Golder Associates

DISPERSION MODELLING IN NEW ZEALAND PART 1 – ASSESSMENT OF METEOROLOGICAL MODELS

DECEMBER 2007

DISPERSION MODELLING IN NEW ZEALAND
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on behalf of

FRST programme *Protecting New Zealand's Clean Air*

prepared by

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Executive Summary

This report contains practical advice for users of the meteorological models TAPM and CALMET. These models are the drivers of dispersion models run for industrial and urban air quality assessments. Recommendations are made arising from several case studies of industrial sites in New Zealand.

The report contains specific guidance on the configuration of each model, and on techniques for model validation. As the focus is on the meteorological simulations, rather than pollution dispersion, the recommendations apply equally to urban air quality investigations.

The report examines the challenges to running the models in New Zealand's complex terrain, and limitations posed by the scarcity of meteorological data away from urban areas. It provides guidance on how these may be overcome by using the best features of each model in combination. These features are TAPM's good performance in simulating the larger-scale three-dimensional meteorology and CALMET's ability to parameterize the detailed effects of terrain on the near-surface flow.

Findings and recommendations arising from this work are collected together after the case studies are presented. The key recommendations are as follows.

1) TAPM is suited to cases where the meteorological features can be resolved on a grid with spacing greater than 1 km. If the meteorology is driven by the terrain, it becomes a matter of the model's ability to resolve the topography.
2) Validation of TAPM should be carried out using statistical performance indicators in addition to an hour-by-hour visual comparison of results with observations.
3) CALMET is suited to sub-km resolutions. Terrain effects at these scales are parameterized by the model.
4) Validation of CALMET is more subjective, as the observations are used as inputs to the model. Nevertheless, several performance criteria are suggested.
5) If there are no local meteorological observations, and the resolution needs to be better than 1 km, TAPM results may be used to drive CALMET, as if they were observations.
6) If there are surface-based climate sites, but no observed vertical profiles, then TAPM profiles may be blended with the surface observations, and the combined profiles used to drive CALMET.

If recommendation (5) or (6) is being followed, care must be taken when blending TAPM results with observations, as they may not be consistent with each other. Methods for doing this are contained in the report.

The Ministry for the Environment good-practice guide for atmospheric dispersion modelling (2004) contains recommendations on the use of meteorological models. Those recommendations are reviewed in the light of the authors' experience since the publication of that document.

1. Meteorological Modelling for Air Quality Assessments

1.1 Introduction

This technical report provides practical advice and recommendations to consultants, industry, and air-quality technical specialists at regional councils regarding two models that are commonly used in assessments of air quality. It addresses important issues and problems associated with dispersion modelling, with the aim of improving the way dispersion modelling is carried out in New Zealand (NZ). They are presented by way of several case-study examples. The report provides an update of some of the advice contained in the Ministry for the Environment's (MfE's) good-practice guide on dispersion modelling (MfE, 2004).

This work was carried out as part of a research programme funded by the Foundation for Research, Science and Technology (FRST), entitled *Protecting New Zealand's Clean Air.* The programme commenced in October 2004, carrying out fundamental science to underpin the implementation of the National Environmental Standards (NES) for air quality, which are promulgated by the MfE. It is therefore end-user focused, the primary stakeholders being government ministries, territorial local authorities, consultants and industry. The programme is a collaborative venture between two Crown Research Institutes (CRIs), one university and three environmental consultants. A summary of the programme, and a downloadable selection of research results published to date, may be found at http://www.niwascience.co.nz/ncces/air_quality/.

Dispersion modelling research is in progress to adapt, test and evaluate models for NZ conditions, and to demonstrate their use in practical situations, such as to make predictions of air quality in 2013, the target year for clean urban air. It has become apparent over the last few years that there is a need to improve the way meteorological information is incorporated into dispersion modelling studies. This specific issue is addressed in depth here with reference to industrial sites, but the general results and recommendations coming out of the work apply equally to any modelling assessment – industrial or urban.

1.2 Aims of the Report

The main aim of this report is to provide advice for practitioners on running the models TAPM (The Air Pollution Model) and CALMET, assessing their performance, and producing meteorological fields for dispersion modelling. After some introductory remarks in this section, the case studies are presented in detail in Sections 2, 3 and 4. These sections address:

1) The use of TAPM for high-resolution applications, and the model-validation process.
2) The use of CALMET in general, with specific guidance on parameter settings.
3) The blending of outputs from both models in regions of complex terrain and sparse data coverage.

They will guide the reader through the meteorological modelling process, from model configuration to model performance assessment. Findings and recommendations arising from the studies are collected together and summarized in Section 5. Note that this document is technical in nature, and is not intended as an introduction to modelling for a general audience.

1.3 The Good-Practice Guide for Dispersion Modelling

The good-practice guide (GPG) was issued in 2004 (MfE, 2004). It was particularly forward looking, promoting the use of advanced meteorological and dispersion models as more realistic alternatives to steady-state Gaussian-plume models. Steady-state models are often used beyond the limits of their applicability, and the good-practice guide provided advice on the use of models such as CALPUFF, TAPM and MM5. At that time, a guideline was published in New South Wales, which focused on

Gaussian-plume models such as AUSPLUME (DEC, 2005). In NZ, an effort was made to not be prescriptive, provided that models were used appropriately for each application.

Gaussian-plume models use meteorological data at a single point to represent the whole domain of interest in relatively flat terrain. NZ's terrain and coastline are complex, generally necessitating the use of dispersion models which can incorporate three-dimensional details of the meteorology, especially for simulations of dispersion over ranges beyond the industrial site boundary. In addition, NZ's urban air quality problems often occur in calm conditions. Complex terrain effects and calm winds cannot be represented by a Gaussian-plume model.

However, some of the suggestions and recommendations of the GPG had not been thoroughly tested in the regulatory arena – consultants in the meantime have largely stayed with AUSPLUME for industrial assessments (which is often appropriate for predictions of short-range impacts). However, researchers *have* put the more advanced models to the test, and ideas on best practice have evolved in the last two or three years, using models such as CALGRID, TAPM, WRF and CAMx for urban air quality research. There is also a gradual migration toward the use of CALPUFF for industrial assessments in NZ. In Australia, TAPM is growing in popularity, but its dispersion modules have not, to the authors' knowledge, been used for industrial assessments in NZ.

1.4 Meteorological Modelling in NZ's Complex Terrain

There are several challenges to obtaining a good model simulation of the meteorology of NZ. These include NZ's geographical complexity and the limited availability of climate data for high-resolution applications. Also, there can be many ways of providing these inputs to dispersion models, and guidance is needed on good practice. There is a contrast here with the dispersion component of any modelling study, in that although the dispersion model may be complex, the user's choices are limited.

Section 5 of the good-practice guide (MfE, 2004) describes how TAPM and CALMET work, and their advantages and disadvantages. However, there is little expansion on specific issues or provision of advice. With several years' experience since then, the modelling community can fill in some of the gaps, and specific advice on the use of these models is provided in this report. Statements made in the MfE guide on meteorological modelling are given in Table 1.1, which provides updated comments based on the authors' experience.

Complex terrain and coastlines characterize NZ. The meteorology is consequently complex, with land/sea breezes, terrain-induced flows, drainage, pooling of cold air and temperature inversions. All of these affect pollution dispersion, all can operate on sub-kilometre scales, and none may be represented well by the meteorology of a single point, or a single vertical profile.

The ability of commonly-used models in NZ to represent small-scale meteorological features is compared in Table 1.2 by providing responses to questions posed on the models' desired capabilities.

The questions are phrased so that the preferred answer would be 'yes'. Some answers are linked to each other (for example run time and resolution). It should be noted that CALMET produces three-dimensional meteorological fields primarily by extrapolating input data, rather than by solving equations representing atmospheric physics, and the quality of its output is limited by this.

Reading Table 1.2 from left to right, the models become more complex, and arguably more physically realistic, but not necessarily more difficult to use. They also become more resource intensive, and are less commonly used. Even though users have been encouraged to contemplate moving in this direction in the good-practice guide (MfE, 2004), this may not always be necessary, and for many applications AUSPLUME is appropriate.

No model in Table 1.2 can answer 'Yes' to every question. This report focuses on TAPM and CALMET, and addresses some of the difficulties in running each of them.

Table 1.1: Current standing of some comments in the MfE modelling good-practice guide.

Statements in the good-practice guide	Updates due to recent experience
Advanced meteorological models are 'rarely used'.	No longer true – they are used by many air quality consultants in NZ.
CALMET is complex to use.	This is still true, but training and advice are available.
Costs to industry are higher for a CALPUFF assessment, than for an AUSPLUME assessment.	This could be true, but in data-sparse areas meteorological modelling is often carried out using TAPM or CALMET and results extracted for input to AUSPLUME. This is almost as expensive, but does not have the benefits of the extra detail afforded by the advanced model.
Most common prognostic mesoscale models in use in NZ are RAMS, MM5 and TAPM.	RAMS is no longer used for air quality assessments; MM5 has been superseded by WRF (but is not used for commercial air quality assessments); TAPM has increased in popularity.
TAPM should only be used to a horizontal resolution of 1 km.	The consequences of this are becoming clear, and are described below.
Suggested combined approach using three-dimensional TAPM meteorological fields as input to higher-resolution CALMET runs.	Alternative approach described here in which isolated profiles are extracted from TAPM and input to CALMET. This is more flexible, though it remains to be seen whether it grows in popularity.

Table 1.2: Comparison of model features and abilities.

	AUSPLUME	CALMET	TAPM[1]	MM5/WRF
Easy to use?	Yes	No	Yes	No
In use in NZ?	Commonly	Fairly Common	Sometimes	Rare
3-d meteorology?	No	Yes	Yes	Yes
Sub-km resolution?[2]	No	Yes	No	Yes
Complex terrain?	No	Yes	Yes	Yes
Fast run time on a single PC?	Yes	Yes	Yes	No
Calm conditions?	No	Yes	Yes	Yes
Meteorology based on equations of physics?	No	No	Yes	Yes

[1] Discussion of TAPM in this report refers to its meteorological component, not its dispersion modules.

[2] This refers to the meteorology, not the dispersion model's grid of receptors.

1.5 Introduction to Meteorological Modelling Case Studies

The case studies presented are:

Section 2: Edendale TAPM Case Study,

Section 3: Tiwai Point TAPM Case Study, and

Section 4: Tiwai Point CALMET Case Study.

These are self-contained investigations, using meteorological data provided by NZ Aluminium Smelters and Fonterra, for sites at Tiwai Point, near Invercargill, and Edendale, respectively. Emissions data have also been provided for dispersion-model studies which will be reported on later. Note that although these are industrial sites in rural areas, the principal results of this meteorological modelling report apply to any region, urban or rural.

Sections 2 and 3 contain studies using the meteorological component of TAPM, and include standard procedures for comparing model results with surface-based and upper-air data. They also describe the use of statistical performance measures, such as root-mean-square errors, mean absolute error, and index of agreement. There is also examination of and an attempt to explain discrepancies between model results and observations. A description of all model performance measures mentioned in the report is contained in the Appendix.

Section 4 applies CALMET to the Tiwai Point study, and describes methods for supplementing meteorological data with vertical profiles and surface results from TAPM. Several approaches are discussed, depending on the availability of meteorological data. An approach for blending TAPM profiles with surface observations before input to CALMET is discussed, and its use results in smooth transitions between observations and modelled meteorology in the CALMET results.

2. Edendale Case Study – Assessment of TAPM Performance

2.1 Model Description

The meteorological component of TAPM is an incompressible, primitive equation weather forecast model. It includes parameterizations for cloud, rain and snow microphysical processes as well as for turbulence closure and surface fluxes (Hurley, 2005(a)). A detailed description of the basic equations and numerical techniques is given by Hurley (2005(b)). TAPM has been applied to a range of situations from point source to urban airshed dispersion in several locations with good results (e.g., Hurley *et al.*, 2005(c); Zawar-Reza *et al.*, 2005(b)).

2.2 Model Configuration

Monitoring data from Edendale shows an average surface wind speed of 5 m s^{-1} during spring-summer (September to December). This means a transport distance of 18 km during one hour for the average conditions, therefore an inner domain of 20 km x 20 km was chosen. TAPM is not intended to be run with horizontal resolutions higher than 1 km. Therefore, the innermost grid was selected to have 20 x 20 grid points with a horizontal resolution of 1 km. From this, the outer grids were chosen following the recommendations of TAPM's developers (Hurley, 2005(a)). These are that the horizontal resolution of an outer grid should not be more than 4 times the inner grid and that the outermost domain should be larger than 400 km x 400 km but smaller than 1000 km x 1000 km. Furthermore, it is suggested that the model grid consist of at least 20 x 20 horizontal grid points and 20 vertical levels. Table 2.1 shows the geometry parameters used for this application.

Table 2.1: Geometry parameters used to set up TAPM for this study. Each grid contains 20 x 20 cells.

Parameter name	List of parameter values			
Vertical levels	10 50 100 150 200 300 400 500 750 1000 1250 1500 1998 2500 3000 4000 5000 6000 7000 8000 (m)			
Domain-centre Coordinates	46º 18.5′ S	168º 47′ E		
Grid number	1	2	3	4
Resolution	30 km	8 km	3 km	1 km
Area	600 x 600 km	160 x 160 km	60 x 60 km	20 x 20 km

Hirdman (2006) showed that there is little improvement in TAPM simulations as a result of changing more advanced settings such as the deep soil volumetric moisture content (DSVMC) and the synoptic pressure gradient scaling and filtering from the recommended values. Therefore, for this study, the recommended options were used (see Table 2.2 for details). The synoptic analyses for the boundary conditions and the sea surface temperature and Deep Soil Volumetric Moisture Content (DSVMC) were obtained from CSIRO for the period of interest (September to December 2003) as part of the information supplied with the TAPM installation.

Table 2.2: Advanced options used in this study.

Option	Value
Maximum synoptic wind speed	30 m s^{-1}
Synoptic pressure gradient (SPG) scaling	1.0
SPG, temperature and moisture filtering	1.0
Boundary conditions	From synoptic analyses
Surface vegetation	Included
Non-hydrostatic pressure	Not included
Rain processes	Included
Snow processes	Not included
Prognostic eddy dissipation rate	Included

2.3 Comparison with Soundings at Invercargill

2.3.1 Background

The only upper-air information available for the area is from the Invercargill airport soundings, around 35 km south-west of Edendale and therefore outside of the innermost modelling grid but inside the 8 km resolution domain. Data are available three times per day at 00:00, 6:00 and 12:00 NZST, and extend up to 15 km in the vertical.

To compare the model results with the measurements, a pre-treatment of the data was necessary because of the different vertical resolution of the information provided by each source. The observations were averaged in the same vertical layers as the model results between 10 m and 7000 m. The comparison between the model and the measurements will be presented for firstly the temperature, then the wind direction and finally the wind speed. The modelling results were taken at the nearest land grid point (more than 50 % of land in Grid 2) which was about 2 km from the location of the measurements.

2.3.2 Temperature

As shown in Fig. 2.1, TAPM is able to capture the general features of the time series of the vertical profile of the temperature. The recurrent cold periods observed, for example, at the beginning and the end of October are accurately captured by TAPM both in their duration and intensity. This indicates that the vertical structure of the troposphere is generally captured by TAPM in terms of the stability of the different layers.

Fig. 2.2 shows the correlation coefficient between the observations and the model results. Even though the correlation is good for all heights (R>0.8), for layers above 500 m the correlation coefficient is larger than 0.9 which indicates that TAPM better captures the variability observed in the temperature of the higher layers. This is to be expected considering that higher layers are less affected by local features and their characteristics are generally representative of larger horizontal areas, comparable to the model grid size.

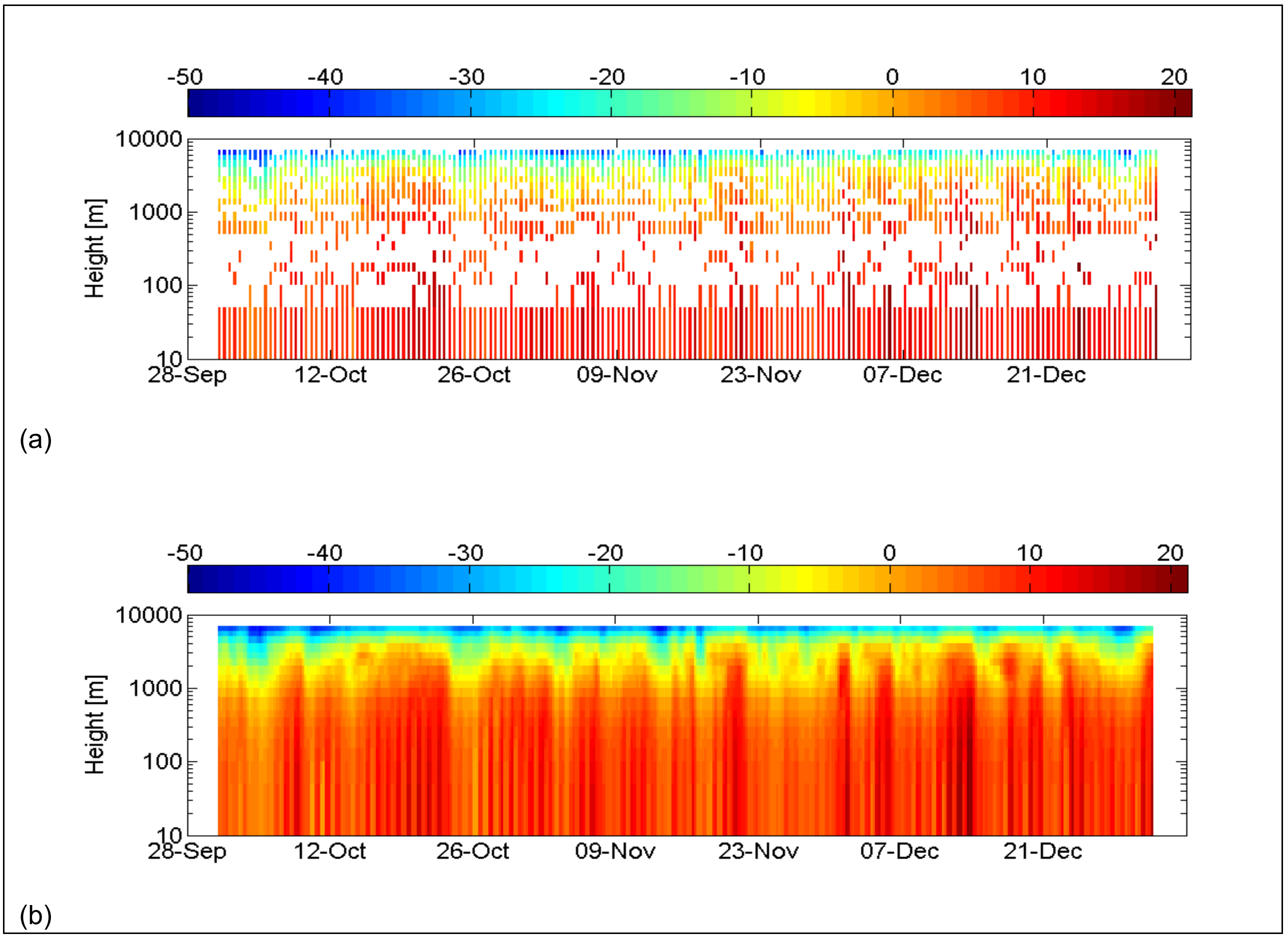


Fig. 2.1: Time series of the vertical temperature profiles [C] (a) observed and (b) modelled for the period October to December 2003 at Invercargill.

