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EVALUATION OF AN AIR QUALITY SIMULATION OF THE LOWER FRASER VALLEY — I. METEOROLOGY

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Abstract—A state of the art nonhydrostatic meteorological model has been coupled with a meteorological preprocessor for use with an advanced photochemical model. The first application of the modelling system is to the Lower Fraser Valley region of British Columbia. The region is characterised by complex topography in a coastal environment, and provides a severe test of the capability of the meteorological model to handle the air flow in the valley. The model performance is evaluated using time series of surface meteorological data, tether sonde data and acoustic sonde measurements of mixed layer depths. A quantitative statistical evaluation shows that the model performs well, but improvements could be achieved with higher spatial resolution. Crown Copyright © 1997 Published by Elsevier Science Ltd. All rights reserved.

Key word index: Mesoscale modelling, air pollution, non-hydrostatic, compressible.

1. INTRODUCTION

A meteorological modelling system, based on a combination of the Mesoscale Compressible Community Model (MC2) with the CALMET meteorological preprocessor, is presented for use with the CALGRID photochemical model. The first application of MC2-CALMET is to an air quality simulation for the 17–21 July 1985 ozone episode in the Lower Fraser Valley region of British Columbia, Canada. This paper describes in detail the results of the meteorological simulation that is used to drive the photochemical simulation, which is presented in a companion paper (Hedley *et al.*, 1996).

During particular years, high-pressure systems over the Pacific Ocean can lead to subsidence and therefore reduced boundary-layer depth and stagnant air flow conditions within the Lower Fraser Valley (Steyn and Oke, 1982). The clear skies lead to strong surface heating of the land mass, and the resulting contrast with the sea-surface temperature forces the development of sea breezes in the daytime. A complicating factor in the evolution of the air flow is the strong modification by mountain–valley breezes caused by solar heating of the valley walls. These thermally forced circulations have been well documented in several studies (Steyn and Oke, 1982; Chen and Oke, 1994; Steyn and McKendry, 1988).

The period from 17–21 July 1985 was characterized by these conditions. Modelling this type of weather situation can be challenging, and it is important to use a sophisticated enough model to simulate most of

the important physical forcing that affects the flow. Tanguay *et al.* (1990, 1992) developed a semi-implicit semi-Lagrangian mesoscale forecast model named MC2 which solves the fully compressible equations of motion over complex terrain. This model was chosen as the meteorological component of the present modelling system because of the virtually unlimited range of spatial scales the model can be applied to, allowing us to model practically any geographical situation.

Although MC2 does not impose any significant restrictions on the allowable spatial or temporal scales, there are practical limitations with respect to computer speed, disk storage and initial data. In addition, one must decide on the best spatial and temporal resolutions to employ given the intended use of the model data. There is probably little advantage to be gained by simulating the atmosphere at time scales of a few seconds if the wind fields are to be averaged over 1 h periods for use as input to a photochemical model.

The CALMET meteorological preprocessor is part of the CALGRID photochemical modelling package developed by Yamartino *et al.* (1992). With CALMET, we are able to combine meteorological model output with observational surface and upper air data, using arbitrary weighting factors that determine the relative influence of measured vs modelled data, to produce a data file for CALGRID. (Note that in the work presented here, the measured data are not used at all in producing the model forecast.) We extended the capabilities of CALMET to include the interpolation of data from the MC2 grid to the CALGRID grid.

Fig. 1. Synoptic situation for the 17–21 July ozone episode: (a) 1000 mb height field for 0400 PST 17 July 1985. Contour lines are every 2 dm. The larger of the two inner squares outlines the meteorological modelling domain, and the smaller square represents the photochemical modelling domain. (b) 500 mb height field for 0400 PST, 17 July 1985. Contours every 3 dm. (c) 1000 mb height field for 0400 PST, 21 July 1985. Contours every 2 dm. (d) 500 mb height field for 0400 PST, 21 July 1985. Contours every 2 dm.

