A NUMERICAL SIMULATION OF TRAPPED LEE WAVES OVER WALES

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Summary: The UK Meteorological Office Mesoscale model is used to simulate a trapped lee wave event over Wales. The resulting steady state gravity wave field is verified using radiosonde data, from which vertical velocity can be deduced. It is found that the form of balloon ascent rate fluctuations can be explained by the model simulation.

1. INTRODUCTION

In the period September 27 to October 21 1989, several short trips were made to a field site in mid-Wales to use radiosondes to study gravity wave activity over the Welsh mountains. Each day, two groups of three sondes were released - one in the morning and the other in the afternoon. The novelty aspect of the experiment was to release three sondes with very short time separation and track them simultaneously. In this way, ascent rate fluctuations could be checked against each other to reveal aspects of the spatial structure of the waves and /or verify steadiness in the wave field. The largest amplitude waves found during the period occurred on the afternoon of October 6 with inferred vertical velocity fluctuations in the troposphere of $\approx 2.5\ ms^{-1}$. The simulation of this gravity wave event will form the subject of this paper.

The operational Mesoscale model of the UK Meteorological Ofice was re-configured to run on a regular 3 Km. grid with 70 X 70 points and with 19 levels in the vertical. The distribution of model levels follows those of the operational model up to 12.01 Km with an additional three at heights 13.61, 15.31 and 17.11 Km. The horizontal diffusion coefficient increases linearly from a background tropospheric value of 500 m^2s^{-1} at (and below) 10.51 Km, to 25000 m^2s^{-1} at a height of 17.11 Km. Newtonian damping of temperature and velocity components is applied above 10.51 Km with a time constant which decreases exponentially with height. These combined damping terms constitute an effective sponge layer in this experiment and absorb most of the upward propagating waves. The horizontal domain covers most of Wales and uses a smoothed orographic height field (Fig. 1) derived from a 500 m resolution dataset. In the experiment to be described, all surface energy fluxes were switched off and the relative humidity was set equal to 1% to ensure a dry integration. The model was initialized at 14Z on Oct. 6 with one of the sonde profiles obtained at the field site. This required vertical smoothing of the wind and temperature fields, together with the use of the geostrophic and hydrostatic relations to provide a linear variation of temperature and pressure consistent with balanced, horizontally-uniform flow. Figs. 2 (a),(b) and (c) show the unsmoothed wind speed, direction and temperature respectively taken from the ascent . A 20 ms^{-1} WNW flow at 1 Km veered with height to become a NNW'ly jet of 55 ms^{-1} at about 10 Km. Fig. 2 (c) indicates a fairly stable low-level flow.

