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North foehn over the central Alps during IOP-15 of MAP: Airborne Lidar and in-situ data compared with a high-resolution simulation

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ABSTRACT

A total of 32 sections of vertical velocity sampled by three research aircraft in stacked mode are presented for the gravity wave mission during the north Foehn situation of 8 November 1999 (IOP-15). The repetitive, but also varying, execution of flight legs documents the overall stationarity of the main wave systems over at least 4 hours and their close linkage to the underlying massifs. Amplitudes are moderate amounting to up to 5 m/s. For the height range between 7.0 and 10.7 km unique sections of remotely sensed water vapour structures appear to be modified by the strongest wave. The observational findings are juxtaposed to a series of nested simulations (down to a horizontal grid size of 0.5 km). A reliable positioning of prominent waves not longer than 15 km necessitates a grid size of less than 1 km. For the sampled upper-tropospheric mixing ratio (between 50 and 600 ppmv) the average agreement with the 2 km simulation is as good as 10%.

1. Introduction

Prior to the special oberving period (SOP) of MAP the strategy of straight, repetitive flight legs across the highest ridges, and possibly along the ambient wind, was shown to be best suited for the documentation of wave systems excited by airflow across a terrain as complex as the Alps (Doyle et al. 2002). On 7 November 1999 it was decided from the operational forecasts available to execute repetitive patterns across the Bernese Alps and the Monte Rosa massif (both with several summits above 4000 m) with three aircraft: the Falcon (DLR) for the top levels, the C-130 (UKMO) for the medium, and the Electra (NCAR) for the lower ones. In such a fashion it was intended to cover well the height interval from 5 to 11 km.

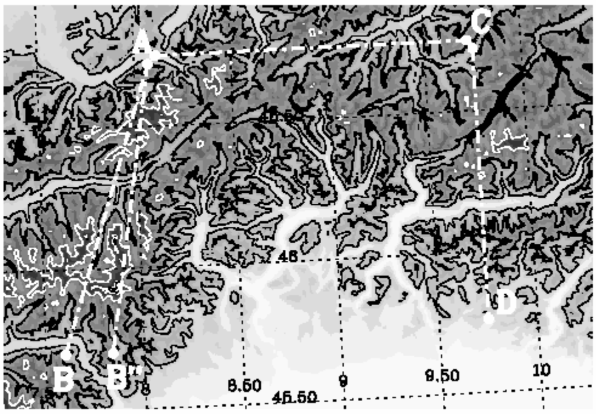

Figure 1: Topography of the region of interest (stereographic projection; scale: 1 : 5.5 Mill.; grey scale interval: 333 m; black: 1666–2000 m; lighter below and darker above; isolines: 1000 m in black, 3000 m in white). Flight tracks: BA – across Val d'Aosta, along Mattertal, across Rhonetal and Bernese Alps to Brienzer See; B'A - alternative leg for Electra crossing Monte Rosa; AC – transfer to the east along 46.75N; CD – north-south legs along 9.75E across Valtellina valley.

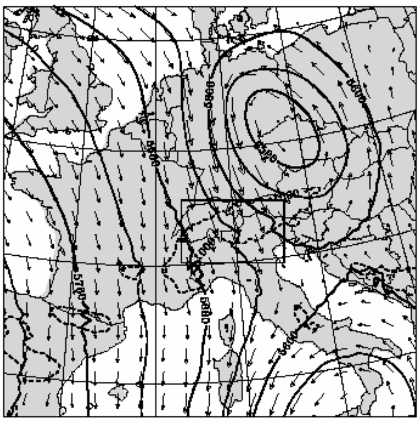

Figure 2: Geopotential and wind vectors at 500 hpa above Europe for 8 November 1999, 12 UT: ARPEGE analysis interpolated to the outer domain of Meso-NH (Δx = 32 km). Vectors at every fourth gridpoint (max. 30 m/s). Rectangle above the Alps (1000 m contour dashed) designates inner domain (Δx = 2 km).

