Numerical Weather Prediction

Evaluation of Downdraughts produced in the Reduced Vertical Separation Study

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Contents

1 Introduction

1.1 Background

Reductions in vertical separation minima from 2,000 to 1,000 ft (610 to 305 m), between the fixed pressure levels which correspond to 29,000 and 41,000 ft (8839 and 12497 m) in an International Civil Aviation Organisation (ICAO) standard atmosphere (FL290 and FL410) have been in force in the North Atlantic for two years. It is proposed to introduce them into the European Civil Aviation Conference (ECAC) area in 2002.

The most important difference between these two areas is the existence of mountains in the latter, which can produce significant downdraughts at these levels. When an aeroplane is close to its ceiling altitude, which is a function of its current weight, its ability to maintain height is limited. It has not been shown that aircraft can maintain a 1000-ft (305 m) separation in the presence of downdraughts of the magnitude and length scale that can occur in central Europe, particularly in the vicinity of the Alps. The possible effect of downdraughts can be examined in terms of typical scales. For example, an aeroplane travelling at 250 ms^{-1}, which experiences a downdraught of 10 ms^{-1} sustained over 10 km, would drop by 400 m.

The opportunity to investigate the effect of downdraughts in the Alps has been provided by the Mesoscale Alpine Programme (MAP). This is an international research initiative devoted to the study of atmospheric and hydrological processes over mountainous terrain. Its aim is to expand our knowledge of weather and climate over complex topography, and thereby to improve current forecasting capabilities. A large-scale field phase in the alpine region took place from 7 September to 15 November 1999. This field phase, or Special Observing Period (SOP), was organised into eight scientific projects. One of these projects was devoted to the study of three-dimensional gravity wave breaking, during which a number of aircraft were used to measure vertical velocities over the Alps. In addition, model runs were performed by the Mesoscale Compressible Community-Canadian fully non-hydrostatic Limited Area Model (MC2). The significance of the programme is that results from the SOP were split into a number of Intensive Observational Periods (IOP) and have been published on the Internet.

Lunnon (1992) provides further evidence that strong vertical motions can exist over mountainous terrain. He reported that a British Airways Boeing 747 fell approximately 9,000 ft (2743 m) near the Zagros Mountains over the town of Zanjan, in Iran, on 29 November 1989, before continuing on its flight to London.

1.2 Report Overview

This report examines specific cases of observed downdraughts in mountainous regions and models the predicted vertical velocities for these occasions. It was decided that the best possible model to use in the time scale of the project was the University of Leeds three dimensional unsteady linear numerical model (3dVOM) developed from the Vosper and Mobbs (1996) model, which models flow over orography. This was chosen in preference to the Met. Office's own models because of the need to model downflow over localised orographic areas. Specific cases have been identified from MAP SOP for which observational data and model data runs have been made and published on the Internet. A further incident of strong vertical motion near the Zagros Mountains over the town of Zanjan, in Iran, in November 1989, Lunnon (1992), is also modelled.

The investigations, which are presented in this report, consist of two main parts, data collection and model representation. The collected data has been obtained from the Met Office Meteorological Data Base (MetDB) and consists of radiosonde upper air pressures, temperature, wind directions and speeds, which collectively comprise subtype temp in the database. Observations were restricted to twelve World Meteorological Organisation (WMO) radiosonde stations within an area 49^{O}N, 45^{O}N, 06^{O}E and 14^{O}E, which are near to the Alps. In addition, data has been obtained and used from WMO radiosonde station 37985, Lankaran, around the time of the Zanjan incident.

In section 2, the 3dVOM numerical model is briefly discussed. This is a three-dimensional model developed from the Vosper and Mobbs (1996) model. This report does not consider the full theoretical treatment of the equations of motion, but instead considers equations that are relevant to the present study.

Section 3 presents tabulated results of downdraught from the 3dVOM model for six days within the MAP SOP period and for five different locations within the Alps. These locations are the Alpine Ridge, Grossglockner, Hohe Tauern, Monte Rosa and Mont Blanc. Graphical figures are presented which show vertical velocity contours as both vertical and horizontal cross sections within the locations. A table of model downdraught maxima is presented for Zanjan for several profiles from Lankaran in November 1989. Model horizontal and vertical cross sections are presented graphically to represent the airflow over the region. There is also a consideration of lee waves over Mont Blanc on 02/11/1999, which is examined as it is coincident with the results of the investigation of Smith et al. (2000), and with an IOP case observed in MAP SOP. Results in this section are produced using a modified version of the makeprofile program, which forms part of the 3dVOM suite, in order to prevent potential temperature inversions with increasing height.

The conclusions as to likely downdraughts, which may be encountered in these two geographical regions, are discussed in Section 4. Recommendations as to separations are also made.

Appendix A discusses the sensitivity of the 3dVOM model to variations in both input and model parameters. The input parameters considered include variations in the temperature profile; for example as can arise by employing a vertical interpolation routine which generates a potential temperature profile that monotonically increases with height. A comparison is made between the vertical velocities generated with and without this constraint on the input potential temperature profile. The model parameters considered are viscosity, the height at which the lower boundary condition is applied and the vertical increment.

In Appendix B, the model orography is discussed for the six modelled locations. These are represented as a 64 by 64 regular horizontal grid for a 1-km separation, horizontally.

Appendix C discusses the IOP cases observed in MAP SOP, which are relevant to this investigation. In addition the Zanjan incident is discussed.

Finally, in Appendix D, the radiosonde temperature profiles are discussed for both the Alps and Zanjan. Six WMO radiosonde stations are chosen for the model analysis according to the discussion contained here.

2 3dVOM Numerical Model

2.1 Description of the Code

The 3dVOM model version 1.2 is a three-dimensional numerical model developed by Vosper and Mobbs (1996) and more recently Vosper and Worthington (2000). Details of the equations of motion to be solved are given in Vosper (2000), which contains a description of the present version of the code, subroutines and variables. The model solves the unsteady, inviscid, linearised, shallow Boussinesq equations of motion for flow over arbitrary orography. The model is based on a finite-difference approximation to these equations and uses a second-order central-difference time-stepping scheme, and a central differencing scheme for the spatial derivatives. Flows in which the internal gravity-wave response is strongly trapped (lee waves) can be simulated by this model.

The present work has required both changes to the makeprofile program in order to generate a potential temperature profile that monotonically increases with height and the coding of a number of graphical programs. Details of the actual input files and computer programs written to be used with this model are discussed in Pickersgill (2001,I), and the sensitivity of key model parameters is discussed in Appendix A to this report. For a general discussion of the theory of lee wave models, the reader should refer to Pickersgill (2001,II).

2.2 Equations relevant to the present study

A description of the full equations used in 3dVOM will not be attempted in this report, as an adequate description is given in Vosper (2000). However, an important aspect of the present work is an examination of downdraughts between discrete model heights. The formula relating height, z, to the model level number, K, depends on the minimum height in the radiosonde ascent at which the lower boundary condition can be applied, h_{min}, and on the vertical increment, δz. The equation is taken to be:

$$z = (K - 1) * \delta z + h_{min} \qquad (2.1)$$

i.e. for h_{min} = 500m, and δz = 500m, level 1 corresponds to a height of 500m and level 2 corresponds to a height of 1000m.

Equation (2.1) can be rearranged to determine model levels, K, in the 3dVOM model from actual heights, z. Denoting the lower level by suffix 1 and the upper level by suffix 2; the equations are taken to be:

$$K_1 = \text{INT}((z_1 - h_{min}) / \delta z + 1) \qquad (2.2)$$

and

$$K_2 = \text{INT}((z_2 - h_{min}) / \delta z + 1 + 1) \qquad (2.3).$$

Here, K_1 is rounded down and K_2 is rounded up. Equations (2.2) and (2.3) are used to determine model levels which correspond to FL410 and FL290. This is an approximation as, for example, FL410 is at the fixed pressure level that corresponds to 41,000 ft (12497 m) in an ICAO standard atmosphere. Therefore the use of the levels which geometrically correspond to FL410 and FL290 is an approximation, but not a significant source of error in the issue being considered.

3 Results

3.1 The Alps

Of particular interest is the downdraught at aeroplane heights obtained from the model. Values have been obtained for aeroplane heights between 29,000 ft (8839 m) and 41,000 ft (12497 m). Tabulated output results for maximum downdraught over the five Alpine areas are shown in Table 3.1 for the modified makeprofile program of the 3dVOM suite, which prevents potential temperature inversions. The results are displayed for the five WMO radiosonde stations numbered 16044, 16080, 11120, 06610 and 10868 and for the days in MAP SOP discussed in Appendix C. Tabulated values are presented showing the greatest downward vertical wind velocities in ms^{-1}. For δz = 500 m and h_{min} = 2000 m (as used in a number of figures in this report), this corresponds to finding the minimum value for model levels, K, in (2.2) and (2.3) of 14 to 22 inclusive.

In Table 3.1, the hour times e.g. 0506 represent times of observations between 0500Z and 0600Z. The maximum downdraught values can exceed 10 ms^{-1}. Vertical velocities that are less than -15 ms^{-1} are believed to be unreasonable and are set to "<threshold". The results depend more critically on the temperature and wind vertical profile than the orography for which it is examined. As an example, the profile used on 20/09/1999 between 2300Z and 2400Z for station 16080 produces minimum

vertical velocities that are smaller than the threshold for all five locations within the Alps.

Figure 3.1 shows four potential temperature profiles used in the calculation of maximum downdraughts in Table 3.1. The top left shows the profile used on 08/11/1999 between 0500Z and 0600Z for station 06610. This is relatively smooth and produces stable downdraughts. The top right shows the profile used on 20/09/1999 between 1100Z and 1200Z for station 10868. This is less smooth at mid altitudes and produces maximum downdraughts that can approach the threshold. The remaining two profiles correspond to the two cases in Table 3.1 for which maximum downdraughts exceed the threshold. Both have a sharp increase in the value of potential temperature at mid altitudes.

station	hour	Date	Alpine Ridge Minimum ms^{-1}	Grossglockner Minimum ms^{-1}	Hohe Tauern Minimum ms^{-1}	Monte Rosa Minimum ms^{-1}	Mont Blanc Minimum ms^{-1}
16044	0506	06/11/1999	-6.25	-6.38	-6.49	-6.65	-5.79
16044	0506	08/11/1999	-3.45	-3.44	-4.46	-5.35	-5.97
16044	0506	13/11/1999	-2.28	-4.18	-3.60	-4.89	-3.32
16044	0506	20/09/1999	-6.15	-8.92	-6.90	-7.32	-5.34
16044	1112	02/11/1999	-2.71	-4.39	-5.98	-4.76	-3.92
16044	1112	06/11/1999	-6.70	-5.24	-4.99	-4.53	-5.92
16044	1112	20/09/1999	-10.19	-8.53	-8.89	-8.65	-9.78
16044	2324	08/11/1999	-1.56	-2.34	-1.89	-2.83	-3.06
16080	0506	02/11/1999	-2.77	-4.88	-5.49	-4.99	-4.26
16080	0506	06/11/1999	-4.86	-6.37	-6.38	-8.04	-4.63
16080	0506	08/11/1999	-3.42	-4.78	-5.53	-7.06	-5.81
16080	0506	13/11/1999	-1.66	-3.08	-3.56	-2.60	-2.58
16080	0809	20/09/1999	-5.72	-7.64	-6.99	-6.37	-6.39
16080	1112	06/11/1999	-3.88	-3.09	-3.29	-2.92	-4.66
16080	1112	08/11/1999	-3.91	-4.96	-5.33	-4.80	-6.43
16080	1718	02/11/1999	-4.96	-6.02	-5.15	-6.39	-4.52
16080	1718	08/11/1999	-3.54	-3.70	-4.21	-4.90	-6.38
16080	2324	02/11/1999	-6.42	-4.94	-4.85	-5.88	-3.87
16080	2324	08/11/1999	-3.13	-3.63	-4.66	-5.36	-7.42
16080	2324	20/09/1999	<threshold	<threshold	<threshold	<threshold	<threshold
16080	2324	21/10/1999	-2.37	-3.09	-3.09	-4.54	-2.25
11120	0607	02/11/1999	-1.61	-2.12	-2.04	-2.38	-1.72
11120	0607	06/11/1999	-4.56	-3.90	-4.34	-3.53	-4.13
11120	0607	08/11/1999	-3.46	-3.74	-5.62	-7.14	-8.12
11120	0607	13/11/1999	-1.77	-3.26	-3.26	-4.24	-2.72
11120	1213	02/11/1999	-5.79	-5.22	-5.20	-5.59	-5.00
11120	1213	06/11/1999	-2.76	-3.72	-3.75	-2.71	-4.72
11120	1213	13/11/1999	-1.37	-1.88	-1.94	-2.26	-1.99
11120	1819	02/11/1999	-5.30	-5.03	-4.89	-4.69	-5.56
11120	1819	06/11/1999	-1.98	-1.65	-1.71	-1.86	-1.80
11120	1819	08/11/1999	-6.03	-6.12	-7.40	-6.91	-8.68
11120	1819	21/10/1999	<threshold	<threshold	<threshold	<threshold	<threshold

06610	0001	06/11/1999	-6.66	-8.42	-8.51	-8.78	-8.15
06610	0506	02/11/1999	-5.69	-5.86	-5.53	-7.09	-5.80
06610	0506	06/11/1999	-2.99	-4.95	-5.22	-6.55	-4.56
06610	0506	08/11/1999	-4.47	-3.88	-5.33	-5.20	-6.65
06610	0506	13/11/1999	-.84	-1.73	-1.74	-1.53	-1.47
06610	0506	20/09/1999	-2.83	-4.30	-4.27	-3.57	-3.95
06610	0506	21/10/1999	-5.90	-5.33	-6.19	-4.49	-5.81
06610	0809	06/11/1999	-2.55	-3.34	-3.87	-3.94	-2.44
06610	1112	02/11/1999	-7.52	-7.05	-7.71	-8.60	-10.77
06610	1112	06/11/1999	-2.54	-2.49	-2.18	-2.02	-2.43
06610	1112	08/11/1999	-2.69	-3.61	-3.44	-3.90	-4.76
06610	1112	20/09/1999	-2.68	-3.51	-3.12	-2.59	-3.59
06610	1415	06/11/1999	-1.23	-2.78	-2.73	-2.23	-1.88
06610	1718	06/11/1999	-.27	-.37	-.40	-.38	-.38
06610	1718	08/11/1999	-3.38	-3.49	-4.17	-3.54	-4.84
06610	1718	13/11/1999	-.11	-.13	-.16	-.19	-.14
06610	1718	21/10/1999	-4.60	-4.34	-3.85	-4.96	-3.76
06610	2021	06/11/1999	-.32	-.34	-.37	-.24	-.40
06610	2324	06/11/1999	-.42	-.35	-.32	-.31	-.30
06610	2324	13/11/1999	-.20	-.25	-.35	-.35	-.28
06610	2324	20/09/1999	-3.21	-2.76	-3.61	-2.64	-4.08
06610	2324	21/10/1999	-2.32	-5.17	-4.94	-5.45	-3.67
10868	0203	20/09/1999	-6.33	-4.86	-5.11	-3.89	-5.36
10868	0506	02/11/1999	-3.23	-6.00	-6.38	-5.60	-4.71
10868	0506	06/11/1999	-4.33	-4.26	-4.46	-4.92	-6.30
10868	0506	08/11/1999	-3.07	-5.09	-6.92	-9.50	-8.36
10868	0506	13/11/1999	-1.57	-2.93	-3.69	-4.44	-2.62
10868	0506	20/09/1999	-8.16	-5.71	-5.47	-6.98	-6.93
10868	0506	21/10/1999	-2.02	-3.04	-3.28	-3.49	-2.71
10868	1112	02/11/1999	-3.43	-5.01	-4.11	-4.77	-5.01
10868	1112	06/11/1999	-4.68	-3.65	-3.73	-4.09	-4.81
10868	1112	08/11/1999	-3.46	-3.80	-4.61	-5.87	-6.32
10868	1112	20/09/1999	-6.71	-9.40	-10.02	-8.49	-13.47
10868	1112	21/10/1999	-3.96	-3.80	-5.56	-3.92	-2.77
10868	1718	02/11/1999	-6.07	-5.99	-7.00	-8.38	-5.29
10868	1718	06/11/1999	-5.29	-3.75	-4.70	-4.35	-4.18
10868	1718	08/11/1999	-3.92	-3.72	-5.20	-4.90	-6.56
10868	1718	13/11/1999	-3.49	-4.52	-4.53	-4.57	-4.55
10868	1718	20/09/1999	-5.82	-5.32	-6.15	-5.68	-7.66
10868	2021	06/11/1999	-3.32	-2.96	-3.27	-3.90	-2.90
10868	2324	06/11/1999	-3.43	-2.79	-3.28	-3.57	-3.75
10868	2324	13/11/1999	-3.64	-4.84	-4.50	-4.45	-5.42
10868	2324	20/09/1999	-3.75	-4.51	-4.13	-3.40	-5.20
10868	2324	21/10/1999	-4.80	-4.46	-5.53	-5.02	-4.44

Table 3.1 The minimum vertical velocities in ms^{-1} are shown for five WMO radiosonde stations over the five Alpine regions, for each reported radiosonde temperature and wind profile, using the modified makeprofile program of the 3dVOM

suite, which prevents potential temperature inversions. Here the hour times e.g. 0506 represent times of observations between 0500Z and 0600Z. The five regions are the Alpine Ridge centred at (47.50^{O}N,11.00^{O}E), the Grossglockner region centred at (47.08^{O}N,12.71^{O}E), the Hohe Tauern region centred at (47.00^{O}N,12.5^{O}E), the Monte Rosa region, centred at (45.92^{O}N,7.88^{O}E) and the Mont Blanc region centred at (45.82^{O}N,6.85^{O}E).

3.1.1 Alpine Ridge

3dVOM model coloured contours of vertical velocity in ms^{-1} are shown as a horizontal cross section in Figure 3.2 and a vertical cross section in Figure 3.3. Both figures are from a domain centred at (47.50^{O}N,11.00^{O}E), and show model output after 1000 time steps of 4s for no viscosity and h_{min} = 2000m. The profile for station 16044, at Udine/Campoformido in Italy, has been used for the hour interval between 1100Z and 1200Z on 20/09/1999. Positive values show an updraft, and negative values show a downdraught. Figure 3.2 shows contours at model level 18, corresponding to a height of 10,500 m, which is within FL290 and FL410. A wind from a southwesterly direction existed on this day, and the figure shows the position for the vertical cross section from southwest to northeast shown in Figure 3.3. The slice co-ordinates are (39,00) to (65,60), which pass through the maximum downdraught and maximum updraft positions between model levels, K, 14 to 22 inclusive. The terrain is shown as black contours for a grid interval of 1 km. Downdraughts occur over several large areas in the domain.

Figure 3.3 shows the cross section from southwest to northeast with the wind blowing from left to right. The terrain is shown in black and represents the height above (or below) the level h_{min} =2000m. Consequently, the ordinates 0 to 40 represents a cross section from a height of 2km to 22km in half km steps and represent 3dVOM model levels 1 to 41. The horizontal grid separation is that of Figure 3.2, with the interval between grid points approximately 1.0 km. The greatest vertical velocities occur below model level 23 (13 km). At FL290 to FL410 (model levels 14 to 22) the vertical velocity obtained from the entire three-dimensional computed domain has a maximum downdraught of 10.19 ms^{-1}. The horizontal wavelength in Figure 3.3, between crests, is approximately 13.5 km. Downdraughts occur over several successive grid points. In particular the most southerly downdraught area in Figure 3.2, at model level 18, shows that downdraughts can be experienced over a horizontal distance perpendicular to the slice of approximately 59 km.

3.1.2 Grossglockner

3dVOM model coloured contours of vertical velocity in ms^{-1} are shown as a horizontal cross section in Figure 3.4 and a vertical cross section in Figure 3.5. Both figures are from a domain centred at (47.08^{O}N,12.71^{O}E), and show model output after 1000 time steps of 4s for no viscosity and h_{min} = 2000m. The profile for station 06610, at Payerne in Switzerland, has been used for the hour interval between 0000Z and 0100Z on 06/11/1999. Figures 3.4 and 3.5 are analogous to Figures 3.2 and 3.3. A wind from a southwesterly direction existed on this day, and Figure 3.4 shows the position for the vertical cross section from west to east which is shown in Figure 3.5. The slice co-ordinates are (00,52) to (65,42), which pass through the maximum downdraught and maximum updraft positions between model levels, K, 14 to 22 inclusive. Downdraughts occur over a large central area in the domain.

Figure 3.5 shows the cross section from west to east with the wind blowing approximately from left to right. The horizontal grid separation is that of Figure 3.4, except that the interval between grid points is 1.012 km because the slice is not parallel to either axis. The greatest vertical velocities occur below model level 18 (10.5 km). At FL290 to FL410 (model levels 14 to 22) the vertical velocity obtained from the entire three-dimensional computed domain has a maximum downdraught of 8.42 ms^{-1}. Downdraughts occur over several successive grid points. In particular the large downdraught area in Figure 3.4, at model level 18, shows that they can be experienced over a horizontal distance that measures about 65 km when measured in two directions, not at right angles.

3.1.3 Hohe Tauern

3dVOM model coloured contours of vertical velocity in ms^{-1} are shown as a horizontal cross section in Figure 3.6 and a vertical cross section in Figure 3.7. Both figures are from a domain centred at (47.00^{O}N,12.50^{O}E), and show model output after 1000 time steps of 4s for no viscosity and h_{min} = 2000m. The profile for station 10868, at Munchen/Oberschleissheim, Germany, has been used for the hour interval between 1100Z and 1200Z on 20/09/1999. Figures 3.6 and 3.7 are analogous to Figures 3.2 and 3.3. A wind from a southwesterly direction existed on this day, and Figure 3.6 shows the position for the vertical cross section from approximately southwest to northeast which is shown in Figure 3.7. The slice co-ordinates are (10,00) to (55,65). Downdraughts occur over two large areas in the south and centre of the domain, with each covering an area of over 60 km by 12 km.

Figure 3.7 shows the cross section from southwest to northeast with the wind blowing from left to right. The horizontal grid separation is that of Figure 3.6, except that the interval between grid points has increased to 1.216 km because the slice is not parallel to either axis. The greatest vertical velocities occur below model level 21 (12.0 km). At FL290 to FL410 (model levels 14 to 22) the vertical velocity obtained from the entire three-dimensional computed domain has a maximum downdraught of 10.02 ms^{-1}. The horizontal wavelength in Figure 3.7, between crests, varies according to its altitude. Below model level 7 (5 km) the wavelength is approximately 12 km, whereas the wavelength around level 18 (10.5 km) is about 22 km. Downdraughts occur over several successive grid points. In particular the first downdraught area in Figure 3.6, at model level 18, shows that they can be experienced over a horizontal distance of approximately 13 km.

3.1.4 Monte Rosa

3dVOM model coloured contours of vertical velocity in ms^{-1} are shown as a horizontal cross section in Figure 3.8 and a vertical cross section in Figure 3.9. Both figures are from a domain centred at (45.92^{O}N,7.88^{O}E), and show model output after 1000 time steps of 4s for no viscosity and h_{min} = 2000m. The profile for station 10868, at Munchen/Oberschleissheim, Germany, has been used for the hour interval between 0500Z and 0600Z on 8/11/1999. Figures 3.8 and 3.9 are analogous to Figures 3.2 and 3.3. A northerly wind existed on this day, and Figure 3.8 shows the position for the vertical cross section from north to south which is shown in Figure 3.9. The slice co-ordinates are (56,65) to (56,00), which pass through the maximum downdraught and maximum updraft positions between model levels, K, 14 to 22 inclusive. Downdraughts occur over an area in the north extending over 55 km by 20 km.

