarly highlighted the importance of Bottom Boundary-Layer (BBL) dynamics on physical processes higher in the ocean’s water column (J. Xing & Davies, 2010; Ganju & Sherwood, 2010; Simarro et al, 2009). It was found that mixing, transport and fluid flow can be influenced by topography and dynamics in BBL, as well as water depth and internal wave generation. The effect of the ocean BBL on linear wave propagation has been analyzed in (Simarro et al, 2009). The results allowed (Simarro et al, 2009) to present an improved boundary- layer parametrization which takes into account the influence of gravity waves. Experimental BBL research in (Kushnir, 2007), (Kushnir et al, 2007) and (Carr, Stastna, Davies, 2010) indicate the impact of friction and orographic wavelength on BBL development and behaviour. They found that orographically induced wave generation was a key process for the BBL momentum budget. In (Sutherland & Aguilar, 2006), Sutherland and Aguilar showed the importance of boundary-layer separation upon internal waves generated by flow over rough topography. Their experiment showed that the specific shape of topography is more important for wave generation than the momentum roughness.

Despite many field experiments for a range of BBL or SBL roughness, there is no quantitative explanation for all the processes that cause drag to the flow under stably stratified conditions. The behaviour of atmospheric stably stratified flows is still not represented or described well enough. According to linear theory, wave drag at surface is governed by Richardson number Ri , Froude number Fr and Scorer parameter, but still the shape of its divergence in practical situations is unknown. As a result, the role of small-scaled gravity waves is currently neglected in NWP models. This project focus on orographically induced wave drag (τ_{wave}) and its influence on Boundary Layer dynamics. Theoretical and idealized model studies already shown that turbulent drag and wave drag may be of the same order of magnitude during weak flow conditions (Steeneveld et al, 2008), (Steeneveld, Nappo, Holtslag, 2009), but the shape of the divergence of τ_{wave} is unclear. The main objective of this experimental study is to determine the shape of divergence of τ_{wave} and to investigate the effects of orographically induced wave drag on boundary layer dynamics in general. The momentum and energy budget parametrization will be studied in order to take account of τ_{wave} .

2. THE SCIENTIFIC OBJECTIVES

The scientific purpose of the project is to quantify and describe the influence of wave drag caused by ”relatively modest” orography on mixing and momentum budget behaviour in the SBL in order to obtain a better parametrization and understanding than what is currently available. Such a parametrization can then be used to improve existing oceanographic and atmospheric models in (very) stable conditions. In order to achieve the aims of the project, we planned the following objectivities:

- to achieve stable conditions in the stratified water flume with surface corrugation in the bottom for relatively range Fr , Ri and the Scorer parameter
- to measure mean velocity at several levels
- to measure flow fluctuation u , w relative to the mean flow
- to distinguish between turbulence and wave-based fluctuations
- to evaluate linear theory of gravity waves and its impact on momentum budget
- to observe the dependence of wave drag τ_{wave} with height
- to quantify the impact of small-scale orographically induced gravity-wave drag on the dynamic development of the SBL

3. MATERIAL AND METHODS

Ideal conditions to develop theory and parametrization are hard to find in nature, both in the atmosphere and ocean. Therefore, idealized laboratory experiments will make a key contribution to furthering current understanding. Moreover, calculation of momentum and energy budget will be improved by laboratory results. A common challenge in the experiments is to set up and maintain stable density gradients and to measure fluxes in controlled stratified conditions. For that purpose, the CNRS/CNRM-GAME Toulouse stratified water flume is ideal since it has been designed specifically to investigate density stratified boundary layers. Another key aspect of that facility is its ability to generate stratified flow at very high Reynolds numbers, hence similar to those in the real ocean and atmosphere. Also, the facility is the longest, density stratified flume available in Europe and most likely in the world. A flume of a large length is essential for obtaining stationary conditions. In addition the CNRS/CNRM-GAME team has a good expertise on time- resolved density and velocity measurements in turbulent and stratified flows.

The set-up (see Figure 1) allow for the first time a stratified boundary layer developing over a corrugated surface to be studied in the laboratory at high Reynolds number. The corrugation wavelength is 80cm and its height is 10 cm. These corrugations have been equipped with small blocks at their surface to increase the simulated boundary layer depth.