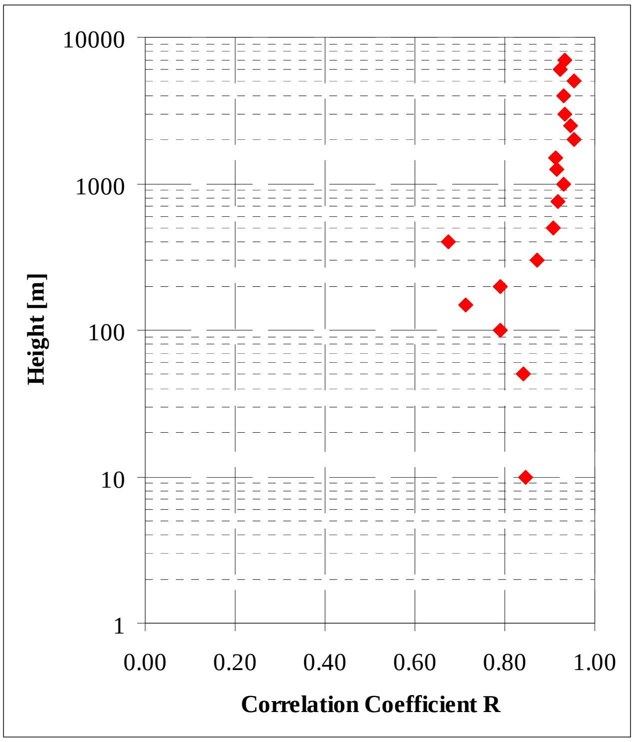


Fig. 2.2: Correlation coefficient (R) between the observations and the modelling results of air temperature as function of height for the period October to December 2003.

2.3.3 Wind direction

Comparing the time series of the observed and modelled wind direction (Fig. 2.3) it is evident that TAPM is able to capture the general circulation of the wind during the period October to December 2003. In fact, the model is able to capture the northerly winds observed at the end of October. Similarly to the temperature profiles, the wind direction is better captured above 500 m.

Fig. 2.4 shows that TAPM captures the distribution of wind direction observed above 500 m well, while there are some differences between the distributions at the surface. The reason for this is not clear, however, it is possible that the surface information (topography and land use) is too coarse to allow a better representation of the small scale phenomena.

Another explanation for this difference could be the impact of the sea breeze circulation on the lower layers of the sounding profile considering the distance from the site to the shore. However, hourly measurements from the same location at a height of 10 m do not suggest a diurnal reversal of the airflow in the lower layers.

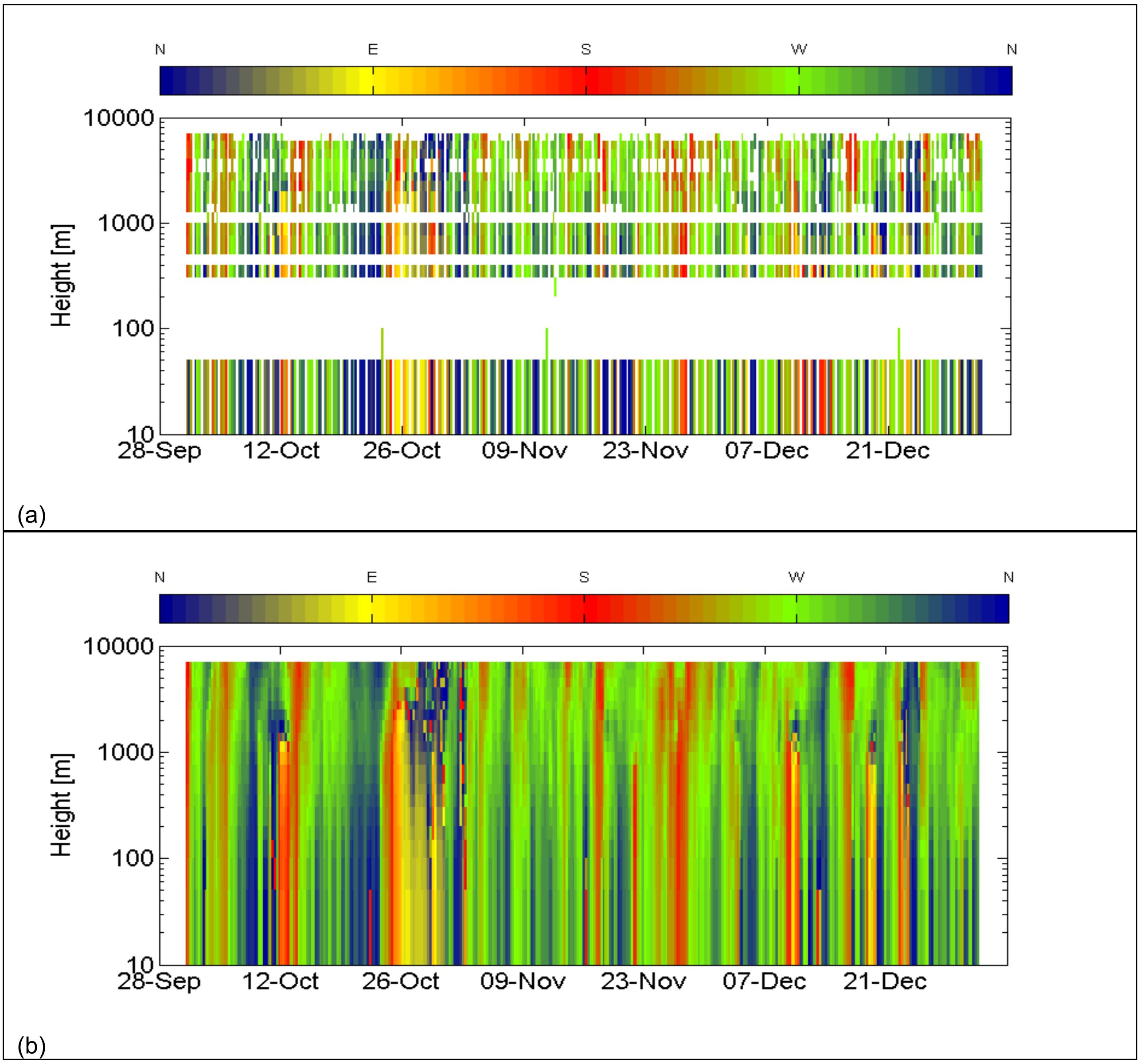


Fig. 2.3: Time series of the wind direction profiles observed (a) and modelled (b) for the period of October to December 2003 at Invercargill.

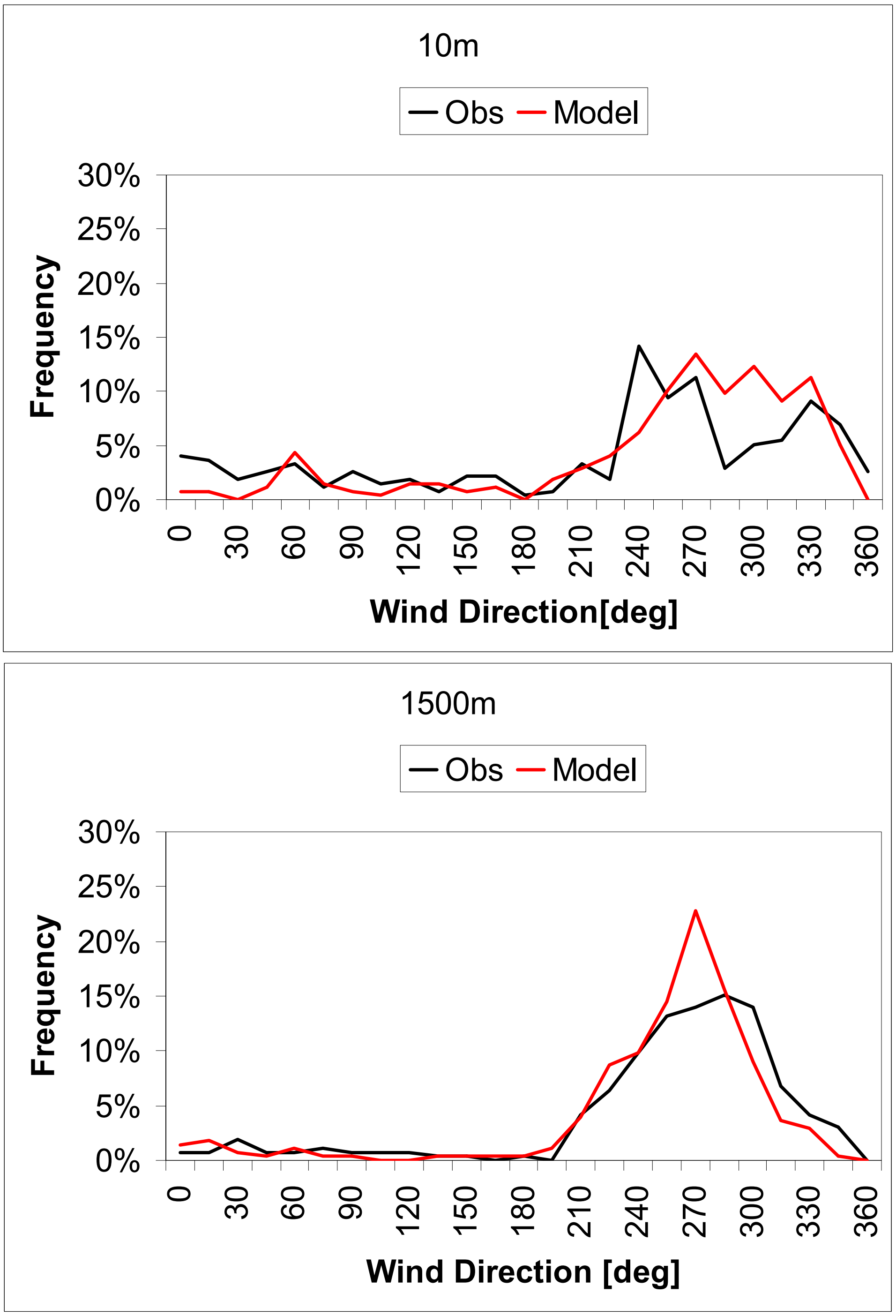


Fig. 2.4: **Frequency plots of the wind direction for two layers (10m and 1500m). The black curves correspond to the observations and the red curve shows the model results for the corresponding layer.**

2.3.4 Wind speed

TAPM is able to capture the major features of the wind speed vertical profile. As shown in Fig. 2.5, the model is able to capture the periods of low wind speeds (e.g. at the end of October) associated with synoptic scale features. Nevertheless, at the surface, the model tends to overestimate the low wind speed (Fig. 2.6), particularly below 2 m s^{-1}, while it underestimates the higher wind speeds (>10 m s^{-1}).

For the upper layers (above 1000 m) the model is able to reproduce the wind speeds within 50 % for low wind speeds and within a 30 % for speeds larger than 15 m s^{-1} (Fig. 2.6).

In general, TAPM is able to capture the observed wind speeds for layers above 1000 m (R~0.9) but for layers closer to the surface, the correlation is smaller (R<0.7) as shown in Fig. 2.7. The differences observed for the surface layers may be related to either shortcomings in TAPM's parameterizations of surface processes or a lack of detail in the surface information (topography, land use, surface roughness, and soil humidity).

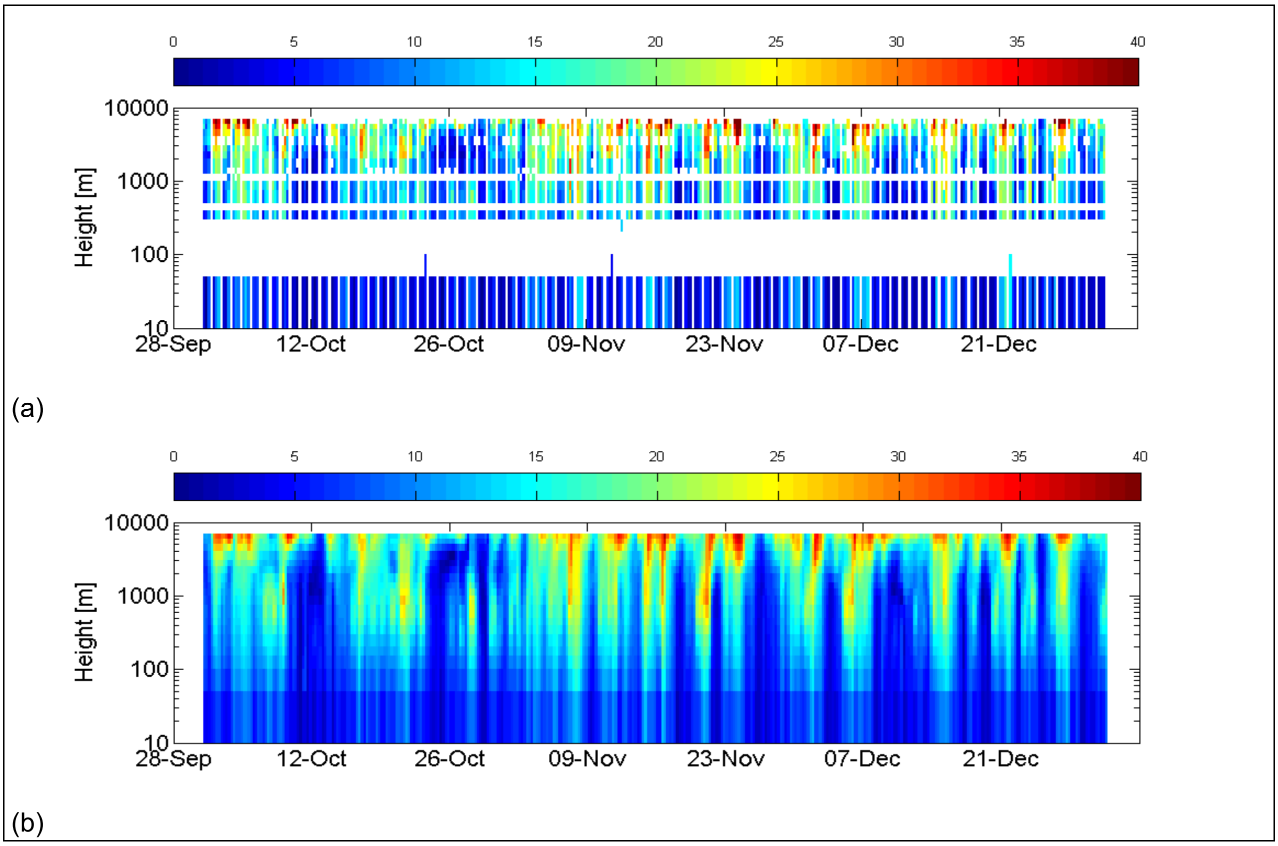


Fig. 2.5: Time series of the wind speed profiles [m s^{-1}] observed (a) and modelled (b) for the period of October to December 2003 at Invercargill.

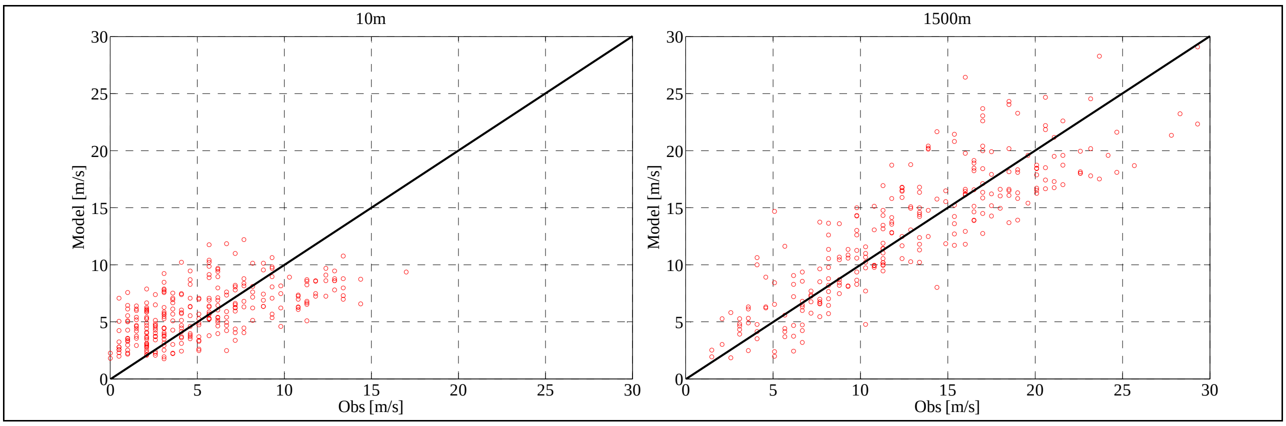


Fig. 2.6: Scatter plots of the wind speed in [m s^{-1}] for two layers (10 m and 1500 m). The black line corresponds to a 1:1 relation.

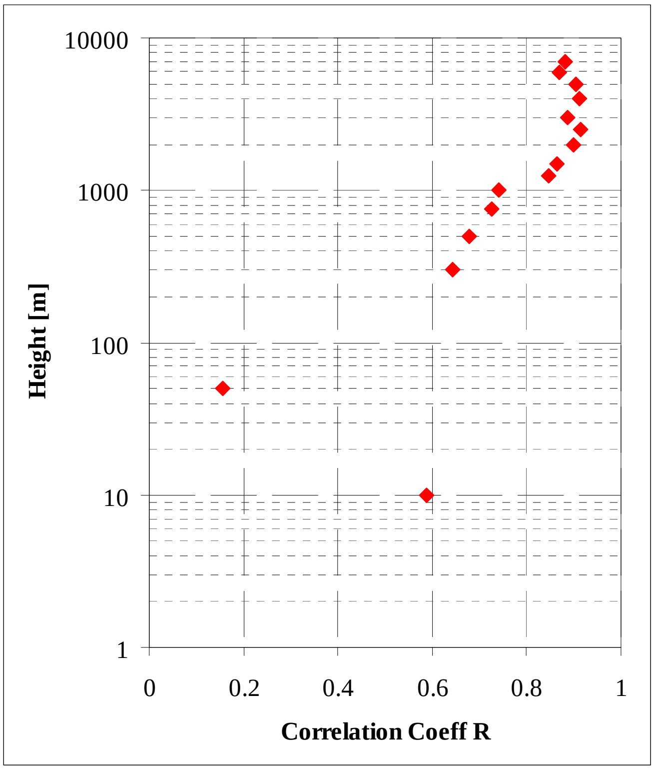


Fig. 2.7: **Correlation coefficient (R) between the observations and the modelling results of wind speed as function of height for the period October to December 2003.**

2.4 Comparison with Surface Measurements at Edendale

2.4.1 Wind direction

To assess the capabilities of TAPM to reproduce the dispersion of SO_2 from the Fonterra plant at Edendale it is first necessary to evaluate the results from TAPM in relation to the wind station located in the site.

The time series shows that TAPM is able to capture the general variations of the wind direction at the Edendale site (Fig. 2.8). Plots of wind direction time series can be messy, but they should be inspected visually to gain a general impression of model performance. However, Fig. 2.9(a) shows that there is significant scatter between the model and the measurements and that the model tends to shift the wind towards the north, for south-westerly winds.

This shifting is more evident in the frequency plot shown in Fig. 2.9(b). This figure shows that while the observations show that the prevailing wind is from the south-west, the model indicates that most of the time the wind is from the north-west. The reason for this shifting is unknown but it could be related to the surface roughness considered by TAPM and the relatively coarse resolution of the topography information (1 km) that may not represent small scale features that could have an impact on the measurements.