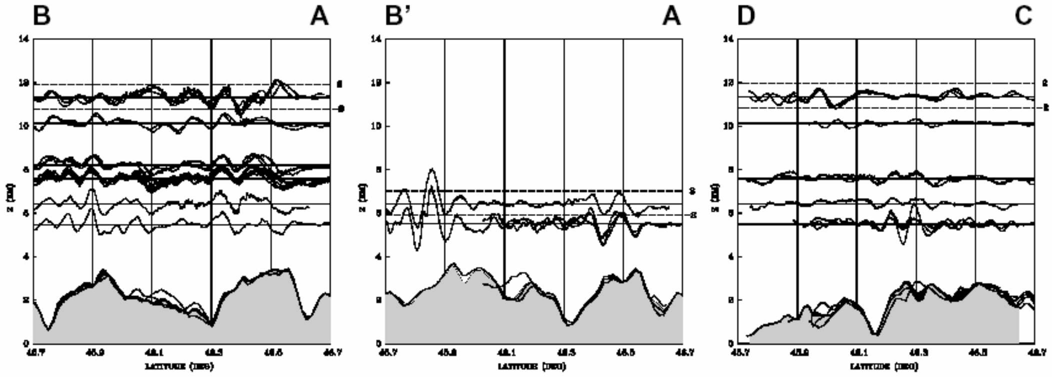

Figure 3: 32 legs of vertical velocity (w) in 3 cross-Alpine sections (cf. Fig. 1: 18 in BA, 4 in B'A, 10 in DC) sampled by three aircraft in two levels each (Falcon: 11.4 and 10.1 km; C-130: 8.2 and 7.6 km; Electra: 6.4 and 5.5 km) during the period 0955 to 1425 UT. Full horizontal lines designate flight level and w=0; dashed lines the ± 2 m/s thresholds for the uppermost level. Topographic sections are extracted from the Meso-NH 2-km orography exactly underneath the reported tracks (hence the slight variations). The flow is from the right (N).

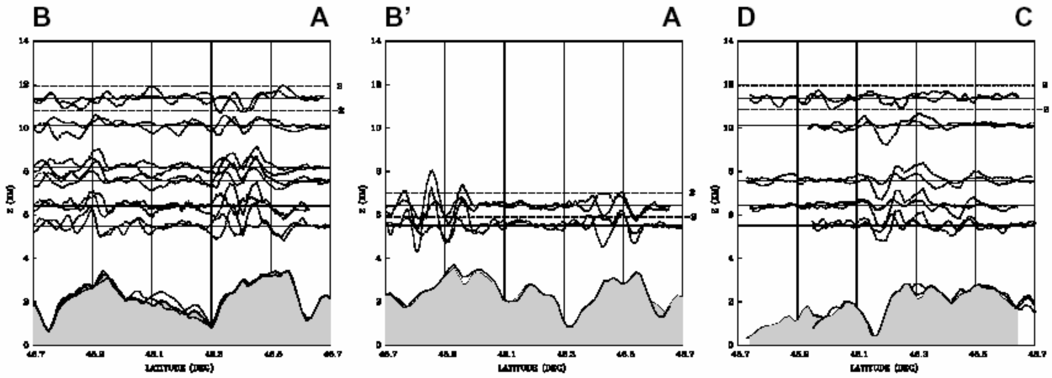

Figure 4: Comparison between measured (full lines) and modelled vertical velocity (dashed lines) for each of the 13 levels in the three sections of Fig. 3 (in the same layout). Modelled values are valid for 1300 UT.

Halfway through the mission, the chief scientist of the Electra asked for an altered southern way point B' in search for higher vertical winds directly in the lee of the Monte Rosa and later managed to direct the entire fleet to a transfer section (AC) and repeated north-south legs (CD) across the Monte Disgrazia massif north of the west-east oriented Valtellina in Italy. The position of these legs above the highly structured and steep Alpine topography is displayed in Fig. 1. A distinct cyclone centred over Bohemia directed a steady northerly flow towards the Alps with hardly a change of wind direction with height (Fig. 2). Over Switzerland winds of about 20 m/s prevailed in the 500 hPa level.

The focus of this presentation lies in the determination of the locations, lengths and amplitudes of the north foehn generated mountain waves through the inspection of in-situ measured vertical velocities. Furthermore their impact on the fine-scale structure of the upper-tropospheric moisture field is determined by novel remote measurements of the water vapour mixing ratio by a DIAL laser system (Poberaj et al. 2002). All the measurements are compared with episode simulations using the non-hydrostatic model Meso-NH (Stein et al. 2000 and references therein).