2. THE 17–21 JULY 1985 METEOROLOGICAL SITUATION

The meteorology during the 17–21 July ozone episode was characterized by sunny, high-pressure conditions. Maximum temperatures were over 30°C within the valley for several days. The clear skies and nighttime radiation cooling led to minimum overnight temperatures of less than 15°C at most stations. The 1000 mb height field for 0400 PST July 17 is shown (Fig. 1a) for the coastal region of British Columbia and Washington State. A high-pressure system is situated to the West over the Pacific ocean. There is only a very weak pressure gradient over the Lower Fraser Valley, and therefore little horizontal forcing of surface winds. At 500 mb (Fig. 1b), a weak short wave is moving eastward away from the Lower Fraser Valley. To the west and slightly south, an upper-level ridge is apparent.

The synoptic situation hardly changes over the next few days. By 0400 PST 21 July, the high-pressure system over the Pacific has weakened somewhat, but clearly has remained relatively stationary for the past 96 h (Fig. 1c). The surface pressure gradient is vir-

tually nonexistent over the Lower Fraser Valley, and at 500 mb (Fig. 1d), it can be seen that the southern half of the region shown has no height gradient of any significance. At this time, however, we do see evidence of a short wave approaching from the west.

The anticyclonic weather pattern described above is ideal for the development of a stagnant lower troposphere. Subsidence within the anticyclone leads to the suppression of mixed layer depths, and the lack of horizontal pressure gradients prohibits the development of large-scale air flow. The only significant air motions are those due to the small-scale thermal forcing caused by the land–sea temperature contrast and differential slope heating, and the resulting mesoscale circulations tend to recirculate pollutants rather than carry them away.

3. MODELLING DOMAIN AND INPUT DATA

The horizontal domain chosen for MC2 is shown in Fig. 1a as the larger of the square outlines. The domain is a square region on a polar stereographic map

true at 60° north latitude. The extent of the domain is 550 km × 550 km, and roughly centred on Vancouver. For the simulation, a 10 km horizontal resolution is used.

The complex topography in this region demands that the top of the modelling domain be sufficiently high in order to minimize the spurious reflection of gravity waves off the top boundary. In this case, the model lid is imposed at 25 km above the ground level. There are 31 levels in the vertical, with varying thicknesses (Table 1). Near the surface, the vertical resolution is 200 m. We attempted to use finer grid spacing near the surface in preliminary simulations, but we found that it was necessary to use prohibitively small time steps to maintain numerical stability. At the top of the domain, a sponge layer is used to damp any reflections that might occur.

A time step of 60 s was used. At this spatial and temporal resolution, MC2 required 40 min of computer time on a Silicon Graphics Power Indigo to simulate every hour of real time. In the early phase of this study, several experiments were run using much higher vertical and horizontal resolutions for short periods of real time. The fields produced in the higher-resolution simulations were far more complex, and appeared more realistic than the lower-resolution results presented here. However, given that our focus is on the photochemical results, we feel that the current simulation provides an adequate representation of the major features of the flow. Although higher spatial resolution would clearly be beneficial, the increased computer time and disk storage space is prohibitive at this stage.

Initial and boundary conditions for MC2 were extracted from the six-hourly archived CMC data. The CMC data were available on a 3° resolution latitude–longitude grid at 11 pressure levels from 1000 to 50 mb. No attempt was made to introduce additional data into the initial conditions. The lateral boundary conditions were interpolated linearly in

time at each time step between the archived data intervals. The updated boundary value data are introduced gradually over the outermost few grid points to minimize the generation of transients at the boundaries.

The hourly MC2 output is interpolated vertically and horizontally onto the CALMET grid. Figure 2 illustrates the subdomain on which the MC2 output is interpolated for use in the CALMET simulation. The horizontal interpolations are performed with two-dimensional bicubic splines. All results shown below are calculated on this 5 km resolution, Universal Transverse Mercator (UTM) domain. The shading indicates the height of the topography according to the gray scale shown. The locations of the measuring stations are indicated with squares for the surface stations, circles for the acoustic sondes, and a triangle for the tethersonde at Queen Elizabeth Park.

The vertical interpolation involves gridding the relatively coarse MC2 output onto the finer vertical CALMET grid using surface layer similarity theory to provide better estimates of the wind and temperature profiles near the surface. The 11 CALMET layer faces are located at the following heights: 0, 20, 80, 160, 260, 410, 660, 1200, 3600 and 5000 m.