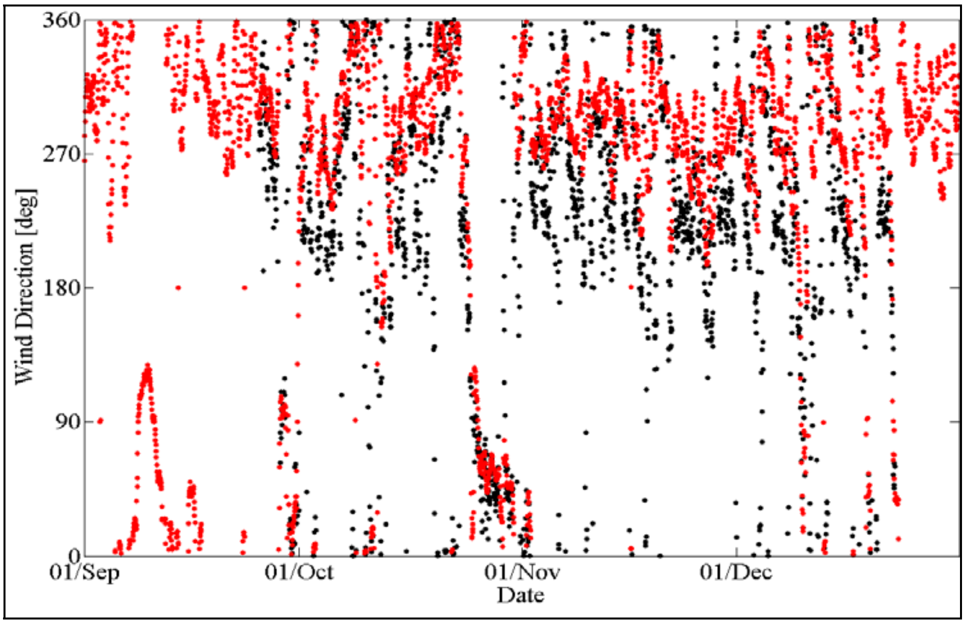
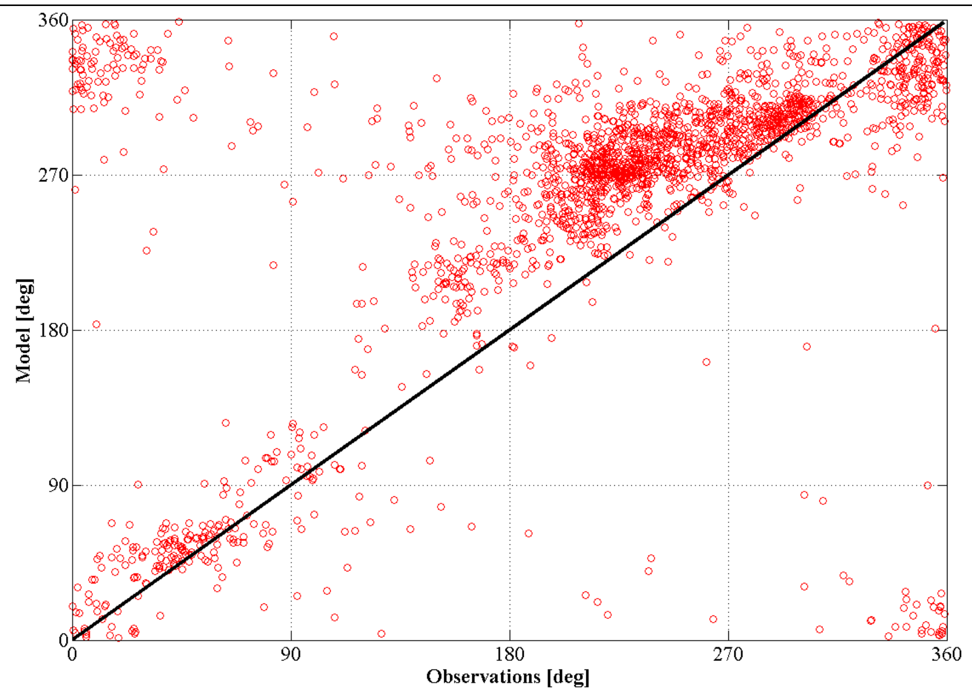


Fig. 2.8: **Time series of the wind direction modelled (red dots) and observed (black dots) at the Edendale site for the period of September to December 2003.**



(a)

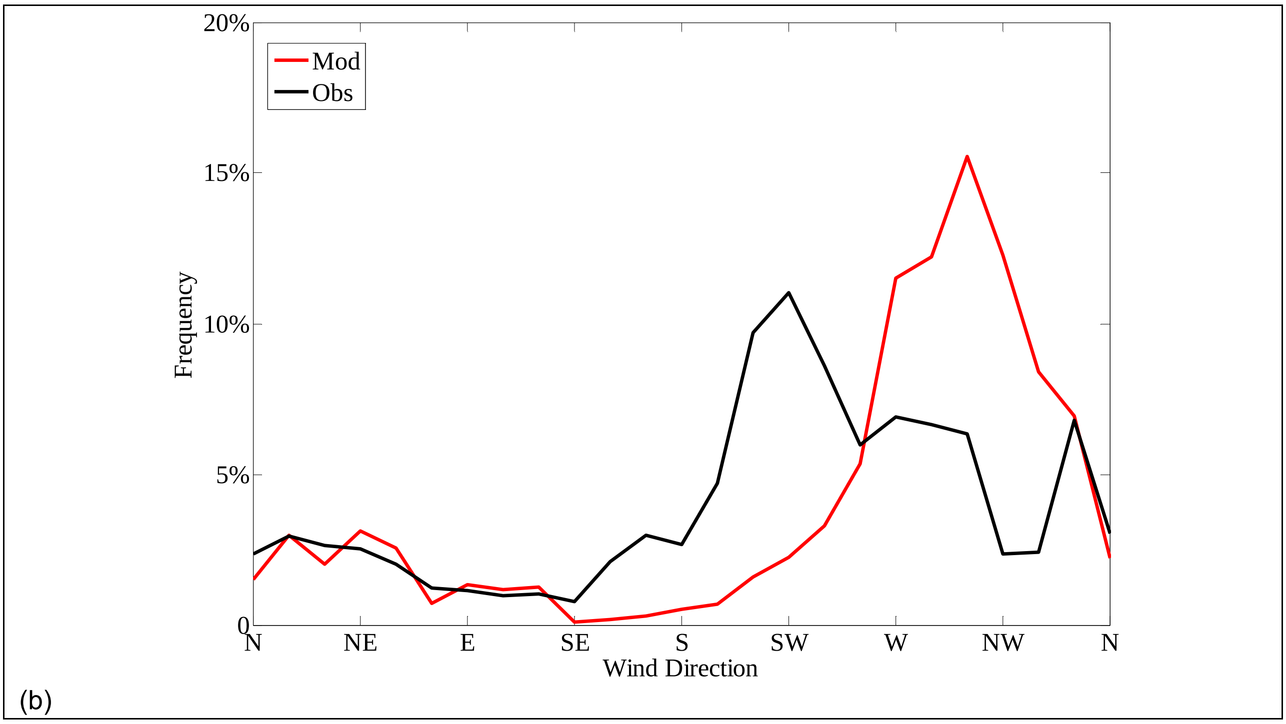


Fig. 2.9: Scatter plot (a) and frequency plot (b) of the wind direction both modelled and observed at the Edendale site for the period of September to December 2003. The black line in the scatter plot indicates a 1:1 relation.

2.4.2 Wind speed

The time series shown in Fig. 2.10 indicates that TAPM is able to reproduce the main characteristics of the observations at Edendale, including the periods of high and low wind speed. However, as it is shown in Fig. 2.11, TAPM tends to underestimate the average wind speed during the day, although still within the variability of the measurements.

The scatter plot for the wind speed shown in Fig. 2.12 indicates that the correlation between the model results and the observations is relatively low (R=0.56) and that the model tends to overestimate the wind speed for calm periods (observed wind speed smaller than 2 ms^{-1}) and underestimate it for higher winds (>10 $m\ s^{-1}$). Nevertheless, the model is generally within 50 % of the measurements.

This behaviour is similar to that shown for the Invercargill site. In general, mesoscale models all tend to overestimate the wind speed for calm periods. On the other hand, the grid size used by the models means that the variables are in general representative of 1 grid square while the measurements could be representative of a much smaller scale, leading to differences between the models and the observations. Nevertheless, TAPM seems to capture the major features of the wind speed observed in Edendale and it seems to give a relatively accurate picture of the wind field in the area.

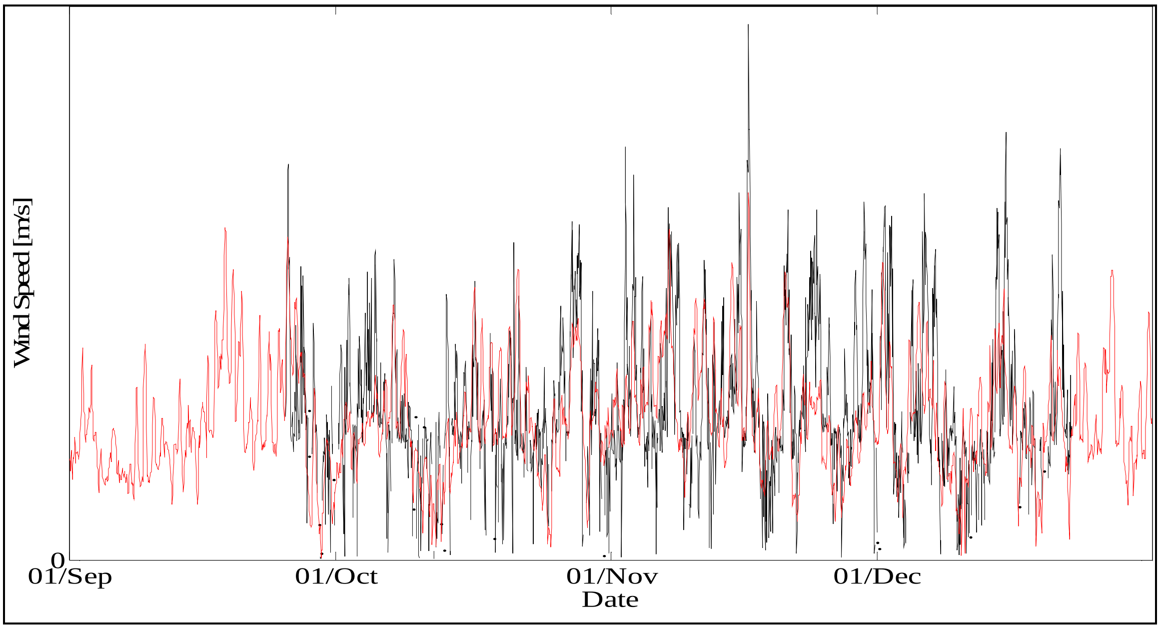


Fig. 2.10: **Time series of the hourly wind speed both modelled (red) and observed (black) at the Edendale site for the period of September to December 2003.**

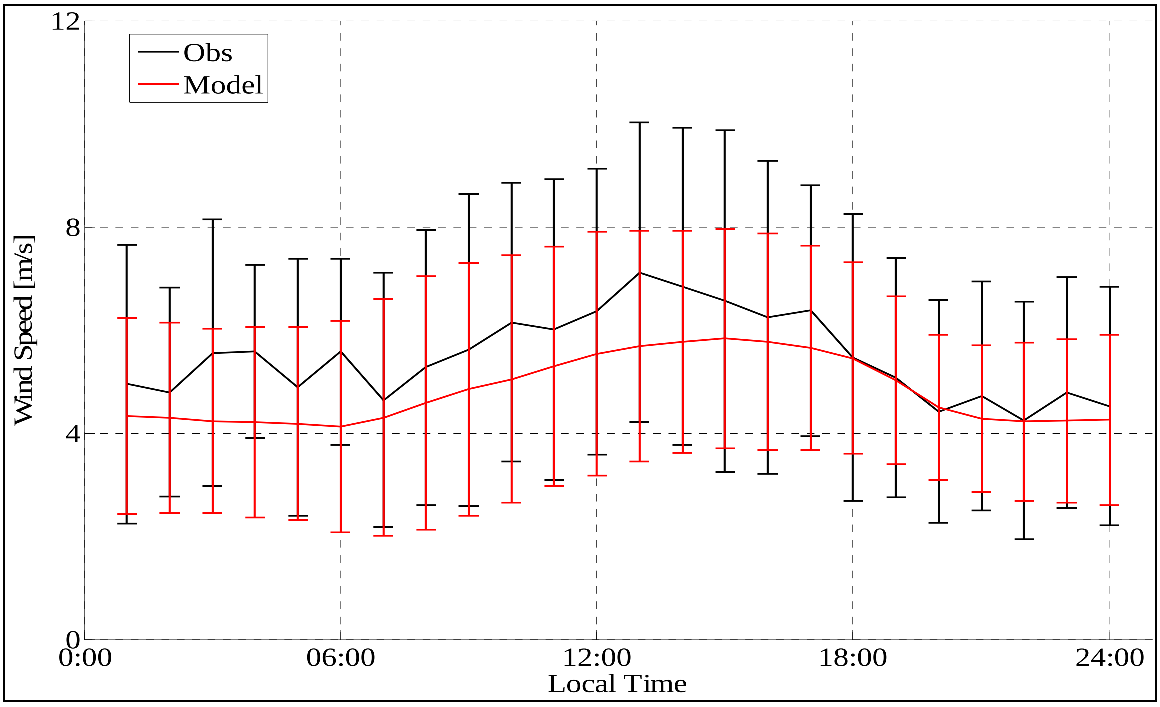


Fig. 2.11: **Diurnal variation of the observed (black) and simulated (red) wind speed at the Edendale site for the period September to December 2003. The indicated error bars correspond to one standard deviation from the mean.**

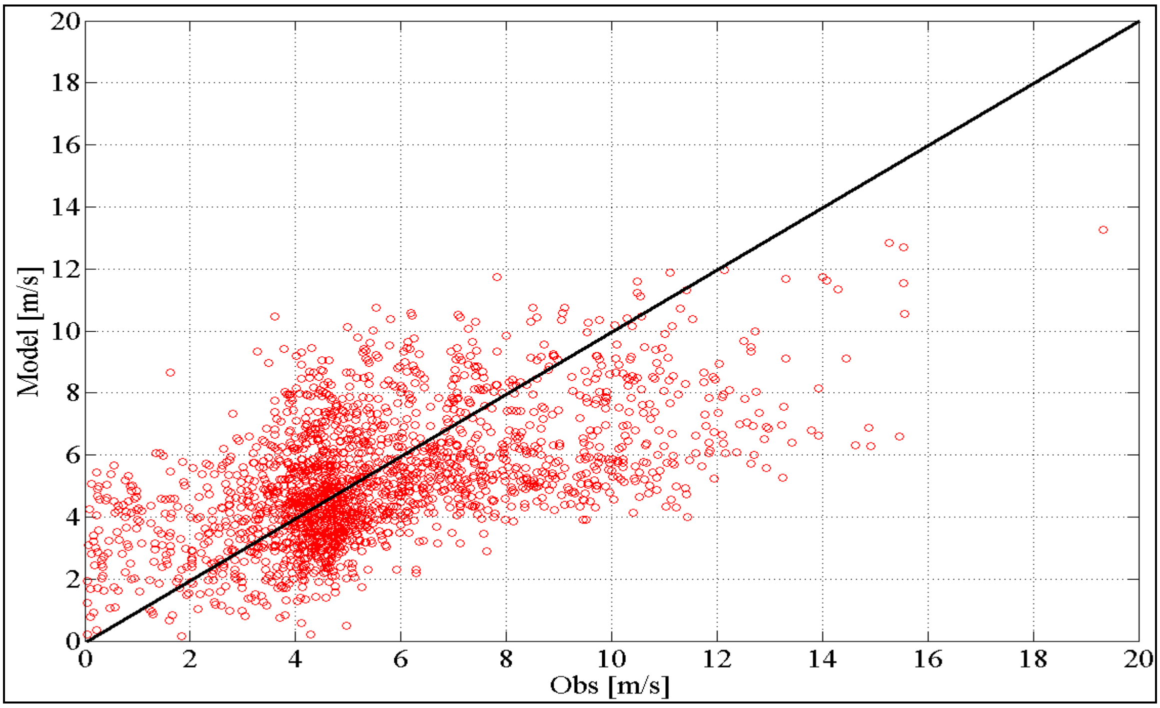


Fig. 2.12: Scatter plot of hourly measured and modelled wind speed at the Edendale site for the period of September to December 2003. The black line indicates a 1:1 relation.

2.4.3 Model performance indicators

From the time series and scatter plot analyses one may conclude that TAPM is generally able to reproduce the patterns observed at Invercargill and Edendale. However, objective estimates of the model performance are required to assess the simulations quantitatively. Model performance indicators are defined and discussed in the Appendix.

Table 2.3 shows performance indicators for TAPM when compared to the vertical information from Invercargill at four levels: Surface (10 m), 500 m, 1500 m and 3000 m. Table 2.3 shows that the model is able to generally capture both the mean and the variability of the measurements, particularly above 500 m. Furthermore, the error estimates indicate that the errors of the model decrease with increasing height. This is also evident in the IOA profiles shown in Fig. 2.13. The model shows a consistently better performance higher in the troposphere with the IOA indicating an improvement of more than 15% for the temperature and wind components above 1000m.

Table 2.3: Performance indicators for the Invercargill sounding site for the TAPM simulation for the period October to December 2003. The standard deviation is denoted by σ.

Parameter	Height [m]	Observations Mean	Observations σ	Model Mean	Model σ	MAE	RMSE	$RMSE_S$	$RMSE_U$
Wind Speed [m s^{-1}]	10	5.3	3.6	6.0	2.3	2.4	2.9	2.3	3.7
	500	11.6	5.8	12.5	5.8	3.8	4.8	2.1	5.2
	1500	12.9	6.2	13.2	5.8	2.5	3.2	1.2	3.4
	3000	15.6	7.1	15.5	6.2	2.7	3.5	2.1	4.0
Temperature [C]	10	11.1	3.6	10.6	3.5	1.6	2.1	0.9	2.2
	500	6.5	4.0	7.5	3.2	1.5	1.9	1.3	2.3
	1500	0.2	4.9	1.1	4.5	1.8	2.3	1.3	2.7
	3000	-7.4	5.5	-5.0	5.0	2.9	3.3	2.8	4.4
u [m s^{-1}]	10	3.0	4.7	3.8	3.8	2.6	3.1	1.9	3.6
	500	7.5	7.9	9.2	7.4	4.2	5.3	2.8	6.0
	1500	10.1	7.5	11.0	7.0	2.9	3.7	1.5	4.0
	3000	12.6	8.0	13.1	7.2	2.6	3.2	1.7	3.7
v [m s^{-1}]	10	-0.6	3.1	-1.5	3.3	2.4	3.0	1.6	3.4
	500	-1.9	6.8	-2.4	6.6	3.0	4.1	1.5	4.3
	1500	-2.2	6.5	-1.4	5.8	2.7	3.7	1.8	4.1
	3000	0.3	8.4	-0.1	7.5	2.8	3.8	2.1	4.4

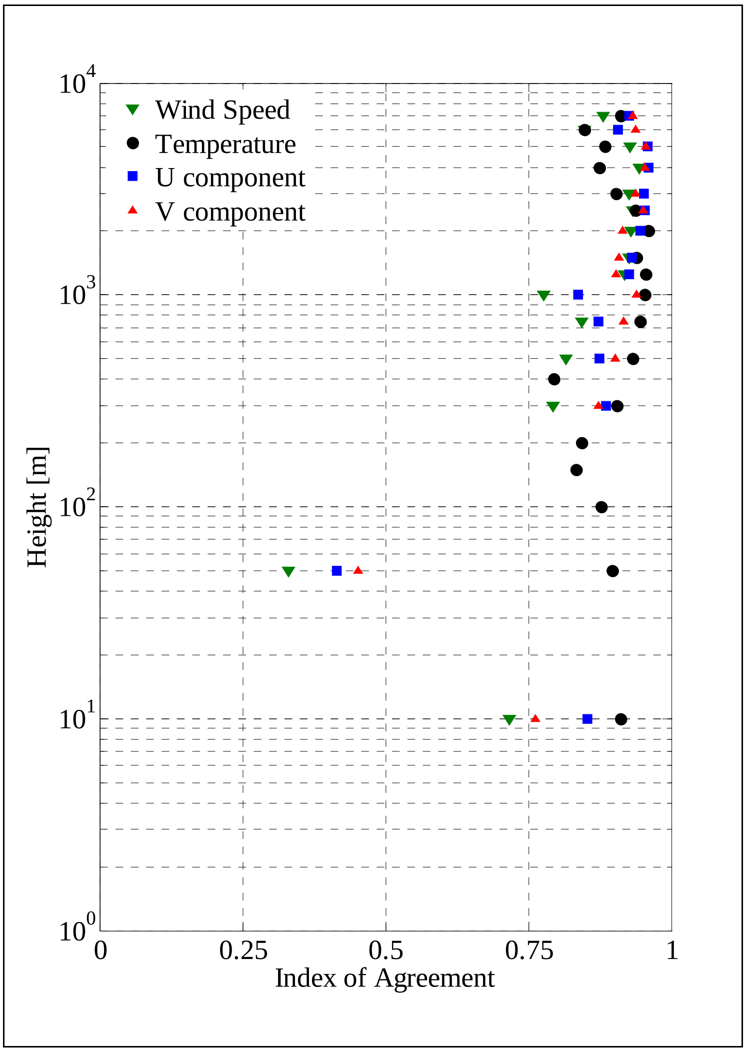


Fig. 2.13: Vertical profile of the index of agreement (IOA) between the TAPM results and the measurements at Invercargill for the period between October and December 2003.

