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Taihoro Nukurangi

Estimating Regional Methane Emissions Using Aircraft Measurements of Vertical Concentration Profiles

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NIWA Science and Technology Series No. 37

ISSN 1173–0382

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Final Report of NSOF
NSO603

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NIWA
Wellington

April 1997

Cataloguing in publication

Wratt, D.S.
Estimating Regional Methane Emissions using Aircraft Measurements of Vertical Concentration Profiles / D.S. Wratt, M.J. Bell, G.W. Brailsford, A.M. Bromley and K.R. Lassey.
Wellington, NZ: National Institute of Water and Atmospheric Research Ltd.,
1997. (NIWA science and technology series : 37)

ISSN 1173-0382
ISBN 0-478-08384-X

I Wratt, D.S. II National Institute of Water and Atmospheric Research Ltd. III Title. IV Series.

The *NIWA Science and Technology Series* is published by NIWA (the National Institute of Water and Atmospheric Research Ltd), New Zealand. It supersedes *NIWA Ecosystems Publications* (ISSN 1172-3726; published by NIWA Ecosystems, Hamilton), *New Zealand Freshwater Research Reports* (ISSN 1171-9842; published by NIWA Freshwater, Christchurch) and *Miscellaneous Publications, New Zealand Oceanographic Institute* (ISSN 0510-0054).

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EXECUTIVE SUMMARY

This report covers the first stages of developing and testing methods for estimating methane emissions from a New Zealand agricultural region, using methane concentration measurements from an aircraft.

The concept behind the aircraft measurements is as follows. Air blowing on to a coastal region after a long over-ocean trajectory will have methane concentrations close to global background levels. As this air flows over farms on the coastal plain its methane content will gradually increase as it picks up emissions from livestock. The differences between vertical methane profile measurements a few tens of kilometres inland, and similar profiles at the coast, give a measure of the amount of methane picked up during the airflow across the plains, and hence of the average surface methane flux.

In this report we:

- Describe the aircraft measurements and the techniques used for analysing the resulting samples.
- Outline the equations governing methane concentrations in the atmosphere over an agricultural region.
- Develop a simple regional budget model to provide initial estimates of surface methane fluxes from the aircraft profile measurements.
- Describe a more sophisticated approach we are developing for surface methane flux estimation from aircraft measurements. This will use the RAMS mesoscale meteorological model to simulate local air flows and turbulence intensities on experiment days, and then use the HYPACT pollution model to simulate the dispersion of methane under the modelled atmospheric conditions.
- Summarise livestock numbers in the Manawatu experimental region, and livestock methane emission rates from the scientific literature and from New Zealand measurements.
- Present methane profile concentrations measured on three separate days, discuss the meteorological conditions influencing the transport and dispersion of methane on these days, and use the simplified regional budget model to estimate surface methane fluxes from the aircraft measurements.
- Describe spatial and temporal variability in measured methane concentrations during a fourth experiment day.

Our case studies show that increases in atmospheric methane as air travels across the Manawatu region are readily detectable with our measurement and analysis techniques. Methane emission rates calculated by applying our simple mathematical model to the aircraft measurements varied between 1.0 x 10^{-7} g/m^2/s (3.2 tonnes/km^2/year) and 1.3 x 10^{-6} g/m^2/s (41 tonnes/km^2/year). For comparison, the average surface methane flux over the Manawatu calculated from stock

numbers and emission factors is 3.1 x 10^{-7} $g/m^2/s$ (9.8 $tonnes/km^2/year$). Thus the methane fluxes calculated from the aircraft measurements are of the expected order of magnitude, but vary by up to a factor of 4 from the fluxes estimated from standard livestock emission factors and livestock data under the assumption that stock are distributed uniformly over the Manawatu.

There are several possible reasons for these discrepancies:

- Stock are probably unevenly distributed over the experimental region,
- There may be other methane sources in parts of the Manawatu as well as ruminant animals,
- The standard emission factors may be inappropriate for the pasture types and season.
- The airflows are sometimes quite complex so that important assumptions made in developing our simple estimation equation are sometimes not valid.

The complex airflows include sea breezes, land breezes, and cold air drainage flows off inland mountains. These complications are most marked when the large - scale pressure gradient over New Zealand is weak.

We make several recommendations for the next year of the aircraft methane profile research programme, including:

- Information must be obtained on the spatial variation of livestock populations.
- The methane profile measurements should be made on days with uniform onshore winds.
- Methane concentrations should also be measured at the ground, underneath the aircraft profile locations.
- Pilot balloon wind measurements to a height of at least 2 km should be made during the aircraft methane measurements.
- More observations should be made of temporal and spatial methane concentration variability, and the sampling time over which each sample is collected should be extended to average out some of this variability.
- Ways of reducing the uncertainty bars on the gas chromatograph methane measurements should be investigated.
- Linked dispersion and mesoscale modelling techniques must be implemented, for interpreting the profile measurements and for estimating surface methane fluxes. (These will contain fewer assumptions than the simple methane estimation model used in this pilot study).

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1. INTRODUCTION

New Zealand's predominant anthropogenic greenhouse gas emissions are methane, carbon dioxide and nitrous oxide. Our national net per capita emissions of methane during 1990 from anthropogenic activities including agriculture may have been as large as 630 kg (MFE 1994), which is much higher than the estimated global average per-capita emission of 70 kg[1]. In fact calculations using Global Warming Potentials from the 1995 IPCC[2] report (Schimel et al, 1996) suggest New Zealand's current methane emissions will have a greater greenhouse warming effect integrated over the next 100 years than our current carbon dioxide emissions.

Important global anthropogenic sources of methane include coal mining, the natural gas and petroleum industry (including venting from natural gas wells, and leaks from pipelines), wet rice cultivation, domestic ruminants (sheep, cows, deer, goats), animal wastes, domestic sewage treatment, landfills and biomass burning (Houghton et al 1992). Natural sources of methane include wetlands and termites. More than 75% of New Zealand's anthropogenic methane emissions are thought to come from ruminant livestock, with sheep providing about 58% of the ruminant source and cattle about 38%. These estimates are based on a model of microbial processes in the rumen of the animals (Ulyatt et al, 1992). The predominant sink of methane is reactions with the hydroxyl radical in the atmosphere, and there is also some uptake by soils. This soil uptake may be affected by changes in land use or by enhanced nitrogen fertiliser input (Houghton et al, 1992).

As a signatory to the United Nations Framework Convention on Climate Change (UNFCCC) , New Zealand has undertaken to report its anthropogenic emissions of methane, and agreed to "limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs" (IUCC, 1992). In future there may be a call for protocols to the UNFCCC which set constraints on national emissions of individual greenhouse gases. Because New Zealand's methane emissions result from economically vital agricultural activities, accurate information on source magnitudes is very important.

The standard way to estimate emissions is to make a national inventory of animal numbers, landfills, natural gas pipelines and other sources, and apply standard emission factors for each (IPCC, 1995). This can be improved by using country specific emission factors based on actual measurements of animal methane releases, related to animal type or feed conditions, as is being done in a collaborative research project between AgResearch and NIWA (Lassey et al, 1995).

This report outlines preliminary steps towards a complementary approach, which uses aircraft-measured vertical profiles of methane concentrations upwind and downwind of an extensive agricultural region. For this pilot study we chose the Manawatu Plain, near Palmerston North.

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[1] This figure was obtained by dividing the IPCC estimate of the 1980 - 90 global anthropogenic methane emission of 375 million tonnes (Schimel et al, 1996), by the United Nations estimate of the 1990 global population (5.3 billion).

[2] IPCC = Intergovernmental Panel on Climate Change

Our goals were:

- To investigate the influence of the air flow and weather conditions on atmospheric methane concentration patterns.
- To begin developing methods for estimating regional methane sources from the aircraft methane profile measurements, which take into account the influences of local meteorology.
- To compare surface methane fluxes estimated from the profiles, with surface fluxes inferred from data on animal populations and per animal emissions.
- To improve the aircraft methane and nitrous oxide sampling strategies to be used in the next phase of the experimental work.

We expected the aircraft profile method would provide an independent check on methane emissions estimated by standard emissions inventory methods. It should also indicate whether there were any major methane sources which had been missed by an inventory, and it automatically allows for animal-to-animal variations in methane emissions (a potential problem with the inventory approach). Also, the profile technique provides a potential method for estimating regional emissions of nitrous oxide, another greenhouse gas resulting from agricultural activities.

In this report we outline the theoretical basis for the profile method, examine the meteorological conditions on four days during which we made methane measurements from an aircraft, and consider the implications of these conditions for estimates of methane concentrations. We develop a simple regional budget model for initial estimates of surface methane fluxes from emissions measurements, and apply it to data from two of the field campaign days.

Unfortunately, estimating surface methane fluxes from aircraft profile measurements is complicated by local meteorological effects such as cold air drainage flows off the inland terrain, sea breezes and land-breezes. We conclude that airflow over the Manawatu may rarely be uniform for long enough for our simple regional budget model to be properly applicable. We outline initial work with a mesoscale meteorological model and a trace gas dispersion model, which take account of local variability in the meteorology, and we describe the air flows simulated by the mesoscale model on one of our experiment days. Implementation of the dispersion model is planned during 1997.

We complete the report by recommending improvements to aircraft sampling and computer modelling techniques for future application to this project, which has now been allocated funding by the Foundation for Research, Science and Technology for the period July 1996 - June 1998.

2. FIELD MEASUREMENTS AND METHANE SAMPLE ANALYSIS.

This study focuses on part of the Manawatu plains, a region of pastoral agriculture on the lower west coast of New Zealand's North Island (Figure 1), for westerly (onshore) winds. At the location chosen for the measurements, the plains extend about 40 km from the coast to the Tararua Mountains, which in this location rise to about 550 m above sea level.

As maritime air travels eastwards over this pastorally farmed area it will accumulate methane and nitrous oxide emissions from agricultural activities, so that concentrations of these gases are expected to increase with distance inland. As explained in detail later, it should be possible to estimate the amount of methane emitted from sources on the ground by comparing the height integral of methane through the atmospheric boundary layer downwind of a region of interest, with the height integral of the methane concentration in the "background" air just upwind of the coast. A second approach is to compare vertical methane profiles above various locations with the concentrations which are predicted by a coupled air flow / trace gas dispersion model, and then adjust the surface release estimates until the measured and modelled profiles show reasonable agreement. Precise measurements of methane concentrations are required for both of these techniques.

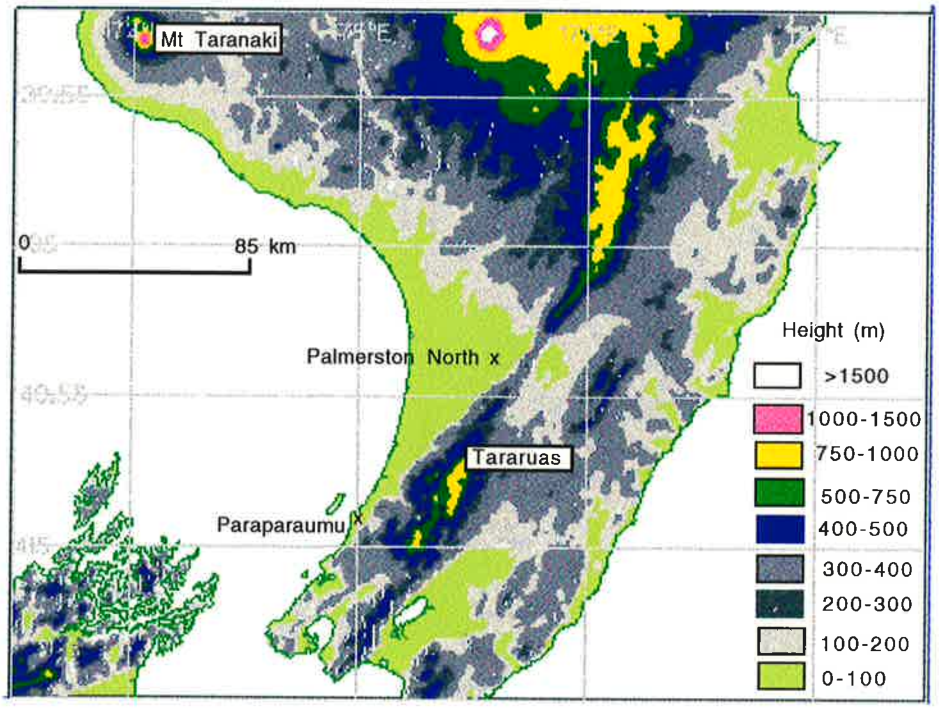

Figure 1: The lower North Island of New Zealand, showing various locations mentioned in the text. The Manawatu Plain is the lowland area extending west of Palmerston North.

Methane Sample Collection and Analysis

Air is collected from a sampling system mounted on a Piper Cherokee aircraft, and analysed later for methane concentrations. The air samples are collected in 1 litre glass flasks with Teflon O-ring seals. Twenty flasks are contained in a large aluminium case along with a Geographic Positioning System (GPS), pressure sensor, and control electronics. A second case contains a power supply and a two stage pump unit. A Teflon air line runs from the wingtip through the wing and into the aircraft cabin, where it connects to the pump unit. The sampler purges the plumbing with a total of 10 litres of air before flushing the sample flask with 10 litres. It then collects an air sample to a pressure of 2,750 Hectopascals (about 2.7 times atmospheric pressure).

The air speed of the aircraft is about 40 m/s. The time taken to fill the 1 litre flask (not including the flushing times) is about 6 seconds. Thus each flask sample represents an average over a horizontal distance of about 240 m.

The samples are returned to NIWA's Wellington laboratory for analysis. There they are dried cryogenically, and the methane concentrations are measured using a gas chromatograph with a flame ionisation detector. Generally five separate aliquots from each flask are run through the gas chromatograph, interspersed with standard samples containing similar methane concentrations. The standard deviation σ of the five flask replicate measurements is used to calculate a standard error as follows, ($N = 5$):

$$\sigma_{\overline{X}} = \frac{\sigma}{\sqrt{N-1}} = \frac{\sigma}{2}$$

This standard error is used as a guide to the measurement uncertainty of the calculated mean concentration from the five samples, and is plotted as an error bar on many of the graphs in Sections 6 - 9. Small sampling theory (Spiegel, 1961) shows there is a probability of 50% that the mean concentration from a large number of measurements from the flask will lie within $\pm\sigma/2$ of the mean from five samples. The precision and absolute accuracy of NIWA gas - chromatograph methane measurements is discussed in more detail by Lowe et al (1994).

Supporting Meteorological Measurements

There are two sources of supporting meteorological information: Observations which are made routinely for weather forecasting and climate monitoring, and special observations made as part of the methane measurement programme.

There are several ground-level wind and climate measurement sites near the Manawatu experimental region. Details of these are provided in the discussion of the meteorology of the experimental days (Sections 6 - 8). The nearest routine upper air meteorological observations are from Paraparaumu Airport (about 80 km to the south-south-west) and from New Plymouth Airport (about 190 km to the north-east). Both of these sites have shortcomings for characterising likely lower atmospheric characteristics over the experimental region. About 8 km to the NW of Paraparaumu is an island with a highest point 520 m above sea level. At Paraparaumu the coastal plain is only about 12 km wide, and bounded on the east by the Tararua mountains. This island and the nearby mountains can cause substantial differences in low level winds between Paraparaumu and the Manawatu experimental site. A major volcanic mountain (Mt Taranaki, 2627 metres) near New Plymouth has a substantial influence on lower atmosphere wind profiles at New Plymouth Airport.

For the first methane sampling flight on 25 May 1995, the main effort was in developing and proving the aircraft sampling system. Some plain language weather observations were noted during the flights, but no special supporting meteorological measurements were made. For the methane measurements flights on 8/6/95 and 29/2/96 small balloon-borne sondes were released from the experiment region to obtain information on the height variation of temperature and humidity, and hence on the atmospheric mixing depth. (The sondes used were "Airsondes" manufactured by A.I.R of Boulder, Colorado. These sondes are designed particularly for profiling the atmospheric boundary layer, and carry wet and dry bulb temperature sensors and a pressure sensor). For the 29/2/96 methane measurement flight we also tracked the sounding balloons by optical theodolite, to determine the lower-atmosphere wind profile.

3. EQUATIONS DESCRIBING METHANE CONCENTRATION

Consider the mass balance in a hypothetical large rectangular box with sides several kilometres long, and a height of several hundred metres, placed over part of the experiment region. The equation for the concentration C of a trace gas (such as methane) at a point within this box is (Stull, 1988):

$$\frac{\partial C}{\partial t} + \mathbf{U} \bullet \nabla C = v_c \nabla^2 C + S_c \qquad (1)$$

where: $U = (U_1, U_2, U_3)$ is wind velocity at the point,
v_c is the molecular diffusivity of the trace gas
S_c covers sources or sinks for processes within the box, such as chemical reactions.

In the atmosphere, turbulent diffusion is generally much larger than molecular diffusion, so the term $\nabla^2 C$ can be ignored. Surface sources and sinks, including animal sources, will be specified at the boundaries of the box. Thus in the absence of significant bulk sources or sinks within the box, equation (1) becomes

$$\frac{\partial C}{\partial t} = -\mathbf{U} \bullet \nabla C \qquad (2)$$

At this scale, the flow can be assumed incompressible (Stull, 1988), ie

$$\nabla \bullet \mathbf{U} = 0 \qquad (3)$$

hence

$$\mathbf{U} \bullet \nabla C = \nabla \bullet (\mathbf{U}C) \qquad (4)$$

Thus integrating (2) through the full volume of the box gives:

$$\int_V \frac{\partial C}{\partial t} dV = -\int_V \nabla \bullet (\mathbf{U}C) dV = -\oint_S (\mathbf{U}C) \bullet dS \qquad (5)$$

Decompose the concentration and wind field into mean (indicated by an overbar) and fluctuating(indicated by an apostrophe) components[3]:

$$\mathbf{U} = \overline{\mathbf{U}} + \mathbf{U}', \qquad C = \overline{C} + C' \qquad (6)$$

Then if we substitute (6) into (5) and take a time average (indicated by an overbar) we obtain:

$$\underset{A}{\int_V \frac{\partial \overline{C}}{\partial t} dV} = \underset{B}{-\oint_S \overline{\mathbf{U}} \cdot \overline{C} \bullet dS} - \underset{C}{\oint_V \overline{\mathbf{U}'C'} \bullet dS} \qquad (7)$$

This equation really just expresses conservation of mass in the box. It states that the rate of change of trace gas concentration in the box (term A) depends on transport in and out of the box by the mean flow (term B), turbulent fluxes of trace gases through the sides and top of the box (part of term C) and source or sink fluxes at the base of the box (also part of term C).

Simplified Equation for Pilot Study Methane Flux Estimates.

In this section we derive a simple equation for trace gas concentration in air flowing across the Manawatu from the ocean, under a number of simplifying assumptions. One of these assumptions is that while wind speed and direction may vary with height (and slowly with time), the wind speed v and direction θ at a given height and time do not vary with geographical location.

This simple equation ("the simple regional budget model") is being used for first estimates of surface emission rates in this pilot study. For the future we are developing a more sophisticated surface emission estimation technique, based around mesoscale air flow and trace gas dispersion models. This will allow us to relax many of the assumptions compared to those used in this "simple regional budget" model.

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[3] The approach taken in equation 6 and equation 7 is called Reynolds Averaging, and breaks the flow and concentration into a slowly varying "mean" component and a more rapidly varying turbulent component (e.g. Holton, 1992). For example, in equation 7, $\overline{C}$ could be the average concentration over 30 minutes at some point, and this 30 minute average could change gradually during the day, at rate $\frac{\partial \overline{C}}{\partial t}$.

