Hydrothermal Characteristics of the Nechako Reservoir

Phase 2 Report 2006/07

Gregory A. Lawrence, Ph.D., P.Eng. [1]
Tel: (604) 822 5371
lawrence@civil.ubc.ca

Roger Pieters, Ph.D. [1,2]
Tel: (604) 822 4297
rpieters@eos.ubc.ca

Bernard Laval, Ph.D., P.Eng. [1]
Tel: (604) 822 2204
blaval@civil.ubc.ca

Yasmin Nassar[1]
Tel: (604) 827 5367
yasmin@civil.ubc.ca

Yehya Imam[1]
Tel: (604) 822 4853
yehya@civil.ubc.ca

Samuel Li, Ph.D. [1]
Tel: (250) 807 8145
samuel.li@ubc.ca

[1]Department of Civil Engineering
[2] Department of Earth and Ocean Sciences
University of British Columbia
Vancouver, B.C. V6T 1Z4

Prepared for

Nechako Enhancement Society
c/o Suite 850-899 West Hasting Street
Vancouver B.C. V6C 2W2

August 23, 2007

Executive Summary

The Nechako Enhancement Society (NES), a joint partnership of Alcan Inc. and the Province of British Columbia, is considering building a Cold Water Release Facility (CWRF) at Kenney Dam on the Nechako Reservoir. The CWRF would draw cold deep water from the reservoir to reduce the temperature of the Nechako River for fish migration. The NES has requested an assessment of the ability of the CWRF to deliver up to 170 m^3/s of 10 ºC water between July 20 and August 20 (a total of 0.47 km^3). We have examined the physical limnology of the two basins adjacent to Kenney Dam (Knewstubb and Natalkuz lakes). In particular, we have:

- Collected temperature profiles in the summer of 2005, 2006 and 2007; these were compared with data from 1990 (Limnotek) and 1994 (Triton).
- Moored a temperature chain and wind buoy in Knewstubb Lake near Kenney Dam from July to October 2005 and compared these data with those collected in 1994 (Triton).
- Setup land-based weather stations for long-term wind monitoring (Jul 2005).
- Analyzed the bathymetry of Knewstubb and Natalkuz Lakes using existing data and selected sounder transects.
- Examined the evolution of the thermal structure of Knewstubb and Natalkuz lakes under extreme conditions using the hydrothermal model DYRESM.

The 10 ºC isotherm was observed at 20-25 m depth in all five summers (1990, 1994, 2005, 2006 and 2007). If the CWRF had been in place it would have been able to satisfy the cooling water requirements in each of these years. However, if the 10 ºC isotherm were, at some future time, to sit at a depth of 40 m the volume of cold water in Knewstubb Lake (0.18 km^3) would not be sufficient to satisfy the maximum cooling water requirement (0.43 km^3). The sill separating Knewstubb and Natalkuz lakes is at a depth of 40 m and would prevent transfer of cold water from Natalkuz to Knewstubb Lake.

The main scientific question that we have addressed is whether or not there are realistic meteorological conditions under which the 10 ºC isotherm will sit at a depth of 40 m or more on July 20. We have used field measurements from 1994 and run DYRESM to predict what would happen if the lake were subject to a strong, but not unrealistic, windstorm averaging 10 m/s for 2 days (approximating winds observed on April 18, 2006). Such a storm, were it to occur in early summer, is predicted to create a 45 m deep surface layer whose temperature is greater than 10 ºC on July 20. When a withdrawal of 170 m^3/s starts on July 20 cold water is drained from Knewstubb Lake, the 10 ºC isotherm drops to below the intake by the start of August, and the cooling water requirement is no longer met. The likelihood of such an event is the subject of continuing investigation. It should be noted that even if the cooling water requirement is not met, the CWRF will still be effective in releasing cooler water that would otherwise be the case.

Table of Contents

List of Figures

1. Introduction

A Cold Water Release Facility (CWRF) is being considered for Kenney Dam, which would draw deep water from Knewstubb Lake (Fig. 1.1) to better control the temperature of the Nechako River for fish migration and spawning, as well as to address other watershed values. An important question in assessing the effectiveness and design of the CWRF is determining the availability of sufficient cold water. While considerable effort was devoted to numerical modeling of the Nechako Reservoir in the early 1990's, comparison to field data was limited, the results were mixed, and a number of uncertainties remain.

This report presents the results of the two years of an applied research project to understand the hydro-thermal characteristics of the Nechako Reservoir to aid in assessing the ability of the CWRF to supply adequate quantities of water at the appropriate temperature. In Section 2 we present the results of a detailed assessment of the bathymetry of Knewstubb Lake. In Section 3 we present the key features of previously collected (1994) meteorological data in addition to data collected as part of the present project. Similarly, in Section 4 we present the key results from thermistor chains moored in Knewstubb and Natalkuz lakes in 1994, and from a thermistor chain moored in Knewstubb Lake in 2005. In the summer of 2005 and 2006 we conducted CTD (Conductivity – Temperature – Depth) surveys at a number of sites in both Knewstubb and Natalkuz lakes; these data are presented in Section 5.

The evolution of the summer stratification is explored using a one-dimensional model (DYRESM) and the effect of spring and early summer storms is described in Section 6. The effect of internal waves at both the sill and near Kenney Dam is explored using short (10 day) runs of a three-dimensional model (ELCOM) in Section 7. An analysis of the factors affecting the ability of the CWRF to release sufficient quantities of cool water is presented in Section 8. This is followed by conclusions and recommendations for future work in Section 9. This comprehensive report includes material given in Lawrence et al, 2006.

2. Bathymetry

Methods

Digital bathymetric data were received from Triton Environmental. These data were created from pre-impoundment areal photographs. Bottom elevations were available except where lakes and rivers existed before the Nechako Dam was constructed. The data consisted of elevations on a 50 m grid along with elevations of breakpoints showing major features. Missing data were interpolated; this effectively neglects the small volume available in small pre-existing lakes, creeks and the Nechako River.

Two types of echo sounding data were collected. First, depth data in Natalkuz Lake were collected using a Humminbird Matrix 10 in July, 2005 and a Lowrance X65 sounder in August, 2005. Across lake transects were collected approximately every 2 km along Natalkuz Lake. Second, in October 2005, a BioSonics DTX scientific sounder (200 kHz, narrow beam) was used to collect entire acoustic returns from which images were constructed. Six transects were conducted at key sites in Knewstubb Lake.

Results

We begin by describing the major features of the study region (Figure 1.1). Kenney Dam was built across the Nechako River at the Nechako Canyon in 1952 to create the Nechako Reservoir. No water is currently released from Kenney Dam: the dam does not have either a spillway or low-level ports. The purpose of the proposed CWRF is to release water from Kenney Dam into the Nechako River. Currently, water is released from the Nechako Reservoir at Kemano for hydroelectric generation or at the Skins Lake Spillway which flows into the Cheslatta system; both of these sites are to the west of the study area, see Boudreau (2005) for further detail.

The Kenney Dam resulted in flooding of the Nechako River valley from the dam to Natalkuz Lake. This section of the Nechako Reservoir has been called Knewstubb Lake. For the purpose of this study we distinguish three regions of Knewstubb Lake:

- Knewstubb Arm (stations K00 to K05, Figure 1.1),
- mid reach (station K06 to narrows), and
- sill reach (narrows-Natalkuz Lake, stations K11-12).

The narrows occurs at an outcropping of rock just north of station K11. The sill, or shallowest section of Knewstubb Lake, occupies the reach between the narrows to the historic Natalkuz Lake.

Figure 2.1 gives contours of the depth in Knewstubb Lake. The deepest part of Knewstubb Lake is located at the dam. However, the historic Nechako River ran through a canyon for much of Knewstubb Arm and as a result the volume of deep water in this region is limited. The width of the deep reservoir expands considerably in the mid-reach where meanders of the pre-impoundment Nechako River are evident.

Figure 2.2 shows the depth along the thalweg (valley bottom) from the Kenney Dam to the east end of Natalkuz Lake. Knewstubb Lake is connected to Natalkuz Lake by a sill with elevation of approximately 812 m. We propose confirming the maximum sill depth with future echo sounding transects.

Figure 2.3 and Table 2.1 give the area and volume of Knewstubb Lake as a function of water elevation. The boundary of Knewstubb Lake is taken to be a line along Easting 359300 at the outlet of the pre-impoundment Natalkuz Lake (Figure 1.2).

Figure 2.4 provides another view of the bathymetry through echo sounding transects using the BioSonics sounder along key transects (marked in blue on Figure 1.2):

a) East-west transect through the Knewstubb mooring site, showing the Nechako Canyon with the original river bed carved a few meters into the canyon (T1);
b) South from the Nechako Lodge, also showing the Nechako Canyon (T2);
c) Big Bend Arm, showing dense tree cover (T3);
d) Knewstubb mid-reach (K08) showing a wider, more U-shaped valley (T4);
e) Narrows with no tree cover (T5); and
f) Sill region (K12) showing main channel and adjacent valleys with tree cover (T6).

We are currently in the process of validating the digital bathymetric data against the sounders and against CTD pressure and line-out records. For the most the comparisons show reasonable agreement however there remain unresolved differences of up to 9 m. We continue to work to resolve these discrepancies, particularly in the sill region. We plan additional sounder transects in the sill region in conjunction with the CTD surveys planned for August 2006.

Table 2.1 Volume and Area of Knewstubb Lake

Elevation	Area	Volume	Elevation	Area	Volume
(m)	(km^2)	(km^3)	(m)	(km^2)	(km^3)
790	3.745	0.009	823	34.975	0.539
791	4.070	0.013	824	36.275	0.575
792	4.400	0.018	825	37.470	0.612
793	4.823	0.022	826	38.765	0.650
794	5.160	0.027	827	40.010	0.689
795	5.505	0.032	828	41.095	0.730
796	5.833	0.038	829	42.220	0.771
797	6.268	0.044	830	43.388	0.814
798	6.755	0.051	831	44.590	0.858
799	7.425	0.058	832	45.673	0.903
800	8.110	0.065	833	46.813	0.949
801	8.895	0.074	834	47.853	0.997
802	9.833	0.083	835	48.948	1.045
803	10.640	0.093	836	50.065	1.095
804	11.473	0.105	837	51.205	1.145
805	12.213	0.116	838	52.408	1.197
806	13.015	0.129	839	53.703	1.250
807	14.015	0.142	840	54.995	1.305
808	15.553	0.157	841	56.298	1.360
809	17.068	0.173	842	57.658	1.417
810	18.060	0.191	843	59.173	1.475
811	19.135	0.210	844	60.655	1.535
812	20.503	0.230	845	61.950	1.597
813	22.018	0.251	846	63.215	1.659
814	23.435	0.274	847	64.575	1.723
815	24.510	0.298	848	65.905	1.788
816	25.873	0.323	849	67.383	1.855
817	28.113	0.350	850	69.035	1.923
818	29.290	0.379	851	71.093	1.993
819	30.468	0.409	852	73.065	2.065
820	31.495	0.440	853	75.303	2.140
821	32.525	0.472	854	78.348	2.216
822	33.693	0.505			

3. Meteorological Measurements

Wind is an important forcing on a reservoir during the stratified summer season. Wind can act to mix warm water down and thereby deepen the thermocline. Wind can also push the warm surface layer to the downwind end of the reservoir; when wind subsides, an oscillation of the thermocline (internal seiching) can occur. Wind induced thermocline motion can result in dramatic temperature changes at a given elevation.

To characterize variability in water temperature structure requires a long-term wind record. Note that wind can vary significantly over a reservoir. This is particularly true of the different reaches of the Nechako reservoir, where it can be windy in one reach and calm in another. We have begun by collecting wind data near Kenney Dam. Wind in Knewstubb Arm will have the most direct impact on the proposed release facility, though, as discussed below, wind in other parts of the reservoir can also be important.

Not only does the wind vary along a reservoir but it will also vary significantly from the middle of the water body to the shore. Appropriate shore sites that are representative of lake winds are generally difficult to find. In order to establish a suitable shore site, we deployed a wind buoy on the lake and established two temporary land-based stations in 2005.

Methods

The location of four meteorological stations is given in Table 3.1. The buoy was located close to the site of measurements in 1994 (Triton, 1995; C. Mitchell, Triton Environmental, personal communication). The buoy was designed to be moored and recovered from a medium sized boat. The buoy was composed of a light-weight aluminum frame supported by floats (See photos in Appendix 3). A compass was included to measure buoy orientation. The buoy was moored in about 75 m of water with a single line running to about 60 kg of anchor. The buoy was deployed in 2005 but not in 2006.

The first temporary land-based station is located at the Alcan enclosure to the east of Kenney Dam. For a permanent station, this location would provide the easiest tie-in to Alcan's data collection network because of existing infrastructure. However, a hill and tree-cover rising behind the site may block wind from the east. In addition, this site is located in the north-south valley of the Nechako Canyon and, as such, may be less representative of east-west winds acting on Knewstubb Lake.

A second temporary land-based station is located on a tower at the Nechako Lodge. The wind monitor is located about 30 m above the ground and about 5-10 m above the tree canopy.

Wind data for mid-June to Mid-October, 1994 were received from Triton Environmental for the following sites:

- wind monitor on Knewstubb Lake (at approximately the same location as the 2005 buoy data),

- wind monitor on Natalkuz Lake, and
- wind monitor near the spillway at Skins Lake.

Further detail can be found in Triton (1995).

In addition, Environment Canada, Meteorological Service of Canada (MSC) installed a permanent weather station at the Skins Lake spillway that is one of the Canadian Reference Climatological Stations (RCS) and part of the Global Climatological Observing Station Network (GSN). The station in name is 'Ootsa Lake Skins Lake Spillway' and hourly data is available online from 13:00 August 22, 2005.

Table 3.1 Meteorological stations, 2005

Buoy: Wind Buoy in Knewstubb Lake near Kenney Dam		
	Location:	UTM 5936906 m Northing & 10 U 370891 m Easting 53º 33.907' N and 124º 56.969' E
	Measured:	Wind speed, wind direction, buoy direction (compass)
	Duration:	July 19 – October 14, 2005
Dam: Meteorological Station at Alcan enclosure east of Kenney Dam		
	Location:	UTM 5938685 m Northing & 10 U 371099 m Easting
	Measured:	Wind speed and direction, air temperature, relative humidity and solar radiation (short-wave)
	Duration:	July 22, 2005 - ongoing
Tower: Wind monitor on tower near Nechako Lodge		
	Location:	UTM 5937311m Northing & 10 U 372790 m Easting
	Measured:	Wind speed and direction
	Duration:	August 18, 2005 – ongoing
Skins: Permanent AES station at Skins Lake		
	Location:	N 53º 46' 19.8", W 125º 59' 47.6"
	Measured:	Wind speed (10m mast), wind direction, air temperature, relative humidity, precipitation, air pressure
	Duration:	August 22, 2005 – ongoing

Results

Meteorological data collected at the three sites near Kenney Dam in 2005-06 are shown in Figure 3.1.1. The same data for the summer of 2005 and 2006 is replotted on a smaller scale in Figure 3.1.2 and 3.1.3. The wind speed was generally similar and all three sites show major wind storms such as that on September 27, 2005 (Figure 3.1.2a-c). Wind speeds are moderate, up to 10 m/s at the buoy. The wind speed at the buoy is almost double the wind speed at the dam and about a third higher than wind speed recorded on the tower. The detailed correlation may depend on direction and/or wind speed and will be investigated further.

The histograms of wind direction for wind velocity greater than 2 m/s (Figure 3.1.1d-f), indicates that the prevailing wind direction is from the south west. This is generally consistent with the anecdotal evidence that wind storms typically come from the west.

The air temperature, relative humidity and solar radiation are shown in Figure 3.1.1g-i. Air temperature varied from summer highs of 30 °C to near freezing in mid-October. Relative humidity varies with air temperature. Solar radiation follows a seasonal decline from summer to fall.

Wind data from 1994 is shown in Figure 3.2 for comparison. The wind speed at both the Natalkuz and Skins lake sites is slightly higher than on Knewstubb Lake. The predominant wind direction is Knewstubb Lake is from the southwest, as in 2005. The predominant direction in Natalkuz Lake is also from the southwest. In contrast the dominant direction at the Skins Lake site is from due west.

The wind speed and wind speed cubed (see §8.1) are compared in Table 3.2 for day 235-285, the longest period of time in common to all the wind records described above. (The results are similar averaging over the full record for each). The average wind on Knewstubb Arm near the Kenney Dam in 2005 is similar to that in 1994. In 2005, the dam and even the tower site, underestimate the wind on Knewstubb Lake near the dam. From the 1994 data, the wind on Natalkuz Lake is significantly higher that on Knewstubb Arm, consistent with anecdotal evidence that Natalkuz is windier and consistent with the considerable exposure and potential funneling of winds from both the Intata and Euchu Reaches into the Natalkuz site (Figure 1.1). The importance of wind in setting the thermocline depth will be discussed in §8.1.

Table 3.2 Average wind speed, $\langle U \rangle$, and the average of the cube of the 4-hr wind speed, $\langle U^3 \rangle$, for day 235-285.

Location	Average wind speed (m/s)	Average of cubed wind speed (m^3/s^3)
Knewstubb buoy, 2005	3.2	59
Dam site, 2005	1.6	12
Nechako Lodge tower, 2005	2.6	17
Knewstubb raft, 1994	2.9	44
Natalkuz raft, 1994	3.6	97
Skins Lake spillway, 1994	2.9	95

4. Temperature mooring

Of importance to the proposed release facility is the water temperature as a function of depth near Kenney Dam. This was measured with a temperature mooring. For comparison, temperature data collected near Kenney Dam and in Natalkuz Lake in 1994 (Triton, 1995) will also be shown.

Methods

A temperature mooring was installed in Knewstubb Lake next to the meteorological buoy and was operational from July19 to October 12, 2005. The mooring was not deployed in 2006. Temperature was measured by 32 Onset internally recording instruments (Hobo Water Temp Pro). The instruments have a resolution of approximately 0.2 °C and data were recorded every 10 minutes. Additional Onset temperature recorders (Stowaway and Tidbit) were used to provide near surface and near bottom temperatures.

The instruments were attached to a line and suspended between a bottom anchor and a subsurface float. This subsurface mooring arrangement ensured that the instruments did not move as the surface water level changed: the instruments were at a fixed location relative to the proposed intake. The water level variation over the mooring period was small (< 0.5 m). Instruments were located every 2 m in 75 m water depth.

Results

Figure 4.1 shows a contour plot of the temperatures in Knewstubb Lake. The water column is sharply stratified with a warm (>12-20 °C) surface layer above colder (~5 °C) deep water. The thermocline, where the temperature changes most rapidly, occurs around the 10 °C isotherm and generally lies between 20 and 25m depth.

Also evident in Figure 4.1 is variation in the depth of the thermocline; typical variations are on order of 5 m. These variations or 'internal waves' are driven by the wind. An example is the response of the thermocline to the wind storm on August 1st (day 213).

The corresponding contour plots for water temperature in Knewstubb and Natalkuz lakes in 1994 are given in Figures 4.2 and 4.3, respectively. As in 2005, the thermocline was relatively sharp and occurs around 20 m in depth. The exception is Natalkuz Lake from mid-July to mid-August (Figure 4.3) when the surface layer undergoes secondary stratification: the surface layer divides into a warm, shallow surface layer (0-12m, >18 ºC) and an intermediate layer (12-20m at 10-14 ºC). During this time there are two thermoclines: one around 12 m and another at 20 m. The surface layer is mixed down into the intermediate layer during the large wind storm in mid-August.

5. Temperature surveys

As we have seen in the previous section, mooring data provides high temporal resolution at one location. However, the temperature structure can vary significantly through a water body and in order to assess this spatial variability, CTD (Conductivity-Temperature-Depth) profiles were collected in mid-July, mid-August and mid-October, 2005 and in mid-August 2006.

Methods

A Seabird SBE19plus CTD with WETStar transmissometer, C-Star fluorometer and Seapoint OBS was profiled at stations throughout Knewstubb and Natalkuz lakes; stations are shown in Figure 1.1 and casts are listed in Appendix 1. Considerable care was required to avoid snagging the profiler on submerged tree limbs. The boat was positioned over the bed of the former Nechako River and careful watch was kept for both trees and brush on the sounder screen. Temperature is accurate to at least 0.05 ºC; only down casts of temperature are shown.

Results

Contours of temperature in Knewstubb Lake are shown in Figure 5.1 for the surveys in (a) July, (b) August and (c) October 2005 and (d) August 2006. The left side of each panel begins near the dam (Station K00) and continues along the centre line of Knewstubb Lake into eastern Natalkuz Lake (N02); see Figure 1.1 for station locations. All four surveys show sharp stratification at the thermocline and there is little variation in lake temperature and thermocline depth along the reservoir.

Overlay plots of temperature for the three surveys are shown in Figure 5.2. In all four surveys, the lake is divided into a warmer surface layer and cold deep water by a sharp thermocline. The surface layer shows some near surface warming or 'secondary stratification' in the top 3 m in July 2005 (Figure 5.2a), to varying depths in August 2005 (Figure 5.2b) and in the top few meters in August 2006 (Figure 5.2d). In contrast, the surface layer is well mixed in October 2005 (Figure 5.2c), consistent with fall cooling. In all four surveys, the deep temperature remains near 5 ºC. The only exception is in the sill reach of Knewstubb Lake (Stations K10-K12) where the deep temperature is up to 1 ºC warmer than the deep temperature in either Knewstubb Lake or Natalkuz Lake. This may reflect increased vertical mixing as a result of the narrow channel and the funneling of wind from Natalkuz Lake.

Temperature data collected by Triton at various locations in Nechako Reservoir in June and August 1994 (Triton 1995) are shown in Figure 5.3. In early June, the reservoir was just beginning to stratify. In August, stratification was well established except for the western part of the reservoir where the stratification was weaker. In the eastern half of the reservoir, the 10 ºC isotherm was between 20 and 25 m. Data from the Kenney Dam embayment from May to October 1991 are shown in Figure 5.4 (Limnotek 1991). While the depth resolution of this data is limited, the 10 ºC isotherm was between 15 and 25 m in Jul and Aug. The 10 ºC isotherm then deepens with fall cooling.

6. Deep water temperatures and DYRESM modelling

Here we investigate* the most likely scenario limiting the volume of cooling water available during the critical period.

An interesting feature of the bathymetry of Knewstubb Lake is the sill separating it from Natalkuz Lake. This sill sits at an elevation of 812 m. To allow for uncertainty in the elevation of the sill we will assume a critical depth of 810 m. If the thermocline drops below this level the cold water from Natalkuz Lake will not be available to replace that removed from Knewstubb Lake.

In 1994 and 2005 the thermocline, as represented by the 10 ºC isotherm, oscillated between 825 m and 835 m – comfortably above the level of the sill (Figure 6.1). However, we need to consider three factors:

- The free surface level was relatively high (≈ 853 m) in 1994 and 2005. For the present investigation we will assume an elevation of 850 m (see Figure 6.2). For consistency depths will be quoted as depths below 850 m even though the surface level may not be at 850 m. Thus the proposed intake extends from a depth of 60 m to 53.4 m, given that its elevation extends from 790 m to 796.6 m.
- Under different meteorological conditions the depth to the thermocline could be much greater. We will investigate the conditions under which this might occur below. Note that in the Arrow Lakes reservoir the thermocline depth has varied by a factor of two from year to year. The thermocline in Williston Reservoir typically sits at a depth of 40 m.
- There were no withdrawals through Kenny Dam in 1994 and 2005; the modeling of Triton (1992) predicts a considerable lowering of the thermocline if withdrawals are made, see Figure 6.1.

We start by examining the consequences of the thermocline falling to an elevation of 810 m by the start of the cooling water period (July 20th). If this occurs the upper bound on the amount of cool water available for withdrawal from the proposed KDRF will be the volume of Knewstubb Lake between 790 m (the intake invert) and 810 m, that is 1.9 x 10^8 m^3. At a discharge rate of 170 m^3/s this volume will be removed in approximately 13 days. The available volume will be reduced by the effects of thermocline drawdown and internal waves, but would be increased by the possibility of blending deep water with surface water. The details of these effects still need to be finalized, but it is clear that if the 10 ºC isotherm drops to 810 m the ability of the proposed KDRF to provide sufficient cooling water will be compromised. Therefore the most pressing task is to determine whether or not there are realistic scenarios under which the 10 ºC isotherm is could drop to 810 m.

---

* Results from this modelling have been included in a conference paper (Appendix 5).

6.1. Depth of the mixed layer:

After spring turnover daytime heating will typically dominate over nighttime cooling resulting in an increase in the temperature and a decrease in the density of the surface waters. The reduction in density will decrease the potential energy (PE) of the water column.

A mixed layer of uniform density can be re-established by wind mixing. This will result in an increase in the potential energy of the water column. In this section we will investigate how windy it needs to be to raise the potential energy. Specifically we would like to calculate the wind energy required to achieve a mixed layer that extends down to a depth H = 40 m (assuming a free surface elevation of 850 m and a critical level of 810 m) at a temperature of T = 10 ºC at the start of the cooling water period (July 20th). There are two conditions that need to be satisfied:

1. There needs to be enough heat input from the time of spring turnover (about May 1st) until July 20th (80 days) to raise the temperature of the water column from 4 ºC to 10 ºC down to a depth of 40 m.

   The heat flux $\tilde{H}$ required to achieve an increase of ΔT in a given period t is:

   $$\tilde{H} = \frac{c_p \, \Delta T \, \rho_w \, V}{t \, A_s}; \tag{6.1}$$

   where the specific heat of water, c_p = 4200 J/kg/ºC; ΔT = 6 ºC; the density of water, ρ_w = 1000 kg/m^3; the volume of Knewstubb Lake down to a depth of 40 m, V = 1.73 km^3; the time available, t = 80 days; and the surface area at an elevation of 850 m, A_s = 69 km^2. Substituting these values in (1) gives:

   $$\tilde{H} = 91 \text{ W/m}^2. \tag{6.2}$$

   This heat flux is certainly possible, as the maximum the incident solar radiation at the latitude of Knewstubb Lake (53'30" N) varies from 200 to 350 W/m^2 over the period of interest (Figure 6.4). While the flux at the water surface will be less because of cloud cover and nighttime cooling, it is still likely to exceed 91 W/m^2. Also data from Knewstubb and Natalkuz Lakes shows that in 1994 and 2005 the upper 20 m had an average temperature of about 15 ºC by July 20th indicating an average net heat flux of approximately 100 W/m^2.

2. Assuming there is enough heat input into the lake, there needs to be enough wind to mix the buoyant warm water down from the surface to a depth of 40 m.

   In the following analysis, the temperature increase due to heating can be assumed to be uniform down to the Secchi depth, SD, and zero below the Secchi depth (Figure 6.3). Readings taken in 2005 gave an average SD = 6 m for Knewstubb Lake. We are interested in how much wind energy is required to mix this fluid throughout the upper 40 m. To increase the temperature throughout the top 40 m from 4 ºC to 10 ºC over 80 days requires an average daily temperature increase $\overline{\Delta T} = 0.75$ ºC/day, corresponding to a daily temperature increase in the upper 6 m,

$$\Delta T_1 = 0.75 \frac{V}{V_u}, \tag{6.3}$$

where V_u = 0.39 km^3 is the volume of the upper 6 m (Figure 6.3). Substituting into (3) gives ΔT_1 = 0.33 ºC/day. At T = 10 ºC this change in temperature results in a density increase $\Delta\rho_1$ = 0.03 kg/(m^3.day). The rate of change of potential energy needed to mix this fluid down to 40 m is given by:

$$\dot{PE} = \frac{\Delta\rho_1 \, g V_u \, \Delta_{CM}}{(86,400 A_s)} \quad \mathrm{W/m^2}, \tag{6.4}$$

where Δ_{CM} is the change in elevation of the centre of mass of this water. An accurate evaluation of Δ_{CM} would require consideration of the changing cross-section area of the reservoir with depth, however, to a first approximation we can write:

$$\Delta_{CM} = \frac{H - SD}{2} = 17 \text{ m}. \tag{6.5}$$

Substituting into (4) gives $\dot{PE} = 3.3 \times 10^{-4}\,\mathrm{W/m^2}$. The energy available for mixing is proportional to the wind speed cubed U_{10}^3 which is approximated by:

$$U_{10}^3 \cong \frac{\dot{PE}}{\eta \rho_a C_D A_s}, \tag{6.6}$$

see Appendix 4, where the wind mixing efficiency $\eta \approx 1.5 \times 10^{-3}$, the density of air ρ_a = 1.2 kg/m^3, and the drag coefficient $C_D = 1.3 \times 10^{-3}$. Substituting gives:

$$U_{10}^3 = 140 \text{ m}^3/\text{s}^3 \tag{6.7}$$

Note from Equation 6.5 that the wind energy required is proportional to $H - SD$, and that to mix to a depth of 40 m requires approximately twice as much wind energy as to mix to a depth of 23 m. So, all else being equal, the average wind energy would need to be approximately double that experienced in 1994 and 2005 to cause mixing to 40 m. This result needs to be qualified since the mixing does not occur uniformly, but occurs predominantly during storms. The depth of mixing will be determined by the strength and timing of storms. The depth of mixing will also be affected by the input of heat and the occurrence of cloud and nighttime cooling.

The above calculations suggest that it is feasible that under the right wind conditions the thermocline might be driven down to a depth of 40 m. We will now use the model DYRESM to test this possibility more thoroughly.

6.2 DYRESM Predictions

The ability of DYRESM to model the thermal structure of the Nechako Reservoir (or more specifically Knewstubb and Natalkuz lakes) is illustrated in Figure 6.5. Contours plots of the temperature data from the 1994 moorings in (a) Knewstubb and (b) Natalkuz lakes as well at the predictions of (c) DYRESM are presented. While at any given time the temperatures at a given depth may be quite different (due primarily to internal wave activity) the measured thermal structures are quite similar and modeled well by DYRESM.

A more quantitative assessment of the effectiveness of DYRESM is presented in Figure 6.6. Comparisons of surface temperature, hypolimnetic temperature, depth of the 10 ºC isotherm and heat content are made. In general the differences between the predictions and the measurements are no greater than the differences between the measurements. The model predictions more closely match the Natalkuz measurements. The Knewstubb mooring was at one end of the reservoir and may not be representative of average conditions in the reservoir. Prevailing winds force warm surface water towards this mooring, and cause set down of the thermocline and increase the local heat content (see Section 7). In this study we have used the Natalkuz data in preference to the Knewstubb data.

