GRAVITY WAVE BREAKING: MAP HARVEST P6

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Abstract: One of the primary objectives of MAP was to understand the generation of gravity waves from high complex terrain, and the breakdown of those waves. Several weak to moderate gravity wave events during the MAP field phase were studied with a remarkable fleet of research aircraft equipped with GPS navigation, gust probes, dropsondes and downlooking LIDAR. These data sets have been carefully analyzed and published in the five years since the project. We review these analyses and compare them with advancing theories and models. Airflow blocking, the turbulent boundary layer and low level shear apparently play significant roles in wave generation and breakdown.

Keywords- gravity wave, mountain wave, wave breaking, research aircraft, boundary layers,

1. INTRODUCTION

As part of the overall MAP Harvest activity, recent progress on mountain waves and mountain wave breaking is reviewed. To limit the scope of the review, we focus on aspects of the problem that connect with MAP objectives and MAP cases. For a broader perspective, we include a brief discussion of work done during the same time-frame by other groups and projects.

As the MAP field campaign was being designed in the late 1990's, the PIs realized that the Alps represented a major challenge for gravity wave research. On the one hand, the predecessor to MAP; ALPEX in 1982, had found little in the way of strong gravity waves. Large scale flow splitting phenomena (Chen and Smith, 1987), lee cyclogenesis and smaller scale local winds like the Bora (Smith, 1987), provided clearer signals. On the other hand, no systematic survey of gravity waves had been attempted in ALPEX, so the lack of gravity waves had not been established. Several reports of large mountain pressure drag had been published (Davies and Phillips, 1985; Hafner and Smith, 1985; Carissmo, et al., 1988), but no evidence that this drag was connected to gravity wave generation had ever been put forward.

Guidance also came from PYREX, recently held in the Pyrenees (Bougeault, 1996). There too, in spite of a more compact structure to the mountain range, few strong gravity waves cases were identified. Explanations related to the complexity of the terrain or its east-west orientation were put forward. The role of friction in reducing wave amplitudes was discussed (Olafsson and Bougeault, 1996).

In contradiction to these pessimistic views were reports of powerful gravity waves associated with "deep foehn". One southerly event occurred in November 1982, the year of ALPEX, but after the Special Observing Period had ended (Hoinka, 1985; Hoinka and Clark, 1991). Also, long duration numerical simulations of Alpine gravity waves (Doyle, private communication) showed significant gravity wave energy. Satellite data showed occasional wave clouds over the Alps, but not more than in other mountainous regions.

On the basis of this mixed information, the gravity wave observational program for MAP was designed primarily to test numerical model predictions. Under the assumption that strong gravity waves would be fleeting and local, research aircraft would be required to respond flexibly to 12 or 24 hour mesoscale forecasts of gravity wave activity. These aircraft, equipped with GPS navigation, fast response gust probes, dropsondes and down-looking LIDAR, brought a formidable array of measuring systems into the predicted gravity wave area. Furthermore, because of the contributions from several nations (i.e. France, Germany, UK and the USA), and the coordination assistance of the MAP directors and the European aviation officials, multiple research aircraft could be brought together to intensely probe a small region. This concentration of aircraft allowed the investigators to use a new approach to flight path design. Instead of having aircraft changing altitudes at the end of each leg to map the vertical structure, the flight crews were mostly asked to run repeated legs. This allowed an unprecedented test of the steady state assumption of mountain wave theory, while still providing some vertical structure information. It is not certain that gravity waves will ever again be so carefully surveyed by multiple aircraft as they were in MAP.

Our starting point in this review is the set of MAP gravity wave missions that have been analyzed and published in peer-reviewed journals (Table 1). The list includes seven events over the two month MAP Special Observing Period in the fall season of 1999. Missing from the Table are other MAP events, such as PV banner and Gap flow events that might also contribute to the GWB objectives. The locations of the gravity wave missions are shown in Fig. 1. As seen in the Table, these events include variety of wind directions. A common element in all the missions was the use of one, two or three research aircraft with dropsonde (D) and LIDAR (L) capability.

