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CONFIDENTIAL

Ash predictions, how successful were they?

A W Hurst
B J Scott

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Ash predictions, how successful were they?

by

A.W. Hurst, B.J. Scott

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EXECUTIVE SUMMARY

The ASHFALL computer program was developed as a quick and easy way of forecasting the amount of ash expected at points around a volcano, if the volcano had an eruption of a certain size, and there was a particular wind pattern. The program used a simplified model of the transport of ash particles, so that a Personal Computer could carry out the calculations in a few minutes. The primary purpose of this program was for Civil Defence applications in volcanic crises, with a secondary aim of volcanic hazard assessment. The program was completed and a report published in 1994 (Hurst, 1994).

During the latter part of the 1995 Ruapehu eruption, and the whole of the 1996 eruption, this program was used to provide ash forecasts. These were maps of the likely ash distribution if Ruapehu had an small ash-producing eruption within the next 24 hours, based on the wind forecasts provided by the Meteorological Service. These were provided to the national and local Civil Defence organisations, and a number of other interested organisations.

This study was done to investigate two aspects of these forecasts, were they accurate, and were they providing the information required by those affected by the eruption.

The analysis of the accuracy of the forecasts shows a good agreement between the forecasts and the actual ash distribution, as reported in (Cronin et. al., 1997, 1998). The main source of error regarding where ash will land is in the wind direction. In other words, if the wind direction forecast is accurate, the ash distribution forecast will also be accurate. The forecast and observed ash distributions could be matched together with ash thickness errors less than a factor of two. This is actually much less than the unavoidable errors in estimating the size of an eruption as it occurs, so there is no real point in trying to get closer agreement. In other words, the ASHFALL model is adequate for its main purpose.

A questionnaire circulated to user organisations found that the form of the supplied ash forecasts was basically what was wanted by these organisations. We discovered a very high level of secondary and tertiary distribution of these forecasts, and the maps need some changes in format to make them easier to read after multiple faxing and copying. Otherwise these forecasts seemed to provide the clients with the information they needed, in as timely a fashion as can be expected with the resources available.

Two scientific papers have been prepared on work partly or wholly funded by this contract. A popular article to publicise these ash forecasts will be published in *Tephra*. Restructuring of the former Ministry of Civil Defence meant that the article was not able to be produced during the period of the contract.

ABSTRACT

The program ASHFALL was developed to enable the rapid calculation of the ashfall from a volcanic eruption, primarily for Civil Defence purposes when an eruption is either thought to be imminent, or is actually underway. It could also be used for the estimation of volcanic hazards and for studies of past eruptions, by calculating the ash distributions produced by a range of possible eruptions, under various likely wind conditions.

During the 1995 and 1996 eruptions of Ruapehu, the program was used to provide forecasts of where ash was likely to travel if a significant eruption occurred, based on forecast wind patterns. For the three significant eruptions that occurred during this period, this note looks at the performance of this program, compared to available information on the ash distribution, and looks at the main sources of error.

For the question of most interest to Civil Defence authorities, namely will a certain area receive any ash at all, the error in the forecast wind direction is by far the most important. If the forecast wind direction is correct, ASHFALL gives a good indication of where ash will fall. The quantity of ash falling downwind is a function more of the size of the eruption, and it is difficult to give more than an order of magnitude estimate of this at the time of the eruption. However, analysis following the 1995 and 1996 eruptions of Ruapehu, when the eruption volumes could be derived from measured ash thicknesses, showed that the ash thickness at any point was generally within a factor of two of that forecast by ASHFALL.

A questionnaire was circulated to 48 organisations who had received ashfall predictions in 1995 and 1996, the response rate was 79%. There was overall a high degree of satisfaction with the information provided. The format of the information was generally found to be satisfactory, although there were requests for bolder lines to outline the area of possible ashfall on the map. This was so the information could still be clearly read after multiple copying and faxing during the distribution process.

1. INTRODUCTION

In 1994 GNS released the program ASHFALL (Hurst, 1994) to produce rapid assessments of the likely ash distribution from a volcanic eruption, given an expected wind pattern, primarily for Civil Defence and related purposes when an eruption is either thought to be imminent, or is actually underway. It could also be used for the estimation of volcanic hazards and for studies of past eruptions, by calculating the ash distributions produced by a range of possible eruptions, under various likely wind conditions.

During the 1995 and 1996 eruptions of Ruapehu, the program was used to provide forecasts of where ash was likely to travel if a significant eruption occurred, based on forecast wind patterns.

This contract was to look at two aspects of the success of these ash predictions, firstly did the ash fall where it was predicted to fall, and secondly, did the predictions tell the end-users what they wanted to know. From the first part of this contract, to evaluate how well the ASHFALL program predicted the actual ash distribution, two scientific papers have been produced. Both of these papers are currently being internally reviewed before submission to a journal, and therefore pre-prints are attached to this report. They are "Performance of a Program for Volcanic Ashfall Forecasting", by A.W. Hurst, which directly arises out of this contract, whilst "Numerical simulations of volcanic ashfall dispersal from the Ruapehu eruptions of 1995 and 1996", R. Turner and A.W. Hurst, combines a NIWA project with this study. It was also intended to produce a more popular article, in a publication like *Tephra*, produced by the Ministry of Civil Defence. Because of restructuring of that Ministry, the article had to be put on hold until the future of *Tephra* was confirmed. At a meeting with the new Director of Emergency Management and Civil Defence on 26 June 1998, it was agreed that it was appropriate to put an article on ash forecasting in an issue of *Tephra* which would be produced in 1998/99. Because of the considerable delay caused by restructuring, we have not been able to include a draft of the proposed article in this report, but will forward it later.

For the three significant ash eruptions of Ruapehu during 1995/96, other workers produced maps of the ash distributions observed on the ground. This gave the opportunity to look at the performance of the ASHFALL program in forecasting the ash distribution, compared to the actual ash distribution, and also to look at the main sources of error. The actual circulation of ash forecasts based on ASHFALL only started on 17 October 1995, after the main ash eruptions of the 1995 sequence. The main reason for this delay was that the first author was sidelined by injuries from a plane crash on 24 September 1995 for the rest of the September-October 1995 eruptions. Accordingly, the analysis of the 1995 eruptions is on the basis of notional forecasts, i.e. the ash forecasts that would have been given by ASHFALL if it had been in use.

The main method used to investigate the second issue, the client satisfaction with the ash forecasts, was a questionnaire (see Appendix 1) which was distributed to 48 user organisations in December 1997. Thirty-eight responses were received, giving a very good response rate of 79%.

Since the draft papers relating to the performance of ASHFALL for forecasting ash distribution are attached, this report basically summarises this part of the study, although it does contain more illustrative examples of forecast ash distributions, and some notes on ground observations of the limits of the area affected by ash.

1.1 Volcanic Hazards

An erupting volcano is hazardous in a number of ways. Lava, poisonous gases and large ejected bombs are mainly a hazard near the erupting crater, although it must be remembered that secondary eruptions of lava from sources on the side of the volcano are common on some volcanoes such as Etna. Hot pyroclastic flows can be produced from directed blasts, or the collapse of an eruption column. Depending on the size of a volcano, these can be the most significant hazard for distances of the order of 10 kilometres. Lahars are a major hazard if there are large quantities of water present on a volcano, such as volcanoes with crater lakes or snow-caps. They can easily be a major hazard 30 to 50 kilometres from a volcano, but will be limited to certain areas, usually river valleys. The most widespread hazard is volcanic ash, the small (less than 4 millimetres diameter) air-borne particles from the volcano's eruption column.

Volcanic ash is a major hazard to life and property from moderate to large volcanic eruptions. Even small quantities of ash can produce considerable inconvenience, with one or two millimetres having the potential to contaminate water supplies, and a few centimetres can cause disruption to agriculture and transport. A thick fall of ash can be a major hazard to life, predominantly by the collapse of buildings under the weight of ash. About 30 centimetres thickness of wet ash, or one metre thickness of dry ash, can cause structures to collapse.

The area at risk of serious ashfall from a volcanic eruption depends on both the characteristics of the eruption and the winds blowing at the time. For estimates of ashfall hazard to be useful in an emergency, they must be able to be produced quickly, with easily available resources. The program ASHFALL was produced for this purpose (Hurst, 1994).

1.2 Program ASHFALL

The code of ASHFALL was based on work by G Macedonio, M T Pareschi and P Armienti of the University of Pisa, Italy (Armienti et al. 1988, Macedonio et al., 1988, 1990), related to their studies of historic eruptions, especially the A.D. 79 eruption of Vesuvius. They produced a program for accurate calculation of 3-dimensional particle diffusion in ash clouds, together with a simpler and quicker 2-dimensional diffusion program, in which only the horizontal diffusion of ash was considered, and in which there was only a single wind direction, although the wind speed could vary with height.

By combining features from these two programs, ASHFALL was produced, as a simple and fast program to predict where ash would fall, given a volcanic eruption of a particular size, and a wind strength and direction that could vary with altitude and time. The logic of the original program had to be significantly rewritten to allow for the interaction of changing winds while the ash particles were still airborne. ASHFALL can also deal with multiple eruptions in one run, either a continuing eruption at a single site, or even an eruption developing over an extended source, as occurred in the 1886 Tarawera eruption.

2. ASHFALL PROCESSES

A volcanic eruption distributes ash over large distances through the incorporation of solid ash particles in an eruption column containing turbulent hot gases, which are buoyant because of their high temperature. Driven by their initial velocity and their buoyancy, these gases eventually reach an altitude at which their density equals that of the surrounding air. Above this height the gases are heavier than the surrounding air, so they lose momentum and the upward velocity decreases, becoming zero at the top of the column. In nearly windless conditions, this leads to a "mushroom" eruption column. A more usual case has the top of the column blown sideways by the wind, with ash raining out of this sideways plume, with larger ash particles falling faster than small particles.

A number of factors influence the expected ashfall thickness distribution. The main factors relating to the volcanic eruption are the eruption column position and height, the total erupted mass and the fraction of ash of different sizes. Since ash particles generally have similar densities, the particle size is the main factor controlling the rate at which ash particles fall under gravity. The main meteorological factor is the wind direction and velocity. This will normally vary considerably with height, between ground level and the top of the eruption column, and may also vary with time during the eruption, as well as varying over the length of the ash plume.

The ash distribution within the eruption column is the result of complex thermodynamic processes, but it is clear that once the ash cloud has left the vicinity of the volcano, the ash distribution is predominantly controlled by wind dispersal and gravitational settling (Holasek et al, 1996). In other words, the volcanic processes produce an initial 3-dimensional ash distribution, but as soon as the ash leaves the eruption column volcanological factors are no longer important.

Since any new eruption is most likely to be at an existing volcano, the position of the base of the eruption column is likely to be known fairly accurately. At present, measurements of the height of the eruption column rely on visual observations from the ground or from aircraft, or on satellite pictures. This means that at night or in bad weather, we may not have a good estimate of height. GNS is working with Professor G. Austin (University of Auckland), to develop an X-Band radar which may be able to image the eruption column in all weather conditions.

For most volcanic eruptions, the other two "volcanic" parameters, the total erupted mass and the particle size distribution, are not likely to be known before the eruption is over. It is often necessary to use estimates of a likely eruption size from previous eruptions of the volcano, either from earlier eruptions in the sequence, or from the historic/geological record of the volcano. Once an eruption starts, and if the eruption column can be seen, some idea of the total erupted mass can be obtained from the observed strong positive correlation of eruption column height with the total size of the eruption (Carey & Sigurdsson 1989). The ash size distribution is not likely to be known until the ash has landed, which is obviously too late to be useful. Therefore in any practical case, an ash size distribution derived from previous eruptions of the same volcano, or other eruptions with similar characteristics, will have to be used. The ash distribution from the Vesuvius eruption of A.D. 79 (Macedonio et al., 1990), was used in the studies here, after increasing the number of settling velocity classes from 9 to 37 to give a smoother distribution (Table 1). Most of the ash had settling velocity between 0.5 and 2.0 metres/s. This gave reasonable results, and it was clear that the overall ash distribution for ranges of the order of 10 to 500 kilometres was fairly insensitive to changes in the particle size distribution. Different ash size distributions affect what proportion of the ash is found at each distance from the volcano, but have little effect on which areas get any ash, apart from the furthest distance reached by the ash cloud, which depends on the smallest ash particles present. Carey & Sigurdsson (1982), suggested that smaller particles tend to aggregate to produce particles with a settling velocity of about 0.3 m/sec. For a 10 km high column, this corresponds to a fall time of

10 hours, so for a typical wind velocity of 20 m/sec, the ash will extend about 700 km downwind from the volcano.

Table 1

Settling Velocity Fractions used for Ashfall

Velocity m/sec	Mass Fraction	Velocity m/sec	Mass Fraction
0.30	.001	0.90	.015
0.32	.002	0.95	.015
0.34	.003	1.0	.025
0.36	.004	1.1	.03
0.38	.005	1.2	.04
0.40	.006	1.4	.04
0.43	.006	1.55	.04
0.46	.007	1.7	.04
0.49	.008	1.85	.04
0.52	.009	2.0	.05
0.55	.010	2.2	.05
0.58	.011	2.4	.05
0.61	.012	2.7	.05
0.65	.013	3.0	.05
0.69	.013	4.0	.11
0.73	.013	5.0	.07
0.77	.014	7.0	.04
0.81	.014	9.0	.08
0.85	.014		

2.1 Wind Direction & Velocity

Balloon soundings of winds are taken every 12 hours at a number of locations around New Zealand, including Kataia, Paraparaumu, New Plymouth, and Gisborne. The soundings generally report winds up to an altitude of 20 km. The data from these soundings are assimilated into large global numerical weather prediction models operating at International Weather Forecasting Centre. The forecasts from these global models are then used to drive regional scale ("mesoscale") models to produce more detailed forecasts for countries such as New Zealand. Forecasts of the wind versus altitude around Ruapehu, or any other appropriate volcano, are provided by the New Zealand Meteorological Service at least twice a day during periods of volcanic alert.

As an indication of the likely errors in these forecasts, Cox et. al., (1998) compared a number of mesoscale models. For the most successful one, RAMS, 12 hour forecasts had a wind direction error of less than 30° for 80% of the time, decreasing only slightly to 76% for 36 hour forecasts. This means that out of every five 12-hour forecasts, on average one of them would have an actual wind direction more than 30° different from that forecast, which would have fairly major effects on where volcanic ash would go.

3. DATA FROM 1995/96 RUAPEHU ERUPTIONS

Ruapehu Volcano erupted in late 1995 and in the middle of 1996. During this time, there were 3 significant ash-producing eruptions that produced a widely recorded distribution of ash that could be compared with predictions from the ASHFALL program. These events were on the 11th and 14th of October, 1995 and on 17 June 1996.

The most detailed studies of ash thicknesses currently available are the isopach (ash thickness) maps of Cronin et al, (1997,1998), based on measurements along roads, and information provided by farmers. The actual thickness measurements from which the maps in these publications were produced is currently being prepared for publication, and hence not available (Shane Cronin, pers. comm.).

The following information summarises the results of the attached paper "Performance of a Program for Volcanic Ashfall Forecasting", by A.W. Hurst, but with more diagrams than could be put into that paper.

For the two eruptions in October 1995, the top of the eruption column was reported as being approximately 10 kilometres above sea level, while the June 1996 eruption may have had a slightly lower eruption column. This is based on the top of that ash cloud being about 7 kilometres high, about 2 hours after the eruption. All three eruptions were small, each producing of the order of 0.01 km^3 of ash deposit. The attached paper contains more information on methods of estimating the total mass of ash produced in an eruption. The best method currently available is a method which assumes a relation between the height of the eruption column and the volume of the eruption. (Carey & Sigurdsson 1989).

The 11 October 1998 eruption occurred at night, from about 2100 until 0500 NZDT on 12 October (0900 to 1700 UT), and the ash cloud drifted north-east, over a very sparsely populated area. The ash deposits from this eruption are therefore not so well defined as the other two eruptions. Fig 1a (from Cronin et. al., 1997) shows the observed ash distribution. As already stated, an ash prediction was not made at the time for this eruption, but Fig 1b shows the results of the ASHFALL program using the 12 hour forecast for winds at Ruapehu at 0000 NZDT on 12 October. There is a broad similarity between the ash distributions, although the actual ash seemed to be more widely spread than expected, indicating a variable wind direction. This was because a wind change affected the ash before it landed. Fig 1c shows the effect of using the wind forecast for Ruapehu at 1200 NZDT on 12 October. Fig 1d is an adapted "forecast". This used the observed wind at New Plymouth, which showed a shift of about 35° clockwise between 0000 NZDT and 1200 NZDT on 12 October, and assuming that this wind shift affected the Ruapehu to East Cape area during the eruption, to give a rather better match with the actual ashfall. In other words, the ash was more widely distributed because the wind was changing between when the eruption started and when the last ash landed.

The 14 October 1998 eruption occurred during the day, starting at about 1600 NZDT (0300 UT), and the ash cloud travelled south-east, across the Desert Road and the Kaimamawa Range into more populated areas of Hawkes Bay. The actual ash distribution is shown in Fig 2a. Fig 2b shows the results from an ASHFALL simulation done at a later date, using the winds forecast at noon on 14 October. The ash distribution calculated with the observed wind from New Plymouth showed a much more extended ash plume than was observed, indicating that, as forecast, the wind strength tended to decrease from west to east.

The June 17 event was the main ash eruption of the 1996 Ruapehu eruption sequence. It was well observed, as it occurred during the day, in fine weather, and the southerly wind blew the ash over a comparatively populated area. Fig 3 shows the plume, as seen in visible light from a GOES satellite, at 0314 UT (1514 NZST) on June 17. The photo clearly shows that there is little ash near the Ruapehu, the result of a decline in ash emission about 1-2 hours earlier. This was correlated with a drop in the seismic tremor level of Ruapehu, shown in Fig 4, which also shows the tremor level for the two October 1995 eruptions. The ash plume starts to bend to the east after crossing the coast about 300 km from Ruapehu, this indicates a changing wind pattern with position that cannot be modelled in the current ASHFALL program, and indicates that proper mesoscale modelling would be needed for longer distances.

The most detailed map of the 17 June ash deposits currently available is that of Cronin et al., (1998), shown in Fig 5a, although detailed analysis of the deposit of ash of different grain sizes is still underway, (B.F. Houghton, pers. comm.). Figs 5b and 5c show the predictions from ASHFALL for two alternative models for the ash source, which both agree well with the main features of the ash deposit. The different heights of the eruption column (7 km for Fig 5b and 10 km for Fig 5c) do not make much difference to the expected ash distribution. Fig 6 shows the map included in "Ruapehu Ashfall - Prediction V96/02" that was released by GNS at 0930h NZST on 17 June 1996, i.e. about one hour after the eruption commenced. The outer contour on this map, corresponding to 1 mm ash thickness for a rather larger eruption (0.1 km^3), included virtually all the area of ashfall on 17 June. Fig 5a also includes an area of ash that travelled to the north-west on 18 June 1996, during a later phase of the eruption. At this time there was a south-westerly wind forecast for Ruapehu, although the very low level winds (below 1200 metres) at New Plymouth were in a south-easterly direction. It is likely that a rather small eruption column was putting ash into a wind pattern in which south-easterly (about 140°) winds were present at low levels rather than the 190° winds that were forecast.

This last very minor ashfall was the only time during the 1995/96 eruptions of Ruapehu when ash was deposited in an unexpected place at a significant distance from Ruapehu. In all other cases, the area affected by ash was within or close to the region forecast as being likely to be affected by ash.

4. QUESTIONNAIRE

During the active phases of the 1995 and 1996 eruptions of Mt Ruapehu, the Volcano Surveillance Group at Wairakei Research Centre issued regular ashfall predictions (see Fig 6 and its caption). These were released as "Ruapehu Ashfall - Prediction xx" with xx in the series V95/01 to V95/26 for those produced in 1995 and V96/01 to V96/53 for those in 1996. The techniques used, data input and output are discussed in detail elsewhere in this report. In this section we discuss the results of a questionnaire sent out to numerous organisations who received the daily ashfall predictions in 1995 and 1996. The objective of the questionnaire was to evaluate the usefulness and quality of the ashfall predictions.

4.1 Methodology

A questionnaire consisting of 22 questions (Appendix 1) was prepared and posted in December 1997 to 48 organisations who had received ashfall predictions during the 1995 and 1996 eruptions. The questionnaire polled recipients on a range of items including;

- Organisation/agency form.
- Method of receiving the predictions.
- Quality and readability of text and figures.
- Information content, usability.
- Actions taken by organisations, decision making processes.
- Internet access, use.

Most questions only required a yes/no answer or a selection from a few options. Free response sections were also added to most questions to allow respondents to qualify and illustrate their responses. The resultant replies have been analysed for content and response frequencies have also been conducted. In total, 48 organisations were contacted and 38 replied, giving a return rate of 79%.

4.1.1 Organisations - Agencies which responded

Respondents included seven Central Government Ministries, two primary emergency response organisations, eight Regional Governments, seven Local Governments and four industrial organisation (private & SOEs). Non respondents included two Local Government bodies responsible for areas which received ashfalls in 1995 and 1996, and three Government Departments/SOE's. Because some respondents requested confidentiality, we have not included a list of organisations.

Thirty-two (84%) of the respondents operate in areas which received some ash during the eruptions, and thirty-six (95%) found the ashfall predictions were useful for their organisation. Thirty-two (84%) of the respondents took some form of action following receipt of the ashfall prediction. Geographically, the entire North Island area was covered.

4.1.2 Distribution

The typical operational procedure at GNS following receipt of the wind data from the New Zealand Meteorological Service was for an ashfall prediction to be prepared by the Duty Surveillance Manager. Once complete, this was distributed by Telecom Smartfax to about 25 users. This was usually achieved early each day. Many of the recipients (76%) copied the ashfall predictions onto other parties. Internal copying ranged from 0-8, while external copies ranged from 0-24. It is known that further copies were made beyond the secondary level but this data is not available. The secondary redistribution numbered at least 171 copies, with 24 (63%) using fax and 18% photocopying.