We now use DYRESM to make some “what if” comparisons between the following four cases:

1. **Default** – predictions made using measured weather conditions in 1994;
2. **Withdrawal** – same as Default, but with 170 m^3/s withdrawal from July 20th to August 20th from a depth of 53.4 – 60 m, corresponding to the depth of the proposed withdrawal facility;
3. **Storm** – same as Default, but with an idealized wind storm of 10 m/s for 2 days applied on July 5th and 6th. This storm was chosen based on the wind data collected during the storm of April 18, 2006, see Figure 6.7.
4. **Storm plus withdrawal** - same as Default, but with our idealized 2 days winds storm applied on July 5th and 6th and with 170 m^3/s withdrawal from July 20th to August 20th.

The predictions for each of these four cases are presented graphically in Figure 6.8. The default case shows the typical development of a warm surface layer about 20 m thick overlying a cool (< 6 ºC) hypolimnion (Figure 6.8b). The withdrawal of water at depth lowers the free surface level. The 10 ºC isotherm drops correspondingly, but the temperature at depth is little changed (Figure 6.8c). The introduction of the storm has a more dramatic impact. During the storm cool deep water is mixed with warm surface water and the surface layer deepens and cools, but importantly remains above 10 C (Figure 6.8d). The 10 ºC isotherm drops from less than 20 m depth to more than 40 m depth, it subsequently rises slightly, but remains just below 40 m for the rest of the summer. When withdrawal is added from July 20th the 10 ºC isotherm is drawn down even further as cool water is drained from Knewstubb Lake (Figure 6.8e).

The variation in the depth of the 10 ºC isotherm and the temperature at the depth of the proposed withdrawal facility are plotted in Fig. 6.8a. These plots confirm our initial hypothesis that the combination of a strong windstorm in spring followed by withdrawal can result in >10 ºC water at the withdrawal depth during the summer temperature control period. While we have presented results for a storm on July 5th and 6th, several other potential storm dates also result predicted withdrawal temperatures >10 ºC, and some even results in predictions >11 ºC (Figure 6.9b).

No model is perfect, and the predictions made above are subject to uncertainty, and a storm of 10 m/s for 2 days is unusually strong. Nevertheless, the DYRESM modeling establishes that the possibility of >10 ºC withdrawal water during the summer temperature control period needs to be taken seriously.

7. Modelling internal waves with ELCOM*

The 3-D hydrodynamic modeling effort of the Nechako system is aimed at explaining how the thermocline depth, particularly at Kenny Dam, is affected by internal waves and how transfer of additional cold water from Natalkuz Lake may be blocked by the narrows.

7.1 Methods

The Estuary and Lake Computer Model (ELCOM) is used as a numerical tool. ELCOM is a three-dimensional hydrodynamic model designed to model the flow field and temperature structure in stratified water bodies. Developed by the Center for Water Research, University of Western Australia, ELCOM has been used to model many lakes and reservoirs around the world. ELCOM is only suitable for short simulations of a week or two. Further details are given in Appendix 6.

The Nechako system is so vast that modeling the whole system at any useful resolution is not feasible with our currently available computing resources. In such a situation, a practical approach is to experiment with the model to identify the extent of the region that has the primary effect on the temperature structure at the point of interest. After several experimental simulations, it was found that all of Knewstubb Lake (from Kenney Dam to the Narrows connecting Knewstubb to Natalkuz Lake) must be simulated in order to replicate the major features of isotherm displacement at the dam wall. We have also included most of Natalkuz Lake in order to explore possible transfer of additional cold water over the sill between Natalkuz and Knewstubb.

The model domain is shown in Figure 7.1. The grid is generally 200 m, except for near Kenney Dam and in the Narrows where the grid is as fine as 50 m, and in west Natalkuz where the grid is as large as 1 km. Note the change in grid size between adjacent cells is < 10% in order to prevent numerical artifacts (e.g. wave reflection) from a rapidly changing grid. The vertical grid spacing is 0.5 m in the top 30 m, increasing gradually to 4.5 m at a depth of 80 m. Further detail is given in Appendix 6.

The model was run for 1994 as this year had moored data from both Knewstubb and Natalkuz lakes. The model was started on Aug 11, 1994 (day 223) during a calm period before a large storm of Aug 21-23, 1994 (day233-235). The model run ended after 13 days on Aug 28 (day 240).

7.2 Results

We focus on the results of two model runs which illustrate the range of behaviour near Kenney Dam. First, we will examine how the model performed against the moored data of 1994 with Run 10A. In this baseline run, the thermocline is approximately 22 m deep, similar to that observed in 1991, 2005 and 2006. We can infer much about the behaviour of the system from this case. The second run, Run 10C, has as its initial condition the

---

* Results from this modelling have been included in a conference paper (Appendix 6).

profile on Aug 11, 1994 from DYRESM run with a storm on Jul 13 and including withdrawal. In Run 10C the effect of withdrawal on a deep thermocline will be explored.

Run 10A, reproducing conditions in 1994, is shown in Figure 7.2. The initial conditions were provided by the moorings in Knewstubb and Natalkuz in 1994 (Figure 1.1). The wind and wind direction are shown in Figure 7.2a,b; as discussed in the preceding sections, the prevailing winds were from the W-SW at both Knewstubb and Natalkuz. In Figure 7.2c, observed temperatures in Natalkuz (lines) show reasonable agreement with the model results (color contours). The wind storm on August 22:

- mixes the mid layer (15-22 m), and
- the thermocline deepens as a result of lake-wide setup that we will see more clearly in the next plot.

In Figure 7.2d, the temperatures observed in Knewstubb near the Kenney Dam (lines) are compared to the model results (color contours). While the model shows general agreement with the mooring data, the variation in the depth of the isotherms is not as large in the model as in the observations; see, for example, the 10 ºC isotherm on day 235. Nevertheless, the general agreement indicates that we have captured most of the dynamics (c.f. Appendix 6).

Figure 7.3 shows a slice along the centre of the reservoir at specific times during the simulation. Wind driven surface setup is particularly clear in Natalkuz Lake (km40 to km60) where the warm surface layer is moved downwind in response to the storm. The initial response to the storm near Kenney Dam (x=0), is a slight upwelling (Fig 7.3b); however as the storm continues the 10 ºC isotherm is downwelled as a result of water moving from Knewstubb mid-reach into Knewstubb Arm. During the storm, the results of mixing in the narrows (x=25) can be seen). After the storm the thermocline begins to return to its equilibrium position.

In the case of Run 10A, the thermocline is 20 m about the level of the Narrows. In this case, additional cold water could be drawn from Natalkuz to replenish cold water withdrawn from Knewstubb. However, were the thermocline to be deeper this replenishment might not be possible. As discussed in the previous section, DYRESM was run with an additional wind storm to simulate extreme conditions.

Figure 7.4 shows the same simulation of ELCOM as in Figure 7.3 except (1) it was initialized with the output from one of the extreme DYRESM runs (Run (g), Appendix 5) and (2) withdrawal is included. In this run the 10 ºC isotherm is close to the level of the sill and no transfer of cold water from Natalkuz to Knewstubb is observed.

8. Conclusions

We have examined the circumstances under which the proposed CWRF will be able to satisfy the summer cooling water requirement (170 m^3/s of water ≤10 ºC from July 20 to August 20 at Kenney Dam). This requirement can only be satisfied if the accessible volume of cold water below the 10 ºC isotherm is greater than 0.47 km^3 (170 m^3/s for 32 days).

Scenario 1 (Insufficient cooling water)

Although it would unusual, it is possible that the 10 ºC isotherm will sit at or below the level of the sill connecting Knewstubb and Natalkuz lakes on July 20. This sill is at an elevation of 812 m, 40 m below the mean summer water level (Figure 8.1). In this scenario the volume of cold (≤10 ºC) water available from Knewstubb Lake is 0.18 km^3, substantially less than the maximum requirement. The potential supply of additional cold water from Natalkuz is blocked by the sill. As water is withdrawn, the 10 ºC isotherm will drop until it falls below the withdrawal level, resulting in withdrawal temperatures >10 ºC. This scenario has not been observed in the five years of existing data, however, hydrothermal modelling indicates that it is possible (discussed below).

Scenario 2 (Sufficient cooling water)

Thermal profiles within the Nechako Reservoir have been measured in 1990 (Limnotek), 1994 (Triton), and 2005-2006 (UBC). In each of these years, the 10 ºC isotherm was located at a depth of approximately 20-25 m during summer. This depth range is sufficiently far above the 40 m deep sill connecting Knewstubb and Natalkuz lakes that there is ample (~1 km^3) cold deep water to satisfy the cooling water requirements (Figure 8.1). As cold water is withdrawn from Knewstubb Lake, cold water can flow from Natalkuz to limit the lowering of the 10 ºC isotherm. In this case, the effect of internal waves and drawdown at the inlet are not a concern.

Hydrothermal modelling

Scenario 1 could occur as a result of wind patterns different from those already observed. With the aid of DYRESM, a widely used 1-D lake model, we have investigated the effect of various wind patterns. We have, for example, explored the effect of hypothetical, but realistic, wind storms in early summer using field measurements from 1994. The wind for 1994 is shown in Figure 8.2a. The addition of a storm of 10 m/s lasting 2 days in early summer gives rise to Scenario 1 (Figure 8.2b). Similar results occur when the storm is applied on other occasions during July. Without this storm the model gives Scenario 2 (Figure 8.2c).

In both scenarios, the lake stratification on July 4th is typical, with a thermocline (10 ºC isotherm) at a depth of approximately 20 m separating a warm (≈14 ºC) surface layer from a cool (<6 ºC) hypolimnion (Figures 8.2b,c). In scenario 2, the surface layer warms and remains at a depth of 20-25 m throughout the summer (Figure 8.2c). During the withdrawal period, only cold (<6 ºC) water is drawn from the reservoir and the thermal structure in the upper 30 m of the water column remains unchanged.

In contrast, when the hypothetical windstorm is applied on July 5 to 6 (Figure 8.2b), the surface layer is rapidly mixed down to a depth of about 45 m, resulting in a 45 m deep layer whose temperature is greater than 10 ºC. Given that the 10 ºC isotherm is now below the depth of the sill (40 m) separating Knewstubb from Natalkuz there can be no transfer of cool water from Natalkuz to Knewstubb. When withdrawal starts on July 20th cool water is drained from Knewstubb Lake and the 10 ºC isotherm drops below the intake invert at 62 m depth. The water withdrawn from the reservoir during August is greater than 10 ºC.

Additional modelling, using the 3-D hydrothermal model ELCOM, showed that in both Scenario 1 and Scenario 2 the presence of internal waves has little effect on the temperature of water withdrawn through the CWRF.

The CWRF would undoubtedly be effective in releasing cooler water than would otherwise be the case in all years. If the CWRF had been in operation during the years with temperature observations (1990, 1994, 2005, 2006 and 2007) the cooling water requirement would have easily been satisfied. However, there may be circumstances under which the cooling water requirement will not be satisfied. We have identified a realistic, but so far unobserved, scenario under which there would be insufficient cooling water. While the probability of such an occurrence is the subject of ongoing research[*], the hypothetical wind storm responsible for scenario 1 was motivated by measurements at Knewstubb Lake in April 2005.

[*] Funding requested in Collaborative Research and Development Grant application to NSERC

Acknowledgements

We would like to thank Josef, Elisabeth, Thomas and Martin Doerig of the Nechako Lodge for their kind hospitality and help in conducting field work. We would like to thank James Rakochy for his time and for suggesting setting out on the lake *very* early in the morning. We wish to thank the Cheslatta First Nations for kind use of their boat. We thank Jim Bull and Mike Mawhinney of the Canadian Centre for Inland Waters, Burlington, Ontario, for their generous discussions and plans for a small buoy. We thank Joel Atwater for design and construction of the on-lake buoy and for able help in the field, including late-night hotwiring of the sounder. Thanks to Aidin Zadeh for help setting up the temperature chain. Greg Lawrence is grateful for the support of a Canada Research Chair.

References

British Columbia Utilities Commission, 1994. Kemano Completion Project Review, Report Recommendations to the Lieutenant Governor in Council. 260pp and appendices.

Boudreau, K. 2005. Nechako Watershed Council Report: Assessment of Potential Flow Regimes for the Nechako Reservoir. Prepared for the NES and NWC, March 2005. 82pp.

Envirocon, 1984. Kemano Completion Hydroelectric Development Environmental Studies: Baseline Information. Section E. Prepared for the Aluminum Company of Canada Ltd., Vancouver, B.C.

Imberger J., R.T. Thompson, and C. Fandry, 1976. Selective Withdrawal from a Finite Rectangular Tank. *Journal of Fluid Mechanics*, **78**, 489-512.

Imberger, J. and Patterson, J. C. (1990) Physical Limnology. *Advances in Applied Mechanics*, 27: 303-475

Klohn Leonoff, 1992. Operational Impact of Internal Waves. Letter Report KLK 3048 prepared for Alcan Smelters and Chemicals Ltd., Kemano Completion Project, Vancouver BC. 8pp.

KDRF Working Group, 1996. Conceptual Alternatives for a Release Facility at Kenney Dam, an Interim Report. 43pp.

Limnotek, 1991. Temperature data from Knewstubb and Murray Lakes, 1991, provided by Limnotek.

Nechako Environmental Enhancement Fund, 2001. Report of the Nechako Environmental Enhancement Fund Management Committee. 38pp.

Nechako Watershed Council, 2002. Proposed Work Plan For the Cold Water Release Facility at Kenney Dam. 44pp.

Spigel, R. H., Imberger, J., K. N. (1986) Modeling the Diurnal Mixed Layer. *Limnology and Oceanography*, 31: 533-556.

Triton Environmental Consultants Ltd., 1991. Nechako Reservoir Hydrothermal Mathematical Modelling. Prepared for Alcan Smelters and Chemicals Ltd., Kemano Completion Project, Vancouver BC. 109pp and appendices.

Triton Environmental Consultants and J. E. Edinger Associates, Inc., 1992. Nechako Reservoir: Investigation of Magnitude of Thermocline Depression in Response to Winds. Prepared for Alcan Smelters and Chemicals Ltd, Kemano Completion Project, Vancouver BC. 64pp and appendices.

Triton Environmental Consultants, 1992. Supplementary Extreme Conditions Hydrothermal Modelling Documentation of Reservoir Temperatures Under 170 m^3/s Maximum Outflows. Prepared for Alcan Smelters and Chemicals Ltd, Kemano Completion Project, Vancouver BC. 26pp.

Triton Environmental Consultants, 1995. Nechako Reservoir Additional Data Collection, Final Report. Prepared for Alcan Smelters and Chemicals Ltd., Vancouver BC. 43pp plus appendices.

Figure 1.1 Map of Knewstubb and Natalkuz lakes

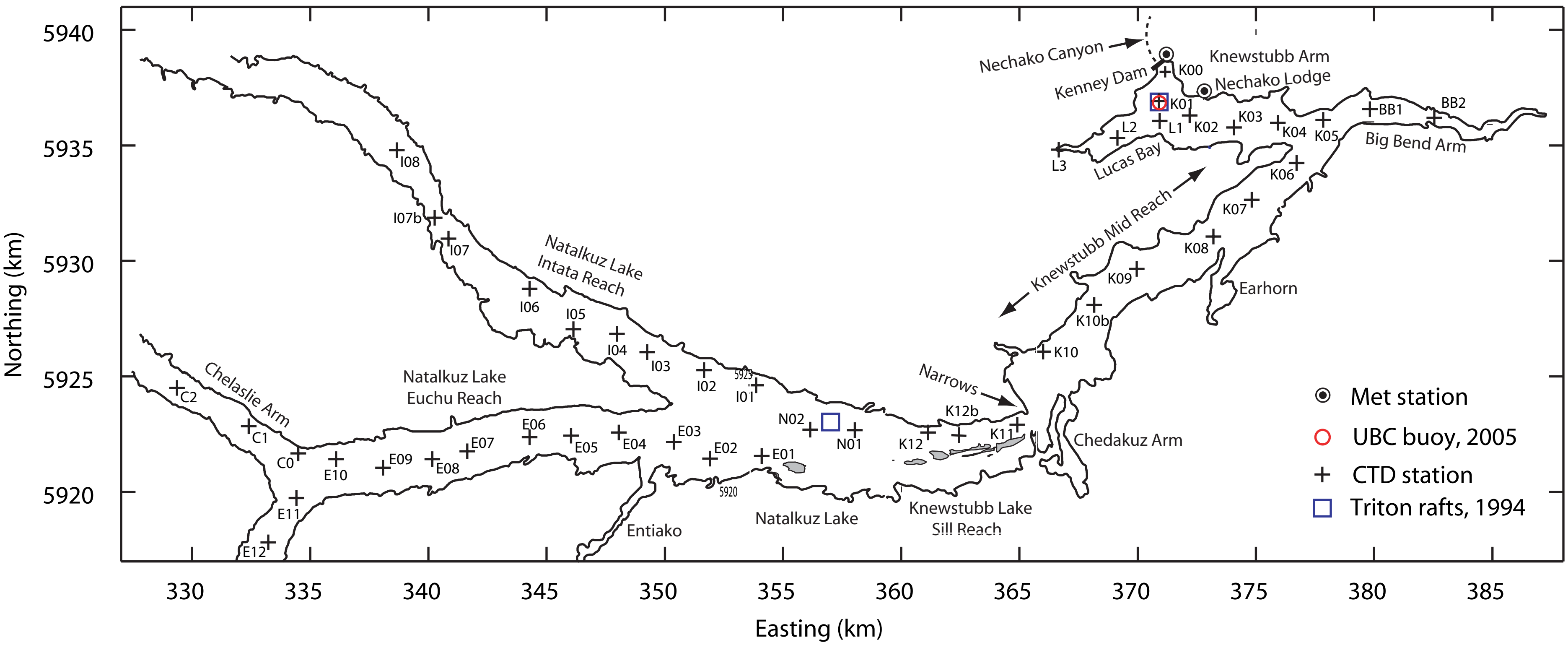


Figure 1.2 Map of Knewstubb lake showing sounder transects

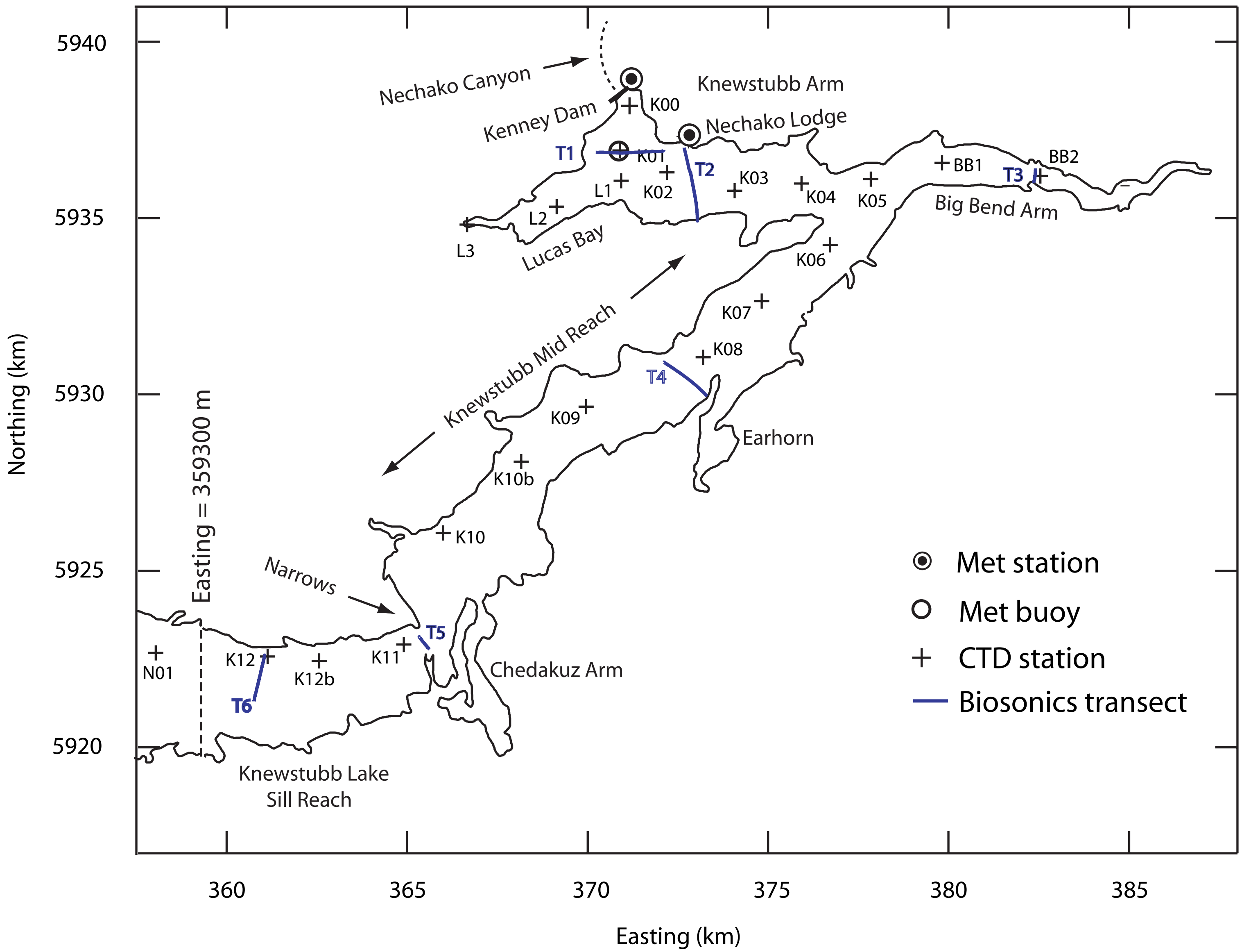
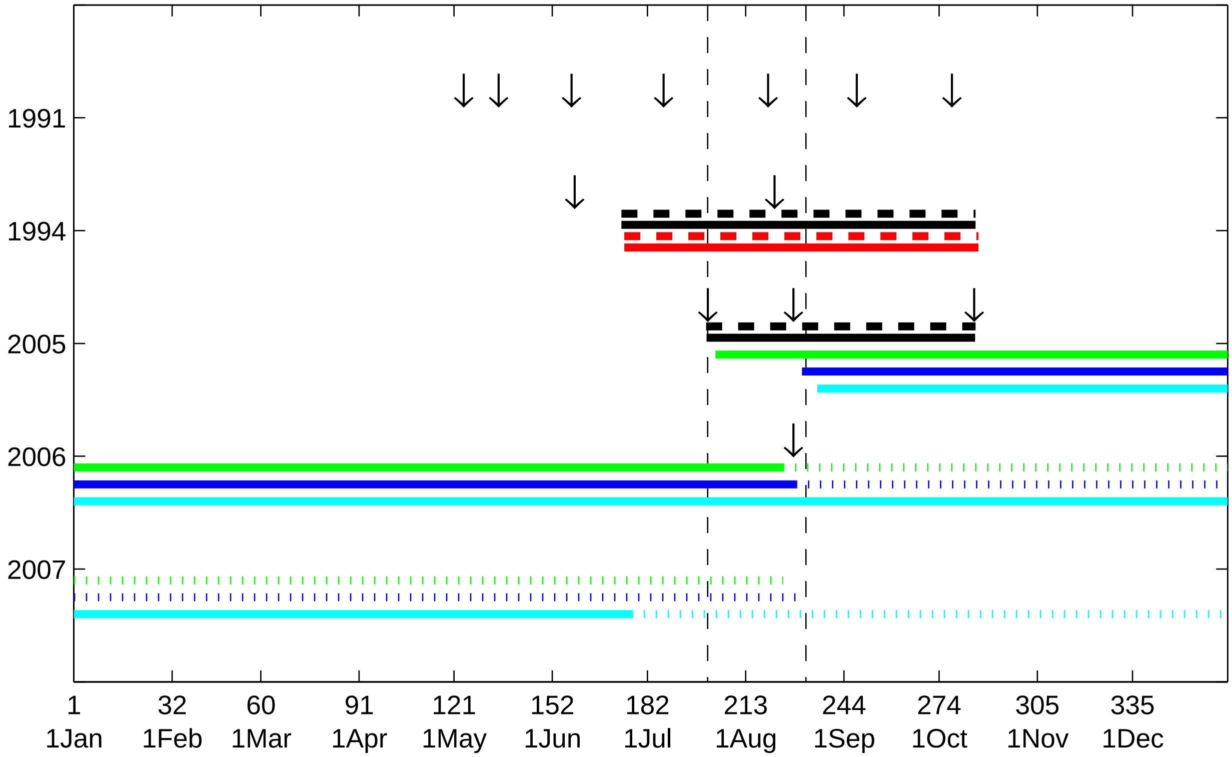


Figure 1.3 Summary of available data for Nechako Reservoir



Legend

Knewstubb Lake near Kenney Dam
Natalkuz Lake
Kenney Dam
Nechako Lodge
Skins Lake

Moored Lake Temperature
Meteorology
Temperature profiles
Data awaiting upload/to be collected

1991 profiles, Knewstubb nr Kenney: 4May 15May 7Jun 6Jul 8Aug 5Sep 5Oct
1994 profiles, 10 stns over Nechako R.: 8Jun 10Aug
2005 profiles, 2X stns Knewstubb/Natalkuz: 20−21Jul 16−18Aug 12−13Oct
2006 profiles, 2X stns Knewstubb/Natalkuz: 16−17Aug

1994 moorings: Kn 22Jun−12Oct, Na 23Jun−13Oct
2005 moorings: Kn 19Jul−12Oct, Na 23Jun−13Oct

MET: ws−wind speed, wd−wind dir, at−air T, rh−relative humidity, sr−solar radiation
Kn94 (ws,wd) Na94 (ws,wd,at,rh,sr)
Kn05 (ws,wd)
Kenney Dam (ws,wd,at,rh,sr) Nechako Lodge (ws,wd)
Skins Lake AES (ws,wd,at,rh) from 22Aug2005

