Seasonal Dynamics of a High Arctic Lake, Lake Linné, Spitsbergen Island, Svalbard

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Abstract

The purpose of this project is to characterize the physical processes in Lake Linné, Spitsbergen Island, Svalbard, that lead to vertical and lateral water temperature differences during the high arctic summer. The observed seasonal dynamics may include overturning, water temperature stratification, and variable timing of maximum water temperature in the lake. These seasonal changes must be quantified before water temperature data from this lake can be used in studies of global warming effects in high arctic lakes.

We used atmospheric and lake temperature data for the period of July 31 through September 4, 2003. We compared atmospheric temperature, wind speed and direction, solar radiation influx, and barometric pressure to lake temperature data from shallow (i.e., 2m) and deep (i.e., 10 m) mooring sites near the center of the lake (i.e., Site G) and on the southern shelf (i.e., Site F). We found that July 31 through August 19 surface water temperatures increased from 4°C to a three day long plateau of 7°C, and then fell to 5.8°C at the end of the observational period. This trend corresponds to concomitant air temperature changes. The increase lags shortly behind warm southerly weather while the cooling trend follows weak northerly winds. Anomalies in water temperature trends correspond to an unsettled time of wind azimuth as the prevailing winds shift from south to north. Changes in water temperature at ten meters mimic surface water temperature changes. Thermal stratification at Site F is lost during periods of strong southerly wind. These winds also correspond to days when surface water temperature at Site F is colder than at Site G.

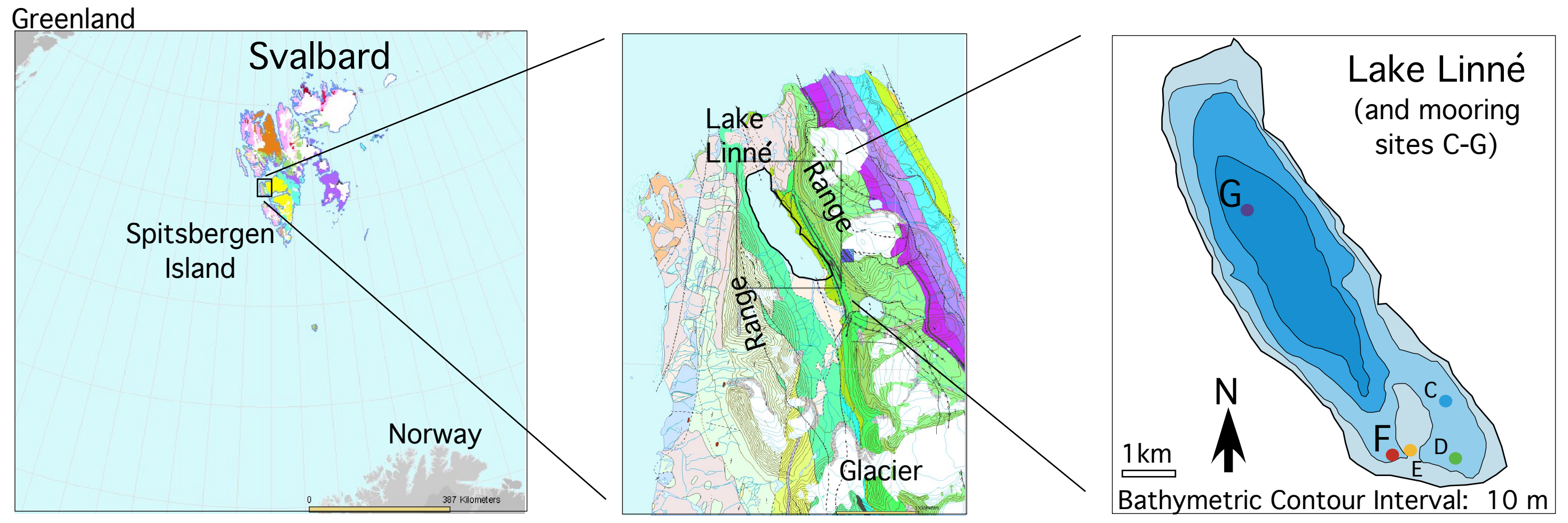
Our observations indicate that air temperature is the dominant control on water temperature at sites F and G through ten meters of water depth. However, strong southerly winds can cause vertical and horizontal changes in water temperature through vertical mixing of intermediate and shallow water, and lateral displacement of surface water. Thus, our single-season data indicate that lake water temperatures are proxies of atmospheric temperature although strong winds perturb the system.

