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# INTERNAL GRAVITY WAVE BREAKING AS A POSSIBLE SOURCE OF MIXING IN THE STABLY-STRATIFIED ATMOSPHERE OF A VALLEY

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**Abstract:** The atmospheric dynamics in an alpine valley under stable conditions (e.g. either at night or in winter) is mainly dominated by down-slope flows. These flows are triggered by horizontal temperature gradients due to the radiative cooling of the slopes on the mountain sides. Internal gravity waves must be generated by these down-slope flows if the atmosphere of the valley is stably-stratified. The waves may be trapped and possibly break, thereby inducing mixing within the valley despite the stable conditions. These points are addressed here, using numerical simulations with the ARPS code. Both an idealized version of the Chamonix valley and the actual topography of that valley are considered in order to investigate the features of the emitted internal gravity waves and to evaluate the potential of the wave dynamics in fluid mixing. We found that the wave characteristics are controlled by the valley dimensions and that the waves are therefore trapped. Ubiquitous wave breaking is observed in the atmosphere of the valley, implying that mixing should be quantified to evaluate its importance.

**Keywords:** ICAM 2007, stably-stratified atmosphere, alpine valley, katabatic winds, internal gravity waves, mixing, numerical simulations, ARPS code.

## 1. INTRODUCTION

As soon as the ground surface is not flat, a horizontal temperature gradient is created at night between that surface and the air above it because of radiative cooling of the ground. A katabatic (i.e. downslope) flow is thereby induced. This flow is a gravity current, namely a jet of cold air confined between the ground and the stable atmosphere above. Katabatic flows are well-known to develop along the gentle slopes of ice shelves (e.g. Derbyshire and Wood, 1994). For steep slopes (larger than about 10 degrees), the features of katabatic flows have also been well documented through *in situ* measurements either on a simple slope (f.i. Helmis & Papadopoulos, 1996) or in a valley (Gryning et al. 1985, van Gorsel et al. 2004): the along-slope velocity is of a few meters per second with a high shear, its maximum value being reached at a height of a few tens of meters above the ground, depending upon the distance from the top of the slope. These flows are highly variable and intermittent. Thus, they entrain or detrain free air while flowing (Baines 2005), possibly trigger shear instability at their top and, in a stably-stratified medium, exhibit oscillations at periods of the order of one hour. The latter behaviour has been reported both on a single slope (Helmis & Papadopoulos, 1996, Bastin & Drobinski 2005) and in a valley.

Whatever the steepness of the slope, internal gravity waves must be generated by these downslope flows when the atmosphere is stable. Until recently however, only few papers mentioned the existence of internal gravity waves in a valley despite oscillations are often reported. The single particle model derived by McNider's (1982) shows that a fluid particle should oscillate along the slope with frequency  $N\sin\alpha$  where  $N$  is the Brunt-Vaisala frequency (assumed to be constant in the model) and  $\alpha$  is the local angle of the topography with the horizontal. When the presence of internal gravity waves is recognized, van Gorsel et al. (2004) assumed that the wavelengths are imposed by the valley dimensions, both horizontally and vertically; hence, the waves are assumed to be trapped and the theoretical period appeared to agree well with the observed period. In the recent theoretical work by Shapiro and Fedorovich (2007) and in the laboratory experiments by Fernando et al. (2006), the possible excitation of internal gravity waves by an unsteady katabatic flow on a simple slope is studied.

The purpose of the present paper is to address the properties and dynamics of the internal gravity wave field emitted by a katabatic flow in an alpine valley under stable atmospheric conditions. Several questions are currently unanswered : what are the wave characteristics? What does happen to the waves once emitted? Does a trapping process always occur in a valley? What are the induced mixing and transport properties? Do the waves interact, possibly resonantly, with the katabatic flow (as observed by Maxworthy et al. 2002)?

To address these questions, we performed numerical simulations which are briefly described in the next Section. The kinematical features of the waves (frequency and wave vector) are reported in Section 3 and preliminary results about their dynamics are described in Section 4.

## 2. METHODOLOGY

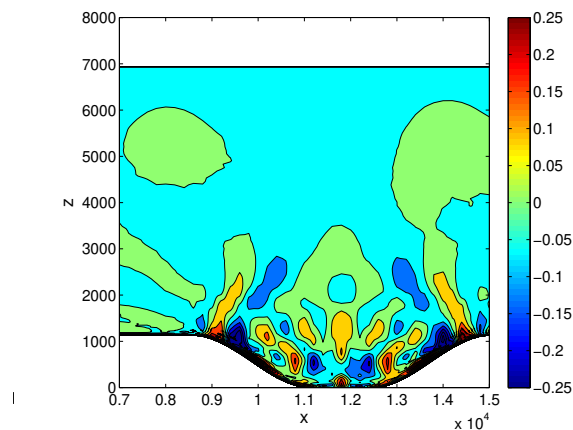
We have carried out high resolution numerical simulations of the stably stratified atmosphere of an alpine valley using the ARPS code (Advanced Regional Prediction System, Xue et al. 2000). We first considered an idealized version of the Chamonix valley before considering the realistic topography of that valley.