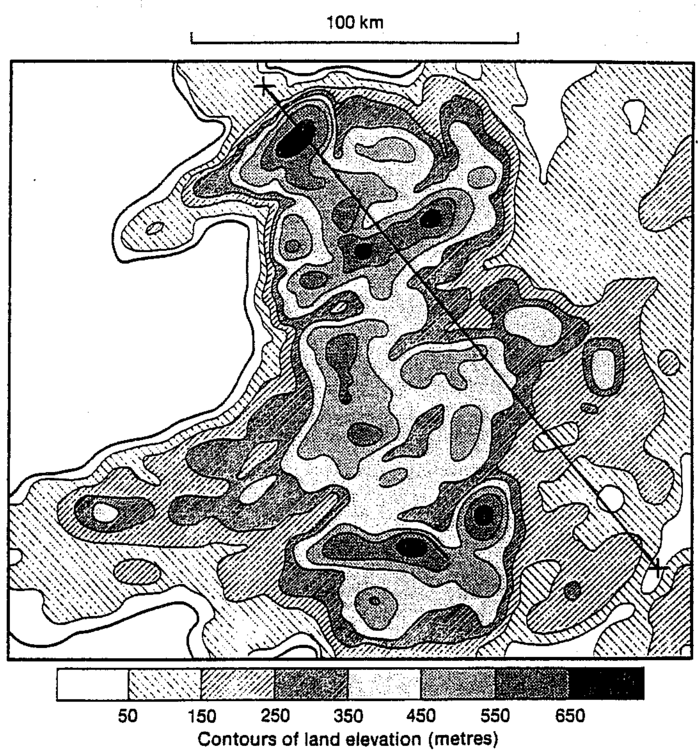


Fig. 1

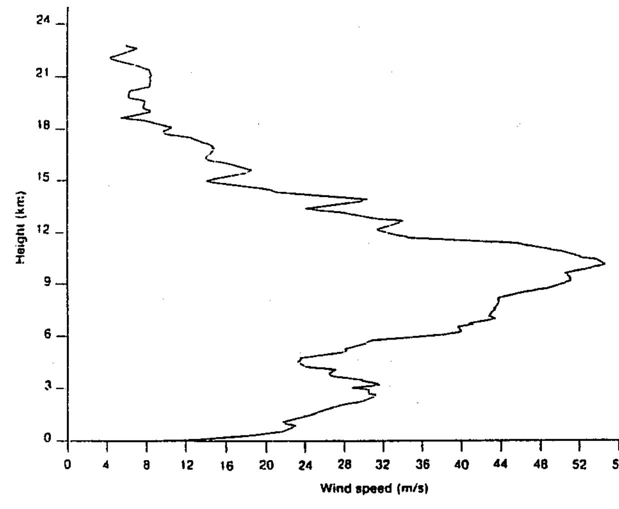


Fig. 2(a)

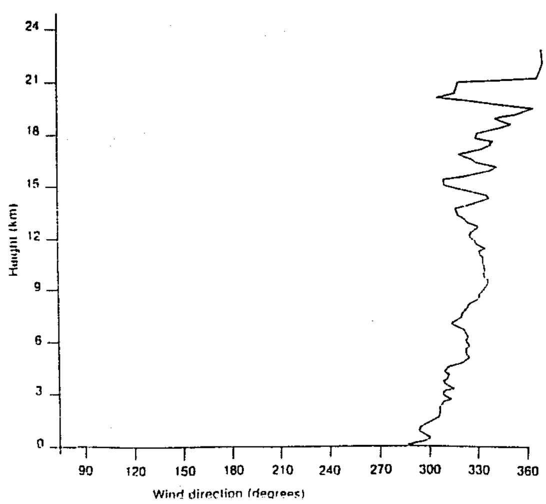


Fig. 2(b)

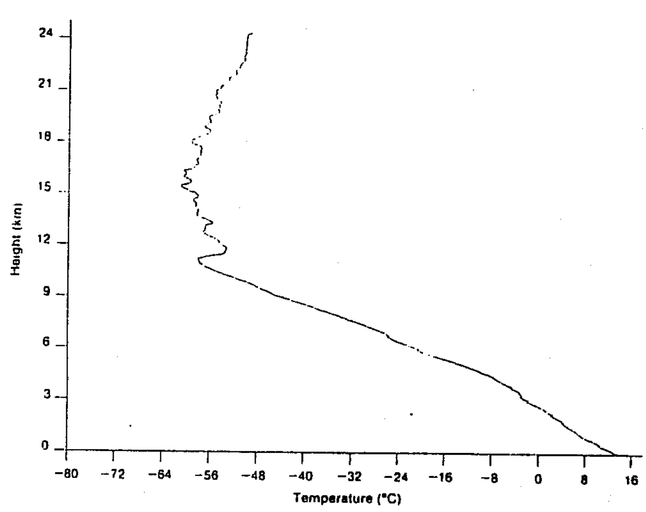


Fig. 2(c)

2. RESULTS

The Mesoscale model was integrated for four hours after which time the flow settled down to a quasi-steady state. The T+4 Hr vertical velocity field at a height of 3 Km above sea level is shown in Fig. 3. A striking pattern of long trapped lee waves (wavelength $\approx$ 22 Km) resulted with a locally enhanced wave amplitude (up to 3 ms^{-1}) downstream of main mountainous regions (see Fig. 1). A vertical cross-section of vertical velocity along the line indicated in Fig. 3 is shown in Fig. 4. Vertical phase lines confirm the trapped nature of the wave motion. Experiments with constant wind flows supporting vertically-propagating waves demonstrate that the sponge layer is quite effective in absorbing wave energy - in spite of its rather poor vertical resolution. In cases such as these, with trapped lee waves, the requirement for an absorbing layer is not so crucial.