Figure 3.9 shows the cross section from north to south with the wind blowing from left to right. The horizontal grid separation is that of Figure 3.8. The greatest vertical velocities occur below model level 14 (8.5 km). At FL290 to FL410 (model levels 14 to 22) the vertical velocity obtained from the entire three-dimensional computed domain has a maximum downdraught of 9.5 ms^{-1}. The horizontal wavelength in Figure 3.9, between crests, is approximately 23 km. Downdraughts occur over several successive grid points. However, wavelengths depend on the slice chosen.

3.1.5 Mont Blanc

3dVOM model coloured contours of vertical velocity in ms^{-1} are shown as a horizontal cross section in Figure 3.10 and a vertical cross section in Figure 3.11. Both figures are from a domain centred at (45.82^{O}N,6.85^{O}E), and show model output after 1000 time steps of 4s for no viscosity and h_{min} = 2000m. The profile for station 06610, at Payerne in Switzerland, has been used for the hour interval between 1100Z and 1200Z on 02/11/1999. Figures 3.10 and 3.11 are analogous to Figures 3.2 and 3.3. A wind from a southwesterly direction existed on this day, and the figure shows the position for the vertical cross section from approximately southwest to northeast, which is shown in Figure 3.11. The slice co-ordinates are (00,10) to (65,45). Downdraughts occur over several areas in the domain, with the largest covering an area of over 57 km by 20 km.

Figure 3.11 shows the cross section from southwest to northeast with the wind blowing from left to right. The horizontal grid separation is that of Figure 3.10, except that the interval between grid points has increased to 1.136 km because the slice is not parallel to either axis. The greatest vertical velocities occur below model level 18 (10.5 km). At FL290 to FL410 (model levels 14 to 22) the vertical velocity obtained from the entire three-dimensional computed domain has a maximum downdraught of 10.77 ms^{-1}. The horizontal wavelength in Figure 3.11, between crests, varies according to its altitude. Around model level 6 (4.5 km) the wavelength is approximately 19 km. Downdraughts occur over several successive grid points. In particular the first downdraught area in Figure 3.10, at model level 18, shows that they can be experienced over a horizontal distance of approximately 20 km.

3.2 Zanjan

Tabulated output results for maximum downdraught over Zanjan, for values of h_{min} equal to 200m, 500m, 1000 m, 2000m, 3000m and 4000 m, are shown in Table 3.2 for the modified makeprofile program of the 3dVOM suite, which prevents potential temperature inversions. The results are displayed for WMO radiosonde station 37985 (Lankaran) for the temperature profiles available near the time of the incident discussed in Appendix C. The hour times e.g. 1200 represent times of observations of 1200Z. The maximum downdraught values are all less than 10 ms^{-1}. An increase in h_{min}, over the range of values chosen, does not necessarily increase the downdraught maximum. In addition, the smallest two h_{min} values failed to produce results for all but one of the profiles. This failure was due to an error in a vertical interpolation routine caused by insufficient radiosonde data near the ground. In order to generate results, as far as possible, for all the available profiles, extra data values have been added to all of the profiles, as discussed in Appendix D. In particular, values have been added from the profile at 1200Z on 28/11/1989 at the 20 hPa and 10 hPa in all but two profiles.

hour	date	Minimum for h_{min} = 200 m	Minimum for h_{min} = 500 m	Minimum for h_{min} = 1000 m	Minimum for h_{min} = 2000 m	Minimum for h_{min} = 3000 m	Minimum for h_{min} = 4000 m
0000	28/11/1989	Failed	Failed	-2.59	-3.10	-3.09	-3.76
0000	29/11/1989	Failed	Failed	-2.63	-5.08	-6.50	-4.88
0000	30/11/1989	Failed	Failed	-1.66	-2.58	-4.22	-3.44
0600	28/11/1989	Failed	Failed	-4.52	-3.56	-4.83	-5.83
0600	29/11/1989	Failed	Failed	-2.65	-1.79	-1.95	-2.22
0600	30/11/1989	-4.04	-3.69	-4.00	-6.22	-8.84	-8.83
1200	28/11/1989	Failed	Failed	-3.85	-7.39	-8.17	-3.22
1200	29/11/1989	Failed	Failed	-3.06	-3.32	-4.00	-5.31

Table 3.2 The minimum vertical velocities in ms^{-1} over the Zanjan region, centred at (36.68^{O}N,48.60^{O}E), are shown for each reported temperature and wind profile obtained from WMO radiosonde station 37985 around the time of the incident reported in Appendix C. The modified makeprofile program of the 3dVOM suite, which prevents potential temperature inversions has been used. Here the hour times e.g. 1200 represent times of observations of 1200Z. A number of values for h_{min} *are shown, however, the smallest two failed to produce results on all but one of the profiles.*

3.2.1 Zanjan contours of vertical velocity

3dVOM model coloured contours of vertical velocity in ms^{-1} are shown as a horizontal cross section in Figure 3.12 and a vertical cross section in Figure 3.13. Both figures are from a domain centred at (36.68^{O}N,48.60^{O}E), and show model output after 1000 time steps of 4s for no viscosity and h_{min} = 1000m. The profile for WMO station 37985, Lankaran, has been recorded at 0000Z on 30/11/1989. Positive values show an updraft, and negative values show a downdraught. Figure 3.12 shows contours at model level 20, corresponding to a height of 10,500 m, which is within FL290 and FL410. A southwesterly wind existed on this day, and the figure shows the position for the vertical cross section, which is shown in Figure 3.13. The slice co-ordinates are (00,20) to (65,35). The terrain is shown as black contours for a grid interval of 1 km. Downdraughts occur over a substantial area of length 65 km (north-south).

Figure 3.13 shows the cross section with the wind blowing from left to right. The terrain is shown in black and represents the height above (or below) the level h_{min} =1000m. Consequently, the ordinates 0 to 40 represent a cross section from a height of 1 km to 21 km in half-km steps and represent 3dVOM model levels 1 to 41. The horizontal grid separation is that of Figure 3.12, except that the interval between grid points has increased to 1.026 km because the slice is not parallel to either axis. At elevations of up to 4 km, the horizontal wavelength is about 9 km. However, at an altitude of 10.5 km, the wavetroughs have merged giving a downdraught continuously over a horizontal distance of 35 km. At FL290 to FL410 (model levels 16 to 24) the vertical velocity obtained from the entire three-dimensional computed domain has a maximum downdraught of 1.66 ms^{-1}.

3.3 Lee Waves in the Alps

Two examples of Lee waves near Mont Blanc on 02/11/1999 are considered in this section. The first coincides to the time and place of the soundings considered by

Smith et al (2000), namely station 06610, at Payerne, Switzerland, for the hour interval between 1100Z and 1200Z, while the second corresponds to station 10868, at Munchen/Oberschleissheim, Germany, between 1700Z and 1800Z on the same day. Both examples use the modified makeprofile program of the 3dVOM suite, which prevents potential temperature inversions.

3.3.1 Mont Blanc Lee Waves during the morning of November 2, 1999
3dVOM model coloured contours of vertical velocity in ms^{-1} are shown as a horizontal cross section in Figure 3.14 and a vertical cross section in Figure 3.15. Both figures are from a domain centred at (45.82^{O}N,6.85^{O}E), and show model output after 1000 time steps of 4s for no viscosity and h_{min} = 500m. The profile for station 06610, at Payerne, Switzerland, has been used for the hour interval between 1100Z and 1200Z on 02/11/1999. Positive values show an updraft, and negative values show a downdraught. Figure 3.14 shows contours at model level 6, corresponding to a height of 3,000 m. A wind from a southwesterly direction existed on this day, and the figure shows the position for the vertical cross section from approximately southwest to northeast which is shown in Figure 3.15. The slice co-ordinates are (00,10) to (65,45). The terrain is shown as black contours for a grid interval of 1 km.

Figure 3.15 shows the cross section from southwest to northeast with the wind blowing from left to right. The terrain is shown in black and represents the height above (or below) the level h_{min} =500m. Consequently, the ordinates 0 to 40 represent a cross section from a height of 500m to 20.5km in half km steps and represent 3dVOM model levels 1 to 41. The horizontal grid separation is that of Figure 3.14, except that the interval between grid points has increased to 1.14 km because the slice is not parallel to either axis. The greatest vertical velocities occur below model level 20 (10 km). The horizontal wavelength in Figure 3.15, between crests, is approximately 14 km.

3.3.2 Mont Blanc Lee Waves during the afternoon of November 2, 1999
3dVOM model coloured contours of vertical velocity in ms^{-1} are shown as a horizontal cross section in Figure 3.16 and a vertical cross section in Figure 3.17. Both figures are from a domain centred at (45.82^{O}N,6.85^{O}E), and show model output after 1000 time steps of 4s for no viscosity and h_{min} = 500m. The profile for station 10868, at Munchen/Oberschleissheim, Germany, has been used for the hour interval between 1700Z and 1800Z on 02/11/1999. Figures 3.16 is similar to Figures 3.14 except that Figure 3.16 shows contours at model level 8, corresponding to a height of 4,000 m. A wind from a southwesterly direction existed on this day, and Figure 3.16 shows the position for the vertical cross section from approximately southwest to northeast which is shown in Figure 3.17. The slice co-ordinates are (00,05) to (65,26).

Figure 3.17 is analogous to Figure 3.15 and shows the cross section from southwest to northeast with the wind blowing from left to right. The horizontal grid separation is that of Figure 3.16, except that the interval between grid points has increased to 1.051 km because the slice is not parallel to either axis. The greatest vertical velocities occur below model level 19 (9.5 km). The horizontal wavelength in Figure 3.17, between crests, is approximately 9 km.

4 Conclusions and Recommendations

The contours of vertical velocity, Figures 3.2 to 3.17, have a number of features in common. The horizontal cross sections show a wave pattern made complex by the nature of the orography. It is noticeable that the contours, which represent the phase of the wave motion, travel upstream with increasing elevation in the top half of the modelled vertical cross sections, but largely do not in the lower atmosphere. This indicates that wave motion can be experienced upstream of the generating mountain range at higher altitudes. Wave amplitudes are largest in the lower atmosphere, and generally occur below FL290. Examples where relatively large wave amplitudes extend above FL290 seem to correspond to a sharp increase in the potential temperature over a small height interval in the atmosphere as indicated in Figure 3.1. In particular, the case examined in Figure A.1, for which the potential temperature is shown in Table A.2 has an instability around 9 km and produces numerical instability at mid altitudes. It is therefore reasonable to conclude that the greatest wave amplitudes between FL290 and FL410 correspond to elevations near atmospheric instability. Downdraughts in a convectively unstable atmosphere are not represented well by the 3dVOM model and may pose a threat. However, downdraughts in a stable atmosphere do not generally pose a threat.

The model data shown in Table 3.1 for selected days in the IOP over the Alps, reveals that after a model run of 4000s of the 3dVOM model, vertical velocity downdraughts of more than 10 ms^{-1} and less than 15 ms^{-1} can be predicted between FL290 and FL410. Out of 76 profiles examined for five stations near the Alps, there was one occurrence for the Alpine Ridge, none for Grossglockner, one for Hohe Tauern, none for Monte Rosa and two for Mont Blanc. Several occurrences of vertical velocity downdraughts greater than 15 ms^{-1} were predicted. However, these indicate that instability is growing in the model results, as these anomalies were restricted to two profiles for every location. Vertical velocity downdraughts between 5 and 10 ms^{-1} have been predicted between FL290 and FL410 on a number of occasions. There are eighteen occurrences for the Alpine Ridge, twenty two for Grossglockner, twenty eight for Hohe Tauern, twenty seven for Monte Rosa and twenty nine for Mont Blanc. An examination of horizontal and vertical cross sections for a number of the largest downdraughts (one for each location) shows that downdraughts are present between FL290 and FL410 over a horizontal continuous region that can exceed sixty five km in certain directions. The best example of this is the case of Grossglockner shown in Figure 3.4. A calculation based on an aeroplane travelling at 250 ms^{-1} across 65 km requires an average downdraught of only 1.92 ms^{-1} to reduce the height of an aeroplane by 500m. The results of this report indicate that the combination of continuous downdraught over horizontal regions as predicted, together with a vertical downdraught, which can exceed 10 ms^{-1}, may be significant in the determination of reducing vertical separation minima.

There is some evidence of traditional lee wave patterns, at lower altitudes, near Mont Blanc. The case examined near noon on 02/11/1999 in Figures 3.14 and 3.15 coincides with that of Smith et al. (2000). The results show that a wavetrain exists travelling from southwest to northeast with a wavelength of about 14km. This compares favourably with the dominant wavelength predicted by model 3 in Smith et al. (2000) for this day and hence demonstrates the reliability of the 3dVOM model. By late afternoon, on 02/11/1999, a wavetrain is observable, in Figures 3.16 and 3.17, to the south of Mont Blanc travelling from southwest to northeast with a wavelength of about 9km. The complexity of the model orography introduces an interference pattern in the northern part of the domain.

The model data shown in Table 3.2 for selected days around the time of the Zanjan incident in the Zagros mountains, reveals that after a model run of 4000s of the 3dVOM model, vertical velocity downdraughts do not exceed 10 ms^{-1}. For a reference model height of h_{min} =1 km, the maximum vertical downdraught at 0000Z on 30/11/1989 reached 1.66 ms^{-1}, although the horizontal extent of continuous downdraught reached a horizontal distance of 35 km. It is therefore apparent that the mechanism, which caused the British Airways Boeing 747 to lose altitude near the town of Zanjan, has not been revealed by the present analysis.

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6 Glossary

ECAC	European Civil Aviation Conference.
FL290	The fixed pressure level which corresponds to 29,000 ft (8839 m) in an ICAO standard atmosphere.
FL410	The fixed pressure level which corresponds to 41,000 ft (12497 m) in an ICAO standard atmosphere.
GLOBE	Global Land One-Kilometer Base Elevation.
ICAO	International Civil Aviation Organisation.
IOP	Intensive Observational Period
hPa	Hecto Pascals
MAP	Mesoscale Alpine Programme.
MC2	The Mesoscale Compressible Community. Canadian fully non-hydrostatic Limited Area Model.
MetDB	The Met Office Meteorological Data Base.

NAG	Numerical Algorithm Group.
PV	Potential Vorticity.
Ri	Richardson number.
SOP	Special Observing Period. Main data gathering phase of MAP. September to November 1999.
temp	Upper Air pressures, temperature, humidities and winds data subtype of the MetDB.
WMO	World Meteorological Organisation.
Z	Universal time.
3dVOM	A numerical model for Lee wave Prediction.

7 Glossary of Mathematical terms

h_{min}	The minimum height in the radiosonde at which the lower boundary condition can be used in 3dVOM, in m.
K	The model level number used in equation (2.1).
K_1	The lower level defined by equation (2.2).
K_2	The upper level defined by equation (2.3).
min_{I1}	The tabulated minimum values in Table 3.2 used in equation (D.1). These are the 26 cases using the extra upper data from 1200Z on 28/11/1989.
min_{I2}	The 26 untabulated values for the profiles using the upper data from 1200Z on 29/11/1989 used in equation (D.1).
n	The number of points in equation (D.1) which equals 26.
N	The variable used to define the damping value in equation (A.1).
N_S	The number of potential temperature smoothings discussed in Appendix A.
p	The pressure in hPa*10 in Table A.1.
T	The temperature in ^{O}C*10 in Table A.1.
U_{MIN}	The minimum velocity magnitude value in the velocity profile used in equation (A.1).
U_0, V_0	The wind speed components in Table A.2.
V	The wind speed in ms^{-1}*10 in Table A.1.
z	Height in m defined by equation (2.1) and used in Table A.2.
z_1	The lower height defined by equation (2.2).
z_2	The upper height defined by equation (2.3).
δx	The x horizontal increment in m used in equation (A.1).
δy	The y horizontal increment in m used in equation (A.1).
δz	The z vertical increment in m used in equation (2.1).
θ	The basic state potential temperature values in ^{O}K in Table A.2.
ν_4	The fourth order damping term defined by equation (A.1), which is applied throughout the computational domain. In this report it is taken to be zero except for a few calculations in Appendix A.
π	The value pi.
ρ	The basic state density in Table A.2.
ϕ	The wind direction in degrees in Table A.1.

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Appendix A. Sensitivity of Model Parameters

A.1 Temperature Profile

A temperature and wind velocity profile has been obtained from the MetDB for station 06610 on 06/11/1999 in the hour interval between 0500Z and 0600Z. This is shown in Table A.1. The unmodified makeprofile program of the 3dVOM suite produces the profile as shown in Table A.2 with an instability around 9 km in the potential temperature profile. The vertical wave amplitude is shown in the vicinity of Monte Rosa in Figure A.1 after 1000 time steps of 4 s for the case of no viscosity, h_{min} = 2000m and δz = 500 m in the model. For this case, an unstable wave amplitude has grown which reaches a minimum of -298489.75 for aeroplane altitudes of 29,000 ft to 41,000 ft (8839 to 12497 m).

As an experiment, the temperature profile has been modified at 300 hPa, by reducing the temperature from –48.7 ^{O}C to –40.0 ^{O}C as shown in Table A.3. The potential temperature profile obtained from the unmodified makeprofile program using this new profile is shown in Table A.4. The modified vertical wave amplitude is shown in the vicinity of Monte Rosa in Figure A.2 after 1000 time steps of 4 s for the case of no viscosity, h_{min} = 2000m and δz = 500 m in the model. For this case, no unstable wave amplitude exists within aeroplane altitudes of 29,000 ft to 41,000 ft (8839 to 12497 m).

p hPa*10	T ^{O}C*10	ϕ deg	V ms^{-1} *10
9510	85	280	77
9250	69	270	159
8500	35	235	216
7000	-49	220	268
5000	-221	220	298
4000	-329	230	345
3000	-487	240	355
2600	-523	240	314
2500	-517	245	309
2000	-517	250	237
1500	-553	275	211
1000	-571	310	154
700	-591	310	82
500	-603	315	103
300	-577	280	93
200	-593	270	206
100	-573	265	231

Table A.1 The pressure, p, temperature, T, wind direction, ϕ, and wind speed, V, obtained from the MetDB for WMO radiosonde station 06610 on 06/11/1999 are shown for the hour interval between 0500Z and 0600Z.

z	U_0	V_0	θ	ρ
2000.00000	21.79153	21.25286	301.31937	.9502045
2500.00000	21.81435	21.19629	301.74390	.9071152
3000.00000	21.83909	21.13927	302.17215	.8640462
3500.00000	21.89868	21.07391	302.66794	.8213432
4000.00000	22.02608	20.99231	303.29510	.7793528
4500.00000	22.25422	20.88660	304.11746	.7384210
5000.00000	22.61607	20.74890	305.19888	.6988940
5500.00000	23.12517	20.56208	306.61426	.6610980
6000.00000	23.68365	20.25605	308.50217	.6252436
6500.00000	24.15389	19.74177	311.02377	.5915005
7000.00000	24.41519	18.95016	314.27402	.5599975
7500.00000	24.55236	18.05347	317.54346	.5303746
8000.00000	24.78675	17.38438	319.58817	.5019461
8500.00000	25.34218	17.27844	319.15454	.4740205
9000.00000	26.28164	17.72723	316.10938	.4458065
9500.00000	26.07303	15.31073	321.42889	.4155176
10000.00000	23.62196	8.12089	341.94751	.3828423
10500.00000	22.30584	5.19090	350.94608	.3538430
11000.00000	21.85895	5.30723	352.09082	.3283901
11500.00000	21.41516	5.64506	353.86768	.3053768
12000.00000	20.56890	4.83669	360.18433	.2840860
12500.00000	19.47970	3.30214	369.33145	.2642789
13000.00000	18.34168	1.57089	379.25568	.2457458
13500.00000	17.33641	.13897	388.04306	.2282891
14000.00000	16.50618	-.86872	395.32422	.2118464
14500.00000	15.80651	-1.55853	401.69241	.1964393
15000.00000	15.19159	-2.04030	407.75558	.1820905
15500.00000	14.61561	-2.42389	414.12146	.1688229
16000.00000	14.03334	-2.81781	421.38867	.1566565
16500.00000	13.42155	-3.27817	429.78937	.1455011
17000.00000	12.78584	-3.79259	439.07690	.1351221
17500.00000	12.13372	-4.34408	448.97244	.1252755
18000.00000	11.47273	-4.91562	459.19699	.1157169
18500.00000	10.81039	-5.49022	469.47171	.1062023
19000.00000	10.15421	-6.05087	479.51758	.0964873
19500.00000	9.51174	-6.58057	489.05585	.0863278
20000.00000	8.89048	-7.06233	497.80740	.0754796
20500.00000	8.29798	-7.47913	505.49353	.0636986
21000.00000	7.74174	-7.81399	511.83527	.0507405
21500.00000	7.22931	-8.04988	516.55365	.0363611
22000.00000	6.76819	-8.16983	519.36981	.0203162

Table A.2 The height, z, wind speed components, (U_0 V_0), potential temperature, θ, and density, ρ, obtained for the profile in Table A.1 are derived using the unmodified makeprofile program of the 3dVOM suite, for h_{min} = 2000m and δz = 500m. There is instability in the θ profile around 9 km where $d\theta / dz$ changes sign.

p hPa*10	T ^{O}C*10	ϕ deg	V ms^{-1} *10
9510	85	280	77
9250	69	270	159
8500	35	235	216
7000	-49	220	268
5000	-221	220	298
4000	-329	230	345
3000	-400	240	355
2600	-523	240	314
2500	-517	245	309
2000	-517	250	237
1500	-553	275	211
1000	-571	310	154
700	-591	310	82
500	-603	315	103
300	-577	280	93
200	-593	270	206
100	-573	265	231

Table A.3 The pressure, p, temperature, T, wind direction, ϕ, and wind speed, V, obtained by adjusting the MetDB profile in Table A.1 at 300 hPa for station 06610 obtained on 06/11/1999 at 0500Z.

z	U_0	V_0	θ	ρ
2000.00000	21.79185	21.25260	301.88052	.9509339
2500.00000	21.81433	21.19631	301.70816	.9070688
3000.00000	21.83873	21.13956	301.54752	.8632342
3500.00000	21.89806	21.07440	301.60028	.8199555
4000.00000	22.02537	20.99288	302.06821	.7777581
4500.00000	22.25366	20.88705	303.15295	.7371673
5000.00000	22.61598	20.74896	305.05630	.6987087
5500.00000	23.12586	20.56152	307.90250	.6626640
6000.00000	23.68483	20.25509	311.37051	.6279151
6500.00000	24.15448	19.74129	314.98062	.5928444
7000.00000	24.41312	18.95132	318.26172	.5560635
7500.00000	24.54197	18.05362	320.84866	.5189615
8000.00000	24.75715	17.37431	322.44690	.4847738
8500.00000	25.27719	17.24235	322.76315	.4567690
9000.00000	26.21405	17.75762	321.90128	.4373926
9500.00000	26.24230	15.93004	325.32108	.4179879
10000.00000	23.87811	8.80710	338.50259	.3863539
10500.00000	22.40151	5.32652	346.63208	.3564961

11000.00000	21.89639	5.22954	350.18970	.3309755
11500.00000	21.49012	5.66751	354.00568	.3081067
12000.00000	20.68517	4.97991	360.72806	.2867601
12500.00000	19.61483	3.50416	369.33469	.2667401
13000.00000	18.47287	1.76920	378.45154	.2479408
13500.00000	17.44603	.28521	386.75974	.2302599
14000.00000	16.59740	-.76732	393.90536	.2136523
14500.00000	15.88461	-1.48915	400.35779	.1981220
15000.00000	15.26192	-1.99003	406.61288	.1836749
15500.00000	14.68358	-2.37972	413.16629	.1703167
16000.00000	14.10404	-2.76754	420.51120	.1580522
16500.00000	13.49555	-3.22044	428.89084	.1468040
17000.00000	12.86228	-3.72934	438.10037	.1363475
17500.00000	12.21174	-4.27727	447.88818	.1264428
18000.00000	11.55146	-4.84725	458.00269	.1168497
18500.00000	10.88893	-5.42230	468.19229	.1073283
19000.00000	10.23166	-5.98545	478.20541	.0976384
19500.00000	9.58718	-6.51969	487.79050	.0875403
20000.00000	8.96299	-7.00807	496.69589	.0767937
20500.00000	8.36660	-7.43360	504.67004	.0651587
21000.00000	7.80552	-7.77929	511.46133	.0523953
21500.00000	7.28726	-8.02817	516.81824	.0382633
22000.00000	6.81933	-8.16325	520.48926	.0225230

Table A.4 The height, z, wind speed components, (U_0 V_0), potential temperature, θ, and density, ρ, obtained for the profile in Table A.3 are derived using the unmodified makeprofile program of the 3dVOM suite, for h_{min} = 2000m and δz = 500m. The instability in the θ profile around 9 km has been largely removed.

