Lake Brunner study: modelling thermal stratification

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Executive Summary

This report describes the application of a computer model to predict daily vertical temperature profiles in Lake Brunner over one year from 19 February 2007 through 18 February 2008. The main goal of the application was to determine whether such computer model predictions could be carried out successfully enough to provide the basis for water quality simulations.

The computer model utilizes information on lake bathymetry, daily meteorological data and daily inflow and outflow data. It accounts for all major physical processes that cause thermal stratification and vertical mixing within a lake or reservoir. The basic output from the model is a series of daily temperature profiles.

The simulations used meteorological data collected from Pigeon Creek climate station, installed for the purposes of this study by NIWA approximately 3 km south of the lake off the Kumara-Inchbonnie Road. Total inflows were estimated from a water balance for the lake, and then partitioned among the three major inflowing rivers (Hohonu, Crooked and Orangipuku rivers) and a fourth residual component, based on information from flow gaugings made during site visits to collect water quality samples. Inflow temperatures were measured in the three major inflowing rivers using Onset self-contained temperature loggers. Model predictions have been compared against four temperature profiles measured in the lake by NIWA for the West Coast Regional Council (WCRC) as part of WCRC's routine monitoring of the lake.

The main difficulties encountered in the model application include:

- uncertainties associated with the inflow data, in particular the partitioning of total inflow from the water balance among the major inflowing rivers;
- uncertainty regarding the applicability of winds measured at the Pigeon Creek climate station to conditions over the lake itself;
- uncertainty regarding the current values for the light attenuation coefficient in the lake;
- the small number of measured temperature profiles with which to assess the simulations.

The model does a reasonable job in capturing the overall patterns of stratification and mixing and maximum and minimum temperatures, although there are discrepancies between some of the measured and predicted profiles. The discrepancies may be due to a combination of problems with the input data and limitations of the model itself.

The quality of the simulations is adequate for the model to be used as a base for coupled hydrodynamic – water quality modeling, although an effort should be made to resolve the issues cited

above before doing so. If it is decided to go ahead with water quality modeling, the limiting factor will be the availability of input data to run and validate the model.

1. Introduction

This report describes the application of a computer model to predict daily vertical temperature profiles in Lake Brunner over a seasonal cycle. The cycle includes warming in late summer with accompanying temperature stratification; cooling in autumn leading to overturn with mixing over the entire depth in winter, and warming with accompanying restratification through spring and summer. The main goal of the application was to determine whether such computer model predictions could be carried out successfully enough to provide the basis for water quality simulations that could be used to examine effects of changes in nutrient loading to the lake.

This report complements a study by Rutherford (2008) on nutrient loads to the lake. Both reports have been funded by Envirolink grants from the Ministry for the Environment with the goal of developing modeling tools that could be used to assist the WCRC in making management decisions relating to Lake Brunner and land use in its catchment. Rutherford (2008) and Kelly and Howard-Williams (2003) provide some discussion on increases in nutrient loading and deterioration in lake water quality that has taken place over the past 10-20 years.

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The simulations for the lake's thermal regime reported here used input data from the following three main sources:

1. Meteorological data were measured at Pigeon Creek climate station, installed for the purposes of this study by NIWA approximately 3 km south of the lake off the Kumara-Inchbonnie Road. Climate data recording began on 8 February 2007. Gaps were minor and missing data were filled in using correlations established between Hokitika AWS and the Pigeon Creek station.

2. Inflow river temperatures were measured by Onset self-contained Hobo-Pro temperature data loggers in the three major inflowing rivers (Hohonu, Crooked and Orangipuku rivers). River temperature data recording began on 6 December 2006. Gaps were minor and these were filled in using multiple regressions established for river temperatures as a function of climate variables and estimated river discharge.

3. Daily inflow volumes were calculated from a water balance on the lake that used water level and outflow discharge data measured at the lake outlet (TIDEDA site number 91405, Arnold River at Lake Brunner, start of record 24 December 1968). The water balance was calculated for the period 1 August 1998 – 19 April 2008. The total daily inflows from the water balance were partitioned among the three major inflowing rivers (Hohonu, Crooked and

Orangipuku rivers) and a fourth residual component, based on information from 19 flow gaugings made during site visits to collect water quality samples over the period 10 January 2003 – 14 August 2007. The partitioning also made a correction for estimated long-term average net rainfall – evaporation over the lake (for which no measurements are available).

Locations of the weather station and inflows are shown in Fig. 1, and photographs of the weather station in Fig. 4.

Predictions have been compared against four temperature profiles measured in the lake at the main-basin lake site (referred to as site GYBS in monitoring records) by NIWA for the West Coast Regional Council (WCRC) as part of WCRC's routine monitoring of the lake, on 22 May 2007, 14 August 2007, 15 November 2007 and 18 February 2008.

The model simulation was initialised using a temperature profile measured on 19 February 2007. The simulation ran for 365 days, ending on 18 February 2008, the date when inflow river temperatures were last downloaded (at the time of writing) from their loggers, and coinciding with measurement of a temperature profile in the lake. The length of the simulation was constrained by (overlapping) availability of data from all of the above sources, including the measured in-lake temperature profiles.

Data available to run the model and to compare with model predictions only span a single complete season. There are not enough data for separate "calibration" and "verification" runs over separate seasons. This is not a serious problem, however, since the model is essentially a physics-based one and there is limited flexibility for varying model parameters to achieve a fit to observations.

The main difficulties encountered in the model application involved uncertainties in the input data required to run the model and data to validate the predictions. These include:

- lack of directly measured time series for major river inflows. This leads to uncertainties associated with the inflow data, in particular the partitioning of total inflow from the water balance among the major inflowing rivers;
- the small number of measured temperature profiles with which to assess the simulations;
- uncertainty regarding the applicability of winds measured at the Pigeon Creek climate station to conditions over the lake itself;

- uncertainty regarding the current values for the light attenuation coefficient in the lake.

The following sections contain descriptions of the model, the study site, the input data used for the simulation, and the results (including comparisons with observations). The potential for extending the modeling to include water quality is considered in the Conclusions section.

This report focuses on the thermal regime of the lake and does not address questions related to oxygen, nutrient or phytoplankton dynamics.

2. Model description

In this study we used the University of Western Australia – Centre for Water Research's computer model DYRESM (Dynamic Reservoir Simulation Model) that predicts temperature profiles in lakes and reservoirs. The model has been widely applied in Australia, New Zealand and overseas, and has been documented in the scientific literature by Imberger (1979) and Imberger and Patterson (1979, 1990), who give overviews and further references. Further documentation can also be found at http://www.cwr.uwa.edu.au/ with links to "services" and "models". The model utilizes information on lake bathymetry (areas within depth contours; volumes below depth contours; outlet elevation(s)); daily meteorological data (incoming solar radiation, cloud cover, wind speed, air temperature, humidity, rainfall); and daily inflow and outflow data. It accounts for all major physical processes that cause thermal stratification and vertical mixing within a lake or reservoir.

The model is referred to as "one-dimensional" because it only simulates vertical variations in water properties. The basic output from the model is a series of daily temperature profiles (and profiles of salinity and density if required). The profiles are meant to be representative of conditions averaged over the horizontal extent of the lake. Hence the model is applicable to lakes in which vertical variations are generally much more pronounced than horizontal variations. These tend to be deeper lakes of relatively small horizontal extent, although it has been used successfully on large, deep lakes, such as Lake Taupo (Spigel et al. 2001, 2003). Lake Brunner should be well suited for model application, given its depth and relatively limited horizontal extent. The suitability could be confirmed if it were possible to measure transects of temperature across the lake, and the isotherms were found to be nearly horizontal for most of the time when the lake was thermally stratified.

DYRESM has a rather unique system for dividing the water column into layers so that it can model temperature stratification that distinguishes it from most other one-dimensional lake models. The layers are not tied to a fixed numerical depth grid, but are free to move up and down in the water column and to adjust their thicknesses in response to mixing, inflow and outflow processes. This so-called “Lagrangian” layering system, in which the layers can move vertically in response to vertical water movements, provides distinct numerical advantages over fixed-grid systems in terms of computational stability and eliminating effects of artificial numerical diffusion. It also allows for increased resolution to be provided in areas where thermal gradients are steep (e.g., the thermocline), with decreased resolution where gradients are small (e.g., the epilimnion and hypolimnion). This improves computational efficiency.

An initial temperature profile must be specified by the user at the start of a model run; in this study the temperatures for 19 February 2007 measured by the NIWA at the main lake station, site GYBS (Figures 1, 2). This date is the closest to the beginning of the meteorological dataset (8 February 2007) for measured in-lake temperature profiles. The model steps through the input meteorological and inflow data one day at a time. At the start of each day the model divides the water column into layers at a resolution set by the user (20 cm was used for Lake Brunner). This resolution needs to be fine enough to accurately model solar radiation attenuation within the water column, turbulent mixing in the epilimnion, evolution of the thermocline, and the intrusion of inflowing waters from rivers or groundwater at their levels of neutral buoyancy in the lake. For reservoirs, the layer thicknesses must also be able to resolve processes associated with managed outflows drawn from several depths.

The model simulates inflow and outflow on a daily basis, but has a sub-daily loop with a time step set by the user to simulate heat, mass and momentum exchange between the lake and the atmosphere and the consequent heating and mixing processes that occur in the lake. One hour is typical for the sub-daily time step, and this was used for Lake Brunner. The model can use meteorological data supplied at time intervals less than a day, but this was not done for this exploratory study.

In some lakes, salinity variations (as concentration of total dissolved solids) make an important contribution to density variations. In most New Zealand lakes, salinity variations are small and their contribution to density variations is negligible in comparison with effects of temperature, and salinity can be neglected. We have assumed this to be the case for Lake Brunner, based on specific conductance data collected during lake monitoring surveys. These measurements show that while variations in conductivity are large enough to be detected and are consistent with other measurements of lake water chemistry, they are small enough to have little impact on density compared to temperature.

3. Study site

Lake Brunner (Figure 1; latitude 42.62°S, longitude 171.45°, elevation 86 m ASL) is the largest lake on the West Coast. It has a surface area of 41.08 km^2, volume 2.261 km^3 and mean depth 55.0 m. The maximum depth on Irwin's (1981) lake chart (reproduced in Figure 2) is 109.3 m. The mean hydraulic residence time, based on an average discharge at the lake's outlet from 1 Jan 2000 to 14 Apr 2008 of 60.58 m^3 s^{-1}, is 1.18 years. It is a natural lake and glacial in origin, enclosed by moraine and outwash deposits, and excavated rock (Pearl et al. 1979), although it is now controlled at its outlet. Lake level varies; the maximum difference in water surface elevation observed since records began is 3.65 m, while the variation over the period of the model simulation was 2.18 m (Table 1).

4. Input data for the model

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4.1. Bathymetry

Bathymetric data used in this study are based on echo soundings made in 1976 and documented in the lake chart of Irwin (1981), reproduced in Figure 2.