Figure 2.1 Depth contours of Knewstubb Lake

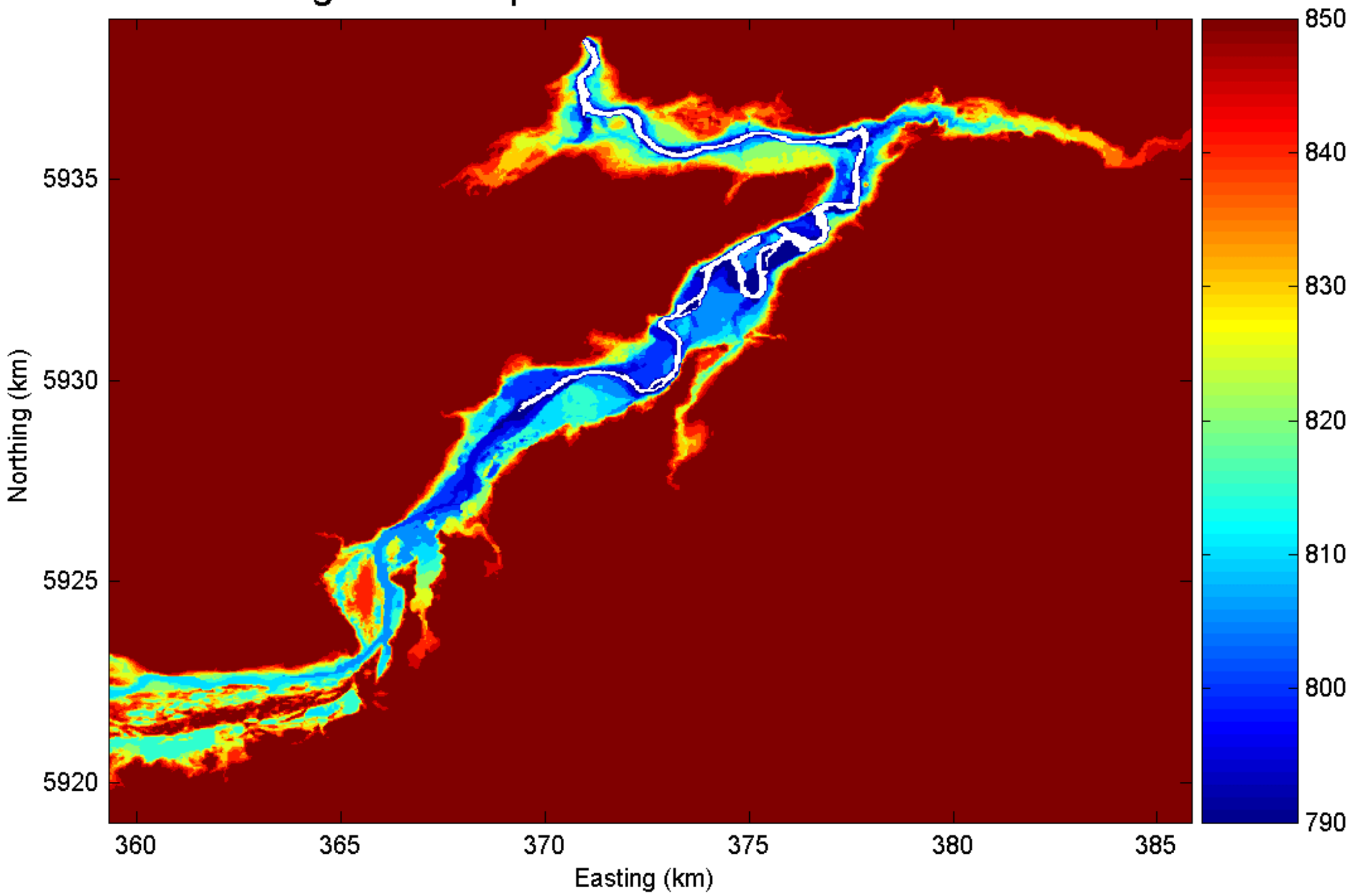


Figure 2.2 Valley depth

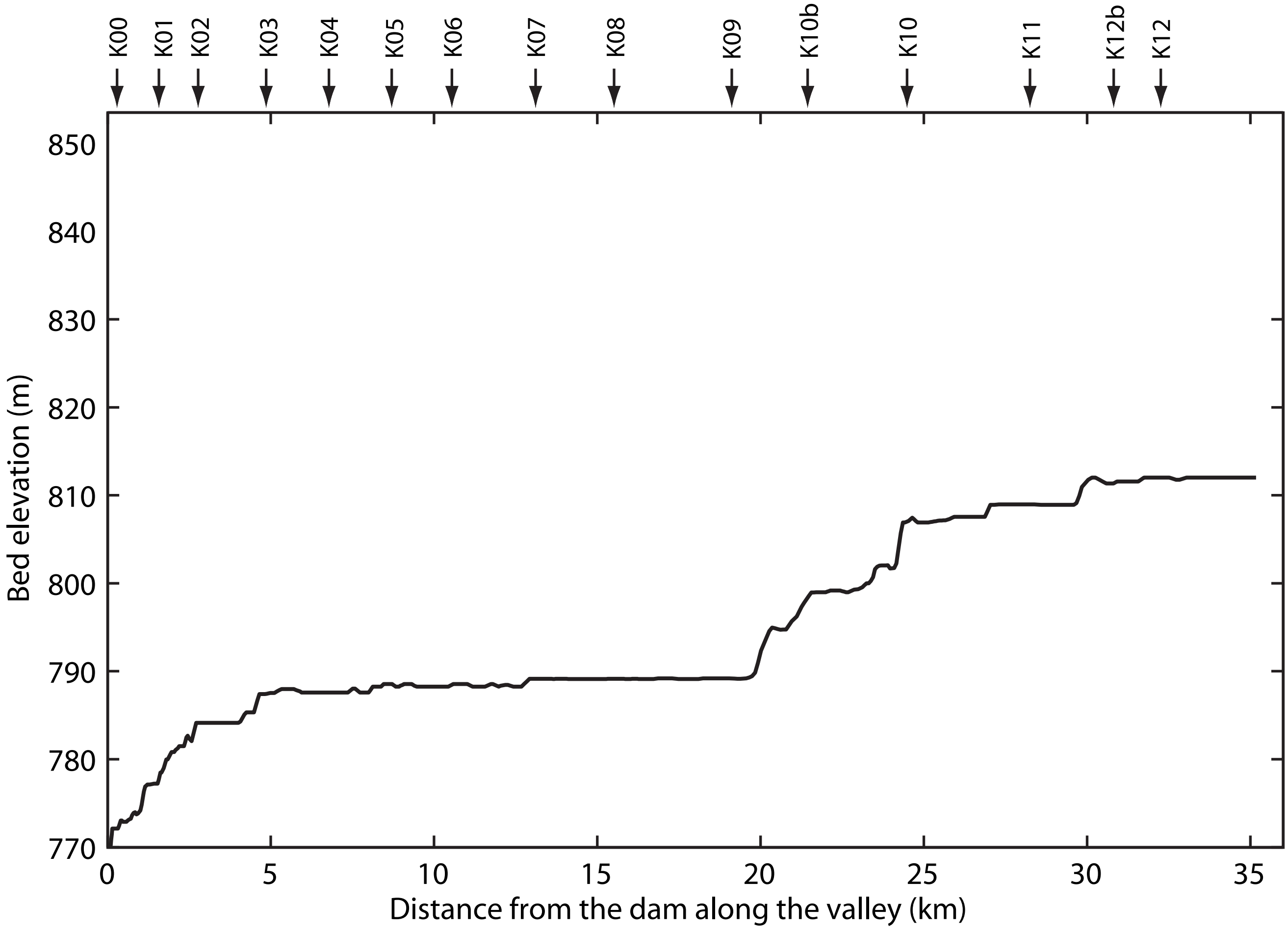


Figure 2.3 Hypsographic curves for Knewstubb Lake

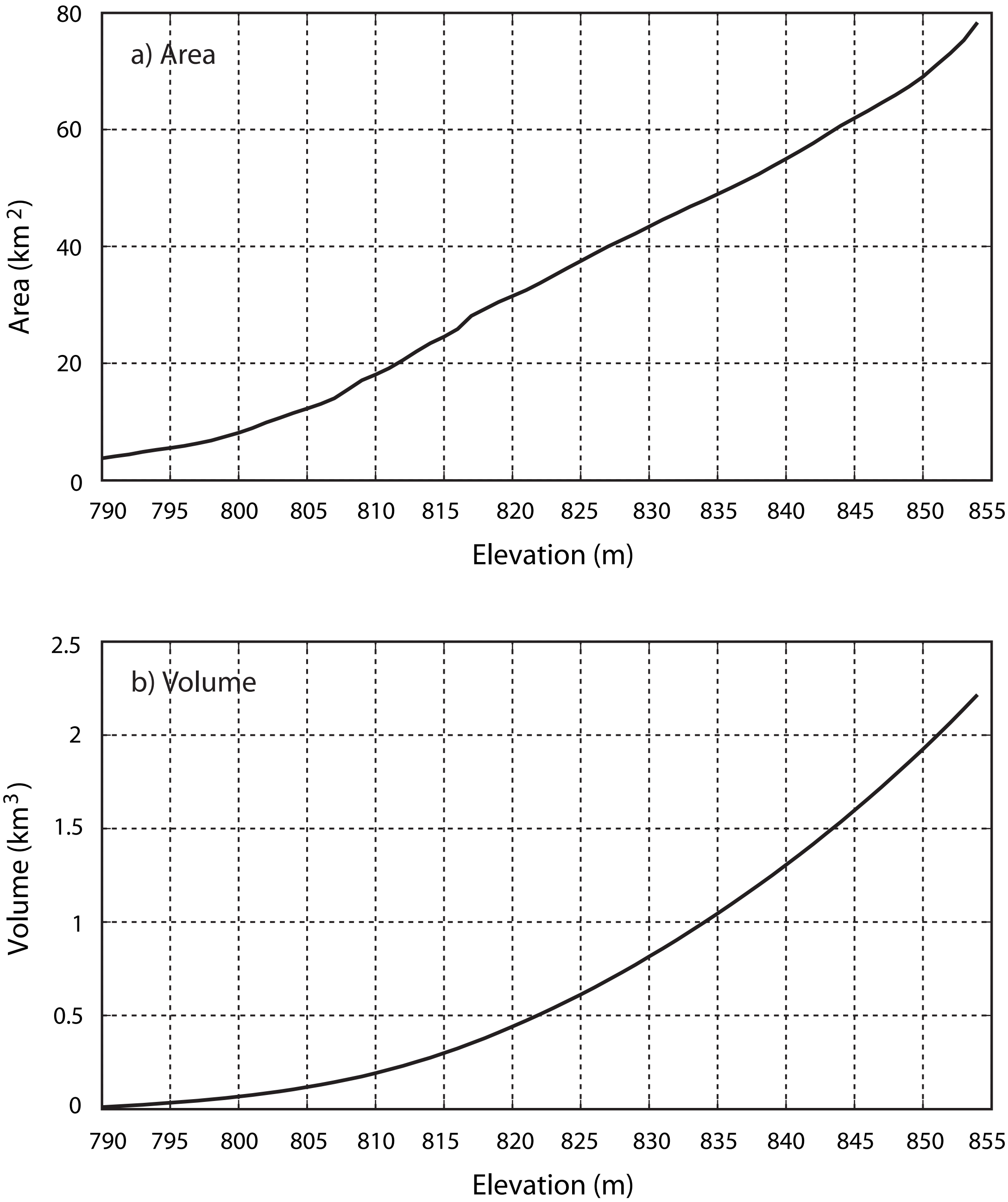


Figure 2.4 Selected sounder transects in Knewstubb Lake

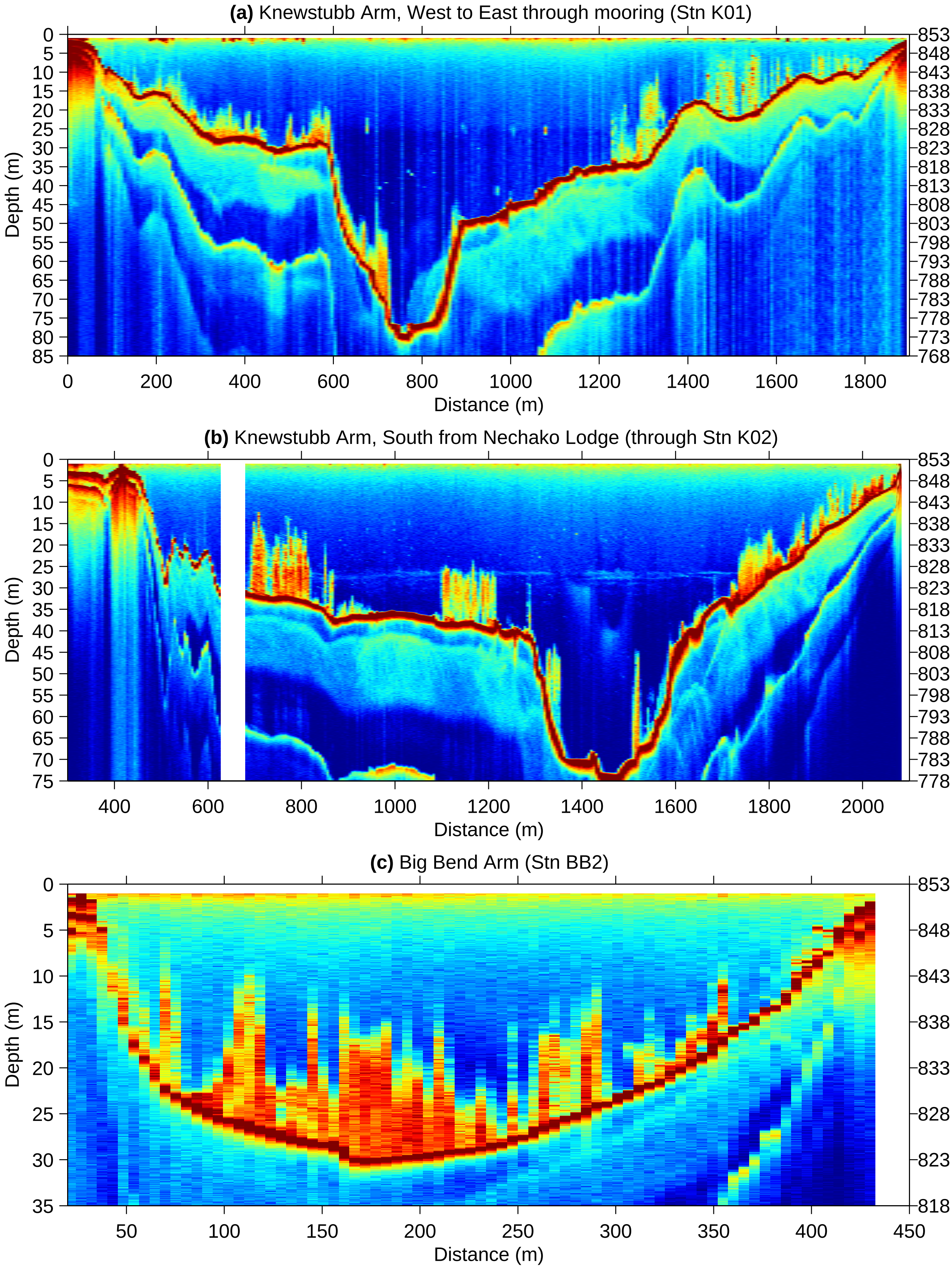


Figure 2.4 Selected sounder transects in Knewstubb Lake(Continued)

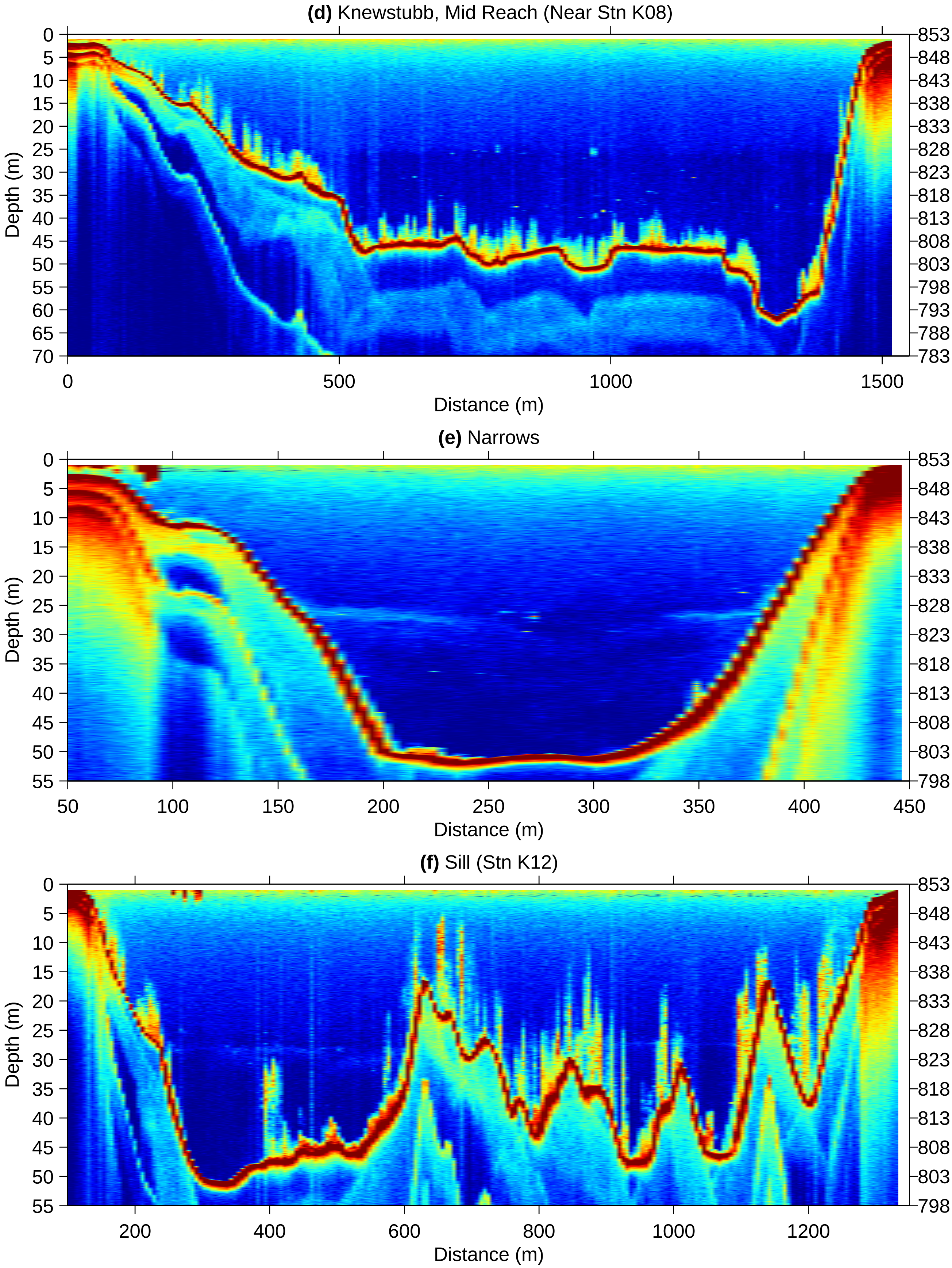


Figure 3.1.1 Knewstubb Lake Meteorological Data, 2005−2006

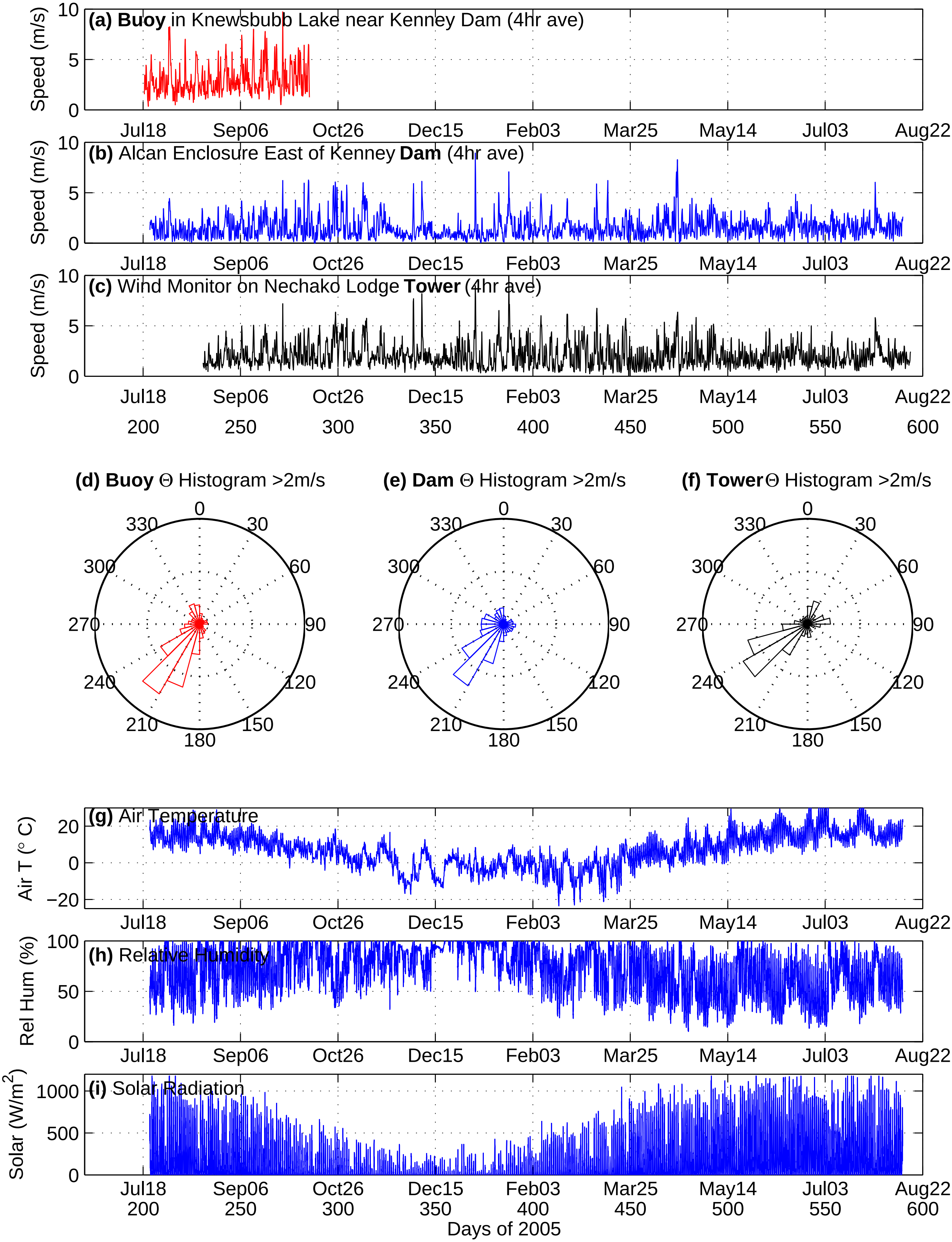


Figure 3.1.2 Knewstubb Lake Met, Summer 2005

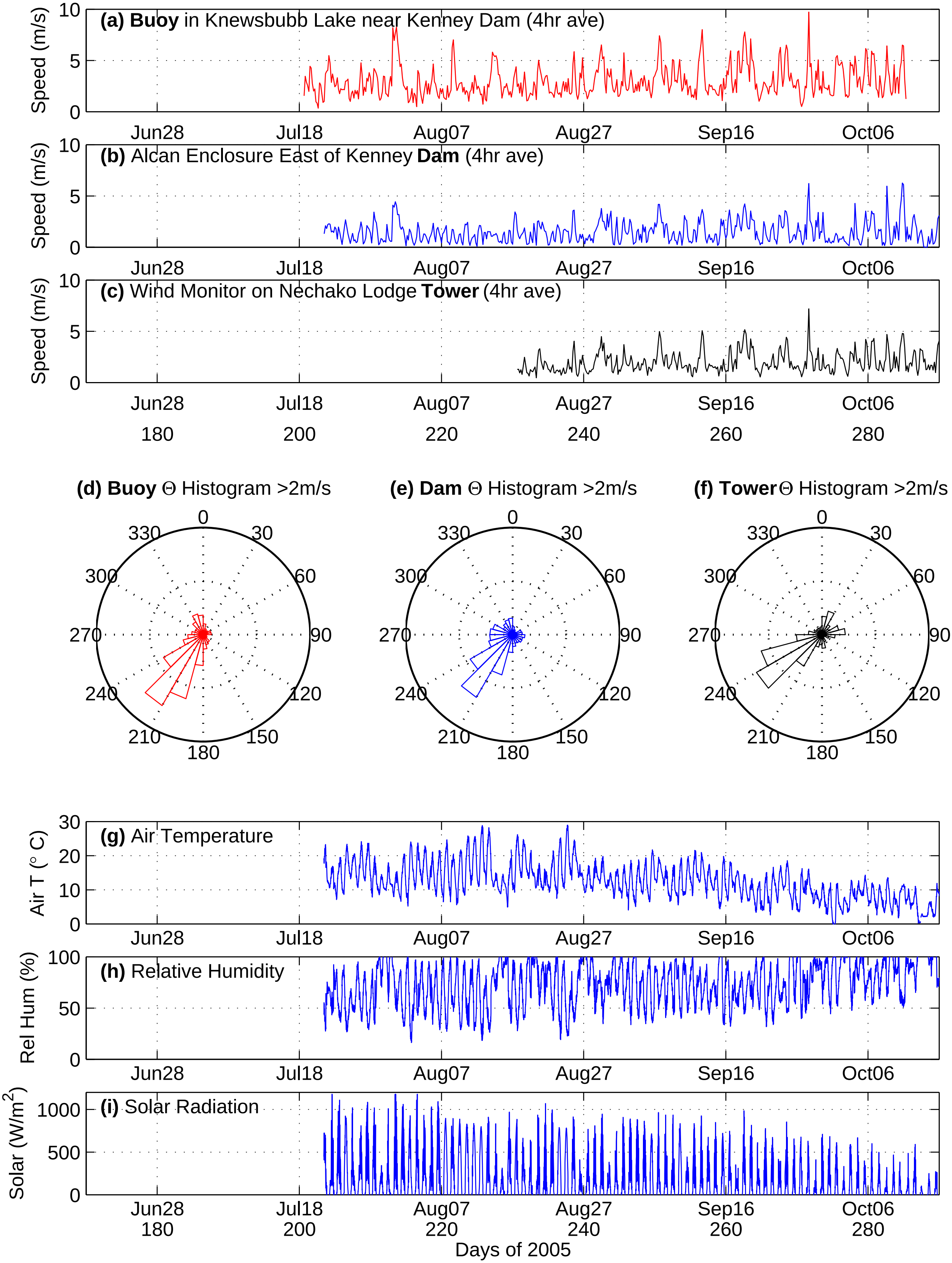
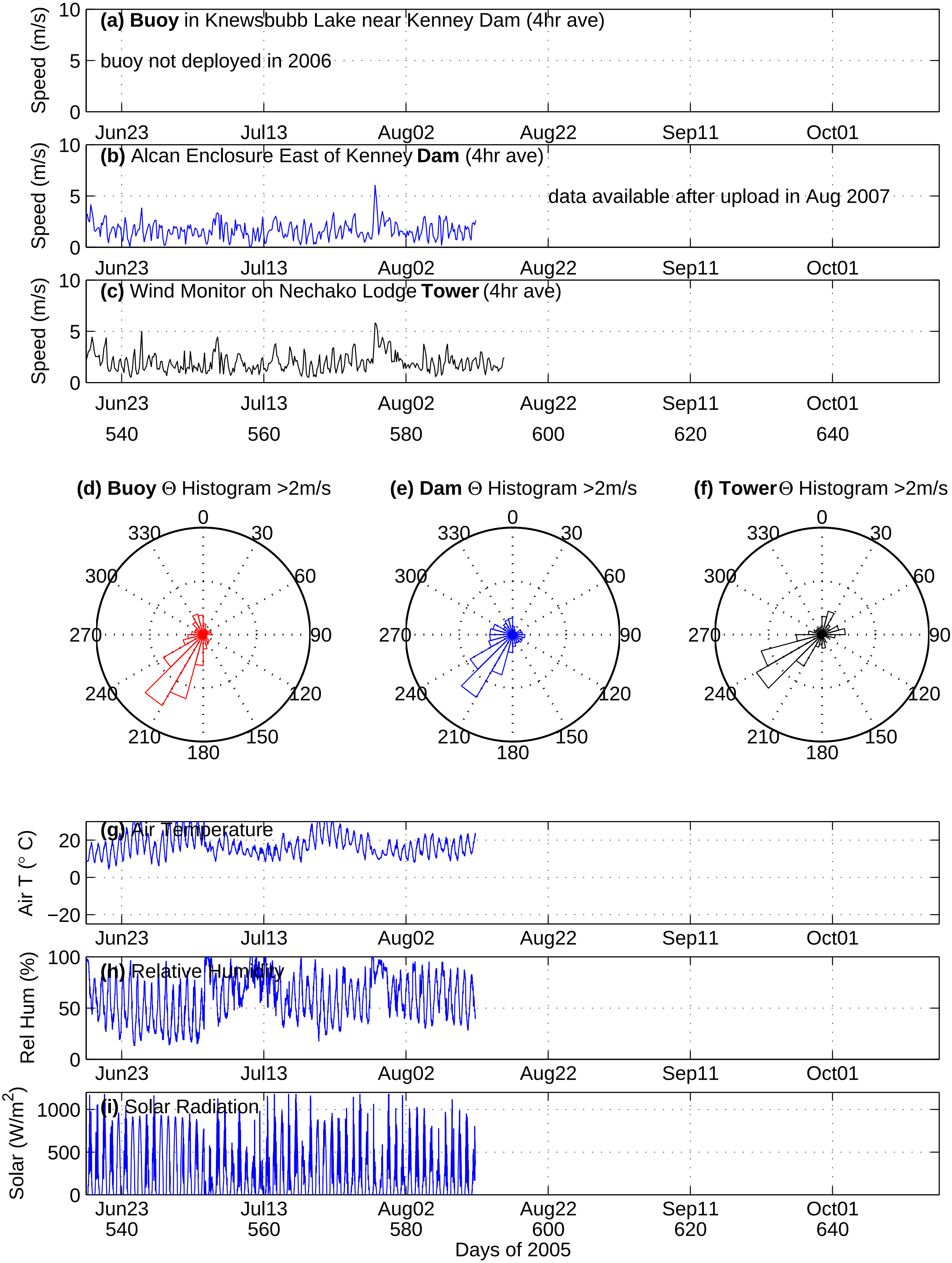


Figure 3.1.3 Knewstubb Lake Met, Summer 2006



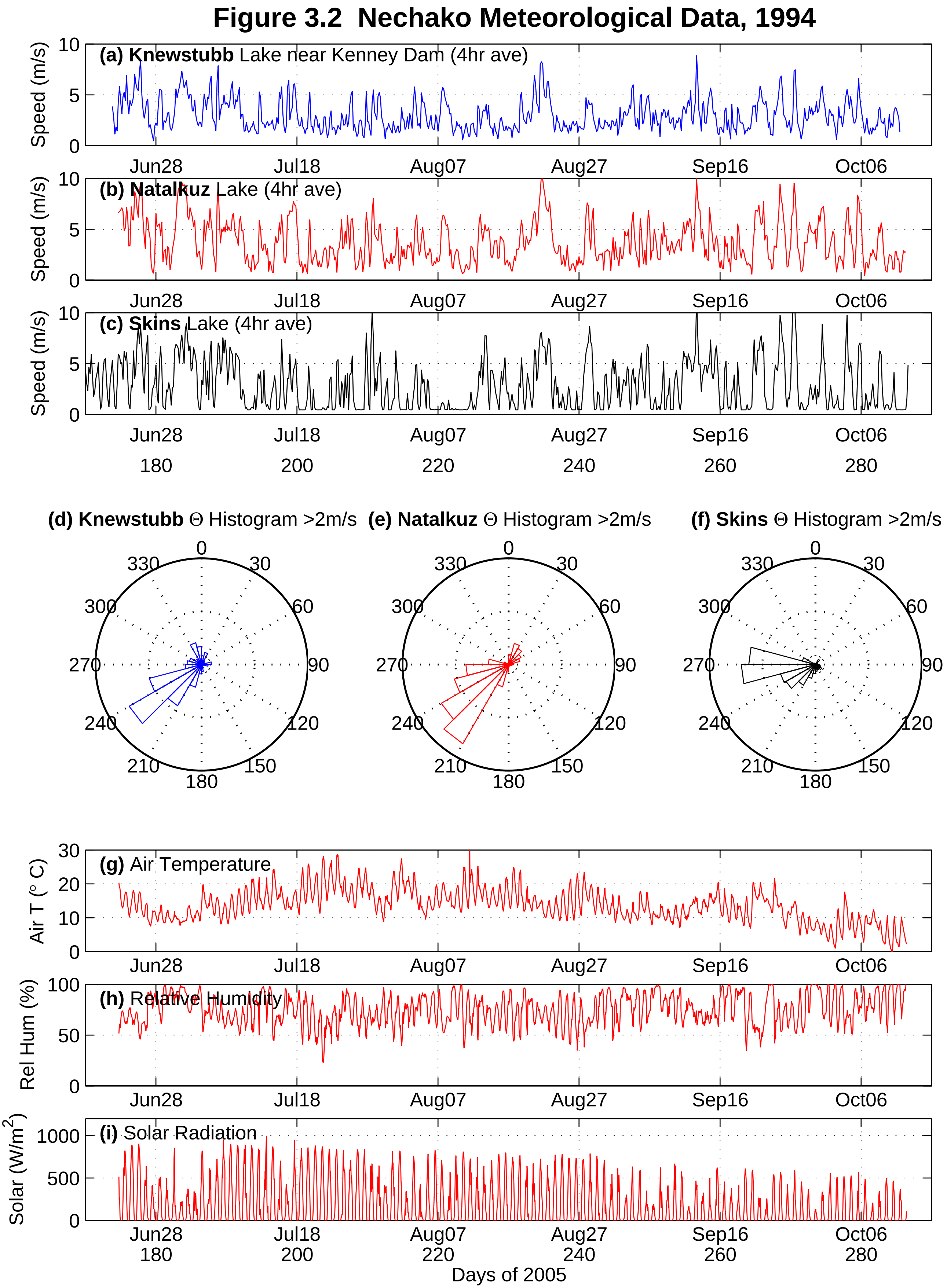


Figure 3.2 Nechako Meteorological Data, 1994
(a) Knewstubb Lake near Kenney Dam (4hr ave)
(b) Natalkuz Lake (4hr ave)
(c) Skins Lake (4hr ave)
Speed (m/s)
0
5
10
Jun28
Jul18
Aug07
Aug27
Sep16
Oct06
180
200
220
240
260
280
(d) Knewstubb Θ Histogram >2m/s
(e) Natalkuz Θ Histogram >2m/s
(f) Skins Θ Histogram >2m/s
0
30
60
90
120
150
180
210
240
270
300
330
(g) Air Temperature
Air T (° C)
0
10
20
30
(h) Relative Humidity
Rel Hum (%)
0
50
100
(i) Solar Radiation
Solar (W/m^2)
0
500
1000
Days of 2005

