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Taihoro Nukurangi

Methods and software for the prediction of clear air turbulence generated by mountain waves

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1 Introduction

This document describes the methods and software developed to help predict clear air turbulence (CAT) generated by large-amplitude mountain waves. These waves and the associated turbulence are particularly prevalent in the NZ region because of the country's rugged topography and the strength of the prevaling westerly winds.

There are several simple methods in a variety of contexts for the prediction of of large-amplitude mountain-waves and associated CAT and other effects: [1] describes a scheme for the the prediction of wave amplitudes for glider pilots; [2] describes some general methods for aviation forecasting use; [3] describes one of the earliest attempts to parameterise the effects of breaking mountain waves on the evolution of the large-scale flow within general circulation models; and [4] discuss forecast guidance from explicit modelling of waves and turbulence over the US. These methods all suffer from the simplifying assumptions made to overcome the complex (fractal) nature of real topography and the subtle variations in flow which real waves are sensitive to. For example, the grids in the models described in [3] are very coarse so that the sub-gridscale variations in the real orography have to be crudely parameterised; while the graphical technique in [1] cannot correctly take into account variations in the wind and buoyancy frequency which determine the propagation of waves away from the mountains in question.

Of course explicit, 3-dimensional modelling of flow of topography is possible but is very expensive in a computational sense, and so is not useful for forecasting over a reasonably wide domain. The work described in this report describes of a model of intermediate complexity which is suitable for routine, day-to-day use in a forecasting environment but which still captures the essential aspects of real topography and real wave propagation which are missing in simpler models. An early version of the algorithm is described in section 2, while the enhancements added for this study are outlined in sections 3 and 4. Section 5 describes some preliminary calculations made for the New Zealand region and in section 6 some conclusions and an outline for further improvements are presented. Details of the software package are given in section 7.

2 The ridge data and model

An algorithm for forecasting mountain-wave related turbulence in the stratosphere is described in [5]. The practicality of the scheme rests on the observation that much of the Earth's topography is organised into relatively long, narrow ridges and the assumption that it is simply the orientation, width and height of the ridges above the surrounding terrain which determines the wave response. In consequence, the first part of the algorithm is devoted to decomposing a global topography dataset into a (large) database of ridges, each with values for these three essential characteristics. Details of this process are given in [5]. Suffice to say that a section of this database for application in the New Zealand region has been kindly supplied by Dr. Julio T. Bacmeister. [1]

The second part of the algorithm in [5] determines the wave amplitude and turbulence (if any) directly above each ridge in the region of interest. The ridge height above the surrounding terrain determines the vertical displacement of the wave field immediately above it, and then hydrostatic wave theory and the conservation of wave momentum flux is applied to obtain the wave amplitudes at progressively higher levels. If at any stage the wave amplitude exceeds a saturation value which depends only on local values of the wind and buoyancy frequency, then the wave amplitude is scaled back to the saturation value and the loss in momentum flux is attributed to turbulent kinetic energy, a measure of CAT. Thus profiles of wave amplitude and CAT activity are calculated above each ridge.

The method has been used with some success to verify that turbulence observed on high-altitude flights of an ER2 aircraft during 'Ozone hole' experimental campaigns in the arctic and antarctic can be related to topography beneath the flight track ([5]; J. Bacmeister, pers. comm., 1995). Limitations of the wave propagation and saturation scheme have become ap-

[1] E.O Hulburt Center for Space Research, Naval Research Laboratory, Washington DC.

parent however: the hydrostatic wave approximation means that there can be no propagation of waves or turbulence upstream or downstream from the ridge location; and recent work shows that the saturation amplitude for waves is not independent of wave parameters but instead depends in a non-linear fashion on wave frequency and wavelength [6],[7]. The ray-tracing model described in the next section is used with the ridge database to overcome these deficiencies.

3 The ray-tracing model

3.1 Background

The 3-dimensional, non-hydrostatic, ray-tracing model of gravity wave propagation used in this report is described in excruciating detail in [6]. In essence the ray-tracing formalism applies to situations in which the wave response sufficiently far from a complex, localised disturbance (such as generated by flow over rugged terrain) can be described by the propagation of a single, monochromatic wavetrain through a 'slowly-varying' background flow (one in which variations occur on a scale much larger than the wavelengths of the wavetrain in question).

3.2 Ray paths and wave amplitudes

The output from the ray-tracer is a path showing the propagation of the wave away from the wave-source, the refraction of the wave by the background wind and buoyancy frequency field, and the variation in wave amplitude as it responds to the decreasing density and various physical processes (such as radiative and turbulent damping). The 3-dimensional, non-hydrostatic nature of the model means that it can accommodate waves which do not propagate purely vertically, and waves with short periods and small horizontal wavelengths which are ignored by many wave propagation models. In short the model is ideal for studying the complete spectrum of waves generated by flow over real topography, and the interested reader is referred to [6] for more details.

3.3 Wave momentum flux and turbulence measures

A new feature of the ray-tracing model implemented for this study is the calculation of the momentum flux associated with each wave. This makes use of an elegant formula in [8] which is extremely convenient given the internal workings of the ray-tracing model [6]. It relates the vertical fluxes of horizontal momentum to the wavevector:

$$(\phi_x, \phi_y) = \rho(\overline{u'w'}, \overline{v'w'}) = AC_{g_z}(k, l) \tag{1}$$

where (k, l) is the horizontal wavevector, ρ the background density, C_{g_z} is the vertical group velocity, and A is the wave activity, defined as the wave energy divided by the doppler shifted frequency. A measure of the turbulent kinetic energy then calculated using a generalisation of the formula in [5]:

$$KE_{turb} \propto |\frac{\partial}{\partial z}(\phi_x, \phi_y)| \tag{2}$$

4 Initialising the ray-tracing calculations

4.1 Outline of method

This section describes how the ridge database is used to initialise the ray-tracing calculations to study CAT generation in the NZ region.

For each ridge within the region of interest, the program interpolates the background wind and buoyancy frequency fields to the longitude, latitude and altitude of the ridgetop, and with these crucial parameters proceeds to calculate the range of total horizontal wavenumbers K_{tot} for which internal gravity waves can propagate. (The waves are assumed to be steady with crests parallel to the ridge). Once this range has been obtained it is split into 5 parts and the amplitude of each component is determined assuming the ridge is Gaussian in shape with a height and characteristic width given by the values in the ridge database. The horizontal wavevector, the wave frequency (zero for stationary waves), and the wave amplitude are then passed to the ray-tracing program for integration.

4.2 Mathematical details

4.2.1 Determining range of propagating waves

Using the notation in [6] propagating waves require

$$m_m^2 \leq m^2 = \frac{K_{tot}{}^2(N^2 - \beta^2 K_{tot}{}^2)}{\beta^2 K_{tot}{}^2 - f^2} - \alpha^2 \tag{3}$$

where m_m is a minimum vertical wavenumber which can be accurately represented within the numerical code, and β is the component of the horizontal wind perpendicular to the ridge crest $(u, v, 0).(k, l, 0) = \beta K_{tot}$. If $\beta^2 {K_{tot}}^2 - f^2 > 0$ this can be rearranged into

$$0 \geq \beta^4 {K_{tot}}^4 + (\alpha^2\beta^2 - N^2){K_{tot}}^2 - f^2(\alpha^2 + m_m^2) \quad (4)$$

If K_{TOT}^2 is the largest positive real root for ${K_{tot}}^2$ from this equation then the range of permitted waves clearly lies in the range

$$(\sqrt{f^2/\beta^2}, \sqrt{K_{TOT}^2}) \quad (5)$$

4.2.2 Determining amplitude of each propagating component

The range of propagating waves obtained in the previous sub-section is divided into 5 representative waves whose amplitudes are determined in the following way. If x denotes a physical coordinate across the ridge and the ridge height is given by

$$h(x) = H_0 \exp(-x^2/L^2) \quad (6)$$

then the Fourier transform is simply [9]

$$\hat{h}(k) = \frac{H_0 L\sqrt{\pi}}{2} \exp(-k^2L^2/4) \quad (7)$$

The amplitude of the wave component is then determined from the linearised boundary condition on $z = 0$

$$w' = \frac{d}{d}h(x) = -\imath\omega^+\hat{h} \quad (8)$$

Here $\omega^+ = \omega - (u, v).(k, l)$ is the Doppler shifted frequency of the wave, and w' is the wave vertical velocity which is related in a simple way via the dispersion relations (e.g. [10]) to the RMS horizontal wave velocity used in the ray-tracing program.