The lake has steep sides around much of its perimeter, down to about 40 m, at which depth slopes become gentler in the west and south. Steep slopes continue to 60 m in the north and to 100 m in the east; the central part of the lake basin is relatively flat. Iveagh Bay occupies a relatively separate basin in the east, and Cashmere Bay a further smaller and more isolated basin opening off Iveagh Bay to the northeast. Water quality in Cashmere Bay can differ from that in Iveagh Bay and in the main basin, but simulations with a one-dimensional stratification model are representative of the main basin and cannot capture such differences.

DYRESM requires data for areas within depth contours and lake volumes below depth contours. Depth-area-volume data, based on digitizing contours in Irwin's (1981) chart, are given in Table 2 and plotted in Figure 3. Variations in lake level and depth have been discussed above and summarized in Table 1.

4.2. Meteorological data

Meteorological data are used in the model to compute exchange of heat, water vapour and momentum between the lake and the atmosphere. In lakes with very long residence times (several years) these exchanges dominate the thermal regime of the lake and control patterns of mixing and stratification. In such lakes inflows and

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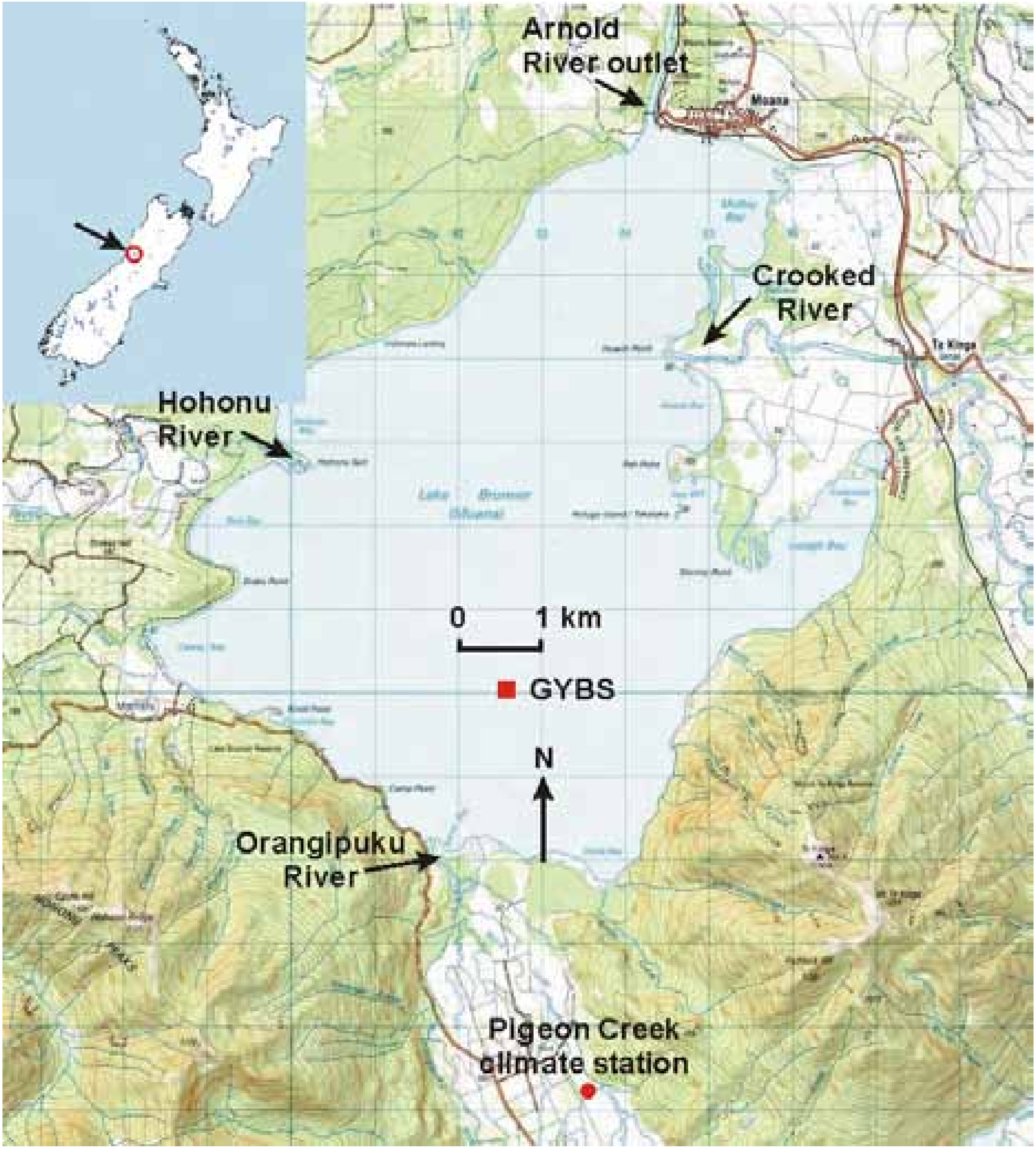

Figure 1: Map showing locations of Lake Brunner (see inset, upper left corner), Pigeon Creek weather station (red circle at bottom of map), the inlets of the three major inflowing rivers, the lake outlet to the Arnold River, and the monitoring site in the main basin (red square, GYBS).

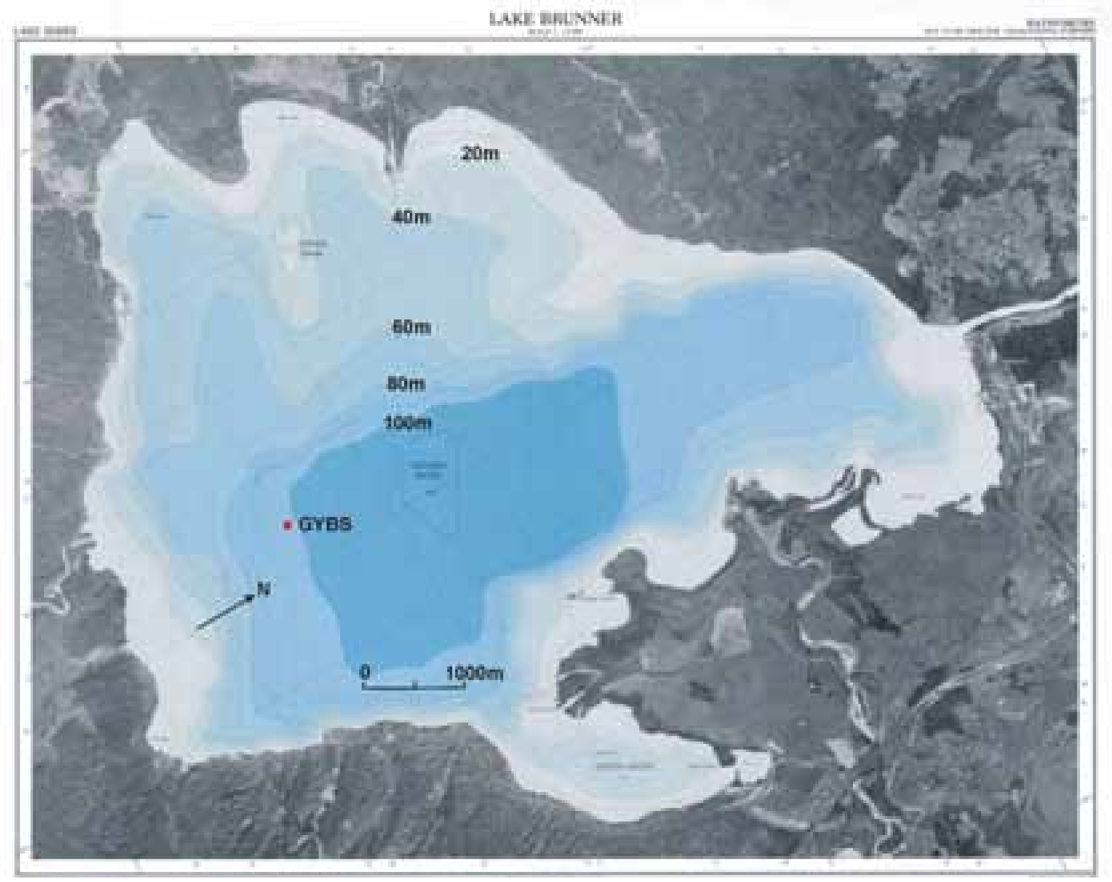

Figure 2: Bathymetric map of Irwin (1981), based on echo sounding surveys 29 February - 2 March 1976. Note the rotation of the map so that north is to the right and upward. Maximum depth shown on the map is 109.3 m. GYBS is the monitoring site in the main basin.

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Table 1: Range of lake levels for entire period of record (24 December 1968 to present) and for period of the model simulation (19 February 2007 – 18 February 2008).

	24 December 1968 – 22 April 2008			19 February 2007 – 18 February 2008		
	Stage (mm) (1)	**Elevation (m ASL) (2)**	**Lake depth at deepest point* (m) (3)**	**Stage (mm) (1)**	**Elevation (m ASL) (2)**	**Lake depth at deepest point* (m) (3)**
Maximum	4541	88.483	112.408	3698	87.640	111.565
Minimum	890	84.832	108.757	1522	85.464	109.389
Mean	2085.3	86.027	109.952	2122.9	86.065	109.990
Max - Min	3651	3.651	3.651	2176	2.176	2.176

Notes:

(1) From TIDEDA site 91405, Arnold River at Lake Brunner

(2) Datum for site 91405 stage, RL = 83.942 m ASL

(3) Depths based on maximum depth of 109.3 m from Irwin (1981), as measured during his bathymetric survey of 29 February – 2 March 1976. Elevation of lake bed at deepest point at time of bathymetric survey = -23.925 m ASL (i.e., 23.925 m below sea level)

Table 2: Depth-area-volume data used for model simulations. Areas are from digitizing the contours on the bathymetric map of Irwin (1981), reproduced in Figure 2. Volumes were computed using the formula for volume V between two parallel areas A_1 and A_2 a distance h apart, $V = h/3\ [A_1 + (A_1A_2)^{0.5} + A_2]$. Values for area and cumulative volume are plotted in Figure 3.