Figure 4.1 Contours of Water Temperature in Knewstubb Lake, 2005

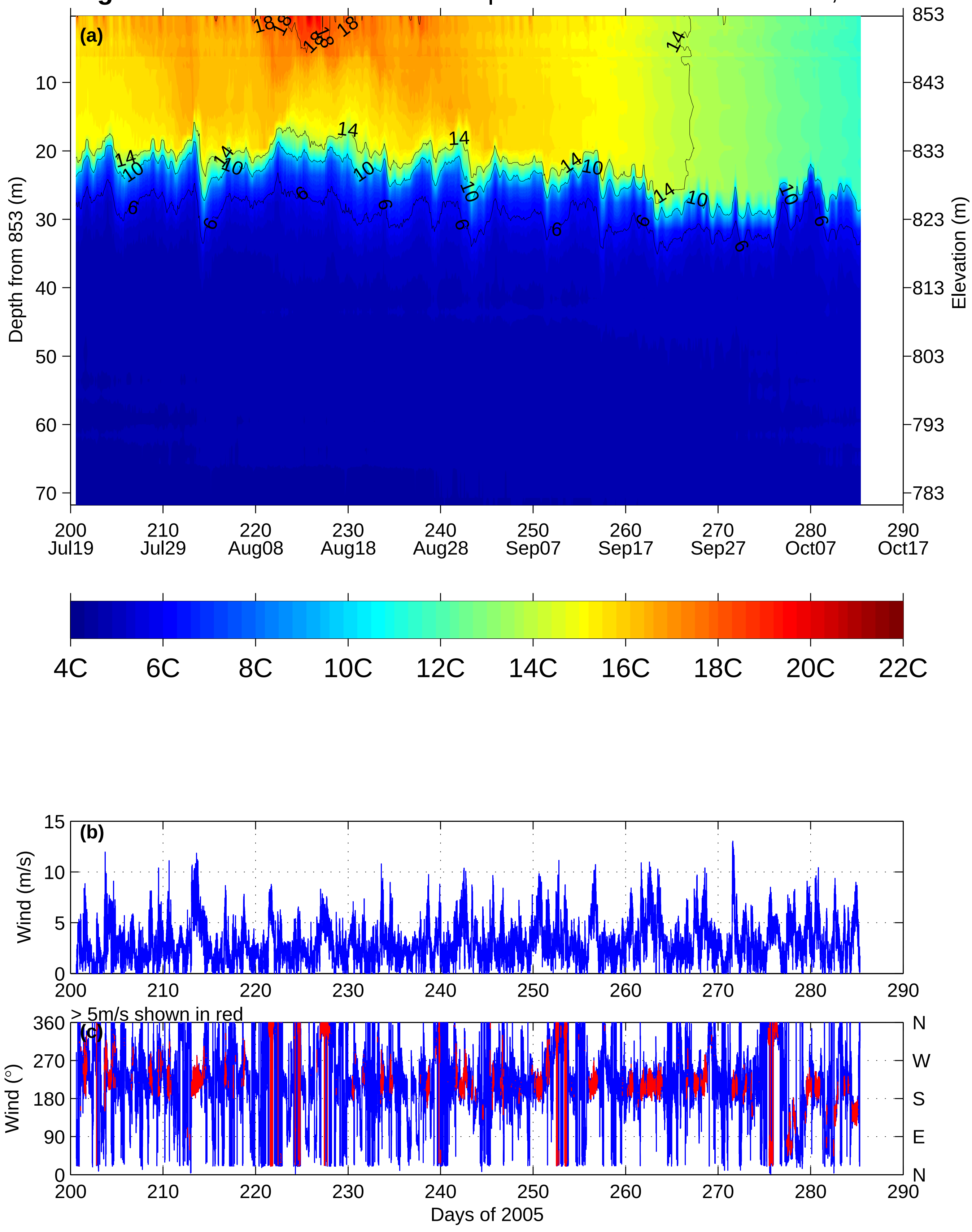


Figure 4.2 Contours of Water Temperature in Knewstubb Lake, 1994

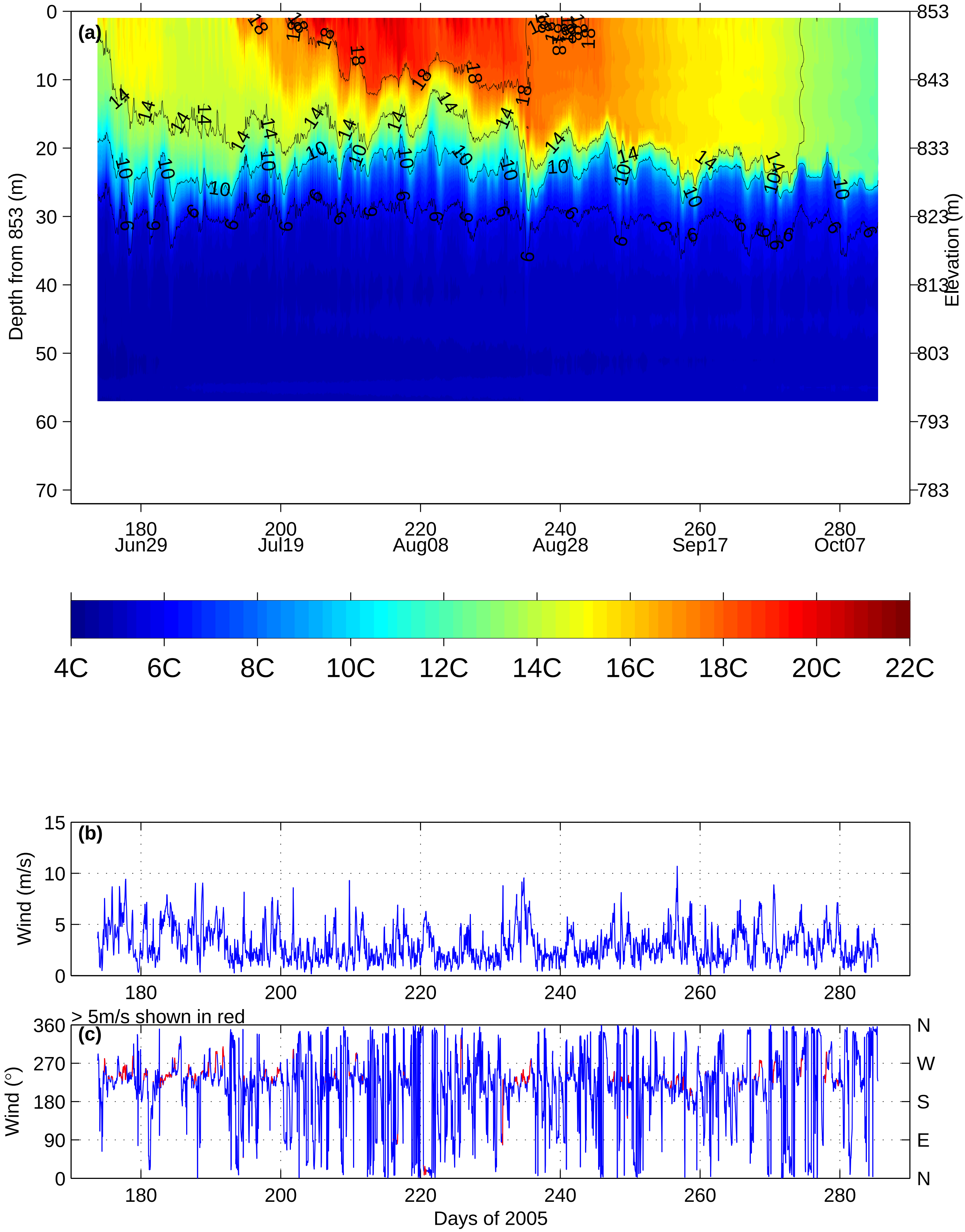


Figure 4.3 Contours of Water Temperature in Natalkuz Lake, 1994

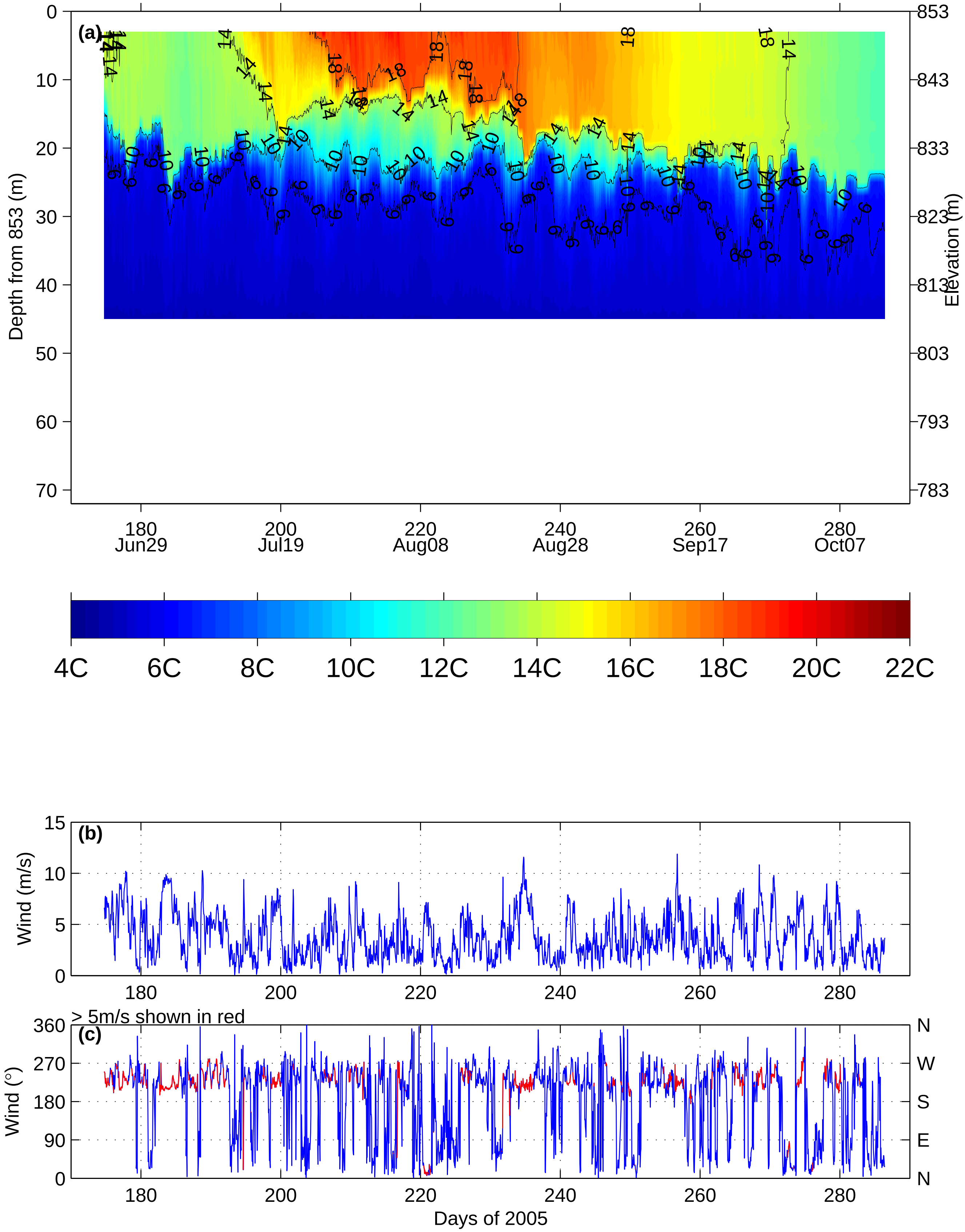


Figure 5.1 Temperature surveys, 2005 & 2006: Contour plots

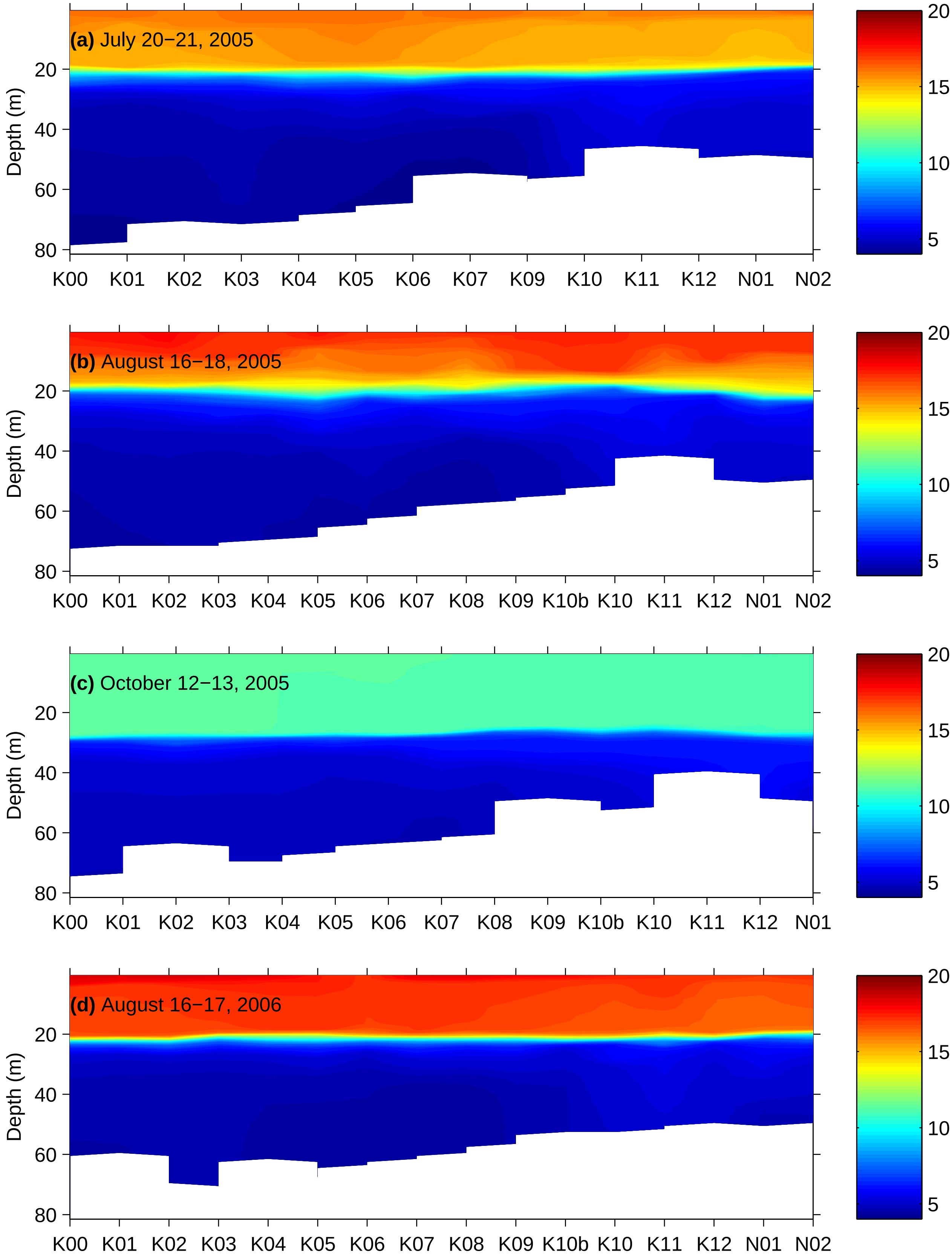


Figure 5.2 Knewstubb Lake Temperature Surveys, 2005 & 2006 − Line Plots

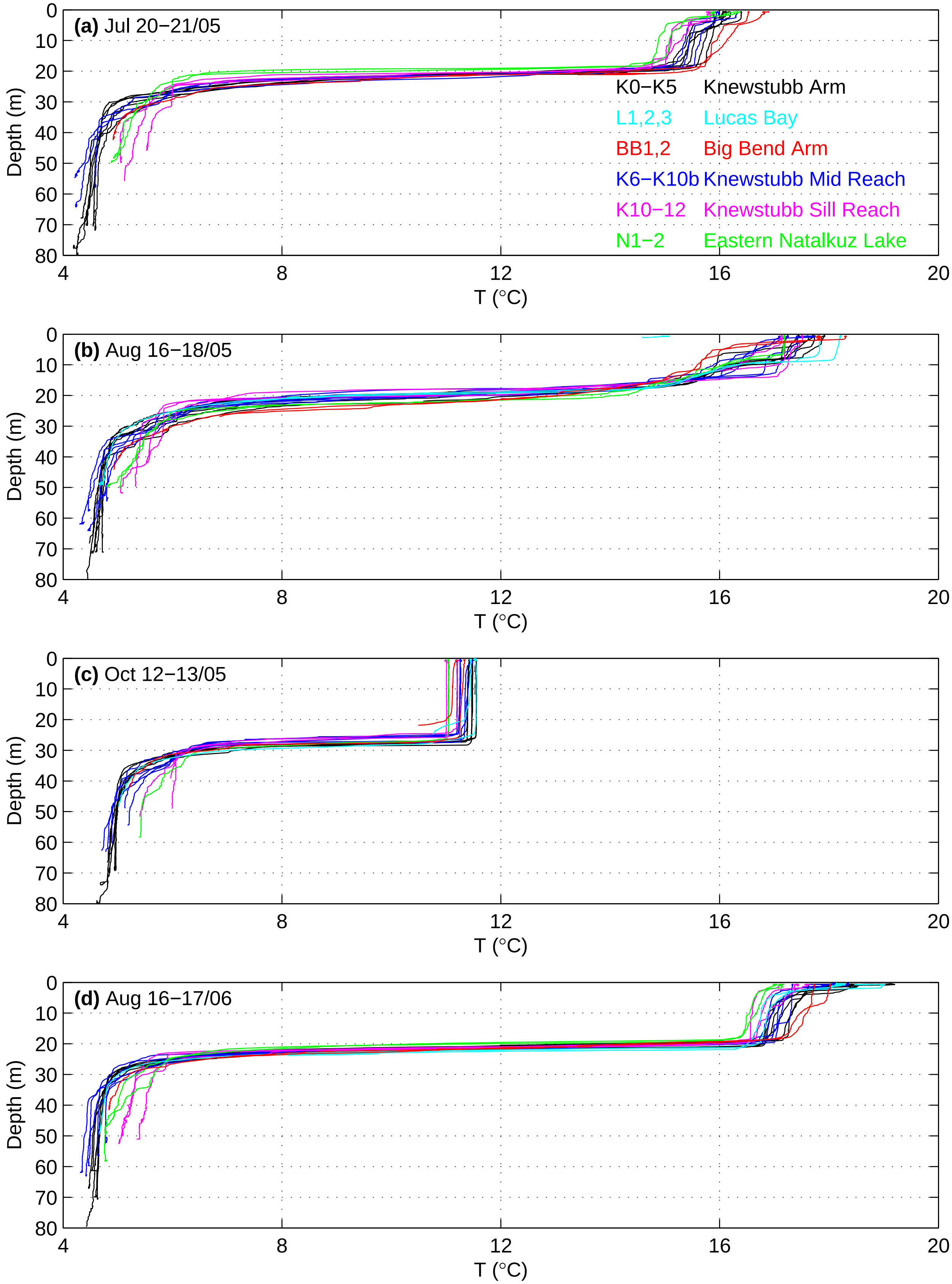


Figure 5.3 Temperature surveys of the Nechako Reservoir, 1994

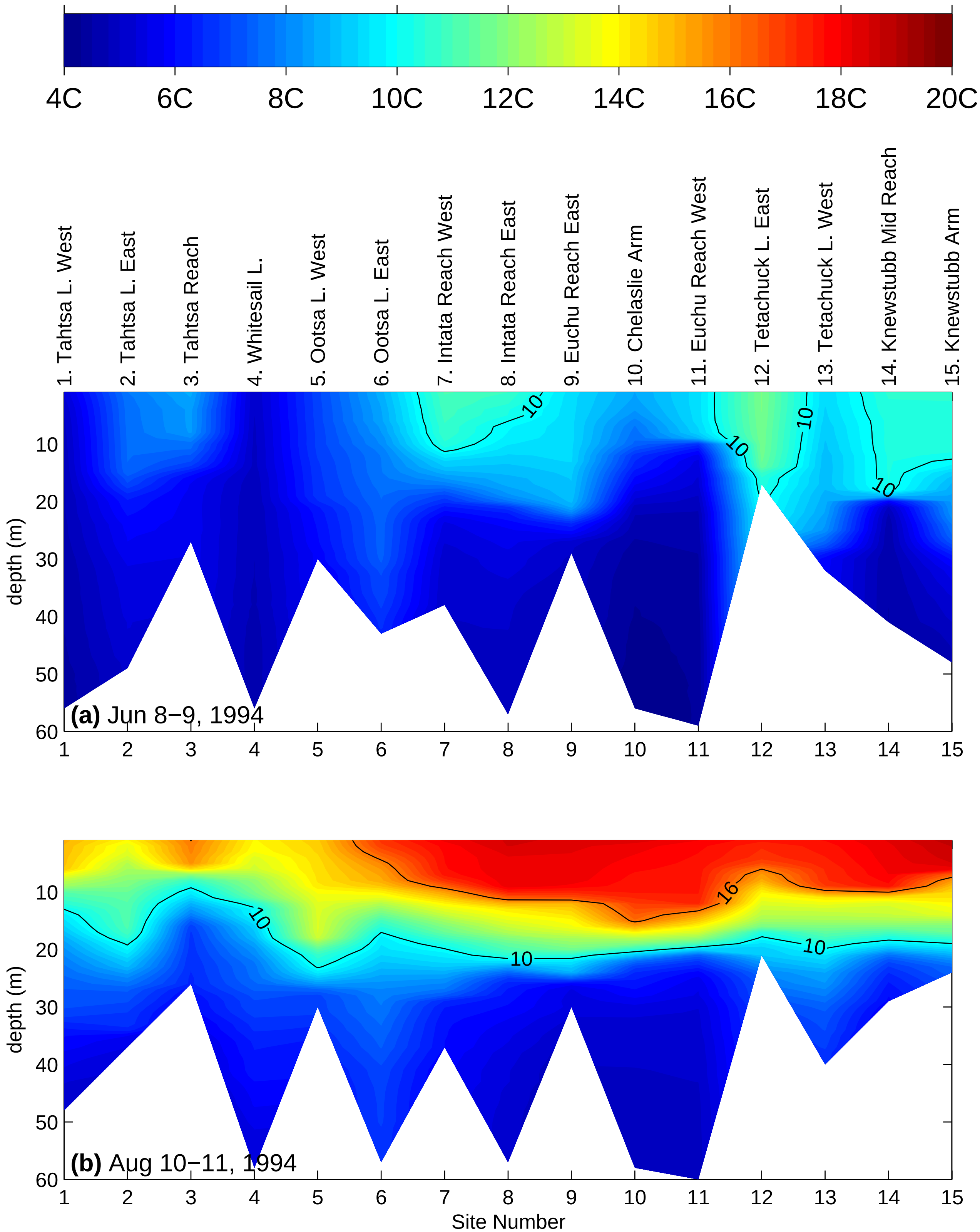


Figure 5.4 Temperature in Knewstubb L. near Kenney Dam, May to Oct, 1991

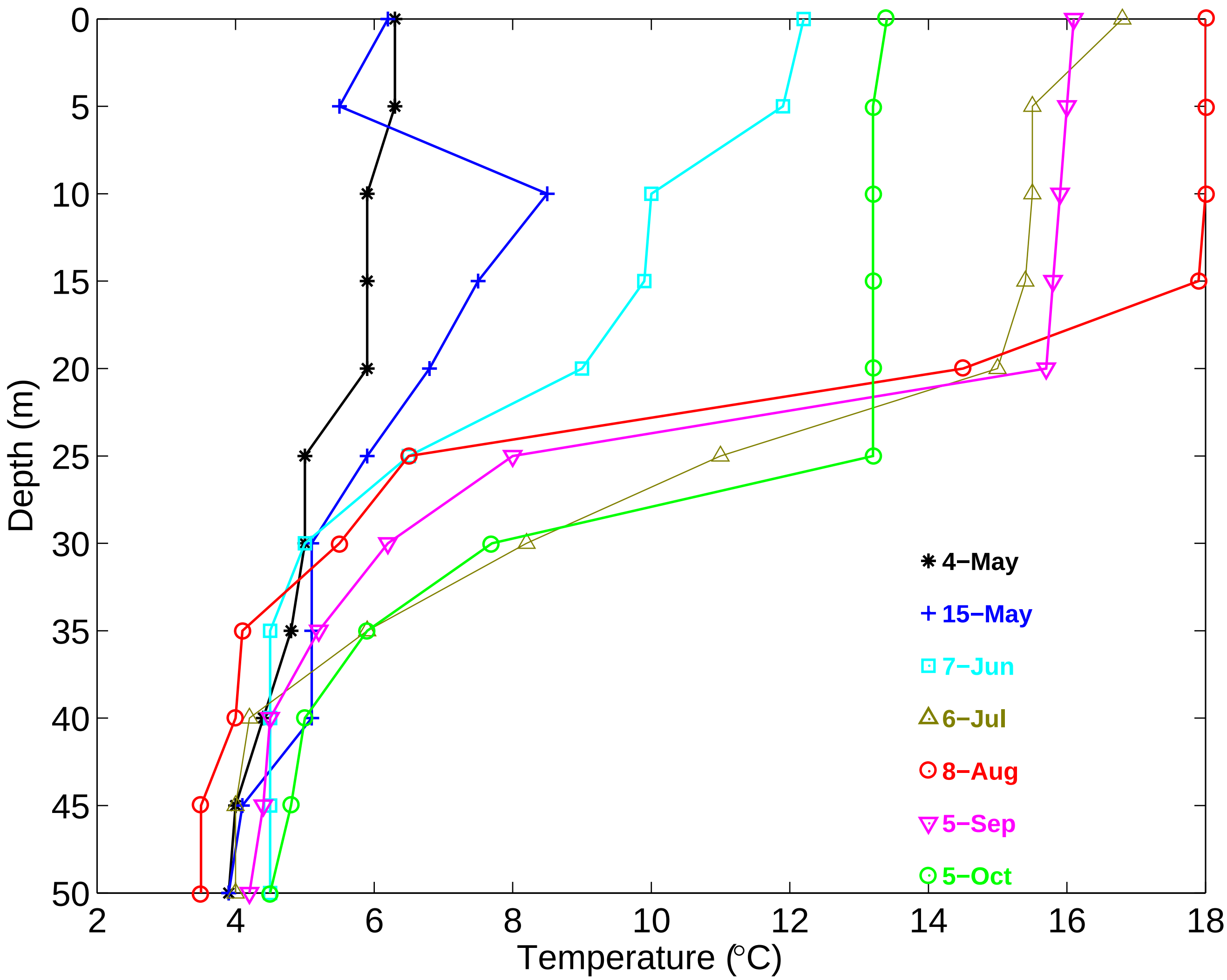
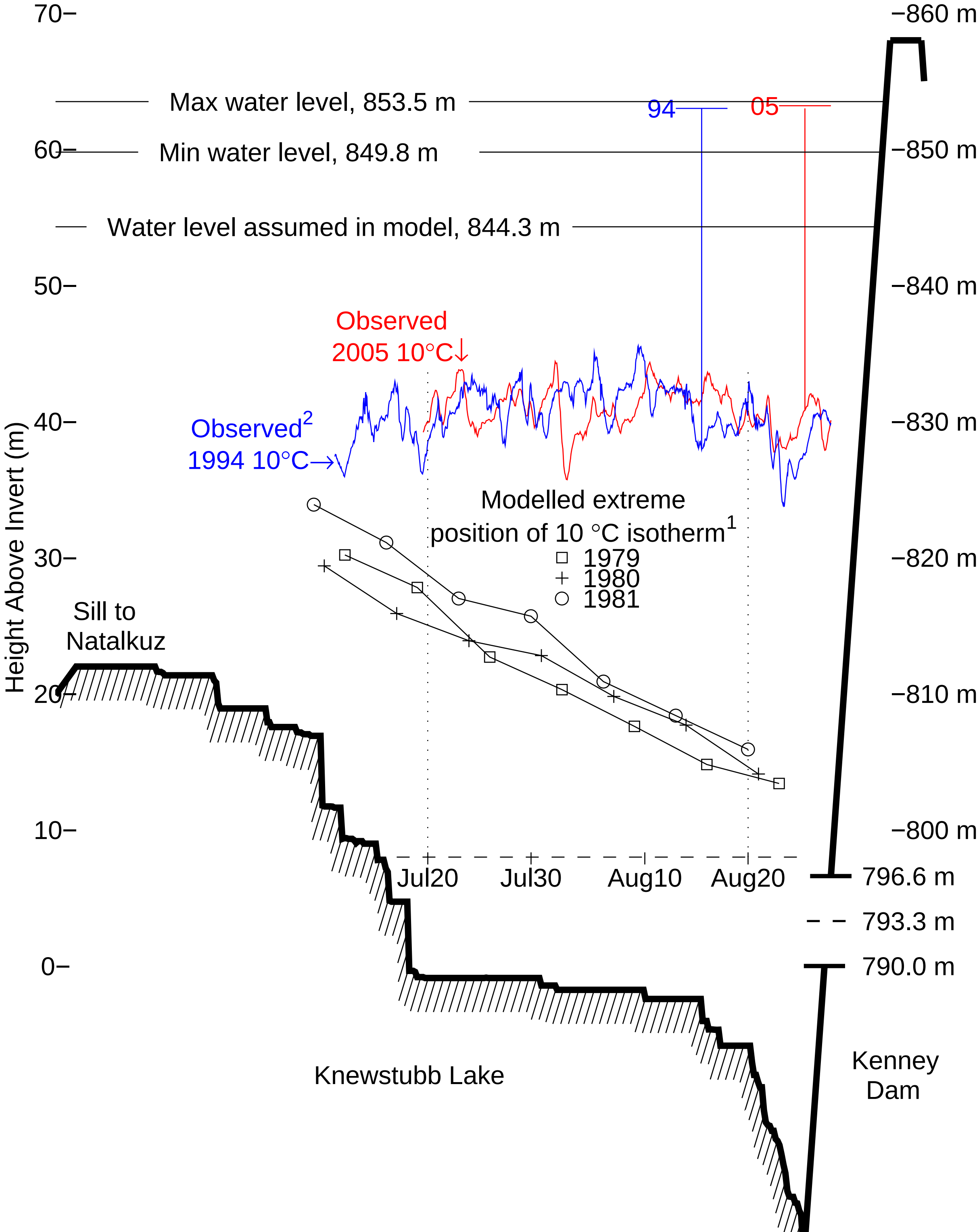


Figure 6.1 Schematic of Knewstubb Lake and Kenney Dam showing bathymetry, water levels and the 10°C isotherm



[1] Triton Env. Consultants, 1992. Supplementary extreme conditions modelling: documentation of reservoir temperatures under 170 m^3/s maximum outflows. 26pp. Surface at 844.3 m.