4. MODEL EVALUATION

4.1. Surface meteorological fields

The simulation was initiated at 0400 PST, 17 July and run for 116 h until 0000 PST, 22 July. The predicted and observed surface wind vector fields for 0400 PST, 18 July, 1500 PST, 19 July, 0400 PST, 20 July and 1500 PST, 21 July are shown in Figs 3a–d, respectively. Note that the plot covers the photochemical modelling domain only (the smaller square in Fig. 1a), and not the entire meteorological modelling domain. These are the wind fields after processing by CALMET, and hence have been interpolated from

Table 1. Heights of the thermodynamic and momentum layers for the meteorological simulation^a

Level	z_t	Δz_t	z_m	Δz_m	Level	z_t	Δz_t	z_m	Δz_m
31	23,524	1476	24,262	1476	15	3396	464	3676	512
30	22,048	1476	22,786	1476	14	2932	380	3164	422
29	20,573	1476	21,311	1476	13	2552	309	2742	345
28	19,097	1476	19,835	1476	12	2243	249	2398	279
27	17,621	1476	18,359	1476	11	1994	199	2118	224
26	16,145	1476	16,883	1476	10	1794	199	1894	199
25	14,670	1476	15,408	1476	9	1595	199	1695	199
24	13,194	1476	13,932	1476	8	1396	199	1495	199
23	11,718	1476	12,456	1476	7	1196	199	1296	199
22	10,242	1476	10,980	1476	6	997	199	1097	199
21	8767	1283	9505	1380	5	798	199	897	199
20	7483	1106	8125	1195	4	598	199	698	199
19	6377	946	6930	1026	3	399	199	498	199
18	5432	801	5904	873	2	199	199	299	199
17	4630	673	5031	737	1	0		100	
16	3957	561	4294	617					

^a All quantities except *Level* have dimensions of m.

Fig. 2. Map of the Lower Fraser Valley and surrounding area. The shading corresponds to the height of the topography (m) according to the gray scale shown. The squares show the locations of the surface meteorological stations, the circles indicate acoustic sonde locations and the triangle shows the tethersonde location. The inset provides an expanded view of the Vancouver area. The top of the map is North. The Canada–U.S. border is shown as the thin line running just south of Abbotsford. The scales along the axes show the UTM coordinates in km.

the 10 km polar stereographic grid to the 5 km UTM grid. The model output has also been interpolated in the vertical from the MC2 layer heights onto the CALMET layers. For the CALMET layers below the first MC2 layer, surface similarity theory was used to estimate the profile structure.

The flow fields at given times for each of the days shown, as well as the days not shown, are remarkably similar. This is a clear evidence that the effect of large-scale forcing is very small, and local forcing dominates the evolution of the flow. At 1500 PST on all five days, there is a well-developed sea breeze with winds blowing up the valley. Evidence of the modulating effect of the slope flows on the sea breeze is visible in the slight southerly components of the wind vectors along the north side of the valley. The effect of the rugged mountains to the north of the valley can be clearly seen, generating upslope flows. The sea breeze is weakest during the middle of the ozone episode on the 19th (Fig. 3b), suggesting that at this time the air within the valley was at its most stagnant. On 21 July, the surface air flow appears to be uniformly strengthening and developing more of a westerly component (Fig. 3d), probably as a result of increased synoptic

scale forcing associated with the approaching of a short wave aloft.

The observed wind vectors are plotted on the maps with thick vectors at 11 sites. There appears to be a tendency for the model to underpredict the surface wind speeds during the sea breeze, but in general there is very good agreement between the observed and predicted surface wind vectors. Even by the fifth day, the model is reasonably accurate in simulating the overall daytime flow conditions, although there are larger errors than on previous days. This relatively slow growth of error in the predicted wind fields over a multi-day simulation for a limited area model is most likely due to the dominance of small scale, local forcing over synoptic scale forcing.