5 Some preliminary calculations for NZ

5.1 Background data

The background fields for these calculations are based on 6-hourly analyses for two days in October 1994 from the Global Analysis and Prediction system

(GASP) at the Bureau of Meteorology in Melbourne, Australia (e.g. [11]). The data have been interpolated from the original global analyses spanning a vertical range from the surface to 10hPa with an R53 spectral resolution in the horizontal and 19 layers in the vertical, to fields on a regular longitude - latitude - altitude grid with a resolution of 2°in the horizontal and 1km in the vertical. The fields used in the ray-tracer are temperature, horizontal wind components, and pressure.

5.2 Experimental procedure

The ray initialisation process described in the above section is applied to each analysis, and the parameters so obtained are passed to the ray-tracer for integration. Horizontal and vertical projections of the resulting ray-paths for the first and last analyses in the sequence are shown in the figures.

5.3 Results

Fig.1 shows the ray paths and regions of potential turbulence for 05Z on 24th October 1994. The first feature to note is the area of strong turbulence at low levels over the central North Island. The mountain ridges of the South Island appear to generate turbulence at low levels but the waves then continue to propagate away from the land-mass to give turbulence in the stratosphere both upstream and downstream from the source of the waves.

The situation six hours later is shown in fig.2. Wave and turbulent activity at lower levels has weakened over both islands as the flow changes, with fewer waves reaching upper levels from the South Island as the wind has strengthened aloft, curtailing wave propagation from below (see [6] for a discussion of this filtering effect).

Fig.3 shows that six hours later at 17Z on 24th October 1994 turbulence has increased dramatically in the troposphere over the South Island while wave propagation over the North Island has all but ceased.

At the end of the two day period at 23Z on 25th October 1994, the situation has reversed, with strong turbulent activity having built up at low levels over the ridges of the central North Island and East Cape, with remaining wave activity propagating out into the Bay of Plenty. In contrast to the situation 30 hours previously, there is virtually no wave activity at all over the South Island at this time (fig.4).

6 Conclusions and further work

The methods and software described in this document clearly shows that the prediction of turbulence associated with mountain waves is possible without sacrificing the subtleties inherent in a correct treatment of wave propagation and without resorting to a complex, computationally expensive numerical model. Significantly upstream and downstream propagation from real topography is possible, opening the possibility that turbulence observed over the oceans at upper levels, which may be thought to be caused by intense marine convection [12] or by shear instability in tropospheric jet streams [13], may in fact be generated by flow over distant mountains. In addition, the software has demonstrated the possibility of CAT prediction in the troposphere, not just at the rarefied heights of the stratosphere as in [5].

Before becoming part of an operational suite however, the methods and techniques presented here clearly need more careful validation against aircraft observations of in-flight turbulence, and work along these lines is planned in the near future with colleagues from the Naval Research Laboratory (NRL) in Washington D.C.

There is another slightly unsatisfactory aspect to the work presented here. The amplitude calculation within the ray-tracer assumes that a single, monochromatic wave is present whereas in reality a Gaussian or any other ridge sets off a host of wave components whose initial amplitude depends on the precise shape of the ridge in question. We have thus assumed here that of the set of five rays initialised for each ridge only one will dominate at a distance from the ridge so that the ray-tracing, amplitude and hence turbulence calculations for this dominant wave will be valid.

Because work is underway at NRL to develop a sophisticated wave initialisation scheme from experiments with a complex 3d numerical model of flow over orography, the method described here will not be developed further. It does however demonstrate the improvements that a sophisticated ray-tracing algorithm will add to the mountain wave model when compared to the purely hydrostatic, vertical wave propagation algorithm used in the first version of the model described in [5]. In addition, the software developed here will form the basis for any future work.

7 Software

The software and data described here are all part of the `grograt V2.6` release which has been archived in directory `/usr/local/grograt` on the NIWA machine `thor`. Look at the `README` file that comes with the distribution for further pointers to information on how to install and run the software.

7.1 Ridge database

The ridge database for the NZ region was kindly supplied by Julio Bacmeister. It is a simple text file with the name `nz_ridges.dat` It covers a range from 120 to 180 °in longitude and -55 to -25°in latitude. For details on its construction, see [5].

7.2 Ray initialisation

The algorithm described in section 4 to initialise the ray-tracing calculations with ridge data is implemented within program `gwrdge` which is now part of the `grograt V2.6` package. The output of this program is a `.ray_in` file containing the initial position and wave parameters for waves which are allowed to propagate from each ridge.

7.3 Ray-integrations

The ray integrations are carried out by the program `grograt` which reads in the background data and a `.ray_ini` file described above. The ray paths are written to a `.ray_paths` file.

7.4 Plotting software

The `grograt V2.6` release is written in reasonably standard FORTRAN77 and will thus run on many machines, but the software to produce the plots described in this document is at present highly machine specific and is not part of the general release. The `ray_paths` files are simple ascii files so that it is relatively easy to write programs to display the rays in the manner shown.

8 Acknowledgements

The work would not have been possible without the collaboration of Dr.s Julio Bacmeister and Steve Eckermann at the Naval Research Laboratory in Washington DC.

9 Figure captions

Fig.1 Ray paths for 05Z 24th October 1994 generated by the ridge initialisation scheme described in the text. a) shows the rays in horizontal projection, b) shows them in in a latitude-altitude projection, with a simplified representation of the silhouette of NZ orography shown in black. The ray-paths are in green with areas of likely turbulence highlighted with a red star whose size is determined by (2). The blue contours are of wind speed at the 6km level in a) and at 172°east in b).

Fig.2 As in Fig.1 but for 11Z 24th October 1994.

Fig.3 As in Fig.1 but for 17Z 24th October 1994.

Fig.4 As in Fig.1 but for 23Z 25th October 1994.

10 References

References

[1] P. Knudsen. A simple mountain wave model. Techical Note 1, N.Z Meteorlogical Service, 1990.

[2] R.H. Hopkins. Forecasting techniques of clear-air turbulence including that associated with mountain waves. Technical Note 155, World Meteorological Organisation, 1977.

[3] T.N. Palmer, G. Shutts, and R. Swinbank. Alleviation of a systematic westerly bias in general circulation and numerical weather prediction models through an orographic gravity wave drag parameterisation. *Quart. J. Roy. Meteor. Soc.*, 112:1001–1040, 1986.

[4] J. Bocchieri. Probability forecasts of clear-air turbulence for the contiguous us. Technical procedures bulletin 430, National weather Service, 1996.

[5] J. T. Bacmeister, P. A. Newmann, B. L. Gary, and K. R. Chan. An algorithm for forecasting mountain-wave related turbulence. *Weather and Forecasting*, 9:241–253, 1994.

[6] C. J. Marks and S. D. Eckermann. A three-dimensional non-hydrostatic ray-tracing model for gravity waves: formulation and preliminary results for the middle atmosphere. *J. Atmos. Sci.*, 52:1959–1984, 1995.

[7] D.C Fritts and K. Rastogi. Convective and dynamical instabilities due to gravity wave motions in the lower and middle atmosphere. *J. Radio Sci.*, 20:1247–1277, 1985.

[8] F. Bretherton. The propagation of groups of internal gravity waves in a shear flow. *Quart. J. Roy. Meteor. Soc.*, 92:466–480, 1966.