[2] Triton Env. Consultants, 1995. Nechako Res. additional data collection. 43pp.

Figure 6.2 Nechako Reservoir Water Level, 1996−2006

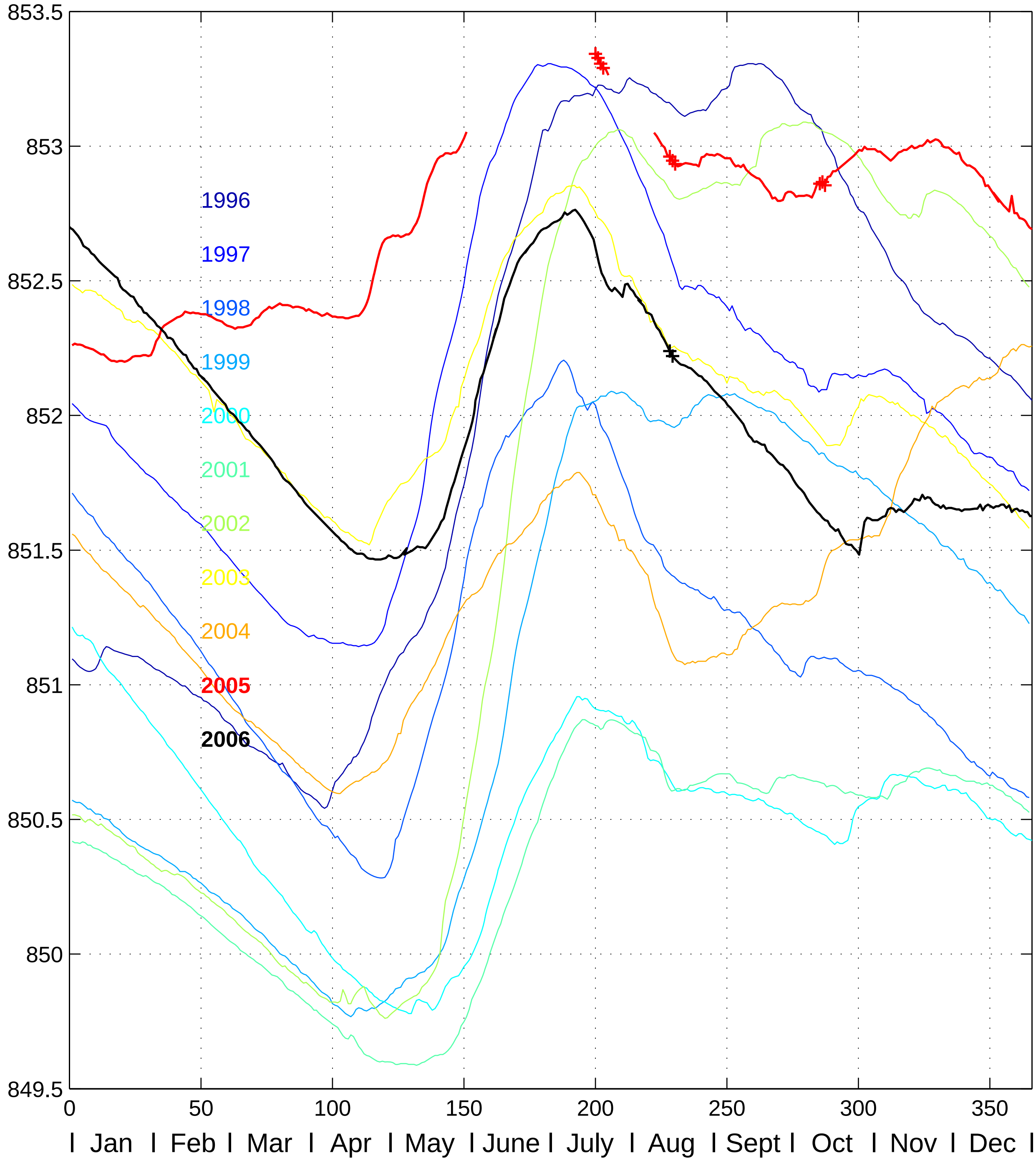
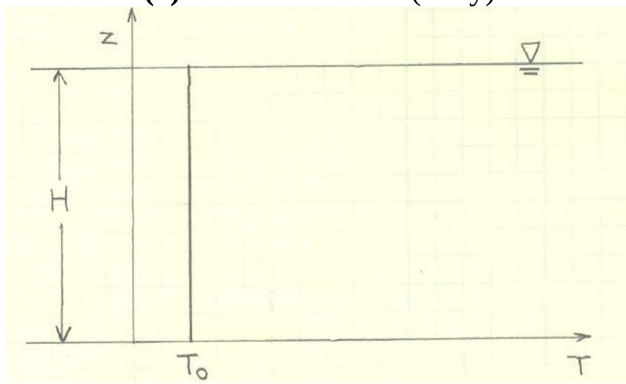
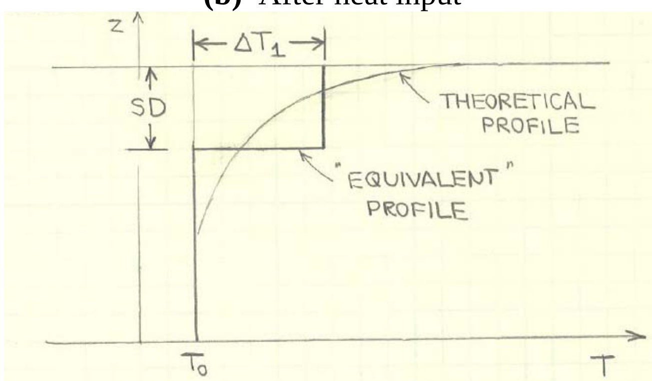


Figure 6.3 Conceptual model of heat input and wind mixing

(a) Initial condition (daily)



(b) After heat input



(c) After wind mixing

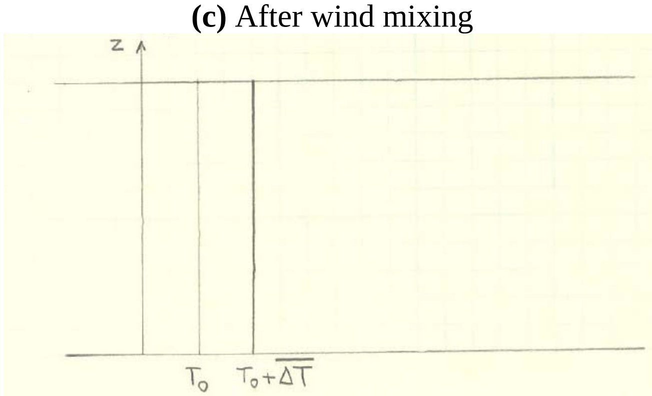


Figure 6.4 Daily average cloud−free solar insolation at Nechako Reservoir

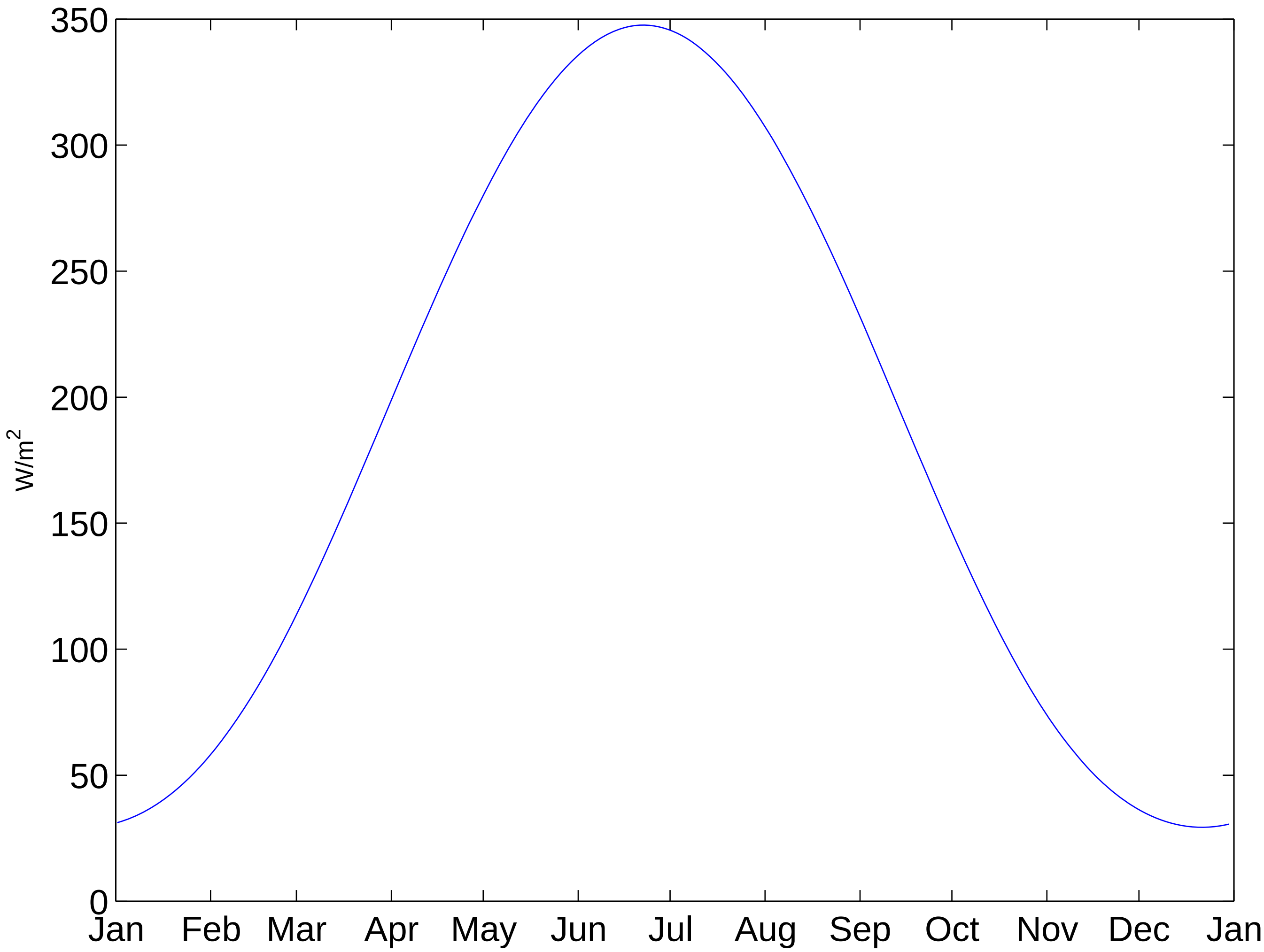


Figure 6.5 Observed and modelled temperatures, summer 1994 (a) Knewstubb, (b) Natalkuz and (c) DYRESM

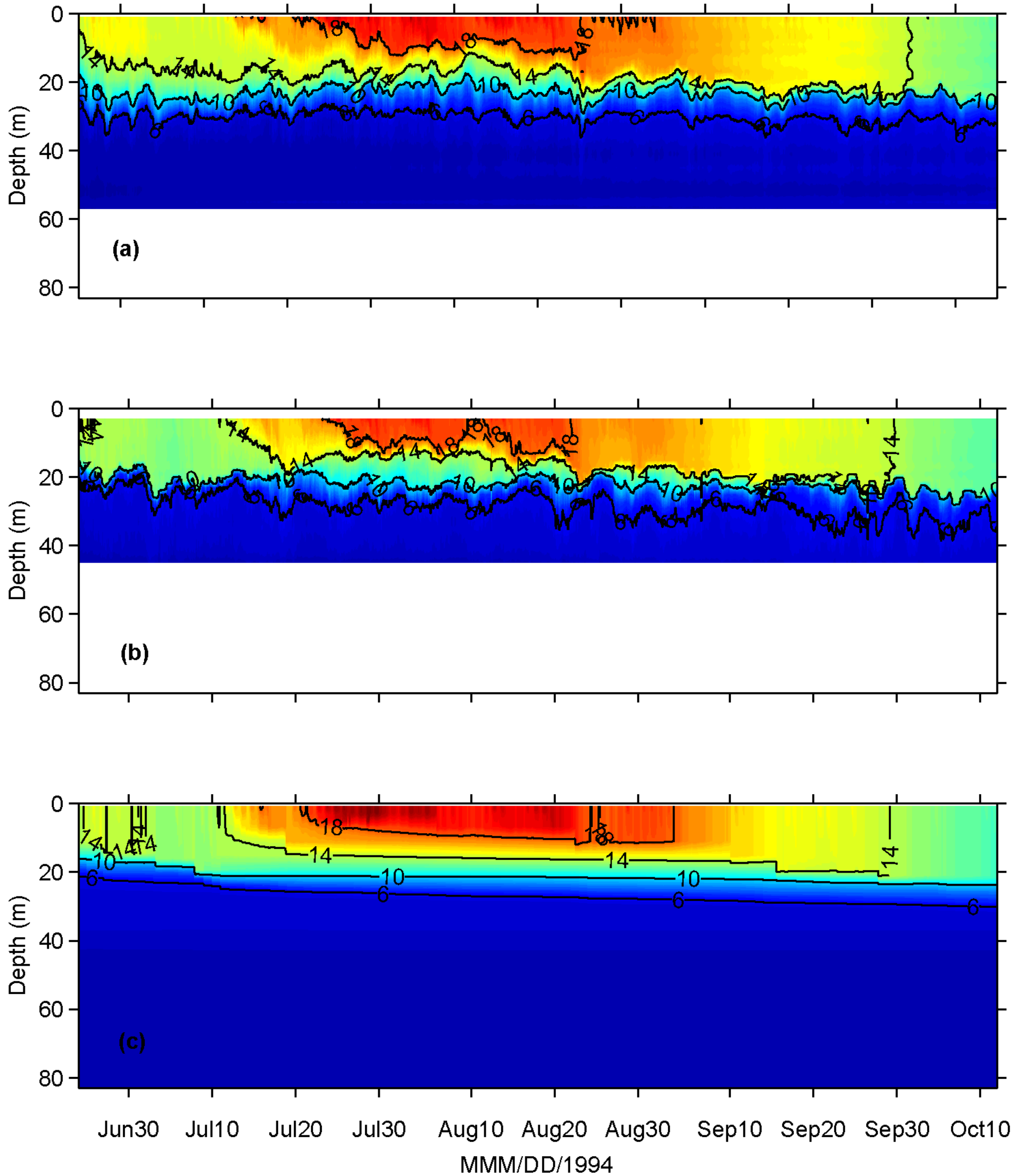


Figure 6.6 Comparison of observations (black) and model results (red) for (a) surface and deep temperature (40 m), (b) depth of the 10 ºC isotherm and (c) total heat content. Knewstubb (dashed black) and Natalkuz (solid black).

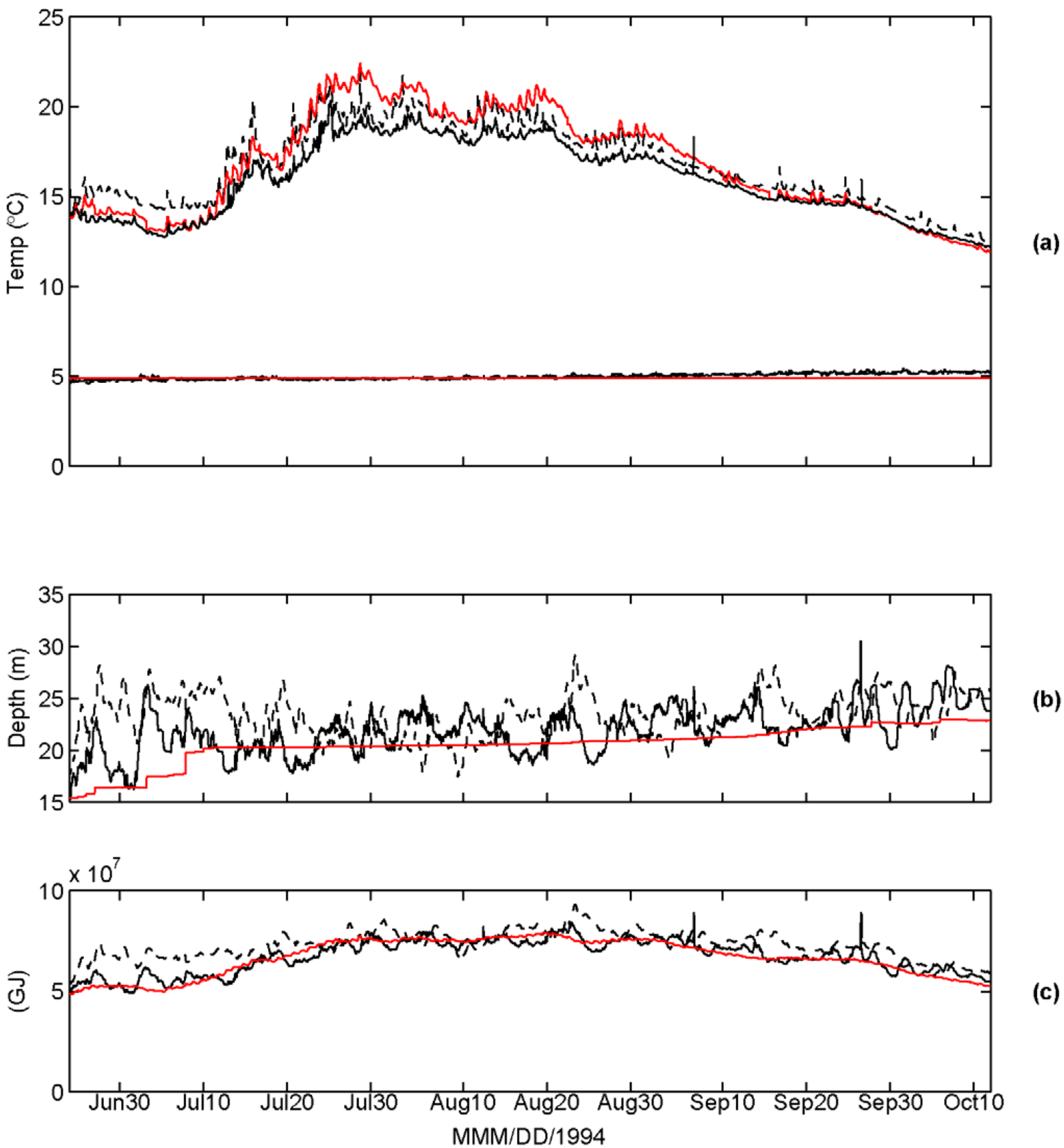


Figure 6.7 Effective wind speed, u_{eff}, during a storm in April 2006, calculated using,

$$u_{eff} = \sqrt[3]{\frac{1}{2N}\sum_{i=1}^{N}(u_T^3 + u_D^3)}$$

where u_T is the wind speed at the tower, and u_D is the wind speed at the dam.

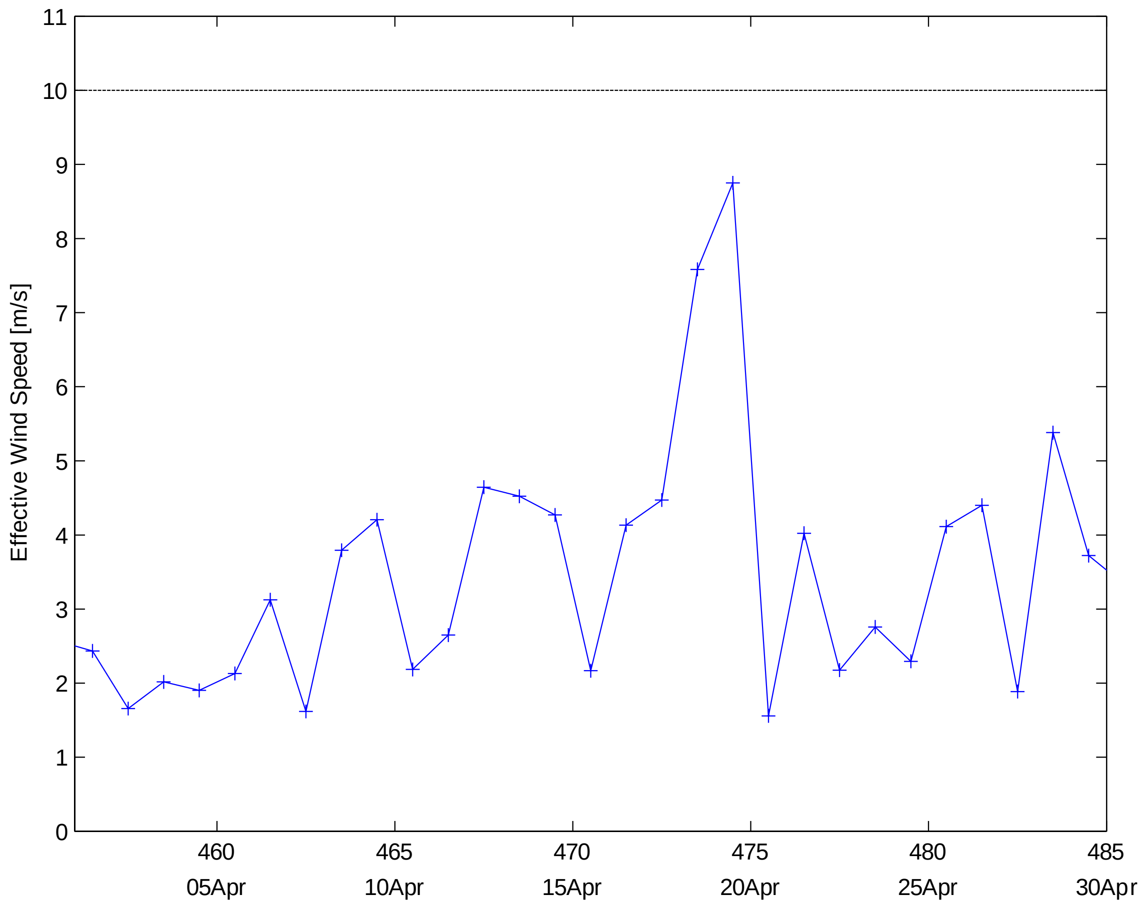


Figure 6.8 Effect of withdrawal and a storm on water temperature in Knewstubb Reservoir. **(a) wind** in Natalkuz Lake, 1994, including an exploratory wind of 10 m/s for 5 and 6 Jul 1994 (grey shade), **(b) default** DYRESM for summer 1994, **(c) withdrawal**, **(d) storm** applied on July 5 and 6, **(e) both** withdrawal and storm.

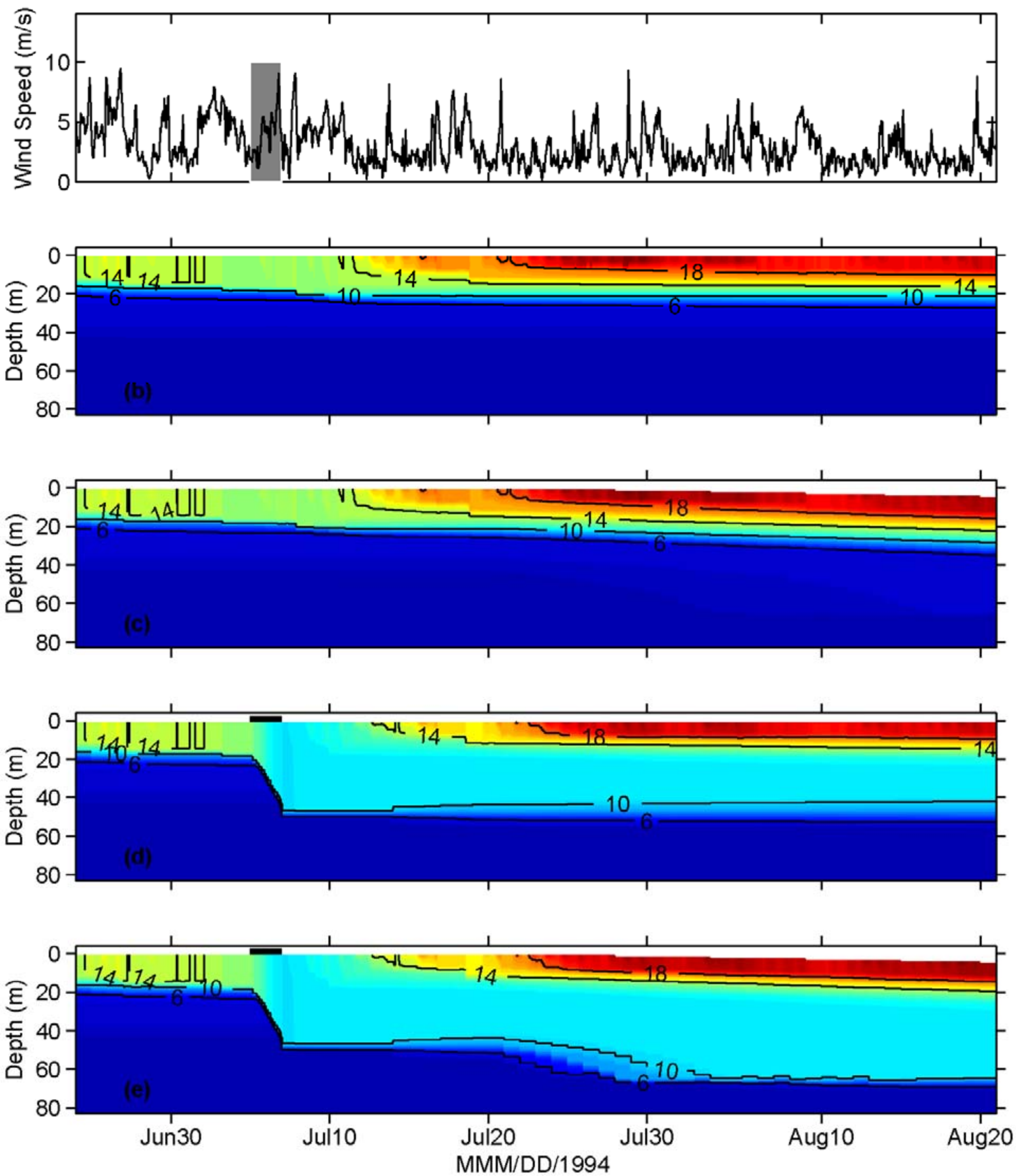
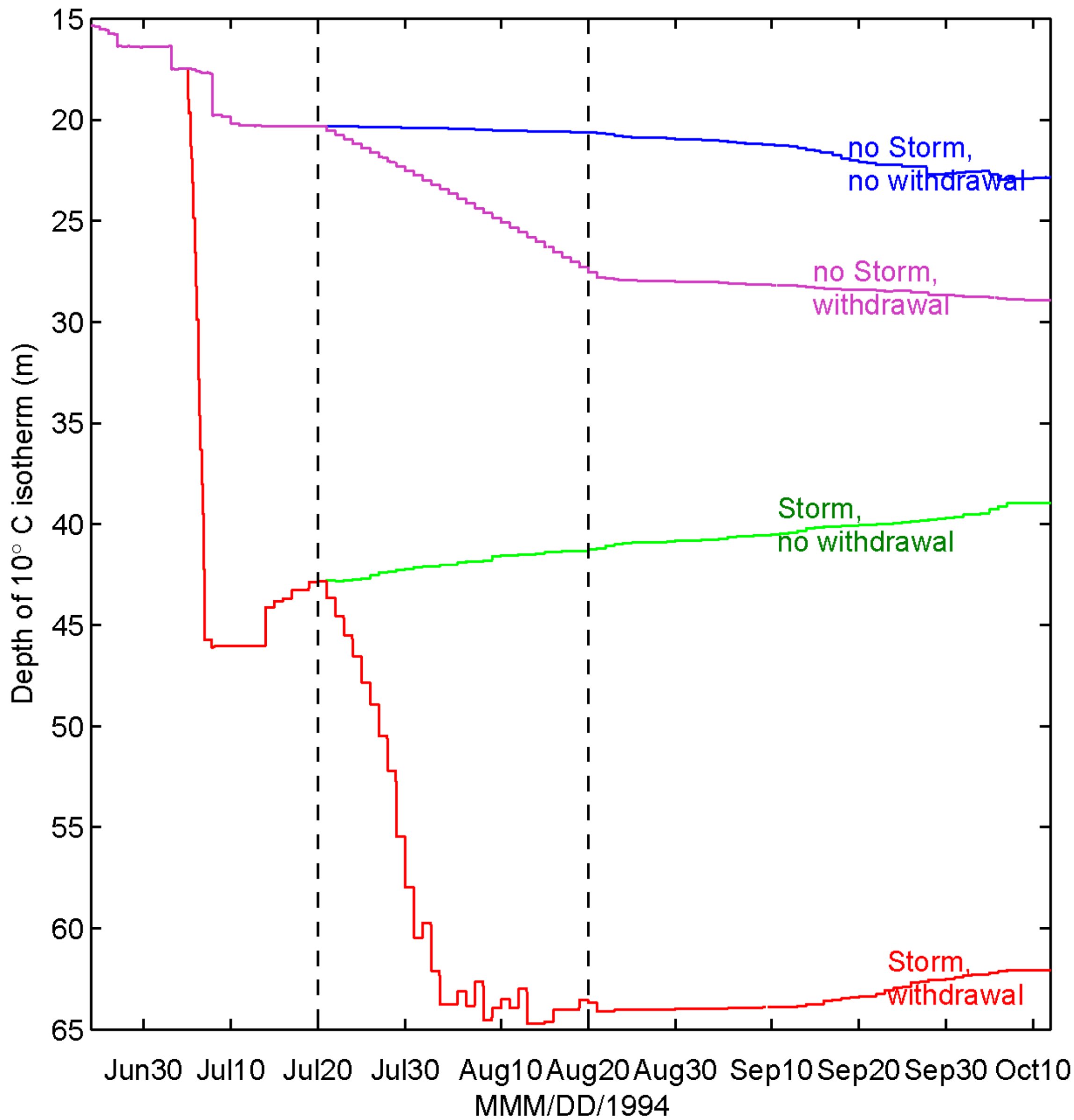


Figure 6.9 (a) Depth of 10 ºC isotherm and (b) withdrawal temperature for different cases.