Introduction

This study characterizes the seasonal development of thermal stratification and heat transfer in Lake Linné, Svalbard, between July 30 and September 4, 2003. Due to its arctic position and influx of glacial melt waters, Lake Linné may serve as a recorder of global environmental change and the response of large lakes to changing environment.

Lake Linné lies between two northwest to southeast trending ranges with 400 m average relief. It receives runoff from Linnébreen glacier whose terminus is 5.5 km to the southeast. The lake is 5 km long by 1 km wide, on average. A shallow (i.e., <15 m) shelf exists across the southeast margin and its greatest depths (i.e., > 35 m) lie in a small elliptical basin in the middle of the lake (see Figure 1).

Figure 1: Location Maps of Svalbard (A), Lake Linné (B), and In-lake mooring sites (C)



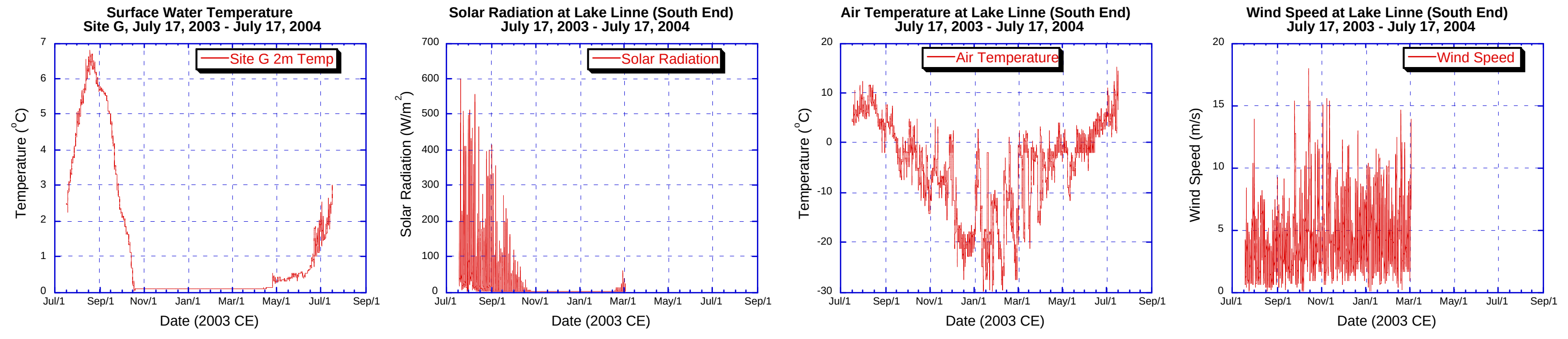
(A) (B) (C)

Background

Heating, heat transfer, and water circulation in most large lakes are well constrained processes. Influential factors include wind-related surface water effects, solar heating, local air temperature, and surface and ground water fluxes. Through ice-free seasons, lakes typically develop thermal stratification (i.e., warm water on top, cold water on bottom) as well as variably time-dependent trends of horizontal and vertical heating and cooling. These characteristics influence the lakes' maximum lake temperatures, number of ice free days, and the spatial and temporal distribution of heat.

On an annual basis, Lake Linné conforms to most expected heating and cooling trends in arctic large lakes (see Figure 2). The lake's ice-free season begins in June and ends in October and overall heating in the lake corresponds to the occurrence of wind action over open water, stream and ground water influx, and solar radiation. Fine-scale observations of in-lake temperature trends, however, reveal detailed heating and cooling that are unexpected. For example: surface water will cool on a sunny day; thermal stratification will suddenly disappear; water temperature on one end of the lake will rise while temperature at the other end remains constant. Consequently, before Lake Linné can be used as a model of limnological response to arctic climate change, a general heat budget and water circulation model is required.