Depth (m)	Elevation (m)	Area within contour (km^2)	Volume between contours (km^3)	Cumulative volume (km^3)
0	109.3	41.077	0.37802	2.26507
10	99.3	34.618	0.33237	1.88255
20	89.3	31.874	0.30294	1.55019
30	79.3	28.741	0.27130	1.24724
40	69.3	25.550	0.23645	0.97595
50	59.3	21.791	0.19968	0.73949
60	49.3	18.200	0.16521	0.53981
70	39.3	14.897	0.13889	0.37460
80	29.3	12.905	0.11614	0.23571
90	19.3	10.369	0.04713	0.11957
95	14.3	8.513	0.03726	0.07244
100	9.3	6.439	0.02673	0.03518
105	4.3	4.324	0.00839	0.00844
109	0.3	0.500	5.0E-05	5.0E-05
109.3	0	0	0	0

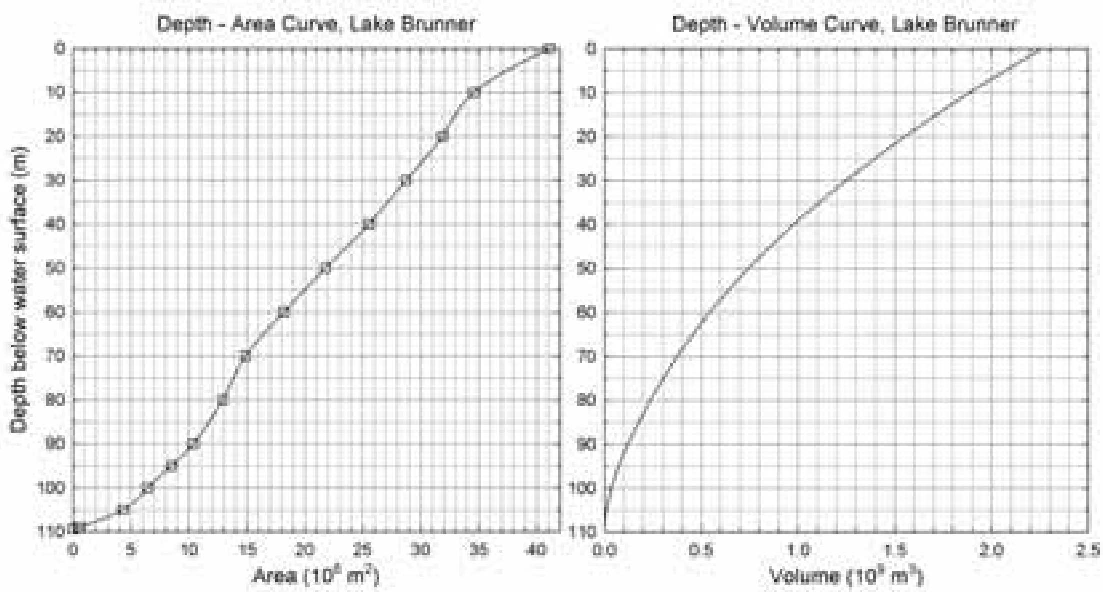

Figure 3: Depth-area-volume curves for Lake Brunner, from data shown in Table 2. Areas are from digitizing the contours on the bathymetric map of Irwin (1981), shown in Figure 2.

outflows generally play a minor role in determining temperature structure in the lake. In contrast, in lakes with very short residence times (weeks), inflows and outflows dominate the thermal regime and control mixing and stratification, with climate factors playing a secondary role. With a residence time of approximately 1.2 years, Lake Brunner falls in neither of these categories. Although it is a deep lake of reasonable size, inflows and outflows are also reasonably large. Hence, one can expect that both climate factors and inflows will play important roles in controlling the lake's thermal regime.

The nearest permanent climate station with continuous records of all required meteorological parameters is at Hokitika, approximately 38 km southwest of Lake Brunner. To obtain meteorological data more representative of conditions over the lake, a weather station (Pigeon Creek climate station) was installed approximately 3 km south of the lake off the Kumara-Inchbonnie Road (Figures 1 and 4). The station has sensors to measure incoming solar radiation, wind speed and direction, air temperature and humidity, barometric pressure and rain. Data for all variables have been measured since 8 February 2007, although rainfall is available starting 23 February. The sampling interval is 10 minutes.

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Figure 4: Pigeon Creek climate station, approximately 3 km south of Lake Brunner off the Kumara – Inchbonnie Road. Photos by John Porteous, NIWA, Greymouth.

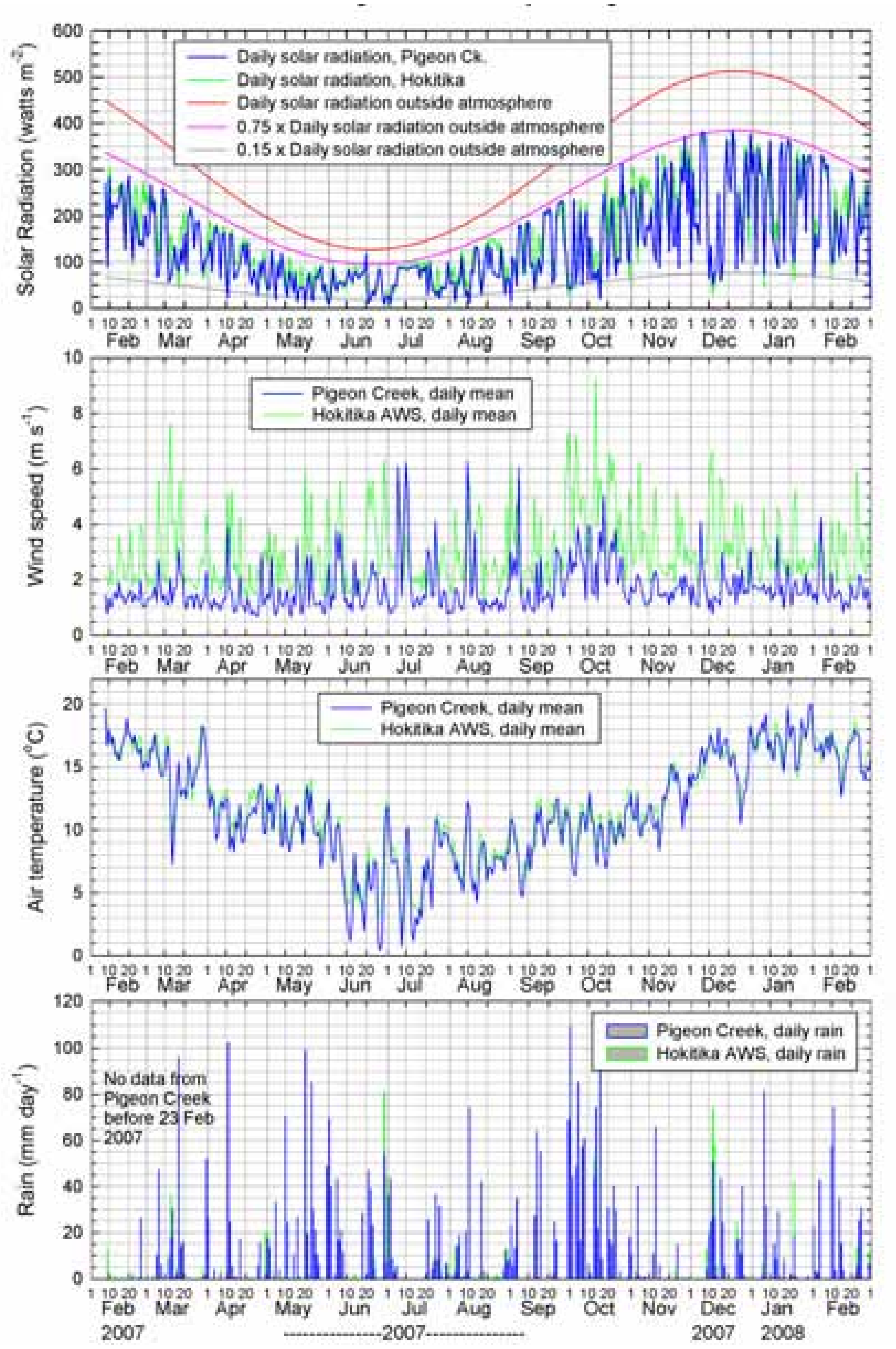

Figure 5: Meteorological data from Pigeon Creek climate station (blue lines) used for modeling; all are daily means, except rain, which are daily totals. Data from Hokitika AWS are plotted (behind the Pigeon Creek data) for comparison.

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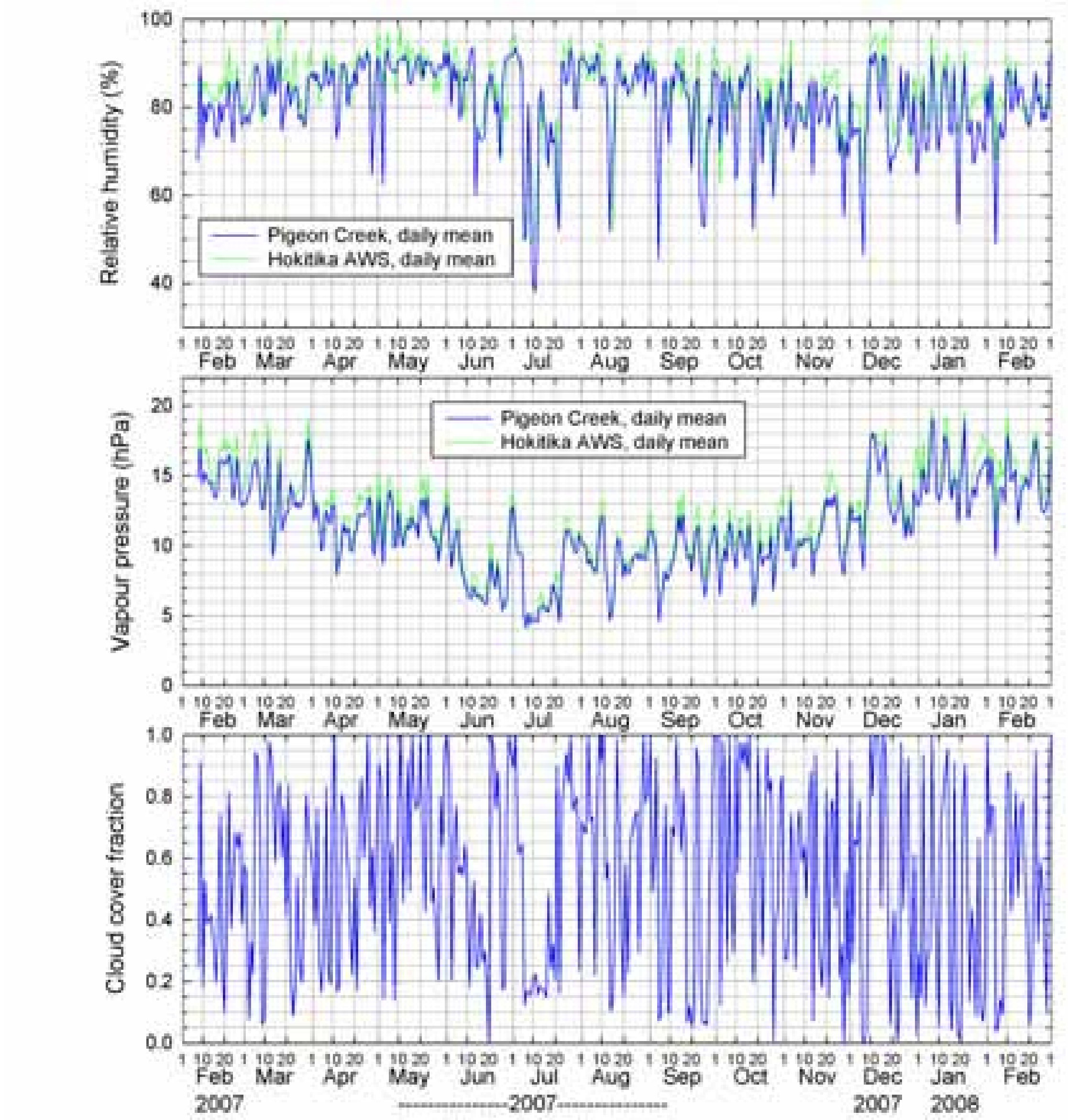

Figure 5 continued.