Previous research showed that (Steeneveld et al, 2010) it was possible to simulate in this flume (stratified) boundary layers similar to atmospheric ones. Studying wave drag divergence requires wave breaking or saturation which will be obtained by larger flow speed close to the surface than aloft. Flow velocities should range between 5 and 15 cm/s, with Brunt-Vaisala frequency of the order of 1 rad.s^{-1}, creating turbulent boundary layer of the order of 0.1m.

4. RESULTS

Figure 2 shows turbulence generated over a corrugated surface (ocean floor or ground) in an exploratory experiment (visualization of fluorescent dye in a vertical laser sheet). Figure 3 presents the preliminary results of an experiment with a towing speed of 9 m/s. At the top the hills are visible. Flow speed increases with height from the surface and the stream lines nicely follow the orography in this case. In the right panel, a wake is visible between the hills and the flow is detached from the orography. Even at the higher levels the streamlines are smooth and follow roughly the orography. The vertical velocity (Figure 3, right panel) follows a structure with upward flow just before the hills and a downward component behind the hills. This structure propagates upward creating wave crests at higher levels and skewed relative to the surface, similar to prediction of linear theory. Preliminary density profiles (not shown) suggests a typical Brunt Vaisala frequency of 0.57 rad.s^{-1} before the run which persists during the run, indicating that a stratified boundary layer has been successfully simulated. Experiments with a smaller towing speed indicate wave dissipation (not shown).

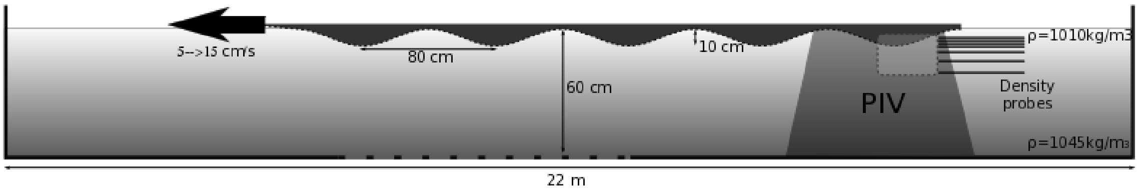

Figure 1 Experimental set-up

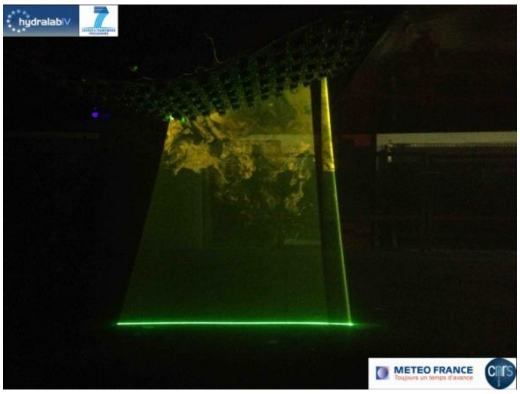

Figure 2 Turbulence generated over a model representing a corrugated surface (ocean floor or ground) in an exploratory experiment (visualization of fluorescent dye in a vertical laser sheet).

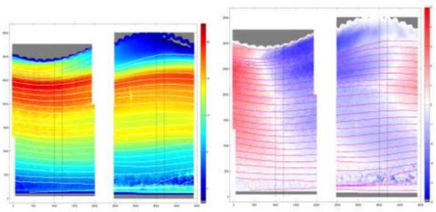

Figure 3 Observed horizontal flow speed and stream lines (left panel).Observed vertical flow velocity (right panel).

5. CONCLUSIONS

A stratified boundary layer flow over regularly undulating orography have been successfully simulated for the first time in the laboratory at high Reynolds number. The experiments conducted in the CNRS/CNRM-GAME Toulouse large stratified water flume show an adequate wave propagation and boundary layer development. Preliminary results indicate that wave drag divergence has been observed in a subset of the runs. Further analysis will explore more deeply the vertical variation of the wave drag flux and the turbulent momentum flux with height.

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