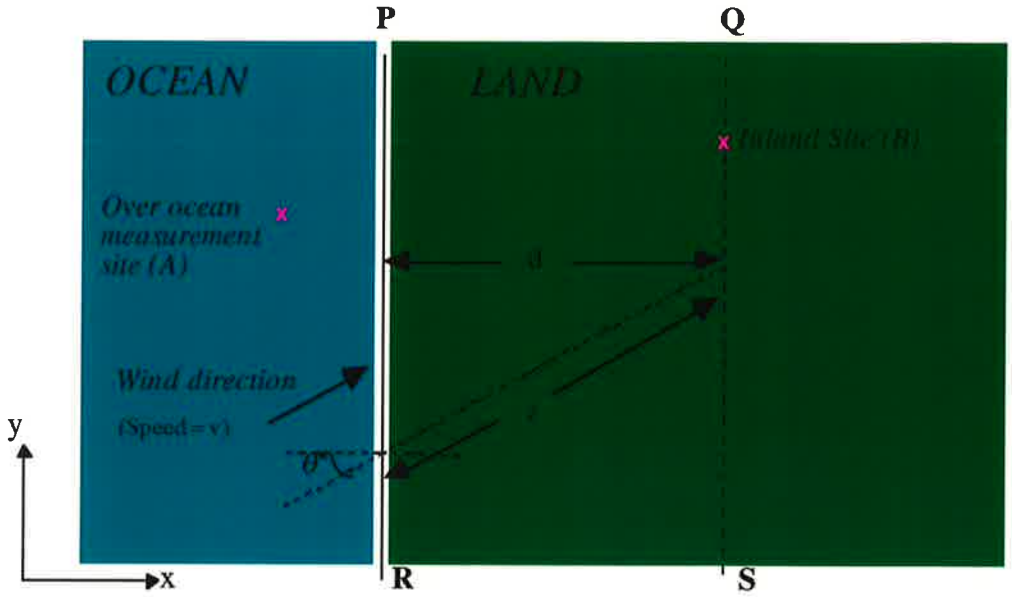

Figure 2: Geometry for onshore flow across a coastal plain.

Suppose the sides of the hypothetical box described in the previous two pages are orientated parallel and normal to the coast, with the y axis of the coordinate system pointing parallel to the coast and the x axis pointing inland. Suppose the upwind edge of the box lies along the coast. Thus the corners of the base of this box are given by points P, Q, S, and R in Figure 2.

Suppose the “low methane” air blowing in off the sea is horizontally homogeneous (no x or y variation in concentration). Suppose also that over the land there is no methane concentration variation along lines parallel to the coast (ie that surface methane sources have no y dependence). Then the net mean and turbulent transport across box sides PQ and RS will be zero. Suppose also that the mean flow is substantially stronger than the turbulent fluctuations in the wind, so that the turbulent transport of methane (term C of equation 7) is small compared to the mean transport when integrated across sides RP and SQ. Then for a steady state situation ($\int_V \frac{\partial \overline{C}}{\partial t} dV = 0$), equation (7) becomes:

$$\int_{\text{Side } SQ} \overline{U}_x \overline{C(x)} dxdy - \int_{\text{Side RP}} \overline{U}_x \overline{C(x)} dxdy - \int_{\text{Ground Surface}} \varphi \text{dxdy} = 0 \qquad (8)$$

where φ is the surface methane flux (kg/m^2), and we assume the box is tall enough for there to be negligible methane flux through the top. Given our assumption of uniformity parallel to the coast, we can remove the y integration from all of these equations, leaving:

$$\int_0^H \overline{U_x}\,\overline{C(X)}dz - \int_0^H \overline{U_x}\,\overline{C(0)}dz - \int_0^X \varphi(x)dx = 0 \qquad (9)$$

where H is the height of the box, and X is the distance from the coast to side SQ of the box
If we use subscripts A and B for the ocean and inland measurement sites respectively, equation (9) gives:

$$\int_0^H \overline{U}_x \overline{C}_B dz - \int_0^H \overline{U}_x \overline{C}_A dz = \overline{\varphi} d \qquad (10)$$

where $\overline{\varphi}$ is the average net source methane flux between the coast and location B, which can be written in terms of wind speed v and direction θ as:

$$\cos\theta\left(\int_0^H \overline{v}\,\overline{C}_B dz - \int_0^H \overline{v}\,\overline{C}_A dz\right) = \overline{\varphi} d \qquad (11)$$

Given that $\ell = \frac{d}{\cos\theta}$, this can be rewritten as:

$$\boxed{\overline{\varphi} = \frac{\int_0^H \overline{v}\,\overline{C}_B dz - \int_0^H \overline{v}\,\overline{C}_A dz}{\ell}} \qquad (12)$$

This is the "simplified regional budget model" which we will use for preliminary estimates of surface methane fluxes from some of the aircraft measurements in Sections 6 - 8. Like equation 7, it is really just a simple mass balance. It depends on a number of assumptions, including:

- Steady state concentration ($\frac{d\overline{C}}{dt} = 0$).
- Wind speed and direction at a given height are the same over the whole region (wind speed and direction can vary with height however).
- No vertical transport (mean or turbulent) though the top of the box (ie at height H). For example no strong convection, or vertical motion from large-scale convergence or terrain forcing.
- Methane emission rates and concentrations are essentially constant for transects parallel to the coast (ie there is no significant net methane transport parallel to the coast).

The model can cope with an increase of the mixing depth h_i with distance from the coast (as may be the case if a thermal internal boundary layer is present over the land under the incoming marine air (Lyons, 1975)), provided the top height for the integration (H) is greater than this mixing depth.

4. COMPUTER MESOSCALE MODELLING TECHNIQUES.

The observed air flows over the experiment region of the Manawatu are often complex, and often do not satisfy some of the conditions required for equation (12) to apply. For this reason we also implemented a mesoscale meteorological model to simulate the air flow, turbulence and temperature structure on days of interest. In the coming year we will link a pollution dispersion model to the mesoscale model, and determine the surface methane fluxes necessary to optimise the match between modelled and measured aircraft methane profiles. These optimised fluxes will become our improved surface methane emission estimates for the region.

The Mesoscale Air Flow Model

The mesoscale model used in this study is RAMS (Regional Atmospheric Modeling System), which was developed at Colorado State University (Pielke et al, 1992). More details about the model and its configuration are given in Appendix 1. To obtain the high spatial resolution desirable for describing the relevant terrain and capturing mesoscale air flow features, the model is run on a series of nested grids. The parent grid covers the whole of New Zealand, with a horizontal grid spacing of 32 km. The second grid has a horizontal grid spacing of 8 km, and the finest grid (which covers the experimental region) has a grid spacing of 2 km. The vertical spacing for all three grids begins at 50 m for the lowest level. This spacing increases with height up to the top of the model domain at 20 km. There are 30 vertical levels.

For this pilot study the model was initialised homogeneously[4] using surrogate upper air profiles of wind, temperature and moisture developed from upper air soundings at Paraparaumu and New Plymouth. In future work we will initialise the model using real spatially varying meteorological fields from an analysis of the large scale weather patterns, and use a scheme in which the developing large-scale fields are used to guide the mesoscale model through time. This facility, using large-scale fields from analyses carried out routinely by the European Centre for Medium Range Weather Forecasting (ECMWF), has been recently implemented within other NIWA research projects.

Dispersion model

We planned to use the Hybrid Particle and Concentration Transport Model (HYPACT), currently being developed at Colorado University. HYPACT uses air flow and turbulence information from RAMS to predict the transport, dispersion and concentration of specified near-ground pollutant releases. In this study we planned to use it to simulate the behaviour of animal methane releases rather than industrial pollution releases.

Unfortunately we found a number of errors in the pre-release version of HYPACT provided by Aster (the company which administers RAMS and HYPACT). We are resolving some of these errors in consultation with Aster, and should be able to use HYPACT with more confidence in the future. We have not presented our initial methane dispersion modelling runs in this report because they are still very much at the development stage.

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[4] Homogeneous initialisation means that the atmospheric temperature, moisture and wind fields used for the start of the model run are assumed to be the same everywhere over the model domain at a given pressure level, although they are allowed to vary with height.

5. LIVESTOCK NUMBERS, AND STANDARD EMISSION FACTORS

One of our goals in this initial study was to compare regional methane emissions estimated from the aircraft measurements of methane profiles, with regional methane emission estimates built up from an "emissions inventory" of animals and other methane sources and "emission factors" summarising average methane emissions per animal.

Livestock Numbers and Distribution

For this pilot study we explored various national and local sources of information, but were forced to use monthly animal numbers for the region as a whole because we could not quickly obtain information on the spatial variations within the region. In the coming year we propose a substantial effort to obtain improved information on animal populations and their distribution.

Monthly animal numbers for the whole of the Manawatu Regional Council area for July 1994 - July 1995 are listed in Appendix 2. Table 1 below summarises information for the period May - July 1995, which includes the dates of the main case studies of sections 6 - 9. The Manawatu Regional Council (excluding Palmerston North City) covers an area of 253,164 hectares.

MANAWATU STOCK NUMBERS BY MONTH				
Estimates are stock numbers at the start of the month.				
(000 head)		May	Jun	Jul
		1995	1995	1995
Open Sheep				
	Adults	742.7	724.4	710.5
	Hoggets	0.0	0.0	302.5
	Lambs - milk	0.0	0.0	0.0
	Lambs - grass	426.0	357.4	0.0
	Total	1168.7	1081.8	1013.1
Open Beef				
	Beef Cattle	93.1	88.2	115.7
	Beef Weaners	30.7	30.7	28.0
	Calves	28.1	28.1	0.0
	Total	151.9	147.0	143.7
Open Dairy				
	Dairy Cattle	60.1	57.5	72.20
	Dairy Weaners	16.3	16.3	16.40
		76.4	73.8	88.60
	Calves	16.7	16.6	0.00

Table 1: Stock numbers for the Manawatu Regional Council area, for the period including case study dates. (Courtesy NZ Meat and Wool Boards' Economic Service). Note that the abrupt changes in some subclasses between June and July are due to reclassification of lambs as hoggets, calves as weaners, and weaners as cattle.

Methane Emission Factors for Livestock

Table 2 summarises livestock emission factors using data recommended by the IPCC guidelines (IPCC, 1995) as suitable for Oceania. Table 3 summarises emission factors calculated by K. Lassey of NIWA through relating each animal class to a "standard breeding ewe" on the basis of feed intake. Methane emission is calculated as 7.25% of gross energy intake, which for the "standard breeding ewe" averages 31.6 g/day of methane (Lassey et al, 1992). Table 3 is consistent with direct methane emission measurements made on grazing sheep in the Manawatu by NIWA and AgResearch scientists. The IPCC-based estimates of Table 2 probably underestimate emissions from animals grazing on New Zealand's high quality pastures, especially for dairy cows whose milk production is close to doube the average estimated for Oceania (Lassey et al, 1997). On the other hand, production of methane from animal manure is probably less than the IPCC - based estimates.

IPCC Default (Tier 1) Methane Emission Factors for Oceania				
	Enteric Fermentation (kg/head/year)	Manure Management (kg/head/year)	Total (kg/head/year)	Total (g/head/second)
Sheep	8	0.28	8.28	2.63E-04
Dairy cows	68	32	100	3.17E-03
Non-dairy cattle	53	6	59	1.87E-03

Table 2: Default IPCC livestock methane emission factors for Oceania (IPCC, 1995)

NIWA Methane Emission Factors for New Zealand				
		Ewe equivalent	Emission factor (kg/head/year)	Emission factor (g/head/second)
Sheep	Adults	1.0	11.5	3.66E-04
	Hoggets	0.6	6.9	2.19E-04
	Lambs-milk	0.0	0.0	0.00
	Lambs-grass	0.2	2.3	7.31E-05
Beef	Beef cattle	6.0	69.2	2.19E-03
	Beef weaners	4.5	51.9	1.65E-03
	Calves	3.0	34.6	1.10E-03
Dairy	Dairy cattle	7.0	80.7	2.56E-03
	Dairy weaners	4.0	46.1	1.46E-03
	Calves	3.0	34.6	1.10E-03

Table 3: Emission factors for New Zealand livestock developed by NIWA staff.

Average Surface Methane Fluxes for the Manawatu Region

The stock numbers from Table 1, and the emission factors from Tables 2 and 3, can be combined into an average surface methane flux estimate for the Manawatu Regional Council area (excluding Palmerston North)[5]. The resulting figures are given in Table 4. The last two columns in Table 4 are based on the average of the June 1 and July 1 stock numbers. (These are the most appropriate data for the two case studies from which we were able to make quantitative methane flux estimates).

Tables 1 to 4 are subject to a number of caveats. The monthly stock estimates for the Manawatu contain several assumptions (eg. hoggets only exist for three months before being reclassified as adult sheep, beef and dairy weaner numbers vary through the year, and the monthly variation in other stock numbers is presumably based on inference from imperfect statistical data). Use of the same "annualised" emission factor for each month and location is also an approximation - these emission factors probably vary with season and pasture type (Ulyatt et al, 1992)

As already discussed, the applicability for New Zealand of some of the Oceania-wide default IPCC emission factors is questionable, especially those for manure management and for enteric fermentation from dairy cows.. Thus we will use the last column of Table 4 for the modelling work described in the remainder of this report.

MANAWATU STOCK NUMBERS BY MONTH								
Estimates are stock numbers at the start of the month.								
		Em factor (g/head/s)		Stock Numbers (000)			CH4 Flux (g/m2/sec)	
				May	Jun	Jul	For IPCC	For NIWA
		IPCC	NIWA	1995	1995	1995	factors	factors
Open Sheep								
	Adults	2.63E-04	3.66E-04	742.7	724.4	710.5	7.45E-08	1.04E-07
	Hoggets	2.63E-04	2.19E-04	0.0	0.0	302.5	1.57E-08	1.31E-08
	Lambs - milk	2.63E-04	0.00E+00	0.0	0.0	0.0	0.00E+00	0.00E+00
	Lambs - grass	2.63E-04	7.31E-05	426.0	357.4	0.0	1.85E-08	5.17E-09
	Total			1168.7	1081.8	1013.1	1.09E-07	1.22E-07
Open Beef								
	Beef Cattle	1.87E-03	2.19E-03	93.1	88.2	115.7	7.54E-08	8.84E-08
	Beef Weaners	1.87E-03	1.65E-03	30.7	30.7	28.0	2.17E-08	1.91E-08
	Calves	1.87E-03	1.10E-03	28.1	28.1	0.0	1.04E-08	6.10E-09
	Total			151.9	147.0	143.7	1.07E-07	1.14E-07
Open Dairy								
	Dairy Cattle	3.17E-03	2.56E-03	60.1	57.5	72.2	8.13E-08	6.56E-08
	Dairy Weaners	1.87E-03	1.46E-03	16.3	16.3	16.4	1.21E-08	9.45E-09
	Calves	1.87E-03	1.10E-03	16.7	16.6	0.0	6.12E-09	3.59E-09
	Total			93.1	90.4	88.6	9.95E-08	7.87E-08
OVERALL TOTAL							3.16E-07	3.14E-07

Table 4: Methane flux estimates from the Manawatu, using emissions inventories and factors from Tables 1 - 3.

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[5] The Regional Council area, excluding Palmerston North, is 2.53×10^9 square metres.

6. CASE STUDY - 25 MAY 1995

The first aircraft methane profile measurements were made on 25 May 1995, between 1309 and 1347 NZ Standard Time. This was an initial flight to test out the gas sampling equipment and the analysis techniques. As described below, we found that the meteorological conditions were unsuitable for estimating surface methane emissions from the aircraft profiles. The case is covered in this report because it illustrates how local air flows (sea and land breezes) can influence methane concentration profiles.

One profile was measured at 40.30°S, 175.20°E (over the sea just west of Tangimoana - See Figure 3), and the other at 40.22°S, 175.64°E (near Colyton, about 36 km inland). The results are shown in Figure 4, and the actual concentrations are tabulated in Appendix C. The error bars shown on Figure 4 are the standard errors explained in Section 2.

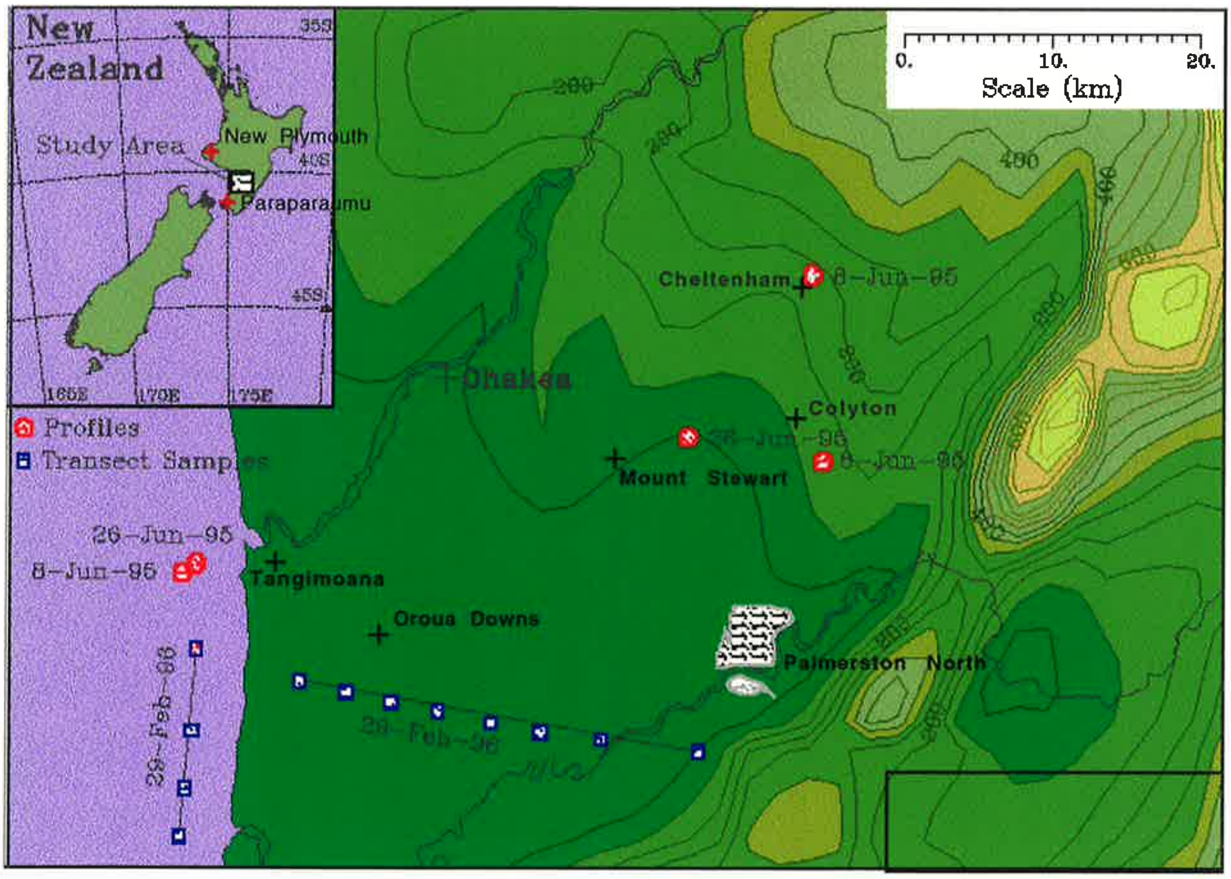

Figure 3: Aircraft methane sampling locations for all of the case studies, and places mentioned in the case study descriptions.

From Figure 4, the methane profiles inland are higher than those over the sea, as would have been expected if the air flow was from the sea on to the land (Section 3). Figure 5 shows the surface wind direction at Ohakea and Palmerston North at the time the methane profile measurements were obtained was onshore (from about 290°). The surface wind speeds themselves are very light at this time (about 2 m/s, Figure 6), and the direction is changing. Through the night and morning the surface wind is from the northeast or north.

The surface weather map (Figure 7) shows the reason for these changing winds. Because there was an anticyclone centred over the North Island, the synoptic scale winds were very weak. Thus the night time and morning surface winds were largely driven by drainage of cold air off the hills to the north and east of the Manawatu Plain, and possibly by some thermal land breeze forcing due to the sea being warmer than the land at night. As the land warmed in the late morning and early afternoon, a sea breeze developed and would have gradually spread inland.

Sea and land breeze flows are typically a few hundred metres deep. Thus the relatively high concentrations of methane in the lowest 500 m over the sea are due to the flow of methane enriched air off the land in the night and morning. Because the wind direction was changing, and was probably not uniform over the experimental region, the simplified regional budget model developed in Section 3 is not valid for this case, and we have not attempted to estimate surface methane fluxes.