2. Vertical velocities

The vertical velocity sampled in 32 legs by the three aircraft within the three sections BA, B'A and DC is collected in Fig. 3 together with the topographies exactly underneath the tracks. The essential findings are: i) most tracks are really repetitve (only slight variations of the overflown ter-

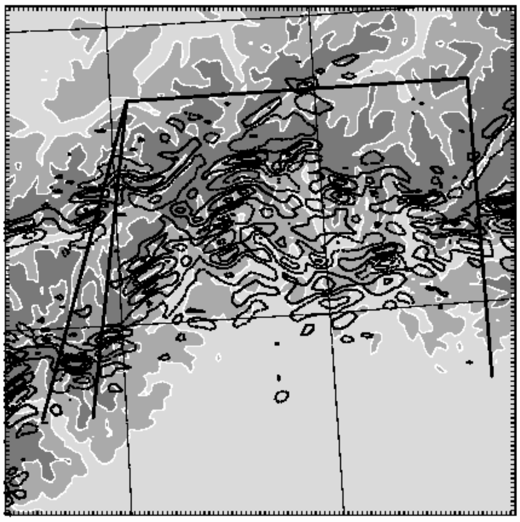

Figure 5: Simulated vertical velocity in 6 km height for 1300 UT superimposed on model orography (grey scale interval: 1000m); isoline increment: 2 m/s for uneven values. Full (dashed) lines designate positive (negative) values. Full degree latitudes and longitudes are dotted; the flight traverses are indicated by full lines (cf. Fig. 1).

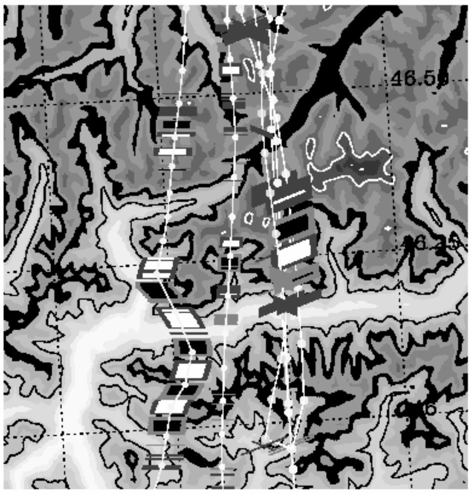

Figure 6: Vertical velocity along tracks across the Valtellina: constant level balloon 37 at 1340 UT (left trace, one dot per 5 min.), balloon 35 at 1000 UT (middle trace), four Electra passages between 1320 and 1400 UT (one dot per minute). Simple (filled) flags designate values in excess of ± 1 m/s (2 m/s) with grey/black for upward and dark grey/white for downward motion.

rain), ii) the prominent waves are stationary and vertically coherent, iii) wavelength (about 15 km) and wave amplitude (mostly less than 4 m/s peak-to-peak) are moderate, except directly in the lee of the Monte Rosa massif (10 m/s peak-to-peak).

A comparison with collocated vertical velocity from a triple-nested simulation initialized with the French ARPEGE analysis at 06 UT (inner grid with Δx = 2 km) is given in Fig. 4 for 13 levels and 1300 UT. A plan view of the simulated wave pattern in a height of 6 km is given in Fig. 5 along with the model orography and the flight sections. Updraughts and downdrafts are coherent as they appear to be clearly linked to the topography, but also spotty due to its irregularities. Fig. 6 depicts an illustrative plan view of measured vertical velocity exceeding ± 2 m/s (by constant level balloons in 3.5 km and the Electra in 5.5 and 6.4 km) in the vicinity of the Valtellina valley.

The overall structure of the most prominent waves is simulated with amazing realism, although the spatial resolution is insufficient to fully recover a wavelength only eight grid meshes long. A fourth nest with a 0.5 km grid yieds improved results (not displayed). The wave amplitudes are overpredicted. Yet the accord between simulated and measured variation in the quite sensitive quantity 'vertical velocity' is much better than for the test case documented in Doyle et al. (2002).

3. Water vapour mixing ratio

During MAP the newly developed DIAL laser system for backscatter and water vapour retrievals was applied in downward looking mode on the Falcon (cf. Volkert et al. 2003 for a mountain wave case with high clouds). An open question was whether wave induced structures can be detected in the moisture field. During the consecutive Falcon legs BA-AC-CD (1305 to 1334 UT) the laser operated without adjustment at the 'weak' H_2O wavelength of 935.608 nm. The retrieved moisture sections down to 7 km are presented in Fig. 7 with the vertical velocity of two C-130 legs superimposed.