A.2 Viscosity Parameter

A fourth-order viscous term is applied to the momentum and thermodynamic equations. The purpose of this is to avoid build-up of energy at the grid-length scale. The damping term, ν_4, is of the form:

$$\nu_4 = N * U_{MIN} * ((\delta x^2 + \delta y^2)^{½} / \pi)^3 \qquad (A.1)$$

Here $\delta x = \delta y$ = 1000.0 m, N is the variable used to adjust the damping and U_{MIN} is the minimum velocity magnitude value in the velocity profile. Table A.5 shows the relationship of downdraught to N for h_{min} = 2000.0 and δz = 500m using the unmodified makeprofile program of the 3dVOM suite. For a range of values of N the maximum downdraught remains finite. However, as its value is further increased to 0.8, the model breaks down. The relationship between h_{min} and maximum downdraught for fixed N is shown in Table A.6. For the values chosen, the downdraught increases with h_{min}.

N	Minimum vertical velocity ms^{-1}	h_{min} m	Timestep s	Number of Timesteps

0.0	-298489.75	2000.0	4	1000
0.01	-51154.77	2000.0	4	1000
0.02	-11044.04	2000.0	4	1000
0.04	-858.96	2000.0	4	1000
0.06	-99.07	2000.0	4	1000
0.08	-15.87	2000.0	4	1000
0.10	-4.68	2000.0	4	1000
0.20	-4.39	2000.0	4	1000
0.40	-3.87	2000.0	4	1000
0.60	-3.36	2000.0	4	1000
0.70	-3.15	2000.0	4	1000
0.80	-18770495184547264000000.00	2000.0	4	1000

Table A.5 The relationship between the minimum vertical velocity (maximum downdraught) and viscosity parameter, N, for fixed h_{min} are shown for Monte Rosa for the hour interval between 0500Z and 0600Z on 06/11/1999. The minimum values are taken between aeroplane heights of 29,000 ft and 41,000 ft (8839 and 12497 m). For small and large viscosity, the value of maximum downdraught becomes large for this profile. The profiles used are those of Tables A.1 and A.2 using the unmodified makeprofile program of the 3dVOM suite, for δz = 500m.

N	Minimum vertical velocity ms^{-1}	h_{min} m	Timestep s	Number of Time Steps
0.08	-3.77	200.0	4	1000
0.08	-6.85	500.0	4	1000
0.08	-11.63	1000.0	4	1000
0.08	-15.87	2000.0	4	1000
0.08	-16.36	3000.0	4	1000
0.08	-17.91	4000.0	4	1000

Table A.6 The relationship between the minimum vertical velocity (maximum downdraught) and h_{min} for a fixed viscosity parameter, N, are shown for Monte Rosa for the hour interval between 0500Z and 0600Z on 06/11/1999. The minimum values are taken between aeroplane heights of 29,000 ft and 41,000 ft (8839 and 12497 m). The profiles used are those of Tables A.1 and A.2 using the unmodified makeprofile program of the 3dVOM suite, for δz = 500m.

A.3 Variation of h_{min}

An investigation of the variation of downdraught with h_{min} is shown in Table A.7. In this table, the viscous parameter is taken to be 0. Although the maximum downdraught increases with h_{min}, it does not appear that reducing h_{min} produces a useful value.

N	Minimum vertical velocity ms^{-1}	h_{min} m	Timestep s	Number of Time Steps
0.00	-155014.02	200.0	4	1000
0.00	-298489.75	2000.0	4	1000

Table A.7 The relationship between the minimum vertical velocity (maximum downdraught) and h_{min} for a zero viscosity value are shown for Monte Rosa for the hour interval between 0500Z and 0600Z on 06/11/1999. The minimum values are taken between aeroplane heights of 29,000 ft and 41,000 ft (8839 and 12497 m). The profiles used are those of Tables A.1 and A.2 using the unmodified makeprofile program of the 3dVOM suite, for δz = 500m.

A.4 Variation of timestep

The variation of the maximum downdraught with timestep is presented in Table A.8. In this table the viscous parameter is taken to be 0 and the duration of the run is kept constant at 4000 s. There is some decrease in maximum downdraught as the timestep is reduced. However, the values are still fundamentally large.

N	Minimum vertical velocity ms^{-1}	h_{min} m	Timestep s	Number of Time Steps
0.00	-298489.75	2000.0	4	1000
0.00	-213335.75	2000.0	2	2000
0.00	-193500.92	2000.0	1	4000
0.00	-184432.58	2000.0	0.5	8000

Table A.8 The relationship between timestep in s and the minimum vertical velocity (maximum downdraught), for fixed h_{min} and a zero viscosity value for Monte Rosa taken in the hour interval between 0500Z and 0600Z on 06/11/1999. The minimum values are taken between aeroplane heights of 29,000 ft and 41,000 ft (8839 and 12497 m). The profiles used are those of Tables A.1 and A.2 using the unmodified makeprofile program of the 3dVOM suite, for δz = 500m.

A.5 Variation of z co-ordinate

The sensitivity of the model to changes in the z co-ordinate interval is investigated in this section. Table A.9 shows this variation for a constant timestep, the viscous parameter taken to be 0 and constant h_{min}. There seems to be no clear relationship between a decrease in δz and the maximum downdraught.

N	Minimum vertical velocity ms^{-1}	h_{min} m	Timestep s	Number of Time Steps	δz m
0.00	-184432.58	2000.0	0.5	8000	500
0.00	-51872228.00	2000.0	0.5	8000	250
0.00	-40454092.00	2000.0	0.5	8000	200

Table A.9 The relationship between z interval, δz, and the minimum vertical velocity (maximum downdraught), shown for fixed h_{min} for a zero viscosity value and constant timestep for Monte Rosa for the hour interval between 0500Z and 0600Z on 06/11/1999. The minimum values are taken between aeroplane heights of 29,000 ft and 41,000 ft (8839 and 12497 m). The profiles used are those of Tables A.1 and A.2 using the unmodified makeprofile program of the 3dVOM suite.

A.6 Variation of number of smoothing on Potential Temperature

The sensitivity of the model is investigated as the number of smoothings applied to the model is varied. The input variables are discussed further in Pickersgill (2001,I). In all previous tables the variable N_S is set to 1. In Table A.10, the variation of N_S is examined for a z interval, δz, of 500m. The maximum downdraught is reduced as N_S is increased.

N	Minimum vertical velocity ms^{-1}	h_{min} m	Timestep s	Number of Time Steps	N_S
0.00	-298489.75	2000.0	4	1000	1
0.00	-876.13	2000.0	4	1000	5

Table A.10 The relationship between potential temperature smoothing iterations, N_S, and the minimum vertical velocity (maximum downdraught) shown for fixed h_{min} for a zero viscosity value and constant timestep for Monte Rosa shown for the hour interval between 0500Z and 0600Z on 06/11/1999. The minimum values are taken between aeroplane heights of 29,000 ft and 41,000 ft (8839 and 12497 m). The profiles used are those of Tables A.1 and A.2 using the unmodified makeprofile program of the 3dVOM suite, for δz = 500m.

A.7 Potential Temperature Profile with no turning at mid Altitudes

The problems encountered with potential temperature profiles generated from the 3dVOM model stem from the values at mid altitudes e.g. Table A.1, in which there is a decrease in potential temperature at around 9 km. The code has been modified to use Numerical Algorithm Group (NAG) routines, which produces a potential temperature profile that monotonically increases with height. The details of the program change are discussed in Pickersgill (2001,I). Figure A.3 shows the difference between the NAG routine data (in blue) obtained from the modified makeprofile program of the 3dVOM suite, and the original data from the unmodified 3dVOM model. The sensitivity of the model to the potential temperature profile for station 06610 is shown in Table A.11. It is clear from this table that when the potential temperature profile is not unstable, the minimum values obtained are generally similar. The modified version of the 3dVOM model produces results that are acceptable when the original version produces values less than the threshold of $-15ms^{-1}$.

hour	date	New minimum value	old minimum value
0001	06/11/1999	-8.78	-8.26
0506	02/11/1999	-7.09	-6.86
0506	06/11/1999	-6.55	<threshold
0506	08/11/1999	-5.20	-3.17
0506	13/11/1999	-1.53	-1.84
0506	20/09/1999	-3.57	-8.24
0506	21/10/1999	-4.49	<threshold
0809	06/11/1999	-3.94	-7.65
1112	02/11/1999	-8.60	-6.64
1112	06/11/1999	-2.02	<threshold
1112	08/11/1999	-3.90	<threshold
1112	20/09/1999	-2.59	-2.21

1415	06/11/1999	-2.23	-1.24
1718	06/11/1999	-.38	<threshold
1718	08/11/1999	-3.54	<threshold
1718	13/11/1999	-.19	-.52
1718	21/10/1999	-4.96	-2.48
2021	06/11/1999	-.24	-.16
2324	06/11/1999	-.31	-.29
2324	13/11/1999	-.35	-.03
2324	20/09/1999	-2.64	-2.12
2324	21/10/1999	-5.45	<threshold

Table A.11 A comparison of the minimum vertical velocity (maximum downdraught) data values shown in ms^{-1} over the Monte Rosa region, centred at (45.92^{O}N,7.88^{O}E), for each local velocity profile obtained from the MetDB for station 06610 obtained on the specified day at the specified time. Here the hour times e.g. 0506 represent times of observations between 0500Z and 0600Z. The maximum downdraught is compared for potential temperature profiles generated using a modified makeprofile program of the 3dVOM suite, which uses NAG routines and produces no turning with height (new minimum value), and the original model which permits potential temperature turning with height (old minimum value). The parameterisation has h_{min} *= 2000m and* δz *= 500m.*

Appendix B. Geographical areas

B.1 Orography

The geographical areas of interest in this report are five regions in the Alps and one that includes part of Iran near the Caspian Sea. The Alps were chosen as a European area of high orography, where mountain waves are known to occur regularly. Particular locations were chosen to coincide with observations made during the MAP SOP period in 1999. In addition an incident of strong downdraught was reported in Lunnon (1992), which occurred in 1989 above Zanjan. These regions are discussed in the following sections. The data that was used to model the orography was obtained from the Global Land One-Kilometer Base Elevation (GLOBE) project.

B.1.1 Alpine Ridge

This region is modelled in Figure B.1 as a 1-km horizontal grid covering 64 by 64 grid points, with the centre taken at (47.50^{O}N,11.00^{O}E). The orography has a few isolated peaks that exceed 2km, in the centre and south, and gentler elevation in the north. Observations were reported in IOP 8b on 21/10/1999, and are discussed in Appendix C.

B.1.2 Grossglockner

This region is modelled in Figure B.2 as a 1-km horizontal grid covering 64 by 64 grid points, with the centre taken at (47.08^{O}N,12.71^{O}E). The orography is dominated by elevations of over 3km in the centre, and valleys in the north and south. Observations of gravity wave breaking were reported in IOP 15 on 6/11/1999, and are discussed in Appendix C.

B.1.3 Hohe Tauern
This region is modelled in Figure B.3 as a 1-km horizontal grid covering 64 by 64 grid points, with the centre taken at (47.00^{O}N,12.5^{O}E). The orography is dominated by elevations of over 3km in the centre and valleys to the north and southeast. Observations of gravity waves were made in IOP2b on 20/09/1999, and are discussed in Appendix C.

B.1.4 Monte Rosa
This region is modelled in Figure B.4 as a 1-km horizontal grid covering 64 by 64 grid points, with the centre taken at (45.92^{O}N,7.88^{O}E). A high peak of over 4km dominates the orography near the centre of the region. (The actual height of Monte Rosa is 4634 m). Observations of gravity wave breaking were reported in IOP 15 on 8/11/1999, and are discussed in Appendix C.

B.1.5 Mont Blanc
This region is modelled in Figure B.5 as a 1-km horizontal grid covering 64 by 64 grid points, with the centre taken at (45.82^{O}N,6.85^{O}E). The orography is dominated by Mont Blanc, which is represented as a peak of over 4km near the centre. (The actual height of Mont Blanc is 4807 m). Observations of gravity waves were made on IOP 13b on 2/11/1999, and further observations were made on IOP 16 on 13/11/1999. These are discussed in Appendix C.

B.1.6 Zanjan
This region is modelled in Figure B.6 as a 1-km horizontal grid covering 64 by 64 grid points, with the centre taken at (36.68^{O}N,48.60^{O}E). The orography is dominated by two ridges, which run from north to east and from west to south with a valley in between. Towards the northwest, the orography slopes downwards towards the Caspian Sea. Observations of strong downdraughts were made on 29/11/1989 at 2347Z and reported in Lunnon (1992). These are discussed in Appendix C.

Appendix C. IOP Cases Relevant to this Study and Zanjan incident

C.1 IOP 2b: Monday, September 20, 1999

Heavy precipitation was observed to the south of the Alps, with strong foehn and gravity wave activity. Two related missions were flown with the Electra aeroplane.

C.1.1 The Electra Mission
The research flight was scheduled for the early afternoon hours, and analysis focussed on times 1200Z and 1500Z.

C.1.2 Support for the gravity wave mission
The following analysis is provided by Michael Sprenger, Christoph Schar and Robert Benoit on the Internet under //www.geo.umnw.ethz.ch/research/map_mc2/. The authors reported that the MC2 team undertook special model analysis in support of the mission planning for the Electra mission. Vertical cross-sections were examined of the flow across the Hohe Tauern region of the Austrian Alps, approximately 80 km to the east of Innsbruck The airflow was found to be from west to east and the MC2 provided valuable guidance in the decision process of the Electra mission. The foehn was already close to decaying (it ended in Innsbruck at 1600Z), however, the MC2 predicted the presence of a strong gravity wave over the Hohe Tauern, which was

confirmed by aircraft observations. Despite the prediction of regions with Richardson number (Ri) <0.25, rigorous gravity wave breaking was not observed in the region for flight levels 16,000 to 22,000 ft (4877 to 6706 m). Observations showed the presence of trapped gravity waves with horizontal scales of ~12 km.

C.2 IOP 8b: Thursday, October 21, 1999

Potential Vorticity (PV) banners and gravity wave breaking was observed north of the Alps.

C.2.1 The Electra Mission

There was a combined PV banner and gravity wave breaking mission with Electra, which flew across the Alpine Ridge at several heights.

C.2.2 Support for the mission

The following analysis is provided by Conny Schwierz on the Internet under //www.geo.umnw.ethz.ch/research/map_mc2/. The author reported the existence of a pronounced secondary PV banner north of the Alps at actual flight levels. Gravity waves were observed for which the vertical velocities showed large variability along the flight tracks, resulting in zones of pronounced shear. The MC2 model was only able to resolve maximum vertical velocities of about +/- 1.8ms^{-1}, as opposed to up to +/- 2.5 ms^{-1} which were observed during the flight. Velocities along and across the flight tracks, as well as wind vectors on the flight level 5800m indicate that the flow was predominantly parallel to the flight track. This was confirmed by observations during the mission. A comparison between measured and predicted potential temperatures along the flight path yield a reasonable performance of MC2. Heavy flooding was observed south of the Alps.

C.3 IOP 13b: Tuesday, November 2, 1999

The gravity wave mission over The Mont Blanc Massiv.

C.3.1 The Flight Plan

The mission consisted of four aeroplanes: Electra, P3, C130 and ARAT.

C.3.2 Analysis

The following analysis is provided by Emanuele Zala and Pierre Pellerin on the Internet under //www.geo.umnw.ethz.ch/research/map_mc2/. MAP SOP forecast report indicated that gravity waves were likely over the Alps. However, the prevalent southwesterly wind direction (parallel to the main alpine ridge) and relatively low wind speeds reduced the initial optimism.

C.4 IOP 15: Saturday, November 6, 1999

PV banners were observed in the southern Alps and gravity wave breaking in the eastern Alps.

C.4.1 The Flight Plan

The Electra and the C130 flew a gravity wave breaking mission over the Austrian Alps in the morning of November 6. In the afternoon the Electra, and P3 as well as the French aircraft Fokker and Merlin participated on a PV banner mission in the southern Alps flying at different heights in the Po Valley and south of Nice.

C.4.2 Weather situation

An extensive trough extended from the North Sea to France with strong cold air advection over the British Isles (-28 ^{O}C in 500 hPa). The trough propagated towards the southeast. It was estimated that the cold air would reach the Mediterranean Sea between 0600Z and 1200Z followed by a fast lee cyclogenesis over the southwestern part of the Po Valley and the Ligurian Sea. The maximum precipitation between 0900Z and 1500Z was expected in the Lago Maggiore and between 1800Z and 0000Z in northeast Italy. The pressure gradients across the Alps were forecasted to reverse: The South-Foehn was forecasted to end and Mistral and North-Foehn in the western parts of Po Valley predicted to start. It was expected that significant PV banners would develop at the same time.

C.4.3 Analysis

The following analysis is provided by Pierre Pellerin and André Walser on the Internet under //www.geo.umnw.ethz.ch/research/map_mc2/. Generally speaking, the occurrence of strong PV banners forecasted by the 3-km MC2 run could be confirmed by the aeroplane mission. Strong wind shear could be observed and wind speeds up to 40 ms^{-1} at 14,000 ft (4267 m) were measured at the flight track south of Nice. Comparison of vertical gravity wave motions measured by the Electra with those forecasted by MC2 on the 1-km grid indicate that the model has captured approximately the right wave amplitudes (the maximum observation was 3.8 and the maximum simulation was 4.1 ms^{-1}). The wavelengths simulated by the model are longer than those observed; this is directly related to the difference between the actual and model orography. The wind direction forecast by the model was not exactly the same as the wind direction observed during the flight. The last wave at 47.6 ^{O}N - 47.8 ^{O}N is probably an effect of the forced wind on the coarser mountains from the 3-km run in the lateral gravity wave absorber zone.

C.5 IOP 15: Monday, November 8, 1999

PV banners and gravity wave breaking mission in the southern Alps.

C.5.1 The Flight Plan

The Electra, the C130 and the Falcon flew a gravity wave breaking mission over the Monte Rosa region. The P-3 as well as the French aircraft Fokker and Merlin participated on a PV banner mission in the southern Alps flying two legs at different heights in the Po Valley.

C.5.2 Weather situation

The cut-off-low was located over Sicily, vertically stacked and quite stationary. It slowly filled and moved slowly southeast. Another cut off, which was not seen from the previous days forecast, built up over northern Germany and moved over eastern parts of Austria. The cross-alpine pressure gradient weakened with the approach of the cut off low from the north. Advected cold air was at higher levels, while surface pressure showed a weak signal of the high level cyclone, and western parts of Europe were still influenced by high pressure.

C.5.3 Analysis

Pierre Pellerin and André Walser provide the following analysis on the Internet under //www.geo.umnw.ethz.ch/research/map_mc2/. The predicted Gotthard and Brenner Jet for November 8 could be confirmed by the aircraft mission and induced strong PV banners as predicted. The spatial occurrence, as well as the amplitude of the Jets, was well forecasted by the MC2 3-km run and supported the PV banner mission. The MC2 simulation for November 8 as well as the prediction from other models allowed the team to expect gravity wave breaking for this day over the Monte Rosa area. The aircraft involved in the gravity wave breaking mission of November 8 did not even observe gravity waves. As a hypothesis this might be explained by an upper level flow which was uncoupled from the lower level flow and thus the aircraft did not 'see' the topography whereas this decoupling was not seen by the MC2 3-km run.

C.6 IOP 16: Saturday, November 13, 1999

Gravity waves mission over the southwestern Alps.

C.6.1 The Flight Plan

The Electra, the C-130 and the Falcon flew the gravity wave mission. Due to the strongest winds over the southwestern Alps, the flight tracks were over the Mont Blanc area.

C.6.2 Weather situation

The centre of the surface Mediterranean cyclone was shifting towards the Pyrenees, as forecasted. Observational data shows rainy weather with local thunderstorms and locally strong east to northeast wind over southwest France and northeast Spain. The surface high-pressure area was still over central and northwest Europe, while there was a deep cyclone over Scandinavia. The centre of the surface cyclone had deepened and moved from the west coast of Spain towards the Pyrenees. The heaviest precipitation was likely in southwest France, lesser rain in southeast France and northwest Italy. A mesoscale surface high was developing in the northwestern Po Valley and the pressure gradient over the French-Italian Alps was becoming stronger. At upper levels, the centre of the deep cut-off low was situated over Spain, the secondary low was north of the Alps, and the main jet stream region was to the north, over Scandinavia.

C.6.3 Analysis

Pierre Pellerin and André Walser provide the following analysis on the Internet under //www.geo.umnw.ethz.ch/research/map_mc2/. The MC2 3-km run predicted only slight vertical motion over the southwestern Alps. A first look at the aircraft data showed that the wave activity was weak as expected from the models.

C.7 Zanjan Incident: November 29, 1989

Incident over the Zagros Mountains

C.7.1 The Flight Plan

At 2347Z on 29 November 1989, a British Airways 747 was near the town of Zanjan in the Zagros Mountains. Suddenly the aeroplane lost air speed and fell from 35,000 ft to 26,000 ft. (10668 to 7925 m) before continuing on its flight to London.

C.7.2 Weather situation

The nearest radiosonde station to the incident was Lankaran, WMO number 37985. Figure C.1 shows the tephigram for 0000Z on 30 November 1989 at Lankaran. The most significant feature is the near static stability as reported by Lunnon (1992) to lie between 210 hPa and 425 hPa.

Appendix D. Obtained Temperature and Wind Profiles

D.1 Temperature Profiles obtained from the MetDB

In order to investigate the results from the 3dVOM numerical model, temperature profiles have been obtained from the MetDB for the days discussed in Appendix C. Table D.1 shows the stations available within an area 49^{O}N 45^{O}N 06^{O}E 14^{O}E. Numerically, the six WMO radiosonde stations having the greatest number of temperature profiles during the days of the IOP cases of Appendix C are: 06610 which has 30 temperature profiles, station 16080 which has 29 temperature profiles, station 10868 which has 28 temperature profiles, station 11120 which has 23 temperature profiles, station 16044 which has 21 temperature profiles and station 10739 which has 20 temperature profiles.

Station 06610 is the closest to Mont Blanc from the twelve reporting stations. Stations 06610 and 16080 are the closest to Monte Rosa. Stations 11120 and 16044 are closest to the Grossglockner and Hohe Tauern regions. Stations 10962, 11120 and 10868 are closest to the Alpine Ridge. However, the coverage from station 10962 comprises only two temperature profiles. This report considers the data from five stations i.e. 16044, 16080, 11120, 06610 and 10868 for each of the IOP case days. Some of the temperature profiles do not contain data up to a sufficiently high altitude for the NAG algorithm to interpolate to heights required by the 3dVOM program. Data at 20 hPa is needed by the model for a 40 layer model and increment of 500 m between levels, together with a last line of data in the input temperature and wind velocity profile which is ignored. In consequence, as no data could be used for station 11120, the last line of profile data was repeated in each profile for this station, in order that the program should use all the available data. Results were now obtained whenever the profile was available up to 20 hPa for station 11120. These fudged profiles for station 11120 allowed 11 data sets to be considered. In addition, two data sets were excluded for station 06610 as they occupied the same time slot interval and contained different wind direction and speed values at 50 hPa and above.