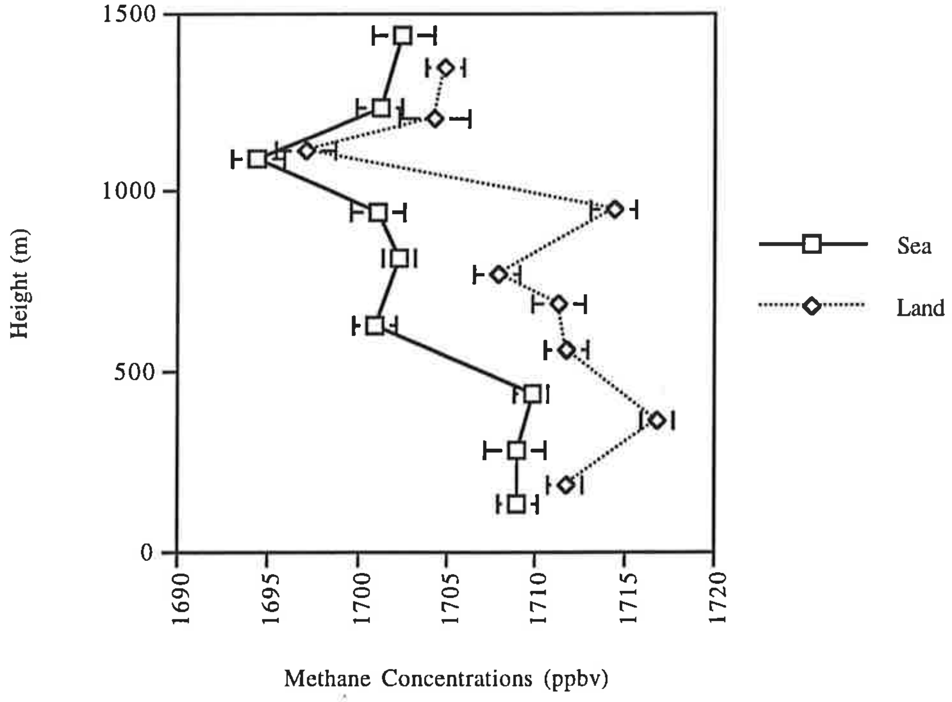

Figure 4: Methane concentration profiles, 1309 - 1347 NZST, 25 May 1995.

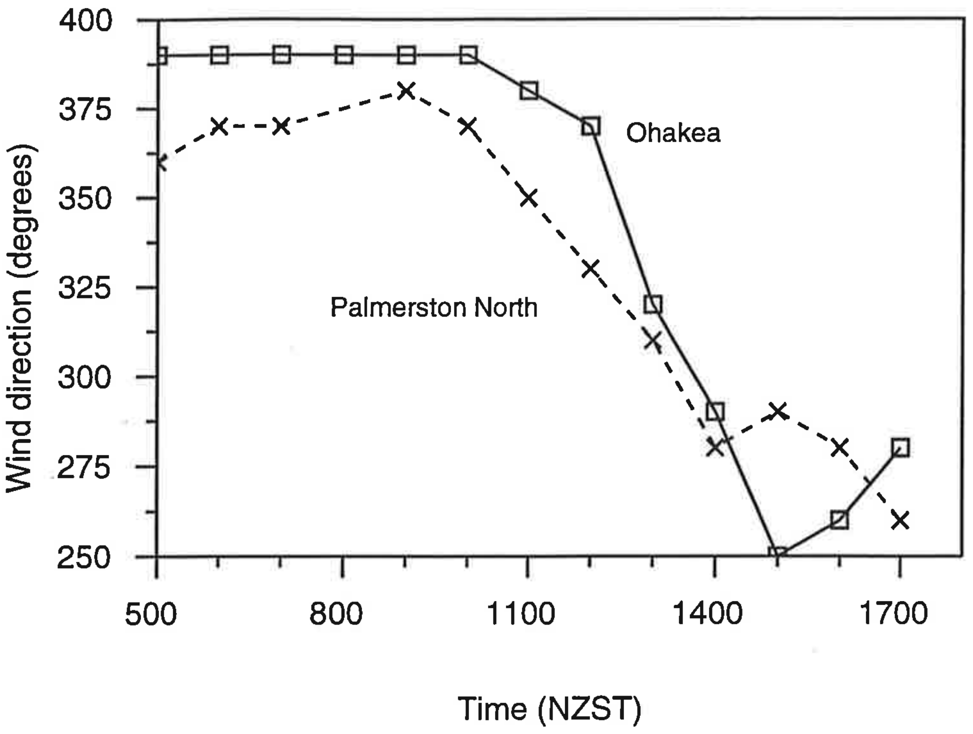

Figure 5: Wind directions at Ohakea and Palmerston North, 25 May 1995. The direction from which the wind is blowing is shown (ie 270° implies a westerly). Winds from the northeasterly quarter have 360° added, so the direction curves remain continuous for a change through north.

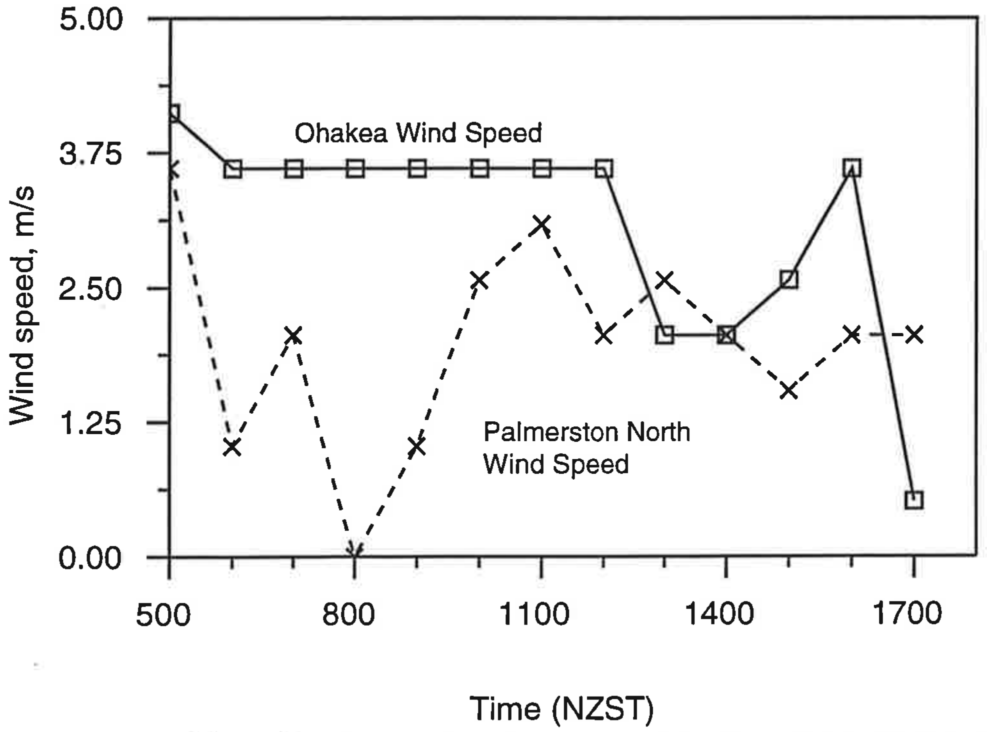

Figure 6: Wind speeds at Ohakea and Palmerston North, 25 May 1995

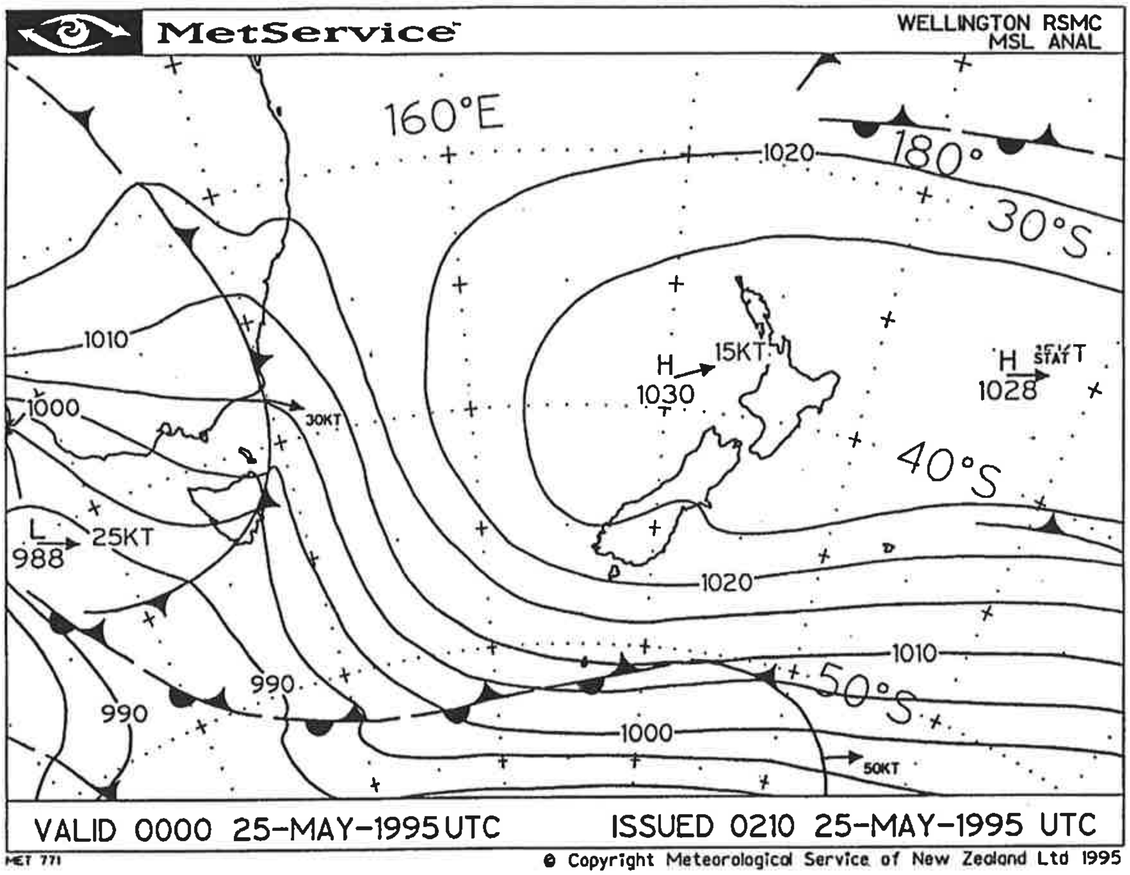

Figure 7: Surface weather analysis for noon NZ Standard Time, 25 May 1996. (Courtesy Meteorological Service of New Zealand Ltd).

7. CASE STUDY - 8 JUNE 1995

The second series of aircraft methane measurements were made between 1223 and 1318 NZST on 8 June 1995. The first profile was measured at 40.32°S, 175.18°E (over the sea just west of Tangimoana), the second profile at 40.25°S, 175.68°E (about 36 km inland, near Colyton), and the third profile at 40.14°S, 175.67°E (about 38 km inland, near Cheltenham). These sites are shown on Figure 3. The results are shown in Figure 13, and tabulated in Appendix C.

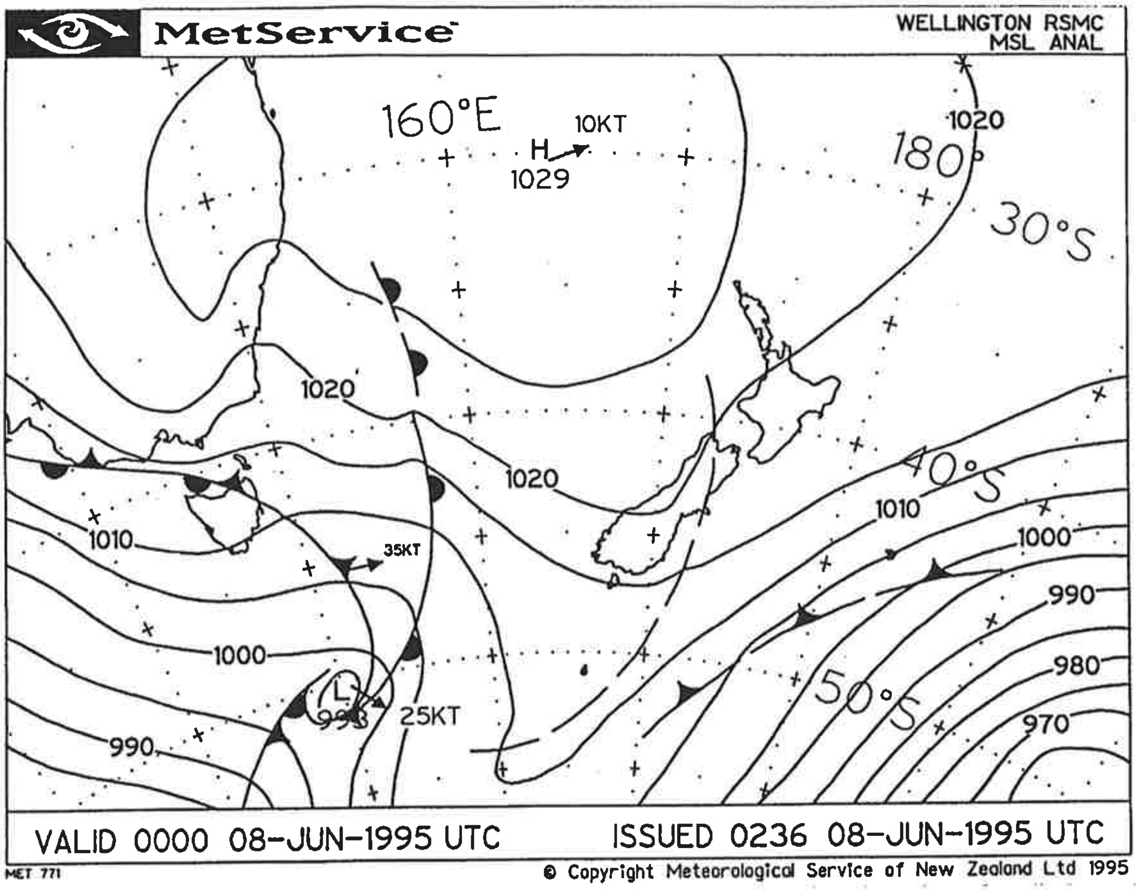

Figure 8: Mean sea level pressure analysis, noon NZST, 8 June 1995. (Courtesy of Meteorological Service of New Zealand Ltd).

Air flows on June 8, 1995

The large-scale pressure pattern over the country at this time favoured relatively weak southwesterly air flow over the North Island, ahead of an anticyclone centred in the North Tasman Sea (Figure 8). However, during the early morning the surface wind at Palmerston North Airport was from the ENE and at Ohakea from the NNE (Figure 9) - directions opposite to the geostrophic forcing from the large scale pressure gradient. These local night-time winds would have been caused by drainage of cold air of the inland hills and mountains, possibly aided by a "land-breeze" due to the sea being warmer than the land at night and in the early morning.

The surface wind direction gradually changed through the morning. By noon there was a wind from the NW of about 4 m/s at both Ohakea and Palmerston North, and these NW conditions continued through until at least 4 PM (Figures 9 and 10). These NW winds would have been caused by a combination of the large-scale pressure gradients and possibly some local sea breeze forcing, as the land warmed up. (Blocking of the large-scale SW flow by the inland terrain may have favoured cross-isobar flow towards the lower pressure).

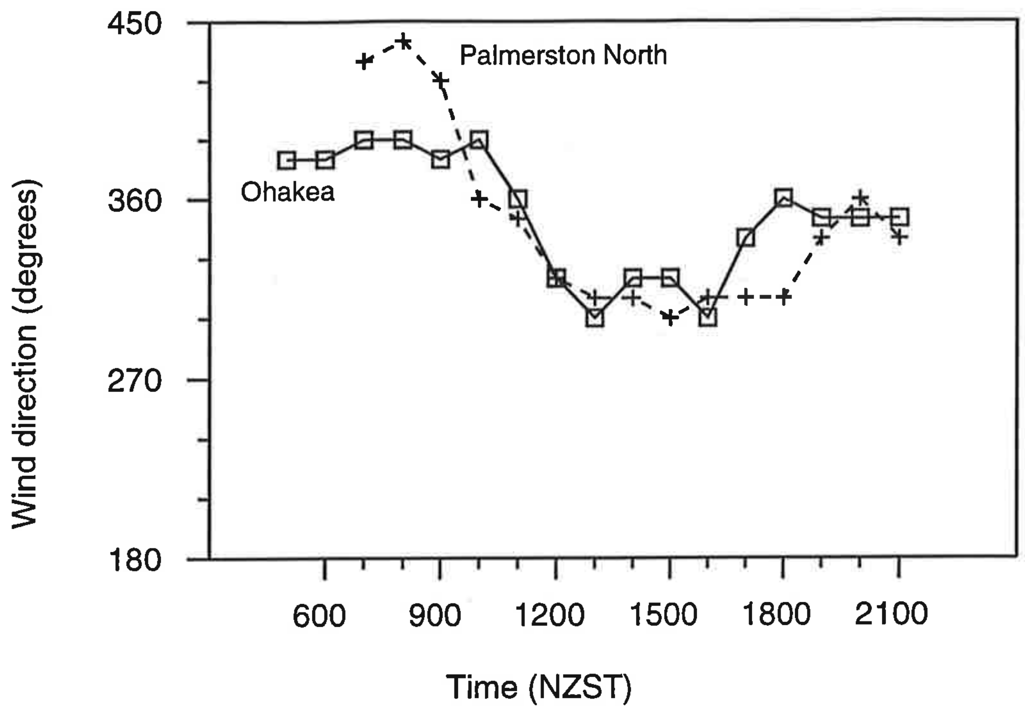

Figure 9: Wind directions at Ohakea and Palmerston North, 8 June 1995

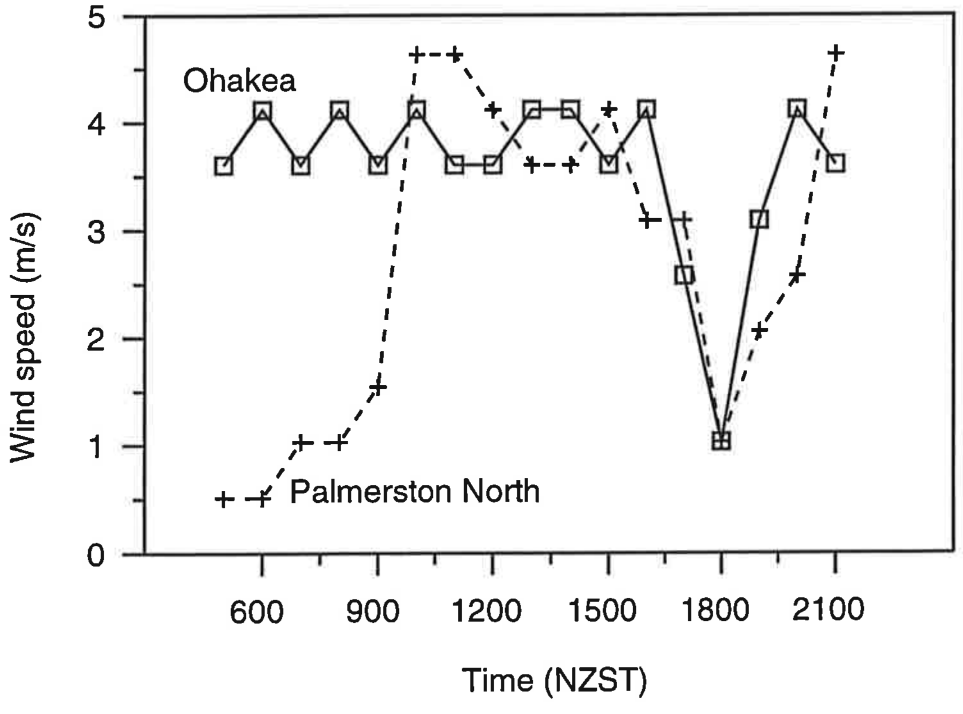

Figure 10: Wind speeds at Ohakea and Palmerston North, 8 June 1995

The mesoscale model simulation of the air flow on 8 June was initialised with a southwesterly flow on the evening of June 7th (Appendix A). This was consistent with the synoptic-scale weather pattern over the country and the wind profiles from Paraparaumu and New Plymouth Airports. By midnight, the model suggested low level drainage flows from three areas (the Manawatu Plains, South Taranaki and Tasman Bay), and the synoptic southwesterly flow, interacted to form a convergence zone over the sea about 30 km west of the Manawatu coastline. By about 10 am the modelled drainage flows were replaced by westerlies and the convergence zone disappeared. At noon (near to the time of the aircraft methane measurements) the model indicated that onshore flow extended across the Manawatu Plains to the mountains.