Performing the same analysis for the results given by TAPM for the Edendale site, the general conclusions are similar to what was observed at Invercargill (Table 2.4). TAPM gives a reasonably accurate prediction of the wind parameters but its performance is not as good as for the upper layers for the Invercargill sounding. Also, the model seems to be more than 15% more accurate for the zonal component (*u*) of the wind than for the meridional component (*v*). The reason for this difference is not clear and may be related to the impact of larger scale meteorological features that have a more important zonal component while the meridional wind is dominated by small scale processes. However, since there is no information about the vertical structure of the atmosphere at Edendale, its performance on this site cannot be fully assessed.

Table 2.4: Performance indicators for the Edendale site for the TAPM simulation for the period October to December 2003.

Parameter	Observations Mean	Observations σ	Model Mean	Model σ	MAE	RMSE	$RMSE_S$	$RMSE_U$	IOA
Wind Speed [m s^{-1}]	5.6	2.7	5.0	2.0	1.8	2.4	1.6	1.7	0.72
u [m s^{-1}]	2.6	3.8	2.9	3.3	1.9	2.5	1.4	2.0	0.87
v [m s^{-1}]	0.8	4.1	-2.0	2.5	3.1	4.4	3.5	1.9	0.70

3. Tiwai Point Case Study – Assessment of TAPM Performance

3.1 Introduction

Simulations with TAPM are set up through a Graphical User Interface (GUI) which allows the user to define the geographical area of interest, choose the resolution of modelled meteorology, set the desired air pollution modules, and specify a whole raft of other desired parameters. Compared to other more sophisticated research-grade models, the GUI limits the choice of parameter options. For example, the user would have a choice of turbulence parameterisation schemes in other models. TAPM was designed to be used mainly by the consulting and air quality management community, where users might not have the necessary background for modelling, yet still need an advanced tool for environmental impact assessment projects related to discharges into air. Although the choices offered through the GUI are rather limited, users usually only run simulations with the default settings. For example, different deep-soil moisture values can be set for different months, but it is easier to leave the rather dry default value of 0.15 kg/kg. Soil moisture can have an impact on boundary layer development which can directly impact wind speeds and mixing layer heights leading to different predicted pollution concentrations. This section of the report is concerned with the validation of the meteorological model for the NZ Aluminium Smelter (NZAS) site at Tiwai Point.

3.2 Model Configuration

TAPM version 3.0 has been used to model winter and spring meteorology at NZAS site at Tiwai Point for the period of five months from July to November 1996. The details of the model configuration are given in Table 3.1. The hourly observational data were obtained from the NZAS meteorological station which is located at the north-western end of the smelter at an elevation of approximately 5.0m. The anemometer is installed 14m above ground level. Fig. 3.1 shows the locations of the smelter and the meteorological station.

Fig. 3.1: **Gridded map of the Tiwai Point area, showing locations of the NZAS plant, meteorological sites and other land features.**

Table 3.1: Model Configuration.

Grid Parameterization	Grid 1	Grid 2	Grid 3	Grid 4
Grid points	25 x 25	25 x 25	25 x 25	25 x 25
Grid spacing (km)	30	10	3.5	1.5
Vertical levels	25	25	25	25
Centre Latitude	46º 35.5' S			
Centre Longitude	168º 23.0' E			
Advanced/Experimental options				
Synoptic pressure gradient, temperature and moisture filtering			1.0	
Synoptic pressure gradient scaling factor			1.0	
Boundary Conditions			From synoptic analysis	
Surface Vegetation			Included	
Non-hydrostatic pressure			Included	
Rain processes			Included	
Snow processes			Included	
Prognostic eddy dissipation rate			Included	
Extra Surface Parameters				
Soil Moisture			Default	
Soil Temperature			Default	
Sea Surface Temperature			Default	

3.3 Comparison of Model Output with Observations at the Tiwai Point Meteorological Station

The model output has been compared with the surface measurements from the Tiwai Point meteorological station. Model predictions were extracted at the nearest grid point to the monitoring site on the inner grid (1.5 km spacing), 10m above ground. Performance statistics were based on the recommendations of Willmott (1981) and Hurley et al.(2002), and show that TAPM successfully reproduces the major features of all the four meteorological parameters namely wind speed, temperature, west-east U-component and south-north V component (Table 3.2). The index of agreement (IOA) of the four meteorological parameters is greater than 0.75.

Table 3.2: Model performance statistics: Comparison of model results with observations for five months of winter and spring 1996. ρ is the correlation coefficient.

Parameter	Mean		Std. Dev.		ρ	RMSE	RMSEs	RMSEu	IOA
	Obs	Model	Obs	Model					
Wind Speed [ms^{-1}]	5.03	5.96	3.40	2.80	0.63	2.86	1.89	2.14	0.77
Temperature [ºC]	8.28	9.03	3.99	2.68	0.86	2.30	1.85	1.37	0.88
U-Component [ms^{-1}]	2.19	2.47	5.00	4.75	0.82	2.98	1.16	2.75	0.90
V-Component [ms^{-1}]	-0.25	-1.50	2.66	3.51	0.68	2.89	1.28	2.59	0.77

3.3.1 Wind speed

Time series of modelled and observed wind speed (Fig. 3.2) indicate that the model was able to capture the trends in the wind speed. The mean difference in the modelled and observed wind speed is about 1 ms^{-1} (Table 3.3). The highest mean difference (1.6 ms^{-1}) between observed and modelled wind speed occurred during September while the lowest (0.3 ms^{-1}) occurred in November 1996.

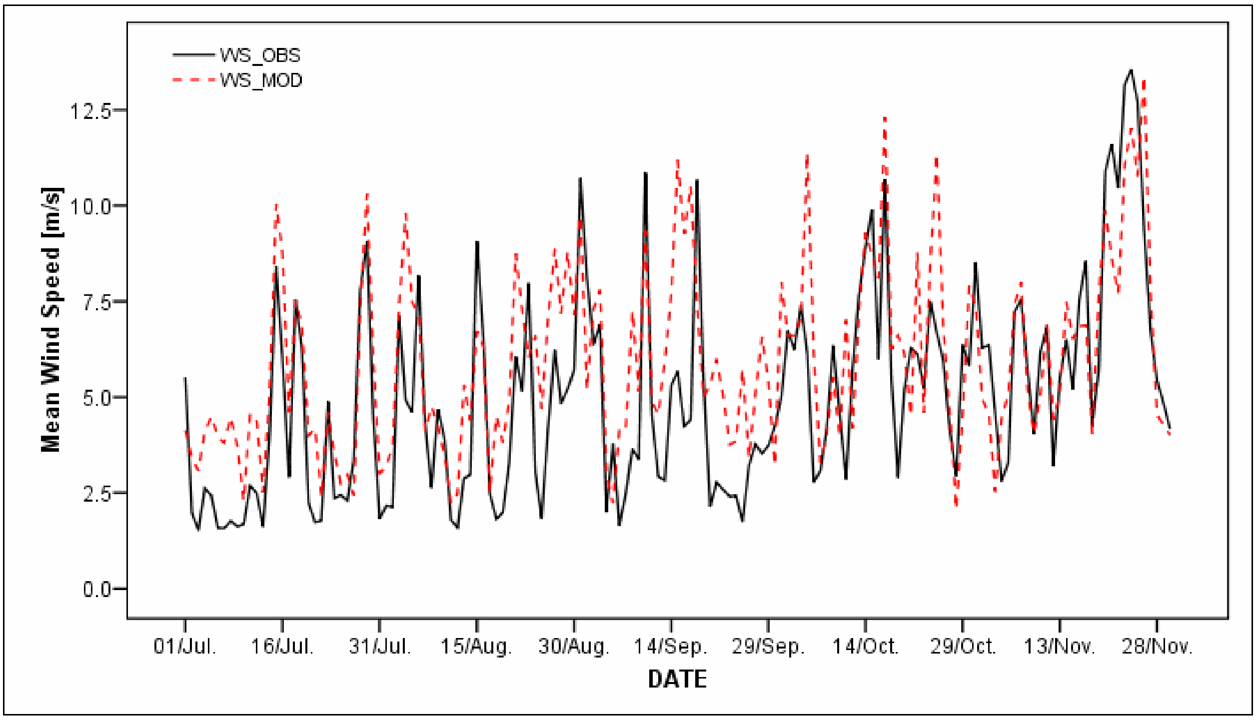


Fig. 3.2: Time series of modelled and observed wind speed.

Table 3.3: Descriptive statistics of observed and modelled wind speed.

Month	**Jul-96**		**Aug-96**		**Sep-96**		**Oct-96**		**Nov-96**		**Average**	
Statistic	Obs	MOD	Obs	MOD	Obs	MOD	Obs	MOD	Obs	MOD	Obs	MOD
Mean	3.5	4.7	4.5	5.8	4.3	5.9	5.9	6.8	7.0	6.7	5.0	6.0
Std. Dev.	2.7	2.4	3.1	2.4	3.1	2.6	3.0	2.9	3.8	3.0	3.4	2.8
Min.	0.4	0.2	0.7	0.8	0.5	0.3	0.7	0.1	0.8	0.4	0.4	0.1
Max.	14.8	12.4	14.8	11.5	15.1	14.4	15.7	15.6	19.0	16.6	19.0	16.6

TAPM generally over-predicted wind speed; this over-prediction was highest during winter months (July, August and September) when the mean wind speed was relatively low. This overestimate at low wind speed is a common feature of mesoscale models. This is also in agreement with probability density function (pdf) plot of the observed and modelled winds (Fig. 3.3). This shows the low frequency of the modelled wind speed less than 3 ms^{-1}, while for strong wind conditions the pdf of modelled and observed wind speed are in good agreement.

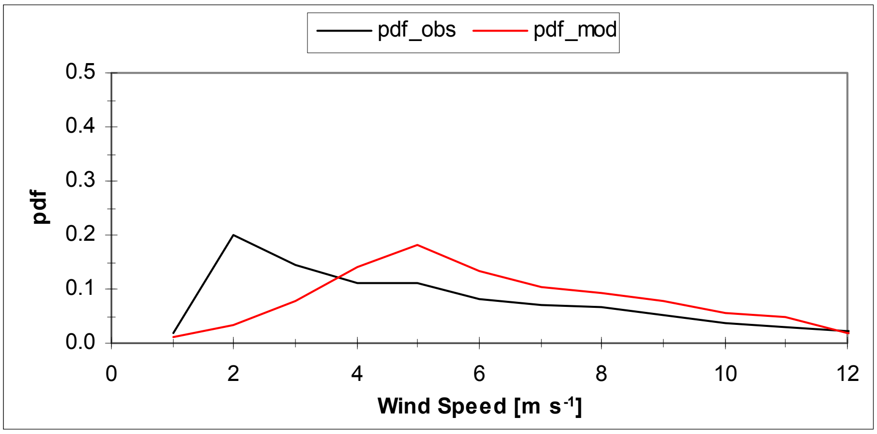


Fig. 3.3: **Probability density functions of observed and modelled wind speed for five months from July to November 1996.**

The two distributions (observations and model results) have been examined over the diurnal cycle. Fig. 3.4 suggests that the modelled wind speed differs from the observed wind speed during night time and early morning hours. Under the nocturnal inversion conditions the wind speed was low while in the afternoon hours due to the surface heating and increased turbulence in the lower atmosphere, the wind speed was the highest. TAPM generally over-predicted low wind speed during night and early morning hours. In contrast, during the afternoon hours modelled wind speed was in good agreement with observed winds. TAPM's difficulties in simulating low wind speeds in the nocturnal boundary layer is also described by several studies conducted in NZ (for example Heydenrych, 2002; Hirdman, 2006; Zawar-Reza et al., 2005(b)).

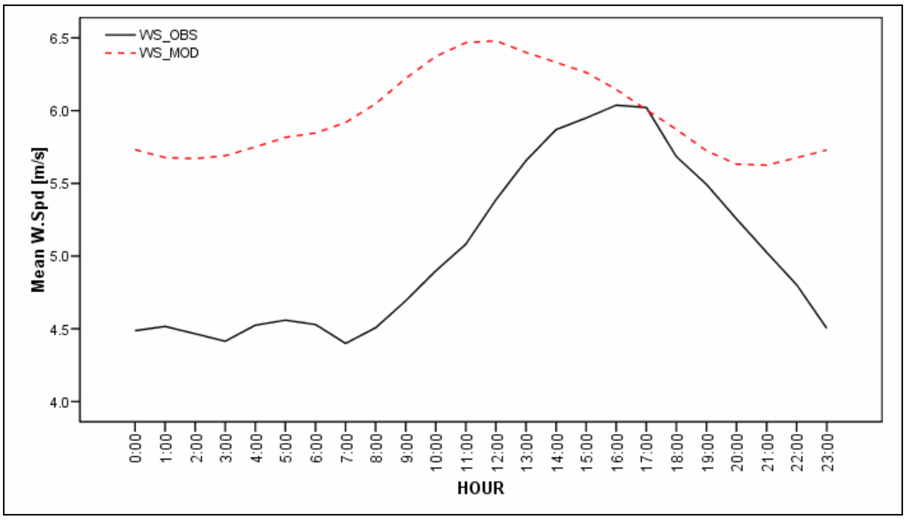


Fig. 3.4: **Observed and modelled wind speed over the diurnal cycle for five winter and spring months from July to November 1996.**

The modelled and observed wind speed has good agreement with a correlation coefficient of 0.63, although it is lower than other meteorological parameters (Table 3.2). A scatter plot of the observed and modelled winds (Fig. 3.5) shows that the model tends to overestimate wind speed lower than 3 ms^{-1}, and underestimate it for wind speed > 10ms^{-1}.

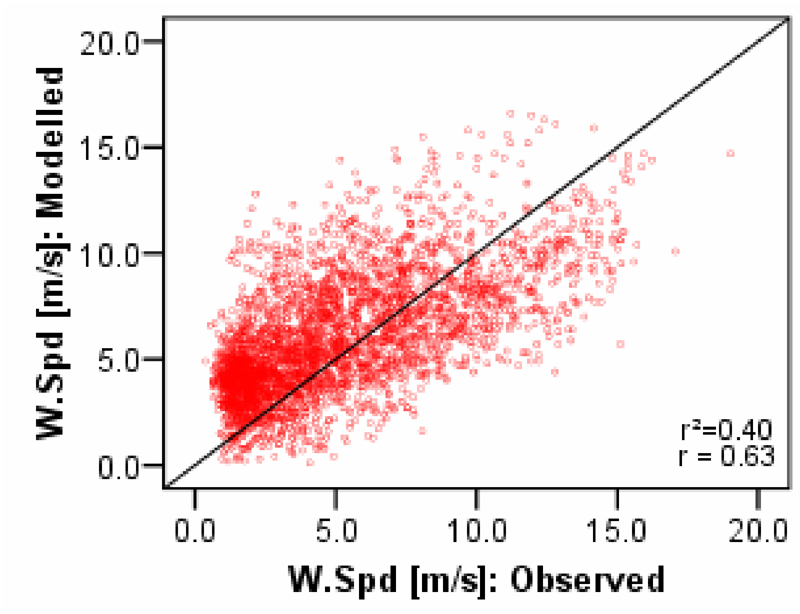


Fig. 3.5: Scatter plot observed and modelled wind speed for five months from July to November 1996.

3.3.2 Temperature

The model predictions of temperature were in good agreement with observations (IOA=0.88) and TAPM was able to capture the trend in the observed temperature data; the RMSE was also the lowest (Table 3.2), although the time series of observed and modelled temperature (Fig. 3.6) suggest some over-prediction in the modelled temperature field at low observed temperatures.

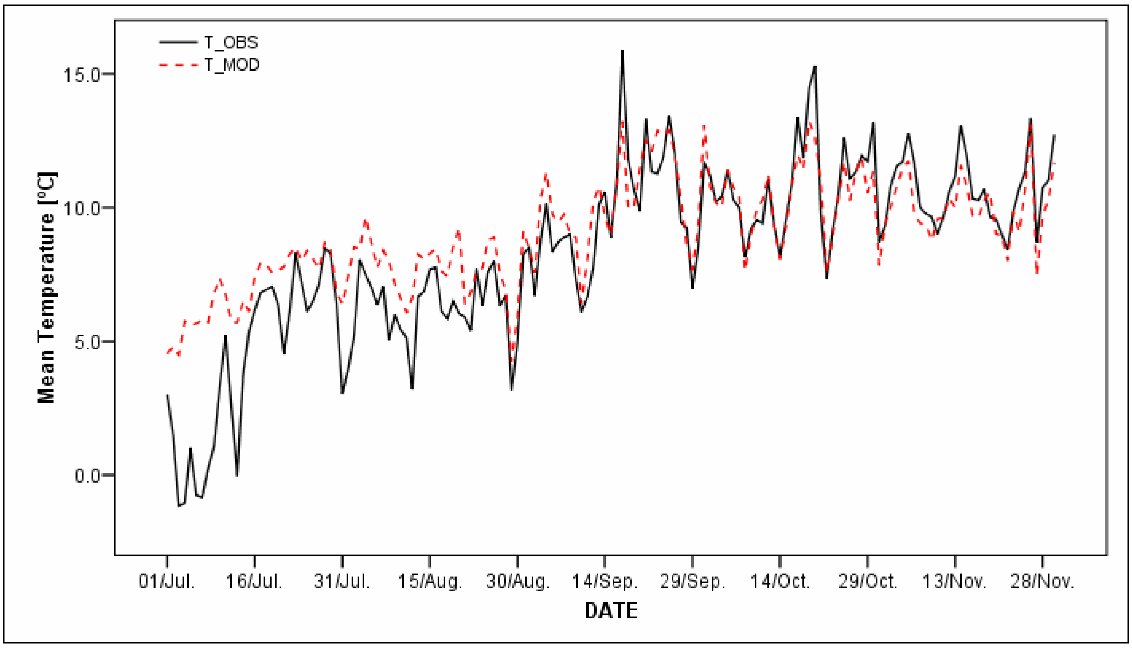


Fig. 3.6: Time series of modelled and observed temperature over a period of five months from July to November 1996.

The average monthly descriptive statistics (Table 3.4) show that the modelled monthly mean temperatures were higher than observed mean temperatures during the winter months but slightly lower than the observed means during spring months. The largest error occurred in the month of July when the average modelled temperature was 2.8ºC higher than the average observed temperature. TAPM consistently over-predicted the minimum temperature throughout the simulation period of five months. However, for the last two relatively warmer months the agreement between the modelled and observed temperature data was better than the winter months.

Table 3.4: Descriptive statistics for temperature.

Month	**Jul-96**		**Aug-96**		**Sep-96**		**Oct-96**		**Nov-96**		**Average**	
Statistics	Obs	MOD	Obs	MOD	Obs	MOD	Obs	MOD	Obs	MOD	Obs	MOD
Mean	4.1	6.9	6.3	7.7	9.8	10.2	10.7	10.4	10.6	10.0	8.3	9.0
Std. Dev.	3.6	1.9	2.6	1.9	3.5	3.0	2.7	2.4	2.3	1.8	4.0	2.7
Min.	-4.3	2.6	-0.9	3.2	1.4	4.6	4.8	5.2	3.1	5.9	-4.3	2.6
Max.	10.0	12.2	13.4	13.5	22.9	18.8	20.4	17.9	19.0	15.2	22.9	18.8

The pdfs of the temperature (Fig. 3.7) suggest that most of the difference between modelled and observed temperature lies in the -4^{o}C to 11^{o}C range. The model predicted too few occurrences of cold temperatures (which occur in July, the coldest month).