Date	Number of Profiles	Station	Latitude	Longitude
20/09/1999	5	06610	46.82	6.95
20/09/1999	3	07180	48.68	6.22
20/09/1999	4	10739	48.83	9.20
20/09/1999	3	10828	48.10	9.25
20/09/1999	5	10868	48.25	11.55
20/09/1999	1	10962	47.80	11.02
20/09/1999	2	11120	47.27	11.35
20/09/1999	2	16044	46.03	13.18
20/09/1999	6	16080	45.43	9.28
21/10/1999	4	06610	46.82	6.95
21/10/1999	3	07180	48.68	6.22
21/10/1999	2	10739	48.83	9.20
21/10/1999	3	10828	48.10	9.25
21/10/1999	4	10868	48.25	11.55
21/10/1999	4	11120	47.27	11.35
21/10/1999	4	16044	46.03	13.18

21/10/1999	4	16080	45.43	9.28
02/11/1999	4	06610	46.82	6.95
02/11/1999	3	06842	47.38	9.65
02/11/1999	5	06843	46.72	9.42
02/11/1999	4	10739	48.83	9.20
02/11/1999	3	10828	48.10	9.25
02/11/1999	4	10868	48.25	11.55
02/11/1999	4	11120	47.27	11.35
02/11/1999	3	16044	46.03	13.18
02/11/1999	4	16080	45.43	9.28
02/11/1999	3	07180	48.68	6.22
06/11/1999	9	06610	46.82	6.95
06/11/1999	2	06842	47.38	9.65
06/11/1999	4	10739	48.83	9.20
06/11/1999	7	10868	48.25	11.55
06/11/1999	5	11120	47.27	11.35
06/11/1999	4	16044	46.03	13.18
06/11/1999	7	16080	45.43	9.28
06/11/1999	3	07180	48.68	6.22
06/11/1999	2	06843	46.72	9.42
08/11/1999	3	06610	46.82	6.95
08/11/1999	3	06843	46.72	9.42
08/11/1999	3	10739	48.83	9.20
08/11/1999	4	10868	48.25	11.55
08/11/1999	4	11120	47.27	11.35
08/11/1999	4	16044	46.03	13.18
08/11/1999	4	16080	45.43	9.28
08/11/1999	2	16087	45.27	11.28
08/11/1999	2	06842	47.38	9.65
08/11/1999	3	07180	48.68	6.22
08/11/1999	1	10828	48.10	9.25
08/11/1999	1	10962	47.80	11.02
13/11/1999	5	06610	46.82	6.95
13/11/1999	3	10739	48.83	9.20
13/11/1999	4	10868	48.25	11.55
13/11/1999	4	11120	47.27	11.35
13/11/1999	4	16044	46.03	13.18
13/11/1999	4	16080	45.43	9.28
13/11/1999	3	07180	48.68	6.22
13/11/1999	2	16087	45.27	11.28

Table D.1 The number of profiles for each station in the MetDB which contain temperature and wind profiles for the IOP days of Appendix C.

D.2 Temperature Profiles obtained for Zanjan

Temperature profiles are not available from the MetDB for the Zanjan incident in 1989. Eight upper air data profiles from late November 1989 have been obtained for WMO station 37985 (Lankaran) around the time of the incident discussed in Appendix C. These have been used in order to run the 3dVOM numerical model.

Only one data set provided information up to 10 hPa, and one further data set provided information up to 20 hPa.

The 3dVOM numerical model does not use the last data input line in the temperature profile and wind profile input data. In all but one of the eight profiles, the data caused the version of makeprofile.exe with NAG routines to crash. In consequence, the data was fudged by repeating the last line of data in the two profiles which reached a height of 20 hPa, which ensured that all the data was used. The remaining six were fudged by copying the 20 hPa and 10 hPa data from that of 1200Z on 28/11/1989 into them and repeating the 10 hPa value. This ensured that the 3dVOM numerical model ran with 40 levels and an interval of 500m between levels. The results obtained with this experiment were tested against a further set of profiles in which the remaining six were fudged by copying the 30 hPa and 20 hPa data from that of 1200Z on 29/11/1989.

A similar interpolation problem near the ground required that two profiles needed one extra value inserting. The profile at 0000Z on 30/11/1989 had the value of wind speed and direction at 942 hPa inserted into the 925 hPa data value, and the 0600Z on 30/11/1989 had the value of wind speed and direction at 1015 hPa inserted into the 1000 hPa data value. The comparison between the two profile sets showed that the effect of inserting different values into the profiles at high altitudes was negligible. The mean of a dimensionless function, which calculates the spread of the minimum values, is taken to be:

$$(1/n)^* \sum_{I=1}^{n} [(\min_{I1} - \min_{I2}) / (\min_{I1} + \min_{I2})]^2 \qquad \text{(D.1)}$$

where $\min_{I1}$ are each of the n=26 tabulated minimum values in Table 3.2 which use the extra upper data from 1200Z on 28/11/1989 and $\min_{I2}$ are the corresponding untabulated values for the profiles using the upper data from 1200Z on 29/11/1989. The value for (D.1) was found to be approximately .00021.

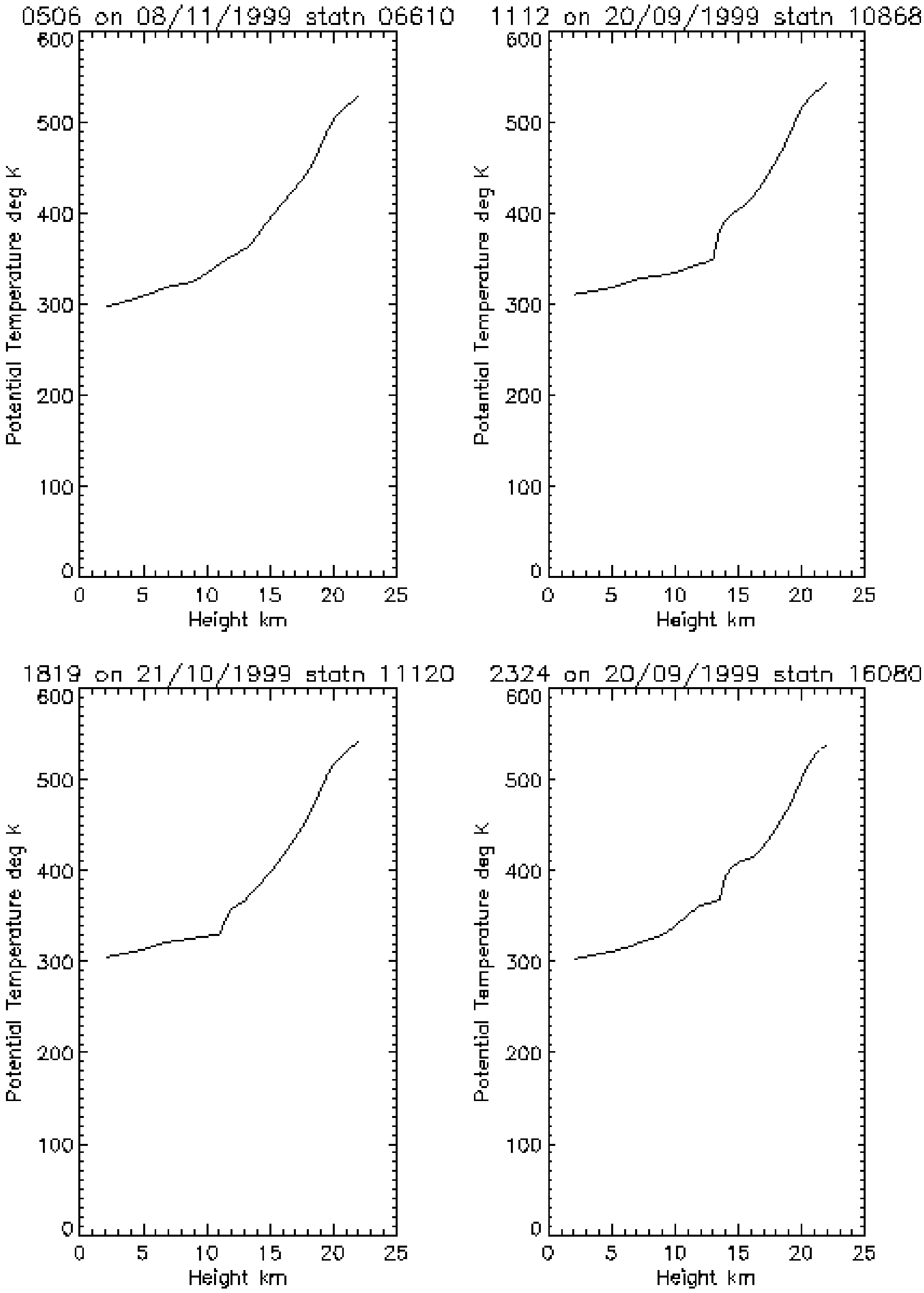

Figure 3.1 Four potential temperature profiles are shown which are used in the calculation of maximum downdraughts in Table 3.1. The profile used on 08/11/1999 between 0500Z and 0600Z for station 06610 is shown top left, while that used on 20/09/1999 between 1100Z and 1200Z for station 10868 is shown top right. The remaining profiles, 21/10/1999 between 1800Z and 1900Z for station 11120 (bottom left) and 20/09/1999 between 2300Z and 2400Z for station 16080 (bottom right) correspond to the two cases in Table 3.1 for which maximum downdraughts exceed the threshold. Both display a sharp increase in potential temperature at mid altitudes.

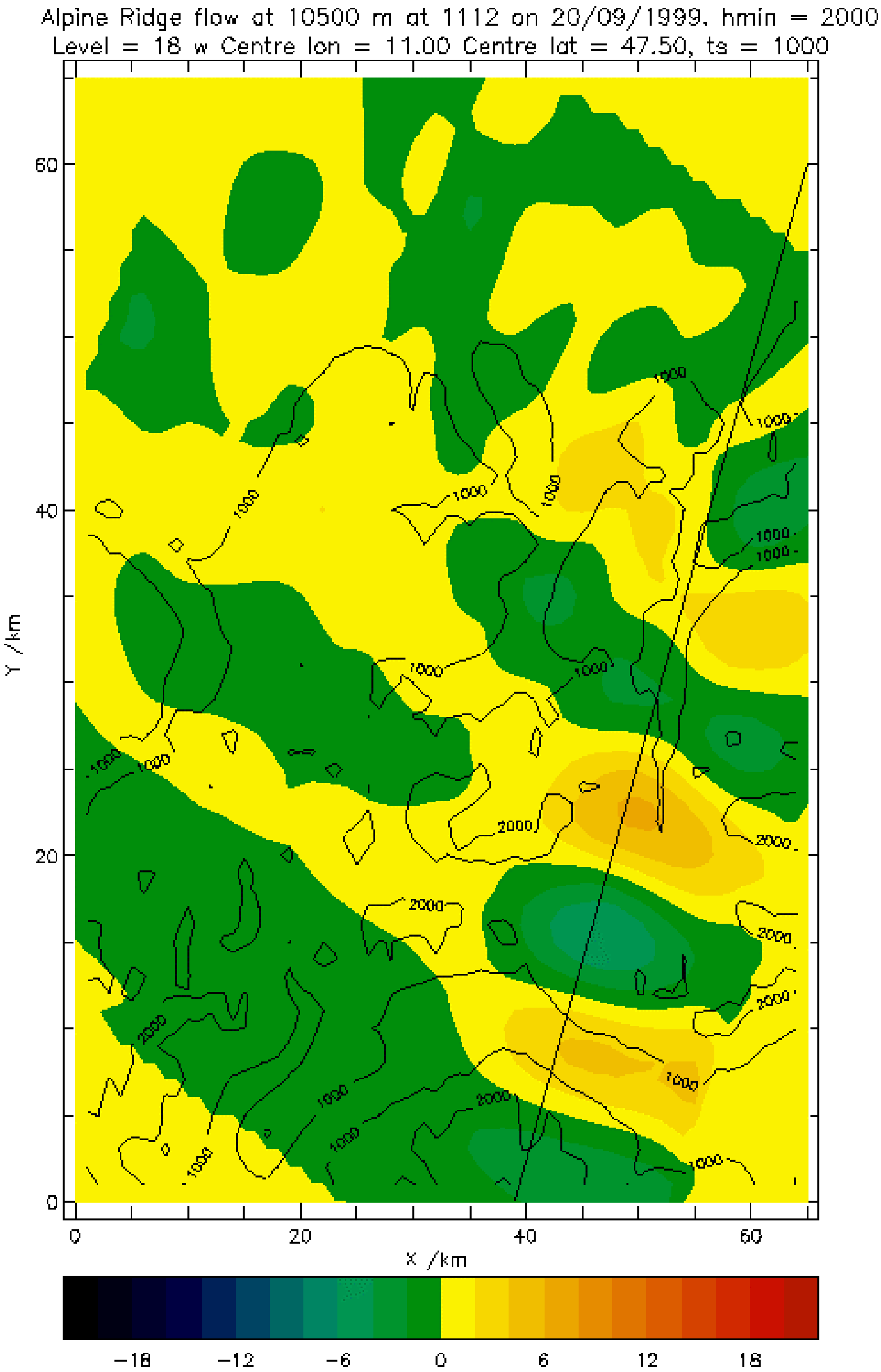

Figure 3.2 Coloured vertical velocity contours, in ms^{-1}, (positive updraft) are shown as a horizontal cross section at model level 18, corresponding to a height of 10,500 m (h_{min} = 2000 m). The domain is in the region of the Alpine Ridge, in the Alps, centred at (47.50^{O}N,11.00^{O}E). These contours have been obtained from a 3dVOM model run after 4000s (1000 time steps). The profile for station 16044 (at Udine/Campoformido, Italy) has been obtained from the MetDB and has been recorded in the hour interval between 1100Z and 1200Z on 20/09/1999. A southwesterly wind existed, and the figure shows the position for the vertical cross section shown in Figure 3.3 with slice co-ordinates from (39,00) to (65,60). The black terrain contours are shown for a grid interval of 1 km. Downdraughts occur over a number of areas.

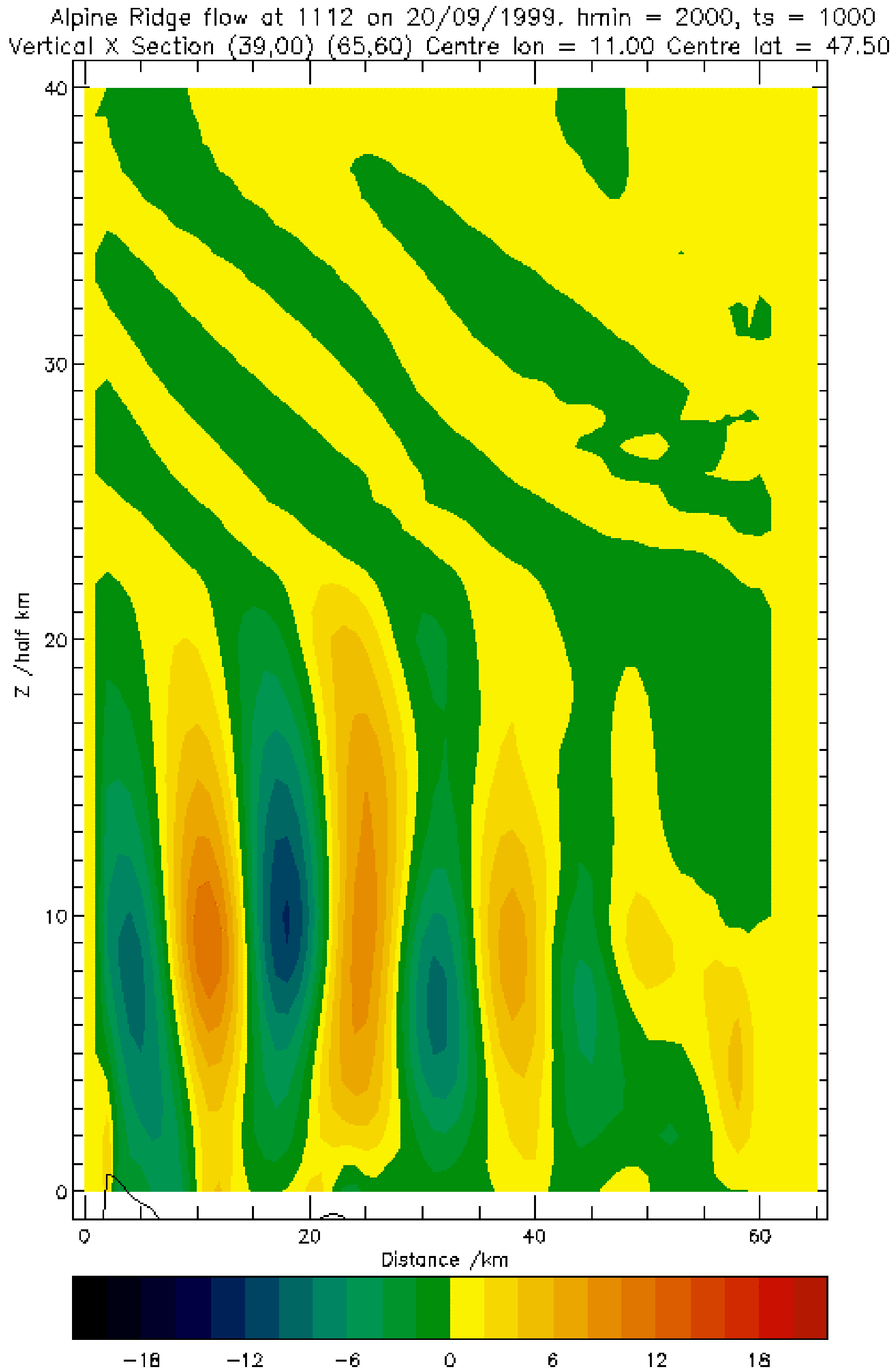

Figure 3.3 Contours of vertical velocity in ms^{-1} over the Alpine Ridge (positive updraft) are shown as a vertical cross section within the same domain and for the same details as Figure 3.2. A cross section is shown from southwest to northeast, (39,00) to (65,60), with the wind blowing from left to right. The terrain, shown in black, is the height above (or below) the level h_{min} =2km. Heights (y-axis) are shown from 2km (0) to 22km (40). The horizontal grid separation is approximately 1.0 km. Greatest amplitudes occur below 13 km for a horizontal wavelength of about 13.5 km.

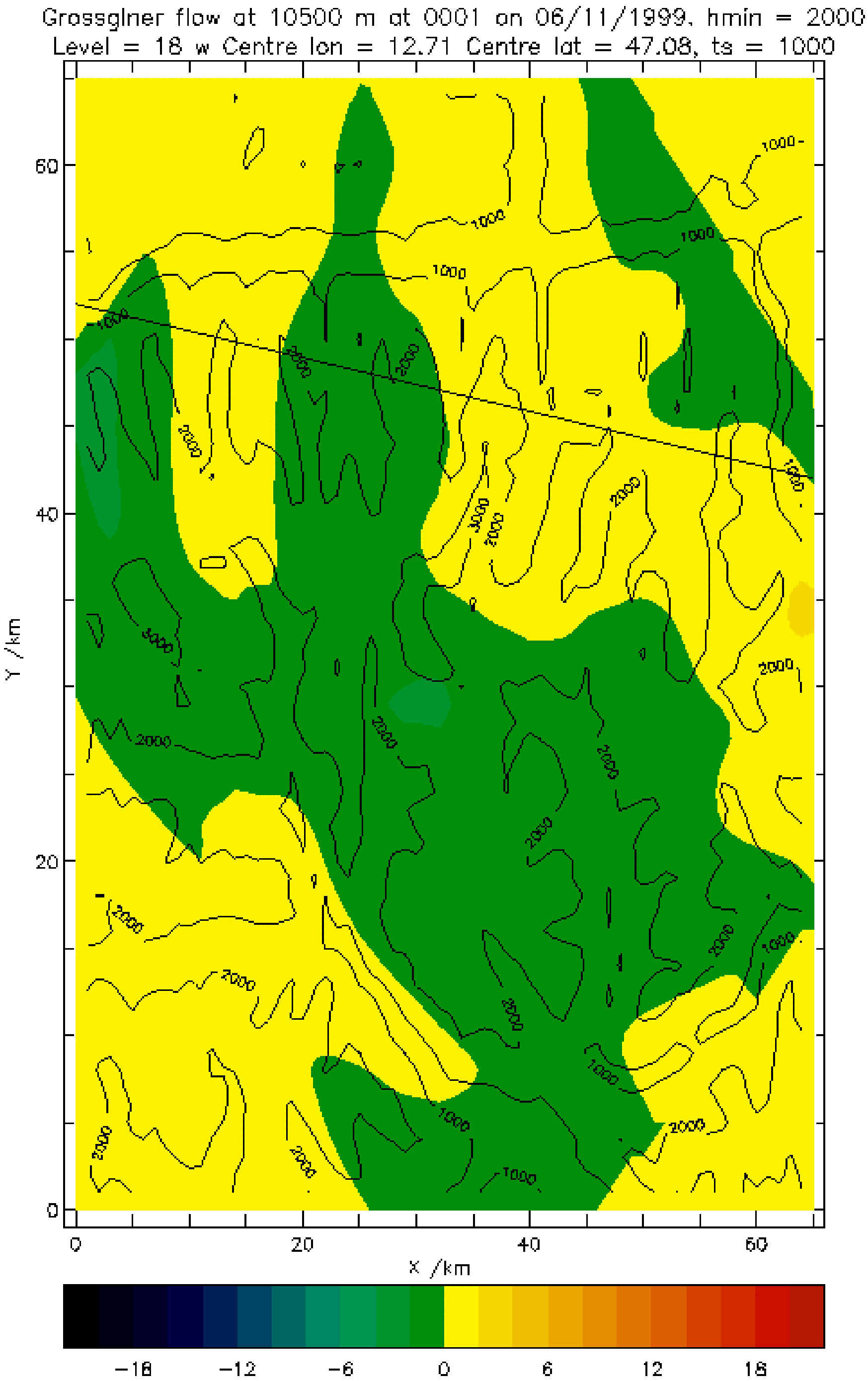

Figure 3.4 Coloured vertical velocity contours, in ms^{-1}, (positive updraft) are shown as a horizontal cross section at model level 18, corresponding to a height of 10,500 m (h_{min} = 2000 m). The domain is in the region of Grossglockner, in the Alps, centred at (47.08^{O}N,12.71^{O}E). These contours have been obtained from a 3dVOM model run after 4000s (1000 time steps). The profile for station 06610 (at Payerne, Switzerland) has been obtained from the MetDB and has been recorded in the hour interval between 0000Z and 0100Z on 06/11/1999. A southwesterly wind existed, and the figure shows the position for the vertical cross section shown in Figure 3.5 with slice co-ordinates from (00,52) to (65,42). The black terrain contours are shown for a grid interval of 1 km. Downdraughts occur over a large central area.