[9] M. Spiegel. *Mathematical handbook.* Schaum's Outline Series, 1968.

[10] E.E. Gossard and W.H. Hooke. *Waves in the atmosphere.* Elsevier, 456pp., 1975.

[11] W.P Bourke. Review of the performance of the Bureau of Meteorology global assimilation and prediction system. In *Proceedings of the 6th BMRC modelling workshop: Data assimilation in meteorology and oceanography.*, 1994.

[12] M. J. Alexander and L. Pfister. Gravity wave momentum flux in the lower stratosphere over convection. *Geophys. Res. Lett.*, 22:2029–2032, 1995.

[13] B. Sutherland and W. Peltier. Internal gravity wave emission into the middle atmosphere from a model tropospheric jet. *J. Atmos. Sci.*, 52:3214–, 1995.

1a

32 WKB breaks down in z-direction
31 Ray stalls vertically -5
30 Ray stalls vertically -5
29 Wave dissipated 5
28 Ray stalls vertically -5
27 Ray stalls vertically -5
26 Ray stalls vertically -5
25 Ray stalls vertically -5
24 Ray stalls vertically -5
23 Ray stalls vertically -5
22 Ray stalls vertically -5
21 Ray stalls vertically -5
20 Ray stalls vertically -5
19 Ray stalls vertically -5
18 Ray stalls vertically -5
17 WKB breaks down in z-direction
16 Wave dissipated 5
15 Ray stalls vertically -5
14 Ray stalls vertically -5
13 Wave dissipated 5
12 Ray stalls vertically -5
11 Ray stalls vertically -5
10 Wave dissipated 5
9 Ray stalls vertically -5
8 Ray stalls vertically -5
7 Ray stalls vertically -5
6 Ray stalls vertically -5
5 WKB breaks down in z-direction -4
4 Ray stalls vertically -5
3 Ray stalls vertically -5
2 WKB breaks down in z-direction
1 WKB breaks down in z-direction

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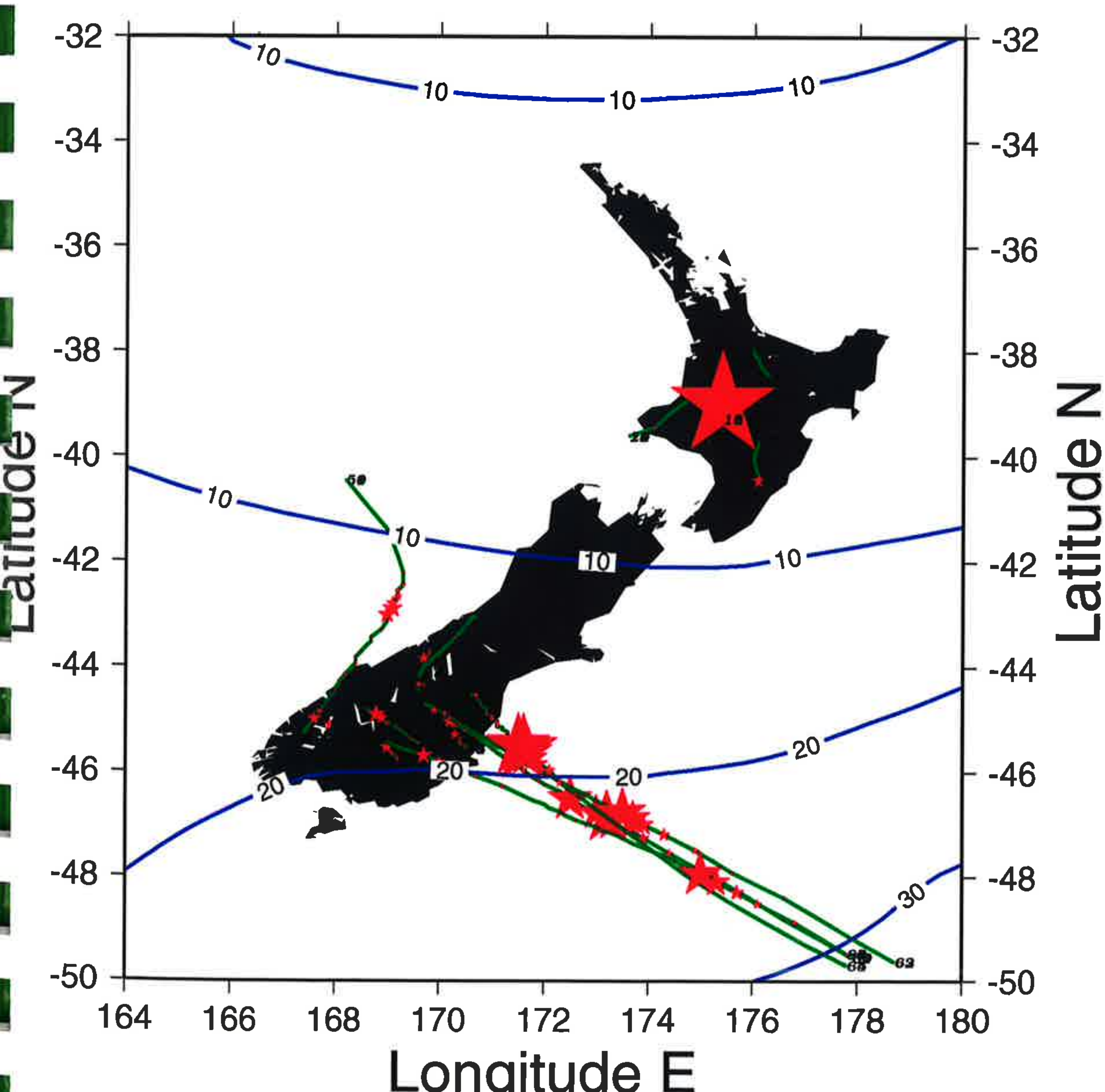
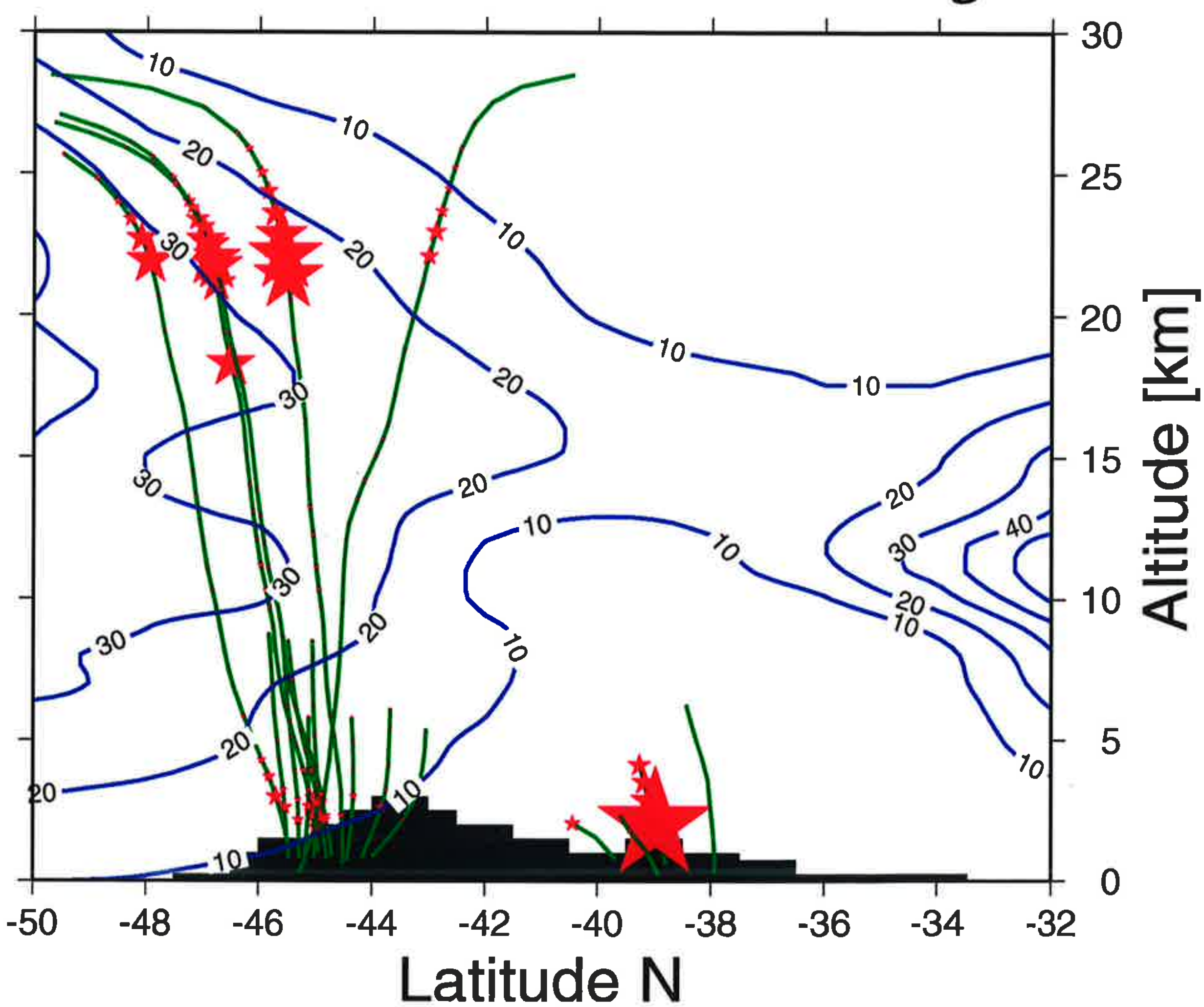