The dimensions of the idealized valley are such that summits at altitude 2700m dominate the bottom of the valley, located at 1000m. The width of the bottom of the valley is 1.2 km and the mean value of the slope angle is  $32^\circ$ . The valley is open at one boundary to allow for the development of an along-valley wind. The simulations model a winter situation for which a  $3^\circ$  difference exists between the ground surface and the air just above it (the ground surface being colder than the air). The horizontal resolution is 200 m. A variable grid is used along the vertical direction, the resolution between 5m above the topography and slowly increasing upwards. Two different temperature profiles have been used at initial time : (i) a linear stable profile displaying a weak inversion at the altitude of the summits and (ii) a temperature profile inferred from in situ measurements, which is stable up to the altitude of the summits and neutral above that altitude.

The initial time of the computation is 22:00 pm, on Decembre 21st, at the latitude of Chamonix valley. No velocity field needs to be imposed at initial time: the temperature difference between the ground surface and the air creates horizontal temperature gradients which trigger the katabatic winds.

## 3. ANALYSIS OF THE INTERNAL WAVE FIELD

Constant contours of the vertical velocity field are displayed in Figure 1 at 22:45 pm. Two systems of waves are visible: one is associated with phase lines directed along the slope of the topography and confined along it, consistently with McNyder's (1982) predictions, while the second system is perpendicular to the first and leads to free wave propagating away from the slope, within the atmosphere of the valley. We focus on this second wave system in the present paper.

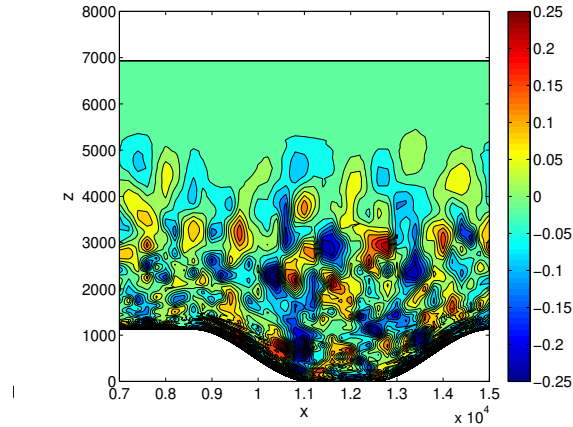


**Figure 1:** Constant contours of the vertical velocity field in a plane perpendicular to the valley axis, at 22:45 pm.

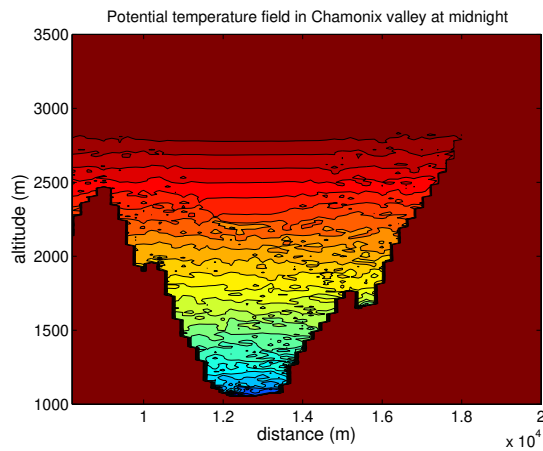
Simple diagnostic analysis shows that the waves propagate in a two-dimensional vertical plane perpendicular to the valley axis,  $y$  say, whether the idealized or the realistic valley configuration is considered. The wavelength along the  $x$  and  $z$  directions are found to be close to the valley dimensions, implying that the waves are trapped by the confined geometry of the valley. The wave frequency, measured independently and when using the dispersion relation, yield consistent values, of the order of 10 minutes.

#### 4. TURBULENCE IN THE ATMOSPHERE OF THE VALLEY

The same figure as Figure 1 is plotted later in time, at midnight (Figure 2): small structures are evident, up to an altitude of 5000 meters over which the waves cannot propagate (because their frequency becomes larger than the ambient Brunt-Vaisala frequency). The occurrence of small dynamical structures is even clearer in Figure 3, where the potential temperature field is plotted for the geometry of the Chamonix valley: overturning regions are visible everywhere within the valley, implying that mixing should occur there.



**Figure 2:** Constant contours of the vertical velocity field in a plane perpendicular to the valley axis, at midnight (idealized valley configuration).



**Figure 3:** Constant contours of the potential temperature field in the Chamonix valley at midnight.

#### 5. CONCLUSION

This academic study has shown that two systems of internal gravity waves are generated by katabatic winds in a valley (this should be the case as well for a simple slope). These wave systems propagate at right angles, with the wave-induced energy flowing either along the slope (with dispersion relation  $\omega = N\sin\alpha$ , where  $\alpha$  is the slope angle with the horizontal), or perpendicular to the slope (with dispersion relation  $\omega = N\cos\alpha$ ). The latter wave system gives rise to trapped waves, with period of the order of 10 minutes, consistently with the finding of van Gorsel et al. (2004) in the Riviera valley at night.

The striking feature of our numerical simulations is that very small scales are generated within the atmosphere of the valley. The only possible mechanisms for this small scale generation are wave interactions and wave breaking (as reviewed in Staquet & Sommeria 2002). Hence, the generation of gravity waves in the stable atmosphere of a valley at night could lead to mixing. This mixing should therefore be quantified and, if significant (as measured by a diapycnal diffusivity for instance), should be parameterized in large scale models.

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