Figures 11a and 11b are West to east cross sections across the Manawatu plains from the model run. Note the upward motion simulated by the model at noon in the foothills about 38 km inland, and the even stronger upward motion above the upwind side of the Tararua mountains (about 47 km inland).

These mesoscale model simulations show clearly that at some times vertical methane concentration profiles over the Manawatu result from a complex interplay of meteorological conditions. For example on the night of 7/8 June, agriculturally produced methane from the Manawatu would have been carried out over the sea in the low level drainage flow, then carried aloft in the convergence zone and transported back towards the North Island in the upper level south-westerlies.

Figure 12 shows the potential temperature and mixing ratio profiles measured at 1 pm from a balloon released over Colyton in the inland Manawatu. Figure 13 shows the methane profiles measured from the aircraft over a coastal location and two inland locations.

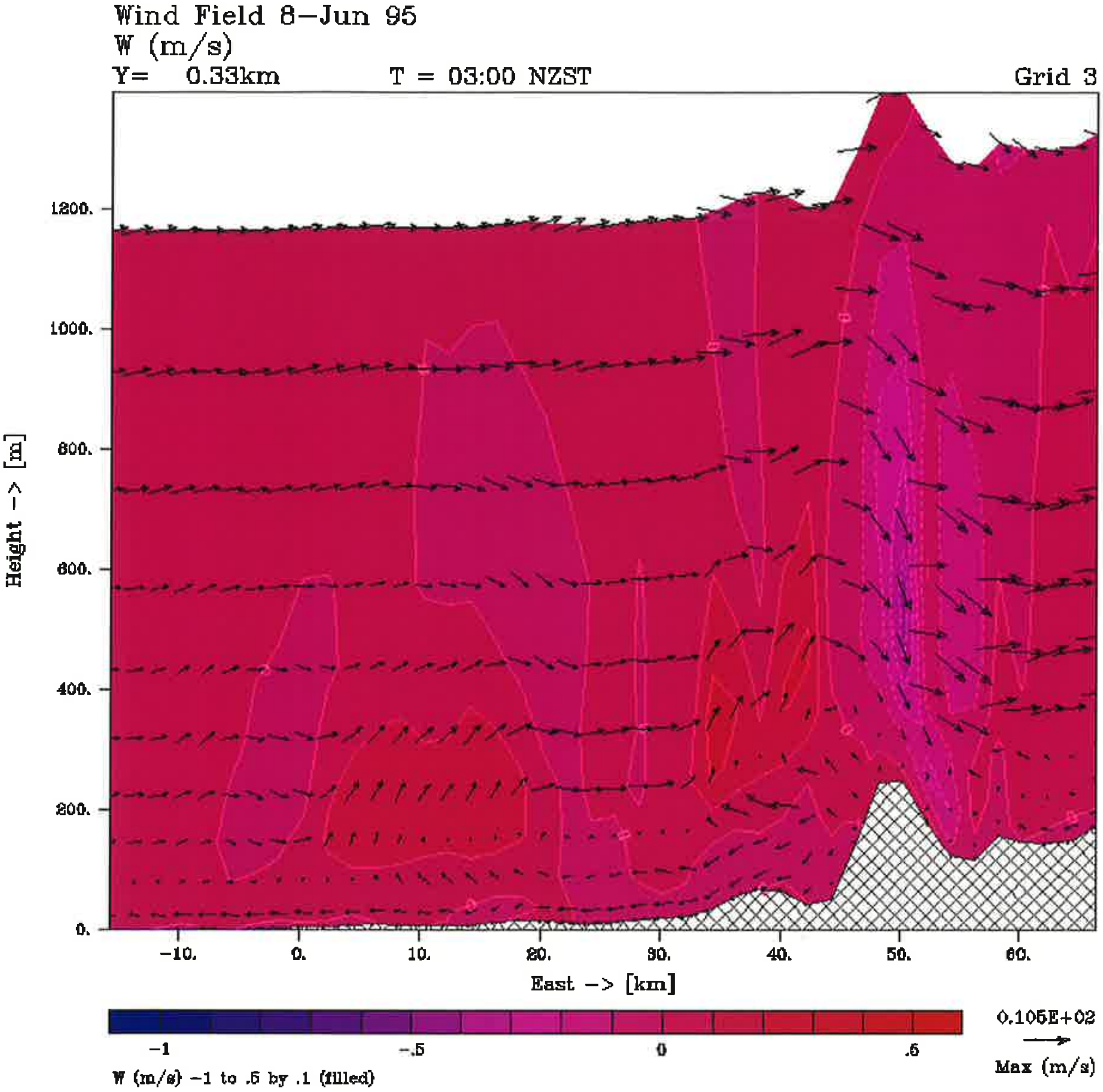

Figure 11a : E-W cross section through Palmerston North from the RAMS model simulation, for 3 am on 8 June 1995. The black arrows indicate the wind speed and direction in the x-z plane (the z component is exaggerated). The dotted contours, and the colours indicate the magnitude of the vertical component of the wind. The x - coordinate value is 0 at the coast.

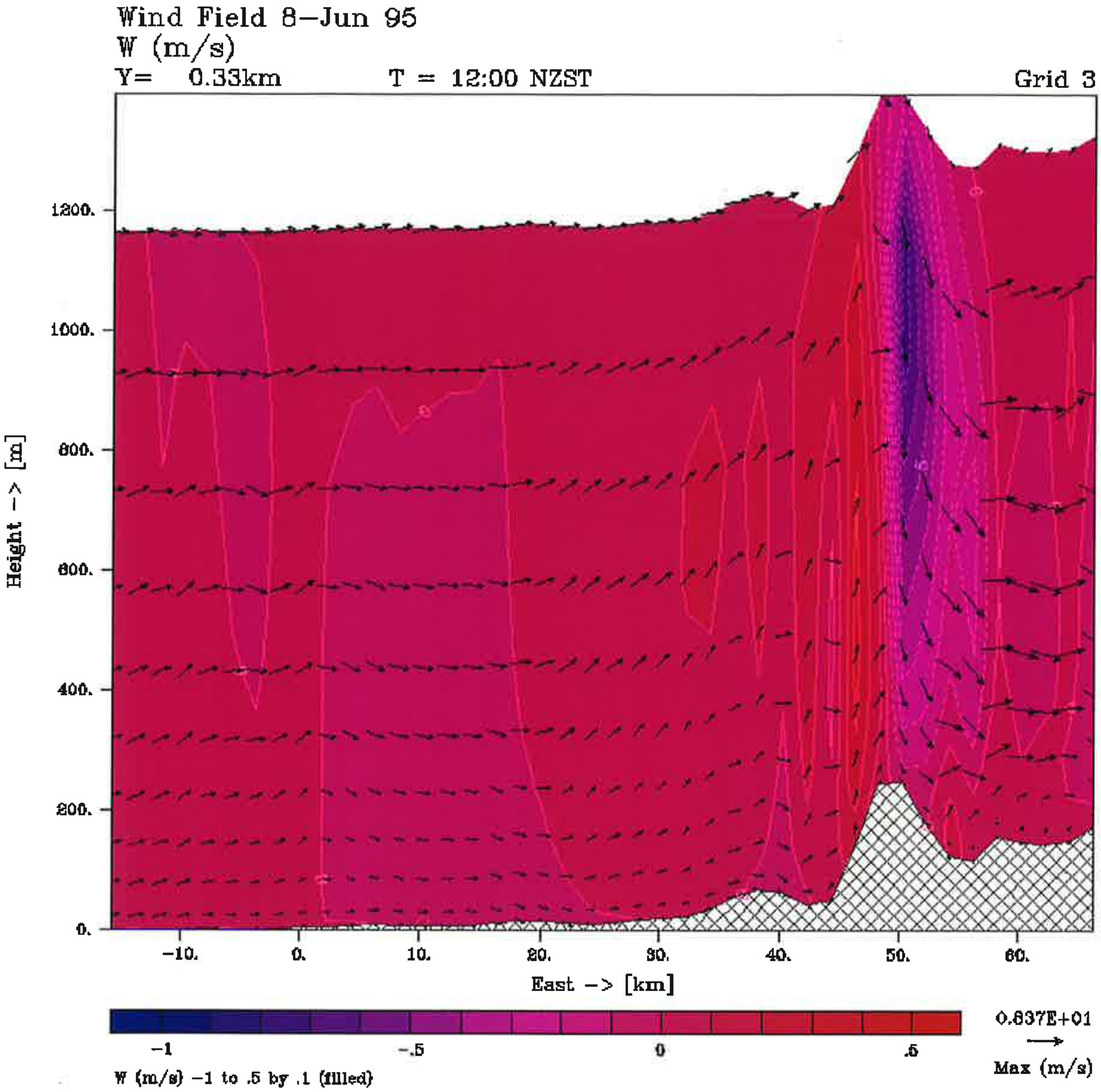

Figure 11b : E-W cross section through Palmerston North from the RAMS model simulation, for noon on 8 June 1995. The contours, arrows and shading are explained in the caption for figure 13 a.

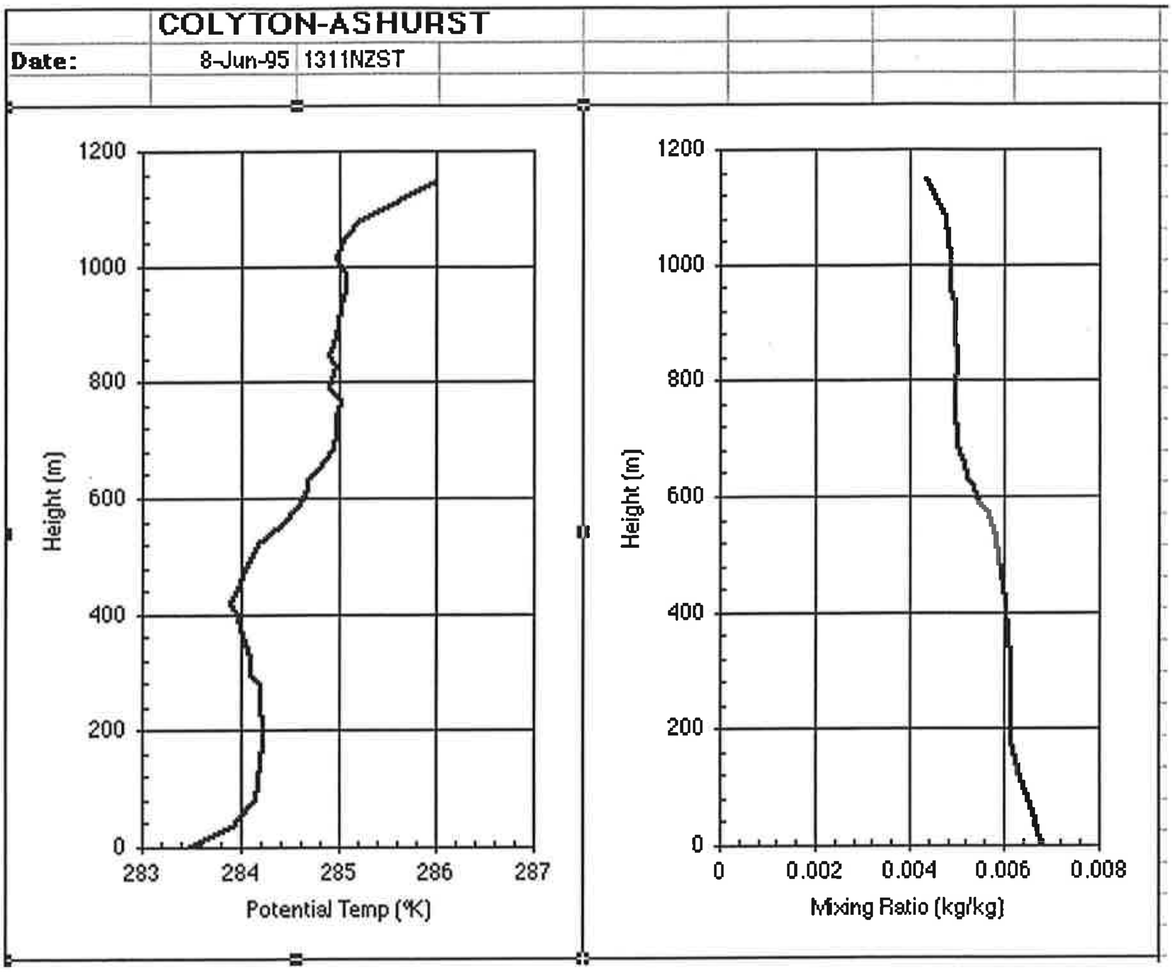

Figure 12: Height profiles of potential temperature and mixing ratio from Airsonde balloon soundings near Colyton, 1311 NZST, 8 June 1996.

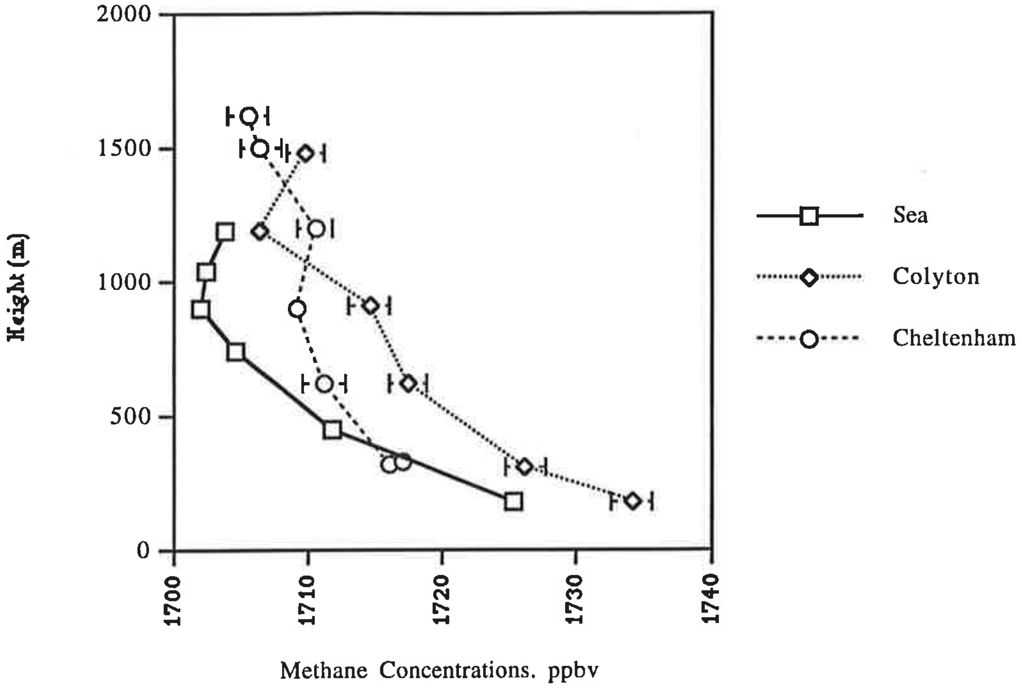

Figure 13: Methane concentration profiles, 1223 - 1318 NZST, 8 June 1995

Surface Methane Flux Estimates for June 8.

Since a northwesterly wind had spread right across the Manawatu plains by the time of the aircraft measurements, we tried estimating the surface methane fluxes using the simple regional budget model of Equation 12. For this model, we used a 10 m wind speed of 4.1 m/s from 310° (figs 9 and 10). We assumed the height variation of wind speed u followed a logarithmic profile (eg. Stull, 1988):

$$u = \frac{u*}{k}\ln\left(\frac{z}{z_o}\right)$$

where k is von Karman's constant, z is height above ground, and z_o is surface roughness length. For an assumed surface roughness length of 3 cm (typical of pasture land), u_*/k =0.706 m/s reproduces the 10 m wind speed of 4.1 m/s.

The distance from the coast to Colyton or Cheltenham along a wind direction of 45° (ℓ in equation 12) is approximately 64 km. We interpolated linearly to estimate concentrations between the measurement heights, and assumed the concentration remained constant between the lowest measurement height and the ground. The ground at the measurement site near Colyton is about 110 m above sea level, and that at the site near Cheltenham is 190 m above sea level.

Therefore we performed the over-sea integration[6] in equation 12 from 10 to 1185m, and the Colyton integration from 110 to 1285 m above mean sea level.

The results from these calculations were:

Surface methane flux estimated from coast and Colyton profiles: 6.0×10^{-7} g/s/m^2.

Surface methane flux estimated from coast and Cheltenham profiles: 1.0×10^{-7} g/s/m^2.

Case study methane flux estimates are discussed further in Section 10. However, we note here that some assumptions used in deriving equation 12 probably failed for this case study. A northwesterly wind of 4 m/s would take about 4 hours to transport air from the coast to Colyton and Cheltenham. Thus the assumption that the wind speed and direction remain relatively constant through the time it would take air to travel across the region, did not hold on this day. A second assumption, that there was no vertical transport of methane through the top of the integration domain, probably also failed for the site near Cheltenham which is in the foothills region where the mesoscale model suggested significant vertical motions occurred.

To test the effect of assuming methane concentrations remained constant between the lowest measurement height and the ground, we made a simple analysis using techniques from. air pollution modelling. We simulated the Manawatu as an area source of methane built up from a series of line sources oriented parallel to the coast, with the vertical spread from each line source following standard Gaussian dispersion equations (Hanna et al, 1982). We used this approach to calculate vertical methane profile shapes for a range of typical daytime dispersion conditions. This work suggests that provided methane sources were uniformly distributed over the Manawatu, the errors in estimated daytime surface methane flux caused by downwards extrapolation of the lowest aircraft measurement would be less than 10 %. Errors could be significantly larger if the surface methane emissions were not evenly distributed.

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[6] A lower bound of 10 m (rather than 0 m) ensures the $\ln(z/z_0)$ factor in the wind speed remains tractable, and will have a negligable influence on the results.

8. CASE STUDY - 26 JUNE 1995

The third series of aircraft methane measurements were made on 26 June 1995, from 1311 to 1402 NZST. The first profile was measured at 40.31°S, 175.18°E (over the sea just west of Tangimoana), the second profile at 40.24°S, 175.57°E (about 23 km inland, near Mt Stewart[7]), and the third profile at 40.24°S, 175.77°E (about 45 km inland near Colyton). These sites are shown on Figure 3. The results are shown in Figure 12, and tabulated in Appendix C.

Air Flows on June 26 1995.

At noon on June 26 there was a westerly airflow over the lower North Island, ahead of a cold front which was progressing up the South Island (Figure 17). The surface winds at Ohakea and Palmerston North were consistently from the westerly quarter (Figure 15), with the wind speed increasing from about 6 m/s at 5 am to 12 m/s at 5 pm (Figure 16). Because of the strong synoptic flow, there is little sign of the spatially and temporarily varying local flow features (drainage flows, sea breezes) experienced on the other two measurement days. The June 26 conditions therefore appear much more suitable for the profile method of methane flux estimation, than those during the previous case studies. (Even so, the methane concentrations at 500-1000 m altitude over the sea are higher than on 8 June and 28 May, suggesting the onshore flow on 26 June might not contain totally "clean" oceanic air. It may contain some methane from flow over the northern South Island, or from evening land breeze / drainage flows off Taranaki ahead of the strengthening pre-frontal westerly flow).

