

# WAVE-LIKE PHENOMENA DURING THE MORNING TRANSITION IN THE PLANETARY BOUNDARY LAYER (PBL): A COMPARISON WITH WATER-TANK EXPERIMENTS.

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## ABSTRACT

Ground-based LIDAR observations of the morning transition in the PBL have been documented since 2002 and revealed anomalous mixing at the top of the Residual Layer (RL). As an example the case of the 14 October 2003 is presented here. Strong wave-like instabilities appear at the capping inversion of the RL. They seem to be due to convectively-driven internal gravity waves. In order to simplify the overall physics, water tank experiments using shadowgraph technique have been carried out to investigate the generation of internal gravity waves from turbulence in a multi-layered system. These experiments are set to provide a better understanding of the morning transition. Atmospheric thermally driven convection and thermal stratification of the PBL are simulated respectively by mean of mechanical stirring and water-salt stratification. Experiments revealed both transfer of energy by wave propagation and “tunneling-effect” transfer of energy by evanescent waves. Results are compared with observations and analytical model.

## 1. INTRODUCTION

The Atmospheric Boundary Layer (ABL) plays a major role in air quality problems, with respect to emission, mixing, dilution, transport of gas contaminants and aerosols particles. The RL has a great impact on air quality via down-mixing of pollutants [1]. To our knowledge, only few studies have been devoted to the morning transition. In the morning, RL is generally represented as a neutrally stratified elevated layer, whose characteristics are generally observed to be initially those of the Mixing Layer (ML) from the previous day [2]. However, in some cases, there is evidence of small stratification of the RL which is therefore able to sustain internal gravity wave propagation. Interaction between stratified layers and turbulence generated by an oscillating grid has been studied in various laboratory settings [3-5]. Turbulent forcing at the boundary between turbulent and stratified layers can generate both internal waves and evanescent waves that radiate into the outer stratified layer,

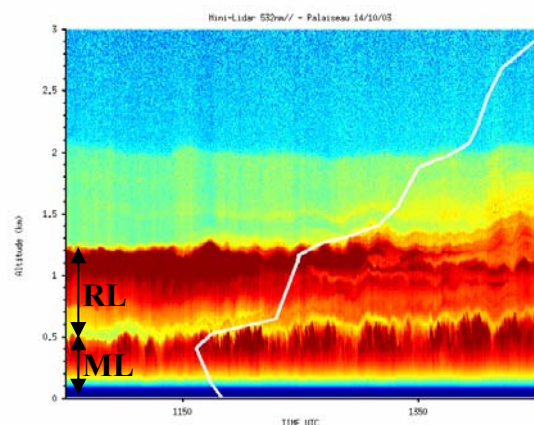
carrying energy out of the turbulent layer [6,7]. The present work aim to understand the conditions for the inversion layer above to sustain resonant modes and lead to breaking at the RL height.

## 2. THE 14 OCTOBER 2003 OBSERVATIONS

An upward looking Elastic Backscatter Lidar (EBL) and a 2 $\mu$ m Heterodyn Doppler Lidar (HDL) have been deployed by the LIMAG Team on the instrumented site of Palaiseau. Zenith lidar observations were performed from 0800 to 1400 UTC. A gradient algorithm has been applied to EBL signal to estimate the RL and ML heights and HDL provides time series of the vertical velocity. The temporal resolution of EBL is 10 s and the spatial resolution is 15 m. The temporal resolution of HDL is 4 s and the spatial resolution is 75 m.

### 2.1 Wave-like phenomena and mixing at the top of the RL

In Fig.1 EBL time series show the end of the morning transition on the 14 October 2003.



**Fig.1** EBL time series of the morning transition on 14 October 2003; Start at 1100 UTC, end at 1400 UTC. The white curve is the potential temperature at 1200 UTC from radio soundings.

The ML reaches 500 m and the RL height is approximately 1200 m. From 1130 UTC to 1320 UTC, waves of amplitude ranging from 50 m to 100 m are clearly visible at the base of the inversion Layer. The wave characteristics i.e. frequency and amplitude can be retrieved from the EBL signal and time series of vertical velocity. After 1320 UTC, mixing occurs at the inversion layer.

### 3. WATER-TANK EXPERIMENTS

#### 3.1 Experimental set-up

Experiments have been performed in a glass tank of horizontal dimensions  $W=20$  cm,  $L=42.5$  cm and of height  $H=29$  cm. A grid made of small holes of 0.5 cm diameter was used, giving a solidity of 56% even if such solidity is known to generate secondary flow [8]. The tank is filled up to 2 cm from the edge with three layers of uniformly salt-stratified water using the standard double-bucket technique. Each layer is separated from the other by a controlled density jump, assuming small salt diffusion during the experiments. The strength of stratification of each layer is represented by the buoyancy frequency,  $N$ , which is defined by

$$N^2 = -\frac{g}{\rho_0} \frac{d\rho}{dz} \quad (1)$$

where  $\rho(z)$  is a background density profile,  $\rho_0$  is a reference density, and  $g$  is the gravitational acceleration. The density profiles have been determined by measuring the refraction index of vertical samples of salt water. The grid is oscillated at the top of the tank by mean of a speed-controlled motor. The grid frequency ranges between 0.5 Hz and 1 Hz, with a stroke of 7.3 cm.