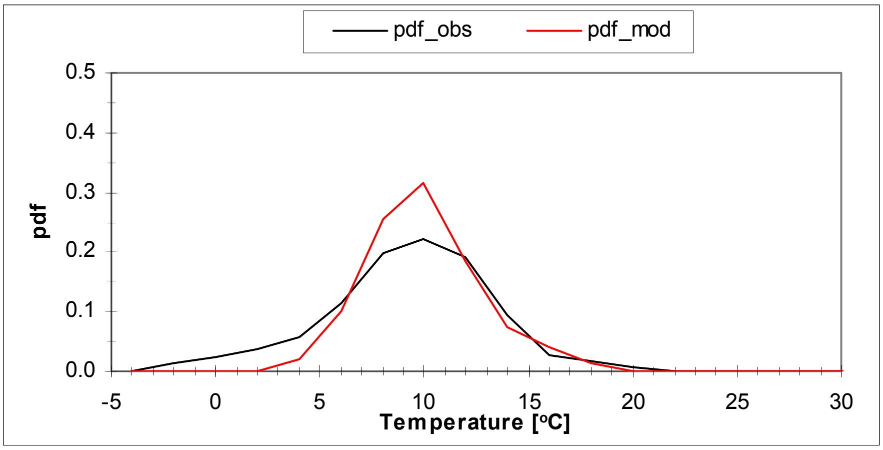


Fig. 3.7: Probability density functions of observed and modelled temperature for five months from July to November 1996.

Over the diurnal cycle TAPM overestimated the temperature, mostly during the night and early morning hours (Fig. 3.8).

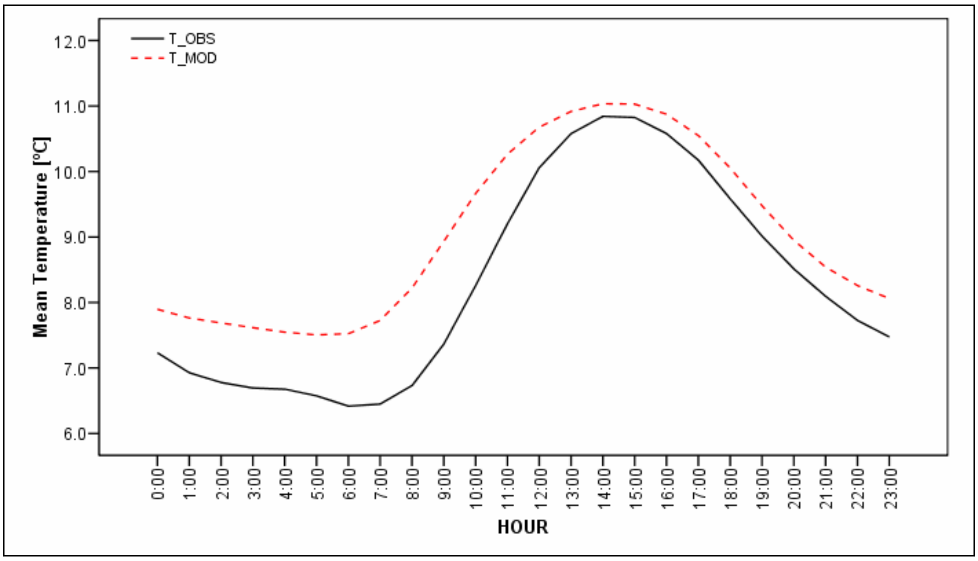


Fig. 3.8: **Observed and modelled temperature over the diurnal cycle for five winter and spring months from July to November 1996.**

The correlation coefficient of modelled and observed temperature was the highest of all the meteorological parameters (r = 0.86). The scatter plot (Fig. 3.9) shows that TAPM over-predicted low temperature (< 4.0ºC) and slightly underestimated peak temperature values greater than 15ºC. The high coefficient of determination (r^2 = 0.73) shows that TAPM was able to account for 73% of the variation in the observed temperature data.

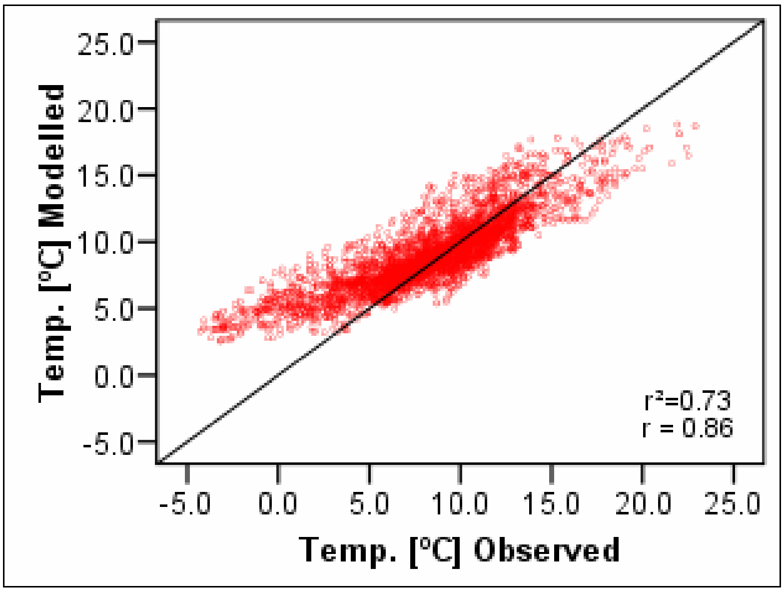


Fig. 3.9: **Scatter plot observed and modelled temperature field for five months from July to November 1996.**

3.3.3 Wind direction

The wind direction has been analysed in terms of west-east "u" component and south-north "v" component. The u-component has the highest IOA (0.9) of all the meteorological variables (Table 3.2). The south-north v-component, however, has a smaller IOA of 0.77. The time series plots of observed and modelled u-component suggest that TAPM successfully predicted the u-component with high accuracy for almost all the five months of winter and spring (Fig. 3.10). TAPM, however, did not predict the v-component with the same accuracy (Fig. 3.11). The preliminary analysis of observational data and TAPM output show that TAPM predicted more north-westerly wind flow was than observed. The north-westerly and south-westerly wind flow in the data each accounted for 42% of the time. TAPM, however, simulated more north-westerly (52%) and fewer south-westerly winds (35%).

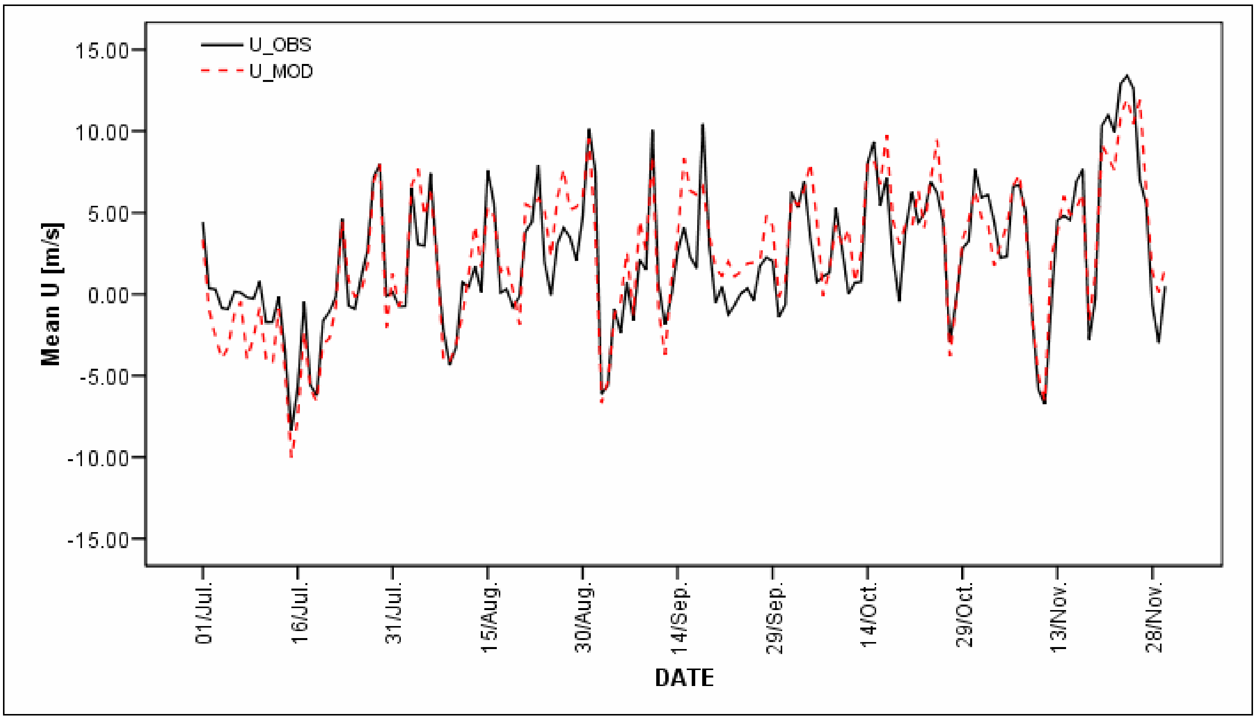


Fig. 3.10: Time series of modelled and observed U-component over a period of five months from July to November1996.

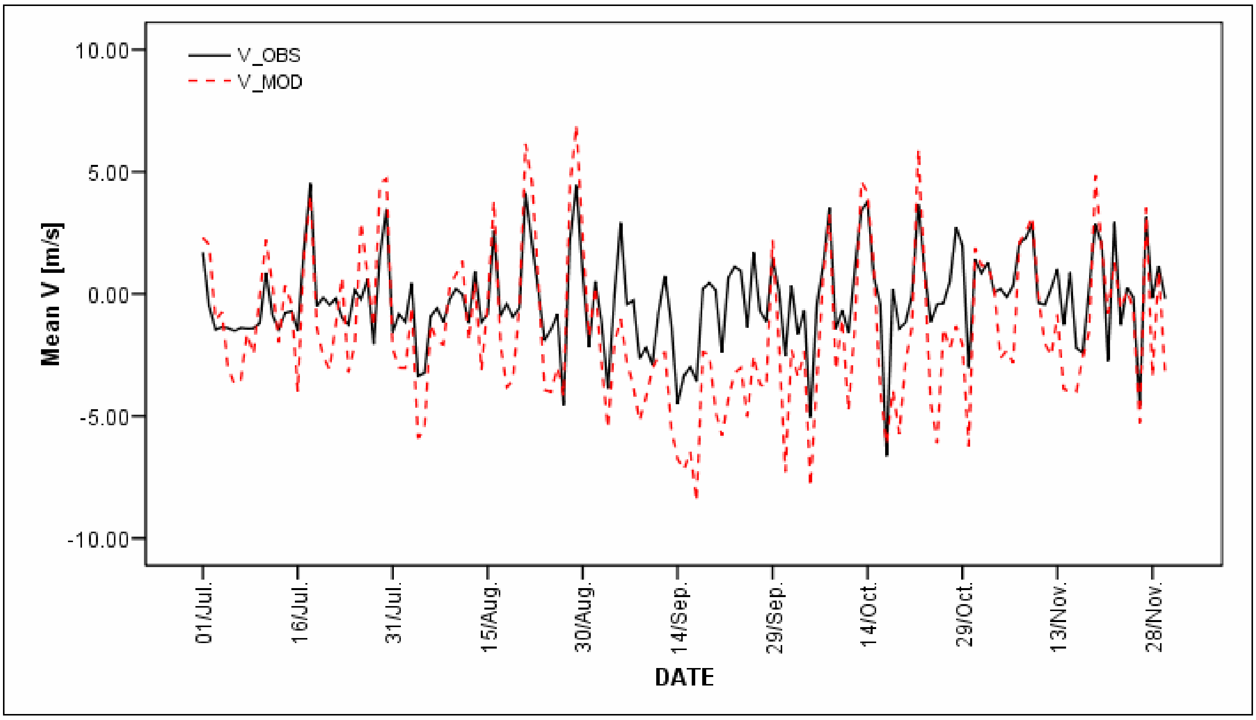


Fig. 3.11: **Time series of modelled and observed V-component over a period of five months from July to November 1996.**

The correlation coefficients of the U- and V-components were 0.82 and 0.68, respectively (Table 3.2). The two statistics are consistent with the strength of relationship between the modelled and observed u and v component values as discussed earlier. The scatter plots of u and v (Fig. 3.12) indicate that TAPM was able to predict the westerly component better than the southerly component.

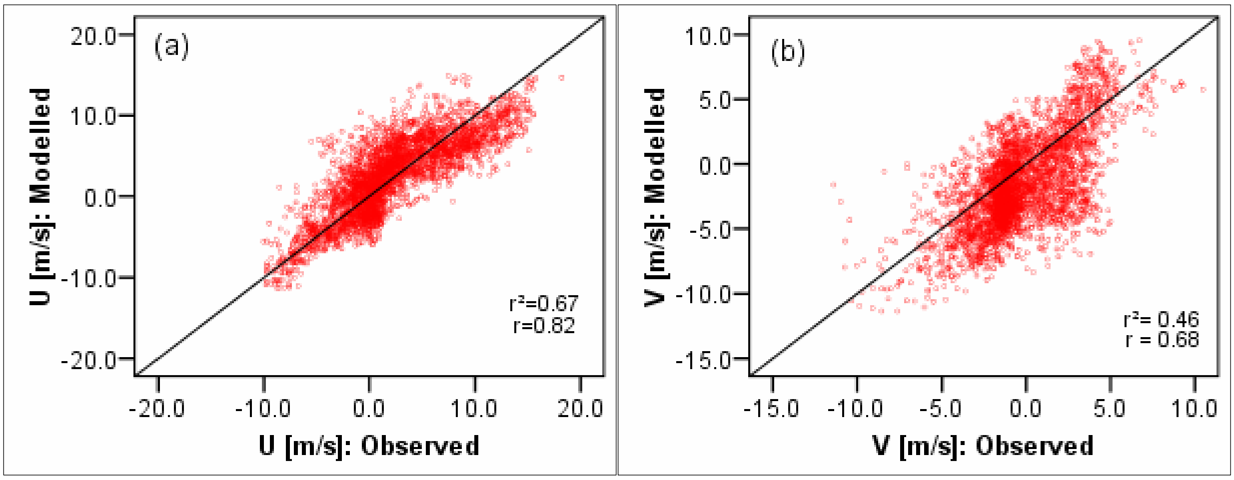


Fig. 3.12: **Scatter plot of U and V for five months from Jul-Nov 1996: a) Observed and modelled U-component b) Observed and modelled V-Component.**

3.3.4 Summary of results

TAPM was employed to simulate the meteorology in the NZAS area. Four predicted meteorological fields (wind speed, temperature, u wind component and v wind component) were compared with the observational data to validate the model. All the four modelled meteorological fields have good agreement with the observational data (IOA greater than 0.75).

The agreement between observed and modelled data was highest for temperature and west-east u-component of wind, while it was lower for wind speed and south-north v-component of the wind. The low performance of TAPM for the v component is due to TAPM's over-prediction of north-westerly winds.

TAPM could not successfully simulate low wind speed and low temperature conditions. Most of the over-prediction is observed during night time and early morning hours when due to nocturnal inversion and absence of solar radiation, wind speed and temperature were low.

3.4 Use of TAPM's Dispersion Routines for Industrial Assessments

Industrial assessments using the dispersion routines of TAPM have yet to be carried out in NZ, although they are more commonly done in Australia (Luhar and Hurley, 2003; Hurley *et al*., 2005(a)). TAPM has been used in NZ and Australia for urban air quality studies (Zawar-Reza *et al.,* 2005(b); Gimson *et al.,* 2005; Hurley *et al.,* 2003). It is arguable that TAPM produces better results than other commonly-used models such as AUSPLUME and CALPUFF (Hurley and Luhar (2005), Hurley *et al.,* 2005(b)). This has not been found to be the case in the complex geography of NZ, although investigations are in progress. However, as ideas of best practice have evolved since the MfE good-practice guide (MfE, 2004), they are still evolving and will no doubt change further. At present, CALPUFF is becoming widely used in preference to, say, AUSPLUME. In the future, TAPM by itself, including its dispersion routines, may become the *de facto* model for industrial assessments.

4. Tiwai Point Case Study – Use of CALMET and TAPM/CALMET Combined

4.1 Background

Use of the CALMET/CALPUFF dispersion modelling system for air quality applications has become increasingly widespread in recent years, including air quality research (Barna and Gimson 2002; Gimson 2005(a); Gimson 2005(b)). The main reasons for this are (a) a growing acceptance that for longer-range effects, Gaussian-plume models are not always appropriate, (b) increases in computing power, meaning more advanced models are less resource-intensive, (c) they are also more user-friendly, and (d) there is regular provision of training in NZ and Australia.

The primary advantage over plume models is the ability of CALMET to utilize spatially-varying meteorological data to produce three-dimensional, time-dependent meteorological fields, at high resolution, with relatively short run-times. This means that detailed meteorological features driven by complex terrain, land/sea contrasts, and large-scale forcing may be simulated by the model. This is true of physically-based mesoscale models (such as TAPM, WRF, MM5, RAMS) as well as a data-driven diagnostic model like CALMET, but CALMET's run times at sub-kilometre horizontal resolution are significantly shorter than prognostic models.

The physical and dynamical meteorology in CALMET is highly parameterized, rather than being represented by physical equations. Slope and valley flows, blocking by terrain barriers, and lake and sea breezes are represented in CALMET, but only if a signature of such features is present in the input data and careful parameter choices are made. Also, as meteorological information is used as inputs to CALMET, the model is difficult to validate – at locations where data are present, the model is always correct. It becomes a matter of judgment as to whether the results are physically realistic, and adequate as a basis for dispersion modelling.

The main constraints on achieving good results with CALMET are its input-data requirements. Outside NZ's urban areas, weather and climate stations are sparse, and there are only three locations in the country where vertical soundings are regularly taken (and these are 12-hourly). Even in the urban areas, there are not sufficient data to represent the three-dimensional, time-dependent structure of the atmosphere realistically. This aspect can be off-putting for users.

Recognizing this possible limitation, CALMET is designed to allow the ingestion of output results from prognostic models, and can easily base its simulation on outputs from MM5 (Scire *et al.,* 1999). In principle, the prognostic model produces fields at a relatively coarse resolution – because its computing requirements are greater – which CALMET then refines by superposing high-resolution physical effects and blending local climate data. This should give the 'best of both worlds' – a good large-scale picture of the meteorological situation from a model, with the details provided by local data sources. This is the recommended way of using CALMET (Robe and Scire, 1998; Chandrasekar *et al.,* 2003). Arguably, one-hourly modelled vertical profiles are preferable to 12-hourly observed profiles.

MM5 is not in common use in NZ for air quality assessments, although it is used routinely for mesoscale weather forecasting by MetService, and as a research tool (Titov *et al.*, 2007). However, TAPM *is* gaining popularity (Zawar-Reza *et al.,* 2005(a)), and may be put to a similar use (as MM5) to supply meteorological information for CALMET runs.

4.2 Case Study Introduction

The purpose of this section is to provide suggestions on the configuration of CALMET, and on suitable parameter setting, and to assess the use of TAPM in providing large-scale meteorological inputs to CALMET. This section also serves to alert potential users to some of the pitfalls in advance of running CALMET and TAPM this way.