The questionnaire respondents included both primary (direct from GNS) and secondary or tertiary recipients. Twenty (53%) of the recipients usually received their copy in the morning, four (11%) morning-afternoon, 13 (34%) in the afternoon and one in the evening. The preferred time to receive the predictions was (71%) mornings, 5% either morning or afternoon, 8% evenings and 3% the previous evening (i.e. before the new working day). Three respondents also requested two per day, a morning and afternoon update.

4.1.3 *Quality*

Thirty-two of the recipients (84%) received their ashfall predictions in a readable state, 16% did not. Of the six who received poor copies, five were secondary recipients. Thirty-four (89%) of the recipients rated the diagram as clear and informative. However, 21% added comments that the linework or font could be improved on. It is clear that the document did not copy well, especially when re-faxed.

The layout of the document is suitable for 89% of the respondents, and it contained the required information for 84% of the respondents.

4.1.4 *Usefulness*

The usefulness of the ashfall predictions was sampled via questions on their usefulness, if action was taken, their primary concerns and the amount of ashfall of concern. We also sought information on how much information the prediction contained and if there was additional information required.

Thirty-six (95%) of the respondents found the predictions useful to their organisations, the two negative responses did not expand on the reasons they were not useful. Many respondents pointed out how the predictions provided advanced warning or a probability that allowed forward planning. Possible impacts could be assessed, potential operational difficulties anticipated and appropriate responses put in place. Organisations with public information roles and media contact found they formed part of the background data needed to keep the public informed.

Most organisations (76%) wanted to know if ashfall could occur in their area and the thickness, however five out of thirty-six respondents would have been satisfied with just the likelihood of occurrence data. A particular interest in ash thickness was only expressed by organisations within 12-15 km of the volcano. Eighty-four percent felt the prediction contained sufficient information for their needs, 11% insufficient and 5% too much. The additional information that could be added focused on very user specific information, i.e. grain size or thickness.

4.1.5 *Internet*

Over 90% of the recipients have internet access and 87% would have used this to obtain the ashfall prediction if they were aware of it being there. However, only 8% actually used the internet to view the ashfall predictions. It should be noted that the ashfall forecasts were often not immediately available on the Internet in 1995/1996, and GNS did not promote this availability.

4.2 Result and Discussion

The primary objective of this study was to identify the usefulness of the ashfall predictions to the recipient organisations, including factors like readability, data content and quality. Although GNS only distributed the predictions to about 25 primary users, the questionnaire has established that they were copied to over 120 additional people or organisations. This large scale secondary and tertiary copying was not anticipated, and many of the comments regarding readability reflect this.

For many respondents, the primary concern/question each day was; are we going to have ashfall, rather than how much. This, coupled with the reproducibility issues, indicates that the graphic portion of the prediction needs to be redesigned. Some users near the volcano were primarily interested in the expected thickness of ashfall that might occur in their area.

Essentially, all respondents used the ashfall predictions as part of their daily planning or response process. Many used them as advance warning so they could anticipate operational difficulties. The possible affect of ash on infrastructure was a big issue. Another major issue was having the information so it could be provided to the public. Given that GNS is unlikely to have the resources for more than one ashfall forecast each day, an early morning distribution is the most useful to most clients.

There is also a point of nomenclature here. There is some concern within GNS that "ashfall predictions" may sound too definite, i.e., may imply that ash will fall, rather than that if there is an eruption, ash will fall here. The title "Ashfall Forecasts" may be more suitable, also all forecasts need a header which clearly indicates whether a volcano is in a general eruptive state, or has actually erupted.

Although most recipients had internet access, few routinely used it to obtain the ashfall predictions, although many indicate they would make more use of it in the future.

Ashfall does have a significant impact and the issuing of ashfall predictions does appear to have served a very useful role for organisations and agencies with response roles. Action taken was typically to protect or minimise the impact on structures or infrastructure operated by the respondents. The prediction formed an integral part of the decision making progress.

5. CONCLUSIONS

For the three small eruptions studied here, the use of ASHFALL with Meteorological Service forecasts gave an adequate indication of the ashfall distribution for Civil Defence purposes. The general features of the ash distribution are not sensitive to the details of the eruption, although there is clearly a need to get an indication of the approximate size of the eruption as soon as possible. For these eruptions, the column height correctly indicated that the eruptions were comparatively small. By far the main source of error is the error in wind forecasts, for which Cox et al (1998) give a 20% probability of a 30° or greater error in a 12 hour forecast. The 11 October 1995 ash cloud was affected by a wind change. In situations when a major wind change is forecast, it would be desirable to give a forecast covering a wider area to allow for this.

For small eruptions such as these, the main interest of Civil Defence and other interested parties is where ash will land, the exact amount of ash expected in any particular area is of secondary interest.

Comparison of the ASHFALL forecasts with the contour maps of ash distribution, which probably represent a rather smoothed version of the original data on ash thickness, generally gives agreement within a factor of two. Since the actual size of the eruption is rather unlikely to be known this accurately at the time, reducing the errors in ASHFALL would not significantly improve the accuracy of the forecasts. The questionnaire revealed a particular interest of respondents fairly near to Ruapehu in the thickness of ashfall they might be subjected to. We currently do not have access to adequate data to check the accuracy of ASHFALL at distances of the order of 10 kilometres from Ruapehu, but will bear this concern in mind for future research.

For long distances from a volcano, ash forecasting tools will produce better results if they are integrated into wind forecasting models, and this might possibly include an indication of how reliable the forecast wind directions are. This is a possible future development of ASHFALL.

Immediate developments will probably be limited to improvements to its ease of use. These are likely to include setting it up to provide automatic ash forecasts for the more active volcanoes based on wind forecasts from the New Zealand Meteorological Service, and the production of more easily readable maps, as requested by a number of the respondents to the questionnaire already mentioned. Another possible feature is to add some indication of the effects of errors in the wind forecasts to the maps of possible ashfall.

The response from the questionnaire has clearly shown that these forecasts were appreciated. There is an obvious need to improve the clarity of the map, so it can cope with a multiple faxing and copying of the original copies. (A comparison of Figs 5 and 6 shows changes that have already been made to improve clarity). More emphasis will be given on outlining the maximum area likely to be affected by ash, given reasonable variations in the wind direction from that forecast. Overall, the idea of a simple map showing where ash would go if a volcano erupts "today" has been proven to be a good one, and shows the worth of a research project which was started when there was no particular reason to expect a revival of Ruapehu volcanic activity.

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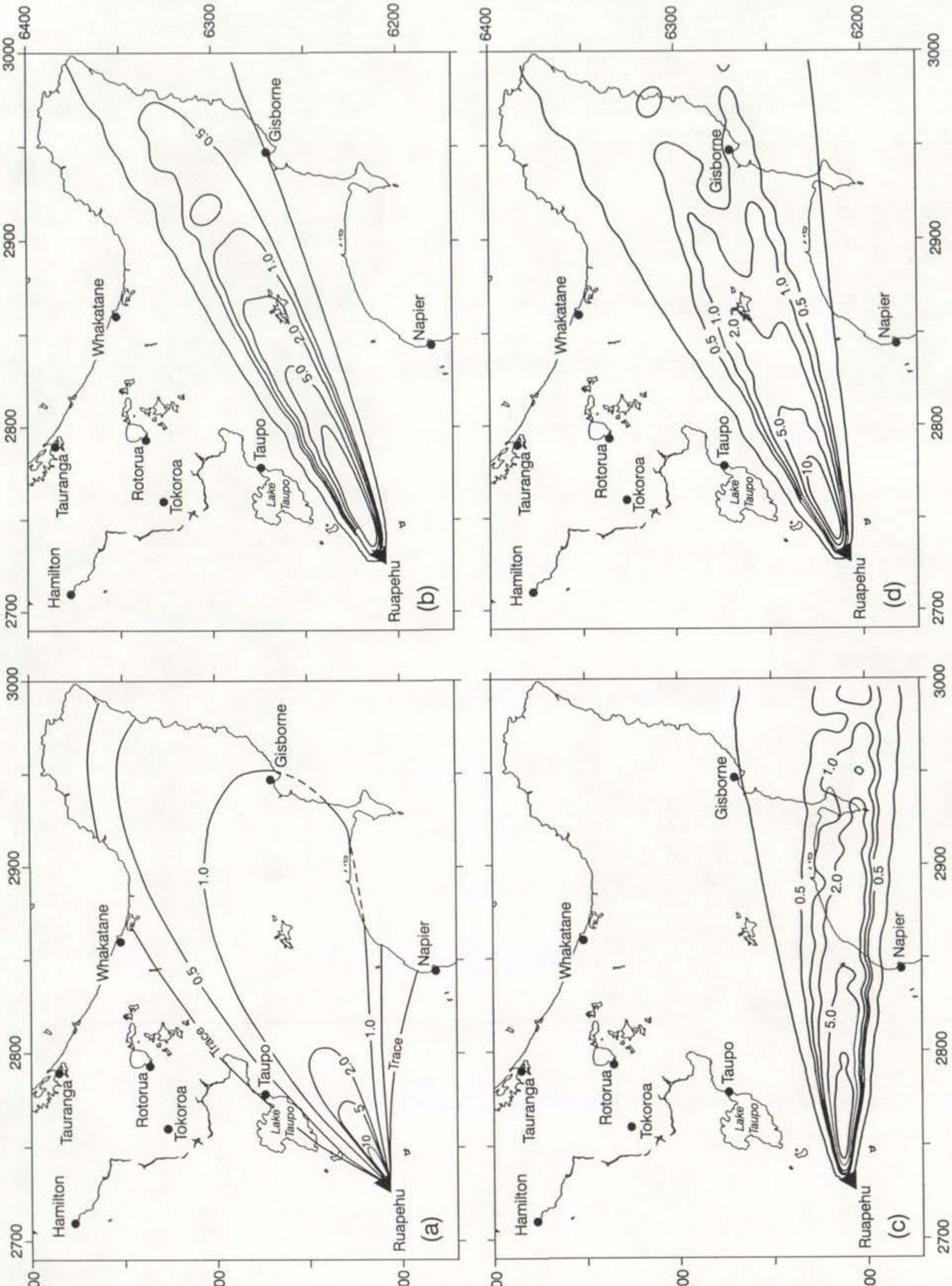

Fig 1. (a) Isopach map of the 11 October 1995 tephra from Ruapehu, from Cronin et al, 1997.

(b) Isopach maps based on ASHFALL model for the 11 October 1995 tephra from Ruapehu, using 12 hour wind forecast issued for Ruapehu at 0000 NZDT on 12 October 1995, a 10 km high eruption column, and a total mass of 0.03 km^3.

(c) Isopach maps based on ASHFALL model for the 11 October 1995 tephra from Ruapehu, using 12 hour wind forecast issued for Ruapehu at 0000 NZDT on 12 October 1995, a 10 km high eruption column, and a total mass of 0.03 km^3.

(d) Isopach map based on ASHFALL model for the 11 October 1995 tephra from Ruapehu, assuming the high altitude wind changed from 225° to 260° during the eruption, a 12 km high eruption column, and a total mass of 0.03 km^3.

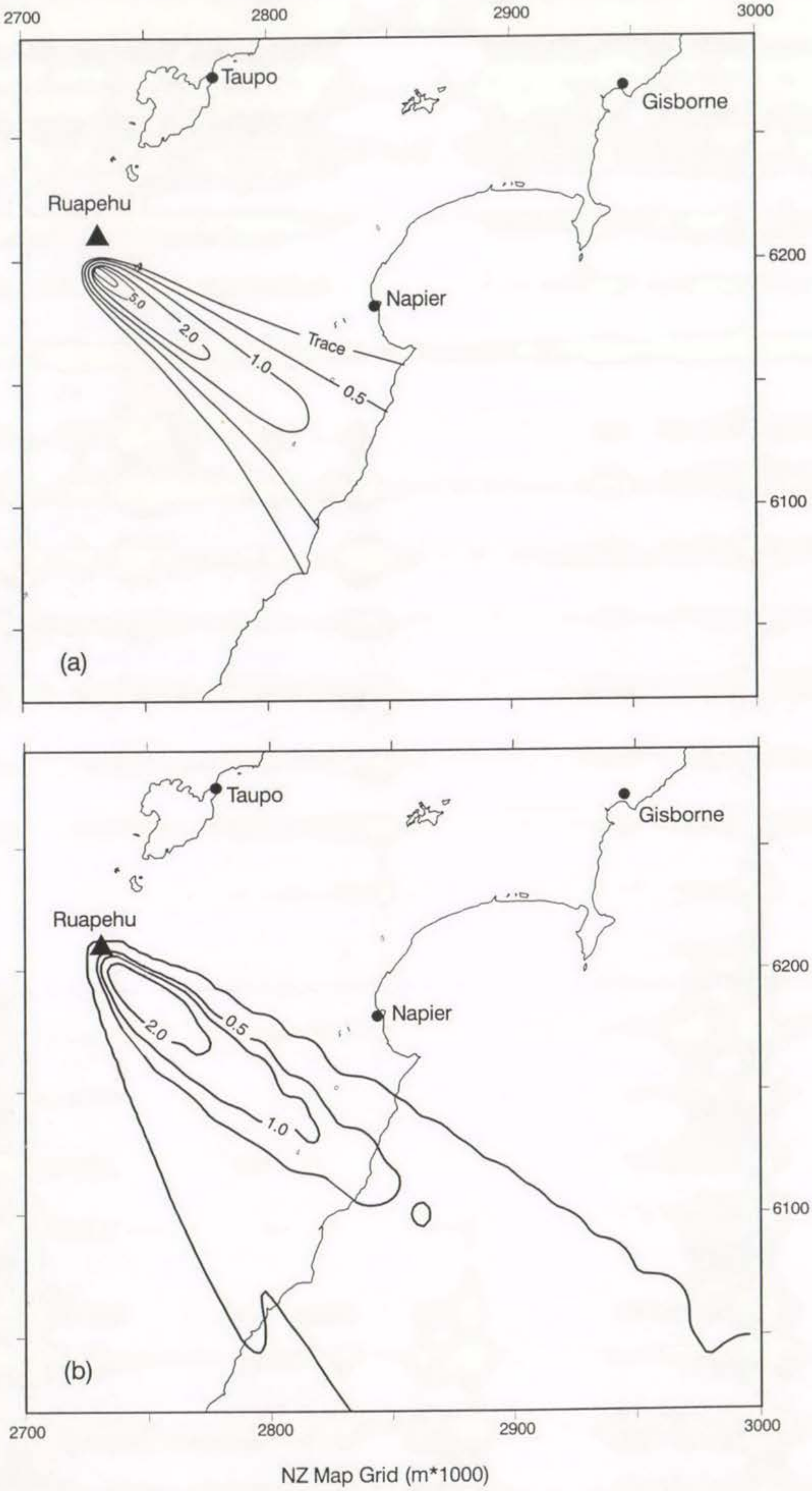

Fig 2. (a) Isopach map of the 14 October 1995 tephra from Ruapehu, from Cronin et al, 1997.

(b) Isopach map based on ASHFALL model for the 14 October 1995 tephra from Ruapehu, using the 12-hour Ruapehu wind forecast made at 1200 NZDT, 14 October 1995, a 10 km high eruption column, and a total mass of 0.01 km^3.

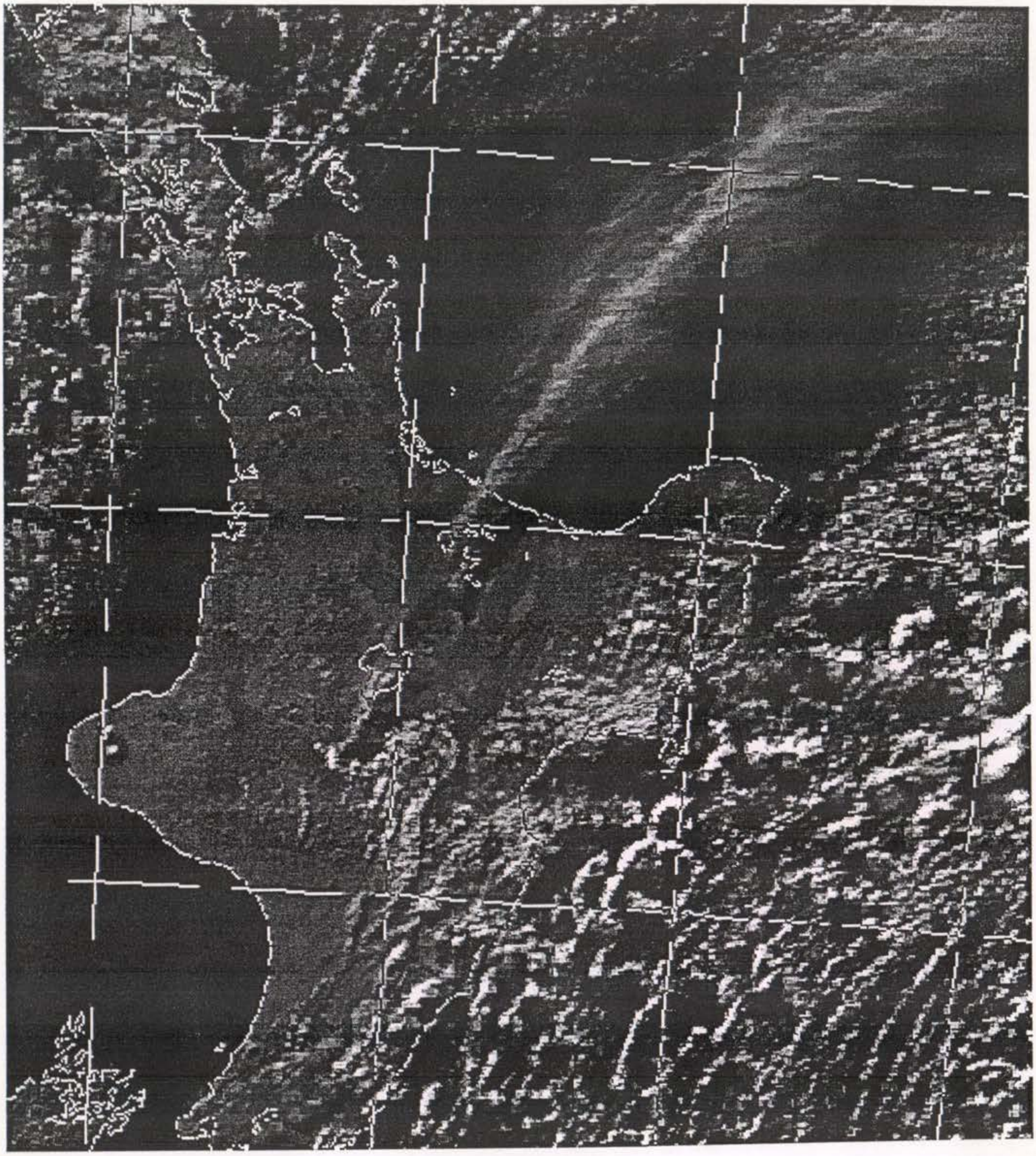

Fig 3. The 17 June 1996 Ruapehu eruption ash cloud, from GOES (Geostationary Operational Environment Satellite)in a visible light image at 0312-0316 UT (1512-1516 NZST). The dashed lines mark 2° intervals in latitude and longitude.

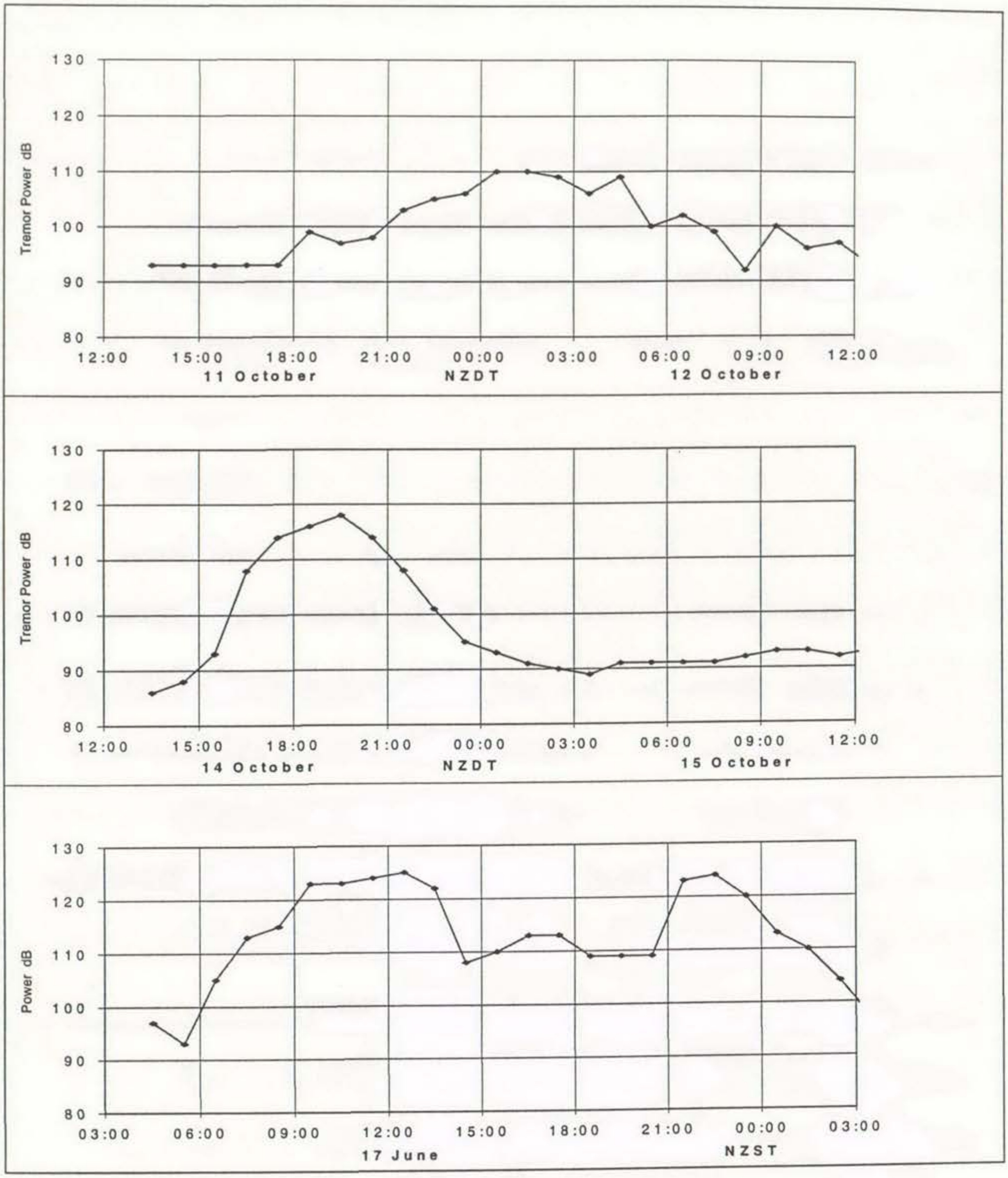

Fig 4. Seismic power levels at DRZ seismometer (1 km north of Crater Lake) from the Tremor Monitoring System for the three Ruapehu eruptions considered here. Because the seismometer was damaged during the 1995 eruptions, the power levels corresponding to the dB figures may have changed between eruptions.