There are some gaps in the data, but these are relatively minor and have been filled in either by linear interpolation (for gaps less than 6 hours) or from correlations established with data from Hokitika AWS (Automatic Weather Station). The scatter plots and regression equations for all correlations are shown Appendix A.

The daily meteorological data with gaps filled in are shown in Figure 5; these are the values used for model simulations. Data from Hokitika AWS are also plotted behind the Pigeon Creek data for comparison.

A few comments regarding the data can be made at this point; further references will be made later in the discussion of model results.

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In addition to solar radiation measured at the weather station, solar radiation outside the atmosphere was computed (red curve in solar radition graph) from formulas found in meteorology texts, e.g., Monteith (1973), partly as a check on the measured data, and partly to assist with estimation of cloud cover. The pink and gray curves in the solar radiation graph provide approximate upper and lower envelopes for the measured data, and were used to estimate mean daily values of cloud cover. Cloud cover is used in the model to calculate longwave (infrared) radiation from the atmosphere (TVA 1972). Measured values of incoming longwave radiation can be specified as part of the model input, but this is not a routine meteorological measurement and sensors are temperamental, so provision is made in the model for calculating it from cloud cover and air temperature. Cloud cover was estimated by assuming no cloud cover if measured solar radiation was greater than or equal to 0.75 q_0 , where q_0 is the solar radiation received outside the atmosphere, and complete cloud cover for solar radiation less than or equal to 0.20 q_0; cloud cover was calculated by linear interpolation for measured solar radiation between these values.

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Vapour pressure in the air (computed from relative humidity and air temperature) is used in the model to compute evaporation from the lake surface and the heat loss that accompanies evaporation, called *latent heat flux*. For every gram of water evaporated, approximately 2500 joules of heat, the latent heat of vaporization, is lost from the water surface. Air temperature is also used in the calculation of *sensible heat flux*, which is heat lost (or gained) because of any difference in temperature between the water surface and the air above it. Both sensible and latent heat fluxes rely on wind and turbulence in the air to carry heat and water vapour away from the lake surface. The calculations for sensible and latent heat fluxes assume that the fluxes are directly proportional to wind speed.

In addition to assisting in transport of heat and water vapour between the lake and the atmosphere, the wind also imparts momentum to the water surface, thereby generating waves, currents and turbulence. Wind thus plays a crucial role in mixing heat downward in the water column. Although DYRESM, being a one-dimensional model, does not model wind-generated lake currents, it does use the energy imparted by the wind to the water surface in its calculations for turbulent mixing.

Wind speed is therefore an important variable in this simulation, where we expect that both climate factors and inflows will play important roles in controlling the lake's thermal regime. Wind enters several calculations – for sensible and latent heat transfer, momentum transfer and turbulent mixing. The graph for wind speed (second panel, Figure 5, shows that wind speeds measured by the Pigeon Creek climate station are usually quite a bit lower than those measured at Hokitika AWS. The correlation between these two sites shows that on average Pigeon Creek wind speed is roughly half that of Hokitika wind speed (Appendix, Table A-1, and Fig. A-2, last two panels). Hokitika wind is measured at a height of 10 m above the ground, while at Pigeon Creek it is measured at 2.5 m above the ground. Wind speed can be expected to increase with height, but this would make a difference on the order of 5%, not 50%. The large difference between the two sites may be real, but it does raise the question of how representative the wind measurements are of conditions on the lake.

4.3. Inflows and outflows

DYRESM requires data for daily volumes and temperatures (and salinities if they are significant) of all major inflowing rivers. It also requires data for daily outflow volumes. If outflows are not specified, the model incorporates them into any overflows that are calculated as part of the daily water balance. The net heat flux supplied to the lake by rivers, due to differences in temperature between river inflows, outflows and the lake, is referred to as an *advective heat flux*. The term implies that the heat is transported or "advected" by the flow of water. In Lake Brunner, with its large inflows, these could exert a significant influence on the lake's heat balance and temperature structure.

Temperatures have been recorded in the three major inflowing rivers– Crooked River, Orangipuku River and Hohonu River – since 6 December 2006 using self-contained Hobo-Pro temperature loggers at a sampling interval of 15 minutes. Hourly and daily averages from the loggers are plotted in Figure 6. There is practically no seasonal variation in the Orangipuku River temperature, possibly reflecting groundwater influence (J. Horrox, C. Chague-Goff, pers. comm.). Seasonal variation is evident in the records for both the Hohonu River and the Crooked River. The amplitude of variation is greater for the Hohunu River, which has a much lower discharge than the Crooked River.

A gap of 17 days occurred between 30 June – 16 July 2007 when loggers could not be downloaded and reset. For purposes of the model run, the gap was filled by establishing correlations between daily average values of river temperatures versus air temperature, solar radiation, vapour pressure, wind speed and (estimated) discharge. A summary of the regression parameters is given in the Appendix, Table A-2. The filled-in record of daily average temperatures, as used for the model simulation, is shown in Figure 7, top panel.

Outflows are available from TIDEDA site 91405, Arnold River at Lake Brunner, but none of the inflowing rivers have flow recording installations. To estimate inflows for the purposes of the model application, daily mean water levels and outflows were used to solve a lake water balance over the period 1 August 1998 – 19 April 2008 for total inflows as a function of outflows and changes in lake level. The daily water balance calculation did not account for daily rainfall on the lake, daily evaporation from the lake or any groundwater inflows or outflows, as there were no measurements available for any of these variables.

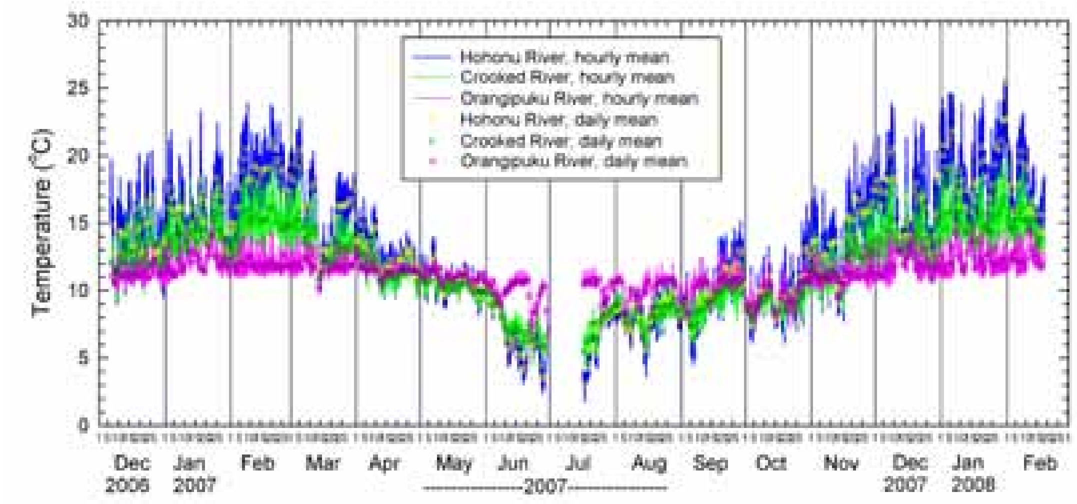

Figure 6: Hourly and daily average temperatures in the Hohonu, Crooked and Orangipuku Rivers, 6 Dec 2006 – 18 Feb 2008. There is a gap of 17 days between 30 June – 16 July 2007 when loggers could not be downloaded and reset.

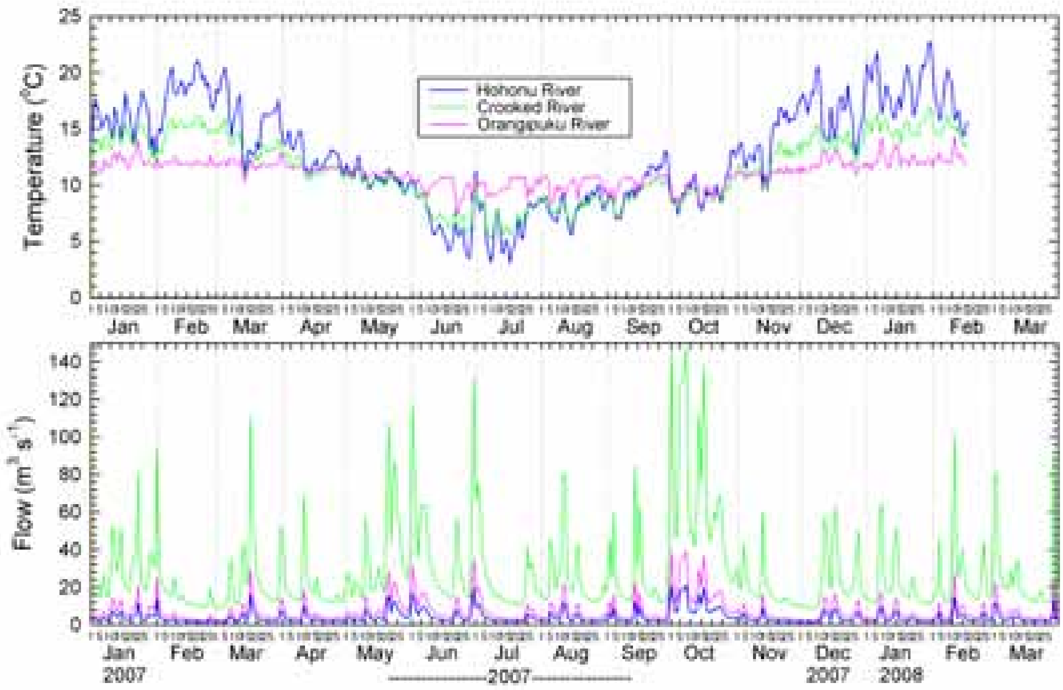

Figure 7: Daily mean river temperatures (top panel) and estimated inflow discharges (bottom panel). Missing temperatures (Fig. 6) have been filled in by multiple regression against meteorological variables and estimated flows.

Spot discharge measurements in the three major inflowing rivers were available from 19 flow gaugings made during site visits to collect water quality samples over the period 10 January 2003 – 14 August 2007. These were used, together with an estimate for average annual rainfall on the lake of 3500 mm minus evaporation of 700 mm, to arrive at the following average contributions for inflows as a percentage of total inflow computed by the water balance: Crooked River, 49%; Orangipuke River, 13%; Hohonu River, 7 %; smaller streams and distributed runoff, 24%; rain minus evaporation, 7%. These percentages were applied uniformly to the full record of the water balance to produce time series of daily inflow volumes for the three major inflows. This is clearly an oversimplification, but is the best that could be done with data available. The resulting estimated inflows are plotted in Fig. 6, bottom panel. Some improvement may now be possible for 2007 onwards given the recent availability of rainfall data from the Pigeon Creek climate station.

4.4. Light attenuation coefficient

The model requires a user-specified value for the attenuation coefficient, K_d, for downwelling irradiance in the water column. Irradiance is the downward component of solar energy flux per unit horizontal area, with units usually given as watts m^{-2}. K_d is used in the model to determine how the incoming solar radiation incident at the lake surface is distributed with depth in the lake. The dimensions of K_d are the inverse of length (1/length), with units usually of 1/metres (m^{-1}). Typical values of K_d range from less than 0.1 m^{-1} in very clear oligotrophic lakes, to greater than 3 m^{-1} in turbid, deeply coloured lakes (see, e.g., Davies-Colley et al 1993).