Several issues associated with meteorological modelling are addressed, using a case-study example. These are:

1) availability of surface and upper-air data for CALMET, on or off the computational domain;
2) validation of TAPM by comparison with surface and upper-air data;
3) how to incorporate TAPM outputs into CALMET runs, through
    a. use of TAPM to supply inputs to CALMET in cases where there are no local data;
    b. use of TAPM to supply upper-air data to CALMET when there are only surface data available;
4) blending model outputs with data when they are in disagreement with each other.

Data have been supplied by NZ Aluminium Smelters Ltd (NZAS) from Tiwai Point, near Invercargill, for a period in 1996. Modelling the dispersion of discharges to air will be the subject of future work, but this serves as a good case-study for meteorological modelling. This is because NZAS is in a coastal environment with hills nearby, there is surface meteorological data available from Tiwai Point, and surface and upper-air soundings are available nearby at Invercargill Airport. An in-depth study of the meteorology of that period using TAPM is carried out in section 0.

Two CALMET domains have been defined in this section, one coarse resolution (1 km grid spacing) and one fine resolution (200 m grid spacing). The preferred grid should be the finer one around the NZAS site which includes Bluff town and Bluff Hill, but the airport site is too distant to be practically included in a domain at that resolution.

The domain extents are shown in Fig. 4.1 and Fig. 4.2, with aerial photographs (from TUMONZ) as background. For a map of the area, see Fig. 3.1.

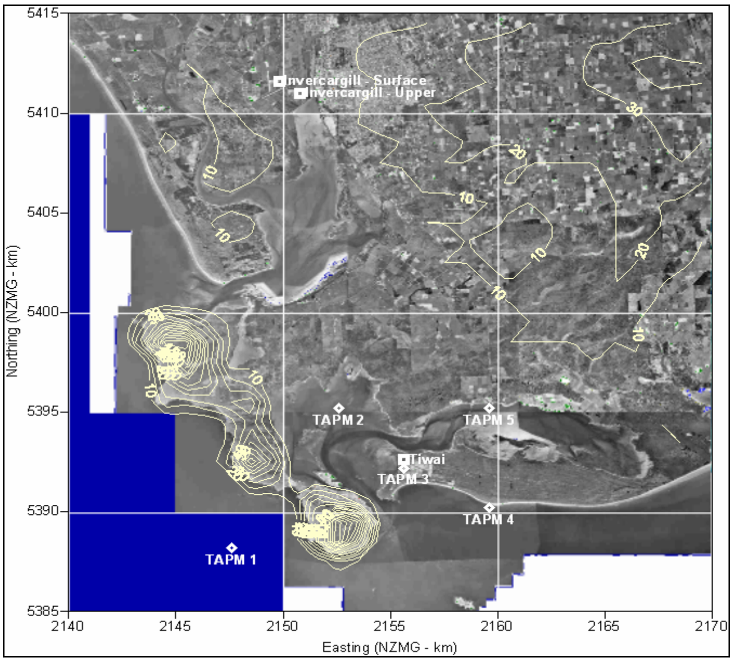


Fig. 4.1: **CALMET coarse domain, 30x30 grid points at 1 km resolution. Model terrain contours are at 10 m intervals. Climate sites at Tiwai Point and Invercargill are marked by white squares. Five selected TAPM grid points – from which model outputs are to be extracted are marked with white diamonds.**

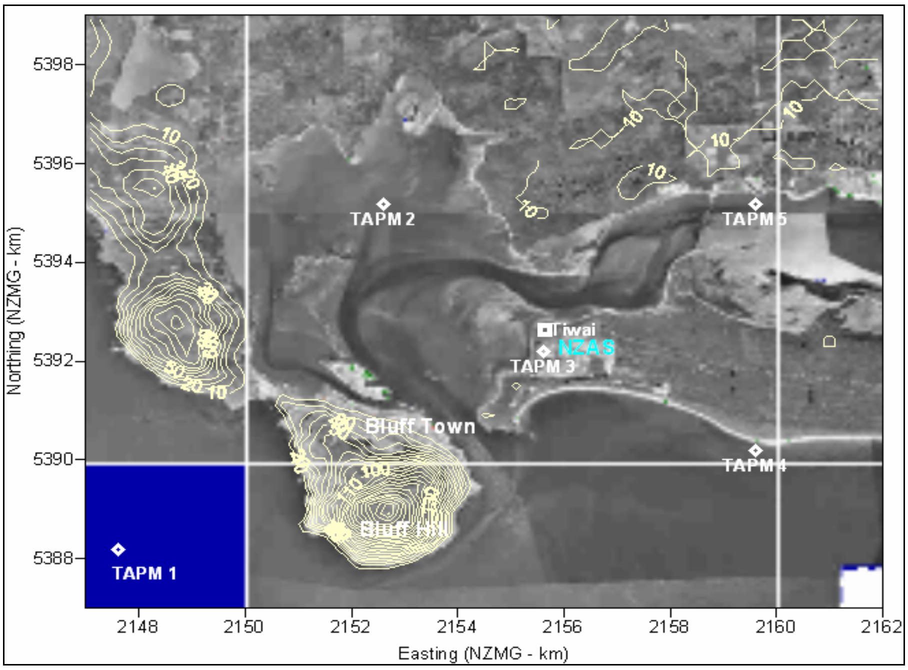


Fig. 4.2: **CALMET fine domain, 75x60 grid points at 200 m resolution.**

As an aside, it is useful to briefly summarize the calculation stages of CALMET. This is because several key parameters[3] only affect the results at certain stages. These are as follows:

[3] Named CALMET input parameters are highlighted here in ***BOLD ITALIC CAPITALS***. The values used in each CALMET run are summarized in Table 4.8.

1) the 'initial guess' – meteorological fields are derived through extrapolation of data horizontally and vertically. At this stage, the range of influence of data sites and the mixing height are considered infinite as they are not known or specified. Hence at every point, and at every level in the domain, the meteorological fields are an average of all data, weighted by distance to data site. Surface data are extrapolated upwards by a user-specified method to the top of the domain. Superposed on this, the height-dependent ***BIAS*** parameter changes the relative weighting of the upper-air data and the surface data, but only at the initial-guess stage;

2) terrain effects – fields are updated to account for slope flows, blocking, *etc*., to produce the 'Step 1' field;

3) 'Step 2' field – values at data points may have been altered by (ii). To return them to their observed values, an objective analysis is carried out, using the meteorological data a second time. At this stage, the radius of influence parameters (***R1, R2***, ***RMAX1 and RMAX2***) are used, and the objective analysis is applied only up to the mixing height.

At several points in the calculation, the wind field is adjusted to ensure it is non-divergent.

CALMET version 6.211 was run using several approaches for the months July to November 1996 on each of these domains. Key user-defined parameters – radius of influence of data points, terrain effects – should depend on the (true) geography of the area and the relative positions of the climate sites, and were not changed between CALMET runs (see Table 4.1). The four approaches are as follows, and are detailed in subsequent sections.

1) Approach I – CALMET driven by observations only (section 4.3);

2) Approach II – CALMET based on TAPM outputs only (section 4.6);

3) Approach III – Blending TAPM upper-air results and surface observations in CALMET (described in section 4.7 but not recommended);

4) Approach IV – Blending TAPM upper-air results and surface observations *before* running CALMET (recommended, described in section 4.8).

The terrain influence parameter is a measure of a typical distance between peaks, and limits the extent of up- and down-slope flows. Site influence parameters should be kept small so that the final wind fields do not swamp the terrain effects.

Table 4.1: CALMET parameters common to all runs.

Description	Name	Value
Radius of influence	***R1, R2***	1.5 km
	RMAX1, RMAX2	3.0 km
Terrain influence	***TERRAD***	4 km

4.3 Approach I – CALMET Driven by Observations Only

Two runs were carried out, on the domains of Fig. 4.1 and Fig. 4.2. Boundary-layer similarity theory was used to extrapolate surface data upwards (***IEXTRP=-4***). Invercargill upper-air data at the lowest model level were ignored as they were available only every 12 hours (***IEXTRP<0***; this also means ***BIAS(1)=-1***). Also, all surface data were extrapolated upwards, no matter how close an upper-air site might be (***RMIN2=-1***). The ***BIAS*** parameter is zero at other levels. Other parameters take their values in Table 4.1, or their default values.

In these runs the meteorology was determined by data from Tiwai Point and Invercargill. With only two locations, the results were generally quite bland, with a gradual spatial change between them. However,

the flow at lower levels was diverted by the hills to the west of Tiwai Point, particularly during the night and in calmer conditions. Example outputs from CALMET are shown in Fig. 4.3.
The coarse-grid run at the surface had wind fields defined by the surface-based sites, with wind changing gradually from one site to the other, such that the wind speed contours curved around each site in a 'dipole' pattern (Fig. 4.3(a) and (Fig. 4.3(b)). This pattern was disturbed by the hills which slowed the flow on the upwind side and accelerated the flow on the downwind side. The data from Tiwai Point were extrapolated upwards, so at higher levels, the dipole pattern was also seen – a wind speed of around 3 m/s at Tiwai alongside a wind speed of around 5 m/s from the Invercargill profile (Fig. 4.3(b)). At this level, terrain effects were no longer visible.

These features were also present in the fine-grid run, with additional detail in the wind fields over the hills around Bluff (Fig. 4.3(c) and Fig. 4.3(d)). (Wind speed contours are not shown on Fig. 4.3(c), as they would obscure the detail in the wind vectors). This shows the effect of Bluff Hill in blocking the incoming flow at low levels.

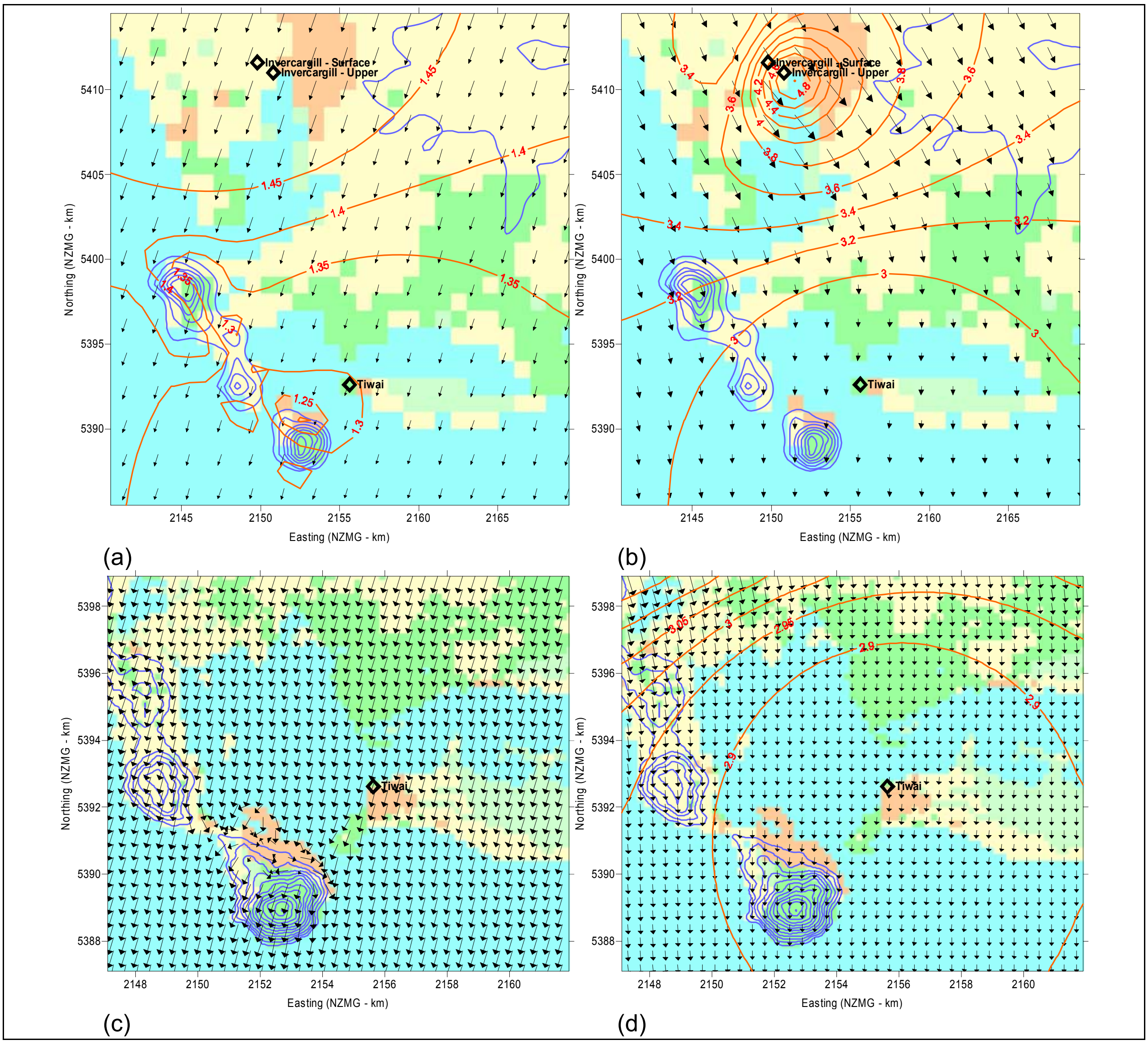


Fig. 4.3: CALMET wind vectors and wind speed contours, 16 October 1996, 1700 NZST; (a) Coarse grid, level 1 (10m), (b) Coarse grid, level 5 (165m), (c) Fine grid, level 1, (d) Fine grid, level 5. Terrain contours at 20 m intervals.
Land use type is shaded; urban areas brown, water blue. Wind vectors are shown from every second grid point. (For clarity, wind speed contours are not shown in (c)).

4.4 Approach I Variation – Nested CALMET Runs

Given the amount of meteorological data available for input, these results are likely the best that can be obtained from CALMET. The results from the fine-grid run provided more detail in the wind field, and, assuming it was realistic with only these data, the 200m resolution would be preferred to the 1 km resolution. However, the 200m run did not include the upper-air data site in the model domain. This may have created problems, as CALMET used those data in the fine-grid run with no knowledge of the intervening topography.

To circumvent this, CALMET has been run in a nested mode[4], where the final results from a coarse-grid run have been used as the initial guess of a fine-grid run. This has the advantage that off-domain terrain features can be allowed to take effect, and the larger-scale wind flow is given a better start in the fine-grid run. In this case though, the terrain between Tiwai Point and Invercargill is fairly flat – results from the nested run on the fine grid were practically indistinguishable from the original fine-grid run results and so are not shown here. If the important terrain features affecting the local flow are resolved on the fine grid then there is probably no advantage in running a nested mode.

To produce the Step 2 field, the surface data were extrapolated upwards to the mixing height, to give a theoretical wind profile. This was done at Tiwai Point on both the coarse and fine grids. The profile shape depended on, for example, the roughness length and the mixing height, which were determined by the land-use type. Therefore, ***the land-use category at climate sites should be the same on each nested grid***. Tiwai Point is at the coast, and on the fine grid is on a land point. On the coarse grid, the site location is on a sea point. For the coarse-grid run, the Tiwai grid point was changed manually from sea to land (coloured green in Fig. 4.3(a)).

4.5 Use of TAPM to Supplement Meteorological Data in CALMET

4.5.1 Background

The available climate data in the Invercargill/Bluff area allowed CALMET to produce physically realistic results, as there were surface and upper-air stations nearby. However, in many parts of NZ, there are no data of either kind. In principle, data may be supplemented or substituted by results from a prognostic model. This is provided the prognostic-model results are trustworthy. The following questions need to be addressed, regarding the use of TAPM for this case study:

1) How well does TAPM simulate the surface meteorology?
2) How well does TAPM simulate the vertical structure of the atmosphere?
3) Can TAPM outputs be used instead of observations in CALMET?
4) How should TAPM results be blended with meteorological observations in CALMET?

An in-depth analysis of TAPM's performance has been undertaken in section 0. A slightly different configuration has been used here, as this work was carried out simultaneously, but independently. Comparisons between the two TAPM runs are not the focus of this report. TAPM results are presented in this section to demonstrate that the performance of TAPM is adequate, and show its appropriateness in providing supplementary information for CALMET runs.

4.5.2 TAPM model configuration

TAPM version 3.0.7 was run for the same case-study period as CALMET. It was run on 4 nested grids – the largest covering most of the South Island, and the smallest focusing on the Invercargill/Bluff region. It

[4] At the time of writing, this option does not work in CALMET version 6.211. The USEPA has adopted CALMET/CALPUFF version 5.8 as a regulatory model which does allow nested runs.

was driven at its outer boundaries by synoptic-scale meteorological from the limited-area forecast model of the Australian Bureau of Meteorology. Deep-soil temperature and moisture were updated using data from Invercargill for the study period. The main model-run parameters are shown in Table 4.2.

4.5.3 Comparison of TAPM results with surface data

Modelled wind components at Invercargill and Tiwai Point were compared paired-in-time with observations, and results shown in Table 4.3. The statistical performance measures used in this section are described in then Appendix. Comparisons for surface temperature are shown in Table 4.4. The local time zone was determined by TAPM according to the grid centre coordinates, as GMT + 11.2 hours, based on longitude 168^{o} 23' E. Care must therefore be taken when comparing TAPM outputs with local observations (where NZST = GMT + 12 hours), and when using TAPM output as input to CALMET.

Table 4.2: Parameters used in the TAPM run.

Grid Centre Coordinates	(2156, 5400) 46^{o} 31' S 168^{o} 23' E	km, NZ Map Grid
Run Period	1 July to 31 October 1996	
Number of grid points	NZ x NY x NZ	25 x 33 x 25
Grid Number	Grid Spacing	Grid Size
1	*30 km*	*750* x *990 km*
2	*10 km*	*250* x *330 km*
3	*3 km*	*75* x *99 km*
4	*1 km*	*25* x *33 km*

Table 4.3: Statistical comparison of wind vector components at Invercargill and Tiwai Point.

	Tiwai Point U	**Tiwai Point V**	**Invercargill U**	**Invercargill V**
Mean of Obs.	1.6 m/s	-0.4 m/s	1.0 m/s	-0.5 m/s
Mean Modelled	1.7 m/s	-1.3 m/s	1.2 m/s	1.2 m/s
St. Dev. of Obs.	4.4 m/s	2.5 m/s	3.6 m/s	2.7 m/s
St. Dev. Modelled	4.1 m/s	3.5 m/s	3.0 m/s	2.6 m/s
IOA	0.90	0.79	0.86	0.83
RMS Error (total)	2.6 m/s	2.6 m/s	2.4 m/s	2.2 m/s
RMS Error (unexplained)	2.3 m/s	2.5 m/s	2.0 m/s	1.9 m/s
Skill Score E	0.5	1.0	0.6	0.7
Skill Score R	0.6	1.1	0.7	0.8
Skill Score V	0.9	1.4	0.9	1.0

Table 4.4: Statistical comparison of temperature components at Invercargill and Tiwai Point.

	Tiwai Point T	Invercargill T
Mean of Obs.	7.8 deg. C	6.9 deg. C
Mean Modelled	8.7 deg. C	8.1 deg. C
St. Dev. of Obs.	4.1 deg. C	5.0 deg. C
St. Dev. Modelled	3.3 deg. C	4.2 deg. C
IOA	0.92	0.91
RMS Error (total)	2.1 deg. C	2.7 deg. C
RMS Error (unexplained)	1.5 deg. C	2.0 deg. C
Skill Score E	0.4	0.4
Skill Score R	0.5	0.5
Skill Score V	0.8	0.8

For all parameters, the IOA was greater than 0.79, which should be considered good. Skill Score V was good for most parameters, although the modelled variability of the southerly component of the wind at Tiwai Point is perhaps too high (Skill Score V is 1.4). The other skill scores were 0.5 or less for temperature, which may be considered good. However, for the wind components they were higher than this value.

Time series of model results and observations are shown in Fig. 4.4. It can be seen that even though the quantitative measures are quite stringent, the general trends in the wind components were good. It should be remembered that the model is a simplified representation of reality, and should not be expected to reproduce it perfectly. It can be seen that times of low wind speed were not represented well by TAPM, and this may have consequences for dispersion from low-level sources.