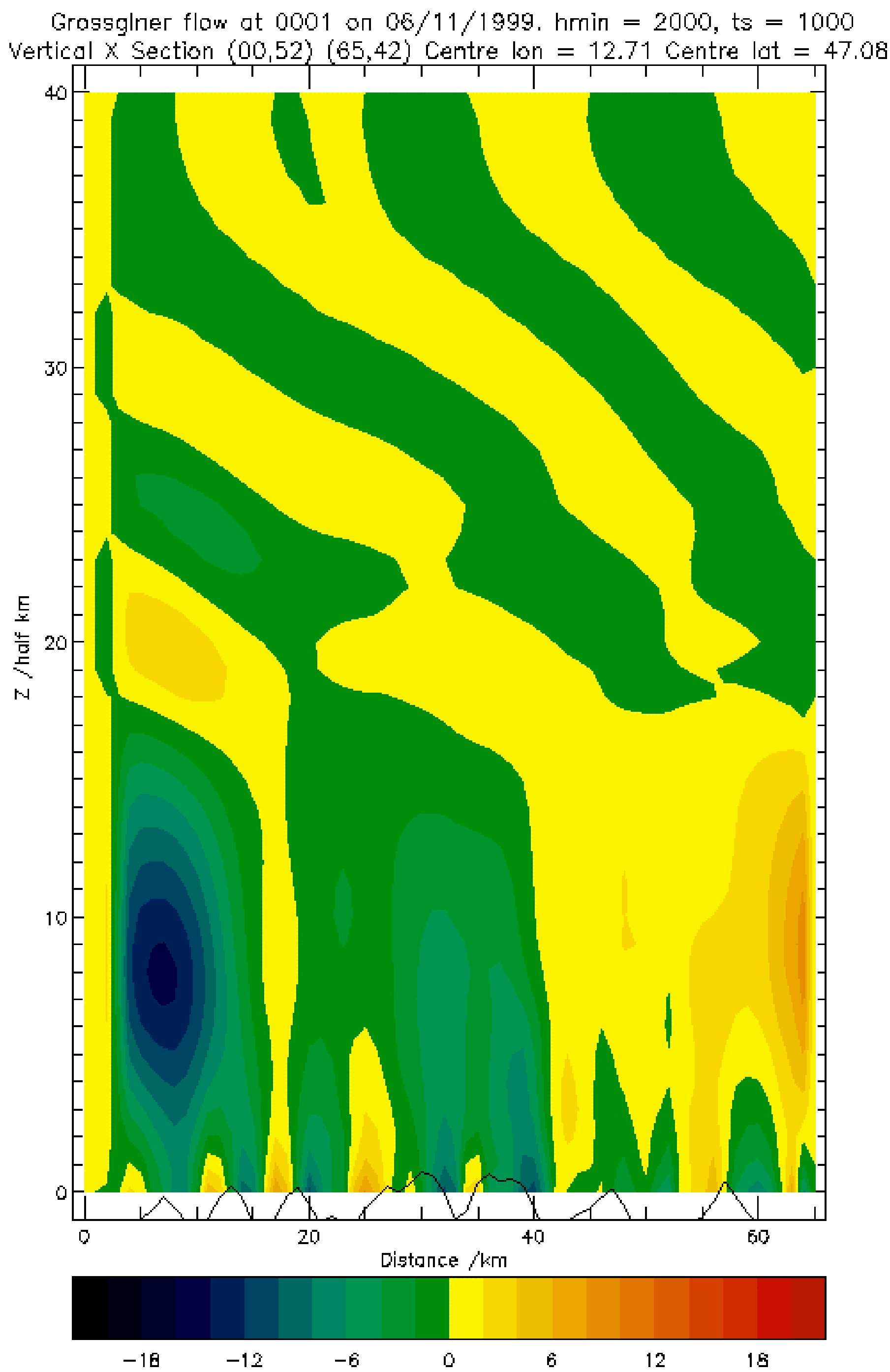

Figure 3.5 Contours of vertical velocity in ms^{-1} over Grossglockner (positive updraft) are shown as a vertical cross section within the same domain and for the same details as Figure 3.4. A cross section is shown from west to east, (00,52) to (65,42), with the southwesterly wind blowing from approximately left to right. The terrain, shown in black, is the height above (or below) the level h_{min} *=2km. Heights (y-axis) are shown from 2km (0) to 22km (40). The horizontal grid separation is approximately 1.0 km. Greatest amplitudes occur below 10.5 km.*

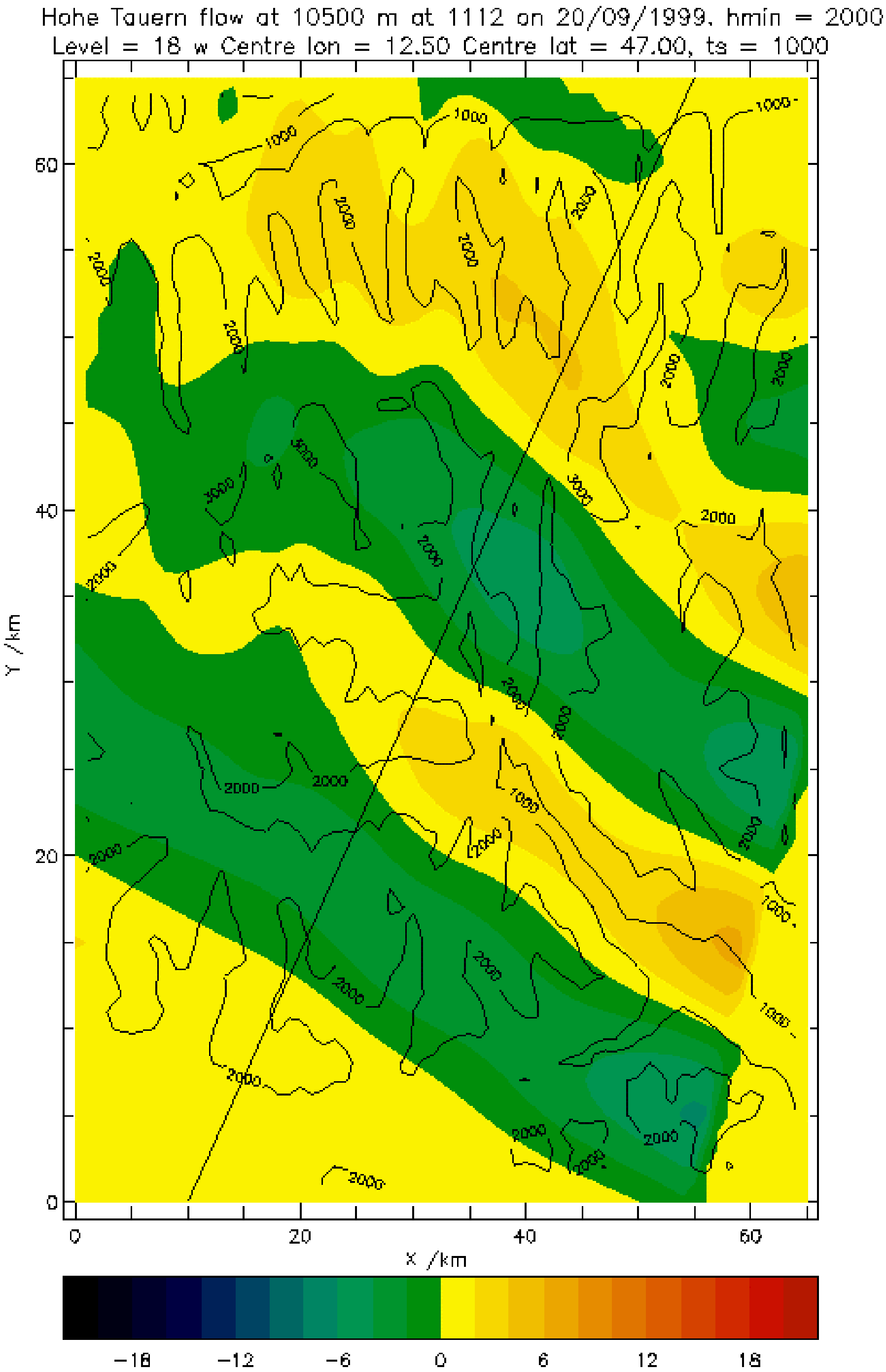

Figure 3.6 Coloured vertical velocity contours, in ms^{-1}*, (positive updraft) are shown as a horizontal cross section at model level 18, corresponding to a height of 10,500 m (*h_{min} *= 2000 m). The domain is in the region of Hohe Tauern, in the Alps, centred at (47.00*^{O}*N,12.50*^{O}*E). These contours have been obtained from a model run of the 3dVOM model after 4000s (1000 time steps). The profile for station 10868 (at Munchen/Oberschleissheim, Germany) has been obtained from the MetDB and has been recorded in the hour interval between 1100Z and 1200Z on 20/09/1999. A southwesterly wind existed, and the figure shows the position for the vertical cross section shown in Figure 3.7 with slice co-ordinates from (10,00) to (55,65). The black terrain contours are shown for a grid interval of 1 km. Downdraughts occur over two areas each extending over 60 km by 12 km.*

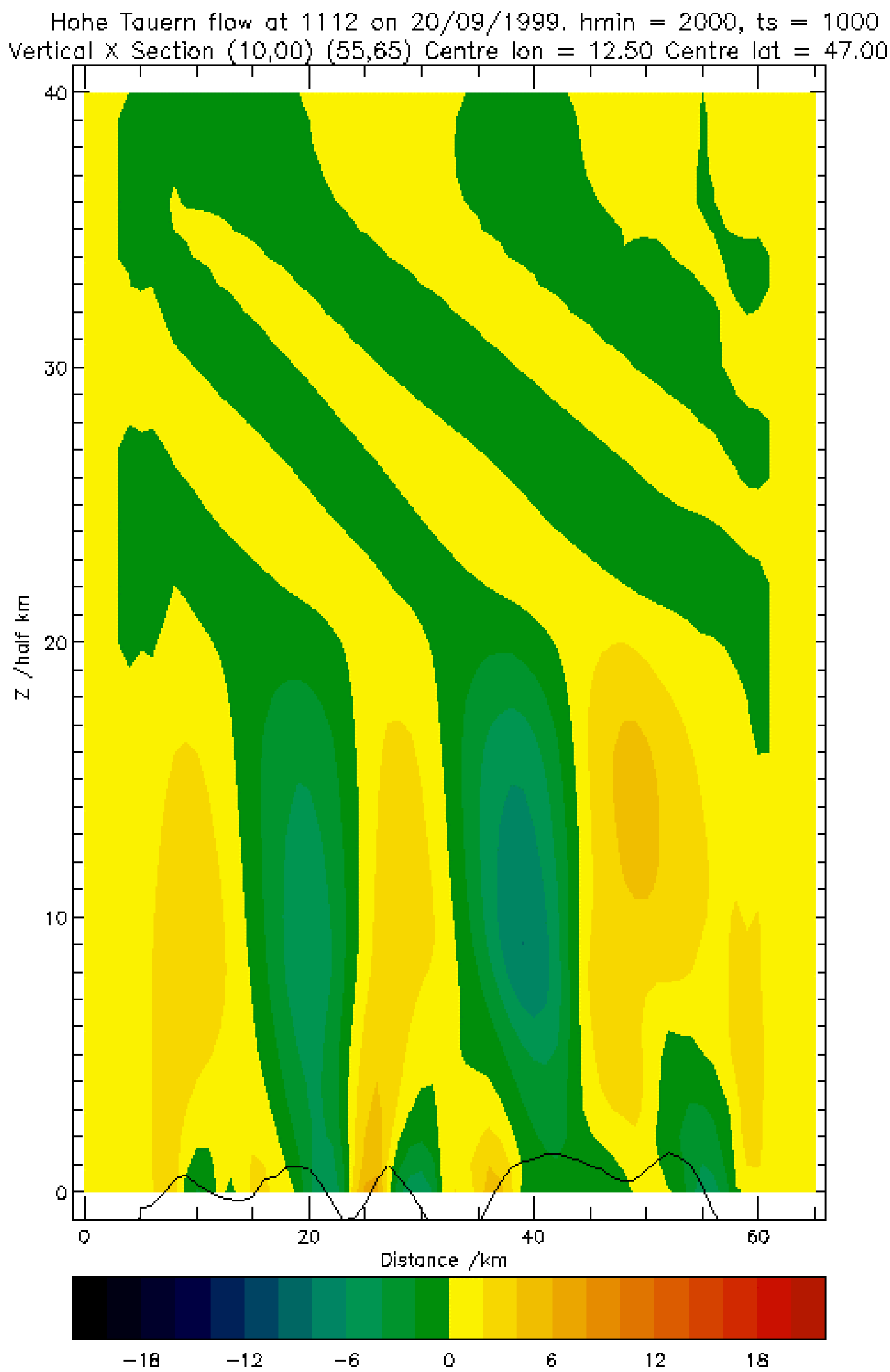

Figure 3.7 Contours of vertical velocity in ms^{-1} over Hohe Tauern (positive updraft) are shown as a vertical cross section within the same domain and for the same details as Figure 3.6. A cross section is shown from southwest to northeast, (10,00) to (55,65), with the wind blowing from left to right. The terrain, shown in black, is the height above (or below) the level h_{min} =2km. Heights (y-axis) are shown from 2km (0) to 22km (40). The horizontal grid separation is approximately 1.2 km. Greatest amplitudes occur below 12 km for a horizontal wavelength of about 12 km below 5 km altitude and 22 km at 10.5 km altitude.

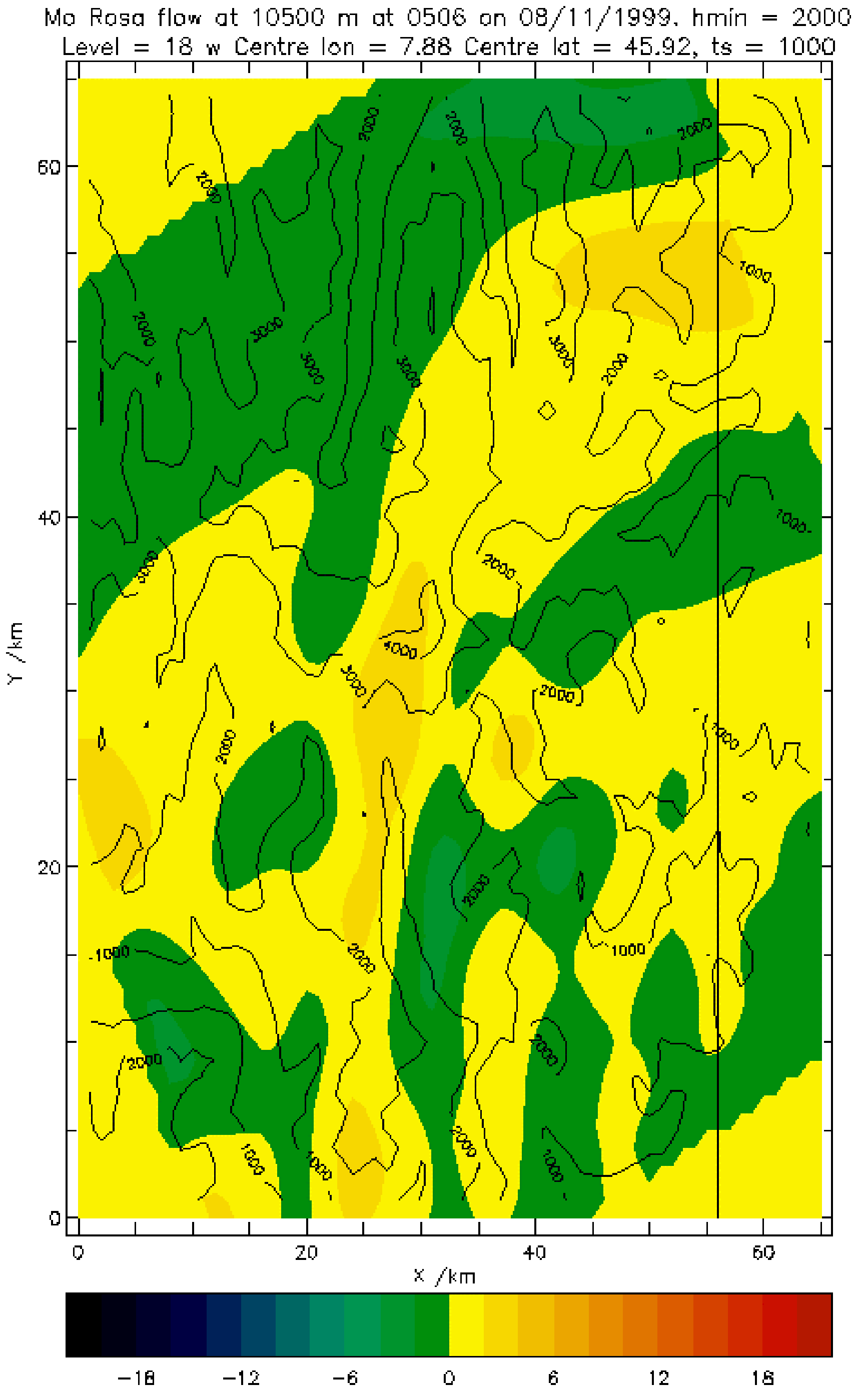

Figure 3.8 Coloured vertical velocity contours, in ms^{-1}, (positive updraft) are shown as a horizontal cross section at model level 18, corresponding to a height of 10,500 m (h_{min} = 2000 m). The domain is in the region of Monte Rosa, in the Alps, centred at (45.92^{O}N,7.88^{O}E). These contours have been obtained from a 3dVOM model run after 4000s (1000 time steps). The profile for station 10868 (at Munchen/Oberschleissheim, Germany) has been obtained from the MetDB and has been recorded in the hour interval between 0500Z and 0600Z on 8/11/1999. A northerly wind existed, and the figure shows the position for the vertical cross section shown in Figure 3.9 with slice co-ordinates from north to south through (56,65) and (56,00). The black terrain contours are shown for a grid interval of 1 km. Downdraughts occur over an area in the North extending over 55 km by 20 km.

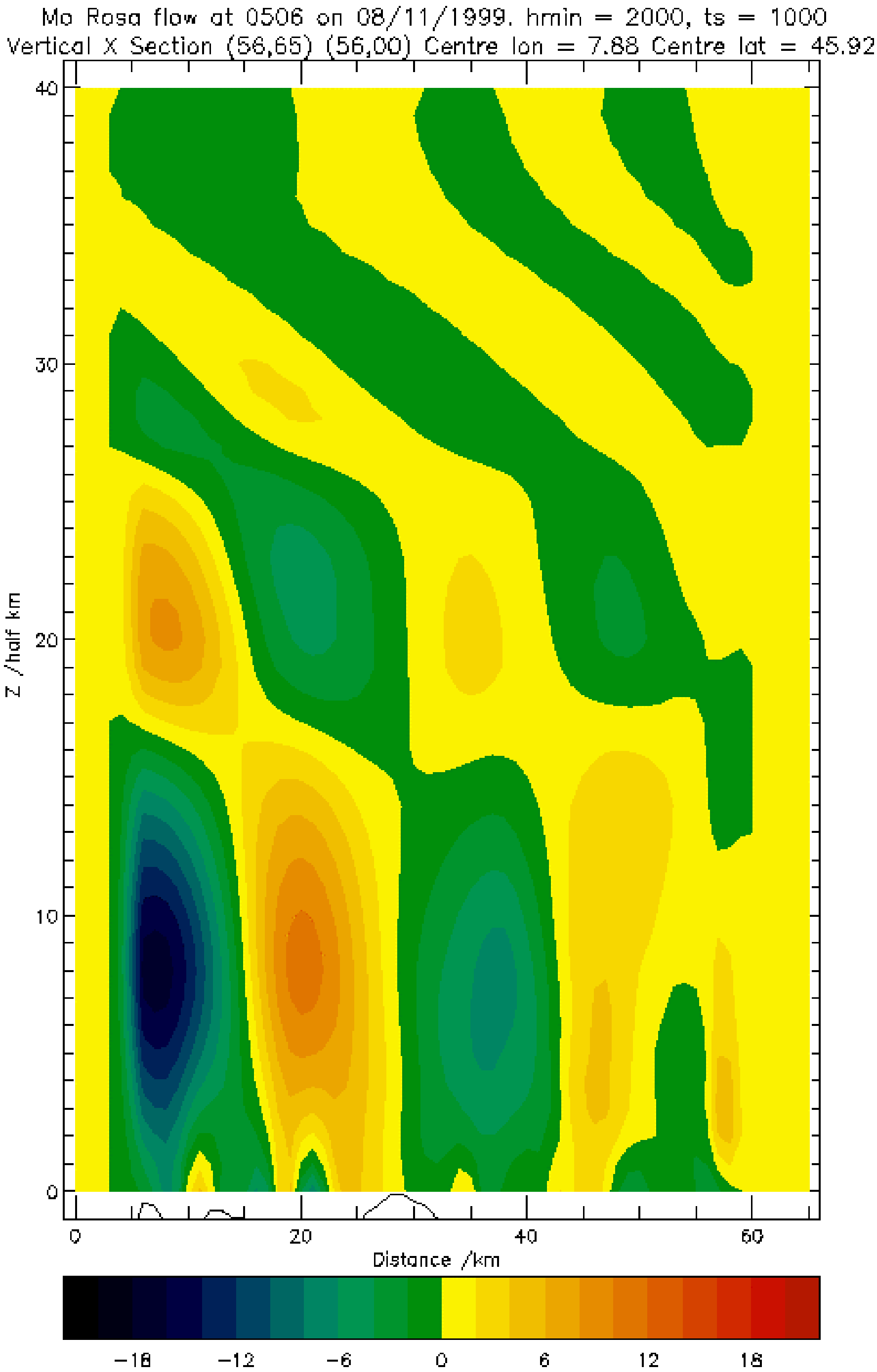

Figure 3.9 Contours of vertical velocity in ms^{-1} over Monte Rosa (positive updraft) are shown as a vertical cross section within the same domain and for the same details as Figure 3.8. A cross section is shown from north to south, (56,65) to (56,00), with a northerly wind blowing from left to right. The terrain, shown in black, is the height above (or below) the level h_{min} *=2km. Heights (y-axis) are shown from 2km (0) to 22km (40). The horizontal grid separation is 1 km. Greatest amplitudes occur below 8.5 km for a horizontal wavelength along the cross section of about 23 km.*

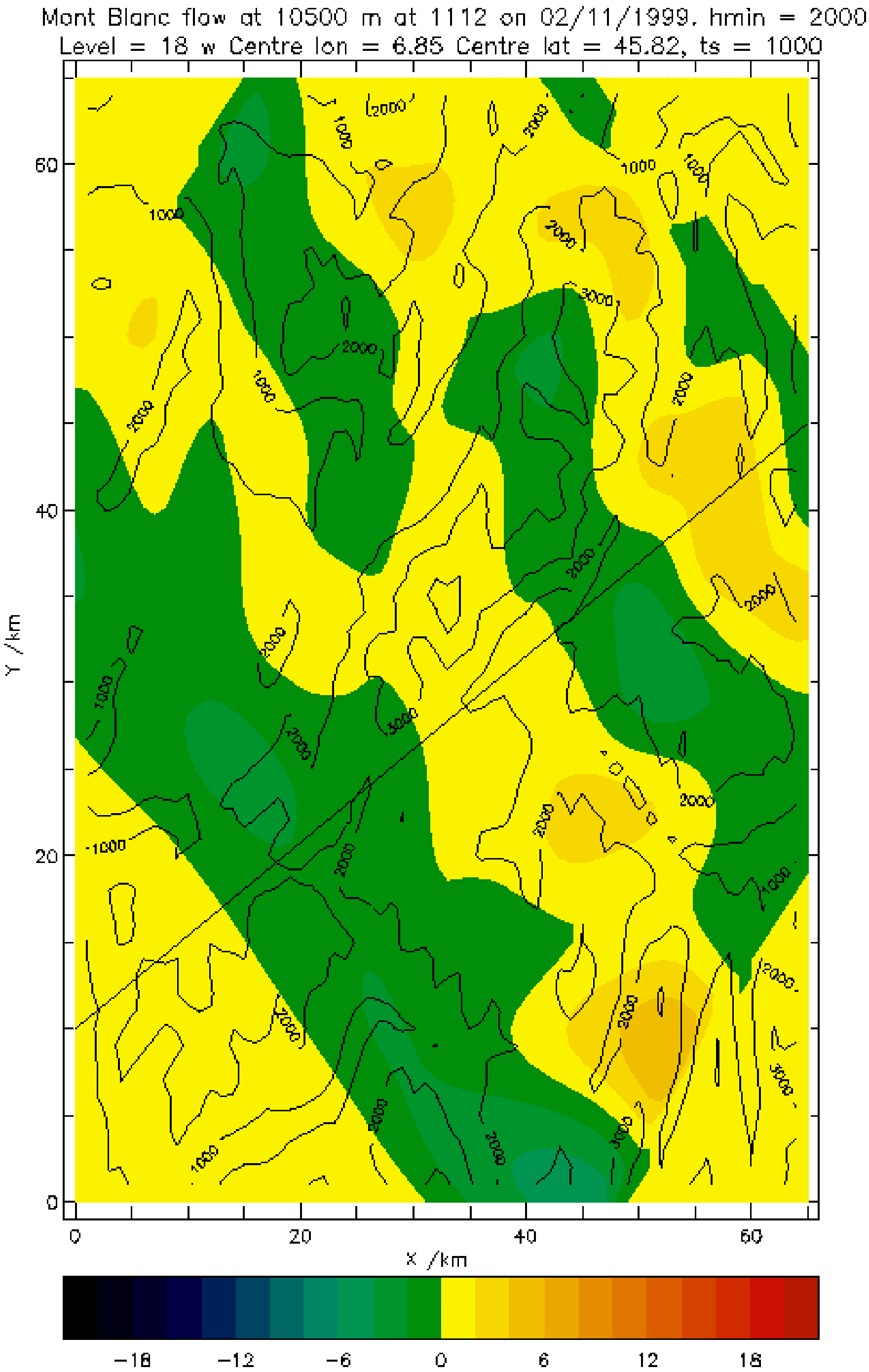

Figure 3.10 Coloured vertical velocity contours, in ms^{-1}, (positive updraft) are shown as a horizontal cross section at model level 18, corresponding to a height of 10,500 m (h_{min} = 2000 m). The domain is in the region of Mont Blanc, in the Alps, centred at (45.82^{O}N,6.85^{O}E). These contours have been obtained from a 3dVOM model run after 4000s (1000 time steps). The profile for station 06610 (at Payerne, Switzerland) has been obtained from the MetDB and has been recorded in the hour interval between 1100Z and 1200Z on 02/11/1999. A southwesterly wind existed, and the figure shows the position for the vertical cross section shown in Figure 3.11 with slice co-ordinates from (00,10) to (65,45). The black terrain contours are shown for a grid interval of 1 km. Downdraughts occur over several areas.