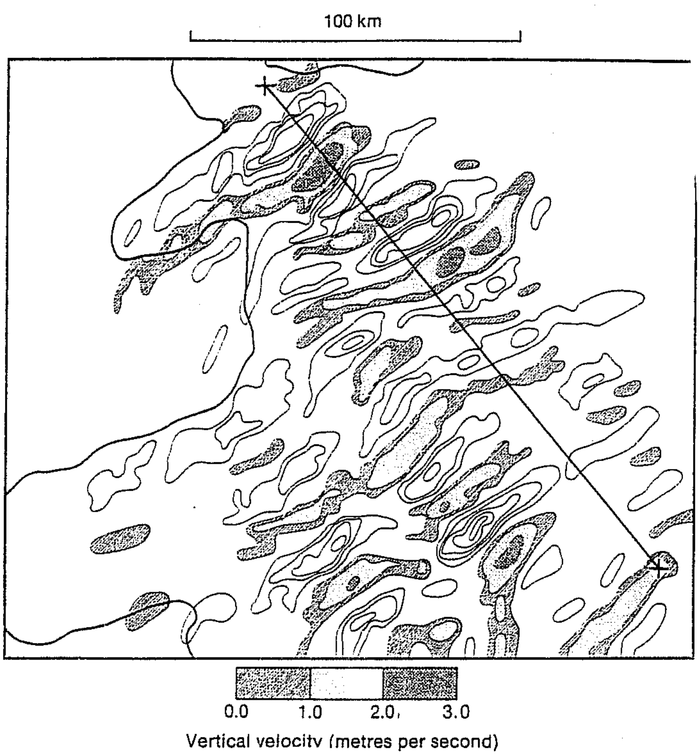


Fig. 3

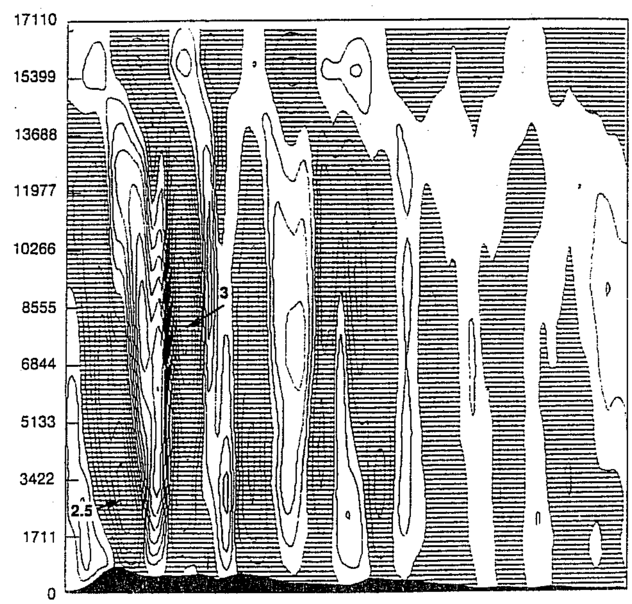
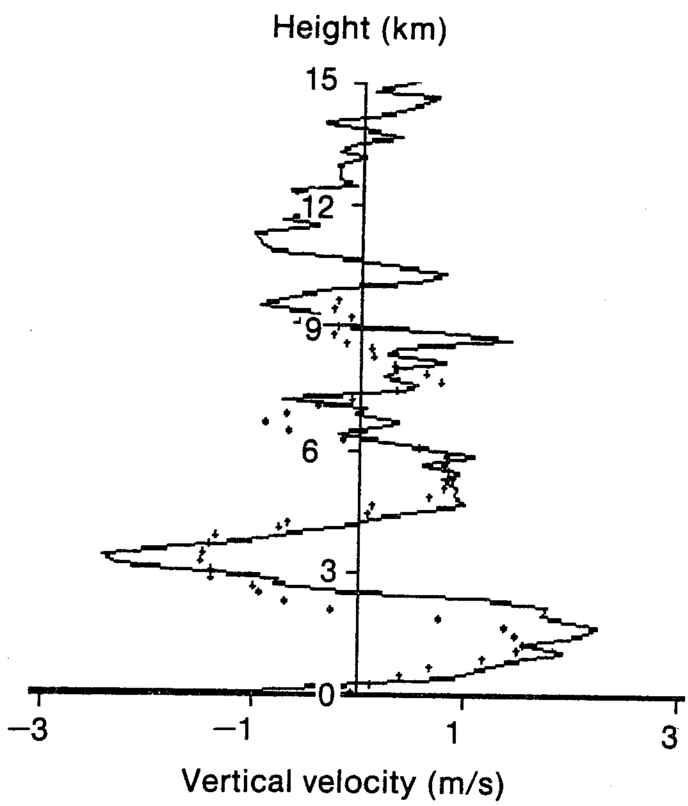