The predicted early morning land breeze for 0400 PST on 18 and 20 July (Figs 3a and c) is very weak throughout the valley, with wind speeds of typically $2\text{--}3\text{ m s}^{-1}$. The flow patterns for 0400 PST on the days not shown are very similar. Along with the development of weak land breezes, another characteristic feature of the nighttime flow is the strengthening of the northwesterly wind current over the strait. It appears to flow closely along the eastern shore of

Fig. 3. Predicted and observed surface wind vectors for (a) 0400 PST, 18 July; (b) 1500 PST, 19 July; (c) 0400 PST, 20 July; and (d) 1500 PST, 21 July. The observed winds are represented by the thick arrows.

Vancouver island. In the early morning hours of 19 July, the Sand Heads station reported winds of up to 8.9 ms^{-1} from out of the northwest, possibly verifying the existence of this current on one day.

In comparison with the observed winds within the Lower Fraser Valley, the model tends to overpredict the development of the land breeze at most stations. Hope Airport is the notable exception, where the model underpredicts the nighttime downslope flow.

The simulated wind current along the strait was not observed at Victoria Airport, and unfortunately the Nanaimo Airport station was inactive during nights. The topographical complexity of the area surrounding the Victoria airport site gives rise to very strong local effects that the model is not capable of simulating at 10 km resolution. It is possible that the real topography along the Vancouver Island coast subdues the development of this wind current.

4.2. Statistical evaluation of surface data

The following statistical parameters, based on recommendations by Willmott (1981, 1982) and Will-

mott *et al.* (1985), are used here to evaluate the meteorological predictions of surface temperature and winds:

(1) Observed and modelled means and standard deviations. For the wind vector data, vector differences and dot products are employed in the calculation of standard deviations.

(2) The slope, b , and the intercept, a , of the least-squares linear regression between the predicted and observed values,

$$P_i^* = a + bO_i$$

(3) Root-mean-squared error,

$$E = \langle (P_i - O_i)^2 \rangle^{1/2}$$

where P_i is the value of a predicted variable, and O_i is the observed value. These are vector quantities in the case of winds. The angle brackets denote the averaging operator. Willmott (1981) showed that the mean-square error, E^2 , can be broken down into the

following two components:

$$\begin{aligned} E^2 &= \langle (P_i^* - O_i)^2 \rangle + \langle (P_i - P_i^*)^2 \rangle \\ &= E_S^2 + E_U^2 \end{aligned}$$

where P_i^* is calculated from the least-squares linear regression shown previously. The two terms E_S^2 and E_U^2 are called the systematic and unsystematic components of the mean-square error respectively. The systematic component is made up entirely of errors due to additive and proportional systematic errors, as follows:

$$E_S^2 = a^2 + (b - 1)^2 \langle O_i^2 \rangle + 2a(b - 1) \langle O_i \rangle.$$

Note that when the least-squares linear regression has zero intercept and a slope of unity, the systematic mean-square error vanishes. The unsystematic mean-square error contains all other types of error due to any nonlinear relation between P and O . Willmott (1981, 1982) makes the argument that removing systematic errors from a model prediction should involve only minor modifications to the model parameterizations, while unsystematic error reduction could require major model revisions. The unsystematic error could be interpreted as the precision of the model, or alternatively, as the potential accuracy of the model after the removal of systematic errors.

(4) The index-of-agreement, d , which is calculated as

$$d = 1 - \frac{E^2}{\langle (|P_i'| + |O_i'|)^2 \rangle}$$

where the primed quantities are the departures from the mean observed value. These are vectors in the case of winds. A value of $d = 1$ indicates perfect agreement, and $d = 0$ indicates absolutely no agreement. This index specifies the degree to which the observed deviations about $\langle O_i \rangle$ correspond in magnitude and sign to the predicted deviations about $\langle O_i \rangle$.

Steyn and McKendry (1988) employed these measures to determine the accuracy of their surface temperature and wind forecasts of a sea breeze. They calculated their averages spatially and analysed the statistics as a function of time. In the current study, there are fewer observing stations to perform the same sort of average, so instead the averages here are calculated for each station over time. Therefore, we cannot directly compare the model performance statistics from that paper to the current work. We will confine our interpretations of the performance statistics to the identification of ways to improve future simulations.

4.2.1. *Temperature.* The time series of observed and predicted temperature are shown for the entire 116 h simulation for Vancouver Airport in Fig. 4a (see

Fig. 4. Predicted and observed time series of temperature in °C for (a) Vancouver Airport and (c) Abbotsford Airport. Scatter plot of predicted vs observed temperatures for (b) Vancouver Airport and (d) Abbotsford Airport. Observed values are indicated by the circles. The least-squares linear regressions are the thick lines. The dashed lines represent the perfect forecast lines.