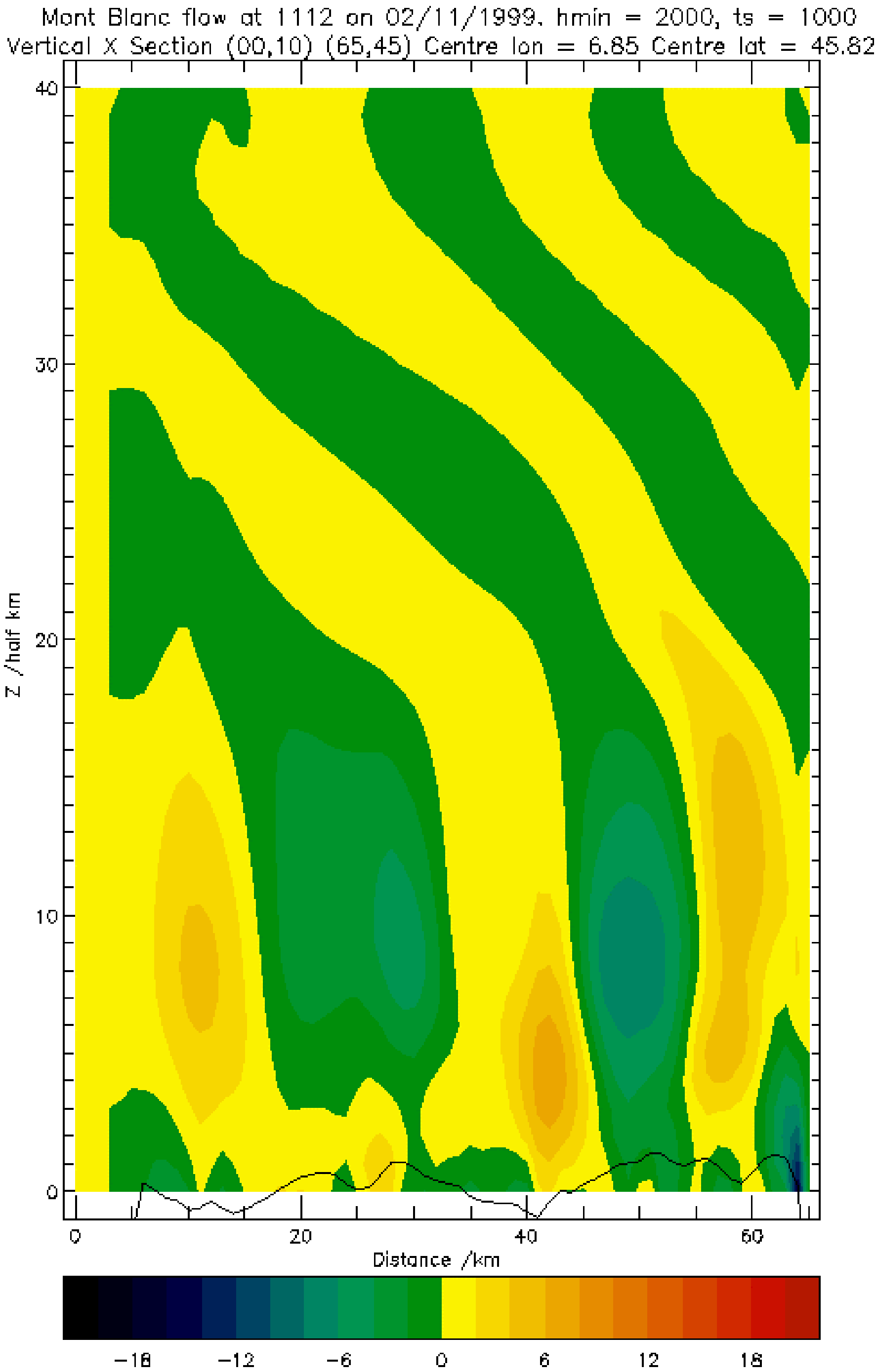

Figure 3.11 Contours of vertical velocity in ms^{-1} over Mont Blanc (positive updraft) are shown as a vertical cross section within the same domain and for the same details as Figure 3.10. A cross section is shown from southwest to northeast, (00,10) to (65,45), with the wind blowing from left to right. The terrain, shown in black, is the height above (or below) the level h_{min} =2km. Heights (y-axis) are shown from 2km (0) to 22km (40). The horizontal grid separation is approximately 1.1 km. Greatest amplitudes occur below 10.5 km for a horizontal wavelength of about 19 km.

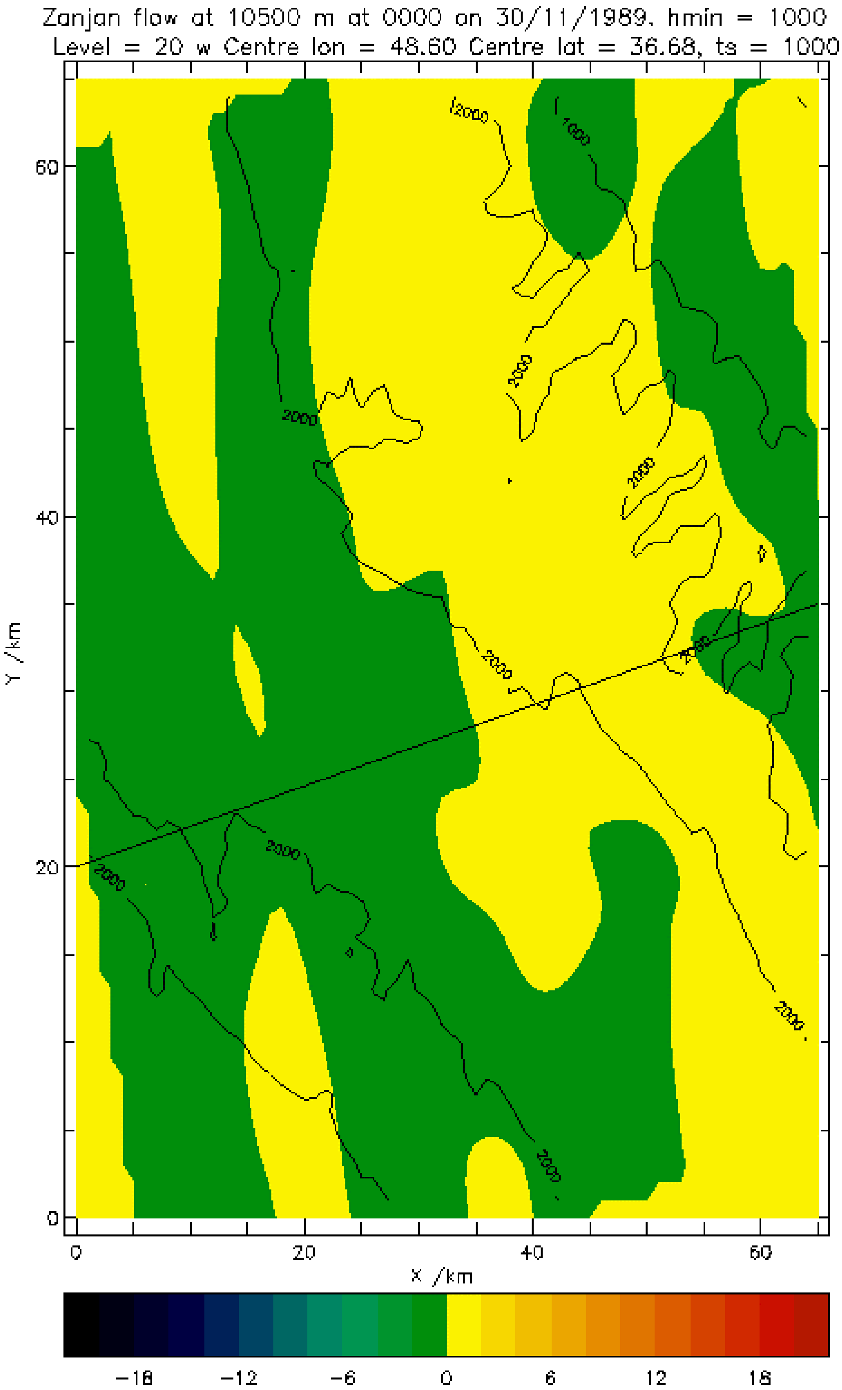

Figure 3.12 Coloured vertical velocity contours, in ms^{-1}, (positive updraft) are shown as a horizontal cross section at model level 20, corresponding to a height of 10,500 m (h_{min} = 1000 m). The domain is in the region of Zanjan, in the Zagros Mountains, centred at (36.68^{O}N,48.60^{O}E). These contours have been obtained from a model run of the 3dVOM model after 4000s (1000 time steps). The profile for station 37985 (Lankaran) has been recorded at 0000Z on 30/11/1989. A southwesterly wind existed, and the figure shows the position for the vertical cross section shown in Figure 3.13 with slice co-ordinates from (00,20) to (65,35). The black terrain contours are shown for a grid interval of 1 km. Downdraughts occur over a substantial area extending over 65 km (north-south).

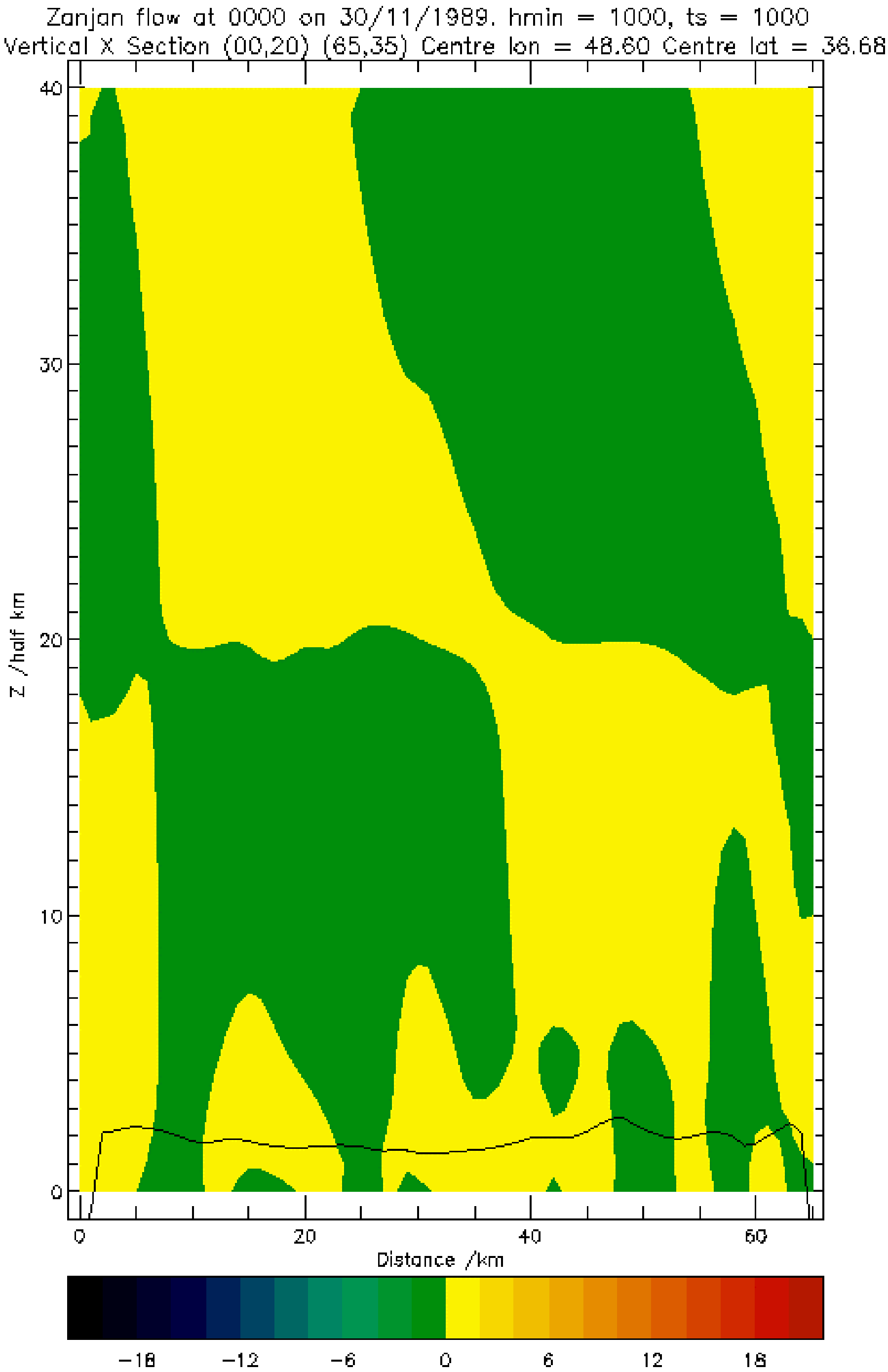

Figure 3.13 Contours of vertical velocity in ms^{-1} over Zanjan (positive updraft) are shown as a vertical cross section within the same domain and for the same details as Figure 3.12. A cross section is shown from southwest to northeast, (00,20) to (65,35), with the wind blowing from left to right. The terrain, shown in black, is the height above (or below) the level h_{min} *=1 km. Heights (y-axis) are shown from 1 km (0) to 21 km (40). The horizontal grid separation is approximately 1.0 km. At elevations of up to 4 km, the horizontal wavelength is about 9 km. However, at an altitude of 10.5 km, the wavetroughs have merged giving a downdraught for 35km.*

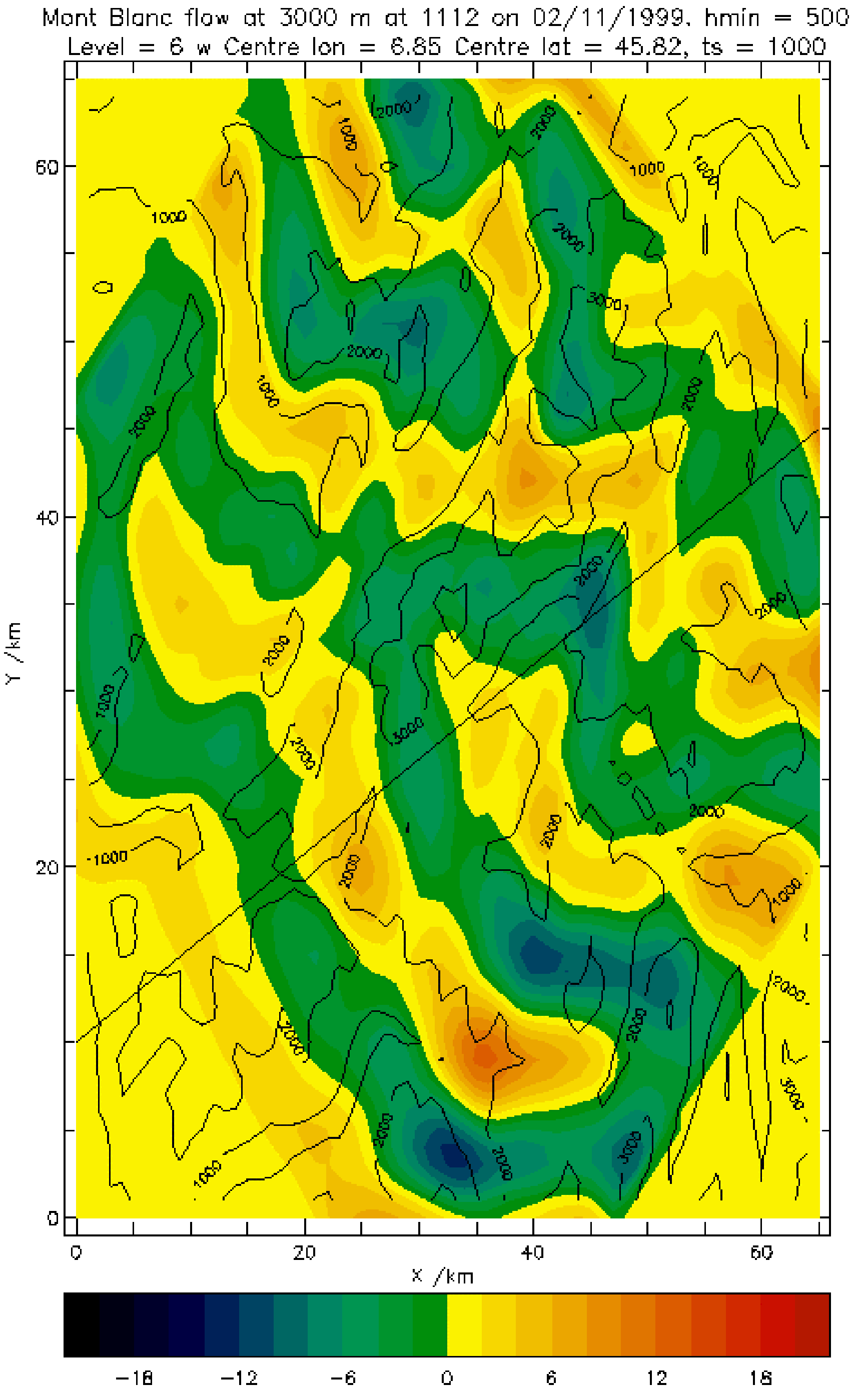

Figure 3.14 Coloured vertical velocity contours, in ms^{-1}, (positive updraft) are shown as a horizontal cross section at model level 6, corresponding to a height of 3,000 m (h_{min} = 500 m). The domain is in the region of Mont Blanc, in the Alps, centred at (45.82^{O}N,6.85^{O}E). These contours have been obtained from a 3dVOM model run after 4000s (1000 time steps). The profile for station 06610 (at Payerne, Switzerland) has been obtained from the MetDB and has been recorded in the hour interval between 1100Z and 1200Z on 02/11/1999. A southwesterly wind existed, and the figure shows the position for the vertical cross section shown in Figure 3.15 with slice co-ordinates from (00,10) to (65,45). The black terrain contours are shown for a grid interval of 1 km. There is a complex wavetrain pattern present over the terrain.