K_d plays an important role in determining the depth of thermoclines and the strength of temperature stratification in lakes. Lakes with higher values of K_d trap solar radiation at shallower depths, leading to warmer surface layers and cooler water at depth. In clear lakes, with smaller values of K_d, solar radiation penetrates to deeper depths, thereby spreading the solar heat over greater volumes of water, leading to deeper thermoclines.

Isolated measurements of K_d in Lake Brunner, generally made as part of larger surveys relating optical properties in lakes to other factors, have been reported by Howard-Williams and Vincent (1985), 0.81 m^{-1}; Schwarz et al. (2000), 0.57 m^{-1}; and Rae et al. (2001) 0.74 m^{-1}. The average of these values is 0.71 m^{-1}, implying a depth of 6.5 m at which 1% of the incoming light remains. Presumably these relatively high values of K_d are due mainly to the brown colour imparted to the water by dissolved organic compounds, as is common in many west coast lakes. Suspended solids concentrations, measured as part of quarterly or bimonthly lake monitoring, are low. The colour of

Lake Brunner was described as "pale brown" by Vincent and Howard-Williams (1981), compared with "blue" for Lake Coleridge, "green" for lakes Rotora and Rotoiti (S.Island), and "dark brown" for lakes Lady, Hochstetter and Haupiri. They reported values of K_d over five depth intervals as 1.52 m^{-1} from 0-1 m, 0.41 m^{-1} from 1-2 m, 0.87 m^{-1} from 2-3 m, and 0.68 m^{-1} from 3-5 m.

Secchi disk depths (Z_{SD}) are often used to estimate K_d via an empirical correlation such as that of Poole and Atkins (1929), cited by Davies-Colley et al. (1993, p. 77), as:

$$Z_{SD} = 1.7 / K_d . \quad (1)$$

Secchi disk depth have been measured in Lake Brunner as part of the WCRC's monitoring programme. M. Scarsbrook (2008), in an unpublished report examining trends in water quality parameters in Lake Brunner, showed that although Secchi disk depths exhibit a wide range of variation (he documented a range of 2.3 to 9.0 m from 1992 to 2008), there has been a declining trend, particularly since measurements of Secchi depth were resumed in 2001. Measurements for 2007 cluster around a value of 4 m. From the above equation, this implies a K_d of 0.42 m^{-1}.

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It was found necessary to use a much lower value of K_d in the model simulations than any of the values given above, in order to obtain results that matched measured temperature profiles. Using values of K_d in the range of those reported in the literature yielded results with much shallower thermoclines and warmer surface waters than are observed. The simulation results shown in this report are for a K_d value of 0.1 m^{-1}. This is unrealistically low for a lake with the relatively dark coloration of Lake Brunner. As noted above, it is a value associated with clear lakes such as Lake Taupo. In spring and summer, the only thing that can offset the shallowness of a thermocline produced by a high attenuation coefficient (which causes solar energy to be trapped at shallow depths) is turbulent mixing induced by wind. It may be that the winds used in the model, as measured by the Pigeon Creek climate station, are much weaker than those that occur on the lake itself, as mentioned above in Section 4.2.

4.5. Other model parameters

There are three further coefficients that enter the calculations in DYRESM for turbulent mixing in the epilimnion. These arise in parameterizations of terms in the turbulent kinetic energy budget and suggested values are based on experiments described in the scientific literature on turbulence, completely independent of DYRESM, as described by Imberger (1979), Imberger and Patterson (1981, 1990) and more recently by Yeates and Imberger (2003) (also see on-line documentation for

DYRESM as described earlier). There is some scope for varying the above parameters to achieve better agreement between simulated and measured temperatures, but is it is limited. Recently-added benthic boundary layer mixing and hypolimnion mixing routines (Yeates and Imberger 2003) were not invoked in these simulations.

5. Results and comparison with measured temperatures

Results of the simulations are summarized in Figure 8 as predicted temperature contours in the time-depth plane. These correspond to lake-wide average temperatures, or temperatures that would be observed at a mid-lake site. Additional aspects are illustrated in Figure 9, which shows time series for heat fluxes to and from the lake and heat content of the lake (top panel), and temperatures predicted for selected depths (bottom panel). Comparison between measured and predicted profiles on the four occasions when profiles were measured in the lake at site GYBS are shown in Figure 10.

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The simulation begins in late summer, when the lake is near its point of maximum heat content and surface temperatures are at their maximum. By mid March autumn cooling is evident as surface temperatures begin to decline and the thermocline deepens. By late June temperatures are nearly uniform with depth, and complete mixing to the bottom is predicted from early July to early September (see also Figure 9 bottom panel; complete mixing is indicated by the overlap of the temperature plots for all depths).

In order to get some idea of the relative importance of the various factors that influence the thermal regime of the lake as a whole, heat fluxes calculated from the meteorological data and surface water temperatures (daily means predicted by the model) are shown in Figure 9 (top panel). The fluxes have been calculated using standard formulae given, for example, in TVA (1972), Monteith (1973) and Imberger(1979). All fluxes are daily means over 24 hours.

The major source of heat for the lake is net radiation at the water surface (blue curve), consisting of: incoming solar radiation minus reflected solar radiation, plus incoming longwave radiation from the atmosphere minus reflected atmospheric longwave radiation, minus outgoing longwave (almost-black-body) radiation from the water surface. Net radiation is generally positive except for periods in winter.

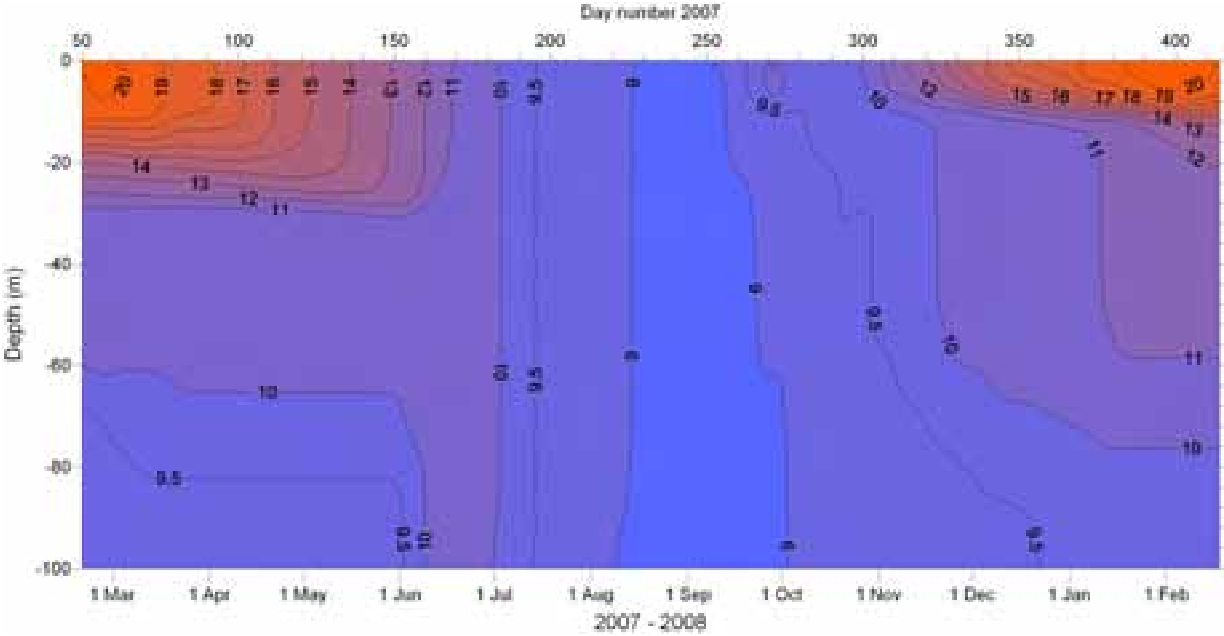

Figure 8: Contours of modeled temperatures, corresponding to those that would be observed at a mid-lake site.

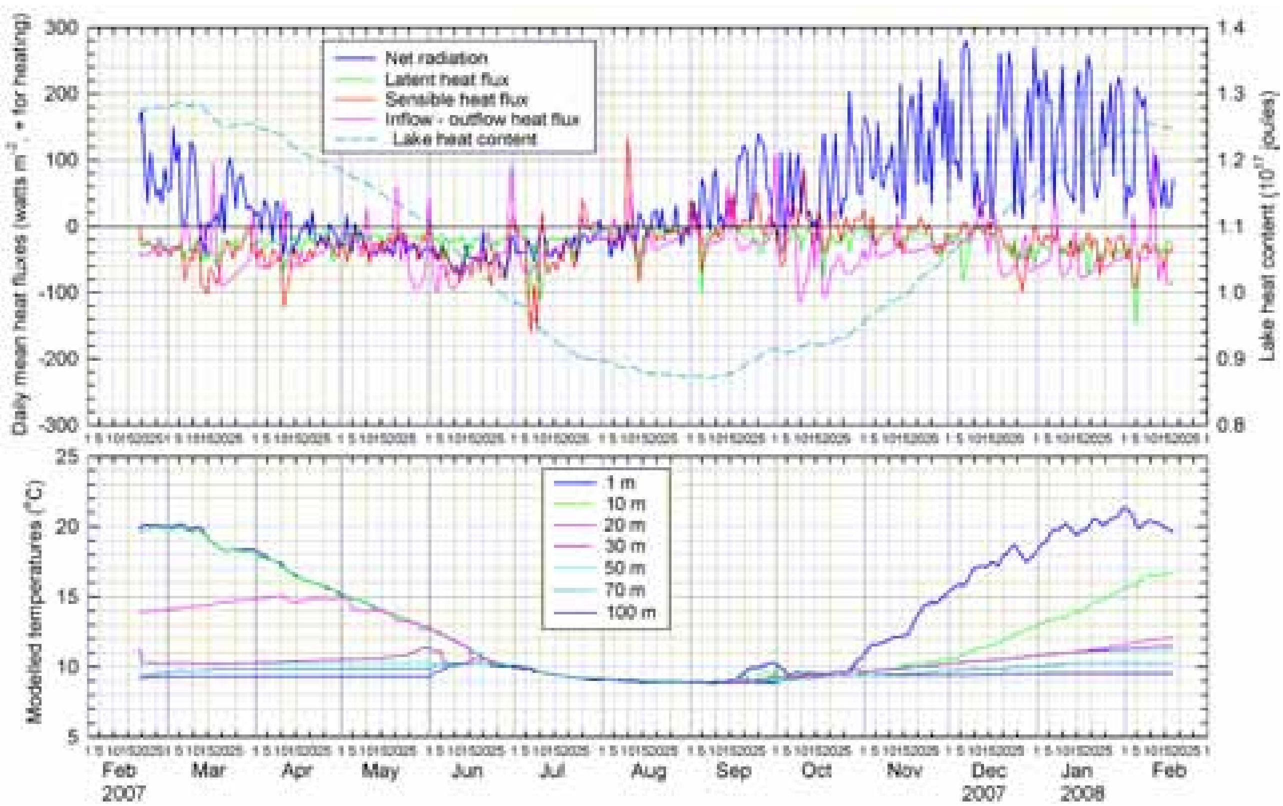

Figure 9: Heat fluxes and lake heat content (top graph); temperatures at selected depths (bottom graph).