Fig. 2 for the station location). Visual inspection of the temperature time series reveals that the model is capturing the overall five day trend, but is lacking in the prediction of maximum and minimum temperatures. This is due to the proximity of the station to the coastline. The short distance between the station and the water is not adequately resolved by the grid, and the modelled station temperature time series is thus strongly moderated by the sea-surface temperature.

The predicted temperature is plotted against the time-paired observed temperature for Vancouver Airport in Fig. 4b. The least-squares fit, P^* , is also plotted, as well as the perfect forecast line with a slope of unity and intercept of zero. It is very clear that the observed and predicted temperatures are strongly correlated, but that the model underpredicts the temperature swings at this site.

In contrast to the Vancouver Airport station, the model reproduces the temperature variation very accurately at Abbotsford Airport (Fig. 4c). The amplitude of the temperature variations in the model is only 2 or 3°C less than that observed. It is clear from the scatter plot of predicted vs observed temperature in Fig. 4d that the model forecast of temperature is excellent at this site.

Table 2 lists the evaluation statistics calculated for these two sites and all other stations that reported temperatures. The values show quantitatively what was noted in the above paragraphs. The mean temperature was predicted very accurately, but the predicted standard deviation was roughly half the observed value. The slope of the least-squares fit was substantially less than one, and the intercept was greater than zero. The systematic component of the RMS error made up most of the total RMS error. Therefore, the statistical parameters indicate that the model produces a good linear fit with the observed temperatures (by virtue of the low unsystematic error and large index of agreement), with accurate prediction of the mean and underestimation of temperature swings (demonstrated by the lower predicted standard deviation, the small slope and the large intercept). Thus, the evaluation parameters used here present quantitative details of the model performance in relatively compact form.

The performance statistics for Victoria Airport and Nanaimo Airport are much worse than those for Vancouver Airport. The least-squares slopes are very

much smaller than one, and the standard deviations are drastically underpredicted for these two sites. These are indications that the effects of the nearby water are again overestimated, but to a much larger degree than for Vancouver Airport.

The inland stations, Abbotsford Airport and Hope Airport, show much less influence of local effects. The slopes and intercepts of the least-squares fits show that the model is predicting the temperature swings very well; this is further confirmed by the close agreement of the standard deviations. In contrast to the previous three stations, these two sites are far enough away from the water that the model adequately resolves the distance, eliminating the excessive moderation of temperature swings by the sea-surface temperature. In both cases, the unsystematic component of the RMS error is small, showing that the scatter of points around the least-squares fit is small. The mean temperature at Hope Airport is underpredicted by about 3.4°C, which could be related to the relatively smooth topography used in the simulation compared to the real topography, leading to overly smooth horizontal temperature fields in the extremely mountainous regions.

4.2.2 Winds. At Vancouver Airport, the predicted time series of wind speed and direction (Figs 5a and b) are quite similar to the observed series, although there are intervals where the errors are large. Comparison of the observed and predicted average wind vector components U and V in Table 3 reveals that the model has a tendency to overpredict the wind speeds and to rotate the winds clockwise. The observed and modelled standard deviations of the wind vectors are in excellent agreement. The E_u component of the RMS error was quite large, revealing that there is a substantial scatter of points about the least-squares fit. However, the index of agreement is reasonably high at 0.576.

The time series of wind speed for Abbotsford (Fig. 5c) shows that in general the model underpredicted the intensity of the sea breeze and overpredicted the land breeze. The underprediction of the peak inland surface temperatures implies that the land-sea temperature difference is also underpredicted, since the surface air temperatures over water are relatively constant. It is possible that this diminished land-sea temperature difference during the day might account for the underpredicted sea breeze. The forecast wind