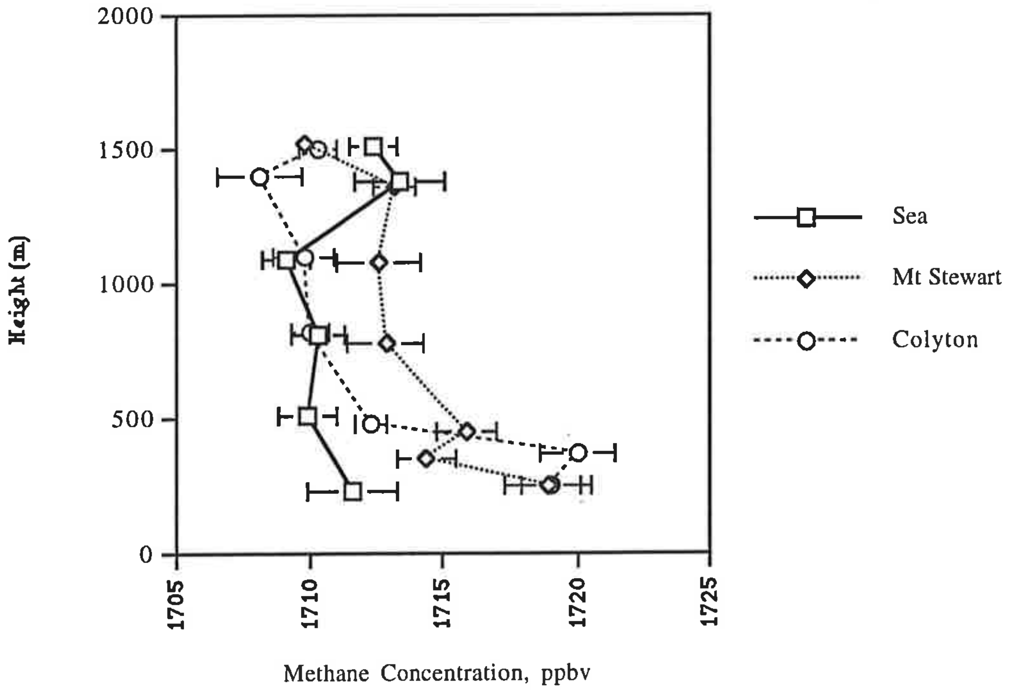

Figure 14: Methane concentration profiles, 1311 - 1402 NZST, 26 June 1995

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[7] Mt Stewart is not really a mountain. Its altitude is 130m, which makes it the highest point locally in an area of rolling country.

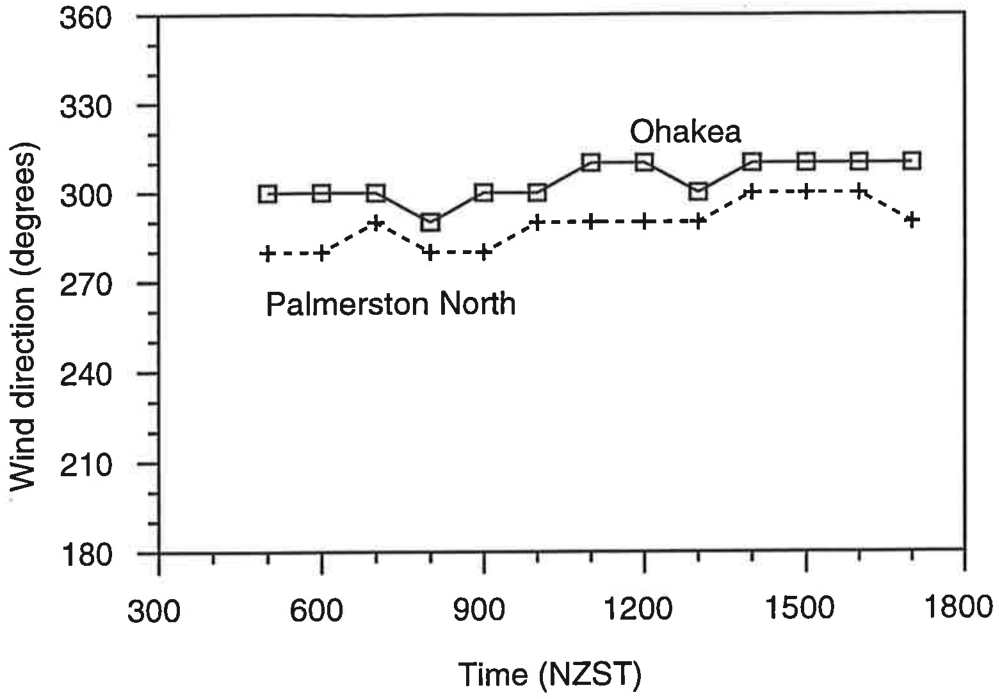

Figure 15: Wind directions at Ohakea and Palmerston North, 26 June 1995

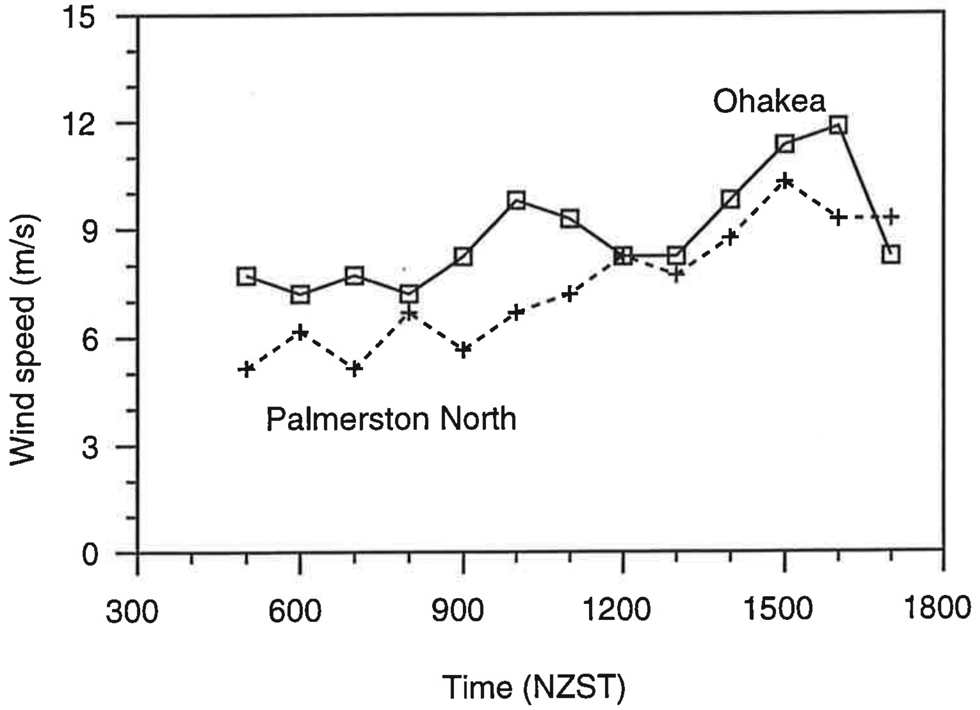

Figure 16: Wind speeds at Ohakea and Palmerston North, 26 June 1995.

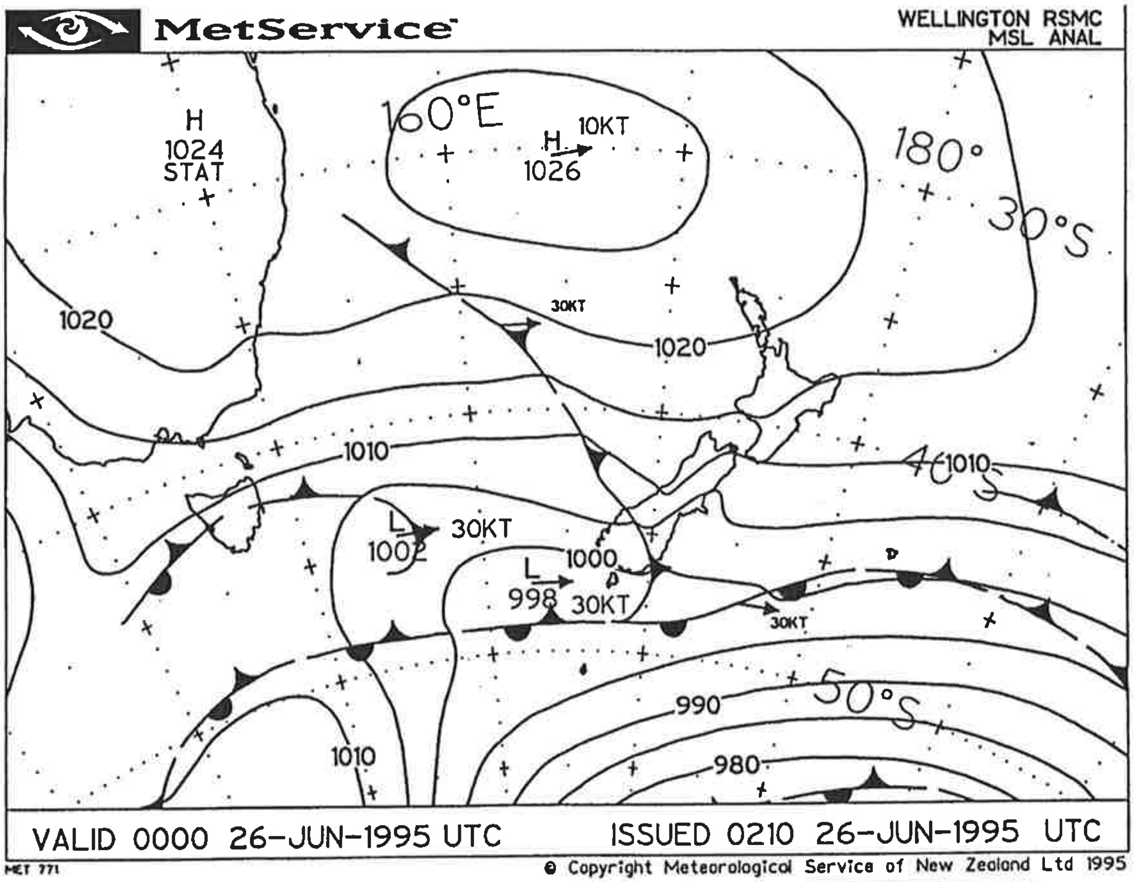

Figure 17: Mean sea level pressure analysis, noon NZDT, 26 June 1995.

Surface Methane Flux Estimates for June 26, 1995

The surface methane fluxes obtained by applying the simple regional budget model (equation 12) on 26 June are given in Table 5. Table 5 also contains the wind, surface roughness and geographical information used for these calculations. The methods used were similar to those outlined in Section 7 for 8 June. These results will be discussed in Section 10.

Wind direction Wind speed at 10m Surface roughness length	300° 8.0 m/s 3 cm
Coast - Mt Stewart Pair:	
Along-wind distance ℓ Height integration interval at coast Height integration range at Mt Stewart Calculated surface methane flux	32 km 10 - 1375 m 110 - 1475 m 1.3×10^{-6} g/m^2/s
Coast - Colyton Pair	
Along-wind distance ℓ Height integration interval at coast Height integration range at Colyton Calculated surface methane flux	64 km 10 - 715 m 110 - 815 m 3.6×10^{-7} g/m^2/s

Table 5: Surface methane flux calculations, 26 June 1995

9. SPATIAL VARIABILITY MEASUREMENTS

The fourth set of aircraft measurements was made on 29 February 1996, to explore the spatial variability of methane concentrations at a constant height. This was a first step towards answering questions such as: How spatially representative are the methane measurements made out over the sea ? Do the aircraft methane concentration measurements over the land exhibit large spatial variations (for example due to local turbulent eddies), or are they a good representation of average methane at a particular distance from the coast ?

Figure 18 shows the latitude and longitude of the twelve samples - the sampling sites are also shown on Figure 3. Four samples were taken at points separated by about 2 km along a line parallel to the coast, from near Himatangi Beach to near Foxton. Then a further 8 samples were taken at points about 4 km apart along a transect inwards from the coast through Himatangi. All of the samples were taken at approximately 310 m above sea level (the precise heights are given in Appendix C). As discussed in Section 2, each flask sample represents an average over a horizontal distance of about 240 m.

The measured concentrations are plotted in Figure 19 (the numbers on Figure 19 correspond to the measurement sites on Figure 18).

Air Flows on 29 February 1996

The synoptic-scale pressure gradient over the Manawatu on this day was weak (fig 26), with a ridge of high pressure over the North Island. This pressure pattern favoured light westerly winds over the field campaign region, but because the gradient was so weak one would expect local thermally - forced flows to occur (night time drainage flows and land breezes, daytime sea breezes). Wind, temperature and mixing ratio profiles obtained from a balloon sounding at 1110 NZST from Oroua Downs, 8 km inland from the coast and about 3 km north of the transect, are shown in Figures 20 and 21. This is a classic sea-breeze flow: onshore up to about 500m altitude, with an offshore return flow above that to around 800m (possibly a remnant of the night-time cool air drainage from the inland mountains), capped by the onshore synoptic flow. A sounding balloon released from Rongotea (about 11 km northeast of Oroua Downs) showed that by 1250 NZST the remnant offshore flow had almost collapsed, and moist air was mixed up to about 800 m (Figures 22,23). Measurements from Ohakea and Palmerston North (Figures 24,25) show the surface easterlies were replaced by onshore flows sometime between 10 am and noon NZST at Ohakea, and between 11 am and noon at Palmerston North.

Methane Concentrations on 29 February 1996

The standard errors in the gas chromatograph methane determinations are less than 1 ppbv. Therefore the variations apparent in Figure 18 represent real spatial variations in methane concentration. The four methane measurements made over the sea all lie within 4 ppbv, but there is much more variability in the over land measurements and they do not increase monotonically with distance inland as would be expected from simple theory (equation 9, Section 3) under uniform onshore flow. This is probably a result of the complex local flows on this day - as explained above, the surface wind at Palmerston North was from the easterly quarter until around noon, whereas at Oroua Downs it was westerly at the time of the transect measurements.

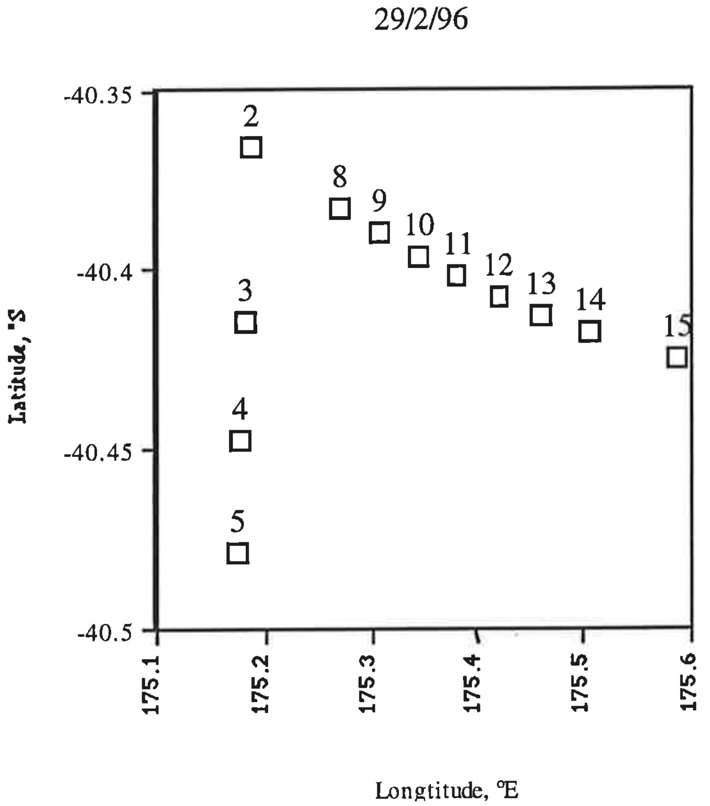

Figure 18: Location at which the samples shown in Figure 18 were taken. A change of 0.1° in latitude corresponds to about 8 km, and a 0.1° change in longitude to about 11 km.

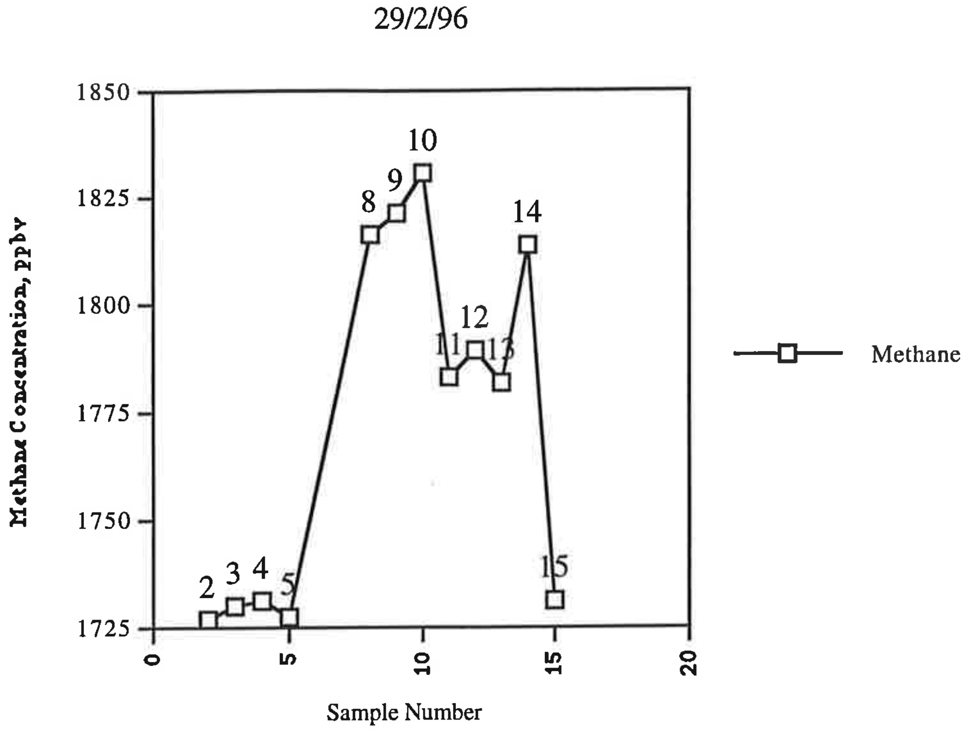

Figure 19: Methane concentrations, 300 m , 1115-1140 NZST, 29/2/96. The data points are labelled by their sample number.