(1b)

85 WKB breaks down in z-direction -4
84 Ray stalls vertically -5
83 Ray stalls vertically -5
82 Ray stalls vertically -5
81 Wave outside latitude range 5
80 Ray stalls vertically -5
79 WKB breaks down in z-direction -
78 Ray stalls vertically -5
77 Ray stalls vertically -5
76 WKB breaks down in z-direction -
75 Ray stalls vertically -5
74 Ray stalls vertically -5
73 WKB breaks down in z-direction -
72 Ray stalls vertically -5
71 Ray stalls vertically -5
70 Ray stalls vertically -5
69 WKB breaks down in z-direction -
68 Ray stalls vertically -5
67 WKB breaks down in z-direction -
66 Ray stalls vertically -5
65 WKB breaks down in z-direction -4
64 WKB breaks down in z-direction -
63 Wave outside latitude range 5
62 Ray stalls vertically -5
61 Wave outside latitude range 5
60 Ray stalls vertically -5
59 Wave outside latitude range 5
58 Ray stalls vertically -5
57 Ray stalls vertically -5
56 Ray stalls vertically -5
55 Ray stalls vertically -5
54 Ray stalls vertically -5
53 Ray stalls vertically -5
52 Ray stalls vertically -5
51 WKB breaks down in z-direction -
50 Ray stalls vertically -5
49 Wave dissipated 3
48 Ray stalls vertically -5
47 Ray stalls vertically -5
46 Ray stalls vertically -5
45 Ray stalls vertically -5
44 Wave dissipated 3
43 Ray stalls vertically -5
42 Ray stalls vertically -5
41 Ray stalls vertically -5
40 Ray stalls vertically -5
39 WKB breaks down in z-direction -
38 Ray stalls vertically -5
37 Ray stalls vertically -5
36 WKB breaks down in z-direction -
35 Ray stalls vertically -5
34 Ray stalls vertically -5
33 Ray stalls vertically -5
32 WKB breaks down in z-direction -
31 Ray stalls vertically -5
30 Ray stalls vertically -5
29 Wave dissipated 3
28 Ray stalls vertically -5
27 Ray stalls vertically -5
26 Ray stalls vertically -5
25 Ray stalls vertically -5
24 Ray stalls vertically -5
23 Ray stalls vertically -5
22 Ray stalls vertically -5
21 Ray stalls vertically -5
20 Ray stalls vertically -5
19 Ray stalls vertically -5
18 Ray stalls vertically -5
17 WKB breaks down in z-direction -
16 Wave dissipated 3
15 Ray stalls vertically -5
14 Ray stalls vertically -5
13 Wave dissipated 3
12 Ray stalls vertically -5
11 Ray stalls vertically -5
10 Wave dissipated 3
9 Ray stalls vertically -5
8 Ray stalls vertically -5
7 Ray stalls vertically -5
6 Ray stalls vertically -5
5 WKB breaks down in z-direction -4
4 Ray stalls vertically -5
3 Ray stalls vertically -5
2 WKB breaks down in z-direction -4
1 WKB breaks down in z-direction -4

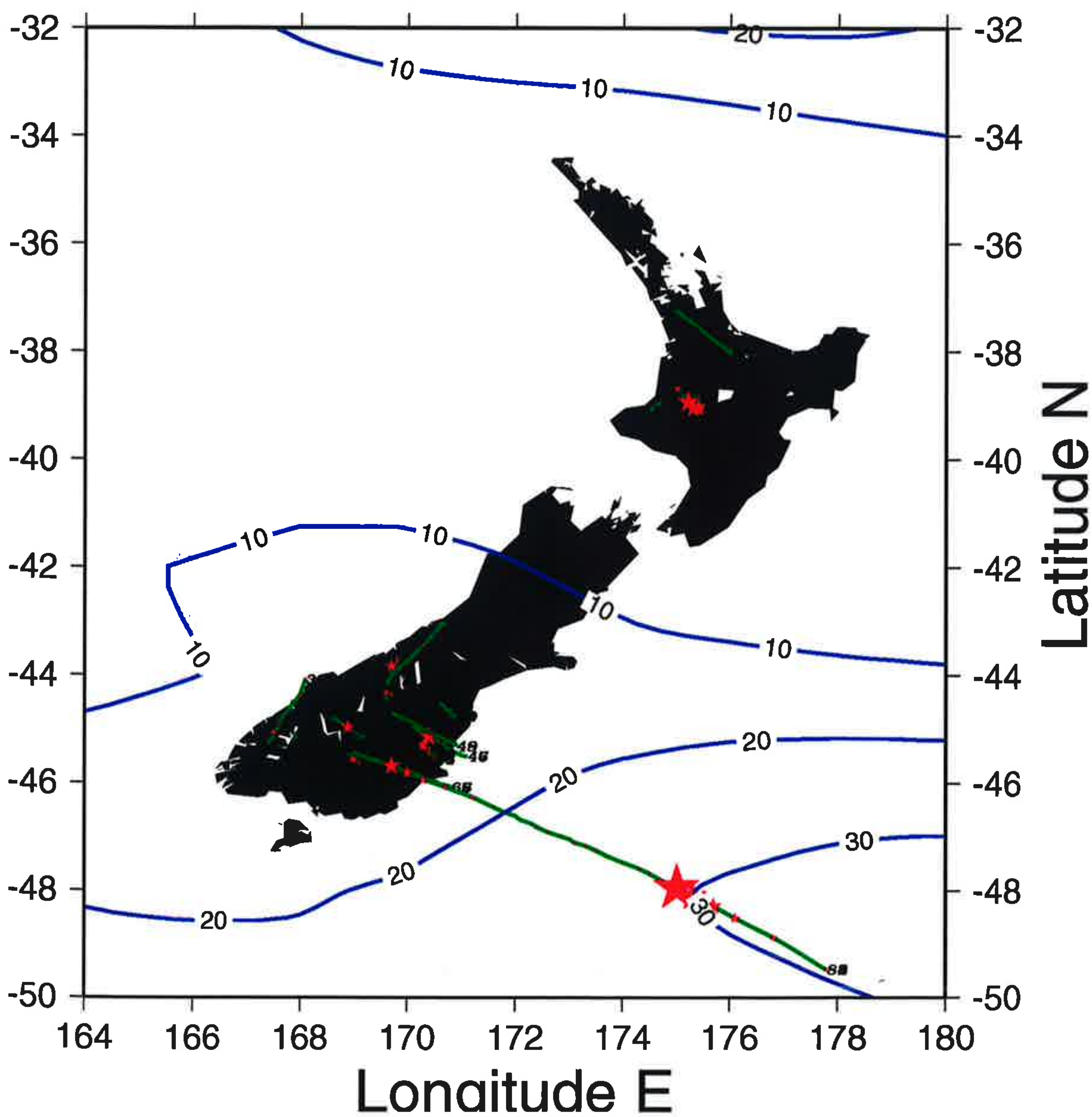
nz94102405.ws 172.0E Ridges



(2a)