Table 2. Temperature time series statistics^a

Station	n	$\langle T_o \rangle$	$\langle T_p \rangle$	δ_o	δ_p	b	a	E	E_s	E_u	d
Vancouver Airport	116	21.36	21.41	3.68	1.88	0.43	12.17	2.31	2.08	1.00	0.82
Abbotsford Airport	116	22.36	23.10	6.46	4.95	0.75	6.32	2.03	1.77	1.00	0.97
Hope Airport	95	25.08	21.65	5.57	3.99	0.65	5.27	4.26	3.93	1.63	0.83
Victoria Airport	116	19.60	20.56	5.17	1.13	0.10	18.68	4.86	4.75	1.01	0.41
Nanaimo Airport	80	25.18	20.83	5.18	1.67	0.30	13.16	5.67	5.64	0.54	0.64

^a The o and p subscripts refer to observed and predicted values, respectively. The standard deviations are represented by δ . The angle brackets denote time averages. The terms n , b and d are dimensionless, while the remaining terms have units of degrees C.

Fig. 5. Predicted and observed time series of wind speeds in m s^{-1} for (a) Vancouver Airport and (c) Abbotsford Airport. Predicted and observed wind directions in degrees for (b) Vancouver Airport and (d) Abbotsford Airport. Observed values are plotted as circles.

Table 3. Wind time series statistics^a

Station	<i>n</i>	$\langle U_o \rangle$	$\langle V_o \rangle$	$\langle U_p \rangle$	$\langle V_p \rangle$	δ_o	δ_p	<i>E</i>	<i>E_s</i>	<i>E_U</i>	<i>d</i>
Vancouver Airport	116	0.86	0.33	1.57	-0.78	2.20	2.17	2.95	2.12	2.05	0.58
Abbotsford Airport	116	1.20	0.63	0.45	0.11	1.82	1.54	1.97	1.53	1.25	0.65
Hope Airport	116	1.46	-0.93	0.83	0.32	4.62	1.91	4.01	3.77	1.38	0.65
Victoria Airport	116	-1.07	0.53	0.70	-2.20	1.72	1.93	3.79	3.37	1.74	0.46
Nanaimo Airport	80	-0.70	-1.06	1.11	-2.17	2.01	1.23	2.97	2.75	1.12	0.49
Sandhead Island	116	0.33	-0.18	1.98	-1.57	3.07	1.84	4.27	3.86	1.82	0.32
Saturna Island	116	2.44	1.24	1.27	-1.77	2.95	1.52	4.48	4.24	1.47	0.50
Tsawassen	44	0.52	-1.70	1.11	-1.56	1.71	2.30	2.88	1.82	2.23	0.41
Vancouver Harbour	116	0.36	-0.42	2.02	-0.70	1.45	2.13	2.80	2.07	1.89	0.50
Jericho	116	1.40	-0.81	1.78	-0.81	2.50	2.30	2.82	1.90	2.08	0.62
UBC	116	0.47	0.30	1.05	0.39	1.35	2.13	1.88	0.68	1.75	0.70

^a The wind components are denoted by *U* and *V*. The *o* and *p* subscripts refer to observed and predicted values, respectively. The standard deviations are represented by δ . The angle brackets denote time averages. The terms *n*, and *d* are dimensionless, while the remaining terms have units of m s^{-1} .

directions were satisfactory (Fig. 5d), although at night when the station anemometer was reporting zero winds, the perceived error between the reported value of 0° and the modeled wind direction is deceptively large. In Table 3 it is seen that the model underpredicted the average wind vector components *U* and *V* and tended to rotate the wind vectors slightly clockwise. The predicted value of the standard deviation compares well with the observed value. The rms error and its components are all reasonably small, and the index of agreement of 0.65 shows that the forecast winds are acceptable.

The wind vector statistics (Table 3) show that the stations on Vancouver Island and in the Strait of Georgia are not handled that well. The possible exception is the Saturna Island station, which has an

index of agreement of 0.50. However, there is a rather large difference in average wind vector for this site as well. The poor performance of the model for these stations could be related to the predicted position and strength of the previously discussed wind current that blows along the eastern coast of Vancouver Island. It is likely that the rugged topography of the Island coast strongly influences the development of this flow and that the low spatial resolution of the model grid fails to represent this adequately.