The major heat losses are latent (green curve in graph) and sensible (red curve) heat fluxes associated with evaporation, wind and air temperatures that are cooler than the water surface. Occasionally these fluxes are positive, resulting in heat gain, if there is net condensation instead of evaporation, and if air temperatures are warmer than the water surface. The graphs of wind and air temperature (Figure 5) help explain the variations in these fluxes. For example, the large values of sensible heat losses between 5-10 July are associated with concurrent large values of high wind speed and low air temperature, while a sensible heat gain on 10 August coincides with relatively high winds and high air temperature.

The net advected flux due to inflows and outflows (pink curve) is basically the difference between the product of inflow discharge and inflow temperature, minus the product of outflow discharge and outflow temperatures (multiplied by water density and specific heat capacity). This flux is of similar magnitude to the sensible and latent heat fluxes. Hence, while the heat flux due to inflows and outflows does not dominate the thermal energy budget of the lake, it is a significant component. Most of the time the advective flux is negative, resulting in a net heat loss from the lake. This is because the outflows are drawn from surface waters, which are generally warmer than deeper waters, while the inflows are usually cooler than the surface waters. The inflows therefore tend to sink when they enter the lake, remaining at their level of neutral buoyancy in the lake until they are mixed into surface waters and eventually drawn into the outflow from the lake.

The total heat content of the lake (computed relative to zero heat at 0°C) is also shown in the top graph (dashed curve, axis on right-hand-side). It lags behind net radiation, with heat content lowest in July-August and greatest in February-March.

Temperature profiles predicted by the model are compared with measured profiles in Figure 10 on the four days that profiles were measured at the GYBS site. While the winter profiles (14 August) show good agreement when the reservoir is mixed, those during the period when the lake is stratified are less satisfactory. There is fairly good agreement between maximum and minimum temperatures and the general pattern of stratification, but there are discrepancies and these are discussed below, together with possible explanations for their causes.

There is a general tendency for the model to predict thermoclines that are steeper than those observed in the lake. This seems to be a weakness of the DYRESM model, as it is observed in simulations of other lakes as well. The only way to fix this is to modify the model code. This is possible but would involve some serious reprogramming.

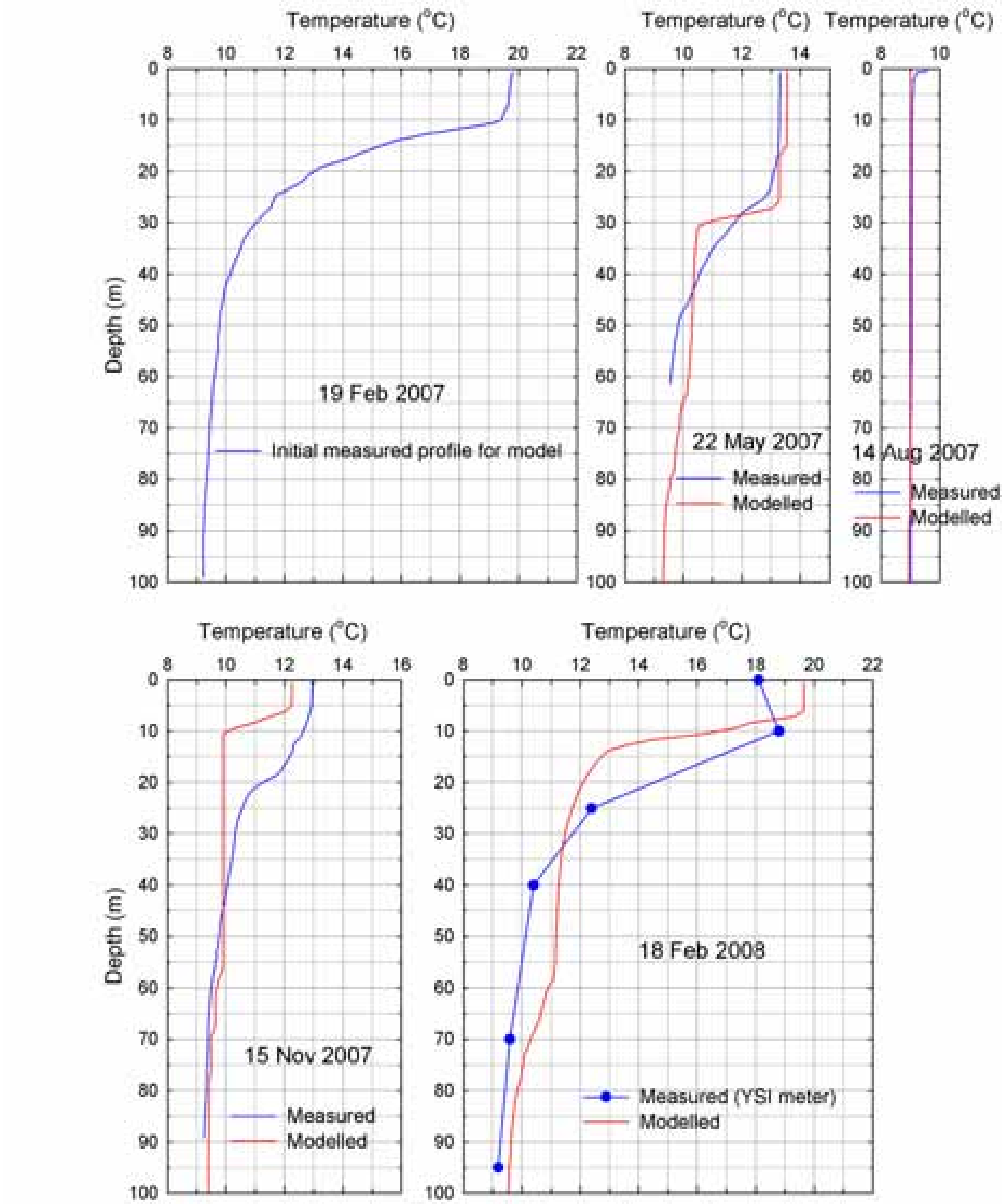

Figure 10: Comparison of predicted and measured temperature profiles

In the autumn profile (22 May 2007) the thermocline appears to be at roughly the right depth, while in the spring and summer profiles (15 Nov 2007 and 18 Feb 2008) it is too shallow. This may be associated with wind speeds measured at the Pigeon Creek climate station being weaker than those over the lake. During autumn, thermocline deepening is driven mainly by seasonal cooling, and wind mixing exerts a secondary influence. In spring and summer, however, there is a net heat input to the lake from the atmosphere that acts to stabilize the water column and strengthen stratification. It is the interaction between net heat input, wind mixing and the light attenuation coefficient that controls thermocline depth in spring and summer. For a given heat input, stronger winds and low attenuation coefficients lead to deeper thermoclines and cooler surface temperatures, while weaker winds and higher attenuation coefficients lead to shallower thermoclines and higher surface temperatures. We have used an artificially low value for the light attenuation coefficient in these simulations (Section 4.4) to achieve the results shown in Figure 10.

The predicted profile for 15 November 2007 not only has a thermocline that is too shallow, but also surface water temperatures that are too low. These low temperatures may be caused (in the model) by cooling due to river inflows, as these frequently enter the lake as surface inflows at this time. If there are errors in the timing and magnitude of the inflows, this will cause errors in the temperature profile. The errors may be associated with the simplistic correction made for rainfall in the original partitioning of the total inflows from the water balance (Section 4.3). The rainfall correction involved using an estimated long-term daily mean rainfall over the lake. During storms, this will greatly underestimate rainfall input and overestimate river inputs. Now that rainfall data are available from Pigeon Creek, it would be possible to redo the partitioning of the total inflows for the period that rainfall data are available, thereby improving the accuracy of inflow heat fluxes. This could not be done within the timeframe of the present project, but should be done if it is water quality modeling is to be carried out.

6. Conclusions

The model has done a reasonable job in simulating the thermal regime of Lake Brunner over a season. When compared with the few measured temperatures available, it has reproduced fairly well the overall patterns of stratification and mixing, and maximum and minimum temperatures. However there are some discrepancies between measured and predicted profiles during the stratified period in terms of steepness of the thermocline and the location of the thermocline in summer and spring. Possible reasons for the discrepancies relate to representativeness of wind data, assumptions made when estimating inflows for the major rivers, and weaknesses in the model itself. There are also uncertainties surrounding the value of the light attenuation coefficient in the lake. If water quality modeling is carried out, ways to reduce these possible sources of error should be considered.

The quality of the simulations is adequate for the model to be used for water quality modeling, using a coupled DYRESM-CAEDYM model. CAEDYM is the University of Western Australia – Centre for Water Research's Computational Aquatic Ecosystem Model. The limiting factor is the availability of input data to run the model. In addition to daily inflow volumes and temperatures, it will be necessary to estimate daily concentrations of nitrate, ammonium, dissolved reactive phosphorus, total nitrogen and total phosphorus in the three major inflows and probably in the rain. These are the absolute minimum. Given its importance for lake colour, it would be well to include dissolved organic carbon also, and tie modeled in-lake dissolved organic carbon to CAEDYM's calculation for light attenuation.

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7. Acknowledgements

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APPENDIX

1. Hourly meteorological data from Pigeon Creek climate station and Hokitika AWS (Automatic Weather Station), and associated correlations.

2. Correlations for river temperatures.

Data from Pigeon Creek climate station, 3 km south of Lake Brunner (Figures 1 and 4 in main text) and from Hokitika AWS are plotted in Figure A-1. Figure A-2 contains scatter plots (showing regressions) of hourly mean meteorological data from Pigeon Creek climate station versus data from Hokitika AWS; data for rainfall are daily totals. A summary of regression equation parameters is given in Table A-1.

A summary of the regression parameters for river temperatures is given in Table A-2.