Fig. 4

A particularly appropriate means for verifying the simulated gravity wave motion is to compute the model's vertical velocity along the path of the sonde and compare this with the sonde's ascent rate after a nominal 'still air' ascent rate is removed. The solid line in Fig. 5 shows the vertical velocity profile inferred from the sonde with crosses marking the mesoscale model vertical velocities at selected heights. The amplitude and phase correspondence is very good and suggests that the model has correctly captured the phase relationship between the waves and the mountains upstream of the field site. The dominant wavelength of 22 Km. has been shown to be the resonant wavelength (for a wave vector pointing southeastwards) by solving the vertical structure equation for mountain waves assuming sinusoidal orography. Since the flow and orography are well resolved on this scale, the model has no difficulty eliciting the correct response. Horizontal diffusion plays a negligible role outside of the absorbing layer : runs with the diffusion coefficient set at 1000 and 2000 m^2s^{-1} are essentially identical.

Solutions to the wave equation show that most of the disturbance energy is trapped in the troposphere though some energy does leak into the stratosphere. The eigenvalue problem for the (complex) horizontal wavenumber (K) obtained by setting w=0 at z=0 and adopting a radiation boundary condition at z=24 Km was solved and gave an imaginary part to K which implies a downstream e-folding scale of about 70 Km. A re-run without the absorbing layer produced somewhat larger wave amplitudes and little downstream decay. It is reassuring that the horizontal flow of wave energy out of the southern and eastern boundaries appears to take place without any obvious spurious reflection. The vertical momentum flux evaluated as a domain average at a height of 1 Km was directed southeastwards and with a magnitude of $\approx$ -0.5 Nm^{-2} . The mean surface frictional drag was found to be very similar - both being very large compared to mean climatological surface stresses over non-hilly terrain.

Fig. 5



3. CONCLUSION

In order to refine the gravity wave drag parametrization schemes used in global forecast and climate models there is clearly a need for both observational campaigns and high resolution simulations with numerical models. The high density of near-simultaneous observations required to give statistically reliable estimates of vertical momentum fluxes and form drag makes the computation of momentum budgets in mountainous regions impractical without the use of numerical models. In this study we have used radiosonde observations to provide a low-level form of verification of the model simulation. Satellite imagery would also be a very useful aid to verification in cases of trapped lee wave motion. In the case studied here upper cloud obscured the lee waves motion at the time of the sonde ascents but later in the day lee waves were identifiable upstream of the Welsh mountains with a distinct horizontal wavelength close to the simulated 22 Km.

The model is currently being used to study vertical momentum fluxes and surface drag in a variety of synoptic types to assist the development of new gravity wave drag parametrization schemes. A particular problem is the flow response and drag characteristics for low Froude number flows. By scaling up the Welsh orographic heights by a constant factor it has been possible to obtain quasi-steady states exhibiting flow blocking, channelling and low-level wavebreaking.