32 Ray stalls vertically -5
31 Ray stalls vertically -5
30 WKB breaks down in z-direction -4
29 Ray stalls vertically -5
28 Ray stalls vertically -5
27 Ray stalls vertically -5
26 Ray stalls vertically -5
25 WKB breaks down in z-direction -4
24 Ray stalls vertically -5
23 Ray stalls vertically -5
22 Ray stalls vertically -5
21 Wave dissipated 3
20 WKB breaks down in z-direction -4
19 WKB breaks down in x-direction
18 Ray stalls vertically -5
17 Ray stalls vertically -5
16 Ray stalls vertically -5
15 Ray stalls vertically -5
14 WKB breaks down in x-direction
13 WKB breaks down in x-direction
12 Wave dissipated 3
11 Ray stalls vertically -5
10 WKB breaks down in z-direction -4
9 Ray stalls vertically 5
8 Ray stalls vertically 5
7 WKB breaks down in x-direction -
6 Ray stalls vertically 5
5 WKB breaks down in z-direction -4
4 WKB breaks down in x-direction -
3 Ray stalls vertically -5
2 Wave dissipated 3
1 WKB breaks down in x-direction -

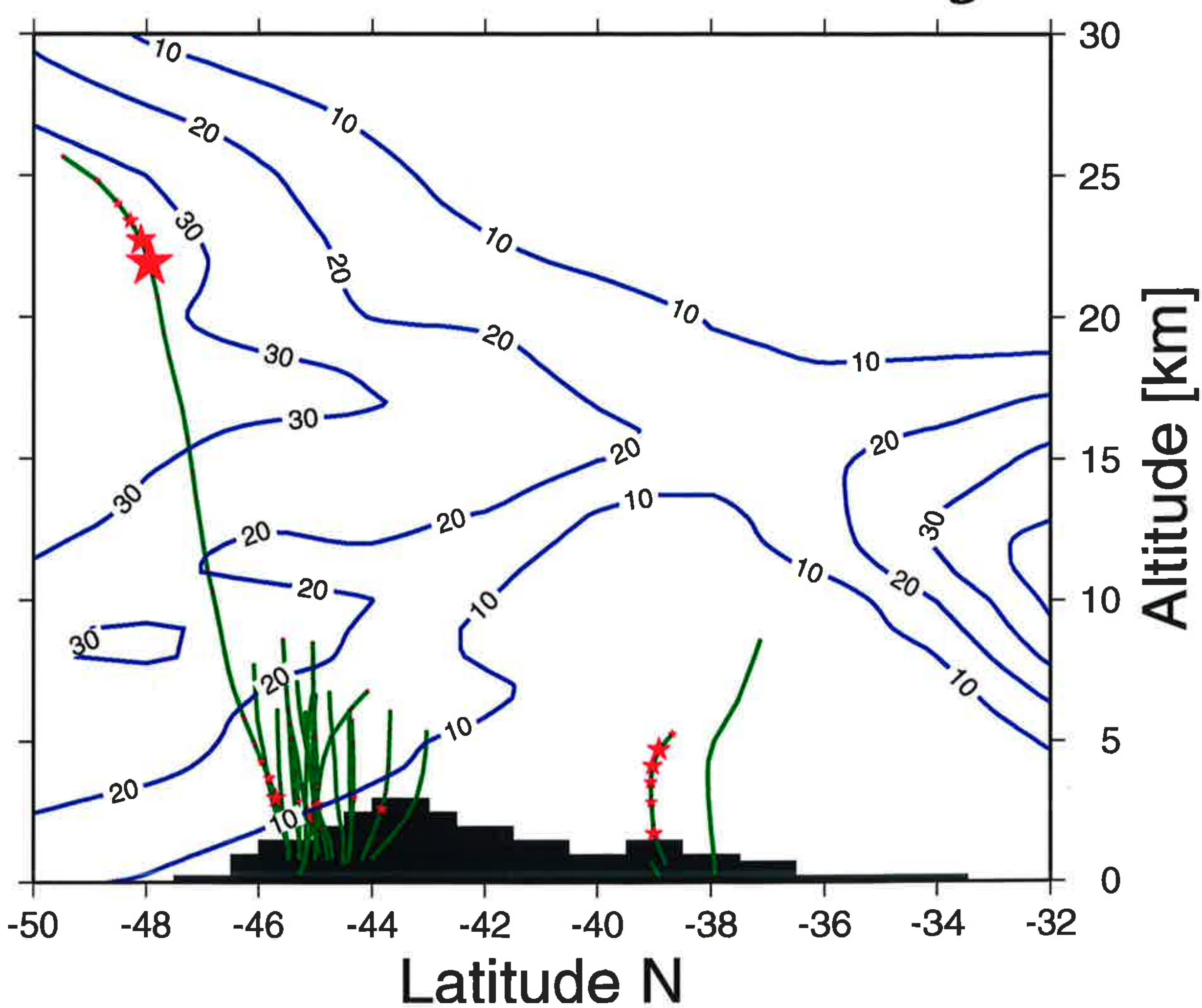
nz94102411.ws   6.0km   Ridges



2b

85 WKB breaks down in x-direction -4
84 Ray stalls vertically -5
83 Ray stalls vertically -5
82 Ray stalls vertically -5
81 Wave outside latitude range 5
80 Ray stalls vertically -5
79 WKB breaks down in x-direction -
78 Ray stalls vertically -5
77 Ray stalls vertically -5
76 WKB breaks down in x-direction -
75 Ray stalls vertically -5
74 Ray stalls vertically -5
73 WKB breaks down in x-direction -
72 Ray stalls vertically -5
71 Ray stalls vertically -5
70 Ray stalls vertically -5
69 WKB breaks down in x-direction -
68 Ray stalls vertically -5
67 Ray stalls vertically -5
66 Ray stalls vertically -5
65 WKB breaks down in x-direction -4
64 Ray stalls vertically -5
63 WKB breaks down in x-direction -
62 Ray stalls vertically -5
61 WKB breaks down in x-direction -
60 Ray stalls vertically -5
59 Ray stalls vertically -5
58 WKB breaks down in x-direction -
57 WKB breaks down in x-direction -
56 WKB breaks down in x-direction -
55 Ray stalls vertically -5
54 Ray stalls vertically -5
53 WKB breaks down in x-direction -
52 Ray stalls vertically -5
51 WKB breaks down in x-direction -
50 WKB breaks down in x-direction -4
49 WKB breaks down in x-direction -
48 Ray stalls vertically -5
47 WKB breaks down in x-direction -
46 Ray stalls vertically -5
45 WKB breaks down in x-direction -4
44 Ray stalls vertically -5
43 Ray stalls vertically -5
42 Ray stalls vertically -5
41 WKB breaks down in x-direction -
40 Ray stalls vertically -5
39 WKB breaks down in x-direction -
38 WKB breaks down in x-direction -
37 WKB breaks down in x-direction -
36 Ray stalls vertically -5
35 Ray stalls vertically -5
34 Ray stalls vertically -5
33 WKB breaks down in x-direction -
32 Ray stalls vertically -5
31 Ray stalls vertically -5
30 WKB breaks down in x-direction -4
29 Ray stalls vertically -5
28 Ray stalls vertically -5
27 Ray stalls vertically -5
26 Ray stalls vertically -5
25 WKB breaks down in x-direction -4
24 Ray stalls vertically -5
23 Ray stalls vertically -5
22 Ray stalls vertically -5
21 Wave dissipated 3
20 WKB breaks down in x-direction -4
19 WKB breaks down in x-direction -
18 Ray stalls vertically -5
17 Ray stalls vertically -5
16 Ray stalls vertically -5
15 Ray stalls vertically -5
14 WKB breaks down in x-direction -
13 WKB breaks down in x-direction -
12 Wave dissipated 3
11 Ray stalls vertically -5
10 WKB breaks down in x-direction -4
9 Ray stalls vertically -5
8 Ray stalls vertically -5
7 WKB breaks down in x-direction -4
6 Ray stalls vertically -5
5 WKB breaks down in x-direction -4
4 WKB breaks down in x-direction -4
3 Ray stalls vertically -5
2 Wave dissipated 3
1 WKB breaks down in x-direction -4