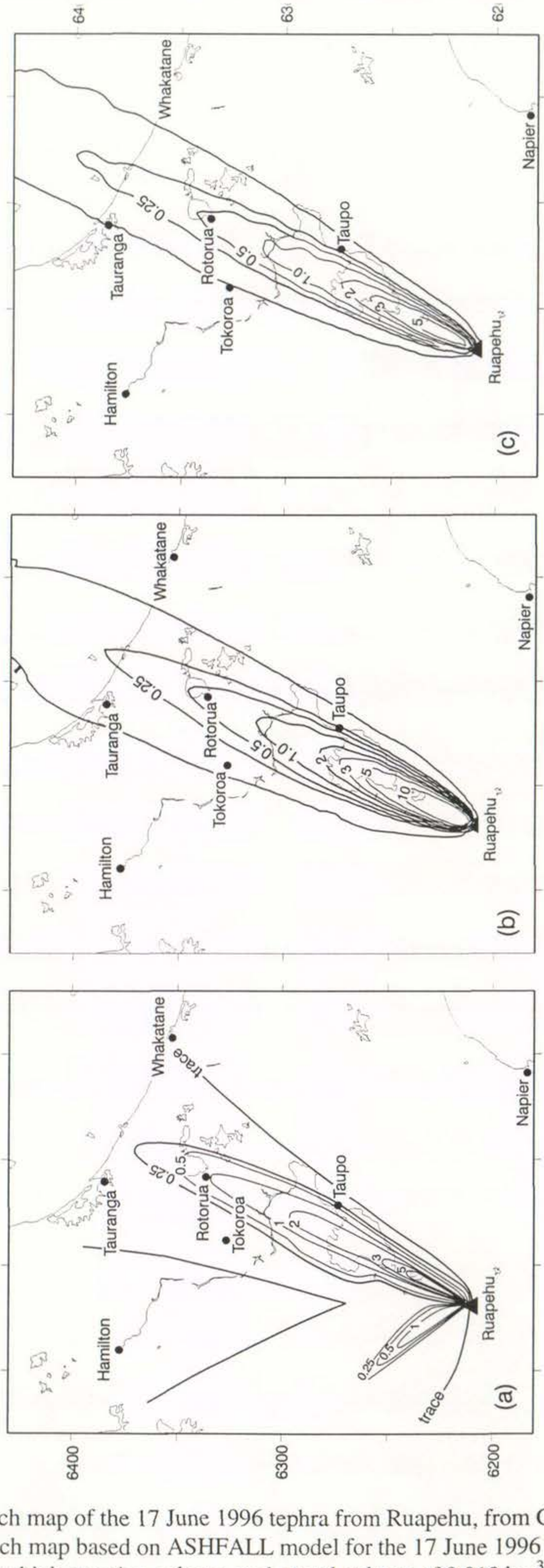

Fig 5. (a) Isopach map of the 17 June 1996 tephra from Ruapehu, from Cronin et al, 1998.
(b) Isopach map based on ASHFALL model for the 17 June 1996 tephra from Ruapehu, for a 7 km high eruption column, and a total volume of 0.012 km^3.
(c) Isopach map based on ASHFALL model for the 17 June 1996 tephra from Ruapehu, for a 12 km high eruption column, and a total volume of 0.006 km^3.

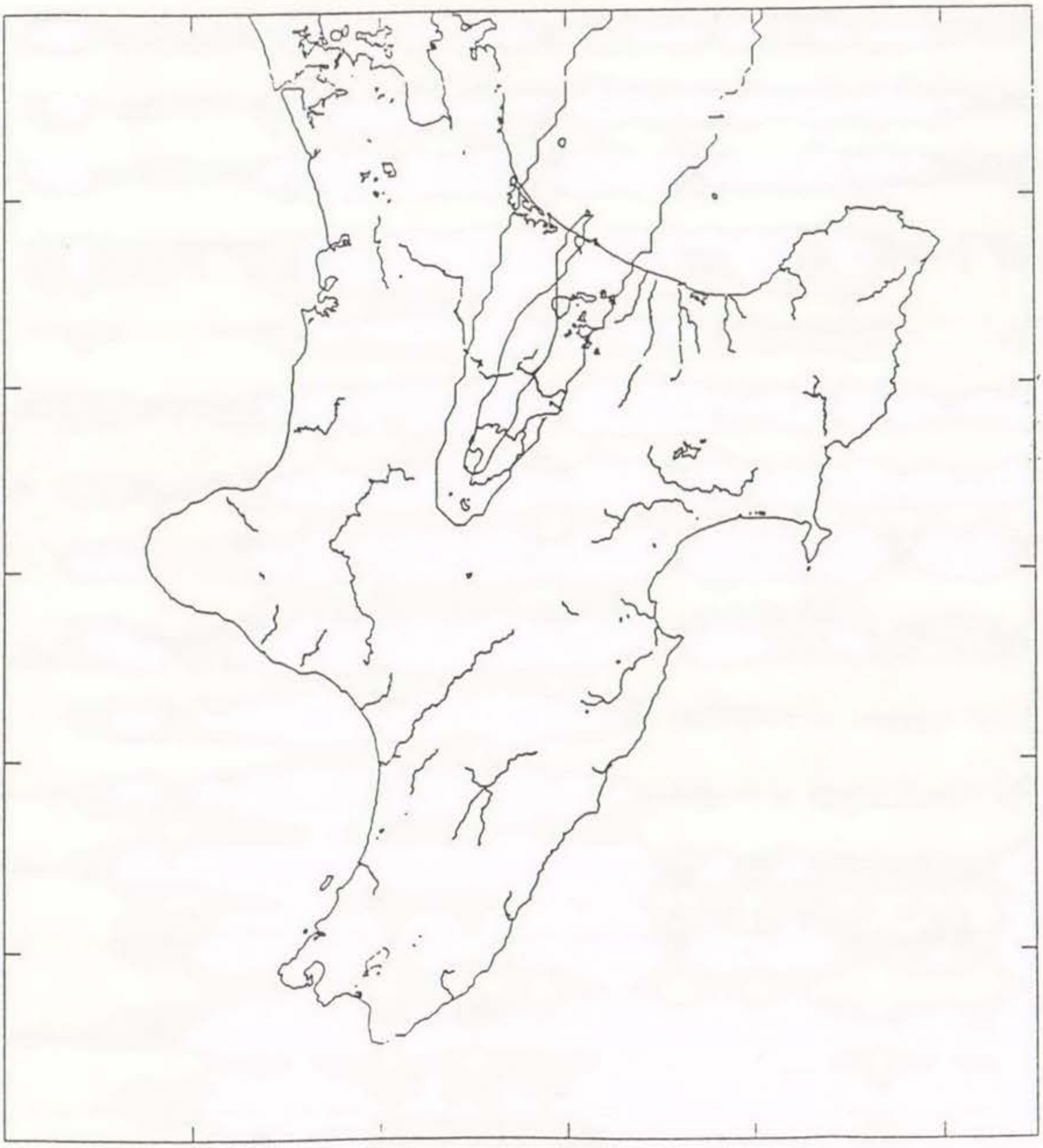

Fig 6. Map of expected ashfall from Ruapehu, as distributed by GNS on 17 June 1996. The following text was distributed with this map: "A large explosive eruption has occur (sic) from Ruapehu at 0825h 17 June, and over the next 12-18 hours, we would expect the ash to be distributed as shown below. This is based on wind observations at 0600h 17/6 and predictions for 1800h 17/6 and 0600h on 18/6. The wind conditions are not expected to change in the prediction window. We would expect 10-15 mm in the Turangi-Taupo area. As a precautionary measure we have modelled an eruption that is slightly larger than those to date. The outer contour represents 1 mm ash thickness."

VOLCANIC ASHFALL - QUESTIONNAIRE

As a follow-on to the medium-scale eruptions of Ruapehu in 1995 and 1996, we have received funds from the Earthquake Commission to evaluate the quality of the ashfall predictions. This project has two parts:

1. A comparison of the predicted ashfalls with the actual recorded ashfalls from the larger events.

2. A questionnaire to the end users evaluating the usefulness, and quality of the ashfall predictions issued during the 1995 and 1996 eruptions.

Please take a few minutes to complete this questionnaire.

1. In what geographic area is your agency/organisation based?

    ....

2. What type of organisation/agency are you?

    Central Government　　Regional Government

    Local Government　　Industry

    Emergency Service　　SOE

    Other

3. From whom did you receive the ashfall prediction?

    Direct from GNS　　Via Ministry of Civil Defence

    Via a Regional Council　　Via a District Council

    Other (please state)

4. What time of the day did you usually receive it?

    Morning　　Afternoon　　Evening

5. Was the ashfall prediction of readable quality as you received it?

    Yes ___________　　No ___________

    If NO, in what way

6. Was the diagram clear and informative?

Yes ___________ No ___________

If NO, in what way

7. Did the prediction contain all the information you required?

Yes ___________ No ___________

If NO, what else could have been included

8. Was the layout suitable?

Yes ___________ No ___________

If NO, what changes would be of assistance? ....

....

9. Did you forward copies to other parties?

Yes ___________ No ___________

If YES:

i) how many? ___________

ii) were they internal or external to your organisation? Internal _________ External _________

(iii) How were they forwarded? Fax Photocopy Other

10. Are the ashfall predictions useful for your organisation?

Yes ___________ No ___________

If YES, how

11. Was one ashfall prediction per day adequate for your needs?

Yes ___________ No ___________

If NO, how often would you like one?

12. What time of the day would you prefer to receive one?

Morning Afternoon Evening

Other ______________________________

13. Did receipt of the ashfall prediction result in action by your organisation?

Yes ___________ No ___________

If YES, what were they?

14. Did the ashfall predictions assist in decision making?

Yes ___________ No ___________

15. Who used the prediction in your organisation? (If more than one please list separately)

15a. Did the ashfall predictions supply:

i) too much information

ii) sufficient information

iii) too little information?

16. What additional information would you like to see included:

17. What was your organisation's primary concern?

a) Will we, or won't we receive an ashfall?

b) How thick would an ashfall be?

c) Both?

Comments:

18. Did your area experience an ashfall?

Yes ___________ No ___________

If YES, i) How often ....

ii) How thick ....

19. Is your organisation concerned with,

i) Any ash ___________

ii) 1 - 5 mm of ash ___________

iii) More than 5 mm of ash ___________

20. Do you have Internet access?

Yes ___________ No ___________

21. Did you view the ashfall prediction on the GNS Web pages?

Yes ___________ No ___________

22. Would you use the Internet to obtain this type of information?

Yes ___________ No ___________

Comments:

Thank you for your time and co-operation in completing this survey. Should you wish to receive a copy of the findings of this survey, please provide a name and contact address below.

Should you wish to discuss this survey, please do not hesitate to contact Bradley Scott, Institute of Geological & Nuclear Sciences, Wairakei Research Centre, Private Bag 2000, Taupo. Phone: 07 374 8211 Fax: 07 374 8199

Performance of a Program for Volcanic Ashfall Forecasting

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ABSTRACT

The program ASHFALL was developed to predict the ashfall that would result from a volcanic eruption, primarily for Civil Defence purposes. It can also be used for volcanic hazard assessments and for studies of past eruptions. During the 1995 and 1996 eruptions of Ruapehu, the program was used to provide forecasts of where ash would land if a significant eruption occurred, based on forecast wind patterns. This paper compares the predictions made by this program with the actual ash distribution for the three major ash-producing events, and looks at the main sources of error.

The accuracy of the forecast wind direction is the main factor affecting the ash distribution. If the forecast wind direction is correct, ASHFALL gives a good indication of where ash will fall. The quantity of ash falling downwind depends on the volume of the eruption, and it is difficult to give more than an order of magnitude estimate of this at the time of the eruption. However, analysis of the three events for which the total eruption volumes could be derived from measured ash thicknesses, showed that the ash thickness at any point was generally within a factor of two of that forecast by ASHFALL.

Keywords: volcanic ash, Ruapehu, prediction maps

INTRODUCTION

Volcanic ash from moderate to large volcanic eruptions is a major hazard to life and property. Even small quantities of ash can produce considerable inconvenience, with one or two millimetres having the potential to contaminate water supplies, and a few centimetres can cause disruption to agriculture and transport. A thick fall of ash can be a major hazard to life, predominantly by the collapse of buildings under the weight of ash. About 10 centimetres thickness of wet ash, or 20 centimetres thickness of dry ash, can cause structures to collapse.

The area at risk of serious ashfall from a volcanic eruption depends on both the characteristics of the eruption and the winds blowing at the time. For estimates of ashfall hazard to be useful in an emergency, they must be able to be produced quickly, with easily available resources. The program ASHFALL was produced for this purpose (Hurst, 1994). The code was based on studies of historic eruptions, especially the A.D. 79 eruption of Vesuvius, by a group at the University of Pisa, Italy (Armienti et al. 1988, Macedonio et al., 1988, 1990). They produced a program for accurate calculation of 3-dimensional particle diffusion in ash clouds, together with a simpler and quicker 2-dimensional diffusion program, in which only the horizontal diffusion of ash was considered, and in which there was only a single wind direction, although the wind speed could vary with height.

By combining features from these two programs, ASHFALL was produced, as a simple and fast program to predict where ash would fall, given a volcanic eruption of a particular volume, and a wind strength and direction that could vary with altitude and time. The logic of the program had to be significantly rewritten to allow for the effect of wind changes while the ash particles were still airborne. This was done by treating each ash settling velocity separately, with a timestep equal to the time taken by particles of that settling velocity to fall by one vertical grid interval. ASHFALL can also deal with multiple eruptions in one run, either a continuing eruption at a single site, or even an eruption developing over an extended source, as occurred in the 1886 Tarawera eruption. Glaze and Self (1991) described a somewhat similar 2-D model, but their model only used a single wind pattern.

ASHFALL PROCESSES

A volcano can distribute ash over large distances through the incorporation of solid ash particles in an eruption column containing turbulent gases, which are buoyant because of their high temperature. Driven by their initial velocity and their buoyancy, these gases eventually reach an altitude at which their density equals that of the surrounding air. Above this height the gases are heavier than the surrounding air, so they lose momentum and the upward velocity decreases, becoming zero at the top of the column. If there is no wind at any altitude, a rare situation in New Zealand, this leads to a "mushroom" eruption column. A more usual case has the top of the column blown sideways by the wind, with ash raining out of this sideways plume, with larger ash particles falling faster than small particles.

A number of factors influence the expected ashfall thickness distribution. The main factors relating to the volcanic eruption are the eruption column position and height, the total erupted mass and the fraction of ash of different sizes. Since ash particles generally have similar densities, the particle size is the main factor controlling the rate at which ash particles fall under gravity. The main meteorological factor is the wind direction and velocity. This will normally vary considerably with height, between ground level and the top of the eruption column, and may also vary with time during the eruption, as well as varying over the length of the ash plume. The normal methods used to get estimates of these factors for making ashfall predictions are described in the following sections.

Many studies have been made of the volcanic factors influencing ash distribution (e.g. Suzuki (1983) and Woods (1988)). Volcano characteristics are important near the volcano, but it is clear that once the ash cloud has left the vicinity of the volcano, the ash distribution is predominantly controlled by wind dispersal and gravitational settling (Holasek et al, 1996).

Eruption column position and height

Both the position and maximum height of the eruption column are needed to run the prediction program. For any likely New Zealand volcanic eruption, there is unlikely to be a major problem in locating the horizontal position of the eruption, i.e. locating which volcanic vent is erupting. The height of the eruption column may be observed from the ground, from aircraft, or by satellite. Once an eruption column has developed it may be difficult to determine its maximum height from the ground. If only the height of the bottom of the spreading-out cloud that develops from the column can be estimated, then the total height is likely to be about twice this height. The bottom of the Mt St Helens Cloud III of Sparks et al. (1986) was at a height of 10 km, and the cloud extended to a maximum height of 25 km. If the eruption has not started, or is increasing in intensity, then the final eruption column height will have to be estimated from the knowledge of previous eruption sizes. Visual methods are difficult in bad weather, or at night. X-Band radar promises to be useful in this case (G. Austin, pers. comm.). The Institute of Geological & Nuclear Sciences and the University of Auckland Physics Department are jointly investigating this technique.

Total erupted mass

It has been observed that the eruption column height is positively correlated with both the rate of eruption, and the total size of the eruption. Carey & Sigurdsson (1989) suggested that for a wide range of Plinian eruptions, there was a close relationship between the maximum sustained height of the eruption column and the total erupted mass (M). Their relationship was

$$\log_{10}M = (Z+60.5)/7.18 \qquad \text{M in kg, Z in km.}$$

So if an eruption is occurring with an eruption column 11 kilometres high, it is likely that the eruption will produce about 10^{10} kg, i.e. about 0.01 km^3 of unconsolidated ash, and so this volume can be used in the ash prediction calculations.

Ash size distribution

The ash size distribution is not likely to be known until the ash has landed, which is obviously too late to be useful. Therefore in any practical case, an ash size distribution derived from previous eruptions of the same volcano, or other eruptions with similar characteristics, has to be used.

Once ash particles leave the eruption column and start falling, their settling velocity will very soon reach the terminal velocity, at which the drag force equals the gravitational force. The terminal velocity of ash particles increases with particle size and density, but cannot be calculated by a simple formula in the range of interest for volcanic ash studies. Walker et al. (1971), found that modelling ash fragments as cylinders gave good agreement with laboratory measurements. Using these results, and the results of Woods and Bursik (1991) who summarised the particle sizes distributions from a number of volcanic eruptions, a reasonable distribution of settling velocities can be selected for an eruption. Hurst (1994) used a file of ash settling velocities (EX401), obtained by smoothing the ash distribution from the Vesuvius eruption of A.D. 79 (Macedonio et al., 1990), which should give a reasonable ash size distribution for eruptions of volumes in the range from 0.1 to 10 km^3. A similar distribution was used for the Ruapehu ash predictions in this paper, but with 37 values of settling velocity, each containing only a small percentage of the total volume of ash. (If a significant proportion of the ash particles have a particular settling velocity, the ashfall prediction contains artificial peaks).

Different ash size distributions affect what proportion of the ash is found at each distance from the volcano, but have little effect on which areas get any ash, except that the furthest distance reached by the ash cloud depends on the smallest ash particles present. Carey & Sigurdsson (1982), suggested that smaller particles tend to aggregate to produce particles with a settling velocity of about 0.3 m/sec. For a 10 km high column, this corresponds to a fall time of 10 hours, so for a typical wind velocity of 20 m/sec, the ash will extend at least 700 km downwind from the volcano.

Wind direction & velocity

Profiles of wind versus altitude are currently measured twice daily by the Meteorological Service of New Zealand using a combination of radiosondes and radar reflecting balloons at Kaitaia, New Plymouth, Gisborne, and Paraparaumu. These profiles generally cover heights up to about 20 km. From these measurements, meso-scale models are used to produce a 3-dimensional model for the current and forecast winds.

As an indication of the likely errors in these wind forecasts, Cox et. al., (1998) compared a number of meso-scale models. For the most successful one (RAMS), 12 hour forecasts had a wind direction error of less than 30° for 80% of the time, decreasing only slightly to 76% for 36 hour forecasts. This means that for 12-hour forecasts, 1 in every 5 forecasts of the wind direction will be out by more than 30° from that forecast. This has a major effect on our ability to predict where volcanic ash will go.

MODEL PERFORMANCE DURING 1995/96 RUAPEHU ERUPTIONS

Ruapehu Volcano erupted in September-October 1995 and in June-July 1996. During this time, there were 3 significant eruptions that produced a widely recorded distribution of ash that could be compared with predictions from the ASHFALL program. These events were on the 11th and 14th of October, 1995 and on 17 June 1996. These three eruptions were all small, each producing ash deposits in the range of 0.005 to 0.025 km^3.

Predictions

During the eruptive periods, the Meteorological Service provided at least two forecasts each day of the expected wind pattern (strength and direction versus height) for the Ruapehu area. Before 17 October 1995 these were just used for indicative forecasts of where ash and volcanic gases would travel. From this date on, ASHFALL was used to provide predictions of ashfall called "Ruapehu Ashfall - Predictions", indicating what areas were expected to be affected by ash if an eruption occurred in the next 12 hours or so. These were distributed to interested parties, mainly by fax.

For small eruptions such as these, the main interest of Civil Defence and other responsible agencies was "where will ash land". The amount of ash expected in any particular area was of secondary interest. The difference between 1 and 2 mm of ash, for example, was not seen as making a major difference to the response that was necessary. Given this prime interest in where ash was likely to fall, the various parameters which affect the ability to forecast the ash distribution can now be considered.

Maximum height data

The height information available for the 3 Ruapehu eruptions studied is as follows.