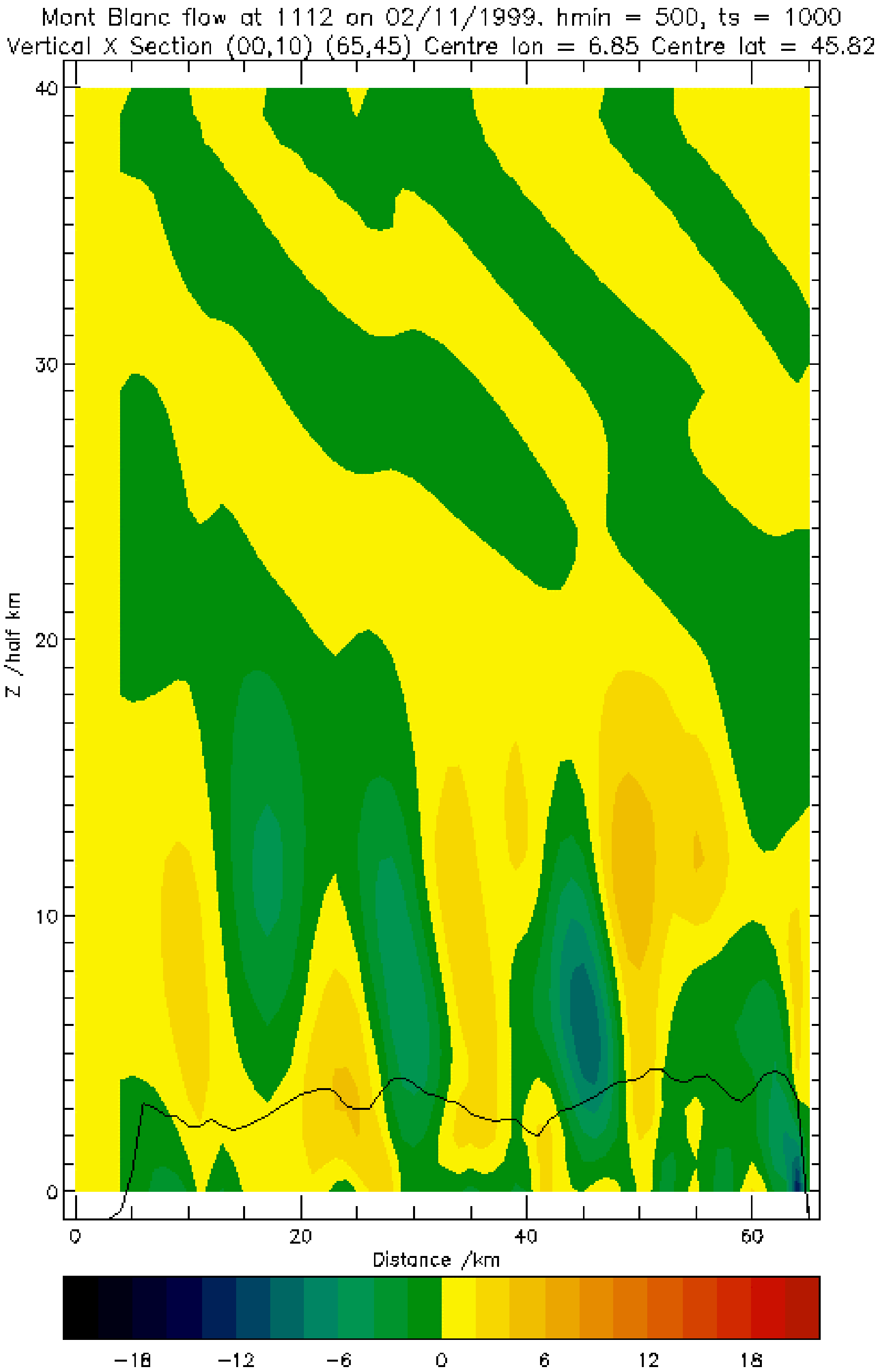

Figure 3.15 Contours of vertical velocity in ms^{-1} over Mont Blanc (positive updraft) are shown as a vertical cross section within the same domain and for the same details as Figure 3.14. A cross section is shown from southwest to northeast, (00,10) to (65,45), with the wind blowing from left to right. The terrain, shown in black, is the height above (or below) the level h_{min} *=500m. Heights (y-axis) are shown from 500m (0) to 20.5km (40). The horizontal grid separation is approximately 1.1 km. Greatest amplitudes occur below 10 km for a horizontal wavelength of about 14 km.*

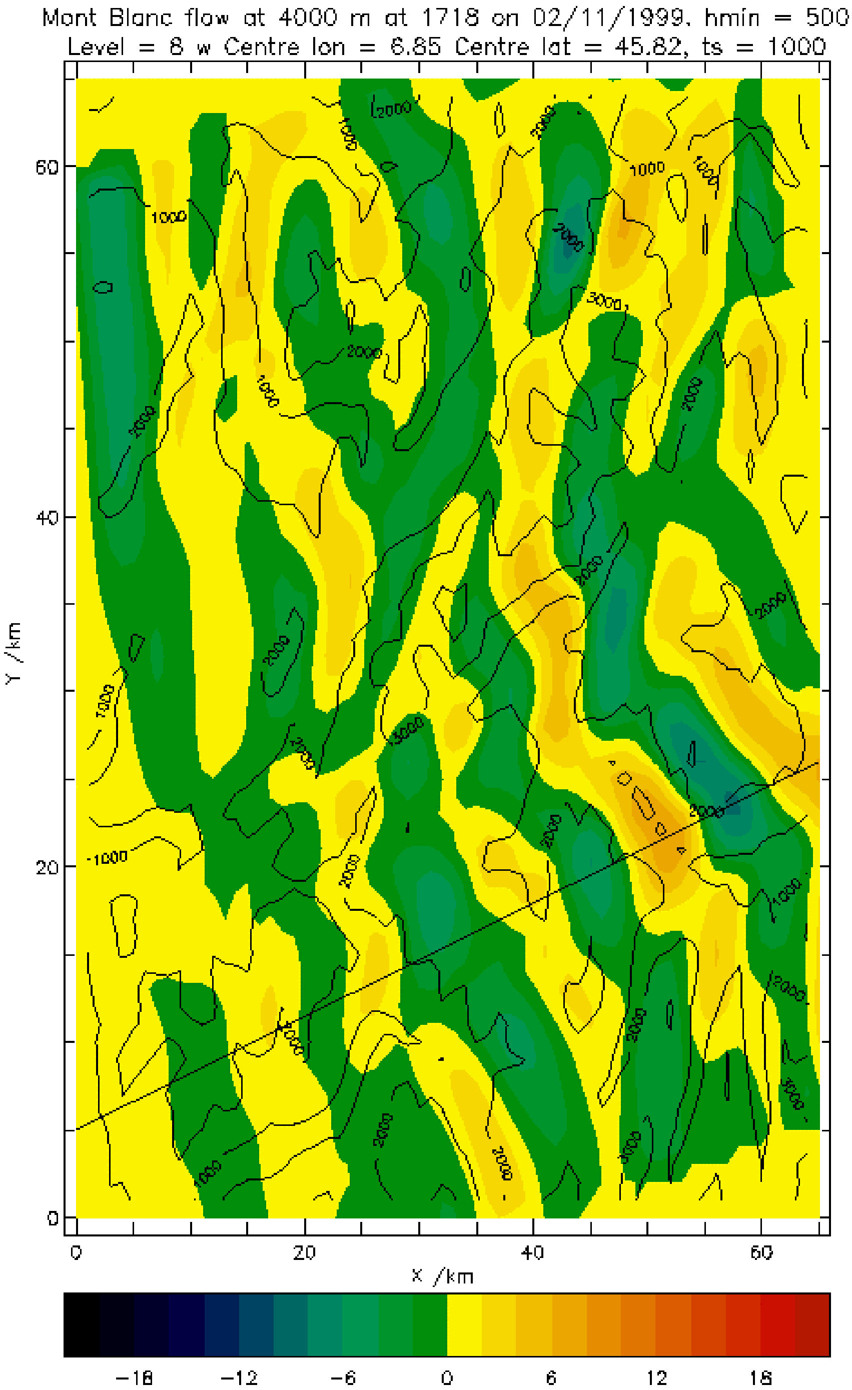

Figure 3.16 Coloured vertical velocity contours, in ms^{-1}, (positive updraft) are shown as a horizontal cross section at model level 8, corresponding to a height of 4,000 m (h_{min} = 500 m). The domain is in the region of Mont Blanc, in the Alps, centred at (45.82^{O}N,6.85^{O}E). These contours have been obtained from a 3dVOM model run after 4000s (1000 time steps). The profile for station 10868 (at Munchen/Oberschleissheim, Germany) has been obtained from the MetDB and has been recorded in the hour interval between 1700Z and 1800Z on 02/11/1999. A southwesterly wind existed, and the figure shows the position for the vertical cross section shown in Figure 3.17 with slice co-ordinates from (00,05) to (65,26). The black terrain contours are shown for a grid interval of 1 km. A wavetrain pattern is present near the slice to the south of Mont Blanc.

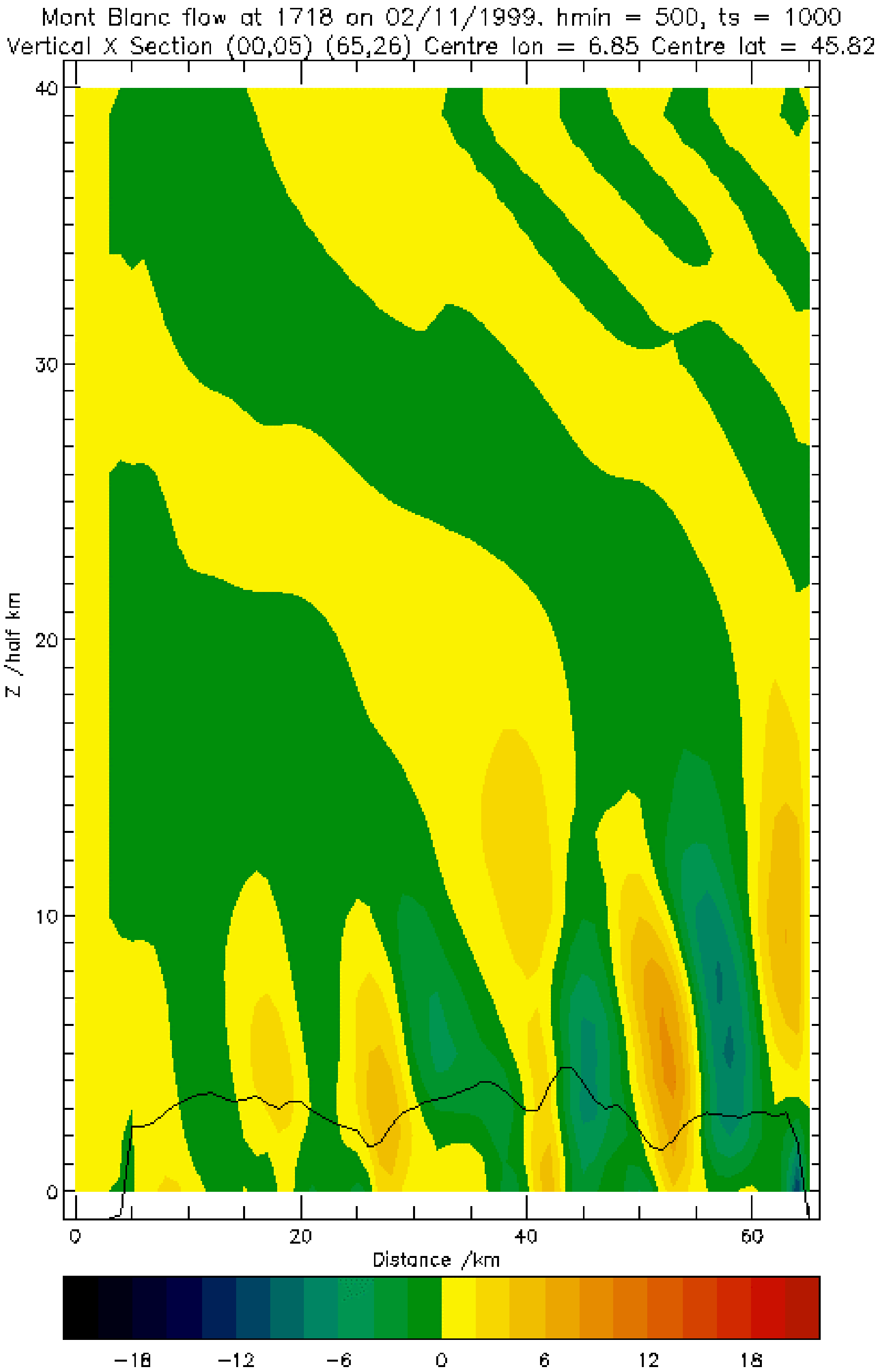

Figure 3.17 Contours of vertical velocity in ms^{-1} over Mont Blanc (positive updraft) are shown as a vertical cross section within the same domain and for the same details as Figure 3.16. A cross section is shown from southwest to northeast, (00,05) to (65,26), with the wind blowing from left to right. The terrain, shown in black, is the height above (or below) the level h_{min} *=500m. Heights (y-axis) are shown from 500m (0) to 20.5km (40). The horizontal grid separation is approximately 1.1 km. Greatest amplitudes occur below 9.5 km for a horizontal wavelength of about 9 km.*

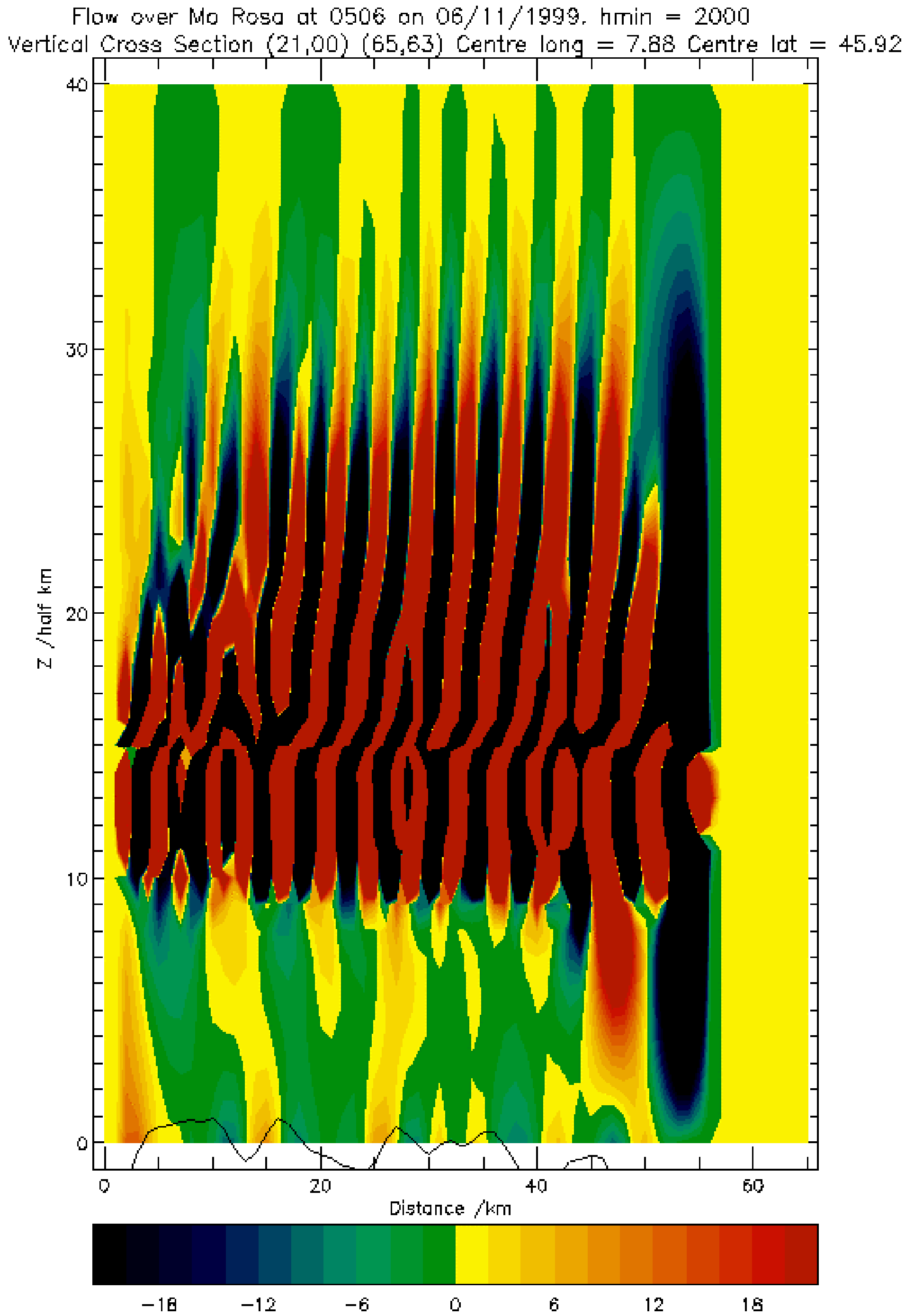

Figure A.1 The vertical wave amplitude is shown in the vicinity of Monte Rosa after 1000 time steps for the case of no viscosity and h_{min} = 2000m. The profile is that shown in Table A.1 on 06/11/1999 for the hour interval between 0500Z and 0600Z for a vertical cross section from (21,0) to (65,63) using the unmodified makeprofile program of the 3dVOM suite.

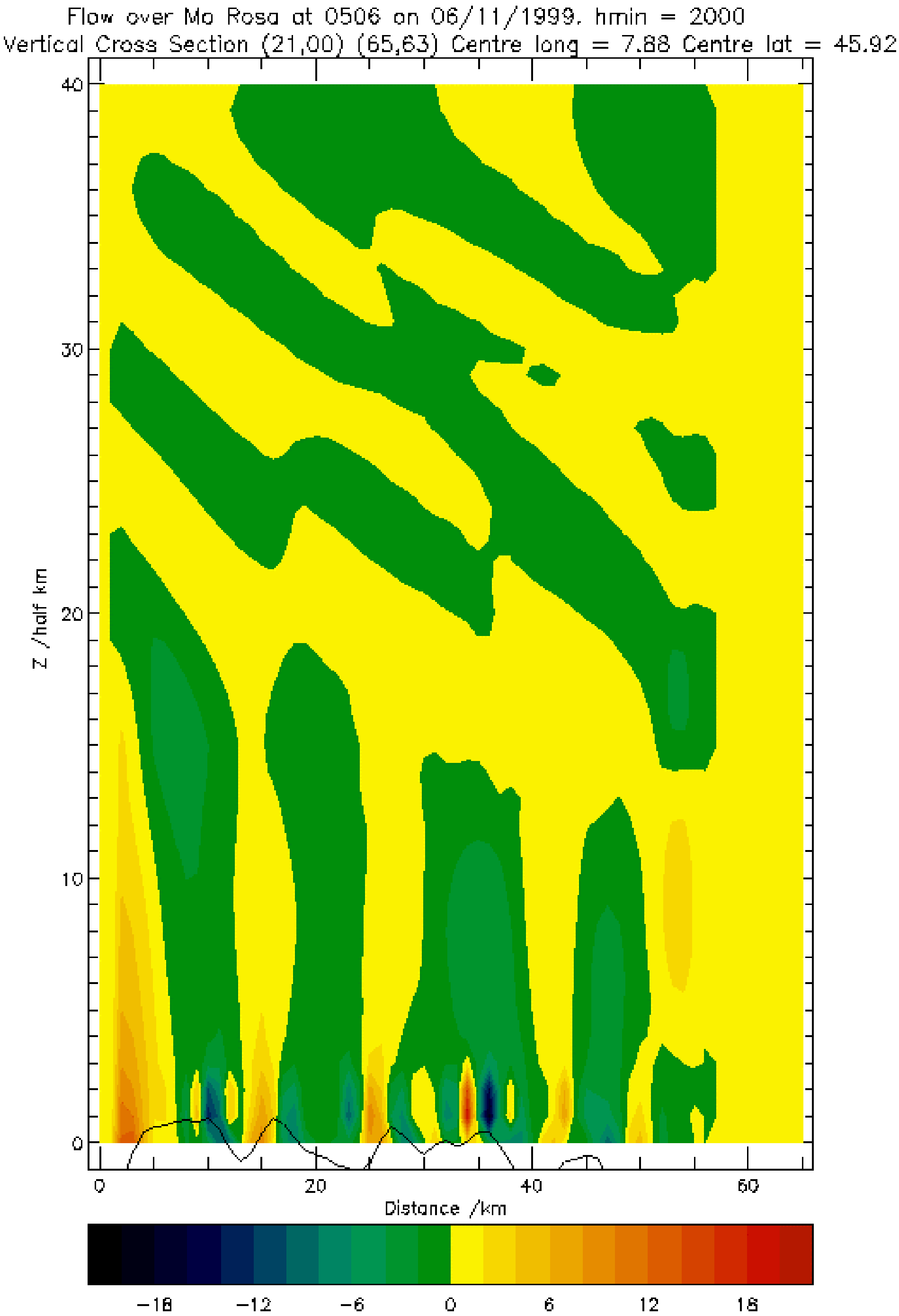

Figure A.2 The vertical wave amplitude is shown in the vicinity of Monte Rosa after 1000 time steps for the case of no viscosity and h_{min} = 2000m. The profile is that shown in Table A.3 on 06/11/1999 for the hour interval between 0500Z and 0600Z for a vertical cross section from (21,0) to (65,63) using the unmodified makeprofile program of the 3dVOM suite. Note that the change in the velocity profile has removed the large wave amplitude at mid altitudes.

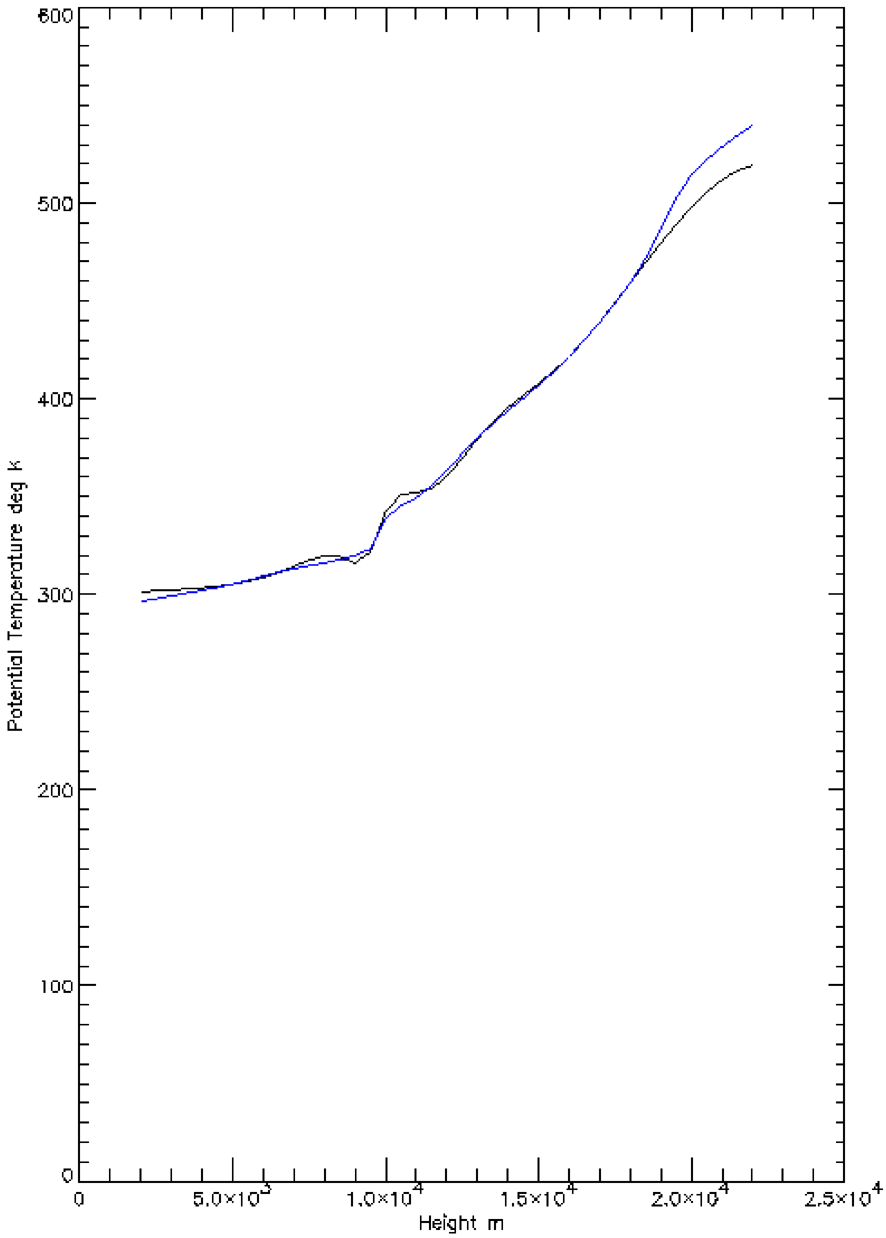

Figure A.3 The potential temperature profile generated by the unmodified 3dVOM model, which allows an inversion, and the new potential temperature profile (in blue) generated by the modified makeprofile program of the 3dVOM suite which monotonically increases with height are shown. The profile is that on 06/11/1999 for the hour interval between 0500Z and 0600Z.