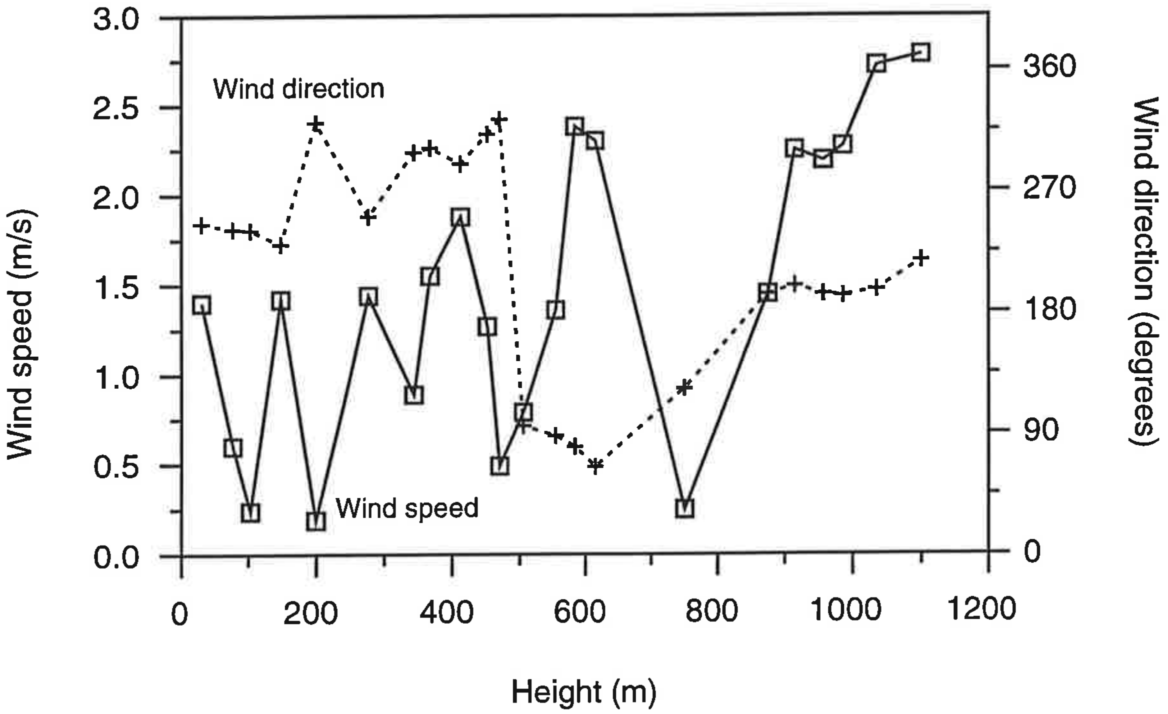

Figure 20: Height Profile of wind speed and direction, Oroua Downs, 1107 NZST, 29/2/96

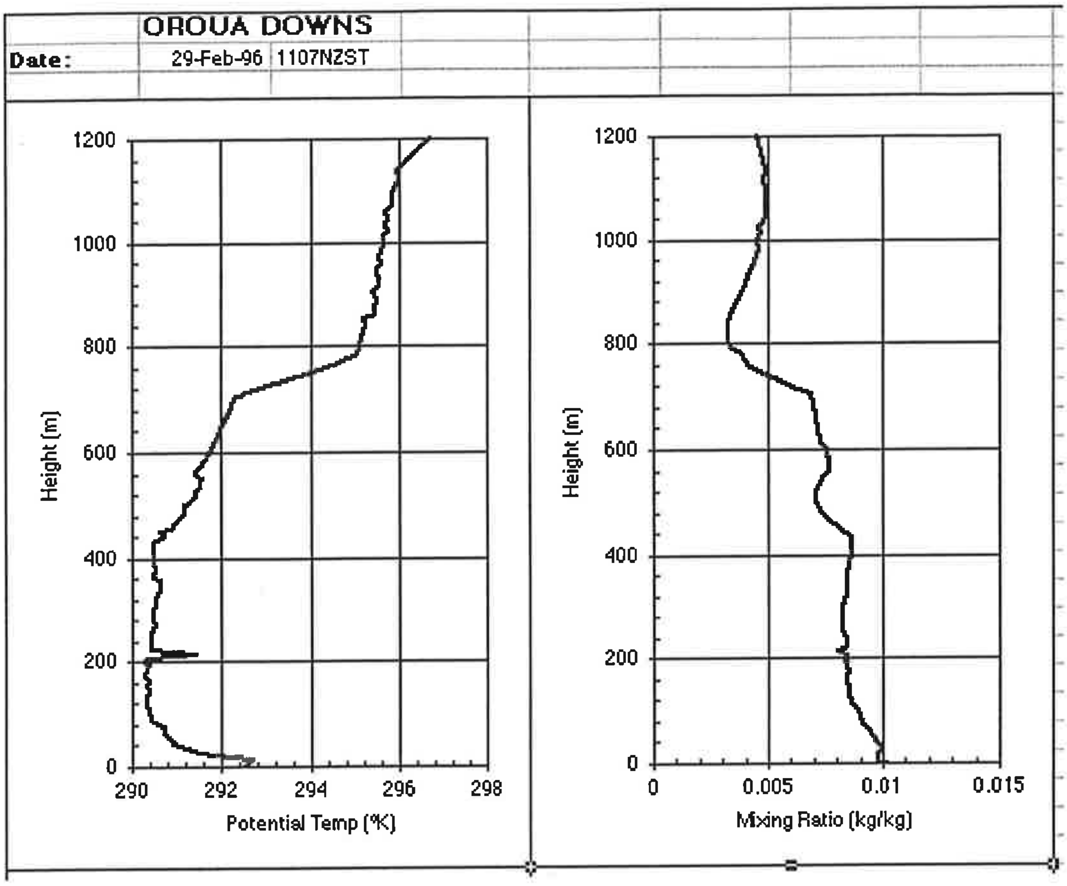

Figure 21: Height profiles of potential temperature and water vapour mixing ratio, Oroua Downs, 1107 NZST, 29 February 1996.

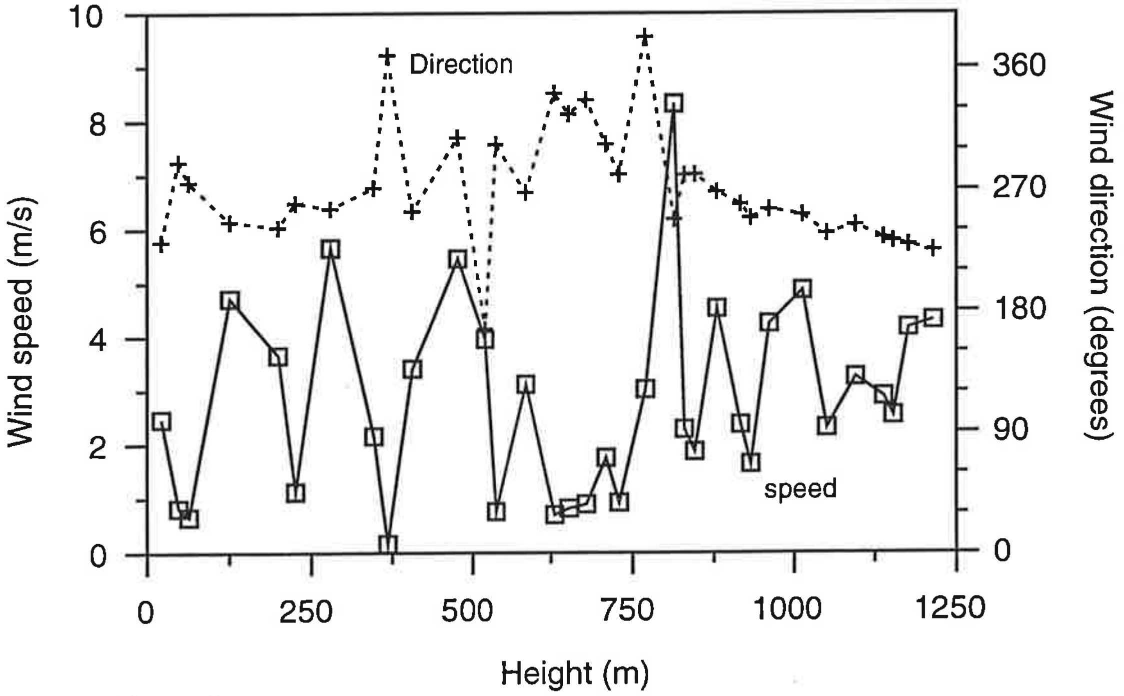

Figure 22: Wind direction and wind speed, Rongotea, 1252 NZST, 29 Feb 1996.

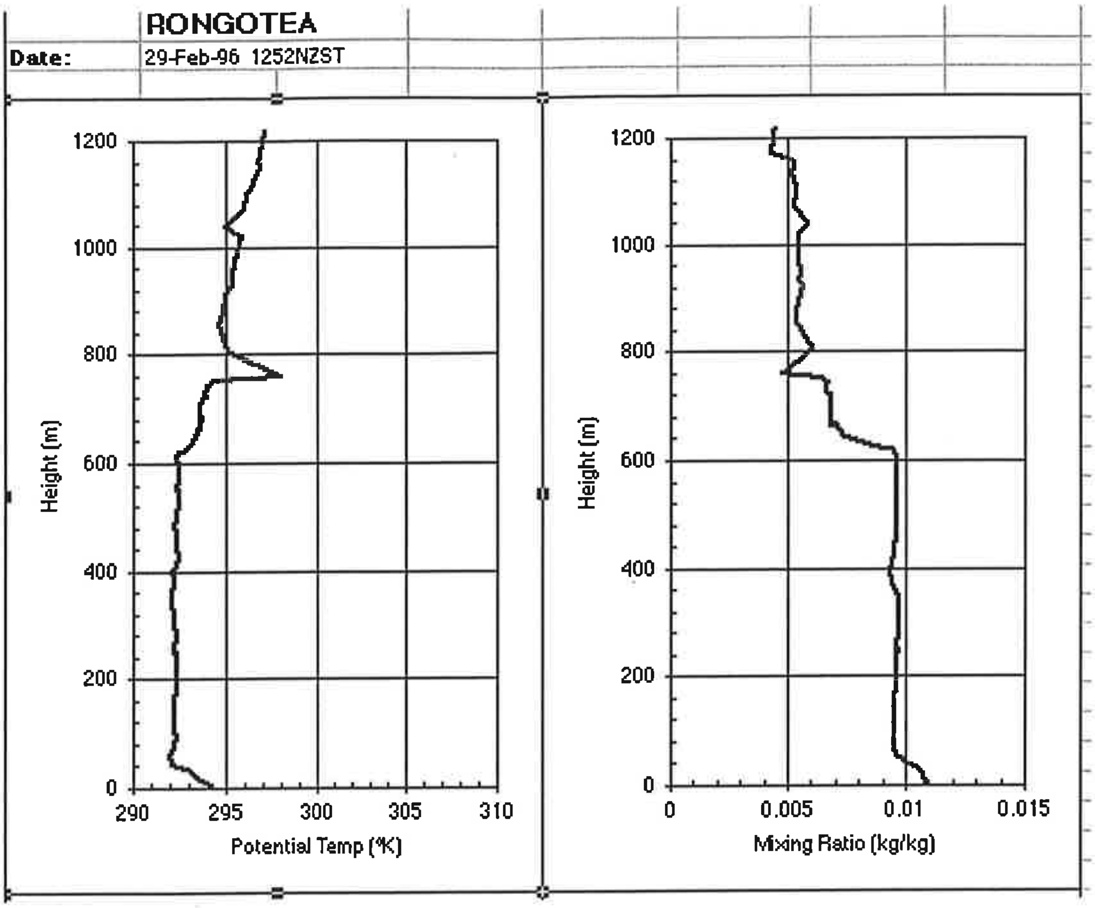

Figure 23: Height profiles of potential temperature and water vapour mixing ratio from balloon soundings at Rongotea.

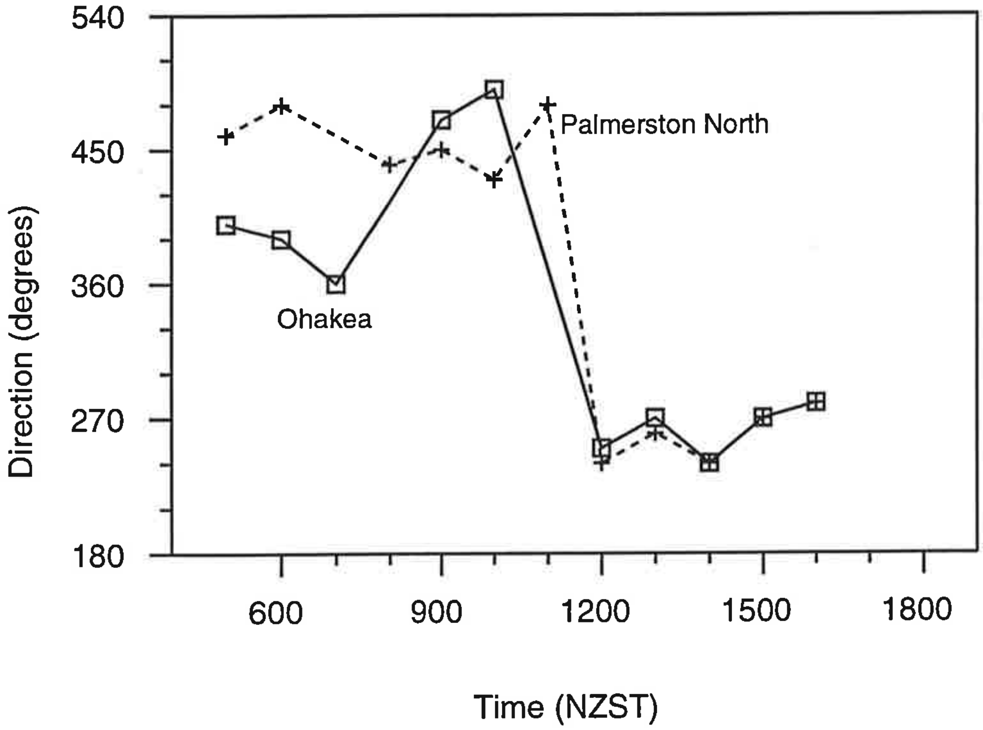

Figure 24: Wind directions at Ohakea and Palmerston North, 29 February 1996

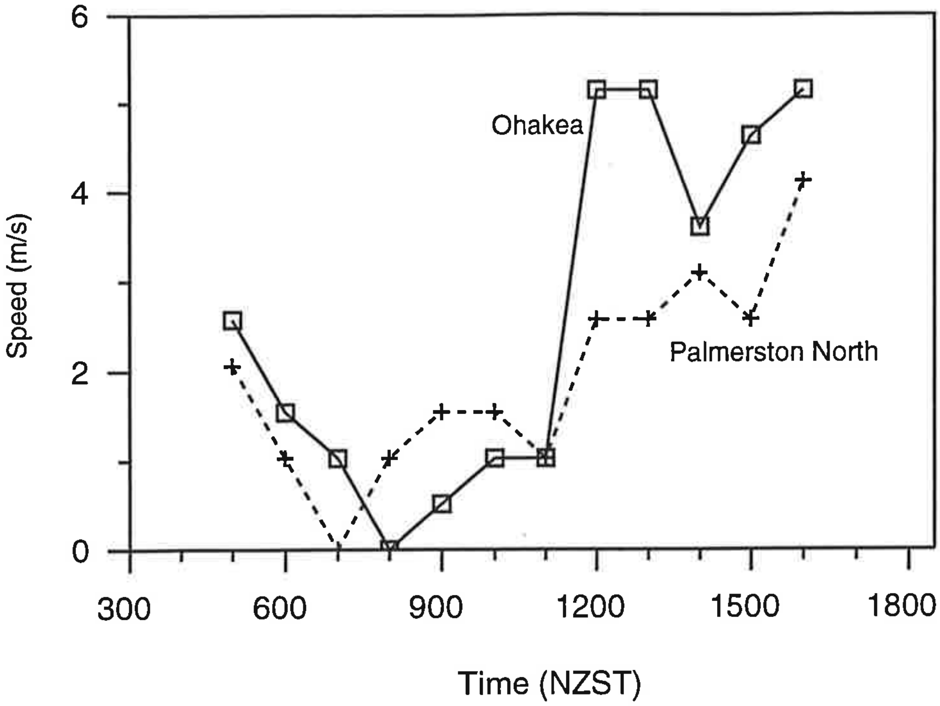

Figure 25: Wind speed at Ohakea and Palmerston North, 29/2/96

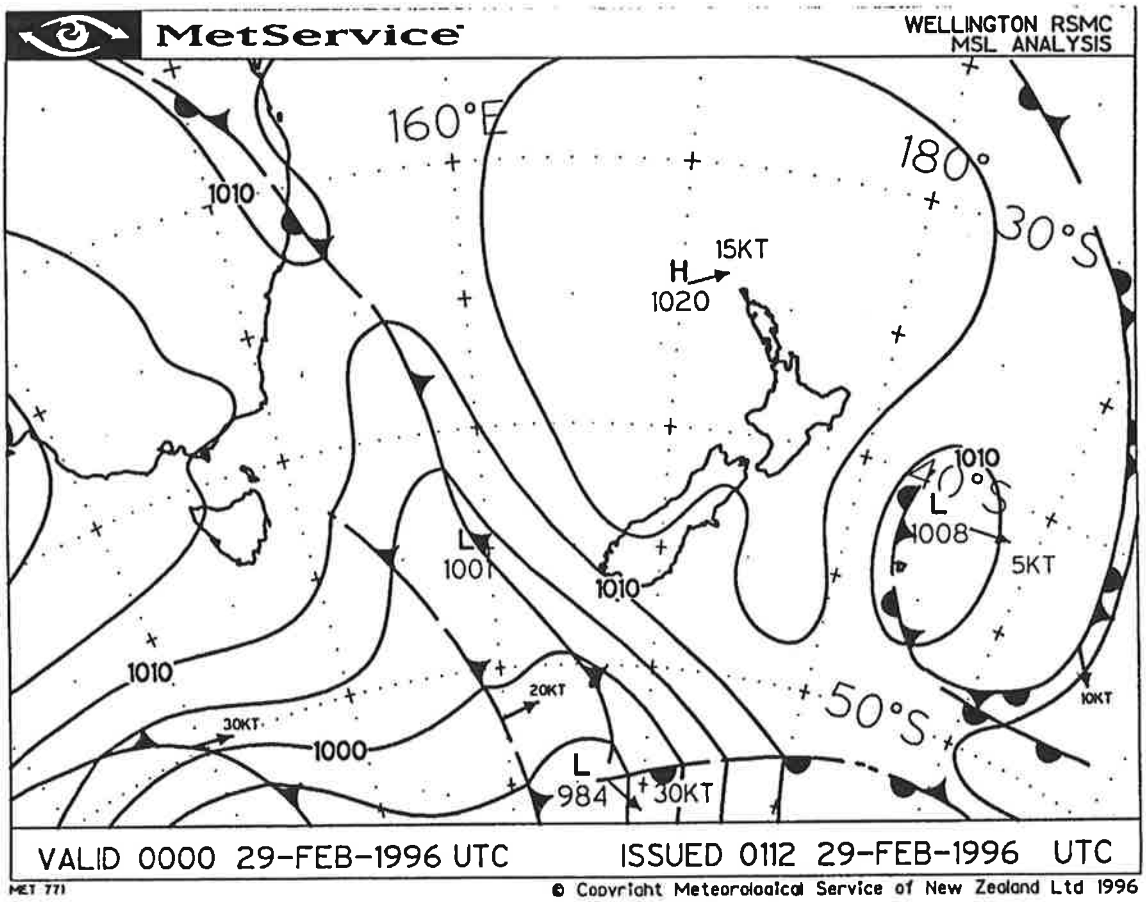

Figure 26: Mean sea level pressure analysis, noon NZDT, 29 Feb 1996. (Courtesy of Meteorological Service of New Zealand Ltd).

10. DISCUSSION AND RECOMMENDATIONS

The results outlined in Sections 6 - 9 confirm that during onshore flows, methane concentrations over the land in the Manawatu agricultural region are significantly larger than those over the sea, and that these differences can be measured by analysing air samples with gas chromatography techniques. We conclude that our idea of estimating surface methane fluxes by measuring height profiles of methane concentration at the coast and inland should be feasible, provided measurements are made after several hours of uniform onshore flow of low-methane "clean" oceanic air.

Date / Time (NZST)	Profiles	Estimated Surface Methane Flux
8 Jun 95 / 1230	Colyton - Coast	6.0×10^{-7} g/m^2/s
8 Jun 95 / 1230	Cheltenham - Coast	1.0×10^{-7} g/m^2/s
26 Jun 95 / 1330	Mt Stewart - Coast	1.3×10^{-6} g/m^2/s
26 Jun 95 / 1330	Colyton - Coast	3.6×10^{-7} g/m^2/s

Table 6: Surface methane flux estimates, using equation 12, Section 3.

Our estimates of surface methane fluxes based on the aircraft profile measurements , assuming there was a uniform onshore flow, are shown in Table 6. For comparison, the average surface methane flux over the Manawatu calculated in Section 6 from stock numbers and emission factors is 3.1×10^{-7} g/m^2/s. Thus the methane fluxes calculated from the aircraft measurements are of the expected order of magnitude, but vary by up to a factor of 4 from the fluxes estimated from the livestock data. There are several possible reasons for these differences:

- The air flows over the Manawatu region are often complex, since they are influenced both by large - scale pressure gradients (as shown on a standard weather map) and local thermal forcing (land breezes and sea breezes). In such conditions our simple model assumptions of uniform wind flows are invalid.

- During strong onshore winds (26 June 1995), the differences in methane concentrations between coastal and inland locations are smaller than for light wind conditions. Under these strong winds, the uncertainty bars on the gas chromatograph methane determinations start to become significant.

- Farm animals are not uniformly distributed over the Manawatu Regional Council area. Therefore, one would expect some differences between the different measurement location pairs given in Table 5.

- Methane emissions from animals are expected to vary seasonally, but this full seasonality is not captured by the animal data and emission factors available for this initial study.

- The aircraft methane concentration measurements are averages over a horizontal distance of about 240 m. This might not be sufficient to smooth the random turbulent fluctuations in concentration which occur in the atmosphere - whereas the theory we used assumes the aircraft measurements truly represent average methane concentrations at a particular distance inland.

- There were no methane observations below the lowest aircraft sampling height (about 180 m above the surface). Our assumption that methane concentrations remain constant with height below the lowest aircraft measurement altitude could cause errors (see Section 7).

These results lead to the following recommendations for the ongoing methane profiles research:

1. Spatially varying estimates of livestock stock populations over the experimental area should be obtained.

2. The methane profile measurements should be performed on days with uniform on-shore winds. (Conditions with weak synoptic flows are conducive to night-time cold air drainage flows followed by daytime sea breezes, and are probably too meteorologically complex to allow good methane flux estimates).

3. Further spatial variability tests of the type described in Section 9 should be performed, on a day with a uniform onshore flow, which has not been preceded by night time drainage / land breeze flows. These should include an over sea flight parallel to the coast, and a flight parallel to the coast but about 20-30 km inland.