The winds for the remaining stations located on the mainland are forecast fairly well, with indices of agreement generally higher than 0.5. The predicted average wind direction at Hope Airport shows quite a large counterclockwise rotation from the observed. This is due to the local effect of the complex topography

surrounding Hope, which is located in a valley with mountains to the north and south, separated by approximately 2 km. This large local effect is also reflected in the systematic component of the RMS error of 3.77 m s^{-1} . At the UBC site, the forecast winds were quite accurate, showing an index of agreement of 0.7.

4.3. Mixed layer depths

The mixed layer depths, z_i , were measured by Prof. Douw Steyn of the University of British Columbia at the three locations in the Lower Fraser Valley during the first four days of the episode. The mixed layer depths at the Delta and Surrey locations were measured using acoustic sondes, while those at Queen Elizabeth Park were determined from tethersonde profiles. Figure 2 shows the locations of the acoustic sondes and tethersonde.

The observed and modelled mixed layer depths for the three sites is shown in Figs 6a–c. The model results for Surrey are in excellent agreement with the measured data (Fig. 6c). At the other two sites, which are closer to the shoreline, the agreement is reasonably good. The model appears to have captured the

day to day trends in mixed layer heights at all of the stations. It is noteworthy that on 19 July at Queen Elizabeth Park and on 20 July at Delta, the model did have a tendency to overestimate the depth of the mixed layer, which could have a significant impact on the accuracy of the air quality prediction in these areas.

4.4. Tethersonde wind profiles

A tethersonde was flown at various times on 17 and 19 July from Queen Elizabeth Park. In Figs 7a–d, the measured wind speed and wind direction profiles are shown for the three soundings bracketing 1300 PST on both days. The interpolated CALMET model profiles at Queen Elizabeth Park for 1300 PST on 17 and 19 July are also plotted. There is a large amount of variability in the measured soundings over quite short periods of time. On both days, the measured soundings display westerly winds of up to 5 or 6 m s^{-1} in the lowest 400 m. The wind speeds decay with height until about 700 or 800 m, where a weak westerly jet of about 4 m s^{-1} is observed in some of the soundings. The model tended to predict lower-level winds with speeds in excess of the observed westerlies, and did not show any evidence of the upper-level jet. The model does not display anywhere near the variability that the measured data does. This is not unexpected given the rather coarse resolution of the MC2 simulation. In general, given the large amount of scatter in the measured soundings, the model appears to have produced reasonably accurate profiles of the winds in the lowest kilometre.

5. CONCLUSIONS

The results of the detailed quantitative error analysis on the surface temperature and wind forecast show that the MC2-CALMET meteorological modelling system predicts the meteorological situation with reasonably good precision for the five day simulation presented. The analysis of the statistics for each individual measuring station proved useful for singling out problem areas such as stations near shorelines or locations with significant local effects, where the grid resolution is inadequate for accurate simulation. The model predictions of mixed layer depths and wind profiles also compared reasonably well against the available measurements.

This study demonstrates that the current configuration of MC2-CALMET generates meteorological fields which are adequate for the purpose of driving the CALGRID photochemical simulations. Although improvements in the meteorological forecast would almost certainly be realized by running MC2 with higher horizontal and vertical resolution, the benefits achieved may not be as significant as the increased costs of the additional CPU time and disk storage space, particularly in light of the fact that only hourly meteorological data are employed by CALGRID.

Fig. 6. Mixed layer depths (m) measured at (a) Queen Elizabeth Park, (b) Delta and (c) Surrey for 17–20 July. Measured values are indicated by the open circles, CALMET model results are shown with the line. The time axis shows the number of hours starting from 0000 PST, 17 July.

Fig. 7. Tethersonde profiles of wind speed (m s^{-1}) and direction (degrees) at Queen Elizabeth Park taken on 17 and 19 July. The CALMET model profile is indicated by the inverted triangles.

However, further sensitivity experiments will be carried out to determine just how large the benefits are for modest improvements in spatial resolution.

Finally, the next major step in the validation of the MC2-CALMET modelling system will be to apply it to the Pacific 93 field study data set (Steyn *et al.*, 1996), which contains a rich array of meteorological and photochemical measurements in three dimensions for a mild ozone episode in the summer of 1993. This will allow us to evaluate the model performance in predicting horizontal and vertical pollutant distributions during a substantially different meteorological situation.

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