The overall findings are: i) the expected layering of moisture from stratospheric mixing ratios of below 100 ppmv above 10 km to more than 300 below 8 km is found, ii) consistent gradients from south (moister) to north (drier) and west (moister) to east (drier) were sampled in the particular situation, iii) especially in section BA the layering is clearly modified in the lee of the Bernese Alps (around 46.4N), consistent with the in-situ probed vertical wave motions.

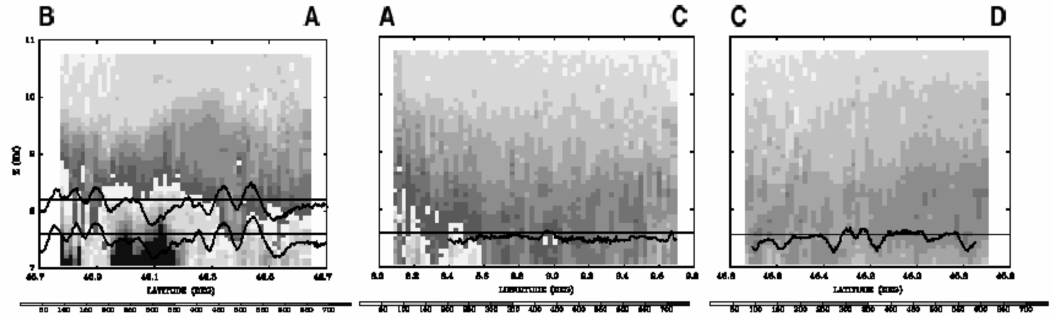

Figure 7: Three sections of lidar-sensed water vapour mixing ratio (in ppmv; grey scale increment: 50; jump to brighter values at 350) in 'triptych-style' from point B to D (cf. Fig. 1). Superimposed are in-situ vertical velocity from the best synchronized legs of the C-130 (cf. Fig. 3).

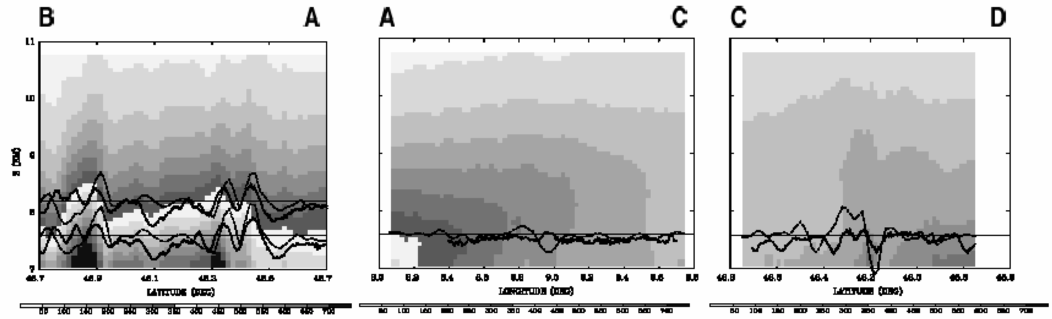

Figure 8: Three sections of simulated water vapour mixing ratio (in ppmv; grey scale increment: 50; jump to brighter values at 350) at 1300 UT in 'triptych-style' from point B to D (cf. Fig. 1). Superimposed are in-situ vertical velocity from the best synchronized legs of the C-130 (full line) and simulated vertical velocity at the same level (dashed; cf. Fig. 4).

The equivalent simulation results are given in Fig. 8. Naturally the modelled humidity field is much smoother, but in remarkable structural agreement. Quantitatively the averaged difference between retrieved and modelled mixing ratio values amounts to only 10%. Thus, the laser spectral purity of 0.75, which was assumed for the retrieval from house keeping laser data, receives an independent backing through the comparison with the model simulation.

4. Conclusions

Stacked, repetitive aircraft traverses served to document the moderate, but over 4 hours stationary wave event during the south foehn situation of 8 November 1999. Realistic simulations of such orographically disturbed three-dimensional flows become feasible, if the appropriate resoltion is available. Remotely sensed upper-tropospheric moisture field open up new lines of cross-validation for both retrieval techniques and simulation models.

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