4. The collection rate for each of the aircraft methane samples should be slowed, to average out turbulent concentration fluctuations. The spatial variability tests recommended above should assist decisions about desirable sampling times. We suspect that given the typical horizontal spatial scales of convective thermal plumes in the atmosphere of around 200m (Stull, 1988), a sample collected over about 2 km horizontal distance may be desirable.

5. Profile measurements from more than about 30 km inland are unlikely to be useful, because of the vertical motions forced by airflow over the foothills and mountains.

6. Methane concentration measurements should also be made at the ground, underneath the aircraft profile locations.

7 Pilot balloon measurements of local wind profiles to at least 2 km altitude should be made at the same time as the methane profile measurements.

8. Attempts should be made to reduce the uncertainty bars on the gas chromatograph methane measurements.

9. Linked dispersion and mesoscale modelling techniques must be implemented, for interpreting the profile measurements and for estimating surface methane fluxes. These will involve fewer approximations and assumptions than the simple regional budget model used in this report. These models should be nested within large - scale synoptic analyses (eg. from the European Centre for Medium Range Weather Forecasting), but should also assimilate some local meteorological information.

ACKNOWLEDGMENTS:

This work was supported by non-specific output funding from the New Zealand Foundation for Research Science and Technology.

Many people assisted us. We wish particularly to thank Dr Martin Manning who proposed the concept for the research, our pilot Jim Rankin, and John Bolshover (NZ Meat and Wool Boards' Economic Service) who provided the livestock population figures.

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APPENDIX A: AIR FLOW AND DISPERSION MODEL DETAILS

INTRODUCTION:

The dispersion of any gaseous emission is entirely dependant on the current meteorology, and in most 'real' cases the meteorology has high spatial and temporal variability on a wide variety of scales. This makes the interpolation (and extrapolation) of the meteorological fields from observations alone insufficient, especially when considering dispersion 20 km or more beyond the source. Thus, to provide the meteorological information necessary for detailed dispersion studies, complex meteorological models which interpolate between observations (diagnostic models), or models which use both observations and systems of equations which fully describe the behaviour of the atmosphere (prognostic models) are required.

Once the meteorological fields are sufficiently defined, dispersion can be studied with the aid of a post-processing model. Two types are generally used; Lagrangian particle dispersion models which advect and diffuse individual particles, the resulting concentration fields being determined from the counting of particles within each grid volume; and Eulerian dispersion models where the emitted species is advected and diffused as a concentration field. The Lagrangian models are commonly applied to point sources much smaller than the spacing between the grid points at which the meteorological model makes its calculations, while Eulerian models are applied to sources with sizes near or above the grid spacing.

As the meteorological observations are of a low density, and the trace gas sources spread over a very wide area, this study makes use of a prognostic model. We will couple this to a Eulerian dispersion model to:-

- gain some insight into the complex three dimensional flows that typically occur around the Manawatu region, and
- reconcile the emissions with the sample data.

The meteorological and the dispersion models for use in this study are both described in the following sections.

METEOROLOGICAL MODEL

The prognostic mesoscale model used in this work is the Regional Atmospheric Modelling System (RAMS, version 3a) developed at Colorado State University. An overview of the model can be found in Pielke et al (1992), and a detailed description of the model equations and numerical solution scheme in Tripoli and Cotton (1982).

The primary function of the meteorological model in the ongoing Manawatu methane research is to provide wind and turbulence fields to the dispersion model, resolved at the appropriate scale. This scale is determined by several controlling factors, including the:-

- resolution of the emissions data,
- scale of the trace gas sampling,
- scales of the atmospheric processes controlling dispersion, and
- available computing resources.

RAMS fields are saved as analysis files which are then read as required by the dispersion model, and/or fed into the RAMS/VAN Visualisation and Analysis post-processing package.

In the following sections we provide generic information about the RAMS model and its application in this study. However the data and times provided in the discussion about model initialisation relate specifically to 8 June 1995, which is the day we have modelled in detail.

Model Configuration

All model runs were made on a Silicon Graphics R4600SC Indy workstation. Table A1 lists technical details of model settings used.

Feature	**Setting**
Numerical scheme	Forward-Backward, 2nd Order, Non-hydrostatic
Top boundary	Wall with six point absorbing layer
Lateral boundaries	Ridley radiative
Lower boundary	11 Level Soil Model
Radiation Scheme	2 - Mahrer / Pielke (other runs)
Cumulus Parameterisation	None
Eddy diffusion	1 - Horizontal deformation; Vertical TKE
Filtering	None
Surface Layer / Soil / Vegetation Model	Yes
Average Seasonal Temperature	14°C
Vegetation Type	Grid point dependant - see text
Initial Vegetation Temperature Offset	-4°C
Soil Type	6. - Sandy Clay Loam
Roughness length	Grid point dependant - see text
Albedo	0.2
Sea temperature	14.5°C
Moisture	Level 2

Table A1 Model settings used in RAMS (for all runs unless otherwise indicated).

Because cloud plays an important role in the radiation budget, we have used Level 2 moist physics which assumes cloud where there is excess water vapour. Boundary layer growth in RAMS v3a is controlled through the vertical mixing determined from a standard prognostic turbulence kinetic energy equation (Mellor-Yamada 2.5). Radiative horizontal boundary conditions developed by Ridley (1991) were used to remove unwanted propagation of water vapour inward from the lateral boundaries.

Model Grids

RAMS employs a terrain - following coordinate system, and a two - way interactive nested grid structure. Three grids are used in this work , the size and resolution of which are chosen according to the demands of the dispersion task, and the scale of the expected orographic influences.

Neighbouring features important to the region's climate are the northern Tararua and the southern Ruahine Ranges to the east, with relief to 1,500 m, the Manawatu Gorge which cuts an east-west passage between them, and the concave coastline to the west and north-west. On larger scales, the Southern Alps, Central Plateau, North Island's divide and Cook Strait all play influential roles in the development of mesoscale flows around the region.

Sensitivity tests on the parent grid (Grid 1) show it must encompass all of New Zealand, and include at least a 6 grid point clearance around the bottom of the South Island and a 4 grid point clearance around the eastern most point of the North Island. Maintenance of the barrier height is critical to obtaining a good estimate of the degree of blocking and flow diversion caused by the land masses. To achieve this the maximum horizontal grid point spacing was found to be 32 km. Grid 1, and its orography are shown in Figure A1.

To establish the requirements of finer grids the dispersion tasks are considered. At this stage the finest resolution is not restricted by the need to account for fine structure in the trace gas emissions, as these are handled as uniform throughout the pastoral portion of the Manawatu region. The dispersion of the trace gas will be dependant on synoptically driven flows (under the influence of the large scale orography), locally derived flows (such as drainage and sea breezes), and the development of the day time convective boundary layer. At this stage the horizontal resolution for Grid 3 is chosen to be 2 km. While this will not completely resolve some of the locally derived effects, it is considered suitable given the coarse nature of the emissions data. Using horizontal nesting ratios of 1:4, this gives an 8 km resolution for Grid 2. The horizontal extend of Grid 2 covers the Central Plateau, Mt Taranaki and the lower North Island, while Grid 3 extends from just off the Manawatu Coast to the east of the northern Tararuas and southern Ruahines, and includes most of the north-south extent of the Manawatu Plains. Grids 2 and 3 and their respective orography are illustrated in Figure A2 and Figure A3.

For all three grids the vertical resolution is 50m in the lowest level, expanding by geometric progression with a factor of 1.2 until a vertical spacing of 1,250 m is reached, and then continuing at that spacing up to 19 km. A total of 30 vertical levels result, which allow for a six grid point Rayleigh friction layer at the top of the model, implemented to absorb upward propagating gravity waves.

A summary of the model grid specifications is included in Table A2. Further work is planned to determine whether finer vertical and horizontal grid resolutions are desirable.

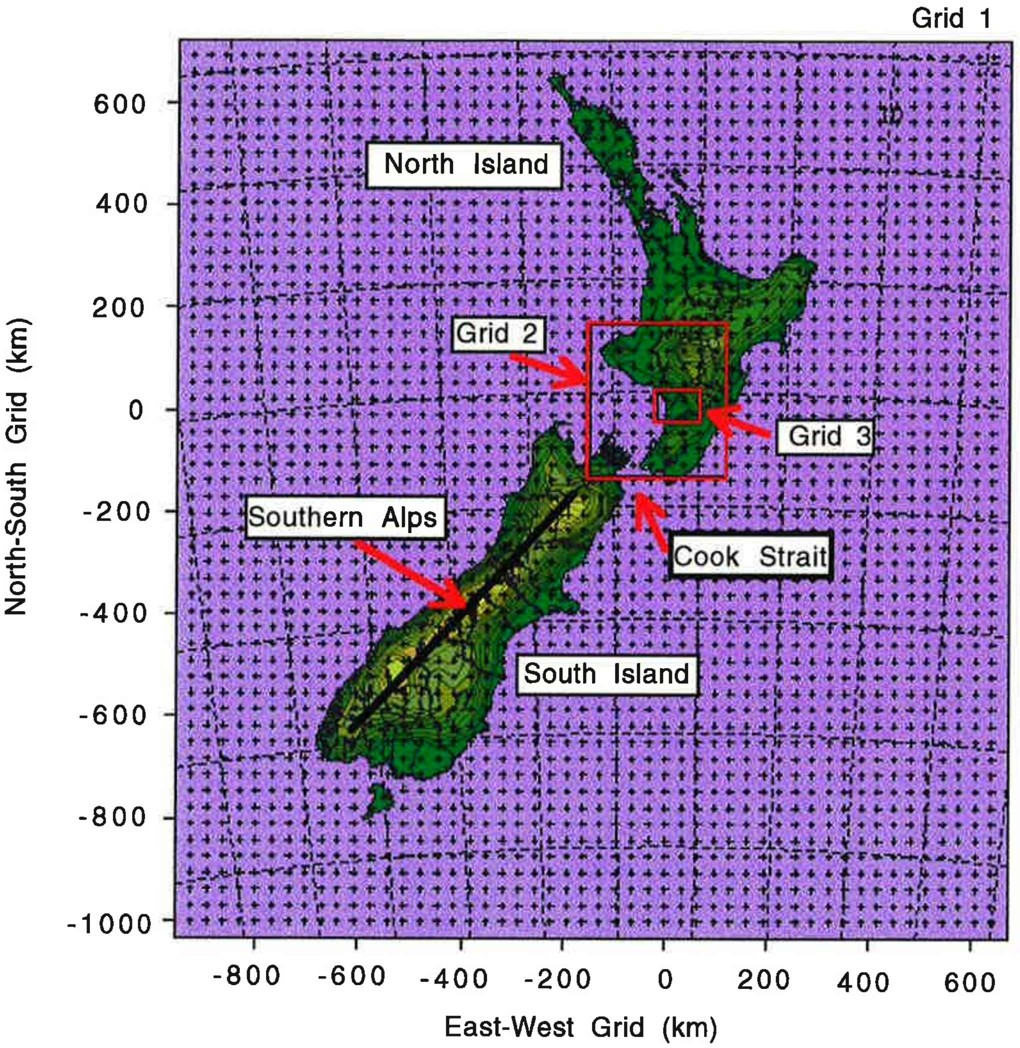

Figure A1 *Grid 1 and its orography at 32 km resolution. Contours are at 100 m intervals. Latitude and longitude lines are also shown, at intervals of 2°*

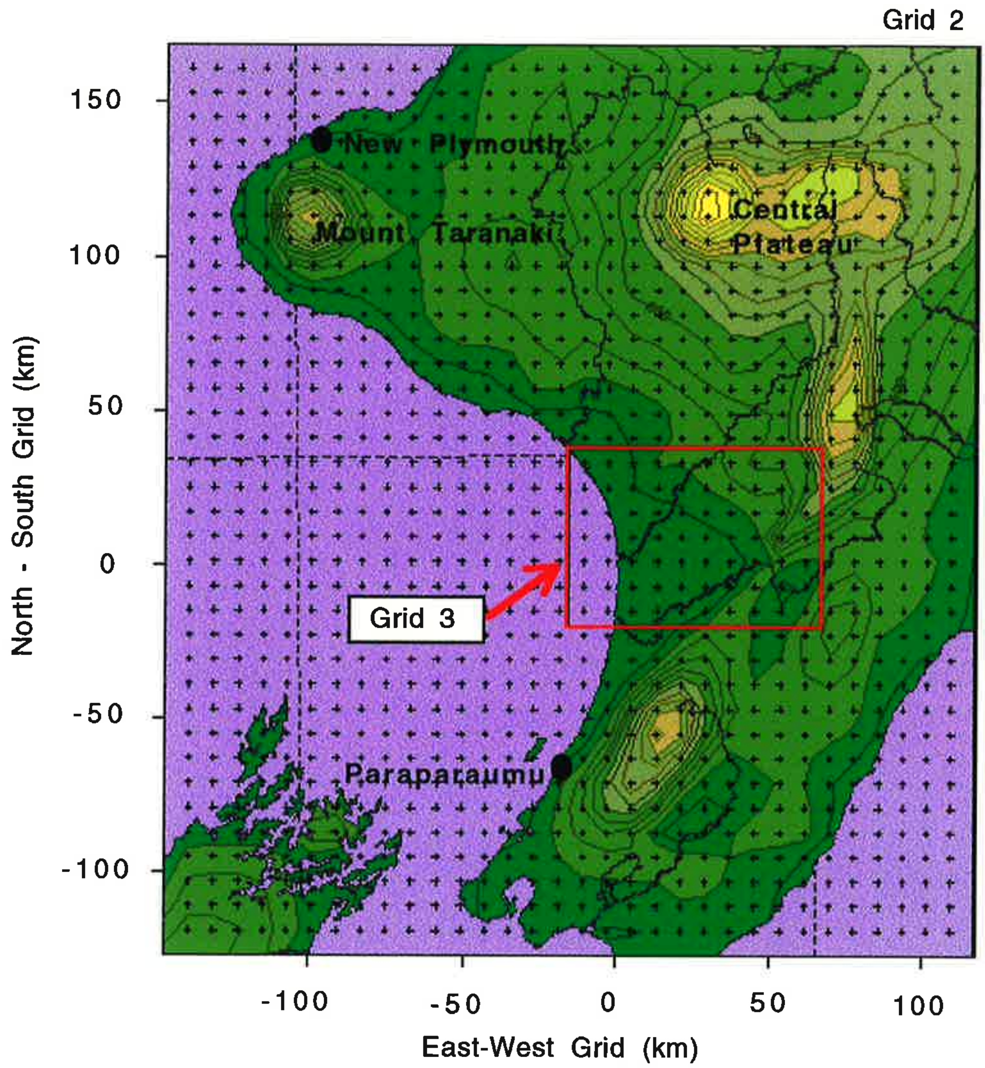

Figure A2 Grid 2 and its orography at 8 km resolution. Contours are at 100 m intervals.

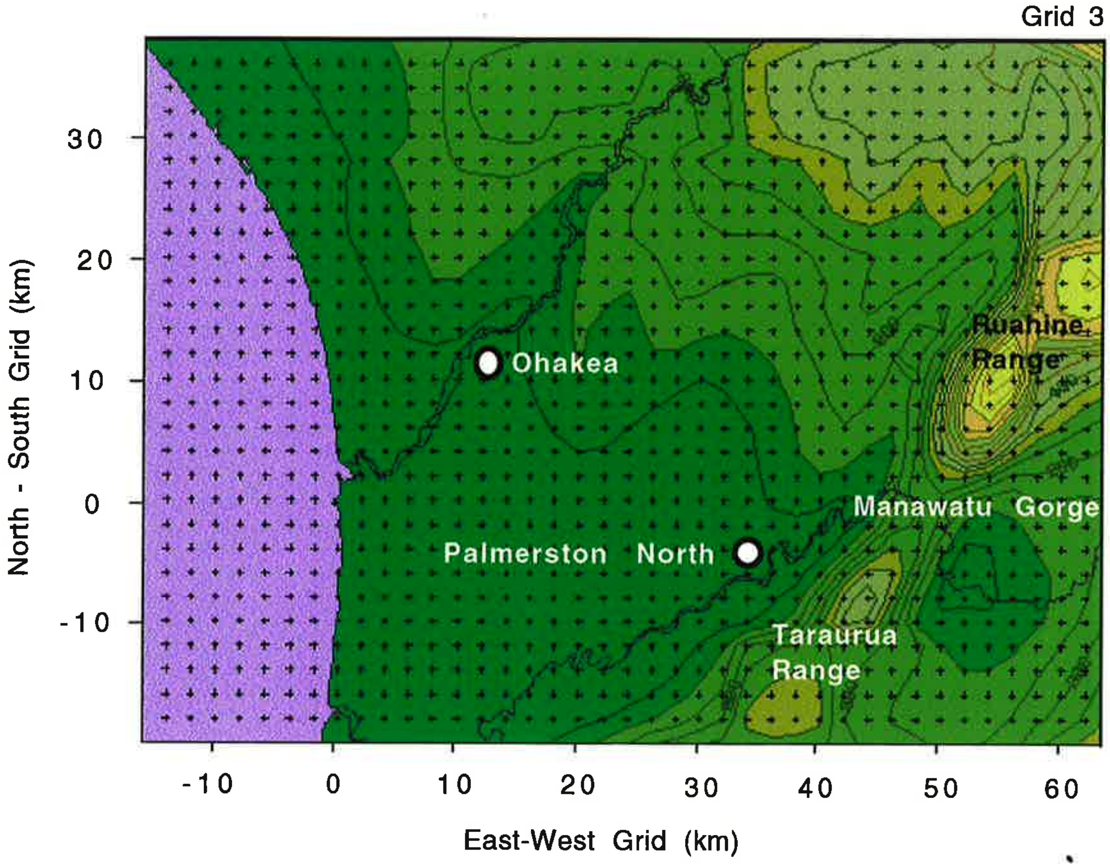

Figure A3 Grid 3 and its orography at 4 km resolution. Contours are at 50 m intervals.

Grid detail	Grid 1	Grid 2	Grid 3
E-W and N-S grid point separation (km)	32	8	2
E-W and N-S grid nesting ratio	-	4	4
Number of grid points E-W	43	34	42
Number of grid points N-S	53	38	30
Grid centre Latitude	-41.240°	-40.128°	-40.236°
Longitude	172.172°	175.047°	175.518°
Grid size (m) East - West	1,334	264	82
North - South	1,664	296	58
Number of atmospheric levels	30		
Lowest vertical grid height (m)	50		
Vertical stretch factor	1.2		
Maximum vertical level thickness (m)	1,250		
Model top (m)	18,900		
Number of soil levels	11		
Long time nesting ratio	1	4	4
Long time step (s)	60	15	3.73
Small time step ratio	3		
Short time step (s)	20	5	1.25

Table A2 Model grid and time step specifications.

Orography

Orography and land/sea percentage in the model were obtained from a data set of New Zealand's terrain available at 500 m horizontal, and 10 m vertical resolution. The topographic height of each grid point is initially taken as the average of the sub-grid scale heights in the data set. In this process the orography for modelling is smoothed, and terrain height lost.

It is well recognised, that to get the correct mesoscale flows, barrier height needs to be well represented in the model orography. This is especially true for New Zealand where the prevailing westerly flow comes up against the south-west north-east aligned mountain barrier. In the distributed RAMS code barrier height is maintained with a silhouette averaging scheme, while Ridley (1991) uses an envelope orography scheme.

In addition to maintaining the barrier height, our application demands that the heights of low lying areas and slope angles be well represented as they play a large part in the determination of the low level flows, and hence advection of the emitted trace gas. This is achieved through the application of the reflected envelope orography scheme illustrated in Figure A4. Whereas Ridley's envelope orography scheme enhances the grid point orography heights by a portion of one standard deviation of the sub-grid scale orography (obtained from the 500 m data set), the reflected envelope orography scheme adds the portion of the sub-grid scale standard deviation to local grid point terrain highs, and subtracts it from the lows. 'Local' here refers to the surrounding grid points within a set radius. For other grid points, proportions of the standard deviation are added or subtracted from the grid point height depending on that grid point's height relative to the local grid point average. Typically the enhancement factor (portion of the standard deviation) is between 0.7 and 1.0, and local radius 2 grid points. An added advantage of the reflected envelope orography scheme is that it maintains the total volume of the land mass, which allows flows through the terrain to be correctly modelled. The final pre-processing step in obtaining the model orography is to apply a 25 point filter which effectively removes any two grid length terrain forcing.