11 Oct. 1995 NZ Army ground observation "approximately 10 km"
Meteorological Service "to in excess of 36,000 feet"(11 km)

14 Oct. 1995 Aircraft report at 1715 NZDT "36,000 feet", (11 km)
Satellite Imagery at 2000 NZDT, "30,000 feet" (9 km) towards Hawkes Bay
(If the smallest ash particles are falling at about 0.3 m/sec, then the top of the ash cloud would be expected to descend at about 1 km/hr, so a lower altitude far out along the plume is reasonable)

17 June 1996 In a satellite image at 1512 NZST the temperatures (from Infra-red Image) gave the top of the ash plume as being 6.7 to 7.4 km altitude. (Turner & Hurst, in prep.). This was about 2 hours after the tremor level dropped, suggesting that the maximum eruption column height may have been about 2 km higher, i.e. of the order of 9 km high.

All these heights are in relation to sea-level, which is appropriate for ashfall, as the areas where ash is falling are at low elevations. However, the column height for the Carey & Sigurdsson (1989) relationship mentioned above is the height above the source vent, i.e. 2.5 km less.

A typical eruption column spreads out horizontally at about 80% of the total height (Macedonio et al, 1988), so most of the ash is in the top portion of the column. The higher the column, the further the ash will travel. Another effect is that wind strength and direction can vary considerably with height. This means that if there was a small eruption, most of the ash would be blown one way by the low-level wind, whereas if there was a larger eruption with a taller column the high-level wind might blow ash in a quite different direction.

Total erupted mass

The estimated volumes of ash falling on land for the three eruptions discussed were about 0.025 km^3 for 11 October 1995, 0.005 km^3 for 14 October 1995, and 0.006 km^3 for 17 June 1996. (Cronin et al., 1997, 1998). From the Carey & Sigurdsson (1989) relation, the first eruption would be expected to have an eruption column height of about 14 km., with 9 km. for the latter two eruptions. Most of the observations of column height gave results several kilometres lower than the figure calculated from the erupted volume, once one has allowed for the base of the column being at 2.5 km elevation. An error of 2 km. corresponds to a factor of two in the erupted mass or volume. In other words, in every case the column height gave a good indication that only a fairly small eruption was occurring, but not an accurate measure of its size. The Carey & Sigurdsson relation is probably the best technique currently available for estimating the size of an eruption in progress. The X-band radar already mentioned offers a future possibility for getting direct information on the volume of ash being produced.

Wind direction & velocity

The Meteorological Service provided forecasts of winds around Ruapehu during these eruptive periods. Actual winds recorded at Paraparaumu and New Plymouth were also used for comparison. A study of the use of the RAMS meso-scale model, concluded that the three methods, meso-scale models, forecast winds (which were also based on a meso-scale model), and simply using wind profiles upwind of Ruapehu, all gave comparatively similar results for the three cases studied (Turner & Hurst, in prep.).

1995-96 Ashfall

The most detailed studies of ash thicknesses currently available are those of Cronin et al, (1997,1998), based on measurements along roads, and information provided by farmers. .

The 11 October 1995 eruption occurred at night, from about 2100 NZDT until 0500 NZDT (12 October) and the ash cloud drifted north-east, over a very sparsely populated area. The ash deposits from this eruption are therefore not so well defined as the other two eruptions. Fig 1a (redrawn from Cronin et. al., 1997) shows the observed ash distribution. Fig 1b shows the results of the ASHFALL program using the 12 hour forecast given at 1308 NZDT 11 October for the winds around Ruapehu at 0000 NZDT on 12 October. Fig 1c shows the results using the next 12-hour forecast, for the winds around Ruapehu at 1200 NZDT on 12 October, with the ash plume having swung about 25° clockwise. The wide angle over which the ash was actually spread indicates that the change in wind direction must have occurred between the start of the eruption and the last ash landing. The combination of these forecasts would have given a reasonable agreement with the actual ash, although it would not have predicted ash at Taupo or the Bay of Plenty coast. Fig 1d is based on an adapted "forecast", which gave a rather better match with the actual ashfall. This used the observed wind at New Plymouth, which showed a shift of about 35° clockwise between 0000 NZDT and 1200 NZDT on 12 October, and assumed that this wind shift affected the Ruapehu to East Cape area during the eruption,

The 14 October 1995 eruption occurred during the day, starting at about 1600 NZDT (0300 UT), and the ash cloud travelled south-east, across the Desert Road and the Kaimanawa Range into more populated areas of Hawkes Bay. The actual ash distribution is shown in Fig 2a (from Cronin et. al., 1997), while Fig 2b shows an ASHFALL prediction based on the winds forecast for Ruapehu at noon on 14 October. The ash distribution was also calculated with the observed wind from New Plymouth. This showed a much more extended ash plume than was observed, indicating that, as forecast, the wind strength at Ruapehu was less than the wind strength at New Plymouth.

The 17 June 1996 event was the main ash-producing event of the 1996 Ruapehu eruption sequence. It was well observed, as it occurred during the day, and in fine weather. The strong southerly wind blew the ash over a comparatively populated area. Fig 3 shows a GOES (Geostationary Operational Environment Satellite) visible light image of the plume at 0314 UT (1514 NZST) on June 17. The photo clearly shows that there is much less ash in the southern part of the plume near Ruapehu, the result of a decline in ash emission about 1-2 hours earlier. The decline in ash emission correlated with a drop in the seismic power recorded at Dome Shelter, about 1 kilometre from the vent of Ruapehu, as shown in Fig 4, which also shows the tremor level for the two October 1995 eruptions. The ash plume in Fig 3 starts to bend to the east after crossing the coast, which indicates a changing wind pattern with position that cannot be modelled in the current ASHFALL program, and indicates that proper meso-scale modelling would be needed for longer distances.

This picture of the plume can also help to determine another parameter, the horizontal diffusion coefficient, which controls the spreading out of the ash cloud. Macedonio et al. (1988,1990) used 3000 m^2/sec in their 3-dimensional model, in which ash diffused both horizontally and vertically. The use of 6000 m^2/sec for horizontal diffusion in a 2-dimensional model with no vertical diffusion seems to give similar results to their models. It also gives ash plumes from Ruapehu that have about the same degree of horizontal spreading as that shown in Fig 3, for cases in which the wind direction was essentially constant.

The most detailed map of the 17 June ash deposits currently available is that of Cronin et al., (1998), shown in Fig 5a, although detailed analysis of the grain size distribution is being undertaken by B.F. Houghton (pers. comm.). Fig 5a can be compared with Figs 5b and 5c, which shows two alternative models for the ash source, which both give results that agree well with the main features of the ash deposit. The different heights of the eruption column and the different volumes (7 km and 0.012 km^3 for Fig 5b and 12 km and 0.006 km^3 for Fig 5c) give similar ash distributions north of Taupo, but the second one gives a better fit for the 3 and 5 millimetre contours. (In the RAMS simulations of Turner and Hurst (In Prep), the maximum height of ash made a significant difference to the distribution). Fig 6 shows the map included in "Ruapehu Ashfall - Prediction V96/02" that was released by GNS at 0930h NZST on 17 June 1996, i.e. about one hour after the eruption commenced. The outer contour on this map, corresponding to 1 mm ash thickness for a rather larger eruption (about 0.1 km^3), included virtually all the area of ashfall on 17 June.

DISCUSSION and CONCLUSIONS

For the three small eruptions studied here, the use of ASHFALL with Meteorological Service forecasts gave an adequate indication of the ashfall distribution for emergency response purposes, that is, indicating what areas were likely to be affected by ash, and for the most affected areas, ash thicknesses to within a factor of 2. The general features of the ash distribution are not sensitive to the details of the eruption, although there is clearly a need to get an indication of the approximate size of the eruption as soon as possible. For these eruptions, the column heights correctly indicated that the eruptions were comparatively small.

For the daily ash forecasts during periods of enhanced volcanic activity, an 0.1 km^3 eruption, as used in Fig 6, seems to be an appropriate size to use. The "Vesuvius A.D. 79" (Macedonio et al., 1990) distribution of ash settling velocities used gave good results, as did the use of 6000 m^2/sec for the horizontal diffusion coefficient. By far the main source of error was the error in wind forecasts, for which Cox et al (1998) gave a 20% probability of a 30° or greater error in the wind direction prediction in a 12 hour forecast.

This paper has concentrated on the accuracy of ash predictions. In related work, we also circulated a questionnaire to 48 organizations who had received ash predictions during these Ruapehu eruptions, to get feedback on their requirements. They expressed a strong interest in knowing where ash would land if there was an eruption in the next 24 hours, with a secondary interest in how thick the deposit might be. They were generally happy with the ash predictions provided, although there were problems reading the ash map after multiple copying and faxing. The readability of the maps produced from ASHFALL has already being improved, and it is likely that an indication of possible wind forecast errors will be added, perhaps by adding lines at 30° from the expected predominant wind direction.

As a stand alone program, ASHFALL is limited by its lack of integration with atmospheric models. It was originally intended to have the capability of having different wind patterns at different locations, and using interpolation in space, just as linear interpolation in time is already applied. This would not significantly complicate ASHFALL, but it would make setting up each run more difficult. The need for this feature was reduced because during the 1995-96 eruptions the Meteorological Service provided Ruapehu wind forecasts as well as the observed winds at the radiosondes.

Likely improvements to ASHFALL include setting it up to provide automatic ash forecasts for the more active New Zealand volcanoes, based on wind forecasts from the Meteorological Service. Further improvements to ash forecasting tools will require their integration into wind forecasting models, after the manner of PUFF (Searcy et. al., 1998). This, like the RAMS - HYPACT combination being used by NIWA (Turner and Hurst, In Prep), uses a 4-dimensional wind model, and a particle release and random walk method of delineating the area of ash, This technique is more appropriate for forecasts of airborne ash hazard, and is not very suitable for estimates of ash thicknesses on the ground. The best way of improving forecasting of ash thicknesses would be to integrate ASHFALL with meso-scale atmospheric models, so that the best possible wind forecasts could be automatically used to produce the ashfall forecasts.

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FIGURE CAPTIONS on Page ii, FIGURES follow Page 11

Numerical simulations of volcanic ashfall dispersal from the Ruapehu eruptions of 1995 and 1996.

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Abstract: Numerical simulations of volcanic ashfall dispersal from the Ruapehu eruptions of 1995 and 1996.

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The prediction of the dispersal of volcanic ash from events such as the Ruapehu eruptions of 1995 and 1996 is important not only for Civil Defence authorities who need to warn people in downwind areas, but for airline companies which have to re-route aircraft to avoid the encounters with volcanic ash clouds which can badly damage expensive jet engines and jeopardise passenger safety. The results of numerical simulations of volcanic ash dispersal using the RAMS (Regional Atmospheric Modelling System) and HYPACT (Hybrid Particle and Concentration Transport Model) models for 3 periods (11-12 October 1995, 14 October 1995, and 17 June 1996) during the recent Ruapehu event are presented here. RAMS is a 3-D atmospheric model that can be used to give detailed predictions of winds for regions such as the volcanic plateau. HYPACT is a particle dispersion model that uses the RAMS generated wind fields to predict the movement and concentration of the volcanic ash cloud. Validation is achieved through comparison of predictions of ashfall concentration with measured ashfall amounts and with satellite images of the ash cloud. Comparison of the performance of RAMS/HYPACT with that of the current Gaussian-plume ASHFALL model currently used for ash-fall advisory guidance in New Zealand indicates that the RAMS/HYPACT suite provides more accurate spatial and temporal forecasts than ASHFALL, but that like ASHFALL it's accuracy is limited by the accuracy of the initial and lateral boundary

conditions provided, and by the accuracy of the geological forecast of eruption plume characteristics. Finally suggestions as to how RAMS/HYPACT might be configured for and implemented into emergency operational procedures are made.

1. Introduction

The Mt. Ruapehu (Elev. 2900 m, Longitude 175.562 E, Latitude 39.289 S) eruptions of 1995 and 1996 had an estimated cost to New Zealand's economy of NZ$140 million (New Zealand Official Yearbook 1997). Contributing to this cost was that imposed on civil aviation due to the closure of airports by ashfall and the need to re-route aircraft due to the presence of ash clouds at flight levels. Aircraft need to avoid these clouds because ash can accumulate on the combustor and remelted ash can accumulate on the inlet to the turbine section which can lead to the engine stalling. Additionally, the abrasive nature of the ash can damage the compressor blades, as well as important areas of the exterior surface (Casadavell, 1994). It is therefore important that volcanic ash advisories, which warn of the location and likely movement of ash clouds, are based on the most recent satellite information and accurate trajectory prediction methods to reduce the incidence of unnecessary (and costly) re-routing. In New Zealand the MetService™ (Meteorological Service of New Zealand Ltd.) produces these advisories, called volcanic ash SIGMET's, and these form part of the inter-agency Volcanic Ash Advisory System (Lechner, 1997). Other agencies involved in VAAS are the Civil Aviation Authority (CAA), the Airways Corporation of New Zealand (ACNZ), and the Institute of Geological and Nuclear Sciences (IGNS).

MetService's VAAS responsibilities include, amongst others, maintaining "a watch over actual and possible volcanic events through the use of satellite and land-based meteorological systems and the use of atmospheric trajectory and dispersion models" and to "use suitable atmospheric trajectory and dispersion models to identify the probable path of ejected ash ...". During the 1995 and 1996 eruptions New Zealand's MetService relied on the Volcanic Ash Advisory Center (VAAC) of the Canadian Meteorological Center (CMC) for the production of the ash dispersal and trajectory forecasts. The VAAC use the three-dimensional Eulerian CANadian Emergency Response Model (CANERM, described in Pudykiewicz 1988 and 1989) to forecast the medium and long term transport of volcanic ash. For the New Zealand region CANERM was operated with a horizontal resolution of 50 km, and it used 11 vertical levels (although it can be operated with a horizontal resolution of 25 km and 22 vertical levels if more detail is required). CMC claims a time of between 30 and 60 minutes to produce results from CANERM from the time of notification of an eruption. Apart from the aviation-oriented CMC VAAC forecasts, during the 1995 and 1996 events IGNS produced for Civil Defence purposes forecasts of volcanic ashfall with the ASHFALL model (details of which are provided in section 2). Essentially ASHFALL uses time-varying wind profiles at a single geographic location along with geological information such as the total volume of ash and distribution of fall velocities to compute ash deposition over the region downwind from the eruption.

Unfortunately, ASHFALL cannot account for any regional variation in winds that may affect ash deposition. Additionally, the coarseness of CANERM's horizontal grid means that orographic effects on the airflow such as topographic flow blocking and lee-wave generation which may affect it's transport and deposition predictions may not be accounted for either. Turner et al. (1996) have demonstrated with the Regional Atmospheric Modeling system (RAMS) that to adequately represent the these kinds of effects for terrain of New Zealand's complexity horizontal much higher resolution (of about 2 km) than 25 km is needed. Given the reliance of New Zealand's VAAS system on these two models it is important to quantify these effects on forecast accuracy. Therefore, this study's main objective is to determine the influence of regional and local weather and airflows, that are not well represented in existing operational models, on the dispersion of material released from volcanoes, in order to identify potentially improved real-time techniques for predicting the atmospheric transport of hazardous volcanic material.

Since a high resolution version of RAMS has been shown to be capable of simulating these topographic effects it is the main tool used in this study. The experimental design for the study essentially involves using RAMS in both high resolution (2.5 km Δx) and low resolution (40 km Δx) configurations to simulate the winds over the New Zealand region for three ash dispersing periods during the 1995 and 1996 Ruapehu eruption episodes. The three periods were Oct 11-12, 1995, Oct 14, 1995, and June 17, 1996. Volcanic ash was transported hundreds of kilometres from the mountain in each case as shown by the isopachs (lines of constant ash depth) in Fig. 1. The effect of model resolution on ash dispersion can be ascertained by comparing differences in the dispersion patterns produced when HYPACT and/or ASHFALL use either the output from the coarse (Δx= 40 km) or high resolution (Δx=2.5 km) RAMS simulations. The effect of spatial variation in the winds can be achieved through comparing the difference in ash deposition between HYPACT and ASHFALL.

Additionally this work provided an opportunity for NIWA to continue it's ongoing effort in calibrating the RAMS and HYPACT models in the New Zealand region. Validation of the model predictions in this study is achieved by comparison with satellite images, radar data, ashfall data, and eye-witness reports. Additionally, the opportunity was taken to test the volcanic plume entrainment model described in Glaze et al. (1997). The major interest being in checking that model's predictions of the maximum height the eruption column could reach.

It should be noted that the dispersion models in this study are not appropriate tools for prediction of volcanic ejecta, such as hot gases and large ballistic rocks, which are hazards that occur close (i.e., within a few kilometres) to the volcano. For any major volcanic eruption it is assumed that the immediate vicinity of the volcano would be evacuated and the air-space above be declared a no fly zone. The dispersion models are most applicable to "sub-Plinian" or "Plinian" eruptions in which a lot of ash is generated (typical of the andesite volcanoes Ruapehu, Ngauruhoe, and White Island). For very large "ultra-Plinian" eruptions, such as would be produced by the Taupo Volcanic Zone rhyolitic volcanoes, the "umbrella" portion of the ash cloud can propagate considerable distances upstream against the prevailing wind the dispersion models may be limited in their applicability. In this case one could only hope to simulate the ash dispersal once it had moved some distance away from the volcano.

The paper is organised as follows, section 2 provides a description of the models used in this study, section 3 outlines the experimental design, the results are presented in section 4, and conclusions along with a discussion are presented in section 5.

2. Models

A brief description of the four numerical model's used in the study now follows.

a. RAMS

Version 3b of the Regional Atmospheric Modelling System (RAMS) was used for this study. The grid configuration used within RAMS consisted of 3 nested Arakawa C grids. The outer grid (grid-1) was a 44x52 grid with a horizontal resolution of 40 km and a timestep of 100 s. The first nested grid (grid-2) was a 62x62 grid with a horizontal resolution of 10 km and a timestep of 25 s. The innermost grid (grid-3) centred over Mt. Ruapehu was a 70x86 grid with a horizontal resolution of 2.5 km and a timestep of 5 seconds. The domain structure for RAMS is shown in Fig. 2. The computational expense involved with this configuration is quite high, and not currently feasible for real-time operational response. However, using this configuration enables the influence of relatively fine-scale topographic flows on ash dispersal and deposition to be assessed. The operational fidelity of the RAMS model, in terms of providing meteorological inputs to either HYPACT or ASHFALL, can be assessed by using only the coarse grid forecast meteorological variables. The vertical grid structure had 22 vertical levels with a spacing of 200 m near the surface increasing to 800 m above 2400 m. The vertical grid structure was the same for all three grids.

The following options and assumptions regarding the model's configuration were invoked: (i) the basic equations were compressible and nonhydrostatic, (ii) a hybrid forward/leapfrog time differencing scheme, (iii) a 2nd order advection scheme, (iv) a prognostic equation for TKE for turbulence closure (v) the vertical co-ordinate was a terrain following sigma co-ordinate, (vi) no cumulus parameterization, radiation or microphysical packages were used, (vii) a rigid lid at 18.5 km, (viii) zero gradient inflow, and an outflow 8 grid-points deep at the lateral boundaries, (ix) roughness length of 1 m, (x) 11-level, sandy loam, soil model, (xi) monthly mean SST, and (xii) mixed woodland land-use.

b. HYPACT

The HYPACT model (described in Walko and Tremback 1995) is a code developed to simulate the motion of atmospheric tracers under the influence of winds and turbulence. Its Lagrangian component enables representation of sources of any size, and the maintenance of concentrated, narrow plumes until atmospheric dispersion dictates that it should broaden. At this point , the Lagrangian particle plume can be converted into a concentration field and then advected using an Eulerian formulation. The Lagrangian particles are moved through space and time based on the interpolated wind velocities plus a superimposed random motion scaled on the local turbulent intensity. Additionally, a spectrum of gravitational settling velocities related to particle size can be specified. Wind components (u,v), potential temperature (θ), and turbulent kinetic energy (*TKE*) are the gridded meteorological variables necessary to drive HYPACT. For this project, gridded time series of these variables are provided by the RAMS model to HYPACT.

For this study, the Eulerian mode of HYPACT was configured to have a horizontal grid spacing of 4 km. Particles representing a somewhat arbitrary volume of volcanic ash of 25,000 m^3 each were released at a rate of 20 per timestep of 100 s. This value gives a volume of approximately 0.1 km^3 for a six hour eruption of constant emission rate, which corresponds to an average depth of 1 mm over an area of 100,000 km^2 . The particles were assumed to be between 1 μm and 150 μm in diameter with an equal probability of any diameter particle being emitted between these limits.

c. ASHFALL

The program ASHFALL (described in Hurst, 1994), which calculates ash thickness was developed from the volcanic ash dispersion model described in Macedonio et al., 1988 and 1990 and Armienti et al. 1988. Their DIFFUSE model performs computationally expensive 3-dimensional particle diffusion calculations for volcanic ash clouds and is unsuitable for Civil Defence purposes. ASHFALL is an adaptation of DIFFUSE where vertical diffusion is eliminated. This simplification eliminates the need for large three-dimensional arrays as at any stage of the numerical integration calculations of ash dispersal are only being made at a single atmospheric level. It has been argued that this is a reasonable assumption given that the vertical diffusion of ash is always less significant than horizontal diffusion and it's effect can be crudely accounted for by increasing the horizontal diffusion coefficient.

ASHFALL uses wind speed and direction at different levels and times along with volcanological information such as the total volume of ash and distribution of fall velocities to calculate the likely distribution of ash thickness resulting from a volcanic eruption. ASHFALL does not consider the effect of lahars, pyroclastic flows, volcanic bombs, and gas clouds. While these represent a significant hazard close to the volcano, these areas are likely to be evacuated whatever direction the ash is expected to travel.

ASHFALL was configured to have a 81(E-W) x 121 (N-S) grid with a horizontal resolution of 5 km and a vertical resolution of 500 m up to a height of 12 km. The domain for ASHFALL is shown in Fig. 3. In most cases a fall-velocity distribution as given in column 2 of Table 1 was assumed for the ash particles. Some sensitivity tests as to the specified fall-velocity distribution were conducted, these are reported on later in the paper.

d. Plume model

As mentioned in the introduction attempts at estimating the height of the eruption columns were made using the plume entrainment model described in Glaze et al. (1997). While they used the model to determine the redistribution of atmospheric water by the eruption column by solving the equations of conservation for mass, momentum, and heat for the four separate components of the eruption column (dry air, water vapour, liquid condensates, and solid particles) the model also determines the level of neutral buoyancy (approximately the level at which the density of the column equals the density of the environment) and the final eruption height (the level at which the vertical velocity of the eruption column reaches zero). Input variables to the model are profiles of atmospheric temperature and moisture, initial upward velocity of the plume (u_0), initial temperature of the plume (θ_0), initial plume radius (r_0), and the initial mass fraction of water vapour, (n_0).