(a)



(b)

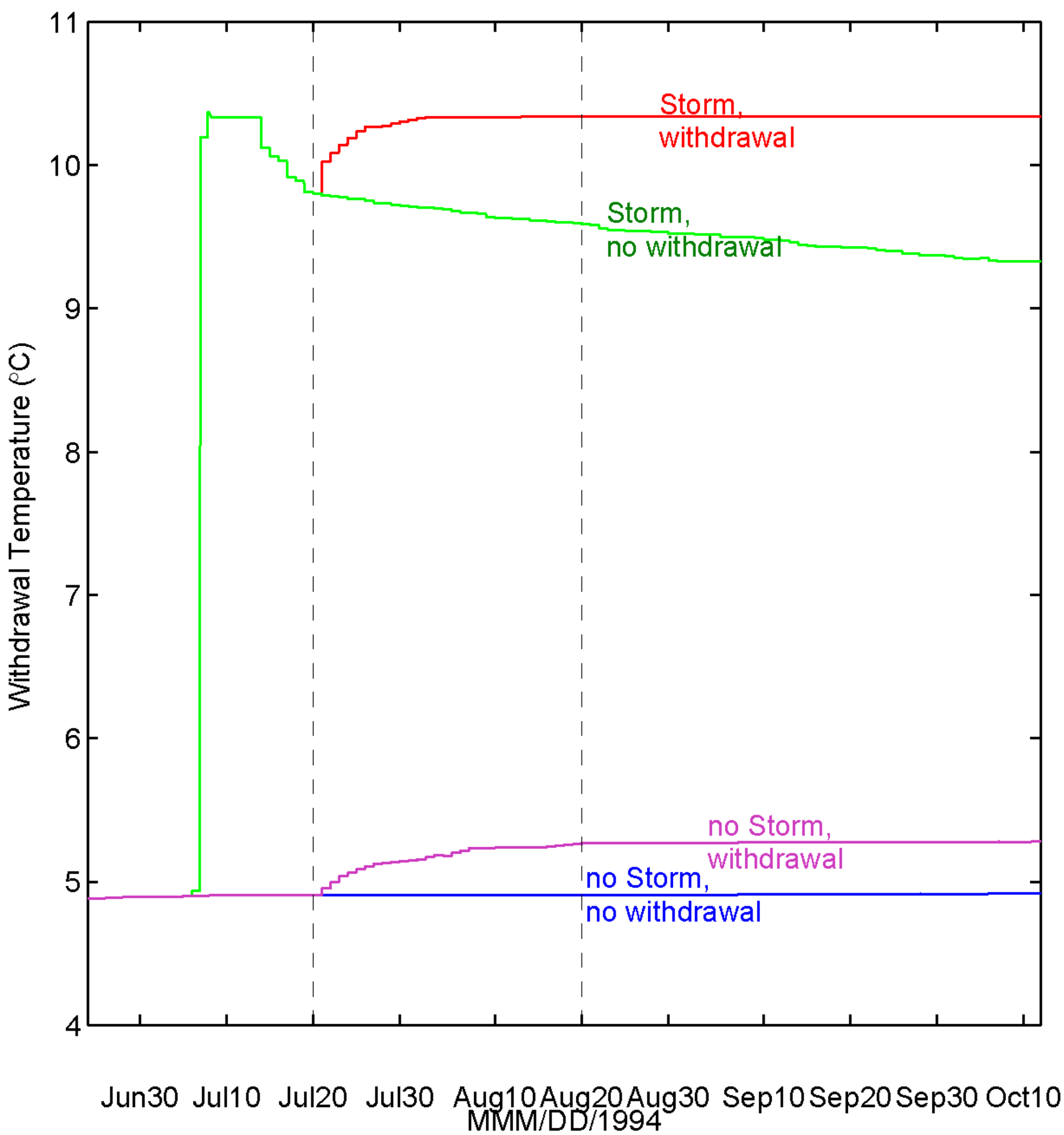

Storm,
withdrawal
Storm,
no withdrawal
no Storm,
withdrawal
no Storm,
no withdrawal
Withdrawal Temperature (°C)
11
10
9
8
7
6
5
4
Jun30
Jul10
Jul20
Jul30
Aug10
Aug20
Aug30
Sep10
Sep20
Sep30
Oct10
MMM/DD/1994

Figure 7.1 ELCOM grid

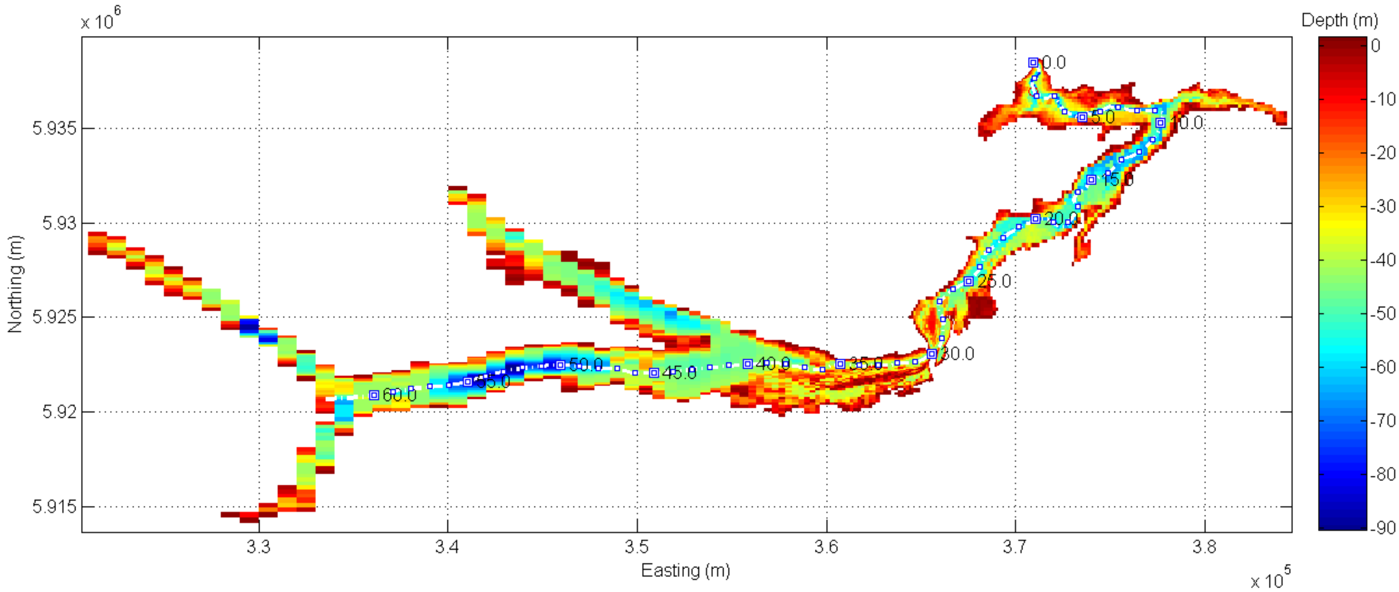


Figure 7.2 (a) Wind speed, **(b)** wind direction and comparison of observed and modelled temperature structure in **(c)** Knewstubb and **(d)** Natalkuz (Run 10A).

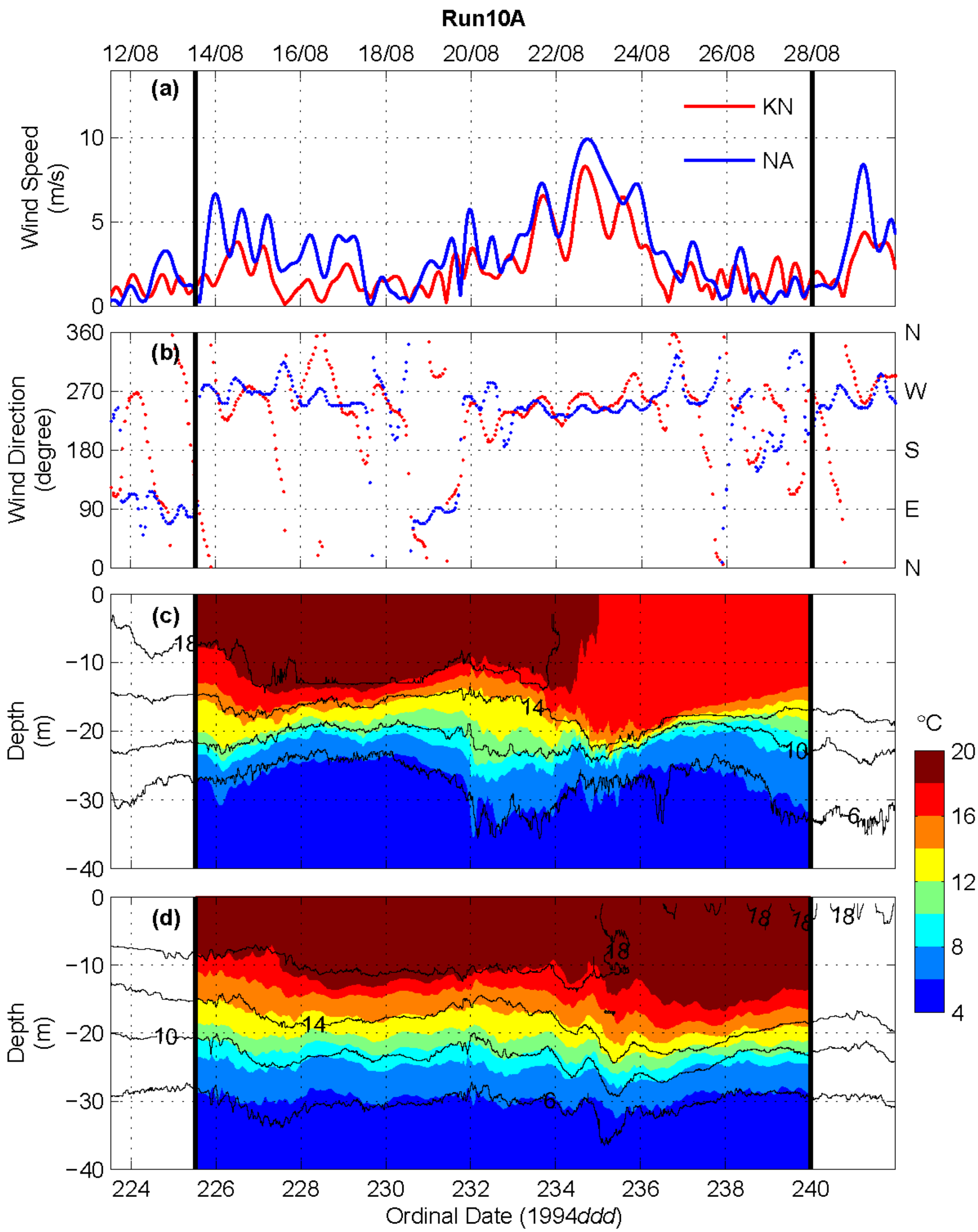


Figure 7.3 Contours of temperature along thalweg (Run 10A)

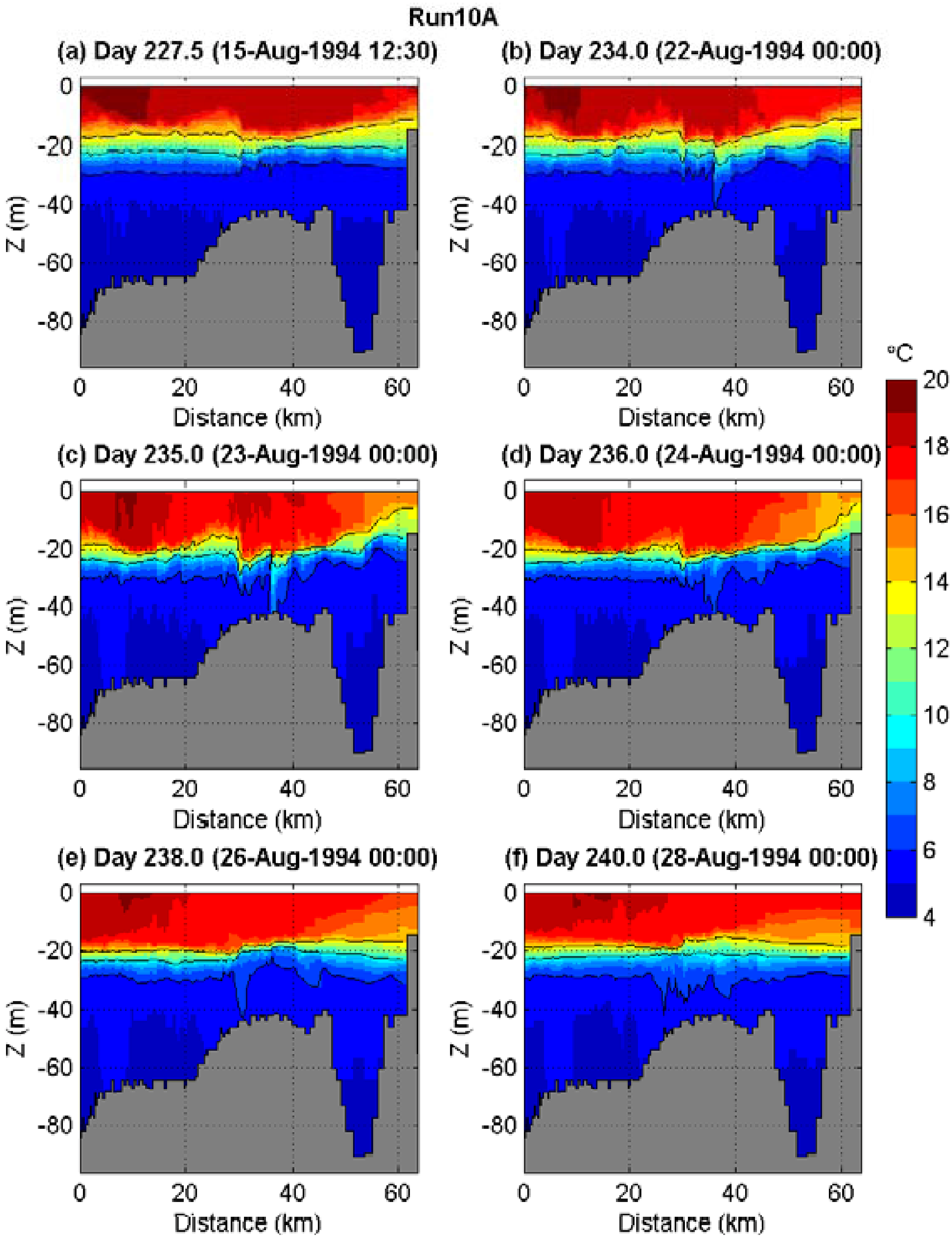
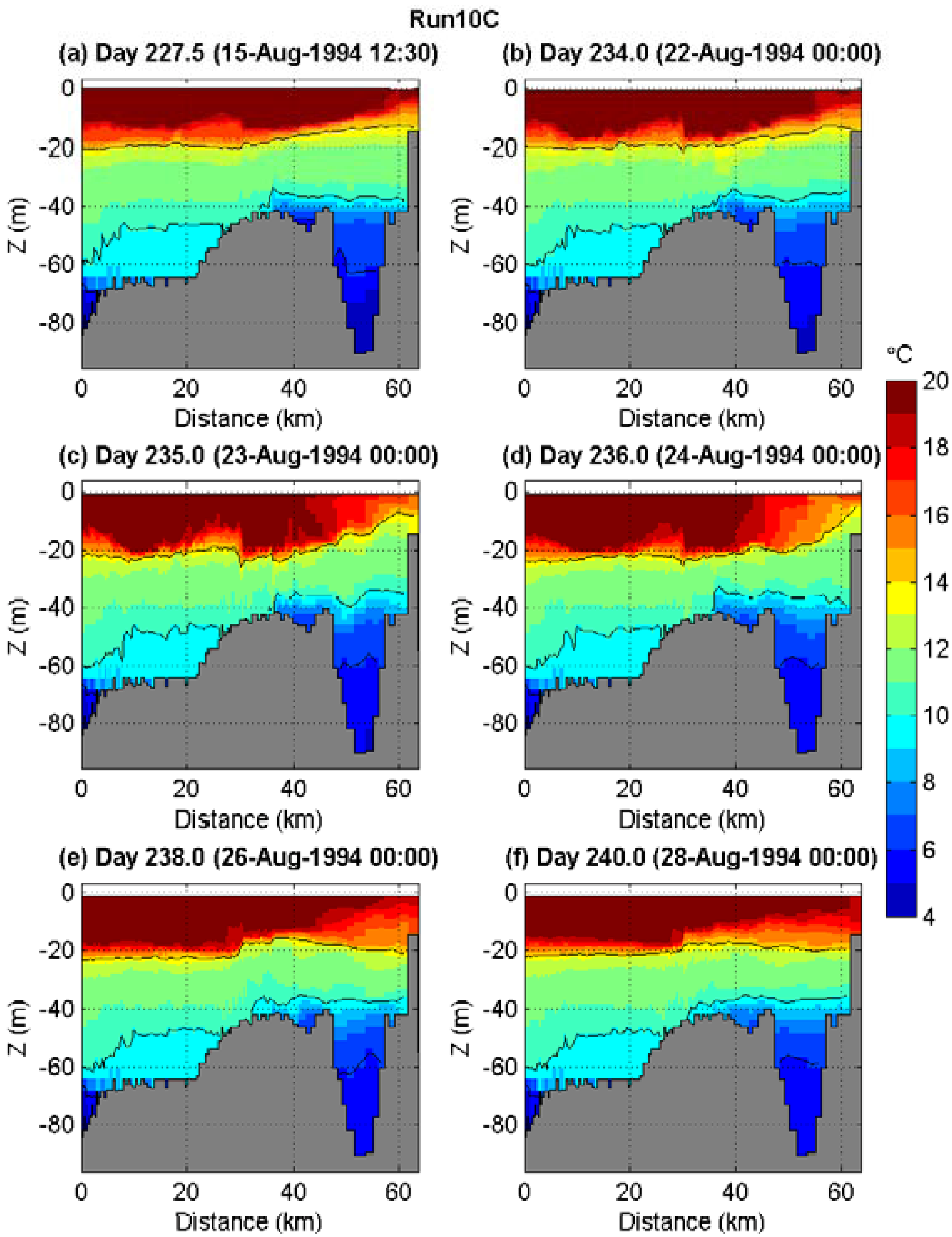
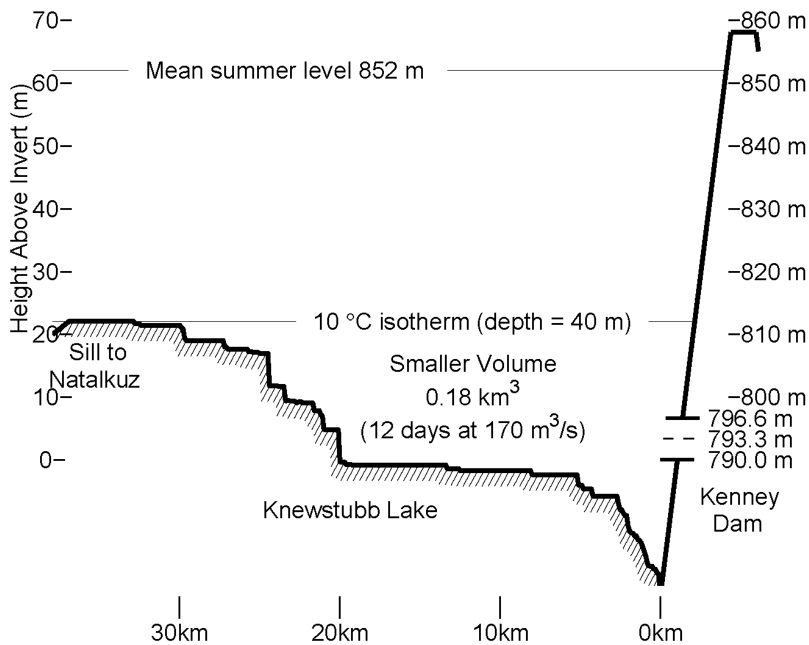


Figure 7.4 Contours of temperature along thalweg (Run 10C)



Scenario 1: Insufficient cooling water



Scenario 2: Sufficient cooling water

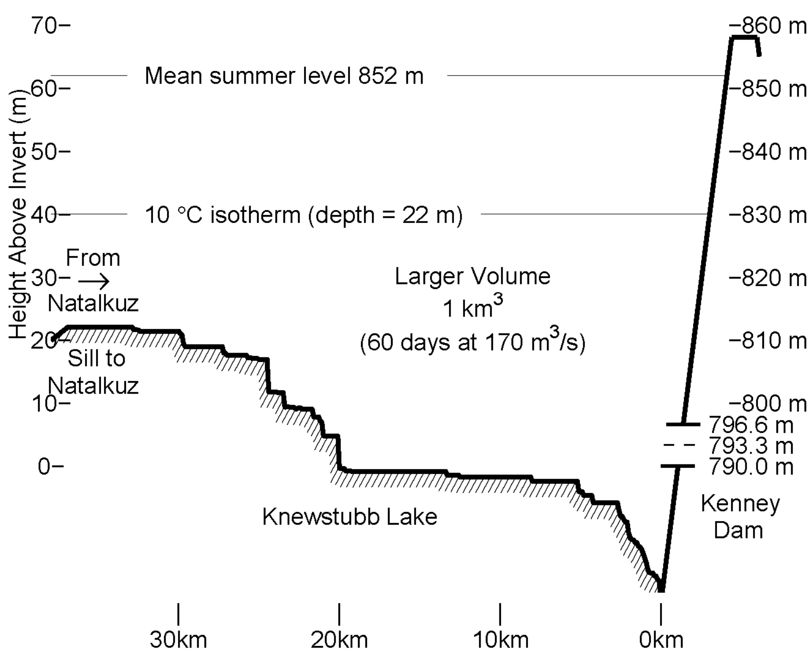


Figure 8.1 Depth along the valley bottom of the Nechako Reservoir near Kenney Dam. Note the sill between Knewstubb and Natalkuz lakes. In **Scenario 1** the 10 ºC isotherm is at or below the depth of the sill on July 20 and the volume of cold water in Knewstubb Lake below this level is insufficient to satisfy the cooling water requirement. In **Scenario 2** the 10 ºC isotherm is above the sill and there is ample cold water available from both Knewstubb and Natalkuz lakes.

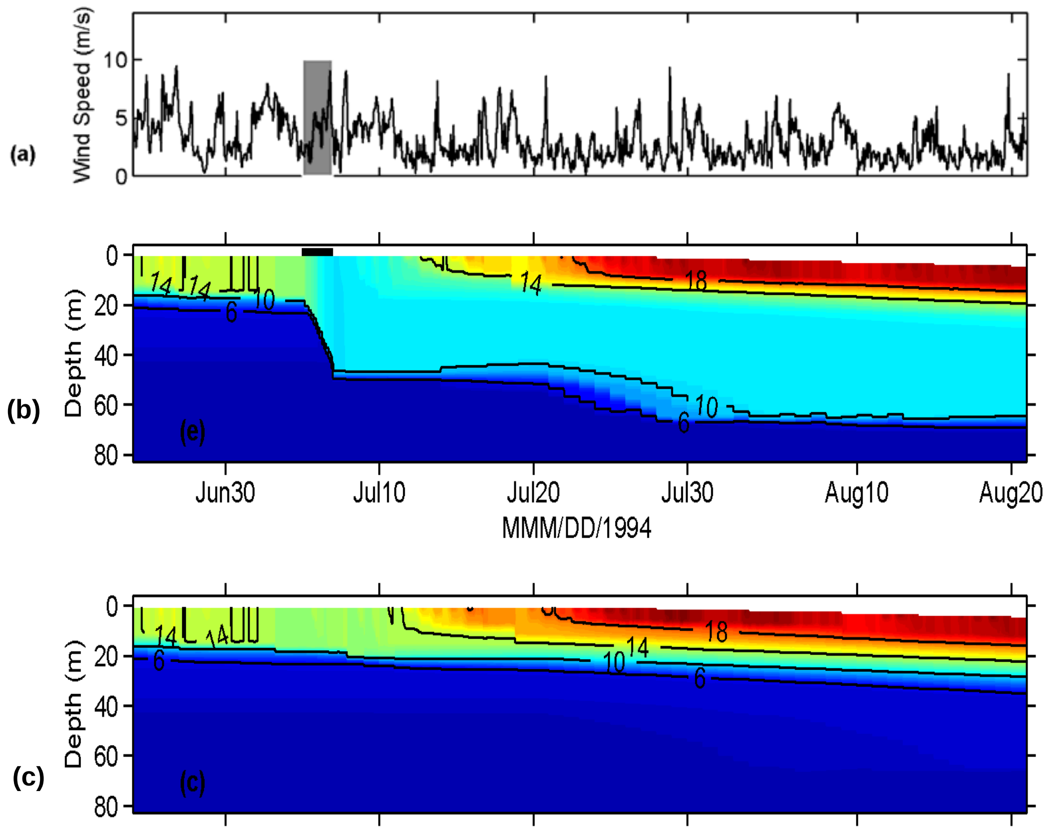


Figure 8.2 **(a)** Observed wind with test storm overlaid. Predicted evolution of the thermal structure including withdrawal **(b) Scenario 1** with wind storm of 10 m/s on July 5 and 6 and **(c) Scenario 2** without windstorm.

Appendix 1
Mooring 2005

Table A1.1 Instrument type, serial no. and depth

HWTP #	Type	Serial	String	Elev (m)	Depth (m)	Sensor #
				853.4	0	
32	HWTP	891611	Surface	852.9	0.32	1
	Stow	3610 & 73153	Surface	851.4	2.10	2
	Stow	1282 & 73154	Surface	849.4	4.10	3
	Stow	73097 & 73151	Surface	847.4	6.10	4
	Stow	1284 & 73155	Surface	845.4	8.20	7
	Stow	58 & 4880	Subsurface	847.1	6.37	5
1	HWTP	891579	Subsurface	845.9	7.53	6
2	HWTP	891580	Subsurface	843.9	9.55	8
3	HWTP	891581	Subsurface	841.9	11.59	9
4	HWTP	891583	Subsurface	839.9	13.57	10
5	HWTP	891584	Subsurface	837.9	15.56	11
6	HWTP	891585	Subsurface	835.9	17.59	12
7	HWTP	891586	Subsurface	833.9	19.60	13
8	HWTP	891587	Subsurface	831.9	21.57	14
9	HWTP	891588	Subsurface	829.9	23.58	15
10	HWTP	891589	Subsurface	827.9	25.58	16
11	HWTP	891590	Subsurface	825.9	27.57	17
12	HWTP	891591	Subsurface	823.9	29.58	Fail
13	HWTP	891592	Subsurface	821.9	31.60	18
14	HWTP	891593	Subsurface	819.9	33.58	19
15	HWTP	891594	Subsurface	817.9	35.60	20
16	HWTP	891595	Subsurface	815.9	37.62	21
17	HWTP	891596	Subsurface	813.9	39.54	22
18	HWTP	891597	Subsurface	811.9	41.58	23
19	HWTP	891598	Subsurface	809.9	43.56	24
20	HWTP	891599	Subsurface	807.9	45.56	25
21	HWTP	891600	Subsurface	805.9	47.55	26
22	HWTP	891601	Subsurface	803.9	49.53	27
23	HWTP	891602	Subsurface	801.9	51.56	28
24	HWTP	891603	Subsurface	799.9	53.54	29
25	HWTP	891604	Subsurface	797.9	55.54	30
26	HWTP	891605	Subsurface	795.9	57.56	31
27	HWTP	891606	Subsurface	793.9	59.54	32
28	HWTP	891607	Subsurface	791.9	61.54	33
29	HWTP	891608	Subsurface	789.9	63.55	34
30	HWTP	891609	Subsurface	787.9	65.63	35
	Tidbit	89256 & 666	Subsurface	785.9	67.59	36
31	HWTP	891610	Subsurface	783.9	69.57	Fail
	Tidbit	089256 & 298666	Subsurface	781.7	71.76	37
	Bottom			784.67	74.73	

Appendix 2
CTD Surveys, 2005

Table A2.1 CTD casts **July, 2005**

No	Stn	Time hh:mm	North (m)	East 10 U (m)	Sound Depth (m)	Line Out (m)	Secchi Depth (m)	Remarks
	Jul-20							
1	K12b	8:06	5922464	362452	44.5	-	5.5	High waves
2	K11	8:31	5922911	364906	-	-	5.5	bot
3	K10	9:26	5926063	366005	-	-	6.5	bot
4	K9	9:53	5929657	370030	57-60	-	5.5	
5	K7	10:21	5932645	374870	62.1	52	5.5	Hit brush, nar chan
6	K6	10:41	5934242	376726	67.7	60.5	5	bot
7	K5	11:03	5936098	377850	69.4	64	5.25	bot
8	BB1	11:31	5936565	379817	52	40	5.5	25m to trees, not bot
9	BB2	11:55	5936188	382548	30	20	5	15m to trees, not bot
10	K1	12:47	5936932	370923	79.3	73	6.25	bot, gray silt
11	K0	13:17	5938208	371102	84.2	77	6	bot, black sediment
12	K2	13:41	5936299	372200	76	70	5.75	
13	K3	14:01	5935781	374075	74.5	68	5.5	bot
14	K4	14:19	5935967	375960	72.2	67	5.75	
	Jul-21							
15	N3	7:50	5924620	353866	61.4	52.5	6.5	bot
16	N4	8:26	5925268	351658	70.6	63.3	7	
17	N5	9:06	5926053	349261	68.1	62	6.5	bot, tan mud
18	E3	9:54	5922171	350377	50		7.5	got caught, recast
19	E3	10:03	5922171	350377	50	38.5	-	redone, same loc.
20	E4	10:38	5922576	348052	77.5	69.5	6.25	bot, light/dark brown mud
21	E2	12:23	5921439	351909	69.5	64	6.5	bot, dark gray silt
22	E1	12:41	5921557	354094	58.9	52.5	6.5	bot
23	N2	13:00	5922696	356144	53	48	6.5	bot
24	N1	13:14	5922673	358037	58.5	48	6.5	bot, line out angle
25	K12	13:30	5922567	361129	57.8	48	6	bot
26	K11	13:54	5922904	364898	46.5	43	5.75	bot, line out angle
27	K10	14:13	5926075	366004	63.7	50	6	
28	K10b	14:32	5928093	368157	57.4	50.5	6.5	bot
29	K9	14:51	5929645	369961	59.5	55	5.5	