nz94102411.ws 172.0E Ridges



32 Ray stalls vertically -5
31 WKB breaks down in x-direction
30 Ray stalls vertically -5
29 WKB breaks down in x-direction
28 WKB breaks down in x-direction
27 Ray stalls vertically -5
26 Ray stalls vertically -5
25 Ray stalls vertically -5
24 WKB breaks down in x-direction
23 Ray stalls vertically -5
22 WKB breaks down in x-direction
21 Wave dissipated 5
20 WKB breaks down in x-direction -4
19 WKB breaks down in x-direction
18 WKB breaks down in x-direction
17 WKB breaks down in x-direction
16 WKB breaks down in x-direction
15 Ray stalls vertically -5
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13 WKB breaks down in x-direction
12 WKB breaks down in x-direction
11 Ray stalls vertically -5
10 WKB breaks down in x-direction -4
9 Wave dissipated 5
8 Ray stalls vertically -5
7 Ray stalls vertically -5
6 WKB breaks down in x-direction -
5 WKB breaks down in x-direction -4
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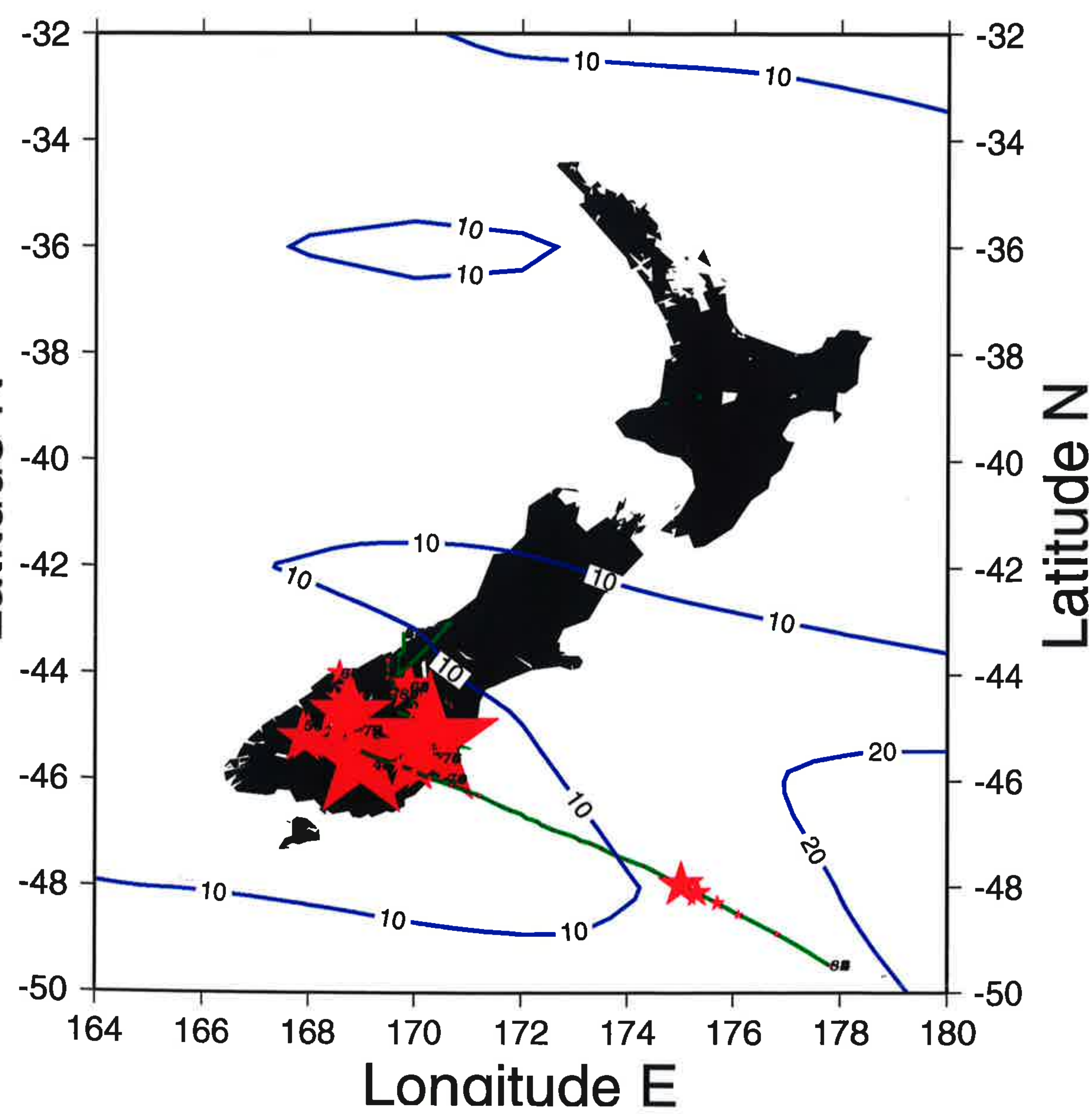
3a