The structure of eruption column could be briefly described as follows (for more details the reader is referred to Self and Walker, 1992 and Sparks et al. 1992). The eruption column consists of a lowermost gas-thrust region, a convective thrust region, and an uppermost umbrella region. The gas-thrust region at the base of the eruption column is a jet produced by a decompression induced expansion of the eruptive mixture as it encounters lower atmospheric pressure at the mouth of the vent. The material within this jet is initially denser than the ambient air and exit velocities are typically in the range of 100 to 500 m s^{-1} . The flow in the gas-thrust region while being quite complex makes up only a small fraction of the total column height and generally has little influence on ash dispersal; the exception being the scenario where the column collapses. For most eruptions, turbulent entrainment of the environmental air into the column and its subsequent heating causes the column to become positively buoyant and above this point (typically a few hundred metres in elevation) the eruption column can be thought of as a convective plume. In some instances, the entrainment and heating of the air is insufficient for the column to reach a state of positive buoyancy and in this case the column collapses and a pyroclastic gravity current that flows close to the terrain is generated. In this instance the dispersion models are inappropriate tools for predicting ashfall dispersal, however the ash will usually only travel a few kilometres from the volcano in this case.

The upper limit of the convective region of the column is that level where the plume loses its positive buoyancy, becomes neutrally then negatively buoyant (this level is called the level of neutral buoyancy). At this point the column will still rise due to its upward momentum, and it will continue to do so until the vertical velocity reaches zero. Between these levels the ash plume will spread out laterally, as vertical displacements are limited, this region is called the umbrella region and is analogous to the anvil of a cumulonimbus thunderstorm cloud. Note, the transport of ash into the umbrella region is very efficient as there is very little ash fallout from the gas-thrust and convective regions, and thus it is the wind dispersal of the ash (along with gravitational settling) from the umbrella region of the eruption column that is most important for civil aviation interests and determining long-range ashfall distributions.

3. Results

In this section the results of the simulations using the RAMS driven HYPACT and ASHFALL models of ashfall dispersal from three periods of the 1995 and 1996 Ruapehu eruption sequence are presented separately.

a. June 17, 1996

The major ash producing eruption of the June 1996 activity began on the morning of June17 at 0700 NZST (1900 UTC June 16). Observer reports indicate that the activity was characterised by two eruption pulses at 0710 and 0825 NZST, and steady activity from 1100 up until 1300 NZST after which a decline occurred. At about 1500 NZST the volcano started to erupt every 10-15 minutes with ash laden plumes reaching several kilometres in altitude. This activity had declined by 1700 NZST. There was another period of strong tremors with lava fountaining between 2200 and 0300 NZST that night, but it is not clear whether any ash was injected during this time. Eyewitness reports and indicated that ash fell in a zone extending N-NE from the volcano to the Bay of Plenty coast between Tauranga and Whakatane (New Zealand Official Yearbook for 1997). The winds over the North Island on this date were generally south to south-westerly aloft with a trend to more southerly flow at lower levels. Skies were clear over the Volcanic Plateau and Bay of Plenty regions (with the exception of the ash cloud), as well as several hundred kilometres out to sea. The 1514 NZST infrared satellite image in Fig. 4a shows the ash cloud extending from its source at Mt. Ruapehu towards Lakes Taupo and Rotorua and then spreading out transversally as it went N-NE out to sea. This infrared image also indicated that the temperatures along the top of the ash plume's centre-line were between 235 and 239 K. Analysis of a sounding from the RAMS simulation valid for 1500 NZST (see Fig. 3) indicates that these temperatures correspond to an estimated height above sea level of between 6.7 and 7.4 km (or between 430 and 400 mb). Fig. 4b shows the visible satellite image for the same time, given the solar declination angle of 17° for this location and time, it can be determined from the shadows cast by the edge of the ash cloud that that part of the cloud is between 6 and 7 km high. Glaze et al.'s theoretical plume model using values typical for volcanoes of τ, u_0, θ_0,, and r_0 (see Table 2) and a vent height of 2531 m (Vandemeulebrouck et al. 1994), and the RAMS sounding (see Fig. 5) yielded values between 8.5 and 11.5 km for the final plume height. The final plume height displayed little sensitivity (less than 1%) to the details of the tropospheric sounding as shown when the warmer and moister soundings from the October 11 and 14, 1995 cases (see Figs. 6 and 7 respectively for the soundings). Table 2 summarises the sensitivity tests undertaken.

Given the disagreement between the three estimates of the height of the plume top, heights within both these ranges were specified in HYPACT. The specified plume top height which produced the best simulated match to the ashfall reports and satellite image turned out to 7 km rather than 10 km. The best fit between simulated ashfall and the observed was achieved with HYPACT when the ash-cloud above the volcano was assumed to be 3 km deep and to have a top at 7 km (i.e. the source was from 4 km to 7 km). The results of this simulation are shown in Fig. 8, and it's apparent that the simulated ashfall pattern has the correct orientation but is displaced to the south-east by about 15 km near Rotorua. Fig. 9 shows the HYPACT simulated ashfall when the source has a much smaller vertical extent of 500m (from 6500 to 7000 m elevation), here the south-east displacement near Rotorua is about 25 km. Note for the simulations shown in Figs. 8 and 9 ash was assumed to be being continuously ejected from 0700 to 1700 NZST on 17 June, and the plots which are valid for 2100 NZST (four hours after the injection has stopped), show only those particles that have fallen below 1.5 km elevation. Fig. 10a shows the HYPACT simulated ash particles that are still suspended in the air and are above 1.5 km elevation at 0315 NZST on June 17, 1996. Comparing this figure with Fig. 4b it's apparent that the plume is again displaced to the south-east by about 30 km over the Bay of Plenty coast. This displacement increases to about 70 km at 178 °E, 36 °N). Fig. 10 b shows the simulated vertical distribution of ash particles at 0300 NZST, the high ground concentrations closer to the volcano are readily apparent. This plot reveals one difficulty with HYPACT in deriving quantitative ashfall amounts in that little ash is simulated to have fallen in the vicinity of the volcano. A remedy to this problem would be to skew the specified distribution of particles within HYPACT towards those with higher fall velocities, however doing this means simulated ash particle distributions at distances from the volcano cannot be obtained unless a large number of particles are specified. Unfortunately that option is computationally very expensive, and thus of little use for emergency response purposes. The results from the plume dispersion simulations discussed thus far have been for HYPACT forced with output from high (i.e., 2.5 km horizontal resolution on the inner grid) RAMS integrations. Use of the coarser 40 km resolution RAMS output (not shown) resulted in similar, but less detailed, patterns being simulated.

Ashfall patterns as predicted by ASHFALL with wind profiles provided by the 00 UTC 17 June 1996 Paraparaumu rawinsonde and high resolution RAMS simulation are given in Figs. 11 and 12 respectively. (The distribution of fall velocities for these simulations is given in column 1 of Table 2.) It can be seen that both patterns are somewhat similar with the Paraparaumu forced simulation being the better, in that it has captured the orientation of the plume more accurately. Both over-predict the extent of the 1 mm isopach, but this is likely due to the fact that the value of 0.1 km^3 total volume of ash ejected was just a rough estimate. Although the Paraparaumu rawinsonde winds were representative of the conditions over the Volcanic plateau on this day, (in which the whole North Island was embedded in a south-south-westerly airstream and Paraparumu was upstream of Ruapehu) this may not always be the case and reliance on remote, albeit, observed wind data, may not always produce such good results. To illustrate this point, upper air winds from New Plymouth for 00 UTC 17 June were also used to force ASHFALL and produced an ashfall distribution (not shown) that was even more displaced to the south-east than the RAMS forced distribution. Using a fall velocity distribution as specified in column 2 of Table 1 resulted in the ashfall distribution shown in Fig. 13. There are only minor differences between the distributions in Fig. 12 and Fig. 13, suggesting that in this case there is little sensitivity to these specified fall velocity distributions.

b. October 11, 1995

Eyewitness (Army personnel and pilots) reports indicate that seismic activity between 2100 NZST on the 11th and 0500 NZST on the 12th were accompanied by a continuous explosive eruption that produced an eruption column between 8 and 10 km high. These height values are in better agreement with that predicted by the plume model for this date (see Table 2) than for the June 17, 1996 case. Winds were generally from the south-west to begin with but then they switched more to the west by the end of the period, this along with the fact that the amount of ash from this eruption (about 0.2 km^3) was the largest since 1945, meant that a much larger area was affected by ashfall than for the other two cases in this study (Fig. 1). No satellite imagery was available, and eyewitness reports indicated that the weather conditions at this time were not conducive to good observations of the ash cloud.

For the dispersion simulations on this date , HYPACT was configured to have a source 3 km deep centred about 8.5 km, and ash particles were released continuously for the 8 hour period from 2100 NZST 11th to 0500 NZST on the 12th. The simulation was stopped at 0800 on the 12th. The ash particles that had settled to below 1500 m, are plotted in Fig. 14. From this figure, it's clear that the HYPACT simulation has produced an ashfall pattern that is slightly more east-west oriented than was observed. HYPACT has not simulated the trace amounts that fell in the north near Opotiki. However, HYPACT did simulate the movement of the elevated part of the ash cloud over this region and it's subsequent movement to the south as the wind switched to the west (Fig. 15).

The ashfall pattern as predicted by ASHFALL with wind profiles provided by the high resolution RAMS simulation between 2100 NZST and 0800 NZST for the grid location upstream of Ruapehu is given in Fig. 16. The extent of the 1 mm isopach from the volcano is well predicted, suggesting the estimate of the volume of volcanic ash for this event of 0.2 km^3 is reasonable. However, ASHFALL fails to capture the falls around Wairoa, and like HYPACT fails to produce the ash that fell to the north. In fact ASHFALL gives no indication that the ash cloud ever got close to Opotiki.

c. October 14, 1995

Seismic reports for this event indicated much stronger tremors than what had occurred on the 11th, however the ash producing eruption was reported to have lasted for only 4 hours between 1530 and 1930 NZST on the 14th and the volume of ash ejected was estimated to have been $0.1\ km^3$. Ash plumes were reported to have risen as high as 11 km, and at 2000 NZST satellite imagery (not shown) indicated the ash cloud at an elevation of 10 km extended over the coast between Napier and Waipukurau. As for the previous case the value for the height of the plume top is again in reasonable agreement with that of the plume model. Winds for this period were strong and steady from the north-north west. Eyewitness reports indicated that the weather conditions were not good for measuring ashfall. However, enough ground observations were made to produce the distribution as shown in Fig. 1.

For the dispersion simulations on this date, HYPACT was configured to have a source 3 km deep from centred 8.5 km, and ash particles were released continuously for the 4 hour period from 1530 to 1930 NZST on the 14th. The simulation was stopped at midnight. The distribution of ash particles that had settled to below 1500 m is shown in Fig. 17a. From this, it's clear that the HYPACT simulation has produced an ashfall pattern that is slightly more oriented to the south east than that reported in Fig.1. The orientation of the elevated (i.e., above 1.5 km) part of the ash cloud (at 2000 NZST) agrees well with the description from the satellite image. It is interesting to note how the low-level ash is displaced to the south east of the upper level ash (Fig. 18b) suggesting that the ash particles encountered more northerly winds as they fell to the surface.

However, the indications from Fig. 1 are that the bulk of the ash fell directly beneath the elevated plume.

The ashfall pattern as predicted by ASHFALL with wind profiles provided by the high resolution RAMS simulated winds valid hourly between 1530 and 2330 NZST on the 14th for the grid location upstream of Ruapehu is given in Fig. 19. The extent of the 1 mm isopach from the volcano is over-predicted, much like that for the June 17 case, again suggesting the estimate of the volume of volcanic ash for this event of 0.1 km^3 is too high. The orientation of the plume has the same kind of error as that for HYPACT, in that the centre of the plume is about 20 km too far to the south at the coast. Given that the distance from this part of the coast to Mt. Ruapheu is about 120 km, this corresponds to an error in simulated wind direction of about 10° .

4. Discussion and Conclusions

The HYPACT and ASHFALL models have been shown to produce reasonable, but not exact, agreement with the observed ashfall patterns for the three major ash-producing eruptions of the 1995 and 1996 Ruapehu eruption sequence. The HYPACT model is superior in reproducing the temporal and spatial movement of the ash cloud, but due to limitations in how the distribution of fall velocities are specified it is currently inferior to ASHFALL in quantifying the depth of ash. Undoubtedly, most of the differences between the observed and simulated ashfall patterns are due to errors in the RAMS simulated winds and to the estimate of total volume of ash ejected per eruption event. The gross scale nature of the observed data made it difficult to assess the quality of the high resolution RAMS simulations, as variations in reported ash thickness can be due to a myriad of factors. Given this, and the fact that there were few large-scale differences between the low-resolution (40 km) and the high resolution (2.5 km) RAMS simulations, it would seem that for operational purposes, the low-resolution RAMS model could be used to provide forcing of forecast data to either ASHFALL or HYPACT to produce adequate forecast guidance. One feature to note about all three RAMS/HYPACT simulations of the ashfall was that the centreline of the simulated ashfall seemed to always be rotated clockwise by about 10°. This was not the case for the airbourne ash at upper levels where the simulations were more accurate. One possible reason for this is that the degree of frictional turning within the boundary layer is being over-predicted by RAMS. Another possibility is that there are internal ash-cloud dynamics, or perhaps there are interactions between the ash-cloud and the atmospheric environment that are being accounted for in the model. For example, the strong shading by the ash-cloud on the ground could have been sufficient to alter the properties and flow within the planetary boundary layer beneath the cloud. Such effects could not be accounted for with RAMS.

Both HYPACT and ASHFALL run very quickly, and scripts can be easily set up so that local ashfall forecasts could be made using both models within 10 minutes of a request for a forecast, provided the appropriate numerical wind forecast is easily accessible. Furthermore, a web-site could be set-up whereby a weather forecaster or geologist armed with some simple instructions could produce these forecasts, without the assistance of the numerical modeler. One advantage with this method, would be that ashfall patterns from a number of different eruption scenarios could be generated by varying inputs to HYPACT and/or ASHFALL such as the height of the ash cloud, time of the eruption, etc.

ASHFALL has one other advantage over HYPACT in predicting ashfall in that it can readily use observed wind profiles from sites such as Paraparaumu, New Plymouth, or Gisborne. However, when it comes to prediction of the airborne movement of ash for civil aviation purposes, HYPACT is superior, as was demonstrated by its performance for all 3 cases examined in this study.

The plume model of Glaze et al. (1997) has been tested for these 3 cases, and it produced good predictions of the maximum plume height reached in the October 1995 cases, but it over-predicted the maximum plume height for the June 1996 case. Unfortunately, given the apparent lack of sensitivity to the typically experienced tropospheric soundings over New Zealand, and the lack of accurate knowledge about the initial plume characteristics, it's doubtful that this model would be of much use for emergency response purposes.

Acknowledgements.

We would like to thank the following individuals and organisations for their assistance in this research: Peter Lechner of the Civil Aviation Administration, Kip Marks, Mark Sinclair, David Wratt, Mike Uddstrom, Neil Gimson and Martin Bell of NIWA for assistance in gathering data, satellite images, and providing advice on using the RAMS and HYPACT models, Bruce Houghton of IGNS for the ashfall data, Alan Seed of University of Auckland for a description of the radar images of the ash cloud, Lori Glaze of NASA Goddard for the plume model. The first author would like to thank New Zealand's National Institute for Water and Atmospheric Research (NIWA) and the Foundation for Research Science and Technology for supporting this work under the auspices of the FRST post-doctoral fellowship scheme under contract C01638. The second author would like to thank the Earthquake Commission Research Foundation for support under contract EQC 97/268.

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Figure 8. RAMS/HYPACT simulated distribution of settled ash particles at 2100 NZST on 17 June 1996. The vertical source was assumed to be 3000 m thick from 4000 m to 7000 m in elevation.

Figure 9. RAMS/HYPACT simulated distribution of settled ash particles at 2100 NZST on 17 June 1996. The vertical source was assumed to be 500 m thick from 6750 m to 7250 m in elevation.

Figure 10. RAMS/HYPACT simulated (a) horizontal distribution of ash particles at 1516 NZST on 17 June 1996, and (b) vertical distribution of ash particles at 1500 NZST 17 June 1996. The vertical source was assumed to be 500 m thick from 6750 m to 7250 m in elevation.

Figure 11. Isopach distribution for the June 17 eruption as predicted by the ASHFALL model using fall velocity distribution 1 and the observed winds from the 00 UTC June 17 rawinsonde launch. Note, the location of Paraparaumu is marked by the P.

Figure 12. Isopach distribution for the June 17 eruption as predicted by the ASHFALL model using fall velocity distribution 1 and the high resolution RAMS simulated winds for the location marked R.

Figure 13. Isopach distribution for the 17 June 1996 eruption as predicted by the ASHFALL model using fall velocity distribution 2 and the high resolution RAMS simulated winds for the location marked R.

Figure 14. RAMS/HYPACT simulated distribution of settled ash particles at 0800 NZST on 12 October 1995. The vertical source was assumed to be 3000 m thick from 7000 m to 10000 m in elevation.

Figure 15. RAMS/HYPACT simulated distribution of ash particles above 1500 m elevation at 2300 NZST 11 October, and 0100 and 0500 NZST 12 October 1995. The orientation of the plume rotated clockwise with time. The vertical source was assumed to be 3000 m thick from 7000 m to 10000 m in elevation.

Figure 16. Isopach distribution for the 11 October 1995 eruption as predicted by the ASHFALL model using fall velocity distribution 1 and the high resolution RAMS simulated winds for the location marked R.

Figure 17. RAMS/HYPACT simulated distribution of a) settled ash and b) airbourne ash particles at 0000 NZST 15 October 1995. The vertical source was assumed to be 3000 m thick from 7000 m to 10000 m in elevation.

Figure 18. Isopach distribution for the 14 October 1995 eruption as predicted by the ASHFALL model using fall velocity distribution 1 and the high resolution RAMS simulated winds for the location marked R.

List of Tables.

Fall Velocity (cm/s)	Distribution 1 (%)	Distribution 2 (%)
0.25	20	10
0.50	20	10
0.75	20	10
1.00	20	10
1.25	20	10
1.75	--	10
2.25	--	10
3.00	--	10
4.00	--	10
5.00	--	10

I r_0 (m)	I u_0 (m/s)	θ_0 (k)	τ	Final plume height (km)
varying τ				
225	150	800	10000	11.7
225	150	800	1000	10.4
225	150	800	100	10.2
varying θ				
225	150	1000	1000	10.5
225	150	800	1000	10.4
225	150	600	1000	10.2
varying u_0				
225	200	800	1000	10.8
225	150	800	1000	10.4
225	75	800	1000	9.3
varying r_0				
275	150	800	1000	11.1
225	150	800	1000	10.4
175	150	800	1000	9.6
125	150	800	1000	8.6
Extreme Combinations				
275	200	1000	10000	11.5

125	75	600	100	8.9
00 UTC June 17, 1996 - Cool and dry				
225	150	800	1000	10.40
18 UTC October 11, 1995 - warm and moist				
225	150	800	1000	10.31
04 UTC October 14, 1995 - warmest and most moist.				
225	150	800	1000	10.44