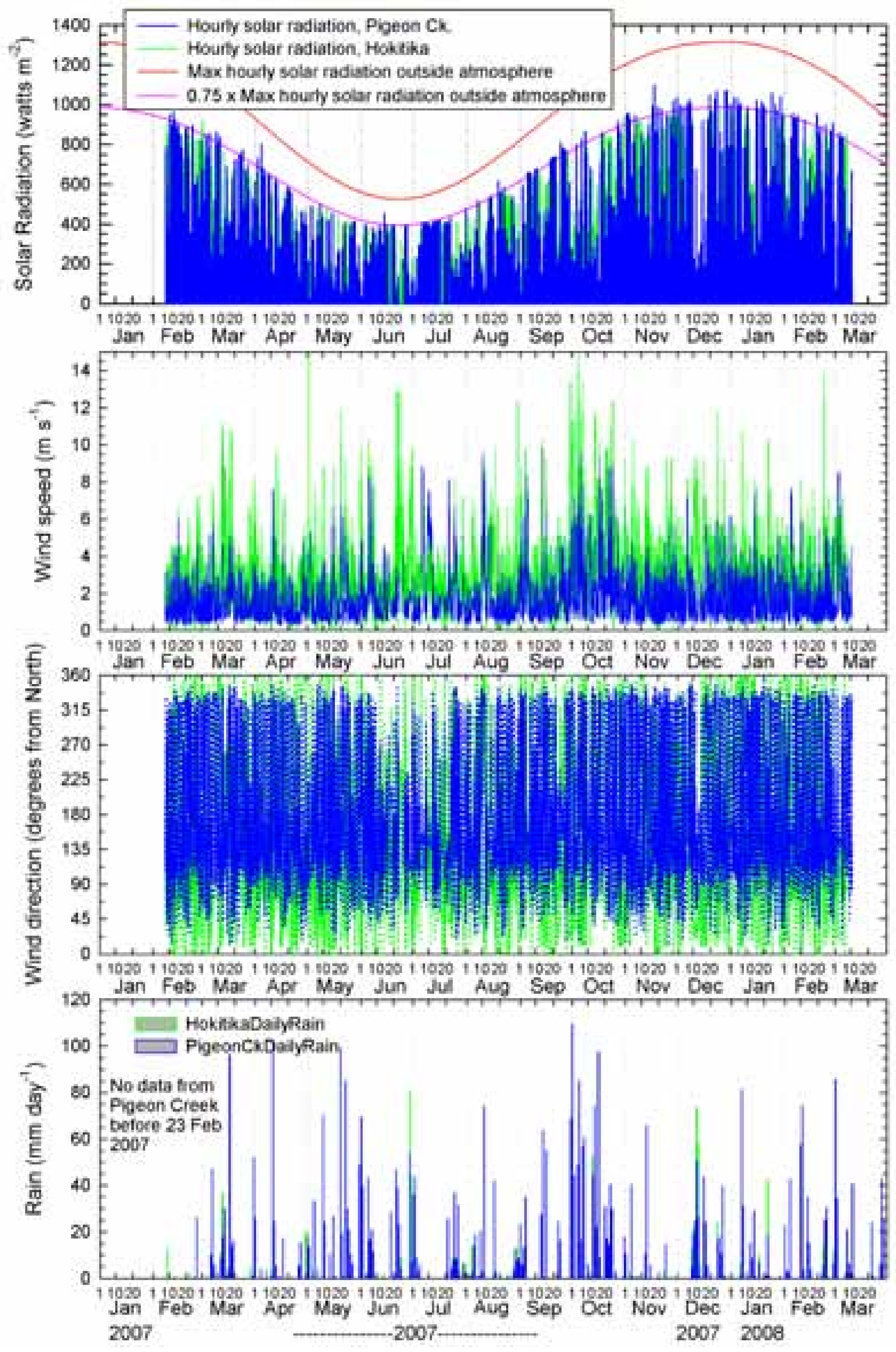


Figure A-1: Hourly data from Pigeon Creek climate station and Hokitika AWS for solar radiation and wind; daily totals for rain.

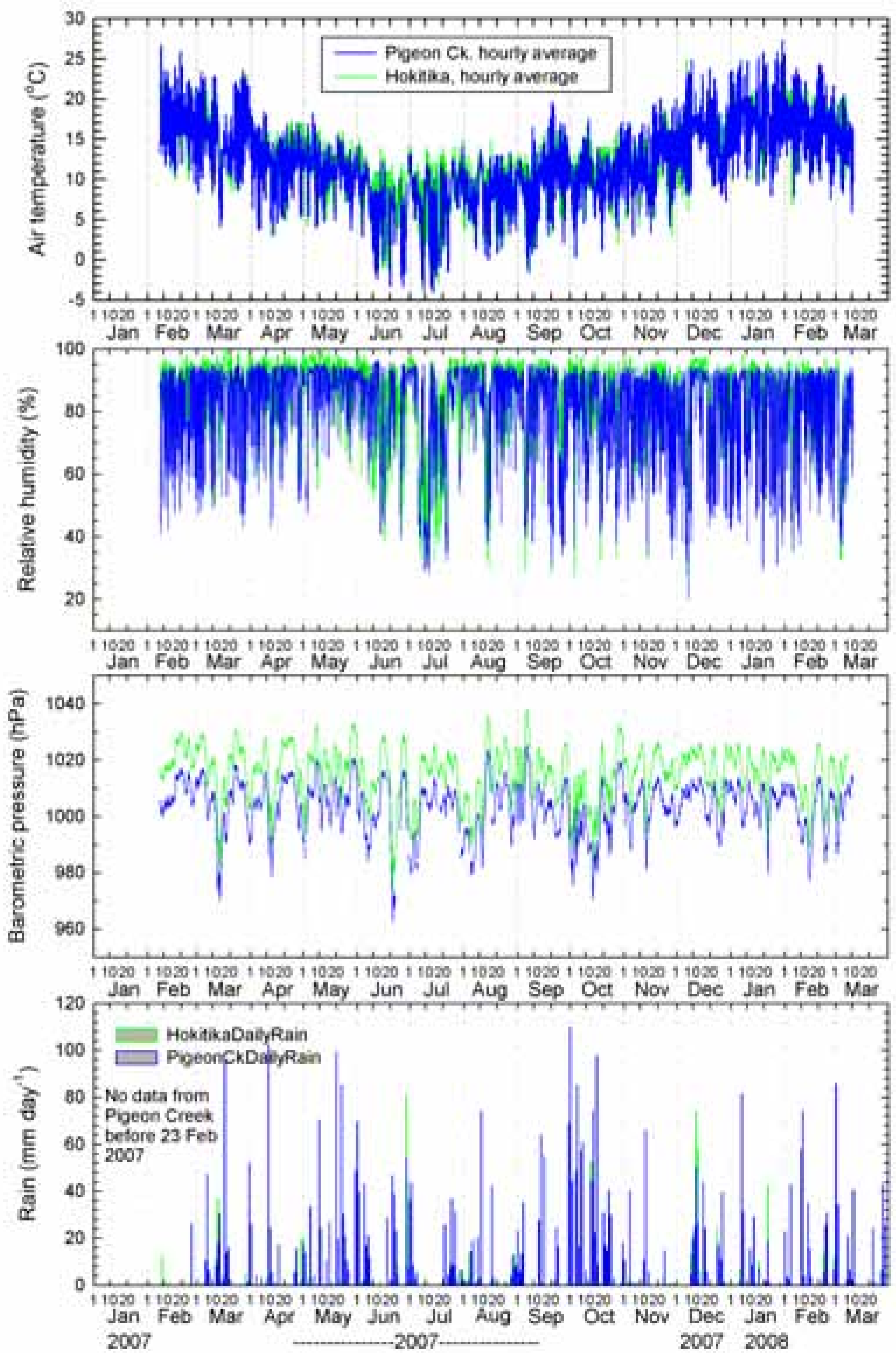
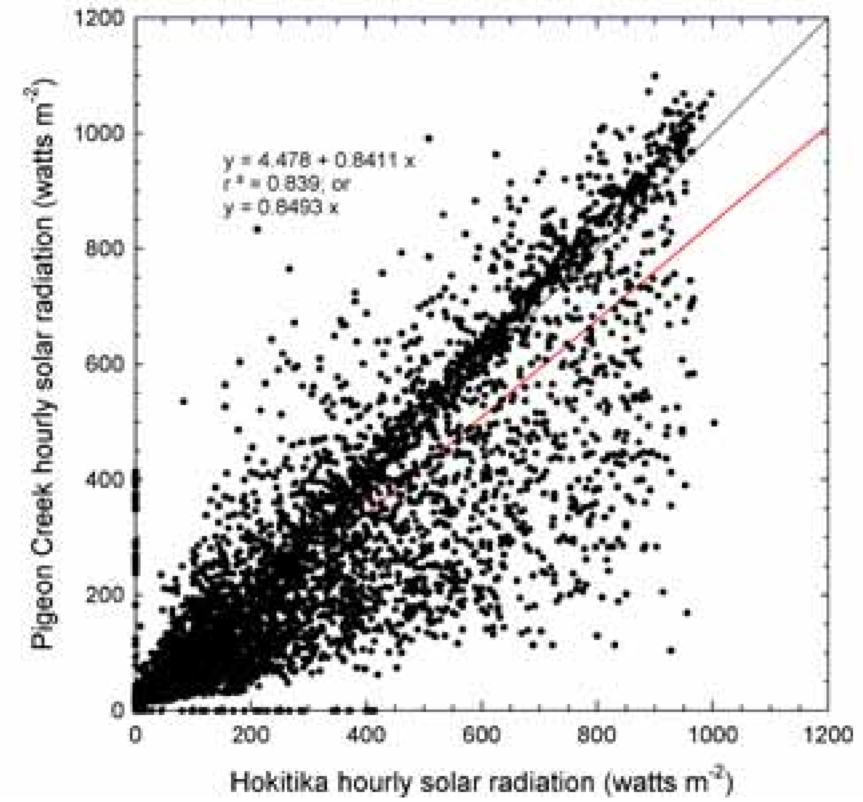
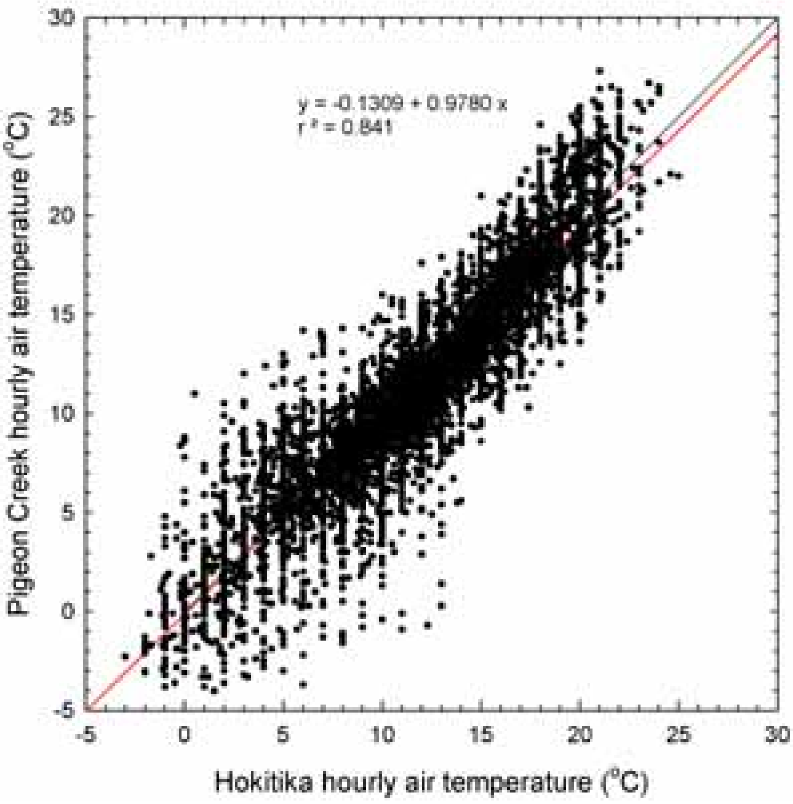