Table A2.2 CTD casts **August, 2005**

No	**Stn**	**Time** hh:mm	**North** (m)	**East 10 U** (m)	**Sound Depth** (m)	**Line Out** (m)	**Secchi Depth** (m)	**Remarks** (CTD - bot for all)
	Aug-16							
1	K01	10:20	5936903	370890	71.85	77	5.5	bushes 58-72?
2	K0	10:49	5938160	371182	85	78	6	
3	LUCAS 1	11:13	5936061	370931	52	48	6.5	bit of brush
4	LUCAS 2	11:37	5935320	369143	25.5	22	6	5m trees
5	LUCAS	12:08	5934814	366656	0.8	0.5	N/A	Near Lucas Cr. mouth
6	K02	12:33	5936227	372277	77	67	6.5	
7	K03	12:49	5935795	374036	73.3	67	6.5	not many trees at stn.
8	K04	13:06	5935974	375937	72	65.5	6.5	
9	K05	13:22	5936104	377860	67.8	64	6.5	
10	BB1	13:39	5936529	379609	46.8	42	6.5	0.5-1.0m trees
11	BB2	13:58	5936201	382454	27	25	6	8m trees
12	K06	14:22	5934259	376734	65.8	60	6.5	
13	K07	14:42	5932611	374824	64.3	58	6	
14	K08	14:58	5931057	373206	66.1	54	4	water looked green
15	K09	15:16	5929661	369991	60	53.5	6.5	
16	K10b	15:34	5928097	368170	56.4	52	6.5	
17	K10	15:48	5926088	365999	68.3	49	6	
18	K11	16:05	5922934	364938	45.1	39.5	6	
19	K12	16:19	5922559	361187	55.2	48	5.5	
	Aug-17							
20	N1	7:30	5922642	358184	53.6	47.5	7	
21	N2	9:01	5922753	356132	53.7	47.5	7	
22	E1	9:16	5921620	354134	58.6	53	6	some silt
23	E2	9:30	5921449	352030	70.2	64	7.5	silt in c-cell
24	E3	9:47	5921970	350670	76	51	7.5	
25	E4	10:03	5922577	348083	79.5	69	7.5	
26	C1	11:26	5922849	332403	68.7	62	5.5	silt
27	C2	12:04	5924501	329370	100.2	95	6	
28	E12	12:51	5917817	333228	64.3	59	6.5	line-out w/ angle
29	E11	13:08	5919742	334421	95.6	82	6.5	
30	C0	13:27	5921665	334490	51.1	46	7	

31	E10	13:39	5921426	336094	52	46	7	
32	E9	13:54	5921053	338077	63	58	7.5	
33	E8	14:08	5921422	340168	83	82.5	8	
34	E7	14:25	5921753	341644	124	115	7	
35	E6	14:46	5922374	344279	86.5	79	6.5	black mud in c-cell
36	E5	15:00	5922444	346027	88.8	87	8	mud in c-cell
	Aug-18							
37	I1	7:41	5924628	353873	60.4	52	6.5	
38	I2	7:56	5925246	351741	71.6	63	6.5	brown silt in c-cell
39	I3	8:13	5926039	349299	68.2	62	6.5	grey silt in c-cell
40	I5	8:50	5927046	346133	55	51	7	
41	I7	9:22	5930959	340852	52.4	50	7.5	line-out w/ large angle
42	I7b	9:43	5931864	340259	48.2	44	7.5	
43	I8	10:18	5934792	338657	52	48	7.5	
44	I6	10:43	5928800	344274	67	60	8	
45	I4	11:00	5926839	347975	60.3	55	8	silt in c-cell

Table A2.3 CTD casts, **October 2005**

No	**Stn**	**Time** hh:mm	**North** (m)	**East 10 U** (m)	**Sound Depth** (m)	**Line Out** (m)	**Secchi Depth** (m)	**Remarks** (CTD - bot for all)
	Oct-12							
1	K1	10:56	5936895	371020	83.5	73	N/A	difficult to feel bottom
2	**	11:15	5936905	371063	60	N/A	N/A	**large buoy
3	K0	12:47	5938160	371162	89	56	6.5	
4	K0(2)	13:05	5938225	371137	86.3	76	N/A	
5	LUCAS 1	13:27	5936075	370835	55.6	47	6	15m trees
6	LUCAS 2	13:43	5945469	369249	29.2	23	6	
7	K02	14:02	5936320	372228	81.8	61	6.5	snag at 50m
8	K03	14:59	5935788	374048	76.5	65	6.5	
9	K04	15:17	5935980	375927	79	65	7.5	
10	K05	15:37	5936103	377837	67.6	63	6.5	
11	BB1	15:54	5936603	379774	49	40	5.5	
12	BB2	16:12	5936281	382668	27	22	5.5	line out @ angle
13	K06	16:30	5934266	376749	662	60	6	
14	K07	16:46	5932652	374825	64	59.5	5.8	
	Oct-13							
15	K09	8:06	5929743	370061	61.7	48	6	
16	K10	8:27	5926059	366049	57.8	47	6	
17	K11	8:43	5922928	364942	46	39	7.5	line out @ angle
18	K12	8:58	5922587	361170	52.8	48	6	
19	N1	9:14	5922659	358058	60.9	N/A	6	
20	K10b	10:09	5928020	368147	60.2	N/A	6.5	
21	K9(2)	10:22	5929645	369890	63.9	48	6.5	repeat
22	K8	10:51	5931175	373115	63.9	58	7	

Table A2.4 CTD casts **August, 2006**

No	**Stn**	**Time** hh:mm	**North** (m)	**East 10 U** (m)	**Sound Depth** (m)	**Line Out** (m)	**Secchi Depth** (m)	**Remarks**
	Aug-16							
1	K01	10:02	-	-	64.6	64	7.1	
2	N02	11:22	5922697	356154	51.8	49	8.2	
3	N01	11:40	5922687	358079	62	58.3	8.15	
4	K12	13:20	5922584	361136	52.5	51.8	7.9	
5	K11	14:17	5922706	365034	51	50.5	7.3	
6	A10	15:10	5926105	366115	58.2	52.5	7.5	
7	K10b	15:32	5928107	368183	55.5	54.5	7.5	
8	K09	15:53	5929683	369979	60	57.5	6.8	
9	K08	16:11	5931056	373268	63.2	60.5	7.05	
10	K07	16:30	5932592	374763	66.1	62.5	6.3	
11	K00	17:16	5938137	371173	78	80	6.0	
12	K01	17:34	5936914	370891	74	60	4.4	10m trees
13	L1	17:47	5936052	370943	53	50	5.9	2m bushes
14	L2	?	5935482	369217	24.9	23.5	5.05	
15	K02	18:29	5936258	372280	74.3	71	5.2	
	Aug-17							
16	K01	8:40?	5936913	370934	82	81	5.5	
17	K06	9:17	5934234	376740	66.8	63	6	
18	K05	9:41	5936108	377848	70	68	5.9	2m bushes
19	BB1	10:02	5936623	379846	43	42	6.1	
20	BB2	10:27	5930273	382703	25.5	23	5.5	3m bushes
21	K12	12:41	5922576	361194	51.8	51	8	
22	K04	14:18	5935993	375954	61.3	65	6.1	11m trees, many
23	K03	14:44	5935703	374077	74.7	71	6	
24	K01	15:02	5936925	370938	80	77	6.1	

Appendix 3
Photos

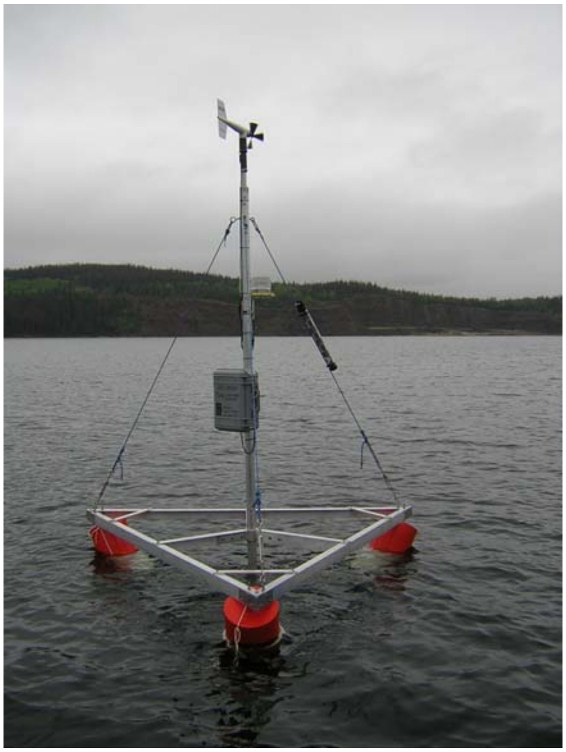


Figure A3.1 Wind buoy on Knewstubb Lake near Kenney Dam, 2005

Figure A3.2 Meteorological station near Kenney Dam, 2005. The UBC station is located on the left side of the Alcan enclosure, with a white wind monitor visible at the top. The road runs over Kenney Dam.

Figure A3.3 Wind monitor on Nechako Lodge tower (on cross bar), 2005. Note the 3 kW wind turbine (Southwest Wind Power Whisper 175, 24VAC) at the top of the mast.

Figure A3.4 The tower at Nechako Lodge (marked with arrow).

Figure A3.5 'River Rat' with (left to right) Thomas Doerig, Joel Atwater & Martin Doerig. Looking east from Narrows rock.

Figure A3.6 Cheslatta Boat at Nechako Lodge dock looking south. The Nechako range is visible in the background.

Figure A3.7 Rock marking the Narrows**.**

Figure A3.8 Looking west from atop the Narrows rock along the Knewstubb Lake Sill Reach; chain of islands just visible on the left and Mt. Swannell (1821 m) clearly visible in the background.

Figure A3.9 Looking east from atop the Narrows rock along Knewstubb Lake mid reach.

Figure A3.10 Kenney Dam (looking west).

Appendix 4
Mixing in the surface layer of a lake

As wind blows over the surface of a lake it generates surface currents and waves, which generate turbulence and mixes the surface waters to form a surface, mixing layer. This is an inefficient process and only a small portion of the wind energy is available to mix the water column. The depth to which wind generated mixing can penetrate into the water column is limited by temperature stratification, since mixing of temperature stratification requires lifting heavier, cold water and pushing down lighter, warmer surface water. The depth of the surface, mixing layer can be evaluated by comparing that portion of the wind energy available to do mixing with the energy required to mix the temperature stratification. This section first describes how to empirically evaluate the energy available to do mixing, then describes how to evaluate the energy required to mix idealized temperature stratifications.

1. Wind energy available for mixing

Wind imparts a shear stress at the air water interface evaluated empirically as:

$$\tau = \rho_a C_D U_{10}^2 \tag{0.1}$$

where ρ_a is air density (1.2 kg m^{-3}), C_D is the drag coefficient taken as 1.3x10^{-3} (Imberger and Patterson, 1990), and U_{10} is the wind speed measured 10 meters above the water surface. The rate of work done by the wind is given by force applied by the wind on the water times the wind speed, given by:

$$P_{wind} = \tau A U_{10} = \rho_a C_D U_{10}^3 A \tag{0.2}$$

where A is the lake surface area and equation (0.1) has been applied.

The wind energy rate available for mixing has been determined empirically as:

$$\dot{E} = \frac{C_N^3}{2} u_*^3 \rho_o A \tag{0.3}$$

(Spigel et al, 1986) where ρ_o is the water density (1000 kg m^{-3}), C_N taken as 1.33 is a dimensionless constant related to the mixing efficiency, and u_* is the wind shear velocity defined as $u_*^2 = \sqrt{\tau/\rho_o}$.

An overall wind mixing efficiency can be determined from the ratio of $\dot{E}$ to P_{wind} as:

$$\eta = \frac{\dot{E}}{P_{wind}} = \frac{\frac{C_N^3}{2} u_*^3 \rho_o A}{\rho_a C_D U_{10}^3 A} = \frac{\frac{C_N^3}{2} \rho_o A \left(C_D \rho_a U_{10}^2\right)^{3/2}}{\rho_a C_D U_{10}^3 A} = \frac{C_N^3}{2}\sqrt{C_D \frac{\rho_a}{\rho_o}} = 1.5 \times 10^{-3} \tag{0.4}$$

Thus, the wind energy rate available for mixing temperature stratification is evaluated as:

$$\dot{E} = \eta P_{wind} = 1.5 \times 10^{-3} \rho_a C_D U_{10}^3 A \tag{0.5}$$

Appendix 5

Response of the Nechako Reservoir to Spring Winds

To appear in the Proceedings of the Fifth International Symposium on Environmental Hydraulics, Tempe, Arizona, 4-7 December, 2007.

RESPONSE OF THE NECHAKO RESERVOIR TO SPRING WINDS

YASMIN NASSAR[1], ROGER PIETERS[2,1], BERNARD LAVAL[1], and GREG LAWRENCE[1]

[1] *Civil Engineering, University of British Columbia, Vancouver, BC V6T 1Z4*

[2] *Earth and Ocean Sciences, University of British Columbia, Vancouver, BC V6T 1Z4*

Abstract In 1952 Kenney Dam was constructed across the Nechako River in central British Columbia. Redirecting water from the Nechako River to the ocean allowed hydroelectric generation with a 727m head, one of the largest in the world, garnering 6MW per cubic meter of water. However, there remains a need to cool the Nechako River below Kenney Dam for salmon returning to spawn from late July to late August. A cold water release facility (CWRF) has been proposed for Kenney Dam which would withdraw cold deep water from the Nechako Reservoir. To aid in the assessment of the proposed CWRF and to determine whether sufficient cold (< 10 ºC) water would be available, we have investigated the hydrothermal behavior of the reservoir using DYRESM (Dynamic REservoir Simulation Model), a commonly used one-dimensional lake model (Patterson et al., 1984). Measured meteorological and lake conditions were used to validate the model and extreme wind conditions were used to investigate the possibility of elevated withdrawal temperatures. The model results indicate that withdrawal temperatures > 10 ºC will be possible in the case of a late spring wind storm.

1. Introduction

The Nechako River is one of the largest tributaries to the Fraser River. The Fraser River drains 25% of the total land area in British Columbia and the economic activity within the Fraser catchment accounts for 10% of the national and 80% of the provincial gross domestic product (4Thought, 2005). It provides water for agriculture, generates power and is used for recreation. The impoundment of water in the Nechako Reservoir has altered the hydrology of the Nechako River system. There is currently no release of water from Kenney Dam (Figure 1): water is either released to the ocean at the east of the reservoir for power production or surface water is spilled mid-way along the reservoir through another catchment and into the Nechako River.

A Cold Water Release Facility (CWRF) has been proposed to mitigate the effects of impoundment by drawing cold deep water from the Nechako reservoir at Kenney Dam to reduce temperatures in the Nechako River for fish migration in summer (July 20th- August 20th). The objective of the CWRF is to supply 170m^3/s of 10^{o}C water during this period. The purpose of the present study is to determine if there are realistic circumstances under which deep water temperatures are too high for the above condition to be satisfied.

The Nechako Reservoir is composed of a series of flooded lakes, 180 km long. However, in this study we consider the basins closest to Kenney Dam: Knewstubb Lake has a maximum depth of ~80 m adjacent to Kenney Dam and connects to Natalkuz Lake through a sill (~40 m depth) at the Narrows (Figure 1). If the 10^{o}C isotherm sits far above the sill, there will be sufficient deep, cold water in Knewstubb to satisfy the cooling water requirement. In addition, deep, cold water can flow from Natalkuz Lake. However, if the 10 ºC isotherm sits below the sill, the supply of cold water from Natalkuz is blocked and the volume of cold water in Knewstubb Lake is insufficient to provide the proposed flow. We examine the response of the thermal structure in the Nechako Reservoir to the proposed withdrawals through the Kenney Dam and to various hypothetical wind conditions.

2. Methods

DYRESM is a one-dimensional hydrodynamic model that predicts the vertical distribution of temperature, salinity and density given the destabilizing forces that act on the water body, such as the wind stress. The reservoir is represented by a set of Lagrangian layers (CWR, 1997). The model parameterizes surface heat, mass, and momentum exchanges, surface mixed layer deepening, and hypolimnetic mixing; default parameters were used in the present study.

DYRESM requires an initial temperature profile and wind speed, air temperature, solar radiation, cloud cover, rainfall, and vapor pressure for the simulated period. The required data were collected by Triton Environmental consultants (1995) from two moored rafts located in Natalkuz Lake and in Knewstubb Lake near the dam (Figure 1) from June 23rd to October 13th, 1994. Meteorological stations on the rafts collected wind speed and direction 2m above the lake. The Natalkuz station also collected air temperature, relative humidity, and solar radiation. Measurements were taken every six minutes and averaged to produce mean hourly values. Rainfall was not available but was assumed negligible as summer is usually dry. Cloud cover, C, was estimated using the formula $C = 1-\{1.28(q_c/q_s-0.22)\}^{3/2}$, where q_c is the no-atmosphere solar radiation, and q_s is the net solar radiation reaching the ground (TVA, 1972).

In addition to the meteorological measurements, temperature chains were hung from the rafts with sensors every 2m. The simulations were initialized using the temperature profile from Natalkuz Lake at the beginning of June 24th.

Due to the complicated geometry of the reservoir, and the presence of a sill in the narrows separating Knewstubb from Natalkuz Lake (Figure 1), it is assumed that no cold water was transferred from Natalkuz to Knewstubb Lake below the depth of the sill (40m) by reducing the model volume below 40m to that of Knewstubb only.

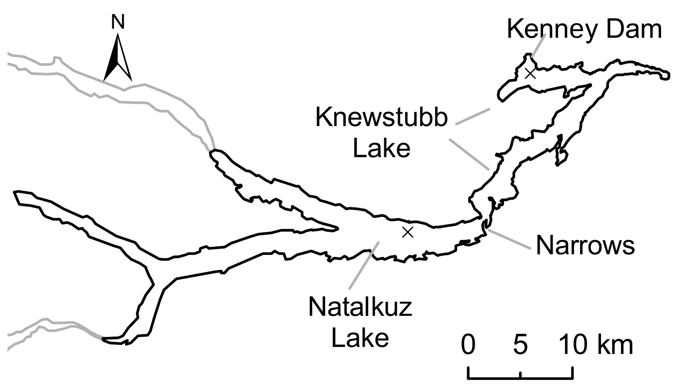


Figure 1 Map showing the location of the Kenney Dam and the narrows with respect to Knewstubb and Natalkuz lakes. ‘X’ marks the location of the data collection rafts.

Three sets of simulations were conducted:

- ***Default*** The first simulation was run to reproduce the thermal stratification observed in 1994.
- ***Scaled winds*** The second set of runs used the default simulation with wind speed increased by a scale factor.
- ***Spring storm with withdrawal*** The third set of runs included a proposed withdrawal from Kenney Dam of 170m^3/s for the period starting on July 20th to August 20th over a depth range 56.9 m to 63.5 m below full pool, corresponding to the location and size of the proposed intake. In addition, a single extreme storm with wind speed of 10m/s over two days was added to the wind record at varying dates through spring and early summer.

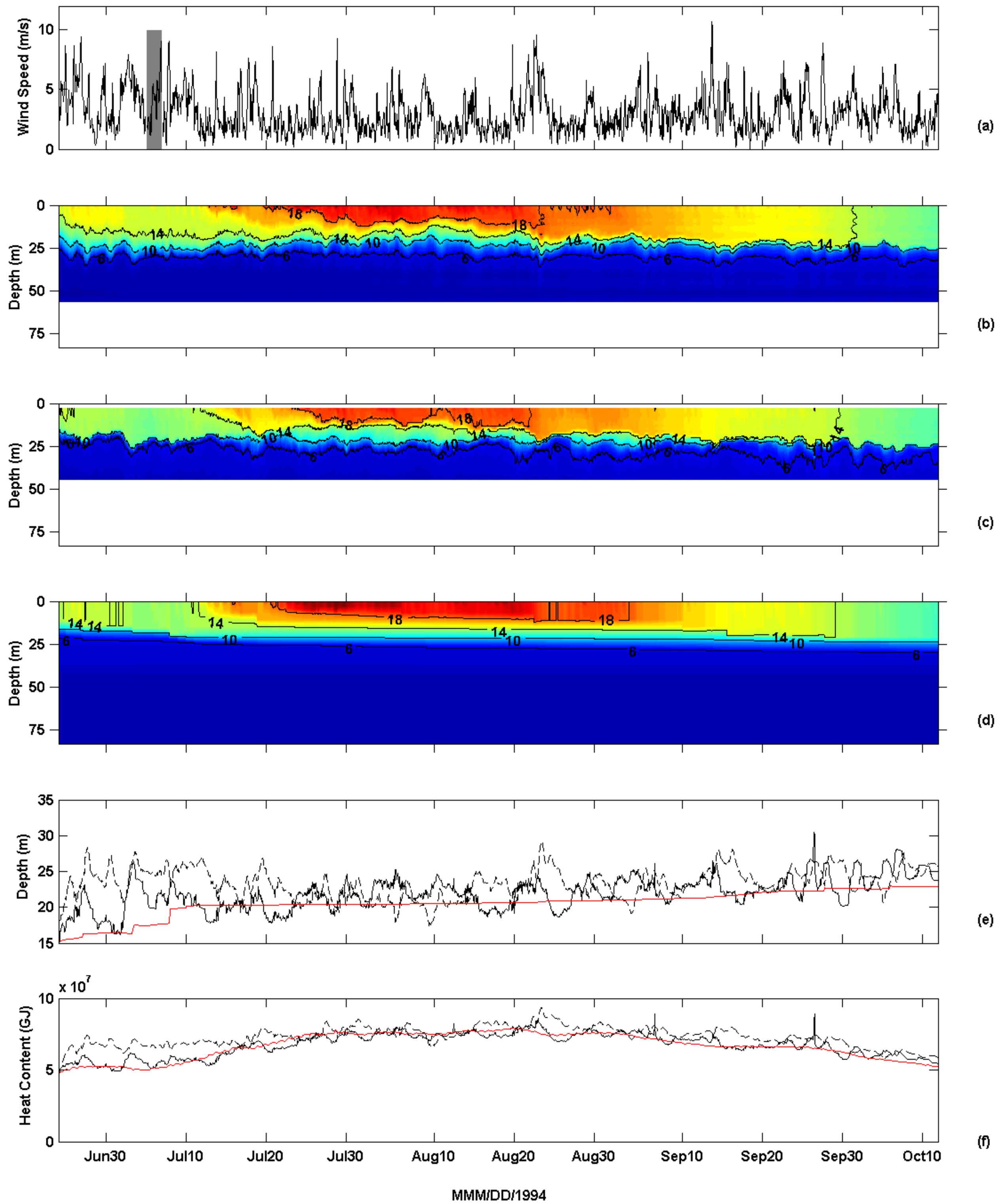


Figure 2 **(a)** Observed wind with test storm (July 5 and 6) overlaid **(b)** observed temperature in Knewstubb **(c)** observed temperature in Natalkuz **(d)** temperature modeled using DYRESM; **(e)** depth of the 10 ºC isotherm and **(f)** total heat content with observed values in Knewstubb (dashed black), Natalkuz (solid black), and model predictions (red).

3. Results

3.1 Default simulations

The ability of DYRESM to model the thermal structure of the Nechako Reservoir (or more specifically Knewstubb and Natalkuz lakes) is illustrated in Figure 2. The wind observed on Natalkuz Lake in 1994 is shown in Figure 2a, along with contours of temperature from the moorings in Knewstubb and Natalkuz lakes (Figures 2b,c). The predictions of DYRESM are shown in Figure 2d. While at any given time the temperatures at a given depth may be quite different (due primarily to internal wave activity) the measured thermal structures are quite similar and modeled well by DYRESM.

A more quantitative assessment of the effectiveness of DYRESM is presented in Figures 2e and 2f where the depth of the 10 ºC isotherm and heat content are made. In general the differences between the predictions and the measurements are no greater than the differences between the measurements. The model predictions more closely match the Natalkuz measurements. The Knewstubb mooring was at one end of the reservoir and may not be representative of average conditions in the reservoir. Prevailing winds force warm surface water toward this mooring, cause set-down of the thermocline and increase the local heat content. In this study we have used the Natalkuz data in preference to the Knewstubb data.

3.2 Scaled wind

The results from the second set of simulations, which scaled the entire wind speed record with a multiplication factor, are shown in Figure 3. As the wind speed increases the 10 ºC isotherm deepens. The temperature at the intake remains between 5 and 6°C until the multiplication factor exceeds 1.3. The deep temperature exceeded 10°C at a multiplication factor of 1.4. This suggests that an increase in wind throughout the spring of 40% would result in withdrawal of water warmer than desired by August 20th.

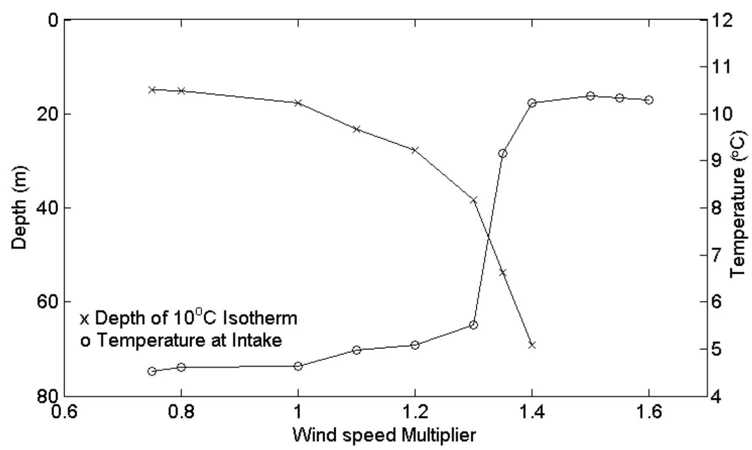


Figure 3 Effect of increasing the wind speed by a scale factor on the depth of the 10 ºC isotherm and the temperature at the depth of the intake on August 20th.

3.3 Spring storm and withdrawal

In the third set of runs an idealized wind storm of 10m/s over two days was applied to assess the possibility of withdrawal temperature above 10°C. These runs also included a withdrawal of 170m³/s during the period of July 20th to August 20th when fish migration occurs. First we examine the effect of a storm on July 5 and 6 (Figure 4). The added storm of July 5-6 occurs shortly after a previous storm in late June (Figure 2a). The combined effect was to mix the 10 ºC isotherm down to ~50 m. After the storm the thermocline broadens slightly, so that by July 20, when the withdrawal begins, the 10 ºC isotherm is at about 45 m depth. The withdrawal of cold deep water lowers the 10 ºC isotherm. By August 20 the withdrawal provides water > 10 ºC.

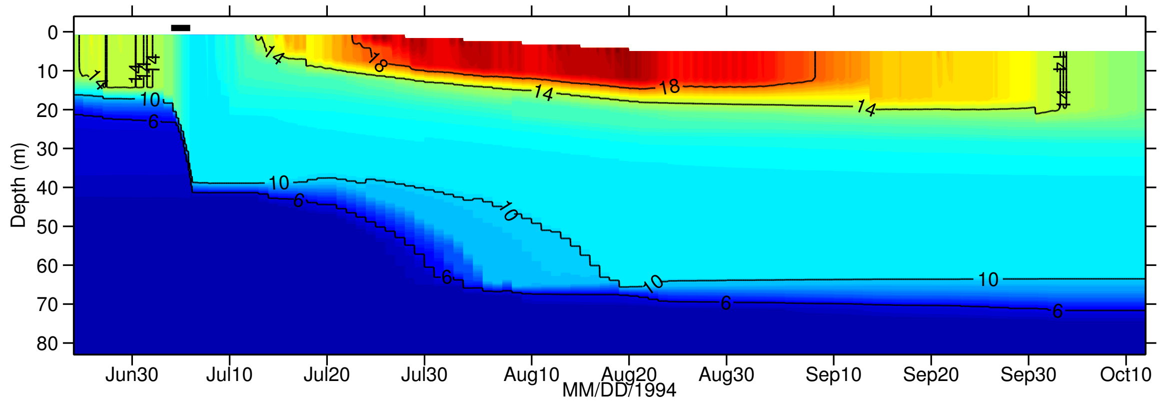


Figure 4 Predicted evolution of the thermal structure following a storm of 10m/s wind on July 5 and 6 (solid bar). The model includes withdrawal of 170 m^3/s from July 20 to August 20.

The effect of adding our hypothetical storm at varying dates through late spring and early summer is shown in Figure 5, where the depth of the 10 ºC isotherm on July 20 and the temperature at the intake on August 20 are plotted as a function of the date of the added storm. The depth of the 10ºC isotherm was greatest (~ 40 m) after 2-day storms starting on June 25 and July 5. Even though the 10°C isotherm didn't reach the withdrawal depth (56.9 - 63.5m deep) at the beginning of the withdrawal period (Figure 5), by August 20th the 10ºC isotherm reached the withdrawal depth and the withdrawal temperature varied from 8.2°C to 11.5°C. In these runs the depth of the 10°C isotherm depends on several factors such as stratification of the surface layer, the wind speed prior the storm event and after it, and the heat content of the top 40m of the water column.

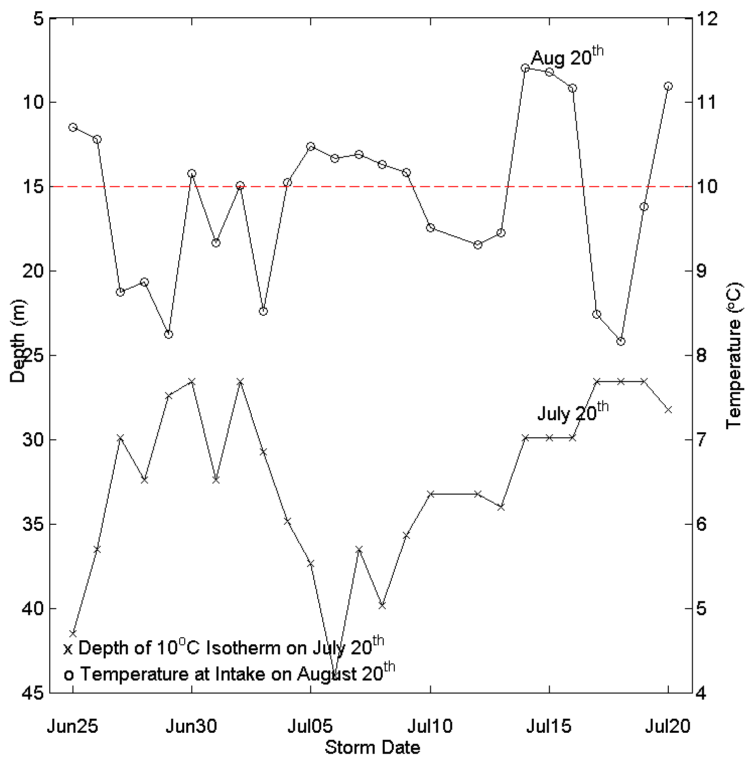


Figure 5 Effect of a spring storm and withdrawal on the depth of the 10ºC isotherm on Jul 20th (+) and on withdrawal temperature on Aug 20th (o).

Two competing effects control the depth of the 10 ºC isotherm. There must be sufficient heat in the surface layer before a storm such that when deepening occurs the temperature of the deepened surface layer remains above 10 ºC. However, if the initial surface layer heat content is too high a given wind will not be able to mix it to a sufficient depth. The appropriate combination of surface layer heat content and imposed wind occurs on numerous occasions in early summer. However, we cannot provide verification of the above results since the wind forcing is hypothetical. We plan to verify our predictions using other numerical models (e.g. ELCOM, GOTM).