Table 1: MAP gravity wave cases in the peer-reviewed literature

#	Date	IOP	Obs. Sys.	Region	Wind	Characteristic	Reference
1	Sept 20	2b	1/D/L	Eastern	S	latent heat, trapped wave	DS03
2	Oct. 21	8	1/D/L	Central	SW	shear and GWB	JD04
3	Oct. 25	10	1/D/L	Eastern	SSW	foehn window, deep GW	V03
4	Nov 2	13	3/D/L	West/ Mt Blanc	SW	stagnant layer, weak deep GW	S02/SB03
5	Nov 7	15	2/D/L	East/Dinaric	NE	Bora, shallow breaking	G05/JD05
6	Nov 8	15	3/D/L	Central	N	blocking, trapped waves, foehn window	J05,S04
7	Nov 13	16	3/D/L	French Alps	SE/E	directional shear.	DJ05

[References: DS2003 = Doyle and Smith, 2003; JD04 = Jiang and Doyle, 2004; V03 = Volkert et al, 2003; S02 = Smith et al. 2002; SB03 = Smith and Broad, 2003; G05 = Grubišić, 2005; JD05 = Jiang and Doyle, 2005; J05 = Jiang et al. 2002; S04 = Smith, 2004; DJ05 = Doyle and Jiang, 2005]

2. REVIEW OF GRAVITY WAVE CASES IN THE CONTEXT OF ADVANCING THEORY AND NUMERICAL MODEL DEVELOPMENT.

In the full paper, we will review the MAP gravity wave findings and compare then with recent advances in theory. We will touch on the following subjects.

- **a.** Observing systems for gravity waves and momentum flux
- **b.** Mountain waves with shear and with critical levels
- **c.** Boundary (and stagnant) layer effects
- **d.** Gravity waves and Foehn, Mistral, Bora
- **e.** Finite amplitude theory using layered models
- **f.** Coordinate systems for complex terrain
- **g.** Mechanisms of GWB and PV generation
- **h.** Predictability

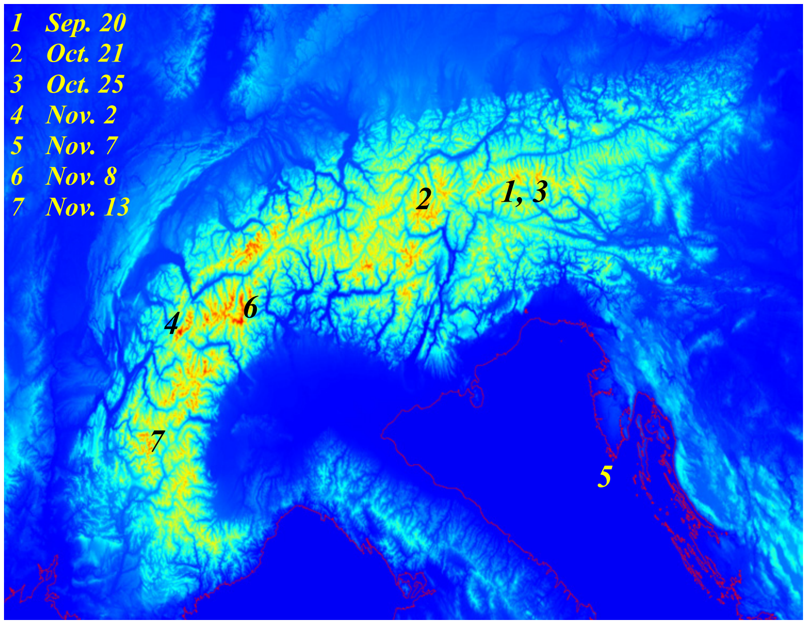

Figure 1. Alpine terrain and locations of MAP gravity wave cases.

3. SUMMARY

Overall, the gravity wave events in MAP were consistent with our knowledge of event climatology in the region. Most of the gravity wave cases in MAP were weak, shallow and rather complicated because of combined effect of blocking, BL effects and low level wind shear. The only exceptions to this were the Sept 20 and October 25 cases. These were both cases of south foehn, similar in some respects to the "near ALPEX" case of November 1982 (see above). The bora event was also dramatic, but shallow, as indicated by previous work.

At the risk of over-simplifying, it seems that there is a clear but uncomfortable lesson here. In complex terrain such as the Alps, the overall massif and the individual peaks work together to block and slow the low level flow. The individual peaks then see an altered flow; weak in the lowest levels and accelerating and turning in the 2 to 3 km range of elevations. It is only the winds above the shear layer that hit the mountain peaks and thereby generate vertically propagating gravity waves. The mountain top shear layers promote a variety of phenomena associated with wave trapping, critical level absorption and other processes

The prediction of these complicated flows is difficult, but current numerical models such as COAMPS® have an encouraging amount of skill. Often however, it takes slight adjustments to the initial fields, the spatial resolution or the turbulence parameterizations to obtain an accurate numerical simulation. This sensitivity implies too, that models that have not been tested or calibrated against MAP or other data, may have large systematic errors in their predicted magnitude of wave generation. It is not sufficient that the models' numerics are able to correctly simulate gravity wave propagation in the free atmosphere.

Our recommendations for future work arise from the apparent importance of the interaction between gravity waves and the physics of blocking, boundary layers and wind shear. These aspects should be studied using all the available tools of theory, observations and simulation.

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