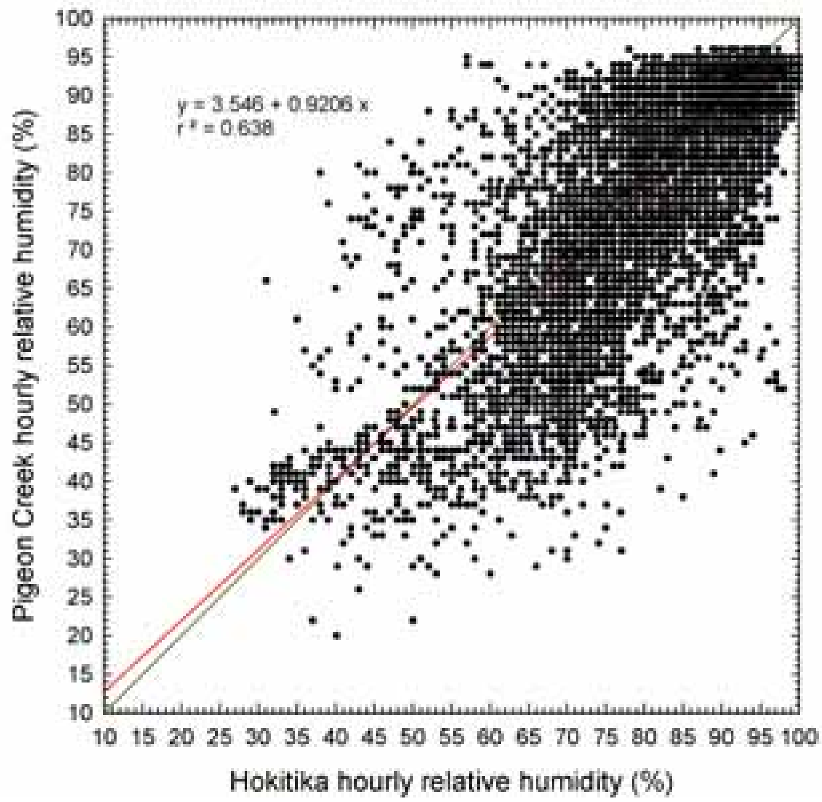
Figure A-1, continued: Hourly data from Pigeon Creek climate station and Hokitika AWS for air temperature, relative humidity and barometric pressure; daily totals for rain.

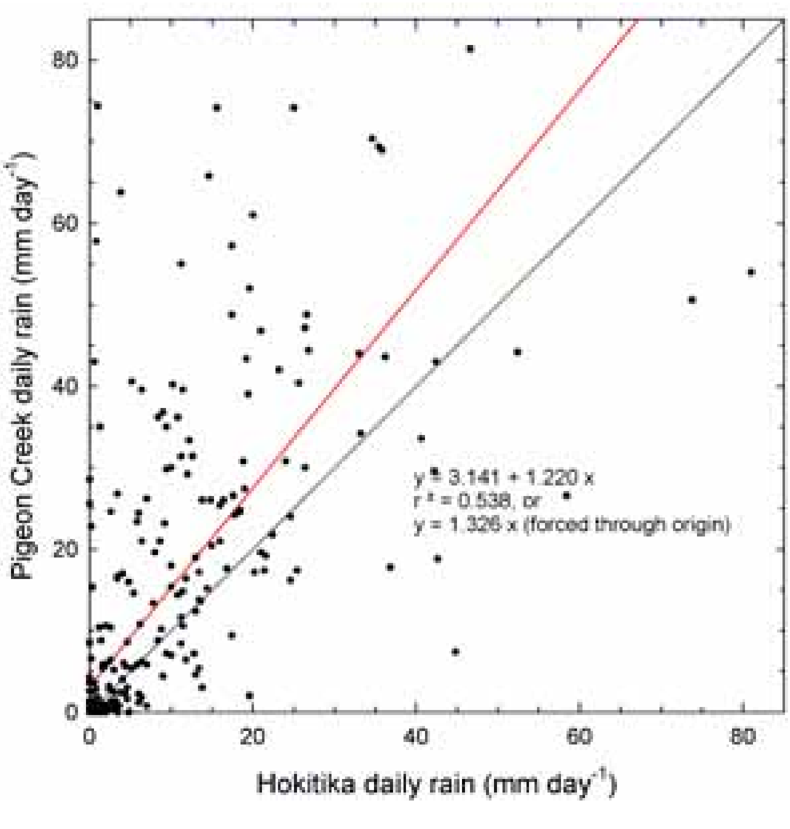


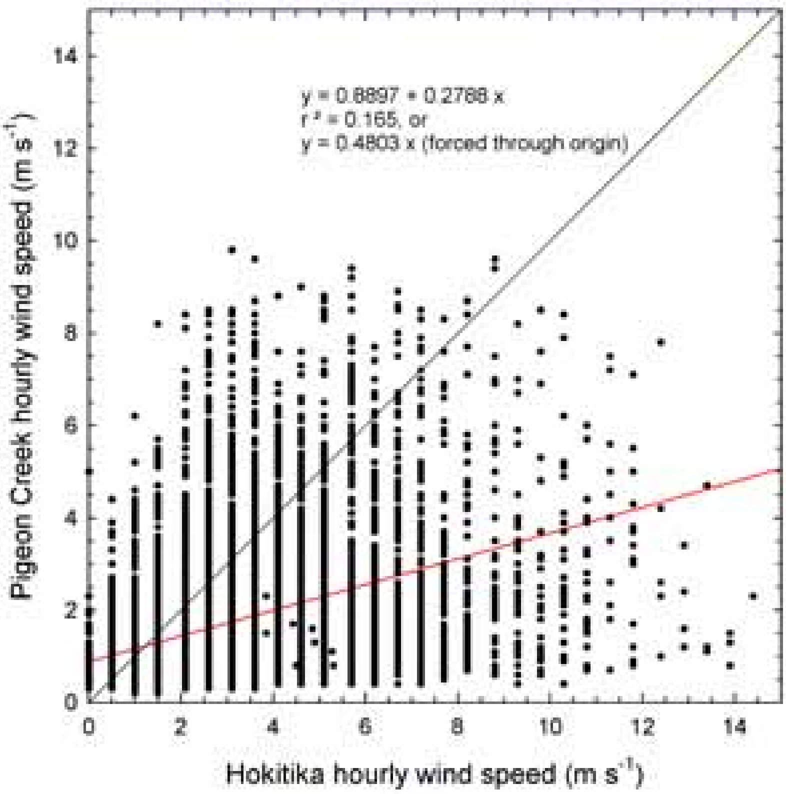
y = 4.478 + 0.8411 x
r² = 0.839; or
y = 0.8493 x
Pigeon Creek hourly solar radiation (watts m⁻²)
Hokitika hourly solar radiation (watts m⁻²)



y = -0.1309 + 0.9780 x
r² = 0.841
Pigeon Creek hourly air temperature (°C)
Hokitika hourly air temperature (°C)


y = 3.546 + 0.9206 x
r ² = 0.638
Pigeon Creek hourly relative humidity (%)
Hokitika hourly relative humidity (%)
10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100


y = 3.141 + 1.220 x
r ² = 0.538, or
y = 1.326 x (forced through origin)
Pigeon Creek daily rain (mm day⁻¹)
Hokitika daily rain (mm day⁻¹)
0 20 40 60 80



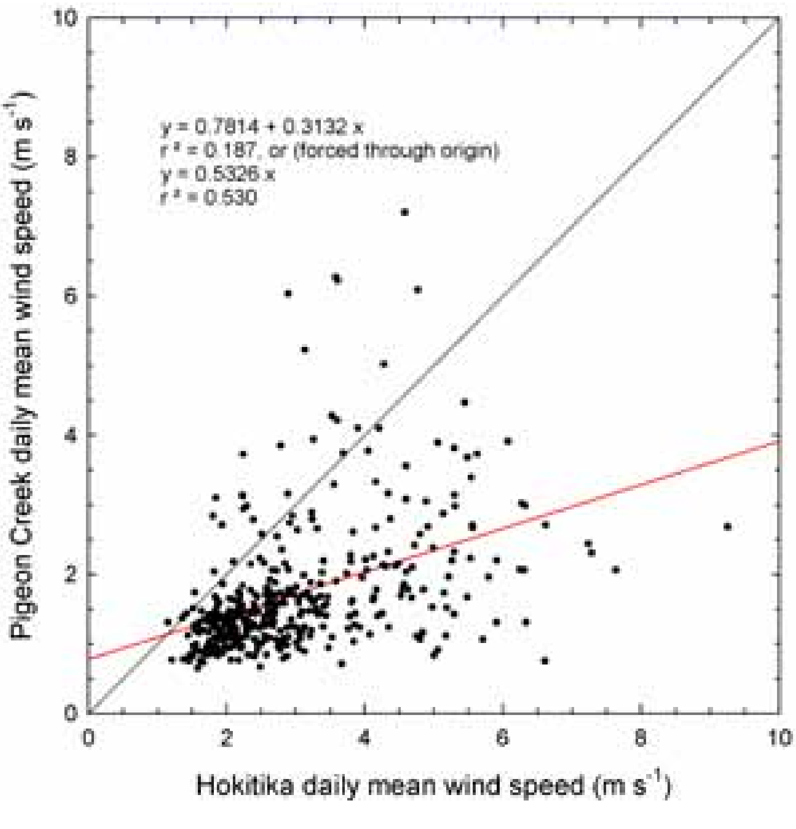


Figure A-2: Correlations and regression equations for hourly meteorological data measured at Pigeon Creek climate station versus data from Hokitika AWS, but daily totals for rain; daily average data for wind are also shown.

Table A-1

Regression statistics for meteorological variables.
Y = b0 x b1 X; Y = Pigeon Creek climate station, X = Hokitika AWS

	Hourly solar radiation (watts m^{-2})	Hourly air temperature (ºC)	Hourly relative humidity (%)	Hourly wind speed (m s^{-1})	Daily wind speed (m s^{-1})	Daily Rain (mm day^{-1})
b0	0	-0.1309	3.546	0.0	0.0	3.141
b1	0.8493	0.9780	0.9206	0.4803	0.5326	1.22
r^2	0.852	0.841	0.637	0.527	0.53	0.538
n	9267	9241	9242	9241	397	432
Std Err	91.9	2.02	9.25	1.39	0.97	13.51

Regression statistics, inflow temperatures for meteorological variables (ºC)
Y(ºC, inflowtemp) = b0 + b1 X1 +b2 X2 + b3 X3 + b4 X4 + b5 X5

	Hohonu	Crooked	Orangipuku	Xi
b0	1.2088	3.6129	8.6520	
b1	0.01201	0.00766	0.00259	Solar (watts m^{-2})
b2	0.6774	0.4025	0.0416	Air temperature (ºC)
b3	0.2812	0.2402	0.1845	Vapour pressure (hPa)
b4	-0.4400	-0.3099	-0.1452	Wind speed (m s^{-1})
b5	-0.1480	-0.0102	-0.0407	Flow (m^3 s^{-1})
r^2	0.930	0.939	0.670	
Std Err	1.196	0.711	0.646	
n	357	357	357	