nz94102417.ws 6.0km Ridges



3b

85 WKB breaks down in z-direction -4
84 Ray stalls vertically -5
83 Ray stalls vertically 5
82 Ray stalls vertically -5
81 Wave outside latitude range 5
80 Ray stalls vertically -5
79 WKB breaks down in z-direction -
78 Ray stalls vertically 5
77 Ray stalls vertically 5
76 WKB breaks down in z-direction -
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73 WKB breaks down in z-direction -
72 Ray stalls vertically -5
71 WKB breaks down in z-direction -
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69 WKB breaks down in z-direction -
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60 Ray stalls vertically 5
59 Ray stalls vertically -5
58 Ray stalls vertically -5
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56 Ray stalls vertically 5
55 Ray passed stop= 30.0km 0
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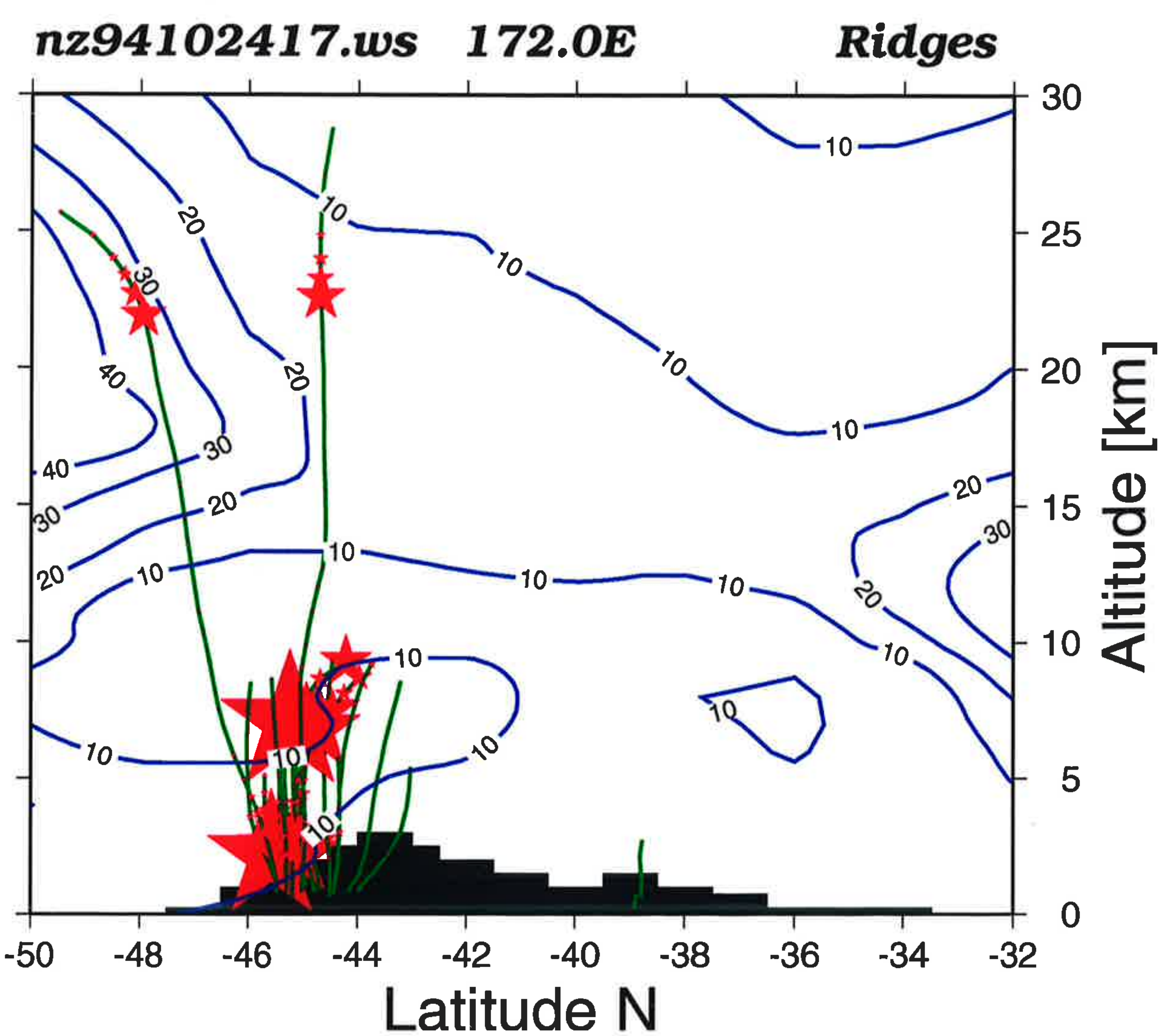
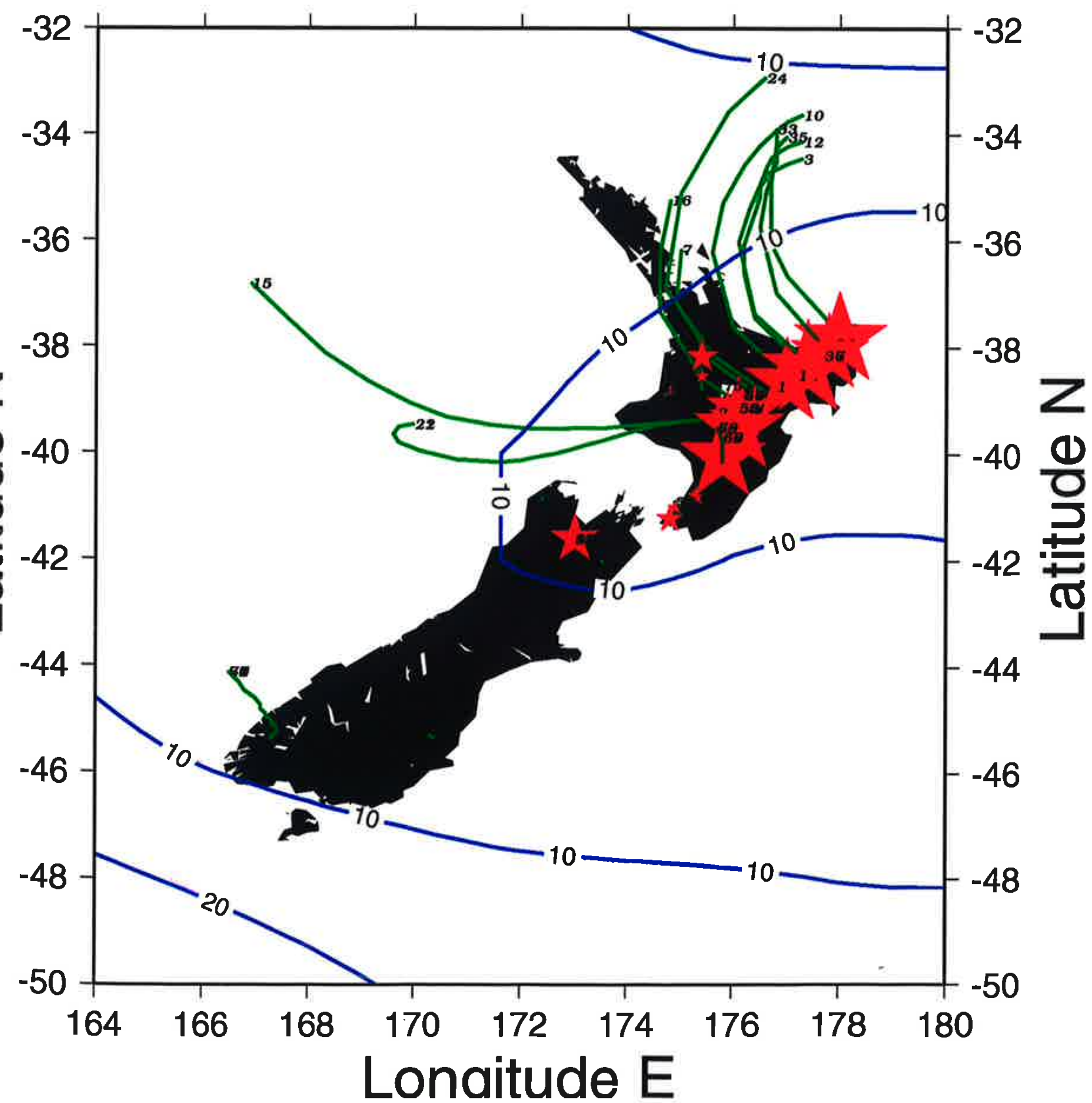
30 Ray stalls vertically -5
29 WKB breaks down in z-direction -
28 WKB breaks down in z-direction -
27 Ray stalls vertically 5
26 Ray stalls vertically -5
25 Ray stalls vertically 5
24 WKB breaks down in z-direction -
23 Ray stalls vertically -5
22 WKB breaks down in z-direction -
21 Wave dissipated 5
20 WKB breaks down in z-direction -4
19 WKB breaks down in z-direction -
18 WKB breaks down in z-direction -
17 WKB breaks down in z-direction -
16 WKB breaks down in z-direction -
15 Ray stalls vertically -5
14 WKB breaks down in z-direction -
13 WKB breaks down in z-direction -
12 WKB breaks down in z-direction -
11 Ray stalls vertically -5
10 WKB breaks down in z-direction -4
9 Wave dissipated 5
8 Ray stalls vertically -5
7 Ray stalls vertically -5
6 WKB breaks down in z-direction -4
5 WKB breaks down in z-direction -4
4 WKB breaks down in z-direction -4
3 Ray stalls vertically -5
2 WKB breaks down in z-direction -4
1 WKB breaks down in z-direction -4