The experiments are set to give more insight into the wave generation during the morning transition. A turbulent region created by the oscillating grid is overlaying a weakly-stratified salt-water layer bounded by an inversion and a strongly-stratified layer, modeling respectively the atmospheric convective layer, the near neutral RL and the free troposphere. We have explored a wide range of buoyancy frequency ratio  $\varepsilon=N_i/N_u$ , where  $N_i$  and  $N_u$  are respectively the buoyancy frequency of the intermediate layer and the upper layer.

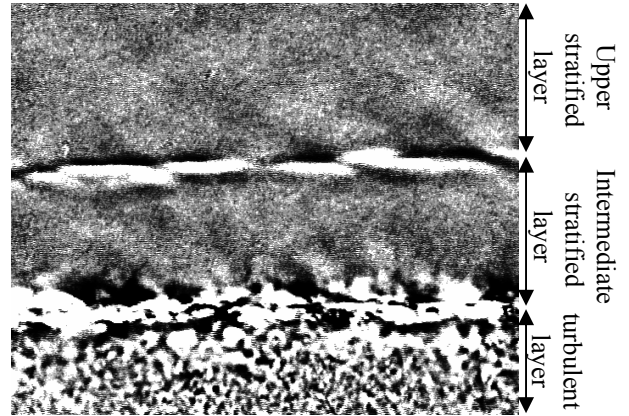
Shadowgraph technique has been used to visualize the turbulent region and the internal wave field. A light source illuminates the water-tank and a white screen is placed behind the tank. A CCD camera is positioned perpendicularly to the front of the tank. 4 Hz acquisitions of the flow are made. The sharp density jumps allow us to visualize clearly the interfaces between the layers.

#### 3.2 Qualitative observations

Fig.2 shows the instantaneous flow. The  $z$  axis has been turned upside-down in order to be similar to the atmospheric case. The wave-field has been enhanced by subtracting the image to a reference image. The lower part is the turbulent region generated by the oscillating grid, with a clear turbulent front. The mid-line is the interface between the two layers of stratified fluids. Waves are clearly visible in the upper and intermediate layers as shown by dark and light oblique regions. Characteristics directions of the wave's propagation are also visible, which allow us to estimate the wave frequency in both layers, using the dispersion relation for internal gravity waves

$$\omega = N \cos \theta \quad (2)$$

where  $\omega$  is the wave frequency ( $\text{rad.s}^{-1}$ ),  $N$  the buoyancy frequency ( $\text{rad.s}^{-1}$ ) and  $\theta$  the angle of the wave number with respect to the vertical. This experiment reveals upward propagation of internal gravity waves in the intermediate layer which is weakly stratified. Part of the wave energy is converted into interface displacement which in turn propagates upward internal gravity waves in the strongly-stratified layer above.

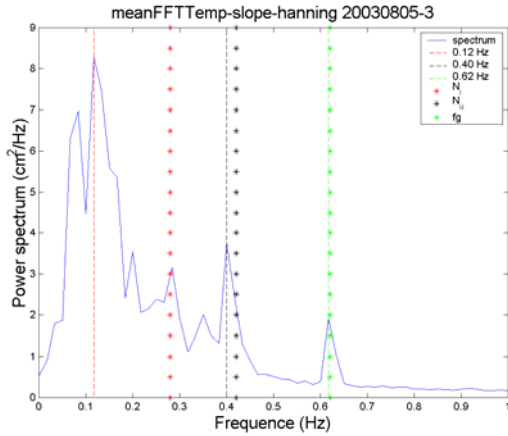


**Fig.2** Upward internal gravity waves in a three layer system.

#### 3.3 Quantitative results

A detection algorithm has been used to provide time series of the relative displacement of the interface between the two stratified layers. The length of the interface detection is approximately 18 cm. Time series of 1min are recorded at a sampling frequency of 4 Hz, enabling a spectral analysis. Fig. 3 shows the frequency spectrum of the time series. This spectrum is divided into three main regions corresponding to different physical behaviors. The first region below  $N_i$  is related to propagation of internal gravity waves in the intermediate layer. The second region lies between  $N_i$

and  $N_u$  and corresponds to the transfer of evanescent waves through the intermediate layer. This region and the peak located near  $N_u$  are due to what we referred as a “tunneling effect” transfer of energy. The third region is located around the grid frequency  $f_g$  and is related to the secondary flow generated by the grid.



**Fig.3** Power spectrum of the time series. Main peak frequencies are dashed lines. Red dotted line is  $N_i$ , black dotted line is  $N_u$  and green dotted line is the grid frequency  $f_g$ .

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