Fig. 1

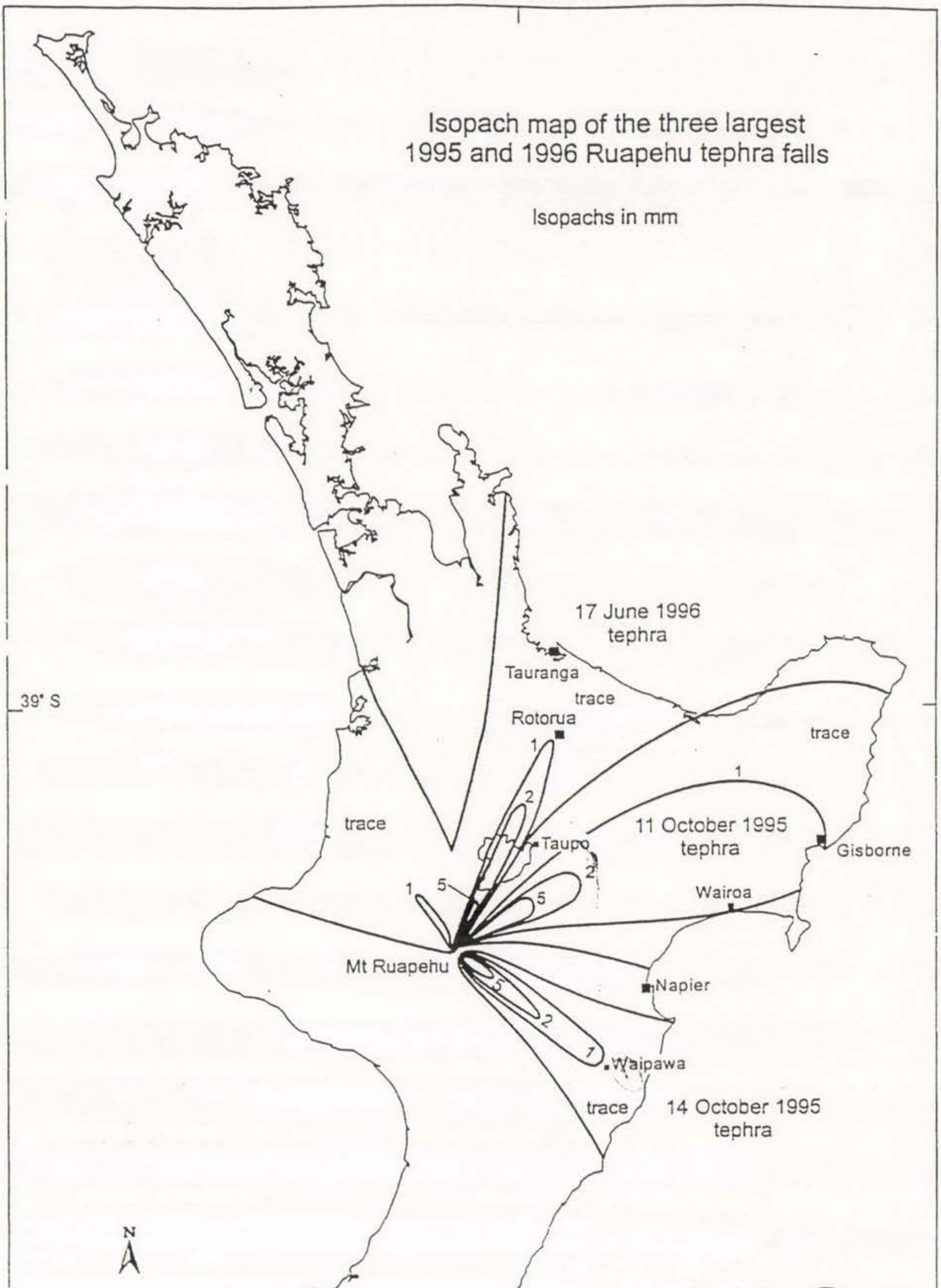

Isopach map of the three largest
1995 and 1996 Ruapehu tephra falls
Isopachs in mm
17 June 1996
tephra
Tauranga
trace
Rotorua
39° S
trace
1
2
trace
Taupo
11 October 1995
tephra
Gisborne
Wairoa
1
5
Mt Ruapehu
Napier
Waipawa
trace
14 October 1995
tephra
N
0 20 40 km
176° E
MASSEY
UNIVERSITY

fig. 2

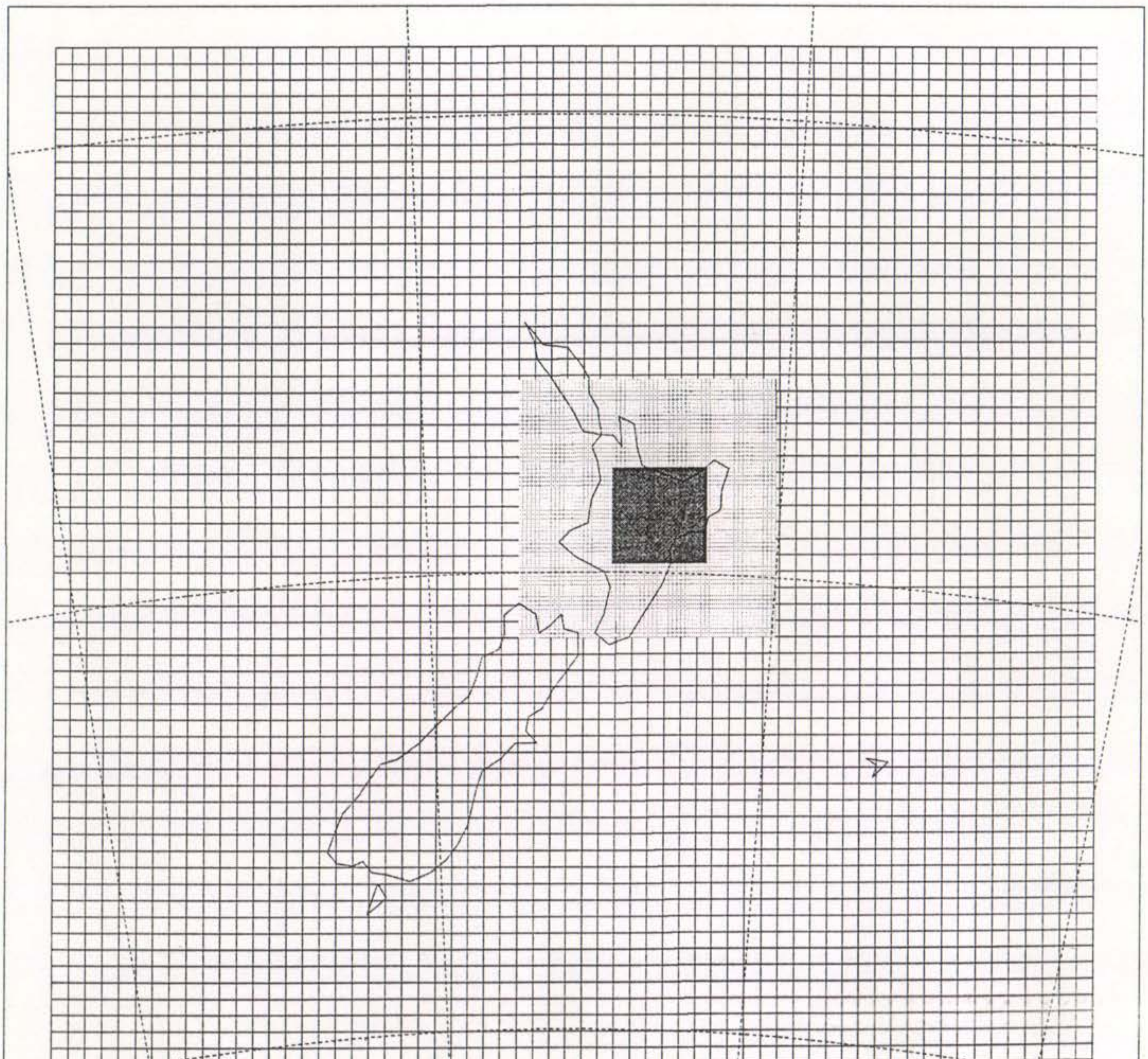
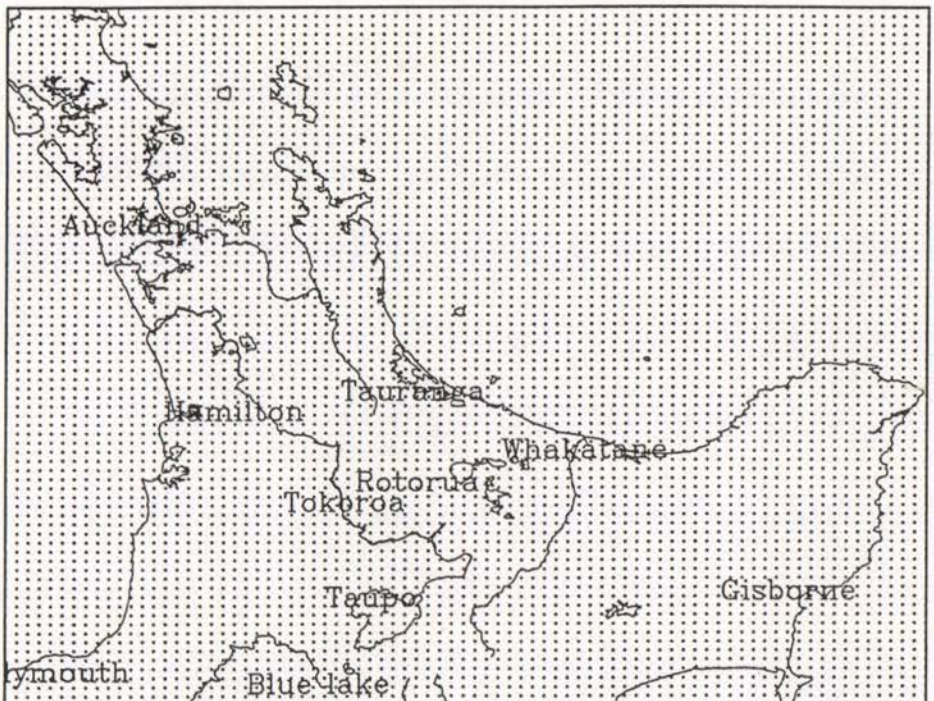
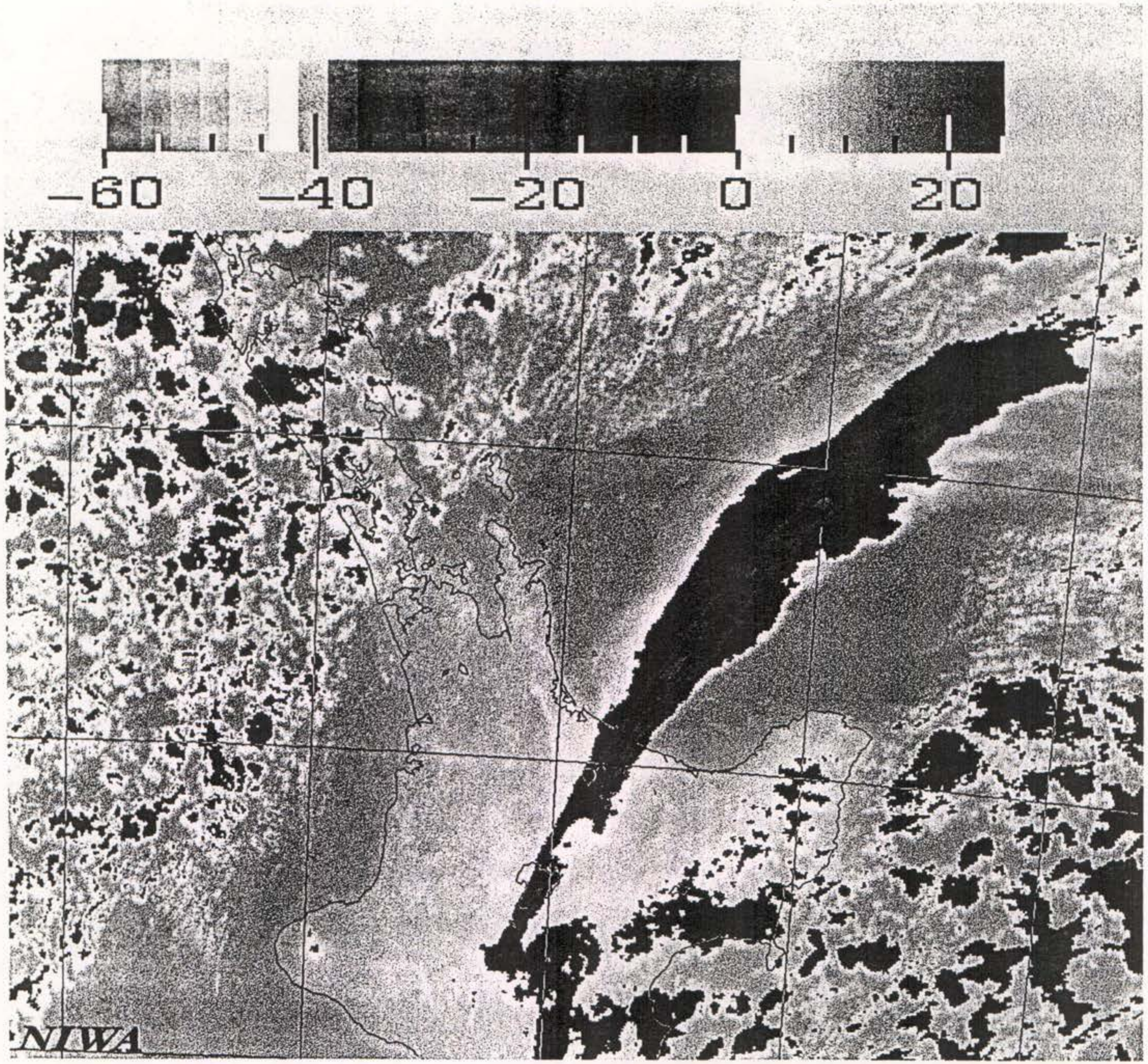


Fig. 3

TEPHRA


Auckland
Tauranga
Hamilton
Whakatane
Rotorua
Tokoroa
Taupo
Gisborne
ymouth
Blue lake
Ruapehu
Napier

NOAA14, Orbit: 07543, 0312-0316 UTC 17JUN96 T4 (11 µm °C)



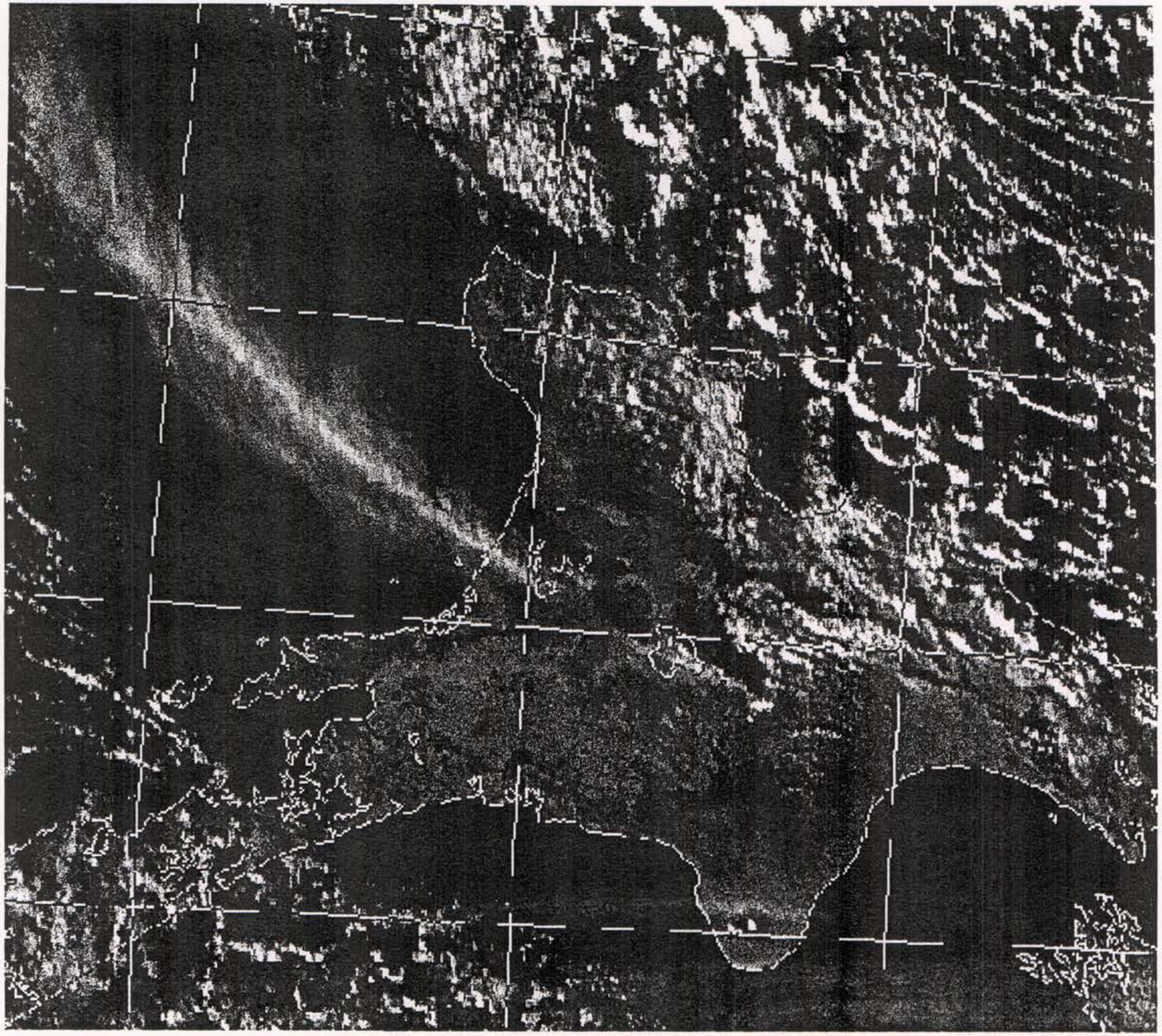
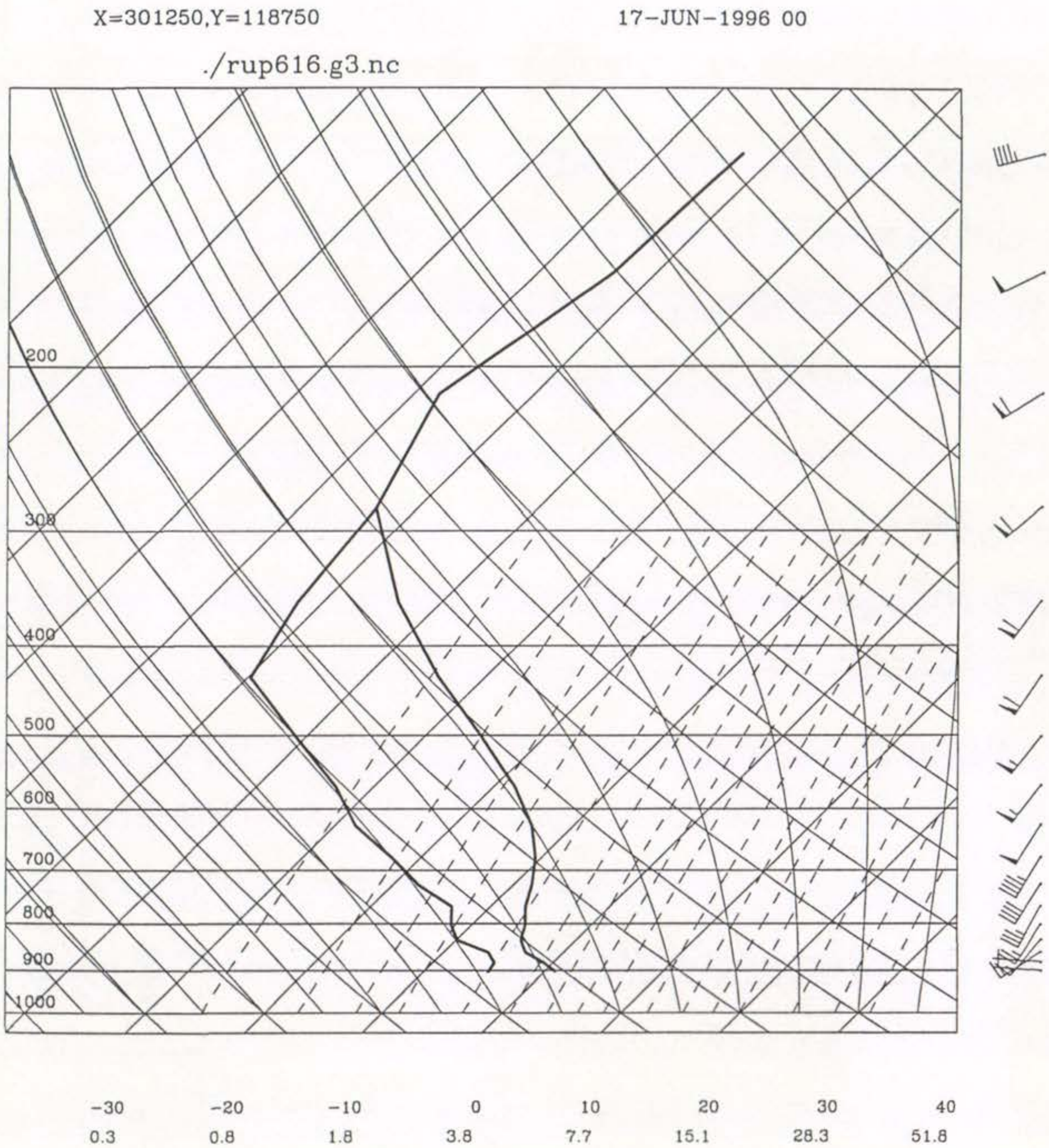


Fig 4a

Fig. 5



X=301250,Y=118750
17-JUN-1996 00
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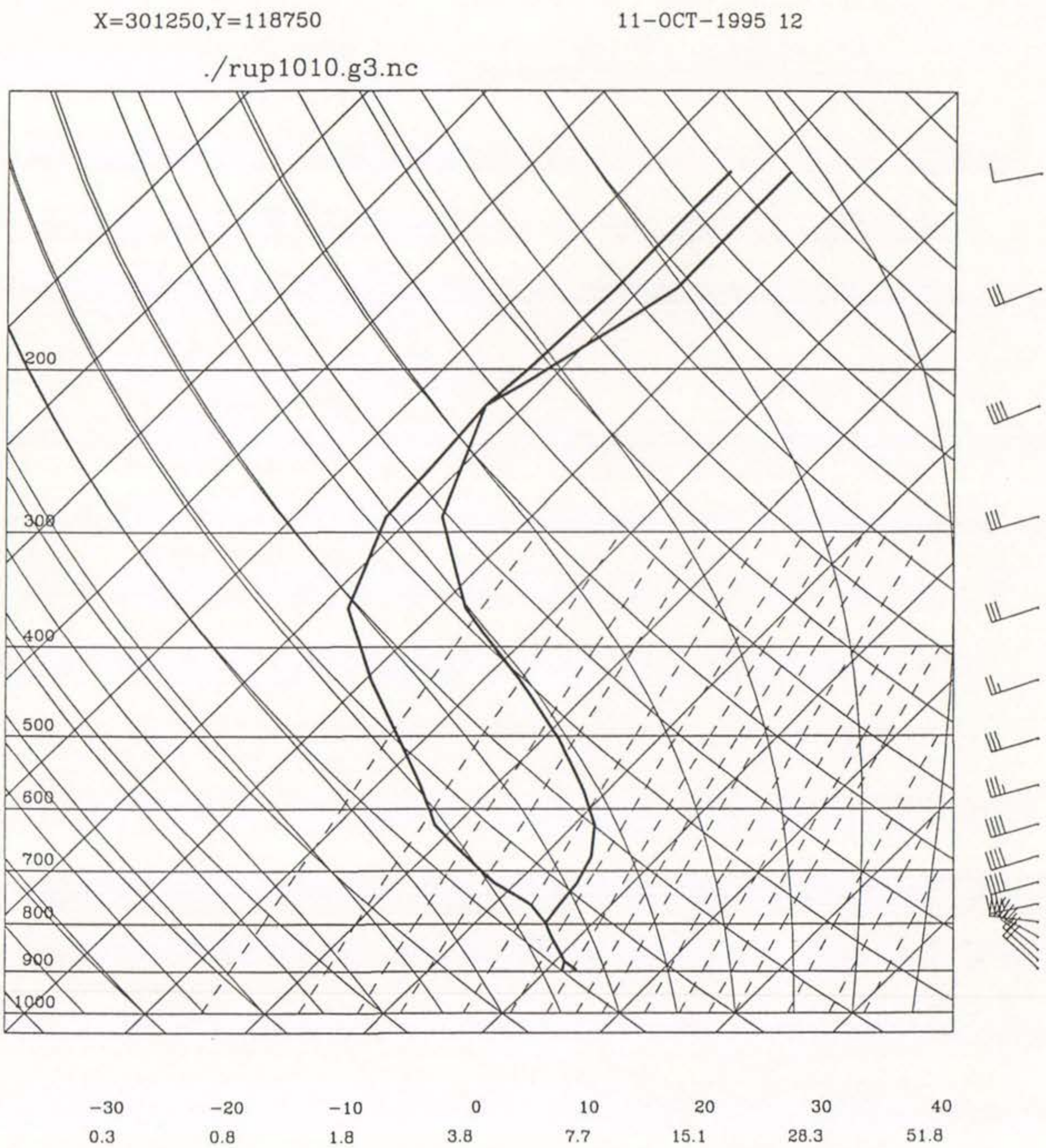
200
300
400
500
600
700
800
900
1000
-30
-20
-10
0
10
20
30
40
0.3
0.8
1.8
3.8
7.7
15.1
28.3
51.8