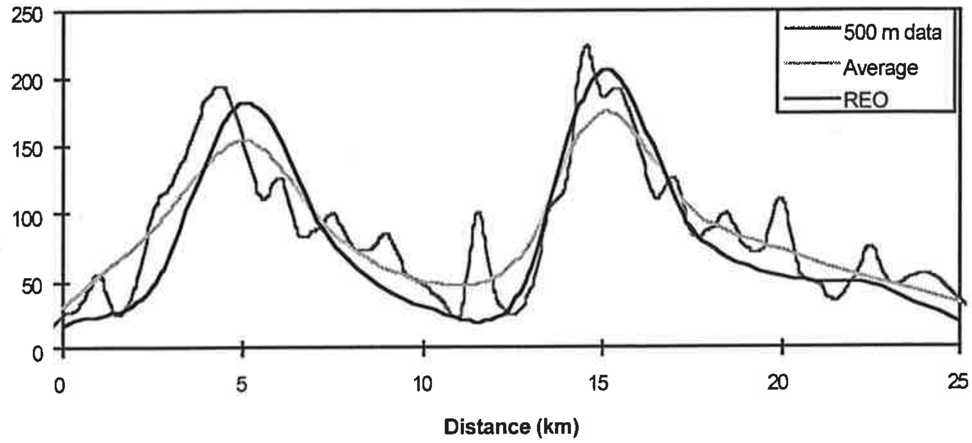

Figure A4 *The reflected envelope orography (REO) scheme. In this two dimensional illustration of the scheme the grid resolution is 5 km, local averaging radius 2 grid points, and the maximum enhancement 0.8 times the standard deviation of the sub-grid scale terrain heights.*

Surface Parameters

Data files of surface roughness and vegetation type have been extracted from 1:50,000 maps in lieu of detailed data sets being available. In the sensitivity runs made, RAMS appeared to produce significantly stronger surface flows than were observed. To alleviate this problem the surface roughness in the model was increased so that it not only represented the roughness of the vegetation cover, but also the sub-grid scale topography. The values indicated in Table A3 were taken from Stull (1988). This approach is undergoing further investigation.

Vegetation	**Terrain**	**Sub-Grid Scale Relief (m)**	**Surface Roughness Z_0 (m)**
Grazed Pasture	Flat	not considered	0.02
Grazed Pasture	Hilly	~50 m	1.0
Evergreen Bush	Mountainous	~200 m	5.0

Table A3 Surface roughness and associated vegetation types.

The average June climatological sea surface temperature off the Manawatu coast was used for all oceanic grid points. In future work this approach should be modified to make use of the available latitude longitude sea surface temperature data sets.

Soil type was estimated to be loamy sand near the coast and sandy clay loam on the inland plain (Cowie and Rijkse, 1977). As the greater proportion of grid 3 is covered by sandy clay loam, this was set as the soil type throughout the model. (Soil type is used in the model's parameterization of soil heat conduction and soil moisture storage).

Start Up Procedure

Grid 1 of the simulation was started at 2000 hours NZST on June the 8th with a 15 second long timestep. This long timestep was increased to 60 seconds at 2030 hours, and at 2330 hours grids 2 and 3 were introduced. This procedure was aimed at settling the simulation as soon as possible after start-up, and to allow sufficient time for it to develop the mesoscale drainage flows which influence the following day's meteorology and methane transport over the Manawatu Plain.

Initialisation Data

The sounding used to homogeneously initialise simulations was compiled using upper air soundings from Paraparaumu and New Plymouth, and is included as Table A4. The work described here covers a synoptically steady period, with very little change apparent during the 19 hours simulated. This is fortunate considering the model initialisation in homogeneous, and progress of the runs are not nudged towards any known observations during the integration. Further work should include non-homogeneous initialisation (for example initialising the model with synoptic-scale analysed meteorological fields), and then progressive nudging of the model runs towards changing synoptic-scale conditions or towards observed local winds.

Pressure (HPa)	Height ASL (m)	Wind Direction (°)	Wind Speed (m/s)	Temperature (°C)	Dew Point (°C)
1012	0	230	1	4.8	3.1
1005	58	230	2	10.6	5.6
997	126	230	3	11	5
992	162	230	5	10.8	4.8
973	322	230	7	9.4	3.9
939	622	230	7.5	6.8	2.3
905	922	225	8	4.2	0.7
877	1177	220	8.5	5.6	-10.4
804	1880	215	9	0	-14
774	2182	210	10	-2.3	-19.3
752	2412	210	11	-3.5	-14.5
681	3190	210	12	-5.3	-33.3
550	4838	210	14	-16.1	-37.1
537	5010	210	14.5	-16.3	-38.3
519	5269	210	15	-18.1	-25.1
504	5485	205	15.5	-18.7	-27.7
345	8200	195	14.5	-40.3	-60.3
304	9033	180	15.5	-46.7	-66.7
242	10521	170	18.5	-58.5	-78.5
193	11920	165	16	-65.7	-85.7
176	12488	205	16	-66.3	-86.3
156	13212	235	16	-58.7	-78.7
96	16282	245	20	-59.5	-79.5
74	17864	240	17	-61.7	-81.7
48	20583	240	17	-58.3	-78.3
43	21345	240	17	-60.3	-80.3

Table A4 Model sounding used for homogeneous initialisation. Note that the surface pressure used was 1012 Hpa.

Soil temperature and moisture are initialised with typical winter values. The initial model soil profiles are given in Table A5. Initialisation using observed values would be beneficial in further work. Note that the initial vegetation and soil temperature offsets (from the temperature of the lowest atmospheric layer) are too low for the 2000 hour NZST model start time, and should probably be set closer to 0°C.

Depth (m)	Temperature Offset (°C)	Soil Moisture Profile (fraction saturation)
0.00	-2.0	0.20
0.02	-1.5	0.25
0.05	-1.1	0.29
0.09	-0.67	0.31
0.12	-0.33	0.33
0.16	0.0	0.33
0.20	0.5	0.33
0.25	1.0	0.33
0.30	1.5	0.33
0.40	2.0	0.33
0.50	2.2	0.33

Table A5 Initial model soil temperature and moisture profiles.

DISPERSION MODEL

The dispersion model we intend to use is the HYbrid Particle and Concentration Transport Model (HYPACT, beta release version 0.2) currently being developed at Colorado State University. This model accepts RAMS output for its meteorological information, so essentially acts as a post-processing step. The resulting concentration fields are fed back into the RAMS/VAN visualisation package allowing output in combination with any of the RAMS fields. We intend to use the Eulerian concentration transport option as the emission sources (animals) are spread over the whole Manawatu region, which is large compared to the grid size and the resolution of the animal spatial distribution information used to prepare the initial emission estimates.

We have made several Lagrangian particle runs with HYPACT but because of bugs in the code of the HYPACT beta release we have not yet got the Eulerian simulations working satisfactorily, and we have not presented any HYPACT results in this report. For the next stage of the modelling work (until the HYPACT problems are resolved) we will use the Eulerian inert tracer transport option available within the RAMS model itself. This approach (using RAMS directly to simulate dispersion) requires a full rerun of RAMS for each emissions scenario. The HYPACT "post-processing" approach is more desirable, since different emissions scenarios can be simulated without re-running RAMS.

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APPENDIX B Stock Numbers by Month, Manawatu Regional Council

(Source: NZ Meat and Wool Boards' Economic Service)

MANAWATU - STOCK NUMBERS BY MONTH.

Estimates are stock numbers at the start of the month.

(000 head)	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
	1994	1994	1994	1994	1994	1994	1995	1995	1995	1995	1995	1995	1995
Open Sheep													
Adults	742.4	724.0	710.6	927.3	911.0	883.4	859.2	830.7	796.5	762.3	742.7	724.4	710.5
Hoggets	290.5	265.0	246.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	302.5
	1032.9	989.0	957.0	927.3	911.0	883.4	859.2	830.7	796.5	762.3	742.7	724.4	1013.1
Lambs - milk	0.0	12.0	209.5	573.1	501.8	134.5	8.2	0.0	0.0	0.0	0.0	0.0	0.0
Lambs - grass	0.0	0.0	0.0	12.0	190.5	524.1	610.3	572.9	532.0	472.5	426.0	357.4	0.0
Total	1032.9	1001.0	1166.5	1512.4	1603.4	1542.0	1477.6	1403.6	1328.5	1234.8	1168.7	1081.8	1013.1
Open Beef													
Beef Cattle	115.9	114.8	113.8	112.7	111.5	109.6	106.4	103.0	100.5	96.3	93.1	88.2	115.7
Beef Weaners	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	28.0
	146.6	145.5	144.5	143.4	142.2	140.3	137.1	133.7	131.2	127.0	123.8	118.9	143.7
Calves	0.0	1.3	17.6	25.5	28.4	28.6	28.5	28.4	28.3	28.2	28.1	28.1	0.0
Total	146.6	146.8	162.1	168.9	170.7	168.8	165.6	162.1	159.5	155.1	151.9	147.0	143.7
Open Dairy													
Dairy Cattle	71.6	71.1	70.7	70.2	69.6	68.6	67.0	65.2	63.9	61.7	60.1	57.5	72.20
Dairy Weaners	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.40
	87.9	87.4	87.0	86.5	85.9	84.9	83.3	81.5	80.2	78.0	76.4	73.8	88.60
Calves	0.0	0.7	10.9	15.8	17.6	17.5	17.3	17.2	17.0	16.8	16.7	16.6	0.00
Total	87.9	88.2	97.9	102.3	103.4	102.4	100.6	98.7	97.3	94.9	93.1	90.4	88.60

APPENDIX C: Methane Profile Measurement Data

Manawatu Methane, 25 May 1995												
	Altitude above msl											
	GPS	GPS	GPS	Pressure	Methane	σ_{n-1}	Start	Start	End	End	start	end
Flask	start	end	mean	mb	ppbv	ppbv	lat	long	lat	long	time	time
											NZST	NZST
2	1427	1440	1433	871.6	1702.5	3.8	-40.3	175.161	-40.3	175.158	13:10	13:11
3	1234	1239	1236	888.7	1701.2	2.9	-40.33	175.19	-40.323	175.185	13:11	13:12
4	1093	1087	1090	903.5	1694.4	3.1	-40.31	175.179	-40.31	175.182	13:12	13:13
5	944	941	943	920.6	1701.1	3.3	-40.33	175.193	-40.326	175.188	13:14	13:15
6	811	813	812	937.9	1702.34	1.98	-40.31	175.18	-40.311	175.184	13:15	13:16
7	624	628	626	954.6	1700.9	2.6	-40.33	175.201	-40.326	175.197	13:16	13:17
8	434	440	437	971.7	1709.77	2.29	-40.31	175.18	-40.313	175.184	13:18	13:18
9	279	279	279	990.2	1708.87	3.9	-40.33	175.204	-40.328	175.199	13:19	13:20
10	129	128	129	1022	1708.94	2.5	-40.2	175.378	-40.315	175.191	13:20	13:21
12	1341	1345	1343	871.9	1704.86	2.5	-40.21	175.63	-40.211	175.635	13:36	13:37
13	1212	1202	1207	887.1	1704.25	4.4	-40.22	175.652	-40.222	175.646	13:38	13:38
14	1110		1110	903.5	1697.03	3.6	-40.22	175.627	-40.215	175.633	13:39	13:40
15	953	19956	953	919.9	1714.38	2.9	-40.22	175.653	-40.225	175.648	13:40	13:41
16	773	767	770	937.6	1707.8	3	-40.22	175.625	-40.218	175.631	13:41	13:42
17	689	685	687	954	1711.35	3.4	-40.22	175.655	-40.222	175.65	13:43	13:43
18	547	563	555	976.3	1711.8	2.6	-40.22	175.626	-40.217	175.631	13:44	13:45
19	360	361	361	989	1716.89	2.1	-40.22	175.649	-40.222	175.643	13:45	13:46
20	0	185	185	1022	1711.7	2.2			-40.211	175.635	13:46	13:47
11	1429	1433	1431	855.2			-40.22	175.653	-40.288	175.162	13:35	13:36
1	1588	1592	1590	857.4			-40.28	175.16	-40.219	175.65	13:09	13:09

note: GPS altitude adjusted for wrong order.
also adjusted lat/long values for same effect.

Manawatu Methane 8 June 1995

	Alt above msl															
	metres			Pressure	Pressure	Air	CH4 ppbv	CH4 ppbv	CH4 ppbv	σ_{n-1}	start		end		Start	End
Flask	GPS	GPS	GPS	mb	Alt	temp	Sea	Colyton	Chelten-	ppbv	lat	long	lat	long	time	time
	start	end	mean		metres	°C			ham						NZST	NZST
1	1183	1189	1186	878.7	1185	4.6	1703.76			4.2	-40.3	175.2	-40.3	175.2	12:22	12:23
2	1051	1052	1052	895.5	1033	5.6	1702.44			2.9	-40.33	175.2	-40.3	175.2	12:24	12:24
3	887	888	887	911.6	890	6.7	1701.98			3.2	-40.3	175.2	-40.3	175.2	12:26	12:26
4	842	876	859	929.2	736	6.9	1704.68			1.4	-40.33	175.2	-40.3	175.2	12:27	12:28
5	495	490	493	963.9	442	9.3	1711.86			2.8	-40.3	175.2	-40.3	175.2	12:29	12:30
6	92	52	72	996.4	175	11.7	1725.36			2.7	-40.34	175.2	-40.3	175.2	12:31	12:31
7	1506	1522	1439	847.5	1476	4.3		1709.76		3	-40.25	175.7	-40.3	175.7	12:47	12:48
9	1166	1164	1165	878.7	1185	3.7		1706.36		2.3	-40.26	175.7	-40.3	175.7	12:50	12:50
10	878	870	874	909.7	907	5.3		1714.55		3.3	-40.25	175.7	-40.3	175.7	12:51	12:52
11	655	662	659	943.8	611	8.0		1717.49		3.1	-40.24	175.7	-40.2	175.7	12:53	12:54
12	304	312	308	980.6	304	10.7		1726.22		3.4	-40.26	175.7	-40.3	175.7	12:55	12:55
13	182	189	186	996.1	178	12.3		1734.11		3.3	-40.23	175.7	-40.2	175.7	12:56	12:57
14	1718	1720	1719	833.4	1611	3.5			1705.59	3.4	-40.13	175.7	-40.1	175.7	13:08	13:09
15	1620	1617	1618	845.6	1494	3.1			1706.49	3.3	-40.15	175.7	-40.1	175.7	13:09	13:10
16	1274	1280	1277	877.8	1194	2.6			1710.59	3	-40.13	175.7	-40.1	175.7	13:11	13:12
17	925	925	925	911	895	5.8			1709.22	1.8	-40.14	175.7	-40.1	175.7	13:13	13:14
18	658	646	652	943.8	611	8.5			1711.29	3.6	-40.13	175.6	-40.1	175.7	13:15	13:15
19		303	303	979.4	314	10.9			1716.02	2.2	-40.14	175.7	-40.1	175.7	13:17	13:18
20	294	286	290	978.2	323	11.0			1716.96	1.3			-40.1	175.7	13:18	13:18

Use Pressure Altitudes as these are more correct

GPS start stop alt are not very good at all due to method and software error

Pressure based on a Foxboro 0-15 psia sensor

GPS values adjusted for offset

Manawatu Methane 26 June 1996

	Alt above MSL, metres			Atmos	Pressure	Air									Start	End
	GPS	GPS	GPS	Pressure	Alt	Temp	CH4	CH4	CH4	σ_{n-1}	Start	Start	End	End	Time	Time
Flask	Start	End	mean	Mb	metres	°C	Sea	Mt Stewart	Colyton	ppbv	Lat	Long	Lat	Long	NZST	NZST
1	1418	1427	1422	844.7	1506	0	1712			2.09	-40.305	175.17	-40.3	175.2	13:11	13:12
2	1291	126	1291	858.6	1375	1	1713			3.9	-40.319	175.19	-40.3	175.2	13:13	13:14
3	1050	1053	1051	889.9	1087	4	1709			2.01	-40.309	175.17	-40.3	175.2	13:15	13:16
4	727	725	726	921.8	804	6	1710			2.21	-40.312	175.19	-40.3	175.2	13:17	13:17
5	459	461	460	956.8	505	9	1710			2.41	-40.314	175.18	-40.3	175.2	13:19	13:20
6	175	175	175	991.2	221	11	1712			3.7	-40.317	175.21	-40.3	5029	13:20	13:21
7	1495	1509	1502	844.1	1512	1		1709.76		1.13	-40.223	175.53	-40.2	175.5	13:31	13:32
8	1322	1331	1327	860.8	1355	2		1713.2		1.82	-40.227	175.59	-40.2	175.6	13:32	13:33
9	1027	1059	1043	890.8	1079	4		1712.62		3.47	-40.236	175.57	-40.2	175.6	13:34	13:34
10	745	754	749	924.9	777	6		1712.85		3.19	-40.247	175.6	-40.2	175.6	13:35	13:36
11	691		691	963.3	450	8		1715.94		2.45	-40.243	175.57	-40.2	175.6	13:37	13:37
12	267	267	267	975.4	350	9		1714.39		2.46	-40.248	175.59	-40.3	175.6	13:38	13:39
13	129	130	129	988.7	241	11		1718.86		3.59	-40.255	175.58	-40.3	175.6	13:39	13:40
14	1564	1564	1564	845.6	1498	1			1710.32	1.46	-40.238	175.78	-40.2	175.8	13:50	13:51
15	1505		1505	856.4	1396	2			1708.07	3.55	-40.248	175.78	-40.2	175.8	13:51	13:52
16	1325	1330	1328	889	1095	4			1709.78	2.54	-40.247	175.76	-40.2	175.8	13:53	13:54
17	850	850	850	920.6	815	6			1710.04	1.62	-40.244	175.76	-40.2	175.8	13:55	13:56
18	504	506	505	959.9	479	8			1712.25	1.23	-40.246	175.76	-40.2	175.8	13:58	13:58
19	347		347	973.8	363	9			1719.99	3.15	-40.246	175.78	-40.2	175.8	13:59	14:00
20		255	255	987.8	248	11			1719	2.51			-40.3	175.8	14:01	14:02

NOTE: GPS altitude and position data altered by shifting up starts by one row to allow for error.

Pressure altitude calculated using 18400*log (1013.3/Pressure)_ (Smithsonian page 144)

Use pressure altitudes as these agree best with actual aircraft altimeter values

QFE=-5.5 mb

QNH=1013.0 mb (msl) at 1254

Cu towers to about 8000 feet

cloud 7/8 Cu

Wind 30-40 kts at 3000 feet

land and QNH = 1011.2 mb at 1419 nzst

Manawatu 29-2-96													
transect at 300 m													
Sample	Alt above msl (m)			pressure	Pr ALT	Methane	σ_{n-1}	start		end		Start	End
	GPS	GPS	GPS	(mbar)	m	ppbv	ppbv	lat	long	lat	long	time	time
	start	end	mean									NZST	NZST
2	305	337	333	979.7	311	1726.35	2.43	-40.366	175.186	-40.362	175.187	11:15	11:16
3	306	366	369	979.1	316	1729.86	1.17	-40.415	175.183	-40.410	175.183	11:17	11:18
4	306		330	979.4	314	1731.03	1.41			-40.448	175.178	11:18	11:19
5	306	270	288	980	309	1727.22	2.16	-40.479	175.174	-40.474	175.174	11:19	11:20
8	307	405	404	979.7	311	1815.97	1.43	-40.383	175.270	-40.382	175.264	11:28	11:29
9	308	432	429	980.9	301	1821.07	1.35	-40.390	175.307	-40.389	175.302	11:29	11:30
10	308	428	427	980.6	304	1830.44	1.66	-40.397	175.344	-40.396	175.338	11:30	11:31
11	308	387	392	980.3	306	1782.96	2.73	-40.402	175.382	-40.401	175.376	11:32	11:33
12	308	344	350	977.2	332	1788.98	2.83	-40.408	175.423	-40.407	175.417	11:33	11:34
13	309	301	301	978.5	321	1781.72	0.71	-40.413	175.463	-40.413	175.457	11:34	11:35
14	309	333	329	981.6	296	1813.25	0.77	-40.418	175.508	-40.417	175.503	11:35	11:36
15	309	217	223	980	309	1731.09	1.43	-40.425	175.586	-40.425	175.583	11:38	11:39