4. Conclusions

DYRESM effectively reproduced the measured thermal structure of the Nechako Reservoir in summer 1994 and was used to investigate the effects of strong winds on the availability of cold water. Increasing the wind speed by 40% resulted in complete vertical mixing. Applying a hypothetical wind storm at various dates during the spring was found to mix the reservoir down to a depth of about 30 to 45m depending on when the storm was applied. The depth of the 10 ºC isotherm and the withdrawal temperature in this case were reliant on the heat content of the water column when applying the wind. Both increased wind speed and spring storms at selected dates resulted in an inability to supply the proposed cold water withdrawal. Future work includes verification of these results from DYRESM and assessing the probability of insufficient cold water.

Acknowledgements

We gratefully acknowledge funding provided by the Nechako Enhancement Society and joint partnership of the Province of British Columbia and Alcan Inc. Greg Lawrence is grateful for the support of a Canada Research Chair.

References

1. Patterson, J.C., Hamblin, P.F., Imberger, J., 1984. Classification and dynamic simulation of the vertical density structure of lakes. *Limnology and Oceanography*. 29(4), 845-861.
2. 4Thought Solutions Inc., 2005. Nechako Watershed council Report: Assessment of Potential Flow Regimes for the Nechako Watershed. Prepared for Nechako Enhancement society and Nechako Watershed Council., Vancouver BC.
3. Center for Water Research, University of Western Australia, 1997. Users Science Manual for DYRESM WQ-1.5.
4. Triton Environmental Consultants, 1995. Nechako Reservoir Additional Data Collection, Final Report. Prepared for Alcan Smelters and Chemicals Ltd., Vancouver BC.
5. Tennessee Valley Authority, Division of Water Control Planning, Engineering Laboratory, 1972. Water Resources research, Laboratory Report No. 14, Norris Tennessee.

Appendix 6

Characterizing the Internal Wave Field in a Large Multi-basin Reservoir

To appear in the Proceedings of the Fifth International Symposium on Environmental Hydraulics, Tempe, Arizona, 4-7 December, 2007.

CHARACTERIZING THE INTERNAL WAVE FIELD IN A LARGE MULTI-BASIN RESERVOIR

YEHYA IMAM[1], BERNARD LAVAL[1], ROGERS PIETERS[2,1], GREGORY LAWRENCE[1]

[1] *Department of Civil Engineering, University of British Columbia, 6250 Applied Science Lane Vancouver, BC V6T 1Z4, Canada*

[2] *Earth and Ocean Sciences, University of British Columbia, Vancouver, BC V6T 1Z4, Canada*

Abstract. Internal waves have a profound effect on outflow temperatures from hypolimnetic withdrawal facilities constructed in dammed reservoirs. The problem of characterizing the internal wave field is not a trivial one particularly in large multi-basin reservoirs with irregular bathymetries. Such difficulty is manifested in Nechako Reservoir, British Columbia, Canada, which constitutes a series of lakes connected by flooded riverine sections. Knewstubb Lake, the basin adjacent to the dam, is irregular in shape and connects to the next basin upstream, Natalkuz Lake, through a constriction and sill. As observed at thermistor moorings in both Knewstubb and Natalkuz lakes, the internal wave field in the reservoir is complex due to interaction of wave modes within and between lake basins. A three dimensional hydrodynamic model, ELCOM, is employed to simulate the internal seiching and wave motions in response to recorded wind events over several weeks during summer. The size (200 km long), complexity and lack of bathymetric information prohibited modeling of the entire reservoir. By modeling progressively larger regions of the reservoir we have determined the extent of the domain required for satisfactory reproduction of the dominant wave patterns near the dam.

1. Introduction

Nechako Reservoir is a large water body in central British Columbia, Canada (Figure 1). Water was impounded in the reservoir through the construction of Kenny Dam in the early 1950s together with other smaller saddle dams. Nechako Reservoir constitutes several lakes connected by flooded riverine sections. The reservoir resembles a hollow ring extending approximately 196km east to west and 75km north to south. With total thalweg length in excess of 430km and surface area of 910km^2, the total reservoir storage is 23.8km^3. At the west end of the reservoir, tunnels discharge 130m^3/s to a 1000MW power generation station [1].

Kenny Dam is not provided with a withdrawal facility; however, a spillway 80km east of the dam releases excess flood water in addition to base flow for fish habitat conservation and other domestic uses. As such, the 9km stretch of the Nechako River downstream Kenny Dam is no longer supplied with upstream flow and is only sustained by local drainage. The region downstream of the spillway was excessively scoured and altered as a result of the artificially high inflows during the past decades [1].

A water release facility is proposed at Kenny Dam. The withdrawal facility provides the benefits of restoring the ecology downstream of the dam as well as the spillway to a pre-impoundment state. The facility, referred to as the Cold Water Release Facility (CWRF), is planned to release surface water, deep water, or a mixture of both. Such flexibility is desired to maintain temperatures downstream of the dam at levels un-stressful to migrating and spawning fish. In particular, the facility would be used to release 170m^3/s at temperatures below 10°C during the hot summer period; from July 20th to August 20th [2]. Towards this target, the invert of the deep offtake is proposed at 63m below the normal operating water level where the total depth at the dam is 85m. The basin directly upstream of the dam, Knewstubb Lake, constitutes of two perpendicular basins, Knewstubb and Big Bend Arms extending E-W and Knewstubb Mid-reach extending N-S. At its south end, Knewstubb Mid-reach is connected to the next basin upstream, Natalkuz Lake, through a constricted sill, the Narrows (Figure 1).

The ability of the CWRF to supply cold water, less than 10°C, is affected by several factors including the seasonal evolution of the thermocline, displacement of the 10°C isotherm caused by wind-induced internal motions, and selective withdrawal layer thickness. Seiching and internal waves can lower the 10°C isotherm from its equilibrium level down towards the deep offtake. At a critical level, the established withdrawal layer may encompass water warmer than the threshold compromising the ability to satisfy target temperatures downstream. An aggravated case can be envisioned if strong winds depress the 10ºC isotherm to the level of the sill, thereby isolating the hypolimnion of Knewstubb Lake from that of Natalkuz and limiting the supply of cold water.

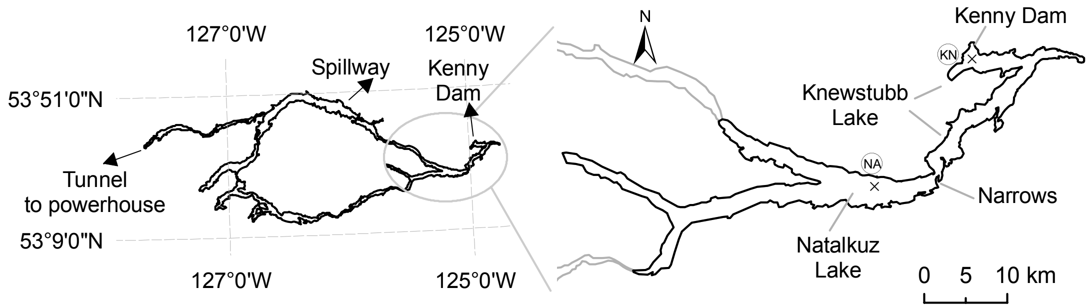


Figure 1: Left: Map of Nechako Reservoir showing Kenny Dam, the spillway, and tunnel to the powerhouse. Right: The two basins immediately upstream of Kenny Dam, Knewstubb and Natalkuz Lakes, connected through the Narrows. xKN and xNA shows the locations of moorings in Knewstubb and Natalkuz Lakes, respectively.

Recently, Anohin et al, 2006, [3] investigated the effect of internal waves on the water quality withdrawn from Lake Burragorang, Australia. Based on field data analysis, these authors concluded that internal waves were the dominant process in determining the temperature and turbidity of hypolimnetic withdrawals. Thus, to predict *a priori* the performance of the proposed CWRF under various scenarios, it is important to successfully characterize the internal wave field in the reservoir. This is not a trivial task owing in part to its complex irregular shape – particularly near the dam, and in part to the modulation of the waves by exchange flow between the interconnected basins. Here, we attempt to describe internal wave structure by means of 3D hydrodynamic numerical modeling supported by a small suite of field measurements.

2. Methodology

2.1. *Hydrothermal Observations*

Thermistor-chain data are available from two moorings deployed in Knewstubb (KN) and Natalkuz (NA) Lakes in 1994, from day 174 to 285 (Figure 1). At the two moorings, wind speed and direction are also available for the same period [4]. The wind fields at the two locations are very similar with a dominant wind direction from W-SW particularly during strong wind events. The 10°C isotherm fluctuated between 15m and 30m depth but was consistently out of phase at the two moorings.

2.2. *The Numerical Method*

The Estuary and Lake Computer Model (ELCOM), developed by the Center for Water Research, University of Western Australia, is a three dimensional hydrodynamic and transport model distinctively useful in modeling basin-scale internal waves in stratified water bodies; [5] and [6]. This capability is achieved using a vertical mixed-layer scheme as opposed to other turbulence closure schemes. ELCOM has been demonstrated to accurately capture the depth of the surface mixed-layer which is required for successful modeling of basin-scale internal waves. ELCOM employs a structured rectangular grid wherein cells containing the free-surface and bottom in any column can partially fill the respective layers.

2.3. *Model Development*

The vast size of Nechako Reservoir inhibited modeling of the entire domain at the required resolution and for the needed periods. The model was applied to several domains of different extents wherein the largest covers Knewstubb and Natalkuz Lakes being the two basins most influential to the CWRF (run-A). A non-uniform bathymetric grid was generated as the base of ELCOM simulations (Figure 2). Directly upstream of the dam, the first few grid cells are of fine resolution, 50m x 50m, the spacing increases by 8% from one cell to the next up to a maximum of 200m. Moving south towards the Narrows, the cell size is gradually reduced down to 50m x 50m. West of the Narrows, the spacing increases by 8% to a maximum of 1km and is fixed at this size to the end of the domain. In the vertical, a fine spacing (0.5m) is utilized for the top 30m. Below that, layer thicknesses increase gradually by 10% to a maximum of 4.5m at the deepest level. Utilizing the same grid, run-B excludes Natalkuz from the simulation sealing the Narrows at Knewstubb side. Furthermore, run-C excludes Knewstubb mid-reach, only extending over Knewstubb and Big Bend Arms with a closed boundary south of the junction with the mid-reach.

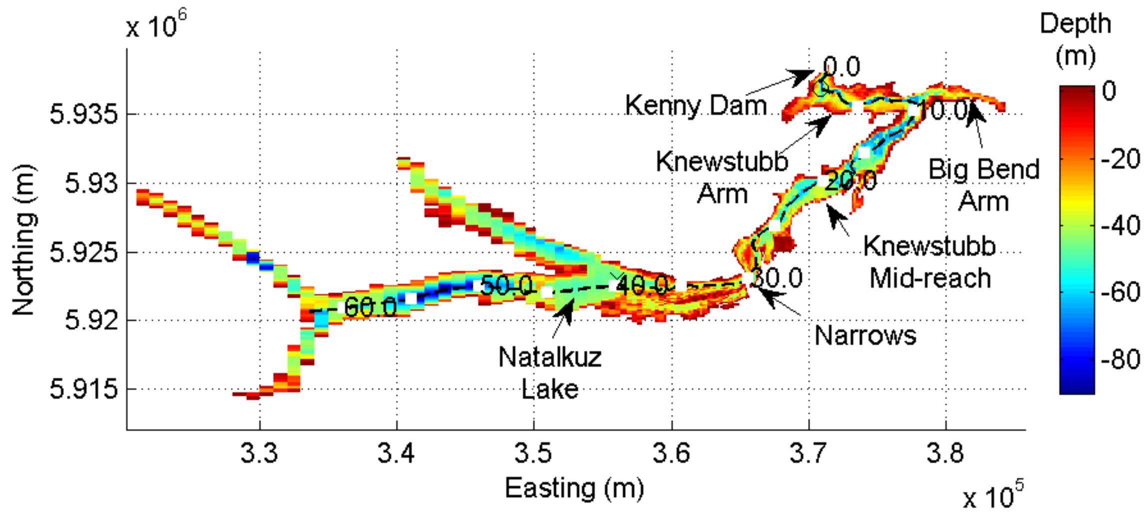


Figure 2: Bathymetric grid generated for ELCOM simulations. The fine resolution is apparent close to the Dam and within the Narrows while coarser cells are obvious at the west end of the domain. The dashed black line represents a curtain along the thalweg for which ELCOM results are illustrated later. The curtain is marked at 5km intervals originating from the dam with distance along the thalweg labeled every 10km.

Measured wind speed and direction at both the KN and NA moorings are used to force the model. Wind measurements from KN are applied on Knewstubb and Big Bend Arms while measurements from NA are applied over the rest of the domain. In ELCOM, surface wind stress is parametrized using a bulk formulation employing a coefficient of drag. The coefficient is adjusted in ELCOM to $1.63{\times}10^{3}$ instead of $1.3{\times}10^{3}$ to account for wind speed being measured 3m above the water as opposed to 10m.

The domain is initialized using thermistor data from both KN and NA moorings. Temperature-depth profiles are specified at the mooring location and interpolated to all grid cells for initial temperatures. First, interpolation is carried on vertically in a linear fashion then horizontally using the inverse distance-weighted method with a power of two. Generally, simulations are started after extended periods of calm weather when isotherms at KN mooring were at approximately the same level as at NA mooring. Ideally, this implies that forced motions are negligible and free internal oscillations are almost damped. Consequently, the start-from-rest assumption becomes acceptable and the period of model spin-up (affected by the specified initial conditions) is reduced.

2.4. *Limitations and Assumptions*

Although ELCOM can handle heat exchange through the air-water interface, thermodynamic fluxes were not incorporated in the simulations. Only short-termed simulations were attempted to explain the effect of internal waves on the CWRF outflow. The longest ELCOM simulation runs for only 15days. At this time-scale, incorporating thermodynamics was deemed unnecessary and inconsequential to the results.

A turbulent benthic layer was specified as the bottom boundary condition over the entire domain with a drag coefficient of 0.005. This imposed boundary includes mixing induced by bottom stirring in the mixed layer model, [6] and [7], and as such is particularly useful in the vicinity of the Narrows were the thermocline is very close to the bottom. The actual drag coefficient is expected to be high since Nechako Reservoir was not logged prior to the impoundment. Well preserved underwater trees likely induce ample mixing particularly as they penetrate the oscillating thermocline entraining warmer water and mixing it with cold water when the thermocline reverses its vertical motion and the associated horizontal currents are reversed as well.

3. Model Application

3.1. *Model Validation*

The model was first validated for the period between day 225.5 and 240. Simulation results from run-A are in good agreement with measurements at the thermistor chains (Figure 3c and 3d). In particular, the model is successful in capturing the vertical mode 2 waves observed at Natalkuz mooring (Figure 3d). At both KN and NA moorings, higher isotherms are better replicated than lower ones. For instance, at KN, the simulated 14ºC isotherm is highly correlated to the observed isotherm with a coefficient of 0.93. The correlation coefficient for the 6°C isotherm drops to 0.62. This vertical discrepancy in the model performance can be ascribed to the poorly resolved drag induced by underwater trees and to the step-wise representation of deep bathymetry of the original narrow river valley.

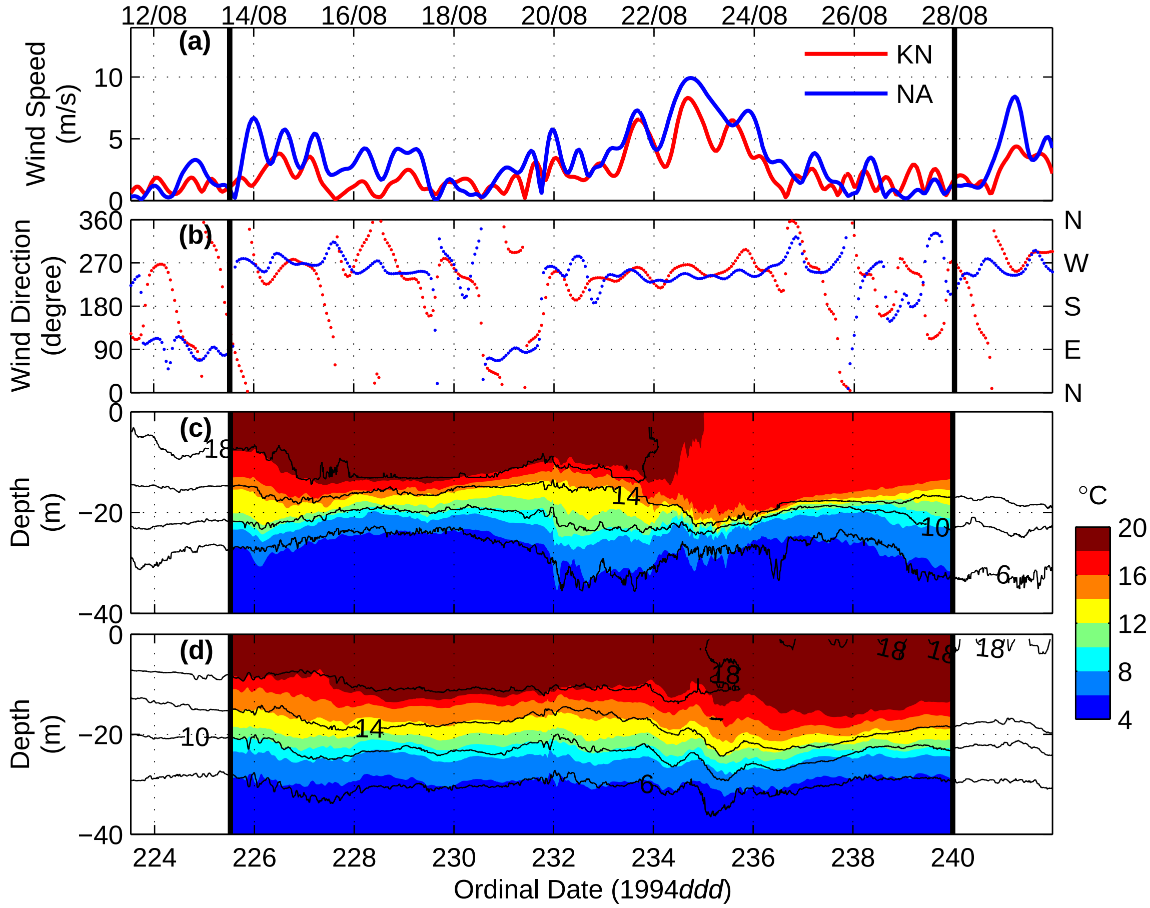


Figure 3: Forcing with measured and simulated isotherm response. Upper two panels show a) wind speed and b) direction measured at KN and NA met stations. Comparison of simulated (color fill) and measured (black solid lines; 6, 10, 14, and 18ºC) isotherm levels for run-A. c) Knewstubb mooring. d) Natalkuz mooring. Wind data is low-pass filtered with a cutoff of 12 hours using a Butterworth filter.

3.2. *Wave Decomposition*

The 10°C isotherm from the three simulations, run-A, -B, and -C are compared to that observed at KN mooring (Figure 4). The mean and standard deviation of the 10°C isotherm is given in Table 1. Run-A shows the best agreement with the mooring data while, as might be expected, the smaller domain runs produce less agreeable results.

Table 1: Basic statistics of the 10° isotherm for the different series.

Series	Mean (m)	Standard deviation (m^2)	Correlation to KN (at no lag)
KN	23.8	1.86	1.00
Run-A	22.8	1.19	0.85
Run-B	21.3	1.38	0.33
Run-C	20.8	0.56	0.32

Run-C, with the smallest domain, doesn’t capture the low frequency motion propagating from Knewstubb Mid-reach and beyond. The three crests of the 10°C isotherm on days 233.87, 234.90, 235.77 (indicated by arrows in Figure 4) are obviously local features excited by the wind blowing over Knewstubb and Big Bend Arms (refer to Figure 3c and 3d for wind forcing). The period of this wave is approximately 24hrs, which is the estimated period for the fundamental oscillation of the basin comprised of Knewstubb and Big Bend Arms. The average depth of the 10°C isotherm is essentially the initial depth with the abovementioned oscillations superimposed on it. Progressing to runs B and A, the 10°C isotherm trend indicates the same locally induced waves are superimposed on lower frequency waves propagating from Knewstubb Midreach and Natalkuz Lake, respectively.

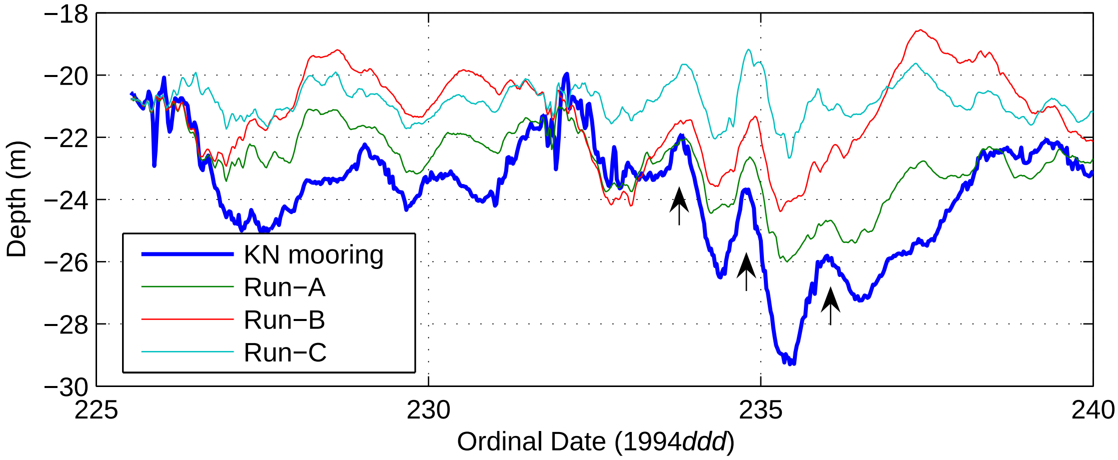


Figure 4: Simulated depths of the 10°C isotherm versus observed depths at Knewstubb Mooring. Arrows indicate the three wave crests referred to in the text.

The 10° isotherm depth is correlated at both moorings with a value of 0.7 (Figure 5). The linearly-detrended low-pass filtered depth, with a cutoff of 48hrs to remove locally excited motions, is correlated more strongly with a value of 0.8. This strong correlation is associated with a lag of 40hrs of Knewstubb isotherm behind Natalkuz. Over the 38km separation distance between the two moorings, the lag is equivalent to wave celerity of 0.25m/s. This celerity value reasonably matches the celerity estimated for the fundamental oscillation in Knewstubb and Big Bend Arms; 0.19m/s. Thus, it is evident that this long wave originates in Natalkuz basin, travels through the Narrows and Knewstubb Mid-reach, and is strongly detected at KN. The spatial structure of the wave is described below as obtained from the simulation results.

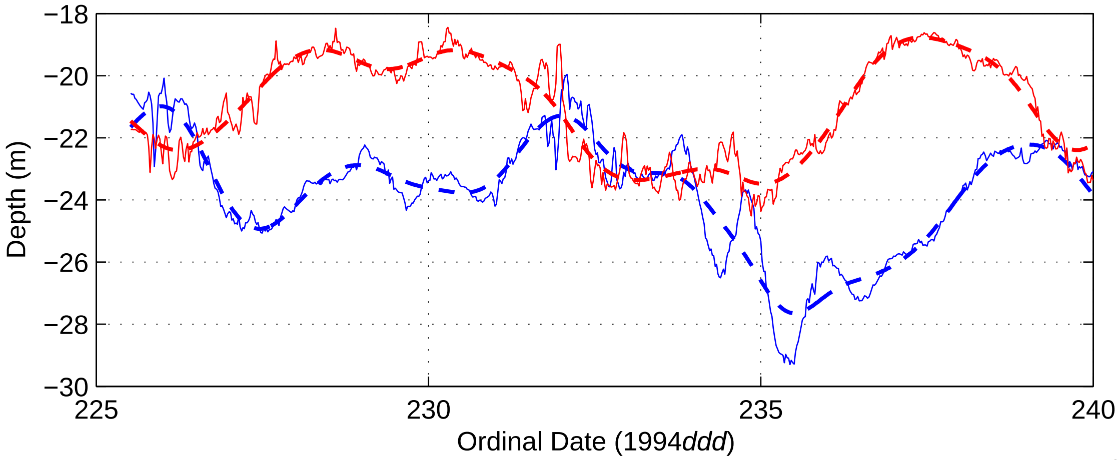


Figure 5: 10°C isotherm depths from KN (blue) and NA (red) moorings versus time. Dashed lines show low-pass filtered series with a 5th order Butterworth filter.

3.3. *Spatial Structure*

On day 235.0, the spatial structure of the thermocline is inferred from the excursions of the 10°C isotherm in response to the strong wind forcing. Since thermodynamic fluxes are excluded from simulations, the volume of water colder than 10°C is conserved except for mixing. The temperature stratification is diffused by vertical mixing, altering the isotherm equilibrium level from its initial value. In the model runs, the depth of the 10°C isotherm at the beginning of the simulation is essentially the initial equilibrium level as a consequence of the start-from-rest assumption. Assuming mixing is negligible, the simulated isotherm depth at later times is compared to this initial level (Figure 6).

In run-C, as the junction is sealed from the south and Knewstubb and Big Bend Arms are modeled as a single contained basin, the 10°C isotherm rises above its equilibrium level on the dam side and depresses below the equilibrium level on the opposite side. In run-B, the 10°C isotherm is completely lowered below the equilibrium level throughout Knewstubb and Big Bend Arms with the same tilt as run-C. The cold volume of water displaced downward in the two arms flows into Knewstubb Midreach and raises up the 10°C isotherm in the Midreach. The 10°C isotherm within Knewstubb and Big Bend Arms is further depressed in run-A than in runs -C and -B. The isotherm is also depressed down in Knewstubb Midreach from its run-B level. Nevertheless, in both basins, the isotherm retains the same local tilts predicted by the previous runs except a short distance downstream the Narrows. The cold water displaced by lowering of the isotherm in Knewstubb Lake upwells at the west end of Natalkuz. The exchange flow between Knewstubb and Natalkuz Lakes is subject to internal hydraulic control at the end of the Narrows as evident by the abrupt change in isotherms levels at 30 and 37km. Observing the evolution of the spatial structure from Run-C through Run-A indicates a relatively linear superposition of oscillations generated in Knewstubb and Big Bend Arms and waves propagating from the Midreach and Natalkuz Lake.

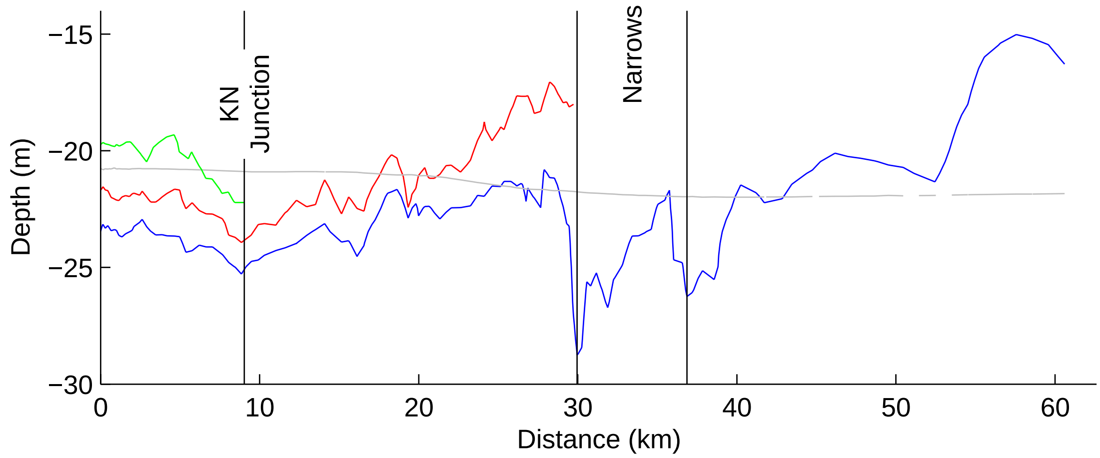


Figure 6: 10°C isotherm depth along the thalweg on day 235.0. Blue, red, and green lines are for runs A, B, and C, respectively. Initial isotherm level is indicated by grey line. Black vertical lines indicate features along the thalweg.

4. Conclusions

The thermal structure of part of Nechako Reservoir has been modeled numerically. By simulating domains of different extents, the internal wave field observed at Knewstubb mooring is decomposed to oscillations originating locally within Knewstubb and Big Bend Arms and to longer waves propagating from Knewstubb Midreach and Natalkuz Lake. For the domain including Knewstubb and Natalkuz Lakes, simulation results show good agreement with thermistors chain data from the two moorings. On average 80% of the internal wave structure at KN mooring can be explained through modeling Knewstubb and Natalkuz Lakes only.

Acknowledgments

This work was supported by a grant from the Nechako Enhancement Society. The field data was provided by Alcan Inc. and Triton Environmental Consultants. The authors thank Rod Bell-Irving for his assistance and Gregory Lawrence is grateful for the support of the Canada Research Chairs program.

References

1. Boudreau, K. (2005). "Nechako Watershed Council Report: Assessment of Potential Flow Regimes for the Nechako Watershed." Prepared for the Nechako Enhancement Society & Nechako Watershed Council. 6-20.
2. Lawrence, G., and Pieters, R. (2005). " Hydrothermal Characteristics of the Nechako reservoir." Prepared for the Nechako Enhancment Society. 2pp.
3. Anohin, V. V., Imberger, J., Romero, J. R., and Ivey, G. N. (2006). "Effect of Long Internal Waves on the Quality of Water Withdrawn from a Stratified Reservoir." J. Hydraul. Eng., 132, 1134.
4. Triton Environmental Consultants (1995). "Nechako Reservoir Additional Data Collection." Prepared for Alcan Smelters and Chemicals Ltd.
5. Hodges, B. R., Imberger, J., Saggio, A., and Winters, K. (2000). "Modeling Basin-Scale Internal Waves in a Stratified Lake." Limnol. Oceanogr., 45(7), 1603-1620.
6. Laval, B., Imberger, J., Hodges, B. R., and Stocker, R. (2003). "Modeling Circulation in Lakes: Spatial and Temporal Variations." Limnol. Oceanogr., 48(3), 983-994.
7. Marti, C. L., and Imberger, J. (2006). "Dynamics of the Benthic Boundary Layer in a Strongly Forced Stratified Lake." Hydrobiologia, 568(1), 217-233.