4a

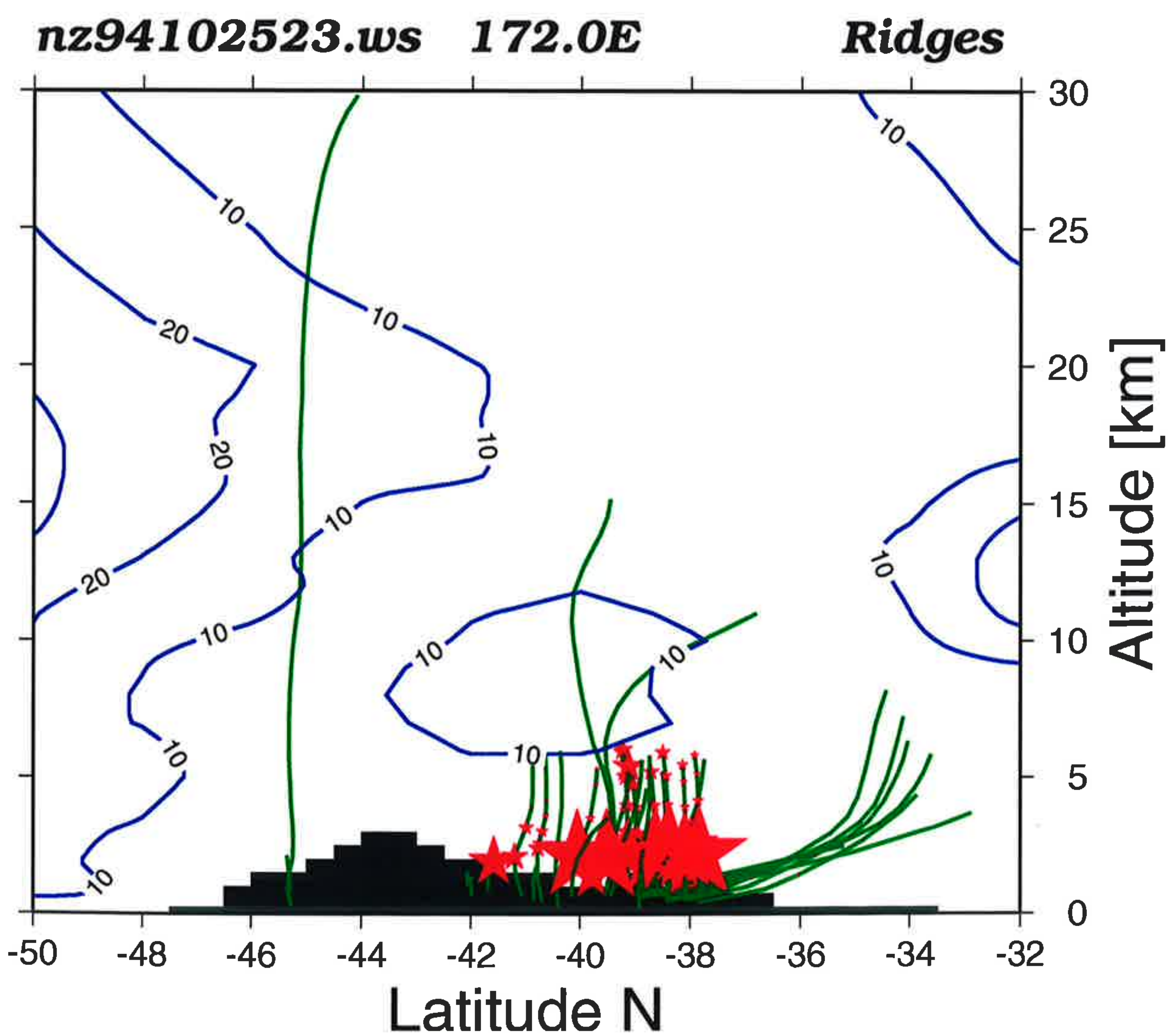
32 Time limit expires 9
31 WKB breaks down in x-direction
30 WKB breaks down in x-direction -4
29 Ray stalls vertically -5
28 WKB breaks down in x-direction
27 Ray stalls vertically -5
26 WKB breaks down in x-direction
25 Ray stalls vertically -5
24 WKB breaks down in x-direction
23 Wave dissipated 3
22 WKB breaks down in x-direction
21 Ray stalls vertically -5
20 Time limit expires 9
19 Ray stalls vertically -5
18 WKB breaks down in x-direction
17 Ray stalls vertically 5
16 WKB breaks down in x-direction
15 Wave dissipated 3
14 Time limit expires 9
13 Ray stalls vertically 5
12 WKB breaks down in x-direction
11 Time limit expires 9
10 WKB breaks down in x-direction -4
9 Time limit expires 9
8 Ray stalls vertically 5
7 WKB breaks down in x-direction -
6 Wave dissipated 3
5 WKB breaks down in x-direction -4
4 Ray stalls vertically 5
3 WKB breaks down in x-direction -
2 Time limit expires 9
1 WKB breaks down in x-direction -

nz94102523.ws 6.0km Ridges



4b ~~3b~~

87 Ray stalls vertically -5
86 Ray stalls vertically -5
85 Ray stalls vertically -5
84 Ray stalls vertically -5
83 Ray stalls vertically -5
82 Wave dissipated 3
81 Ray stalls vertically -5
80 Wave dissipated 3
79 Ray stalls vertically -5
78 Ray stalls vertically -5
77 Wave dissipated 3
76 Ray stalls vertically -5
75 Wave dissipated 3
74 Ray stalls vertically -5
73 Ray stalls vertically -5
72 Ray stalls vertically -5
71 WKB breaks down in z-direction -4
70 Wave dissipated 3
69 WKB breaks down in z-direction -4
68 Ray stalls vertically -5
67 WKB breaks down in z-direction -4
66 WKB breaks down in z-direction -4
65 WKB breaks down in z-direction -4
64 Ray stalls vertically -5
63 Ray stalls vertically -5
62 Ray stalls vertically -5
61 WKB breaks down in z-direction -4
60 Ray passed stop= 30.0km 0
59 Ray stalls vertically -5
58 Ray stalls vertically -5
57 WKB breaks down in z-direction -4
56 WKB breaks down in z-direction -4
55 Ray stalls vertically -5
54 WKB breaks down in z-direction -4
53 Ray stalls vertically -5
52 WKB breaks down in z-direction -4
51 Ray stalls vertically -5
50 WKB breaks down in z-direction -4
49 Ray stalls vertically -5
48 Ray stalls vertically -5
47 Ray stalls vertically -5
46 WKB breaks down in z-direction -4
45 Ray stalls vertically -5
44 Ray stalls vertically -5
43 Wave dissipated 3
42 Ray stalls vertically -5
41 Ray stalls vertically -5
40 Ray stalls vertically -5
39 Ray stalls vertically -5
38 Ray stalls vertically -5
37 Wave dissipated 3
36 Ray stalls vertically -5
35 WKB breaks down in z-direction -4
34 Time limit expires 9
33 WKB breaks down in z-direction -4
32 Time limit expires 9
31 WKB breaks down in z-direction -4
30 WKB breaks down in z-direction -4
29 Ray stalls vertically -5
28 WKB breaks down in z-direction -4
27 Ray stalls vertically -5
26 WKB breaks down in z-direction -4
25 Ray stalls vertically -5
24 WKB breaks down in z-direction -4
23 Wave dissipated 3
22 WKB breaks down in z-direction -4
21 Ray stalls vertically -5
20 Time limit expires 9
19 Ray stalls vertically -5
18 WKB breaks down in z-direction -4
17 Ray stalls vertically -5
16 WKB breaks down in z-direction -4
15 Wave dissipated 3
14 Time limit expires 9
13 Ray stalls vertically -5
12 WKB breaks down in z-direction -4
11 Time limit expires 9
10 WKB breaks down in z-direction -4
9 Time limit expires 9
8 Ray stalls vertically -5
7 WKB breaks down in z-direction -4
6 Wave dissipated 3
5 WKB breaks down in z-direction -4
4 Ray stalls vertically -5
3 WKB breaks down in z-direction -4
2 Time limit expires 9
1 WKB breaks down in z-direction -4



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