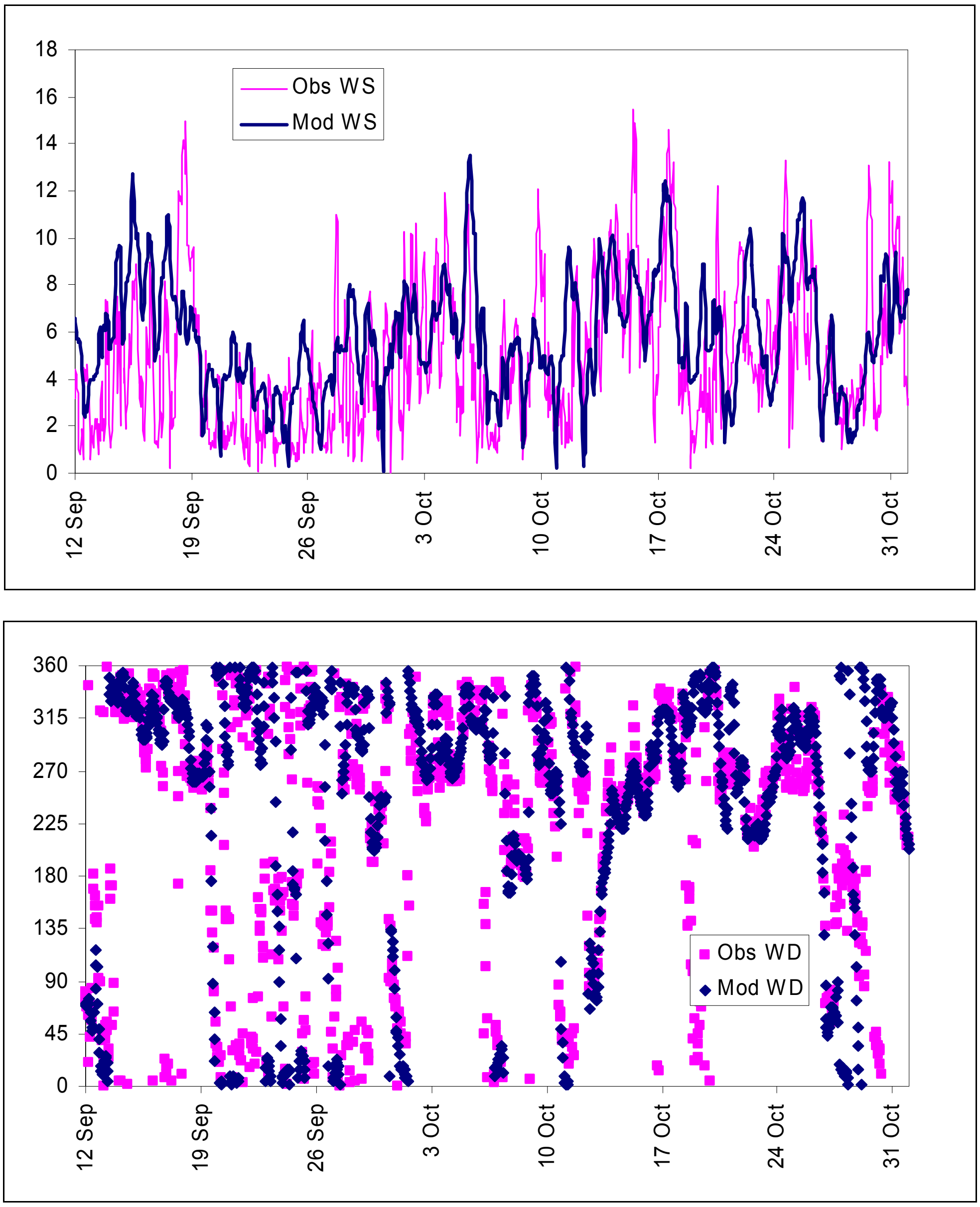


Fig. 4.4: Partial time series of wind speed and wind direction at Tiwai Point.

Results for two-dimensional wind fields over the TAPM model domains are not shown here. A visual inspection of the low-level fields has been carried out for this case, and TAPM's low level wind apparently did not respond well to the presence of Bluff Hill. This was probably due to the relatively coarse resolution of the terrain, which underestimated the height of the hills.

4.5.4 Comparison of TAPM results with upper-level data

TAPM results have been compared with the 12-hourly profiles from Invercargill airport, with similar quantitative measures of performance derived for time series at standard pressure levels. These are shown in Table 4.5.

Table 4.5 shows a general improvement with height of the performance of TAPM – increase of IOA, decrease in skill score E, and Skill Score V reaches 1. This is to be expected, as TAPM was simulating larger-scale features aloft, and the profiles had already been assimilated into the limited area forecast runs which were used to initialize TAPM and drive it at the boundaries. The wind components at the surface had smaller errors (RMSE) at the surface than aloft (though note that there is 12 times as much data at the surface) – this shows that TAPM simulated the mesocale flow well at the surface.

Table 4.5: Comparison of TAPM results with upper-level wind and temperature from the 12-hourly Invercargill soundings. The surface-level comparisons with hourly data from Table 4.3 are repeated here.

Parameter	Level	RMSE	IOA	Skill E	Skill V
U	*Surface*	2.4	0.86	0.6	0.9
	850 mb	3.5	0.95	0.5	1.0
	700 mb	2.9	0.97	0.3	1.0
V	*Surface*	2.2	0.83	0.7	1.0
	850 mb	2.9	0.95	0.5	1.0
	700 mb	2.8	0.97	0.4	1.0
T	*Surface*	2.7	0.91	0.4	0.8
	850 mb	1.5	0.96	0.4	1.0
	700 mb	1.4	0.97	0.4	1.0

Sources of model error aloft are different to those at the surface. Whilst at upper levels the model is essentially simulating the synoptic flow, there may still be errors in the timing of synoptic-scale weather systems such as cyclones, fronts, and large-scale convective systems. Near the surface, the model realism is limited by the specification of geographical features (model resolution) and the representation of physical processes (for example the surface and soil heat and moisture balance and their dynamical effects).

4.6 Approach II – CALMET Based on TAPM Outputs Only

If no meteorological data are available, the meteorology and pollution dispersion may be simulated using TAPM. However, the best resolution obtained with TAPM may be too coarse. Also, the user may have a preference for CALPUFF as the dispersion model. In these cases, the TAPM results may be used as inputs to CALMET – which is run at higher resolution – whose output is used directly by CALPUFF. In following this approach, the realistic, physically-based wind flow from TAPM is modified due to the presence of higher-resolution terrain by CALMET's parameterizations of slope effects.

A selection of points was chosen from the TAPM grid, and surface and upper-air files were produced for CALMET. TAPM has the facility to do this as a post-processing step and the outputs are automatically in the correct format. It only remains for the user to choose suitable locations. Regions of complex terrain should be avoided. In such regions, the TAPM fields at the coarser resolution may not be consistent with the higher-resolution terrain of CALMET. Terrain adjustments are done by CALMET to produce the step-I field, but as the TAPM results are being treated as if they were true measurements, the Step 2 procedures in CALMET would adjust the fields *back* to the inconsistent values from TAPM at the site locations.

For the Tiwai Point case study period, five TAPM sites were chosen over flat ground and water, assuming each is both a surface and an upper-air site. An example of resulting ground-level winds from CALMET is shown in Fig. 4.5. It can be seen that the general northerly flow, which was fairly uniform across the five TAPM sites, was diverted around Bluff Hill by CALMET. Choosing a TAPM site at Bluff Town (see Fig. 4.2 for its location) would result in northerly winds there too, in disagreement with the terrain-following flow produced by CALMET.

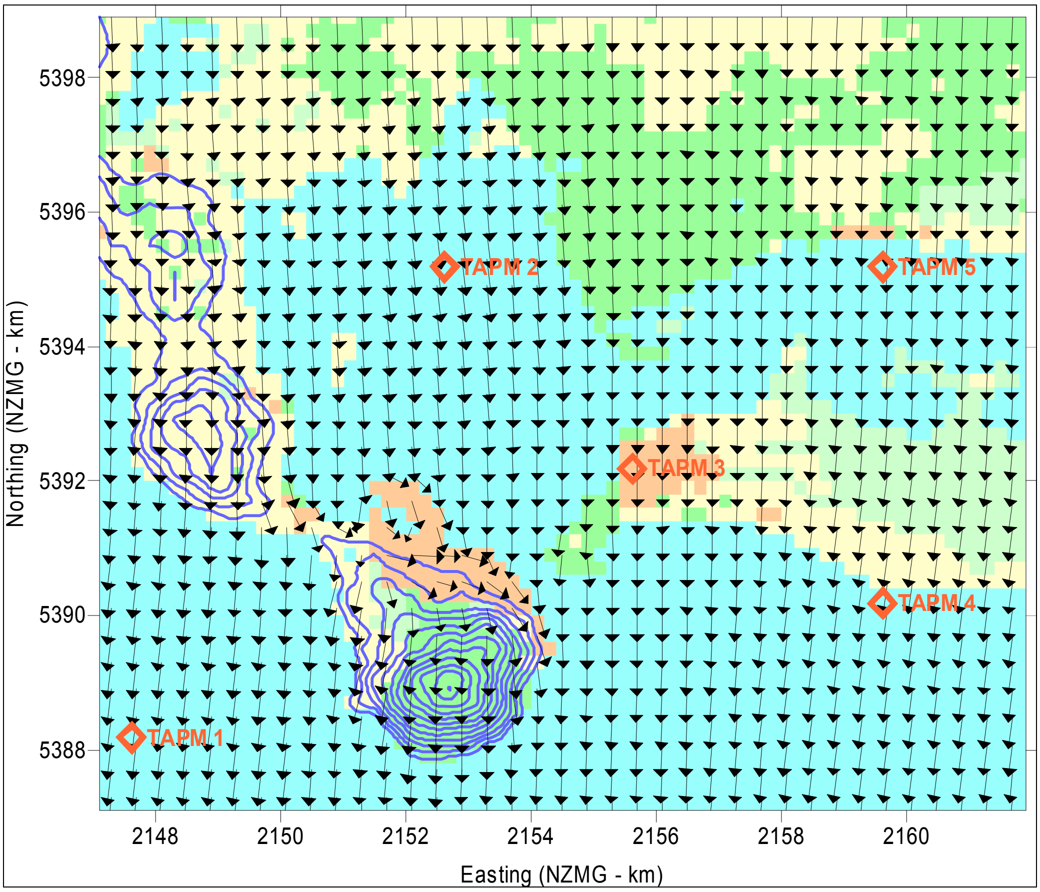


Fig. 4.5: **CALMET wind vectors at the 10m model level on 14 August 1996, 1700 NZST. Inputs are provided by TAPM at the five sites marked by red diamonds – each is used as both an upper-air and surface site.**

Some changes to the CALMET input parameters were required, as upper-air and surface sites were collocated, and upper-air inputs were hourly rather than 12-hourly. These are shown in Table 4.6. All changes served the same purpose, which was to prevent the extrapolation vertically of surface-based inputs, but should all be applied, as the extrapolation could potentially be carried out at several stages in the model before arrival at the final wind fields.

Table 4.6: **Input parameter comparison between examples of CALMET driven by meteorological data and by TAPM outputs.**

Parameter Name	Value if data-driven	Value if model-driven
IEXTRP	-4	1
BIAS *(level 2 and above)*	0	+1
RMIN2	-1	> 0

CALMET is designed to run in a 'no-data' mode, in which three-dimensional meteorological fields are supplied by MM5 as the initial-guess[5]. These may be then modified by the higher-resolution terrain in CALMET, but are not changed further by objective analysis of data. This option is not readily available in NZ[6], but the approach described here is close to it, remembering that using mesoscale model results as if they were data means that the objective analysis stage (step-2) will be carried out.

[5] This is considered the best of several places in the calculations at which the MM5 fields may be ingested into CALMET.

[6] MM5 is not used by the consultant community in NZ, and has been superseded by WRF.

It is important to note that the CALMET results can not be checked quantitatively, let alone validated. All data have been used as inputs – there are no other data to compare outputs with. Approaches followed and parameter values used are chosen by experience. In this work, alternative run configurations have been exhaustively tested, and judged according to how the end-results 'look'. There are several subjective criteria which may be used in the appraisal of CALMET results. These are listed in Section 5.

4.7 Approach III – CALMET Based on TAPM Upper-Air Results and Surface Data

It is most likely that for a modelling assessment in NZ, there will be surface meteorological observations available, but no upper-air profiles nearby.

It should be possible to blend the surface data with modelled profiles, so that the results transform smoothly from being data-driven near the surface, to model-driven aloft (by TAPM). It is easy to mix the two sources of information as inputs to CALMET, and CALMET will run and produce outputs. However, the end result is unlikely to be what was originally intended, and will fall short of the subjective criteria described above. This section shows schematically how CALMET deals with the data sources, and that the smooth transition in the vertical from observations to model results, as desired here, is likely to not happen. It will be seen that the transition from observations to mesoscale-model results occurs in the horizontal at all levels, and that that transition can be discontinuous if mesoscale-model results and observations are not consistent.

TAPM is designed to provide a statistical representation of the meteorology, rather than an accurate hour-by-hour simulation. That is, it should produce the correct types of meteorological situations on the right number of occasions. It does this well, and often does give a good hour-by-hour solution. However, there are times when the mesoscale solution does not match the data from that hour, and this is where care is needed in the blending of these two sources of information in CALMET.

Approaches described in this section that CALMET may use for dealing with different sources of meteorological data are summarized in Table 4.7. Approaches I and II have already been discussed, and result in adequate CALMET results. For air quality assessments in NZ, there are commonly surface data, but no upper-air data, requiring adoption of Approach III or Approach IV. In addition, CALMET can use outputs from MM5 at the initial-guess stage, and local observations need not be available at the objective analysis stage. This is not easy to implement in NZ, as suitable MM5 date are not usually available.

Table 4.7: Summary of possible approaches to meteorological data input to CALMET.

Data situation	Approach	Input Surface Data	Input Upper-Air Data	Recommended approach?
Surface and upper-air available	**I**	Climate Stations	Radiosoundings (12-hourly)	Yes
No data available	**II**	Extracted from TAPM	Extracted from TAPM (hourly)	Yes
Only surface data available	**III**	Climate Stations	Extracted from TAPM (hourly)	No
Only surface data available	**IV**	Climate Stations	Pre-processed profiles	Yes

To illustrate potential problems with Approach III, CALMET has been run with input profiles from four of the five TAPM sites (numbers 1, 2, 4 and 5) instead of the Invercargill profiles. Surface data from Invercargill and Tiwai Point were used. TAPM site 3 is very close to Tiwai Point – it was not used, so as to let CALMET extrapolate the Tiwai Point observations upwards. Two cases have been run to illustrate the effect of choices of the ***BIAS*** parameter. All other parameters were the same as in Approach I.

On many occasions during the four month run, the TAPM wind fields were different from the extrapolated surface data. For example, on the afternoon of 1 August 1996, the TAPM wind at CALMET model level 6 (250 m above ground) was a slow north-easterly. However, the surface data were extrapolated upwards as a more rapid southeasterly. The resulting wind fields from CALMET are shown in Fig. 4.6. Neither of these is realistic, as can be seen by the abrupt change in both wind speed and wind direction with distance, moving away from the site locations. Between the sites (beyond a distance ***RMAX2*** from any site), the final wind field was the Step 1 field. With ***BIAS*=-1** at this level, this is an extrapolation of surface data and so matched the wind over Tiwai Point (Fig. 4.6(a)). With ***BIAS*=+1** at this level, this was an extrapolation of upper-air information, which matched the wind over the TAPM sites (Fig. 4.6(b)).

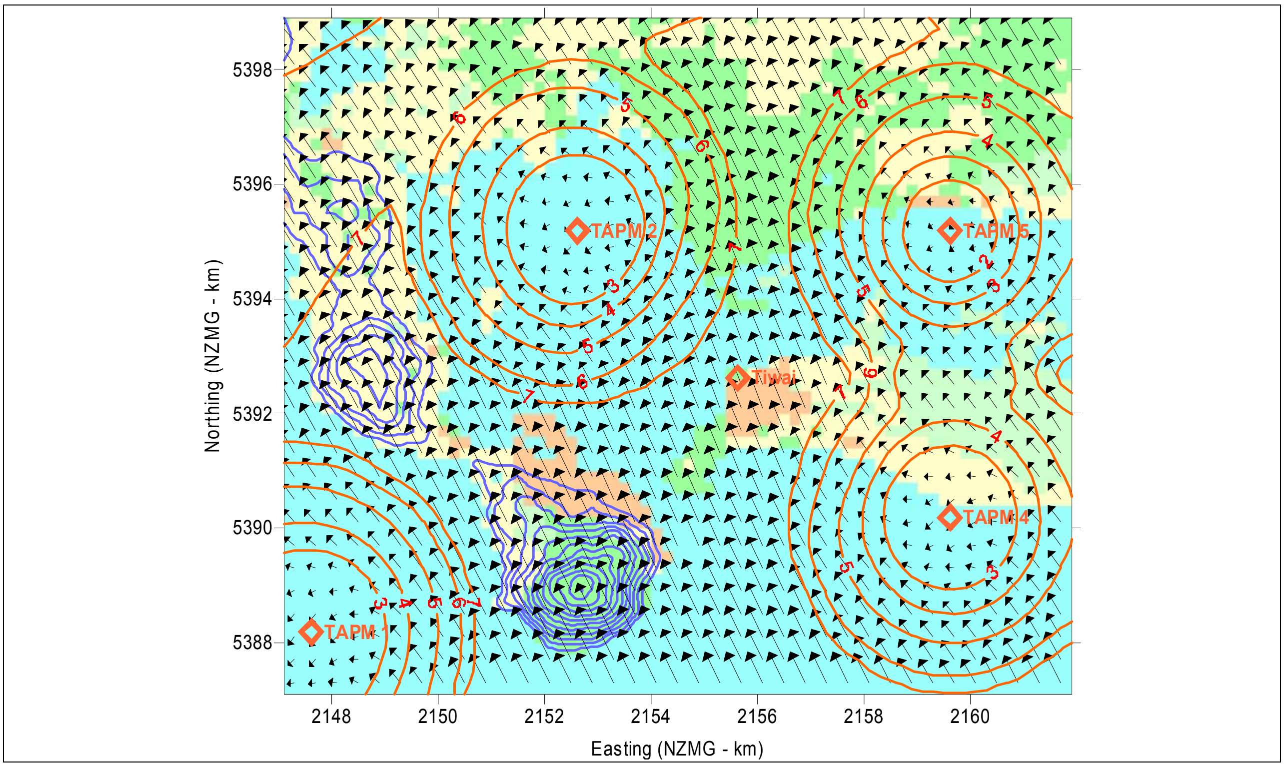
These results are unrealistic, and cannot be improved within CALMET:

1) The discontinuity cannot be removed by changing ***BIAS***;

2) The discontinuity cannot be removed by co-locating a TAPM upper-air site with Tiwai Point. The resulting profile would be the average of the upper-air profile and the extrapolated surface data, and therefore still incorrect. This is also the case if ***BIAS*** is set to zero;

3) The fields may be smoothed by increasing ***R2*** and ***RMAX2***. However, this is unsatisfactory as it would override the terrain adjustments carried out before the Step 2 field is calculated;

4) There is also a discontinuity in the vertical, especially with ***BIAS***=+1, as the model changes from being determined by the surface data (at layer 1) to being determined by the TAPM results (from layer 2 upwards).