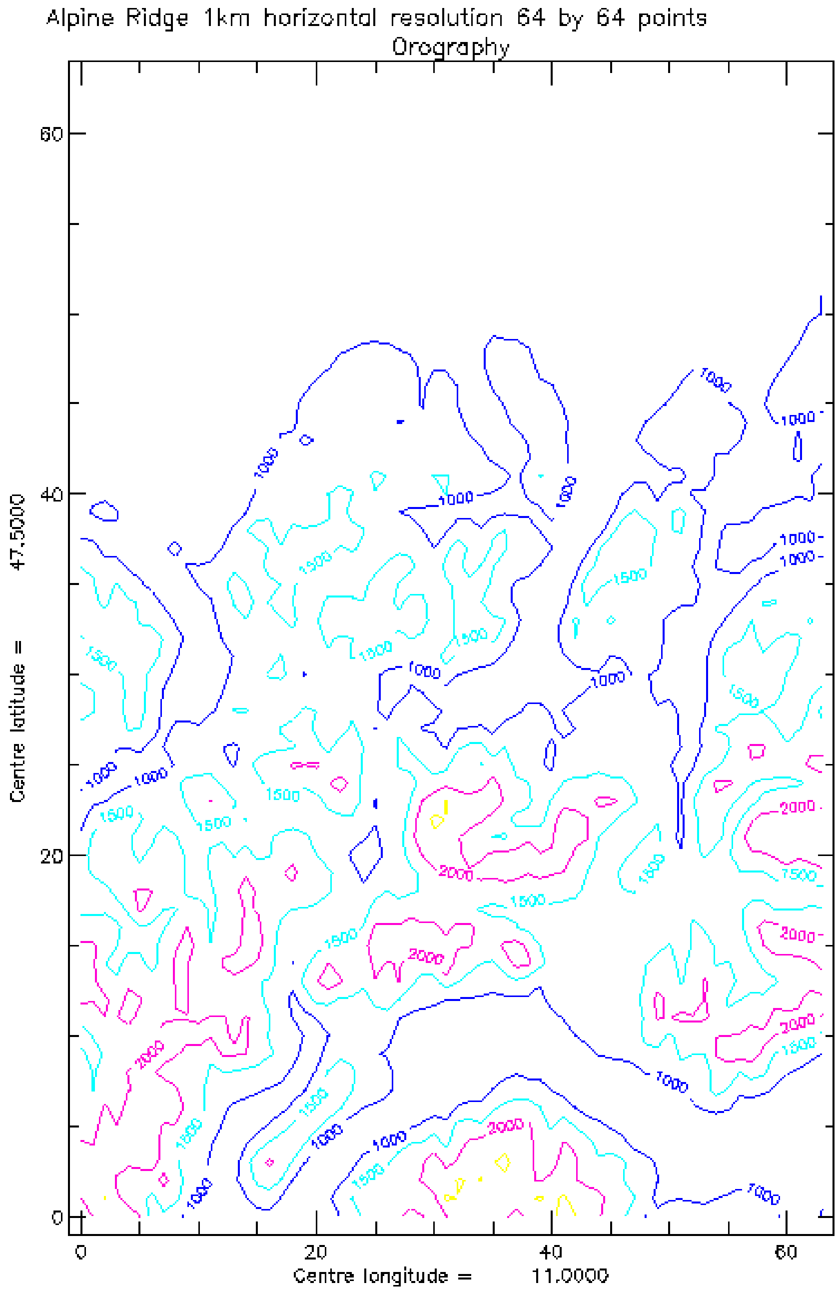

Figure B.1 The 1-km resolution orography for The Alpine Ridge. The domain is centred at (47.50^{O}N,11.00^{O}E).

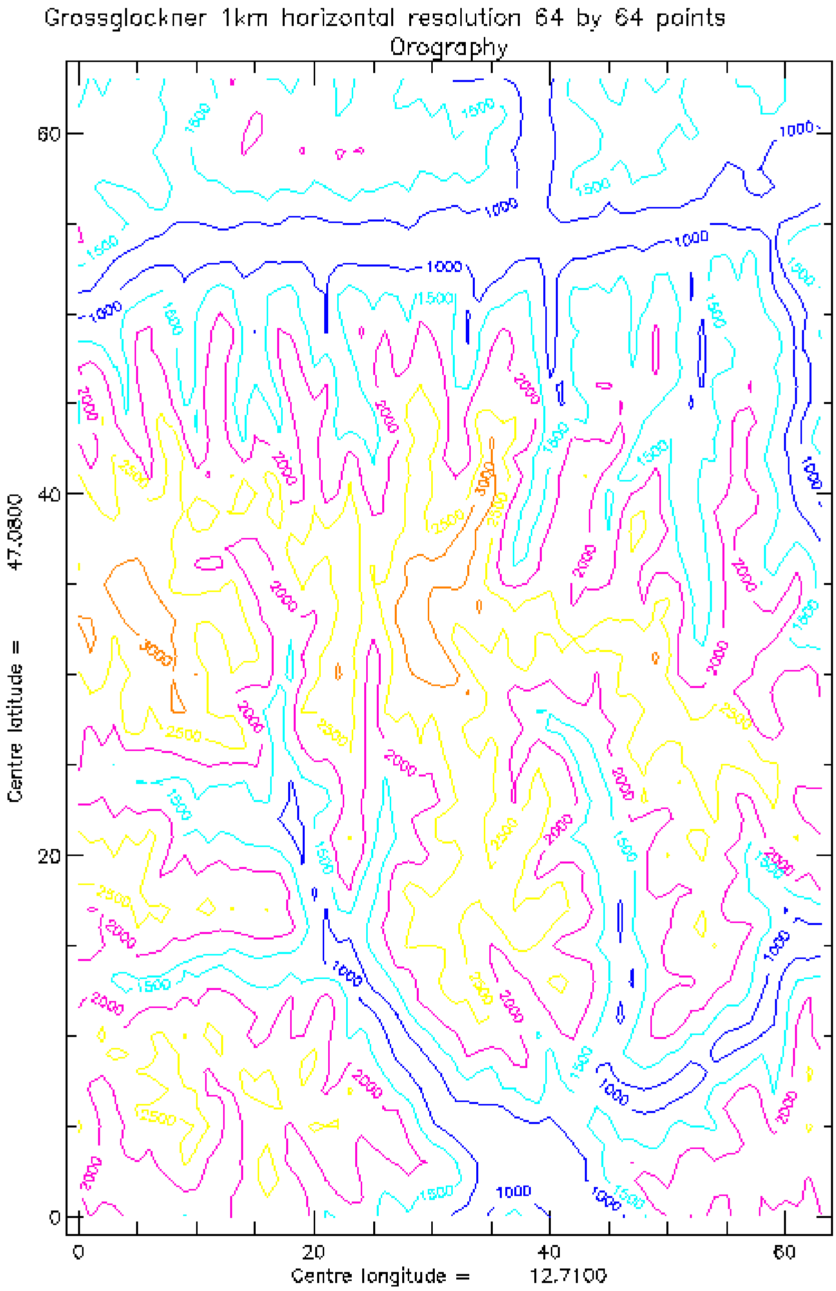

Figure B.2 The 1-km resolution orography for Grossglockner. The domain is centred at (47.08^{O}N,12.71^{O}E).

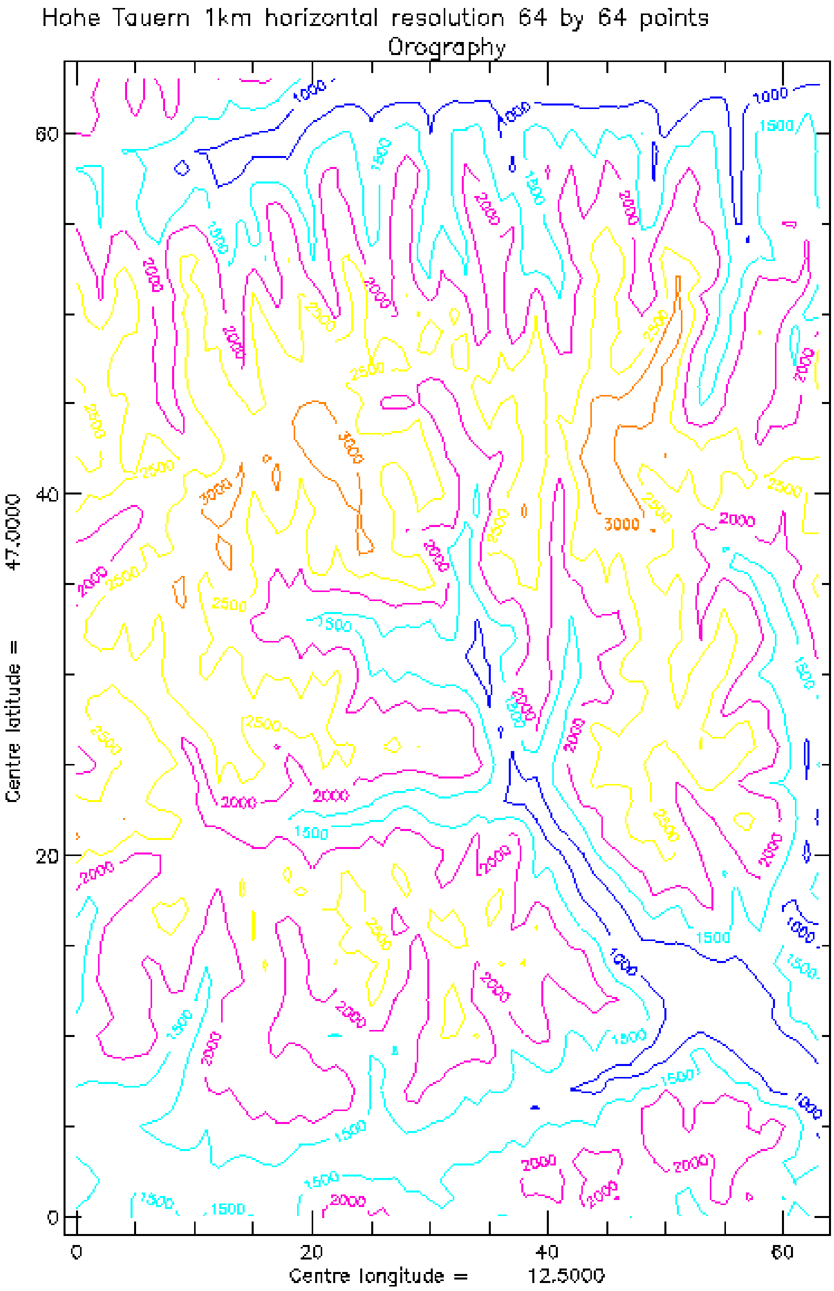

Figure B.3 The 1-km resolution orography for Hohe Tauern. The domain is centred at (47.00^ON,12.5^OE).

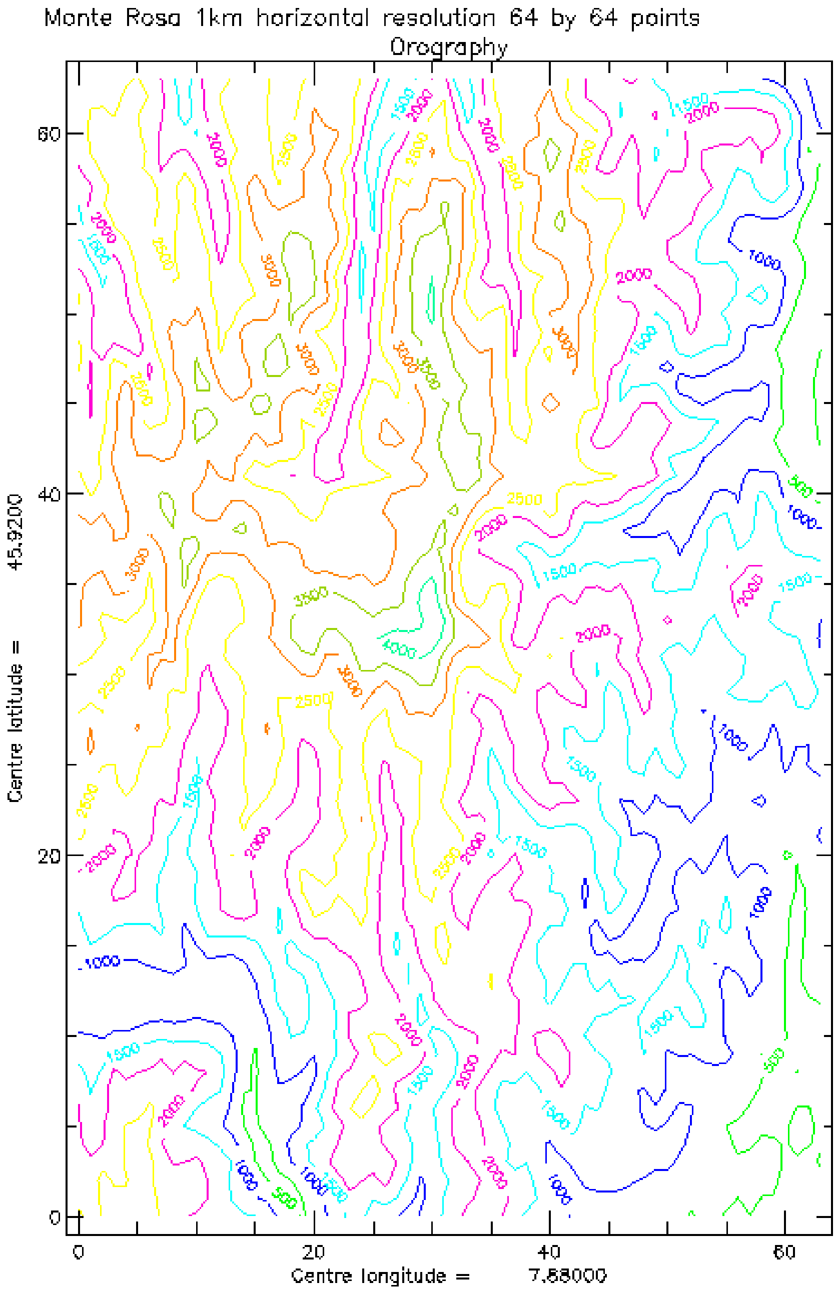

Figure B.4 The 1-km resolution orography for Monte Rosa. The domain is centred at (45.92^{O}N,7.88^{O}E).

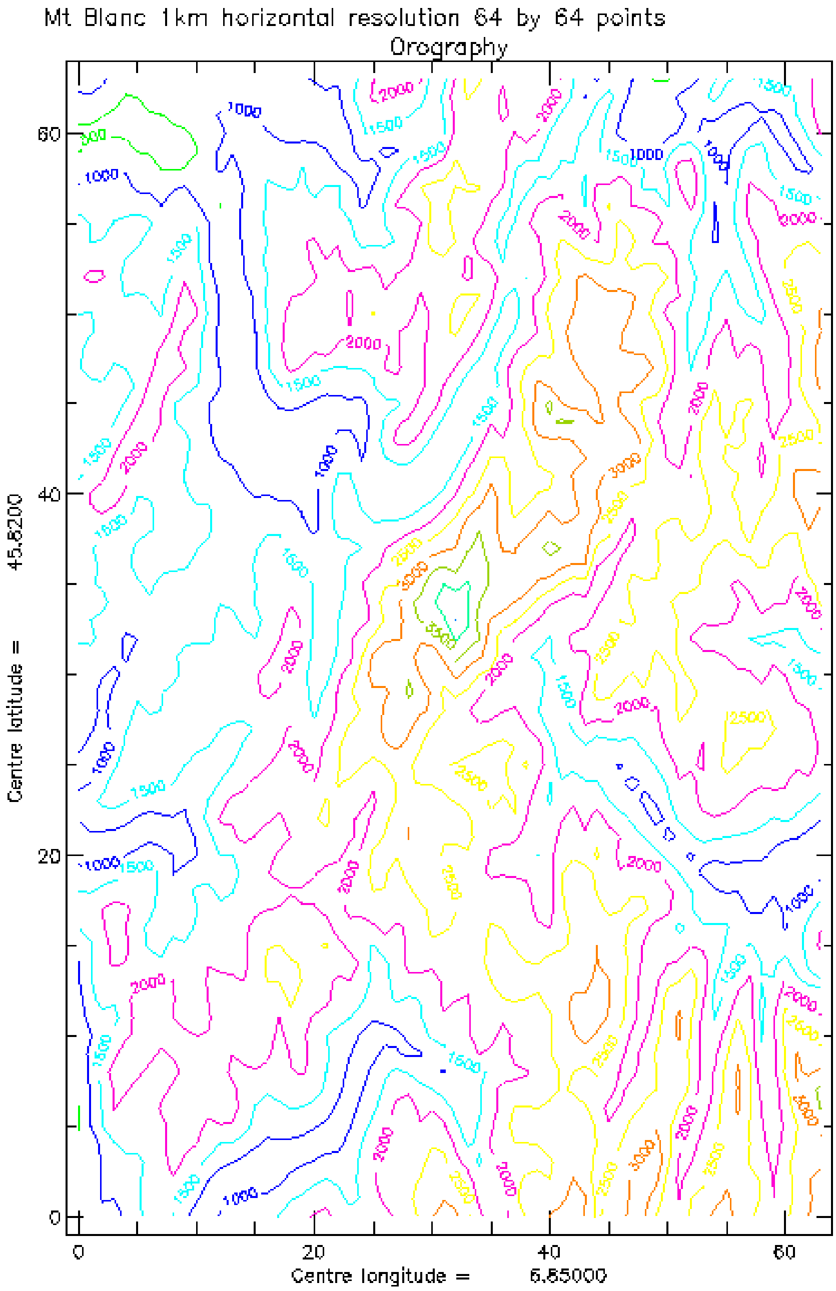

Figure B.5 The 1-km resolution orography for Mont Blanc. The domain is centred at (45.82^{O}N,6.85^{O}E).

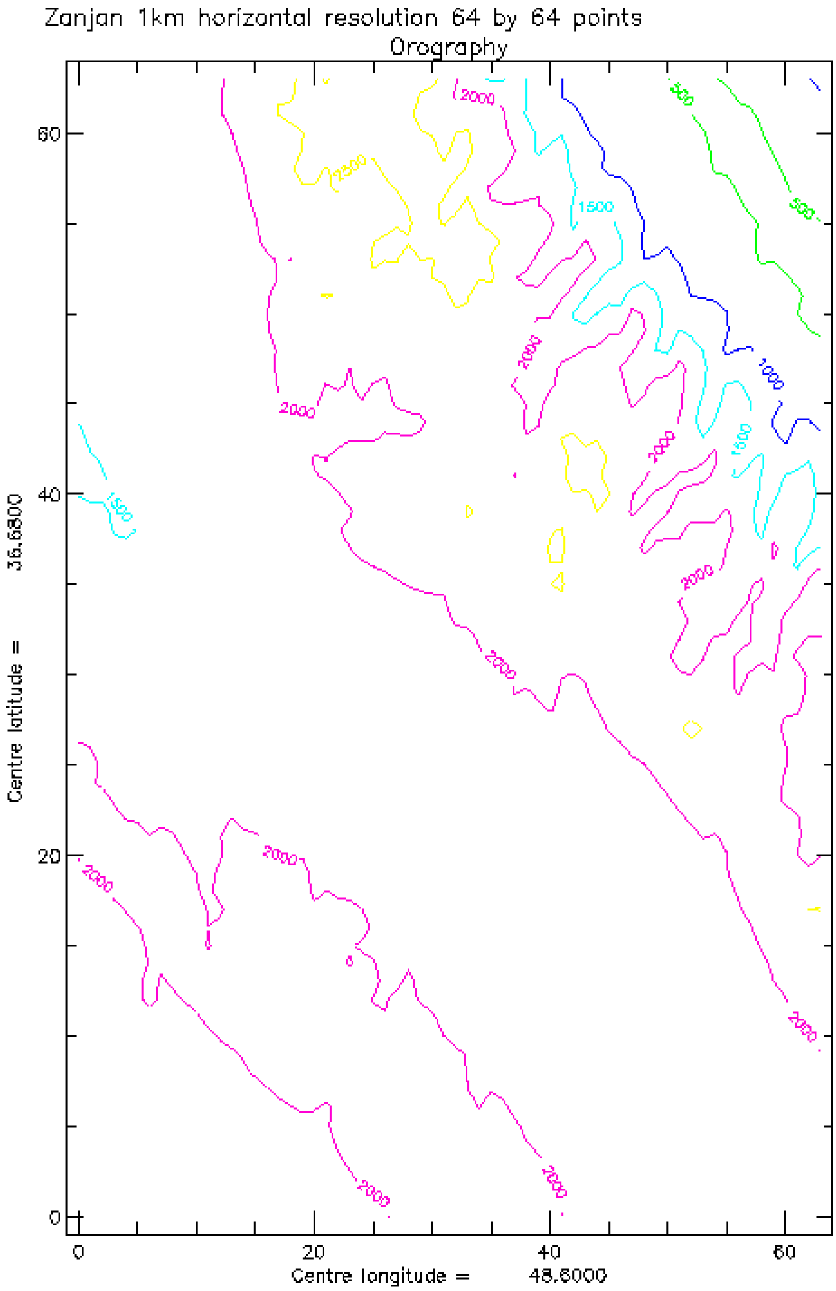

Figure B.6 The 1-km resolution orography for Zanjan. The domain is centred at (36.68^{O}N,48.60^{O}E).

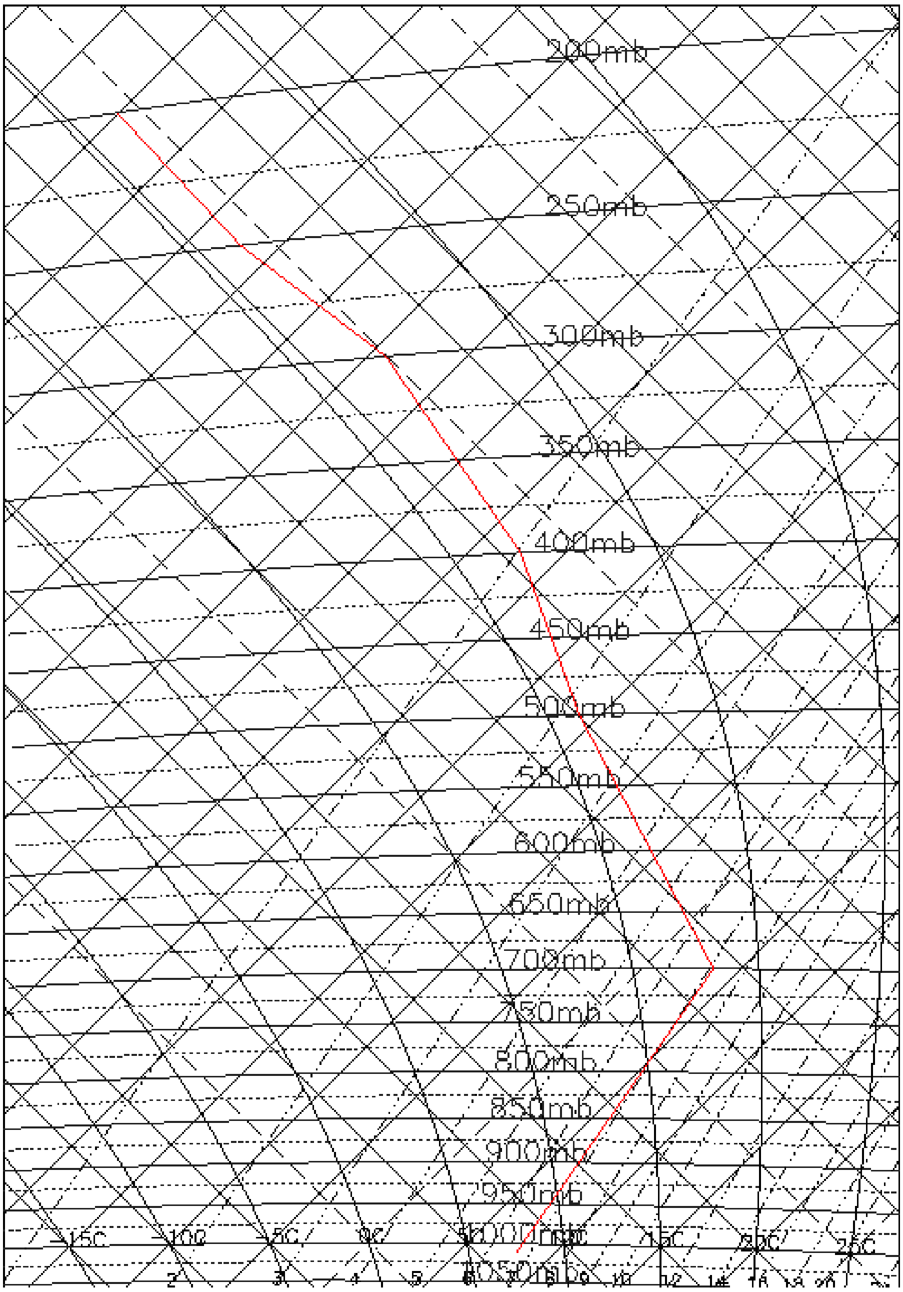

Figure C.1 The tephigram for Lankaran at 0000Z on 30/11/1989 showing near static stability reported by Lunnon (1992) to lie between 210 hPa and 425 hPa. Lankaran, WMO radiosonde station 37985 is the closest to Zanjan.