Fig 6



X=301250,Y=118750
11-OCT-1995 12
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200
300
400
500
600
700
800
900
1000
-30
-20
-10
0
10
20
30
40
0.3
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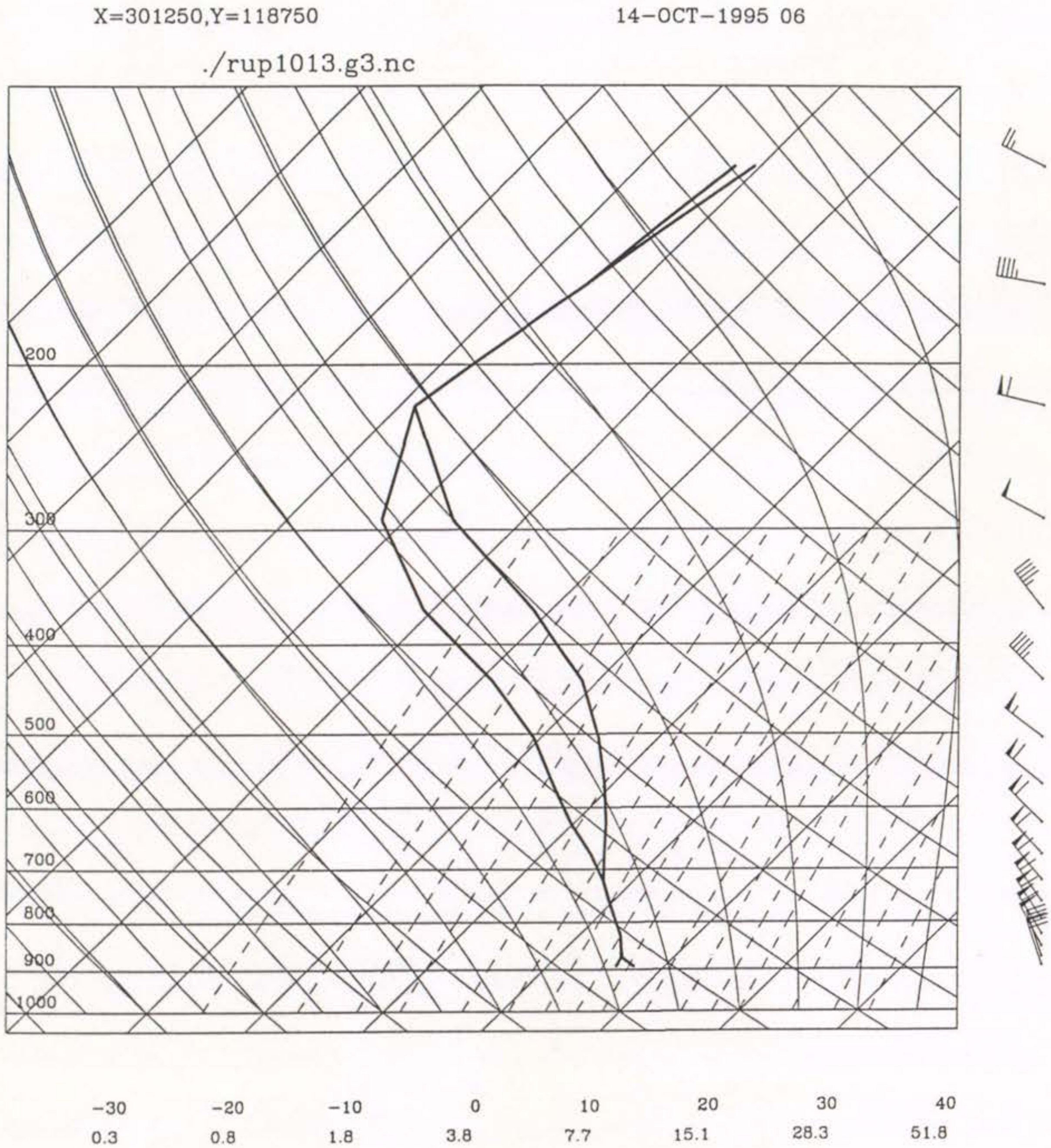
1.8
3.8
7.7
15.1
28.3
51.8

Fig 7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14-OCT-1995 06
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200
300
400
500
600
700
800
900
1000
-30 -20 -10 0 10 20 30 40
0.3 0.8 1.8 3.8 7.7 15.1 28.3 51.8

Fig. 8

RAMS/HYPACT

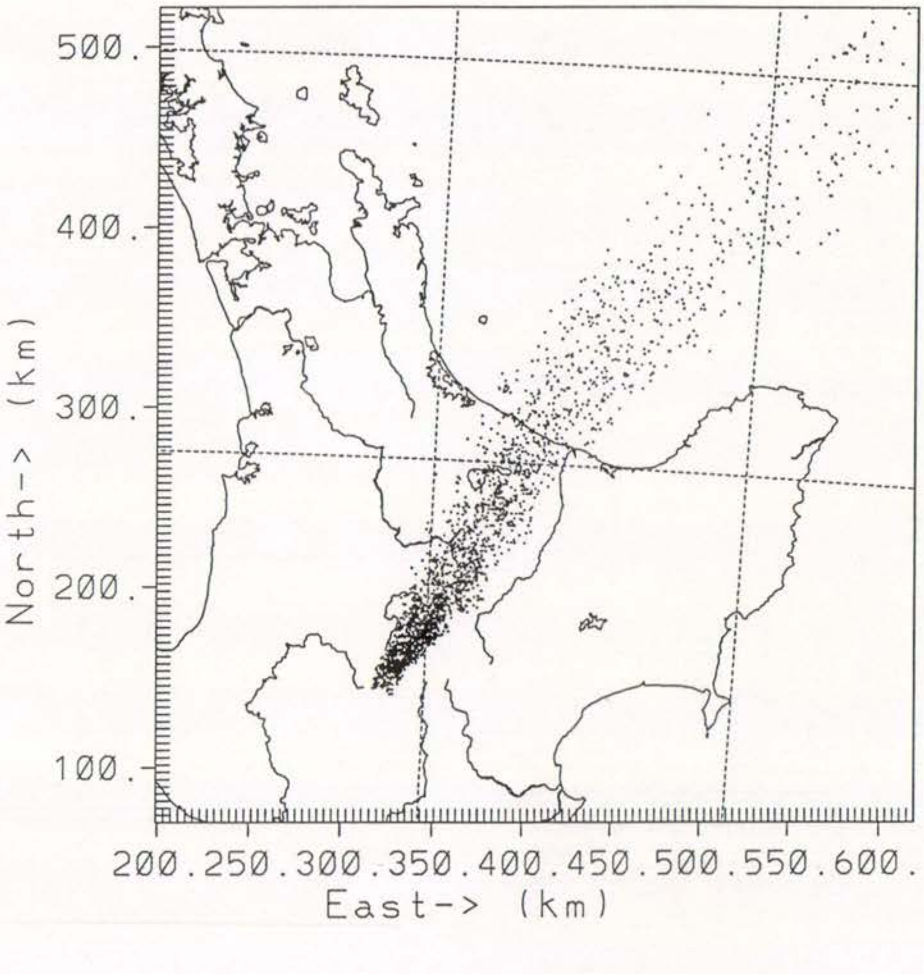

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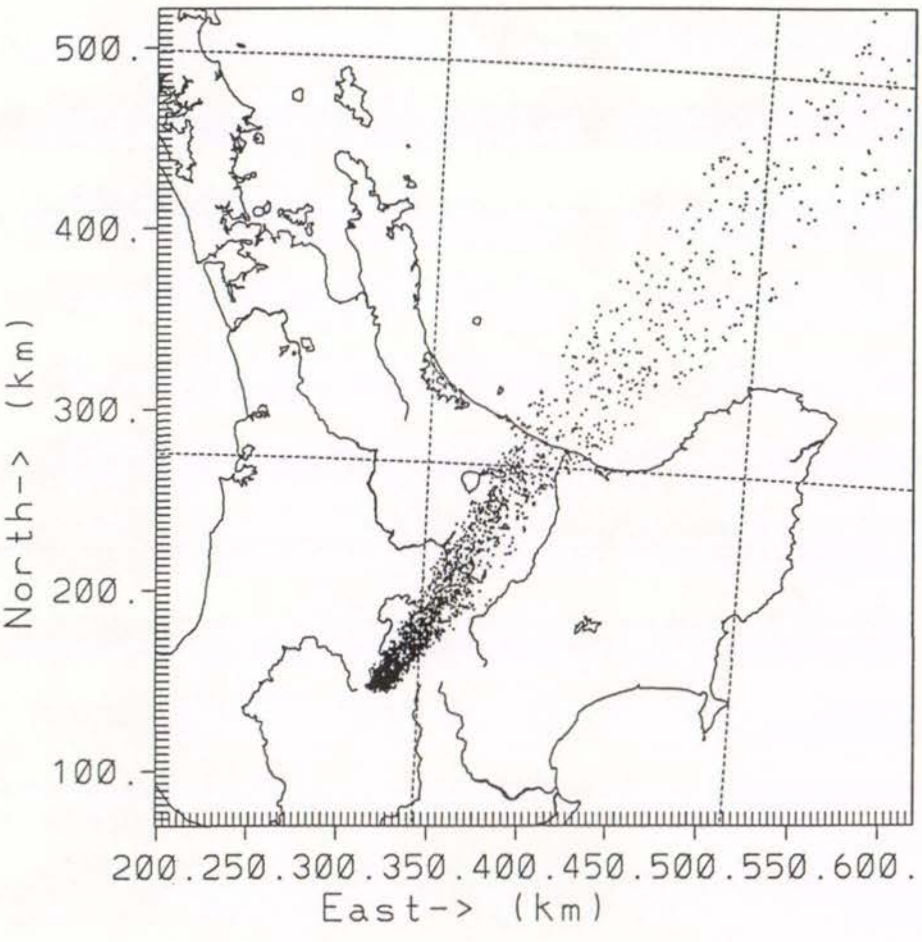
Fig. 9