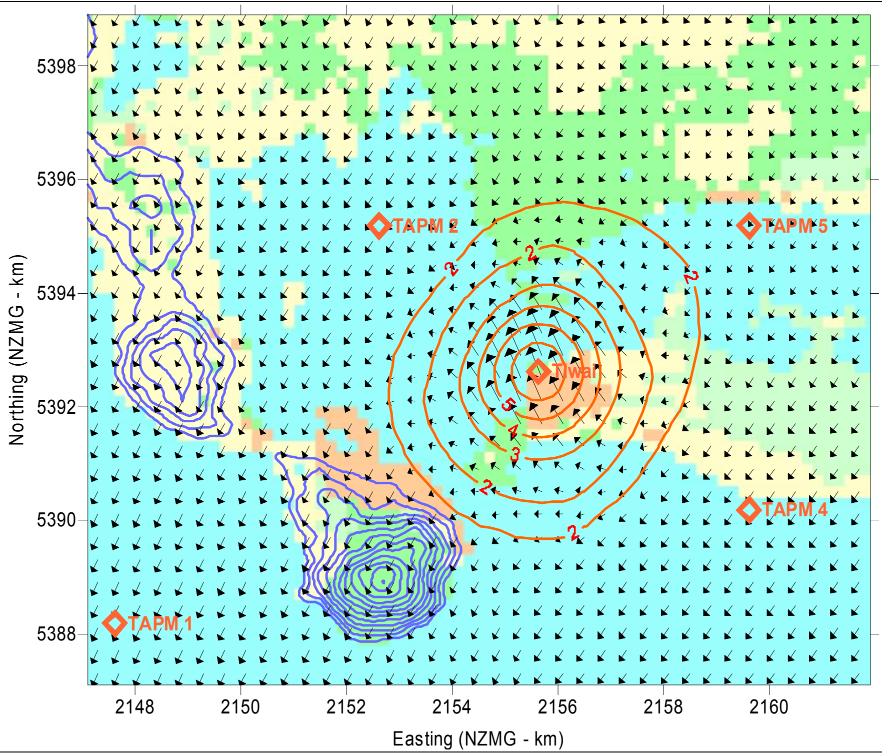


Fig. 4.6: CALMET runs with profiles from TAPM and surface data from Tiwai Point, 1500 (UTC+11) on 1 August 1996. Wind vector arrows and wind speed contours. (a) *BIAS* = - 1, (b) *BIAS* = + 1.

4.8 Approach IV – CALMET Based on TAPM Upper-Air Results and Surface Data (Improved)

Surface-based information and upper-air information are used alongside each other in CALMET, which can lead to unrealistic results if the two sources of information are not consistent with each other. This is not to say that the TAPM profiles are in error, or that the data are in error. It is merely that they have their own limits of applicability, beyond which Approach III of CALMET has taken them. Note that:

1) The extrapolated surface data are applicable only in the so-called 'surface' layer, according to the similarity theory, not in the whole boundary layer as assumed by CALMET;

2) TAPM is ultimately driven by synoptic-scale upper-air data, meaning it should give good results at higher levels in the atmosphere, away from the surface which may not be seen in enough detail by the model;

3) These two regimes may co-exist, one above the other.

As it is impossible to superpose the upper-air data over the surface data in CALMET, the data have been processed in advance so that that superposition has been carried out before CALMET is run. In this case the Tiwai Point data were merged with TAPM profile 3.

A profile of extrapolated surface data and knowledge of the mixing height was still required above Tiwai Point. This has been provided by either of the Approach III runs described above. Their results were different over most of the domain (compare Fig. 4.6(a) and Fig. 4.6(b)), but above Tiwai Point they were exactly the same, as expected.

Hourly profiles extracted from the chosen CALMET run were merged with hourly profiles from the TAPM, and the new profiles were used as inputs to a new (and final) CALMET run. A suggested procedure is as follows:

1) Run TAPM in the configuration described above (and assess the results);

2) Extract profiles above locations where there are surface data, plus a few others, avoiding complex terrain areas;

3) Run CALMET as Approach III[7], using the extracted TAPM profiles and surface data, but not using the TAPM profile over the surface site;

4) Extract vertical profiles and mixing height from CALMET above the surface sites;

5) Merge the CALMET profiles with the TAPM profiles over the surface sites as follows;
   a. Apply to each meteorological parameter – wind velocity components and temperature;
   b. Interpolate the CALMET profiles onto the TAPM levels;
   c. Substitute the CALMET profiles of u, v and T up to $zi/10$ (where zi is the mixing height);
   d. Use the TAPM profiles from zi upwards;
   e. Interpolate linearly in z between $zi/10$ (CALMET) and zi (TAPM);
   f. This produces an updated profile over the surface site.

6) Run CALMET again using the updated profile as input upper-air data – this is the abovementioned Approach IV.

Approach IV is actually like Approach II (TAPM profiles only), except that the meteorological information sources are the surface data and the modified profiles above the surface sites. In neither approach should the surface information be extrapolated upwards, as the profile information has already been made consistent with the surface information.

Examples of the results of three profile-blending processes are shown in Fig. 4.7. In Approach III the profile over Tiwai Point was determined by extrapolation of the surface data according to similarity theory, up to the mixing height (616m), above which it was determined by the TAPM profiles extrapolated *from other sites*. The final profile, for input to the Approach IV run, therefore matched the Approach III profile up to at least 61m, above which there was a transition to the TAPM profile over Tiwai Point. Resulting horizontal wind fields for Approach IV are not shown, as there are no notable features in the upper-air results – there should not be any. The surface winds matched those of Approach I.

[7] A simpler case than the full Approach III could be run. This may only need a simple domain which includes Tiwai Point data and a single TAPM profile at different locations, on the correct land-use category.

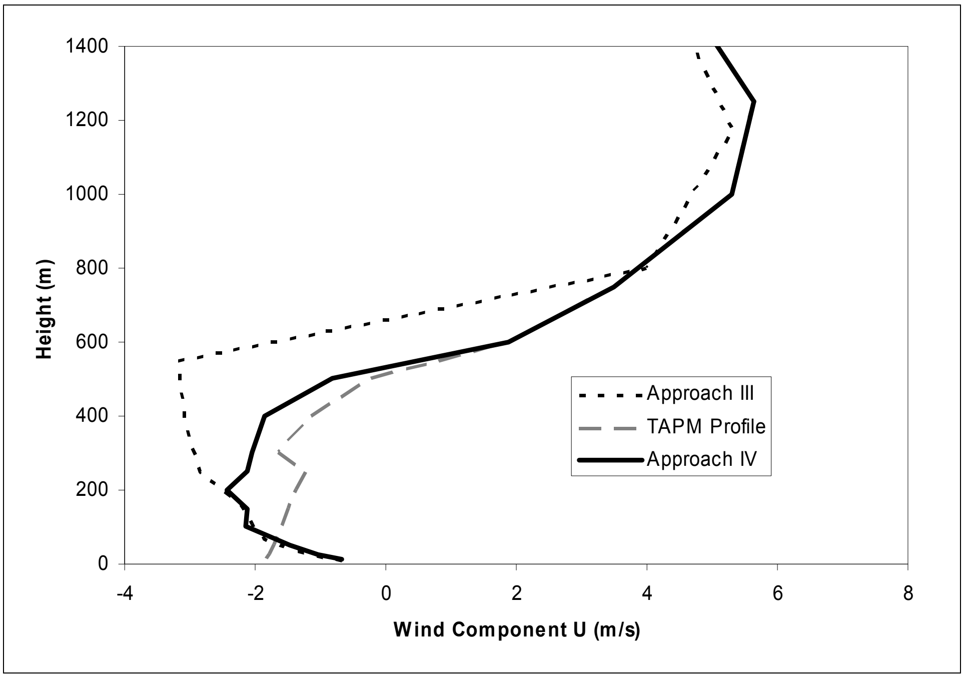


Fig. 4.7: Profiles of wind component U over Tiwai Point, 1500 (UTC+11) on 1 August 1996. CALMET Approach III (dotted), TAPM profile (dashed), final input profile to Approach IV (solid).

4.9 Discussion

This section has focused on some specific issues regarding the running of CALMET in data-sparse areas, which is commonly the case in NZ. A number of approaches have been discussed which may be summarized here.

Approach I – surface and upper-air meteorological data are available: CALMET gives good results.

Approach II – no meteorological data available: Run TAPM and use its surface and upper-air outputs as input to CALMET. CALMET gives good results.

Approach III – only surface data are available; TAPM supplies upper-air profiles: CALMET gives unrealistic results where TAPM results and surface data are inconsistent. Do not use this approach.

Approach IV – surface data are merged into the TAPM profiles before the final CALMET run. CALMET gives good results, like Approach I near the surface, and Approach II at upper levels.

Values of the key CALMET parameters for these approaches are summarized in Table 4.8.

Table 4.8: CALMET parameters used in this section. The bias parameter B in approach III may be any permissible number. Examples are shown in the text with values +1 and -1.

Approach	*R1*	*RMAX1*	*R2*	*RMAX2*	*TERRAD*	*IEXTRP*	*BIAS*	*RMIN2*
I	1.5 km	3.0 km	1.5 km	3.0 km	4.0 km	-4	-1,11x0	-1
II	1.5 km	3.0 km	1.5 km	3.0 km	4.0 km	+1	0,11x1	4
III	1.5 km	3.0 km	1.5 km	3.0 km	4.0 km	-4	-1,11x*B*	-1
IV	1.5 km	3.0 km	1.5 km	3.0 km	4.0 km	-1	-1,11x1	4

Several issues are still largely unresolved, and work is in progress to improve them:

1) ***Specification of cloud information in CALMET*** – hourly values of cloud cover and cloud height are required, but observations, if any, are often day-time only.
2) ***Model domains containing data-rich and data-sparse areas*** – if surface data are available in some locations and not others, there remains the question of how to blend surface data and TAPM results horizontally.

In addition, Approaches II and IV presented here have not been extensively tested. Again, this is in progress, including investigations of the effects of the meteorological results on the dispersion of pollutants modelled by CALPUFF.

5. Findings and Recommendations

During the course of these studies, and experience with the models in other cases, several basic features of TAPM and CALMET have become apparent, that users should be aware of. Before listing these, it should be pointed out that both of these are excellent models: They have been developed by experts, have been the subject of many validation and comparison studies, and are in common use throughout the world. As the physical processes occurring in the atmosphere are far more complex than their representation in a mathematical model, it should be acknowledged that most models simulate reality well. Their deficiencies can often be put down to their use beyond their range of applicability (requirements for use in NZ are usually at the boundary of that range), or to poor-quality input information.

1) TAPM is very much a ‘black box’. Few physical parameters can be changed.
2) TAPM can be unresponsive to terrain forcing, giving spatially bland results. This may be due to the reduction in height when terrain data are smoothed onto the model grid, but this feature can persist even when terrain heights are artificially increased.
3) TAPM can be sensitive to surface parameters, such as soil temperature, soil moisture and sea-surface temperature. The heat and moisture balance at the surface, and therefore boundary layer structure and dispersion characteristics depend on these. Measurements should be used in favour of the model defaults.
4) In general, TAPM performs well at upper levels, but can miss extremes in wind and temperature at the surface. Its finest practical horizontal resolution is 1-km grid spacing, and the user must decide whether this is sufficient to resolve the terrain, land-use and coastal effects at the surface. Also, care must be taken that the model outputs are compared with data representative of the scales resolved by the model. These considerations are true of any prognostic model. If sub-km resolution is required, more sophisticated models such as WRF or MM5 should be used in preference to TAPM. However, running any prognostic model at such a high resolution is computationally expensive, and generally needs parallel processors.
5) CALMET is more flexible that TAPM, in that many parameters may be specified by the user. However, this means that more skill is required in choosing appropriate parameter values and obtaining the best results.
6) CALMET requires surface-based meteorological data. This information is now freely available from the National Climate Database, meaning that long time series of observations may be obtained and examined to choose suitable periods for modelling.
7) CALMET is data-hungry, and the lack of observed vertical profiles in NZ can be a drawback. Methods described in this report can circumvent this, but they require some skill.
8) CALMET requires gridded terrain and land use data, which are not supplied with the model at high resolution over NZ. This has been a problem in the past, but users are likely to have such data in-house. Alternatively, high resolution (around 90m) relief data are available from the Shuttle Radar Topography Mission.

Based on the case studies presented in this report, and the authors' experiences in meteorological modelling, the following recommendations are made.

Recommendation 1 Running TAPM

In data-sparse areas of NZ, where the meteorological features may be resolved by a grid of 1 km resolution, meteorological information for dispersion modelling is best provided by TAPM. Technical recommendations from TAPM's developers are that the horizontal resolution of an outer grid should not be more than 4 times the inner grid and that the outermost domain should be larger than 400 km x 400 km but smaller than 1000 km x 1000 km. Furthermore, the model grid should consist of at least 20 x 20 horizontal grid points and 20 vertical levels.

Recommendation 2 Validating TAPM

TAPM results should be checked, validated where possible, and the process written up and included in the air quality assessment. The checking should include a visual inspection of time series of model outputs, compared with the time series of observations, at the surface and aloft. The validation should also include calculation of performance indicators such as root-mean-square errors, mean absolute error, index of agreement, and skill measures. These are described in the Appendix. These quantify statistically the model's ability to reproduce observed means and variability in meteorological parameters, and provide a more rigorous assessment of the performance of TAPM than a preliminary inspection. They should be applied to the horizontal components of the wind vector, and the temperature, and carefully to wind speed and relative humidity. These particular statistical measures should not be applied to wind direction.

Recommendation 3 Running CALMET

If sub-1 km resolution is required, and the region is data-rich CALMET should be used. In general, the radii of influence of climate data should be small, to allow the terrain adjustment process to produce realistic results. Specifically, ***R1**, **R2**, **RMAX1**, **RMAX2*** should be small, ***R2*** should be not too much larger than ***R1***, and ***RMAX2*** should be not too much larger than ***RMAX1***. The terrain radius of influence should depend on the true topography, not the model-resolved topography. Upper-air data at the surface should be ignored, as it is usually only 12-hourly and interpolated in time, in favour of hourly surface data. If important sources of data are off the high resolution domain, and there is intervening topography, it may be advantageous to run CALMET in a nested mode. A coarse-resolution domain, including the off-domain site, may be run and its results used as the initial-guess for the sub-1 km run, noting that the land-use categories of monitoring sites should be the same for each domain. If the local flow is influenced mainly by local terrain, there is probably no need to do this, and the off-domain data can still be incorporated into the sub-1 km run.

Recommendation 4 Assessment of CALMET results

A quantitative comparison of CALMET results with observations at monitoring sites is not appropriate. At those sites, the observations should be matched perfectly, as they are used as model inputs. The performance of CALMET in its extrapolation between monitoring sites and its accounting for terrain effects should be assessed using more subjective means, as listed below.

1) The flows should be realistically affected by terrain features. This is seen by checking near-surface wind fields under stable conditions. There should be no uphill flow in stable conditions.
2) Changes in meteorology from one location to the next, and one model level to the next, are smooth and continuous;
3) Output wind roses at meteorological sites should match input wind roses;
4) Derived boundary-layer parameters such as mixing height and stability class should be checked for realism, statistically at least, if not hour by hour;
5) Runs of other models used as inputs to CALMET should also fulfil these criteria, and be validated where possible.

Recommendation 5 Using TAPM outputs in CALMET (no observations)

If sub-1 km resolution is required, and there are no local data, TAPM may be run (at 1 km resolution) to provide meteorological information for CALMET, using its outputs as if they were real data. This is **Approach II** of Section 4, where CALMET parameterizes detailed terrain effects which TAPM cannot resolve. The meteorological sites in CALMET are then a selection of TAPM grid points, and outputs are extracted from TAPM and automatically formatted for input to CALMET as surface and hourly upper-air data. Surface and upper-air sites should be coincident, and *away from complex topography*, to let CALMET develop terrain-induced wind flows. Only a few ‘virtual’ stations should be used (and certainly not one for each TAPM grid point); CALMET should not be forced to agree with TAPM’s outputs. Vertical extrapolation of surface inputs should not be done, as the full profiles are provided by TAPM.

Recommendation 6 Using TAPM outputs in CALMET (sparse surface observations)
If sub-1 km resolution is required, and there are surface data, but no upper-air data, TAPM may be run to provide meteorological for CALMET, through the extraction of profiles only, not surface outputs. These may be blended with the surface observations. Care must be taken with this process, as the observations and TAPM outputs will not be consistent from hour to hour. There is no way in CALMET to merge the two data sources smoothly when they differ at particular times. The merging must be accomplished as a pre-processing step, described in **Approach IV** of Section 4. Vertical extrapolation of surface inputs should not be done, as the full profiles are provided by the pre-processed information.

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Appendix – Model Performance Indicators

There are several statistical estimators for the goodness of a simulation, when compared with observations. In this section, three indicators are used:

Root Mean Square Error (RMSE): The RMSE corresponds to an estimate of the error of the model when compared to the measurements. Because it is a non-linear function, the RMSE is biased towards larger errors when larger differences occur and it is therefore a conservative estimate of the difference between the model and the observations. Willmott (1982) indicated that the RMSE can be further divided in two independent errors. The "systematic" RMSE ($RMSE_S$) and the "unsystematic" RMSE ($RMSE_U$) that give information about the noise introduced by the model ($RMSE_U$) and the systematic difference between the model and the observations ($RMSE_S$). In general, it is expected that a "good" model gives values of $RMSE_S$ that approach zero while the unsystematic part (noise) approaches RMSE. This because the systematic part of the error is related to an inability of the model to capture the general trends in the observations, which hypothetically could be improved. On the other hand, $RMSE_U$ represents random errors which could be due to small scale processes, which are not expected to be resolved by the model. These indicators are given by the following formulae:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(P_i - O_i\right)^2}{N}}$$

$$RMSE_S = \sqrt{\frac{\sum_{i=1}^{N}\left(\hat{P}_i - O_i\right)^2}{N}}$$

$$RMSE_U = \sqrt{\frac{\sum_{i=1}^{N}\left(P_i - \hat{P}_i\right)^2}{N}}$$

where N is the number of data points, P_i the model predictions, O_i the observed values and $\hat{P}_i$ the solution of a least-squares linear regression of *P* on O.

Skill Scores: Skill scores are a measure of how the variability and errors in the model relate to the observed variability. They are ratios of modelled standard deviations, or RMS errors, to the observed standard deviation. They are given by

$$Skill_E = \frac{RMSE}{STDEV_{OBS}}$$

$$Skill_R = \frac{RMSE_U}{STDEV_{OBS}}$$

$$Skill_V = \frac{STDEV_{MODEL}}{STDEV_{OBS}}$$

where $STDEV_{OBS}$ and $STDEV_{MODEL}$ the observed and modelled standard deviations, respectively. To demonstrate model skill, $Skill_E$ and $Skill_R$ should be small, and $Skill_V$ should be close to 1.

Mean Absolute Error (MAE): The MAE is an estimator for the average difference between the model and the observations. However, because it is a linear function, it does not give a higher weight to larger differences and it is lower than the RMSE. In a statistical sense, it is one estimate of the *expected* difference between the model and the observations, and is given by:

$$MAE = \frac{\sum_{i=1}^{N} abs\left(P_i - O_i\right)}{N}$$

Index of Agreement (IOA): The IOA is an unbiased measure of the ability of the model to capture the variability and the mean of the observed parameters (Willmott, 1982). It ranges from 0 (no agreement) to 1 (perfect agreement). The IOA is best applied to a comparison of two sets of model results. For instance, if IOA_1=0.80 and IOA_2=0.85, this indicates that Model 2 is 5% more accurate than Model 1. The IOA is given by:

$$IOA = 1 - \frac{\sum_{i=1}^{N} \left(P_i - O_i\right)^2}{\sum_{i=1}^{N} \left(P_i^{'} - O_i^{'}\right)^2}$$

$$P_i^{'} = abs\left(P_i - \overline{O}\right)$$

$$O_i^{'} = abs\left(O_i - \overline{O}\right)$$

where $\overline{O}$ corresponds to the mean observed value.

These performance indicators cannot be used for wind direction because of the circular nature of the variable. Consider the simple case of a constant northerly wind occurring (direction 0 degN), estimated the model as 358 degN. All the performance indicators will indicate poor behaviour when the model is in error by only 2 degrees. These performance indicators should only be reported for wind speed, temperature and the wind components, U and V. Care should be taken with wind speed as this is bounded below by zero, and with RH which is bounded by zero and 100%.