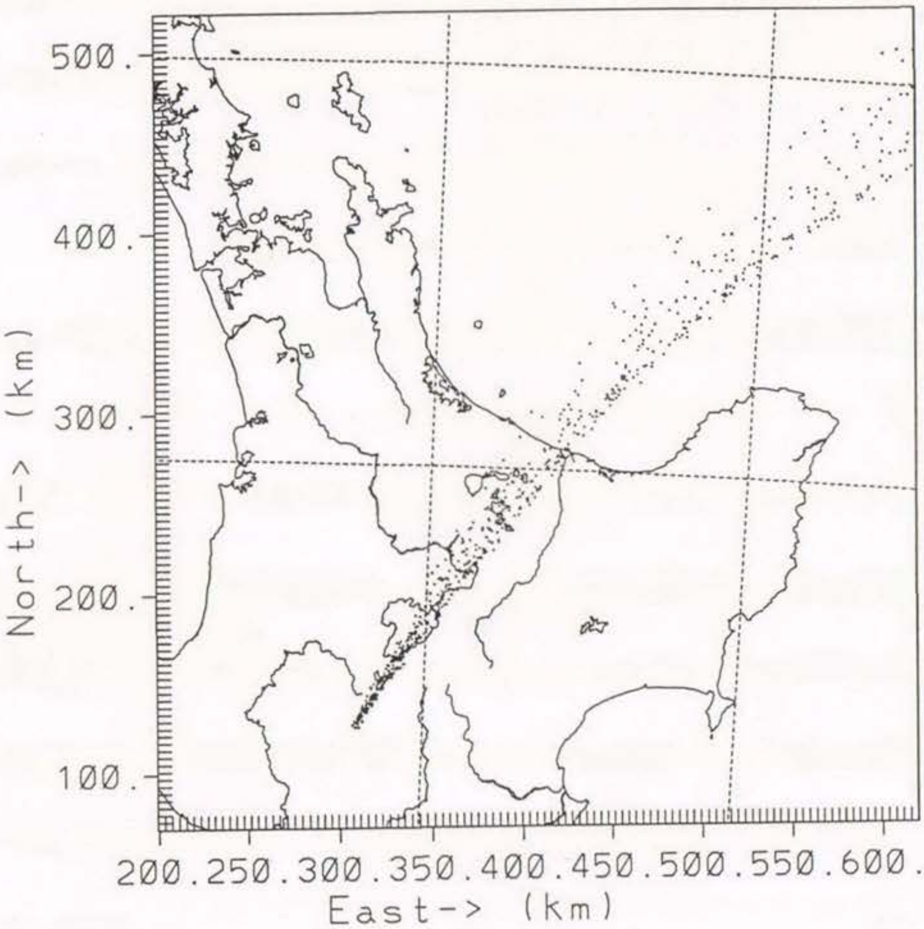
RAMS/HYPACT



0900 UTC

Fig 10 a

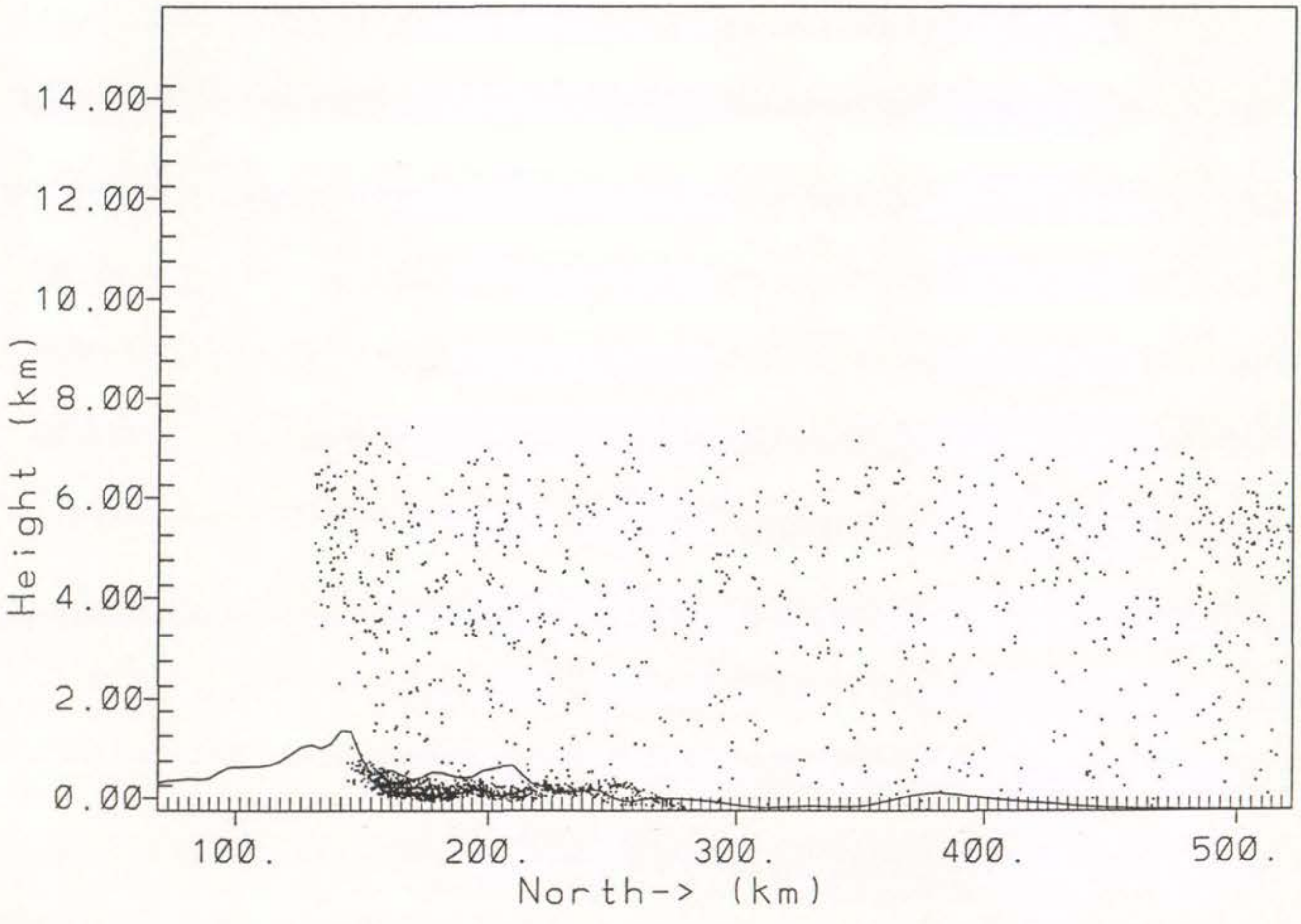
RAMS/HYPACT



0316 UTC

Fig. 10 b

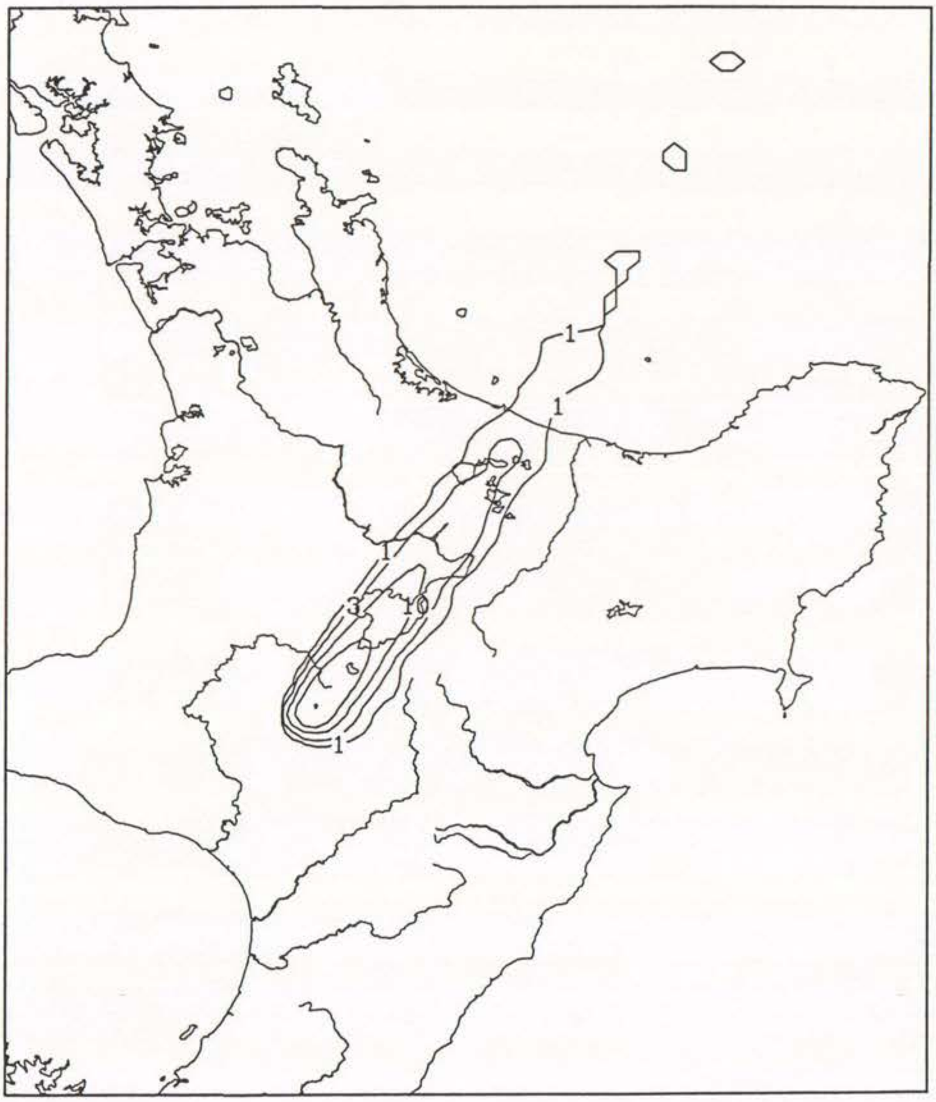
RAMS/HYPACT



x = 315.34 km   0300 UTC

Fig. 11

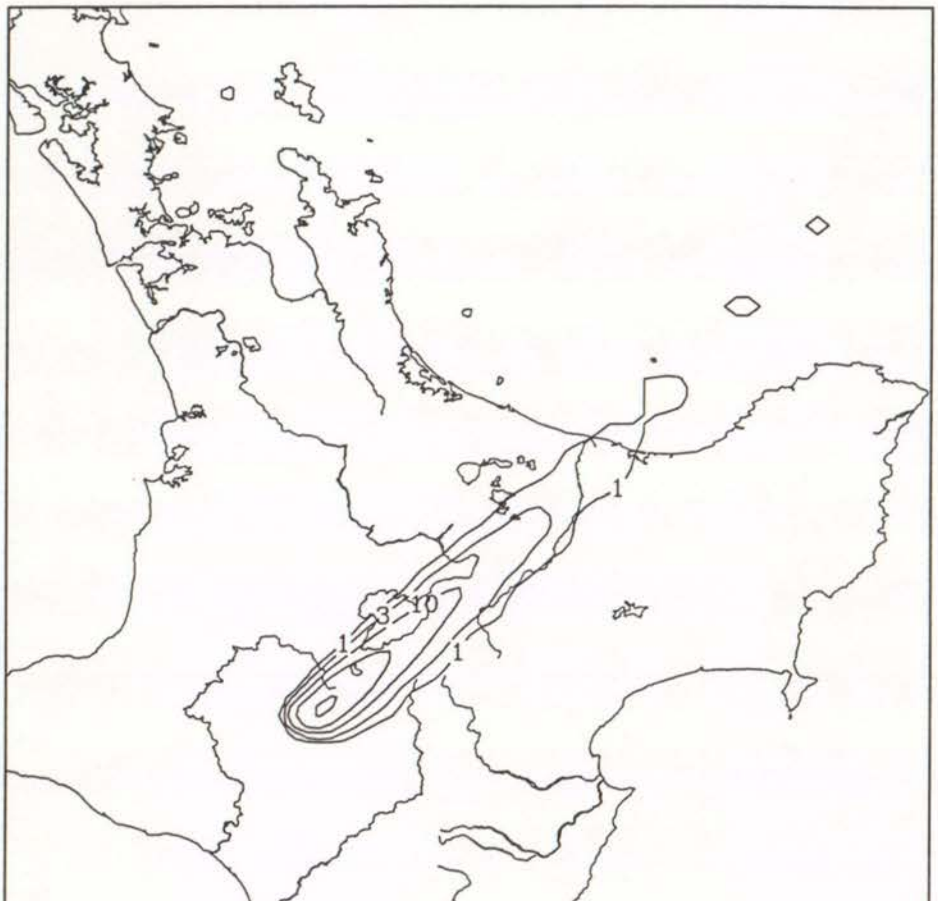
TEPHRA ASHFALL (mm) June 17, 1995



CONTOUR FROM 1 TO 300 BY 0

Fig 12

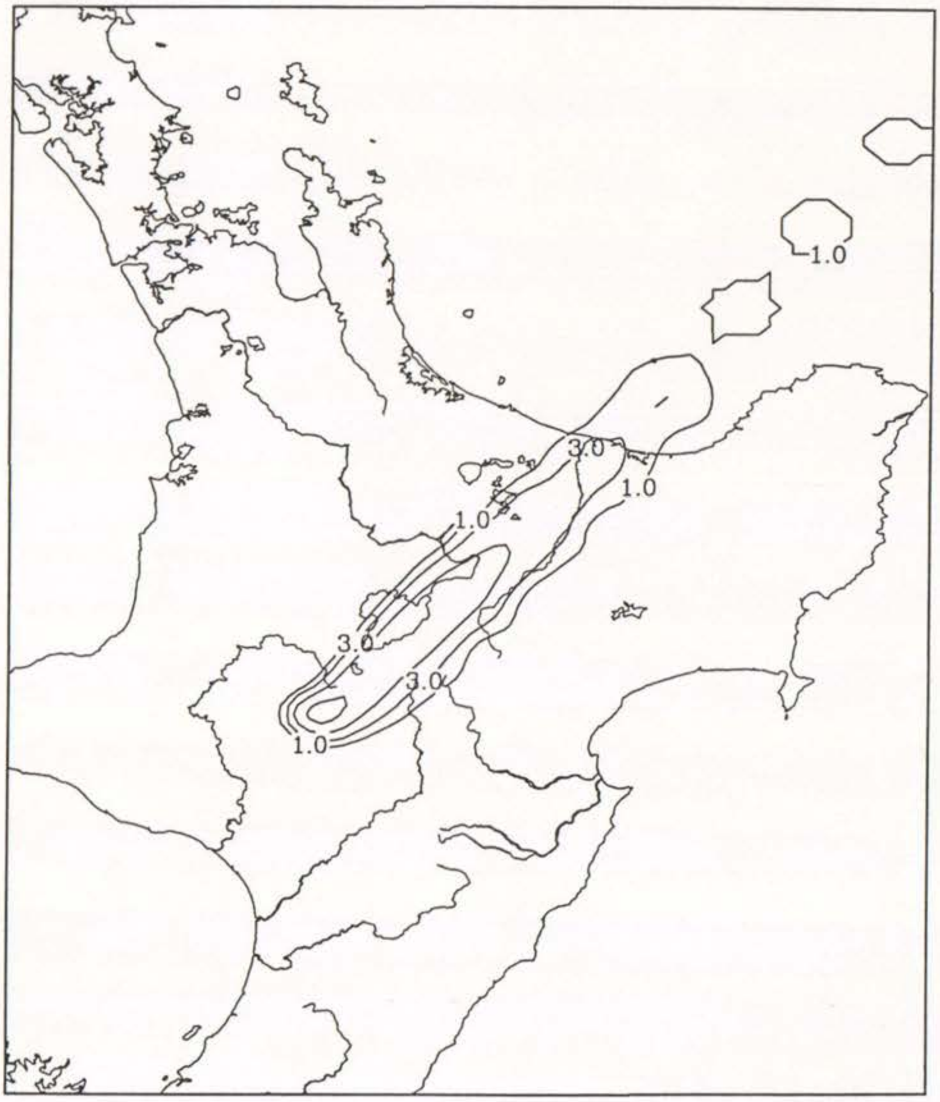
TEPHRA ASHFALL (mm) June 17, 1996



CONTOUR FROM 1 TO 300 BY 0

Fig 13

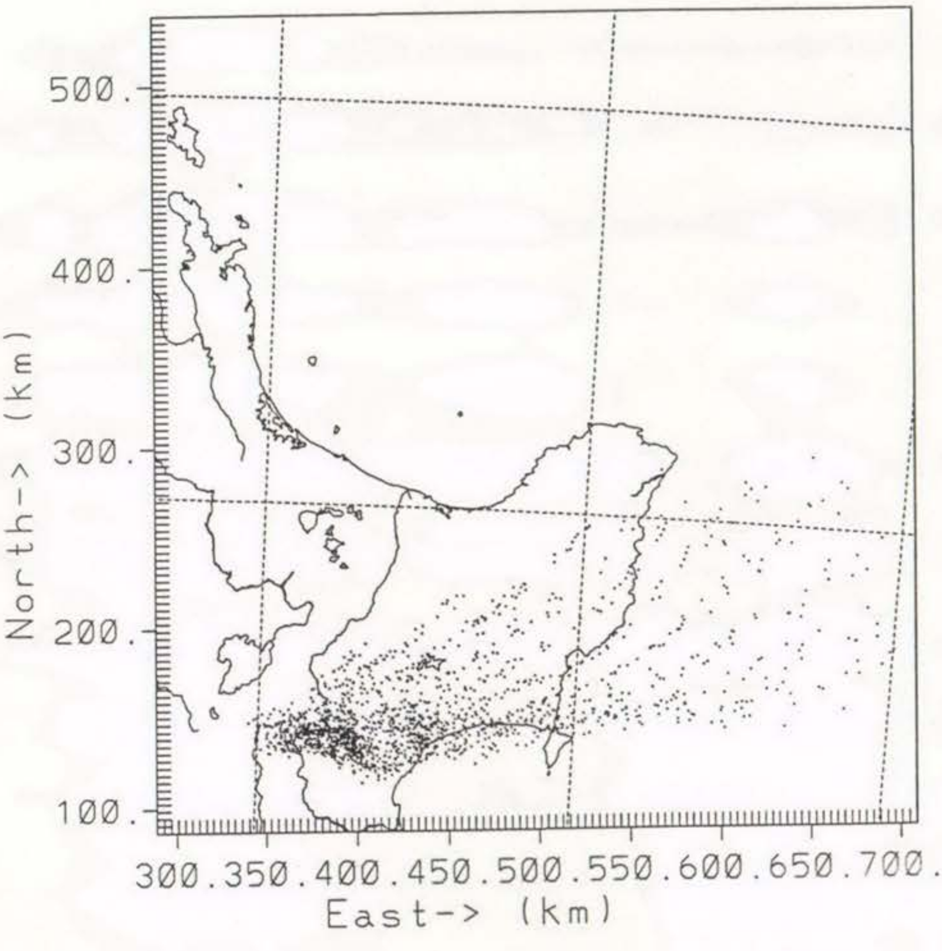
TEPHRA ASHFALL (mm) June 17, 1996



CONTOUR FROM 1 TO 300 BY 0

Fig 14

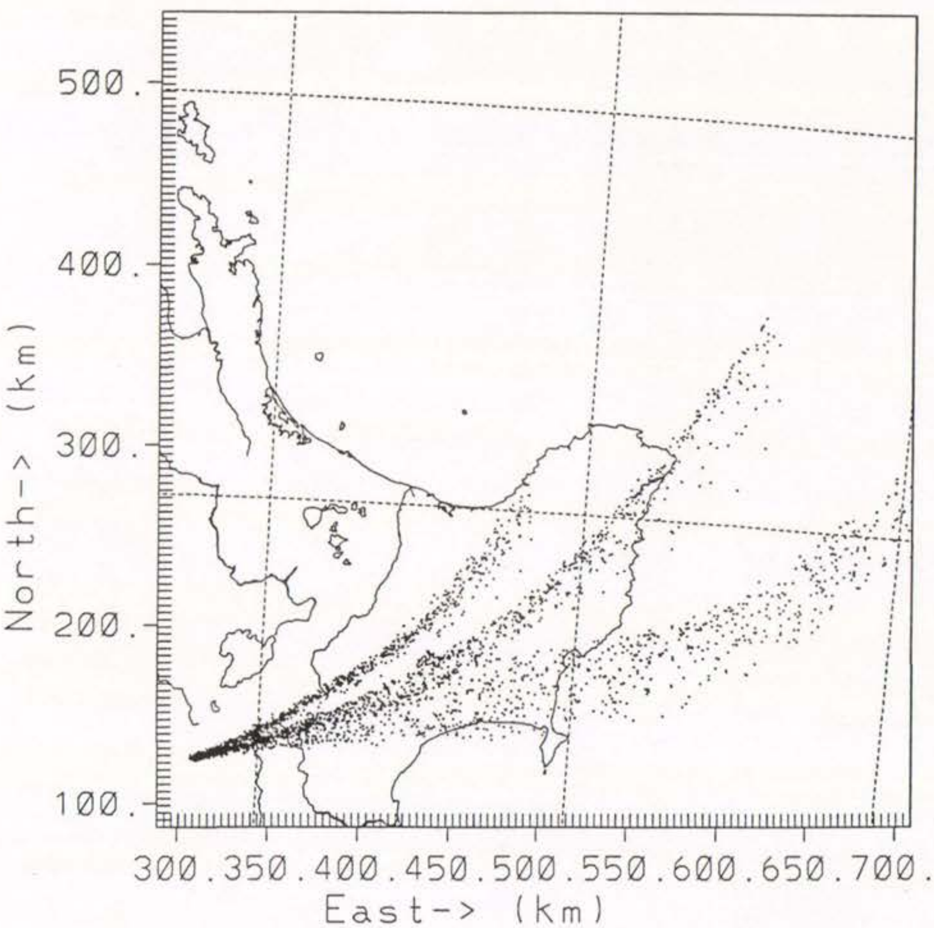
RAMS/HYPACT



2000 UTC

Fig. 15

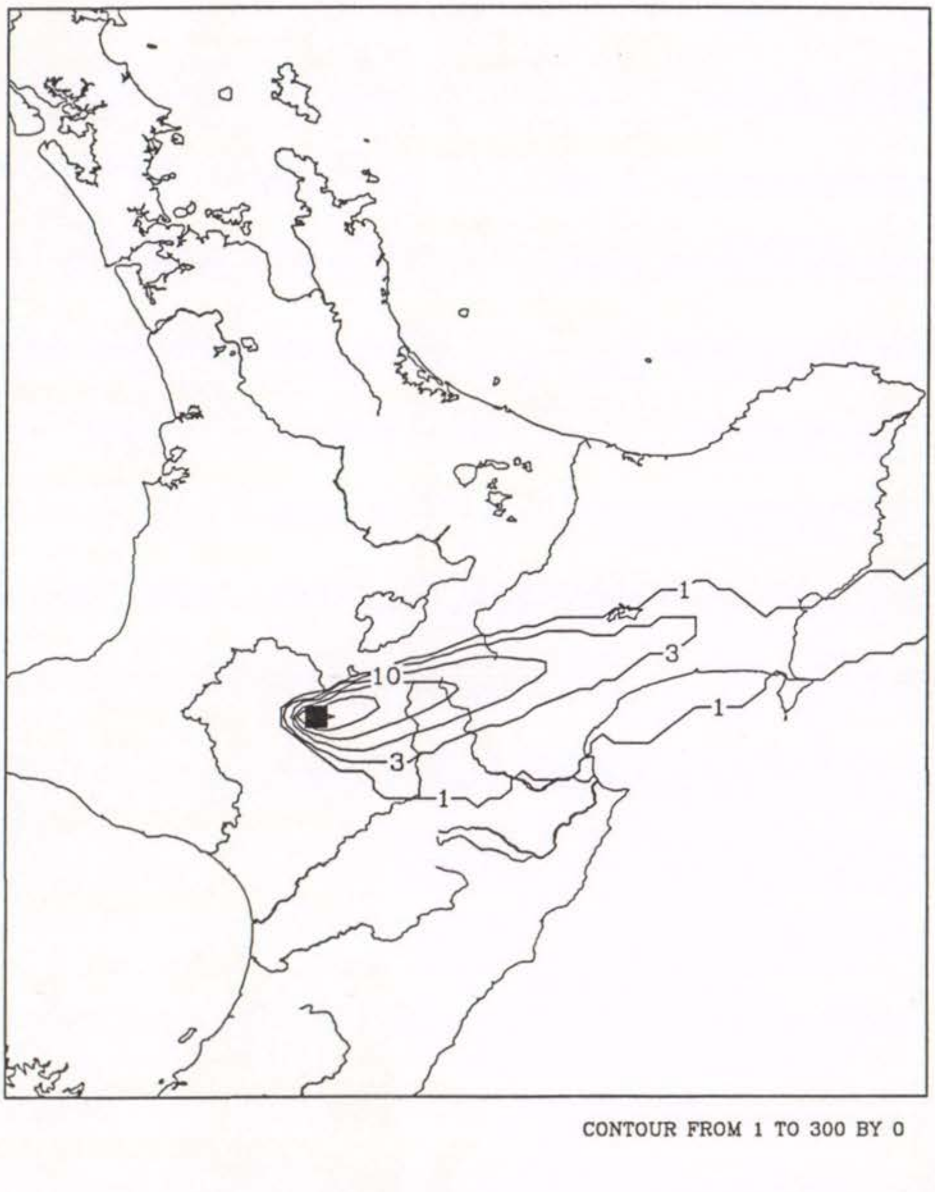
RAMS/HYPACT



z = 6750.0 m   1800 UTC

Fig. 16

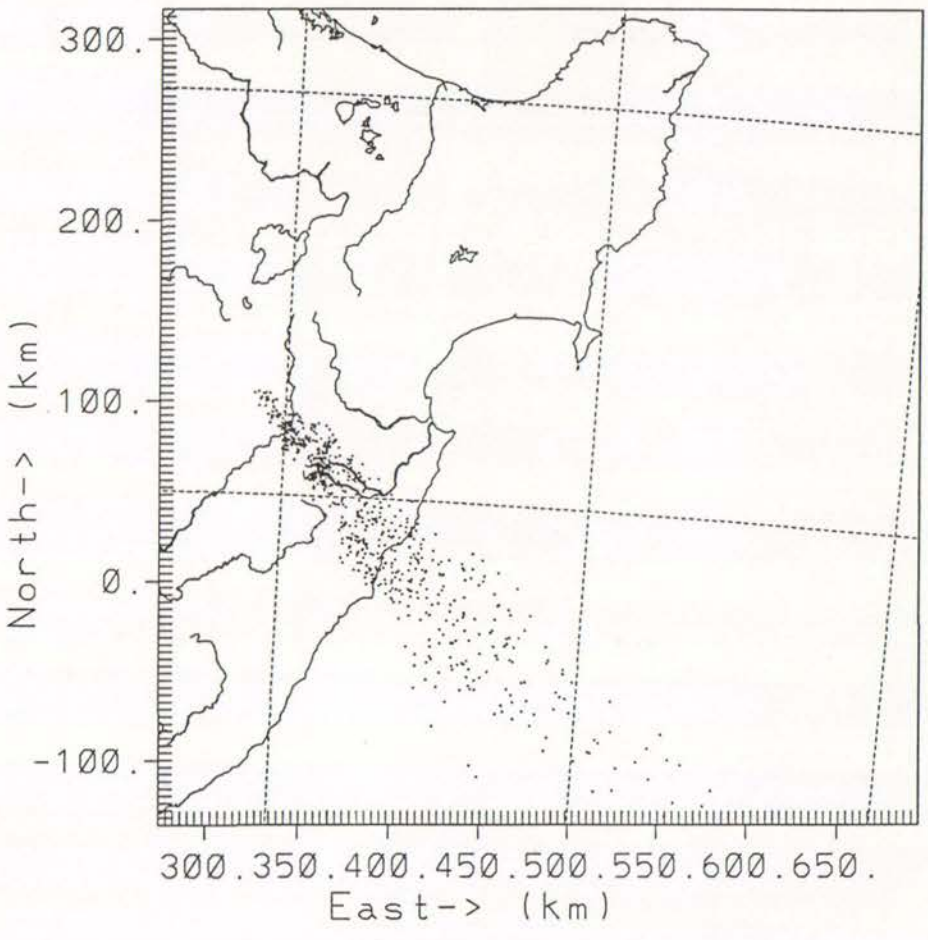
TEPHRA ASHFALL (mm) Oct 11, 1995



CONTOUR FROM 1 TO 300 BY 0

Fig 17 a

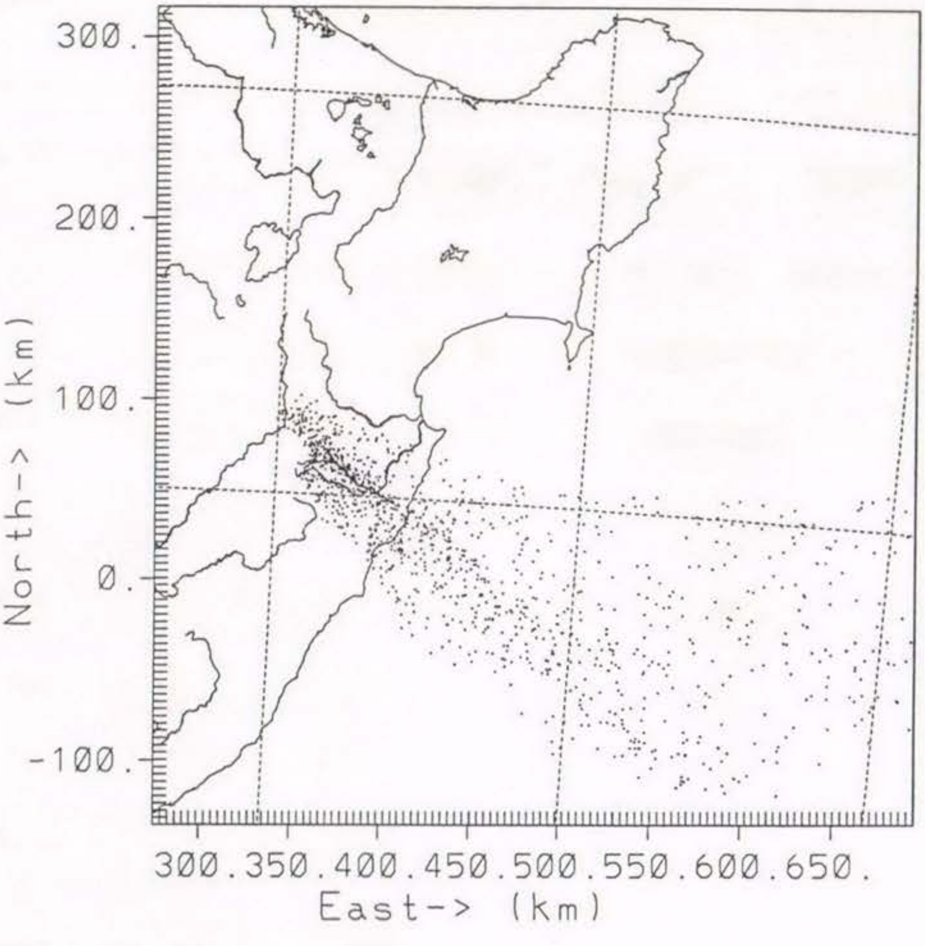
RAMS/HYPACT



1100 UTC

Fig 17b

RAMS/HYPACT



z = 6750.0 m 0800 UTC

Fig. 18

TEPHRA ASHFALL (mm) Oct 14, 1995

CONTOUR FROM 1 TO 300 BY 0

Fall Velocity (cm/s)	Distribution 1 (%)	Distribution 2 (%)
0.25	20	10
0.50	20	10
0.75	20	10
1.00	20	10
1.25	20	10
1.75	--	10
2.25	--	10
3.00	--	10
4.00	--	10
5.00	--	10

I r_0 (m)	I u_0 (m/s)	θ_0 (k)	τ	Final plume height (km)
varying τ				
225	150	800	10000	11.7
225	150	800	1000	10.4
225	150	800	100	10.2
varying θ				
225	150	1000	1000	10.5
225	150	800	1000	10.4
225	150	600	1000	10.2
varying u_0				
225	200	800	1000	10.8
225	150	800	1000	10.4
225	75	800	1000	9.3
varying r_0				
275	150	800	1000	11.1
225	150	800	1000	10.4
175	150	800	1000	9.6
125	150	800	1000	8.6
Extreme Combinations				
275	200	1000	10000	11.5
125	75	600	100	8.9

Table 2 (cont)

00 UTC June 17, 1996 - Cool and dry				
225	150	800	1000	10.40
18 UTC October 11, 1995 - warm and moist				
225	150	800	1000	10.31
04 UTC October 14, 1995 - warmest and most moist.				
225	150	800	1000	10.44

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