Figure 2: Annual water temperature (A), solar radiation (B), air temperature (C), wind speed (D)



(A) (B) (C) (D)

Seasonal Factors

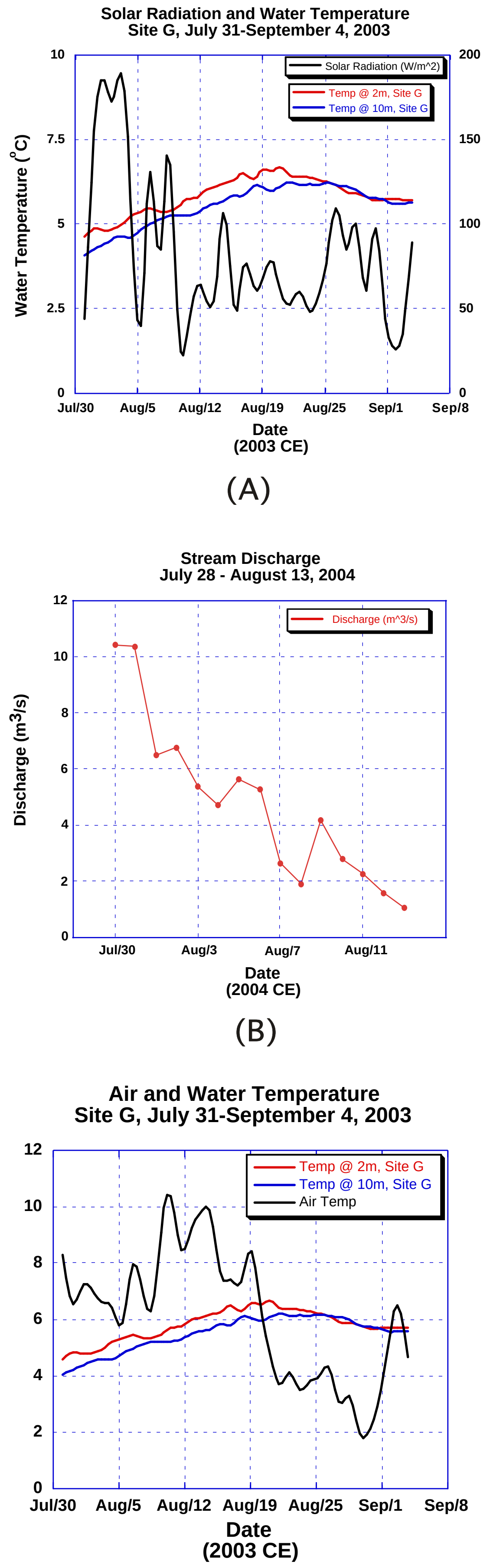
Figure 3: Water heat budget factors; solar radiation (A), stream inflow (B), and air temperature (C)

Although implicated in some lake studies as a source of water heating, our data demonstrate little correlation among epilimnon water temperatures and solar radiation flux.

Figure 3A illustrates daily average solar radiation from a weather station positioned near Lake Linné. These data are fit by a cubic spline curve and plotted with water temperature at Site G which we assume would be immune to influence from surface water influx. (We do not consider the influence of changing solar angle.) The opposition of epilimnon water temperatures and solar radiation on numerous days and through a long-term trend from August 1 to 20 implies solar radiation fluxes do not contribute significantly to epilimnon heating and cooling.

Stream water entering the lake is typically warmer than water in the lake. Warming occurs during shallow stream flow through the stream's 5.5 km reach from the terminus of glacier Linnébreen to Lake Linné. Although flow data are limited to the early season of 2004, we assume the analogous contribution of stream water to 2003 in-lake temperature changes during our observational period is negligible. Even at its maximum (i.e., ~10 m³/s), the total discharge to the lake from the stream (~ 900,000 m³/d) is insufficient to affect temperature change in the significantly greater volume of water residing in Lake Linné (~ 125,000,000 m³) on a daily or weekly basis. We estimate that the maximum temperature change resulting from the daily inflow of stream water is one order of magnitude less than the observed daily changes in epilimnon and metalimnon temperature sensors. Note, however, that the influence of stream flow on early season heating of Lake Linné is uncertain and could be important given the steepness of the hydrograph curve shown in Figure 3B.

Heating and cooling of the lake coarsely coincides with local air temperature changes. Figure 3C presents daily average air temperatures calculated from 30-minute temperature data recorded at a local weather station and fit with a cubic spline. Although some fluctuations in air temperature exist, the overall warm air temperatures coincide with rising lake water temperatures from July 30 to August 20. The cooling of lake water temperatures correlates to a time of decreased air temperatures during the period from August 21 to August 30. Of special importance is the more rapid cooling of epilimnon water temperature relative to metalimnon water, thus implying a direct cause and effect among air temperature and water temperature at Site G during this period of observation.



(A) (B) (C)

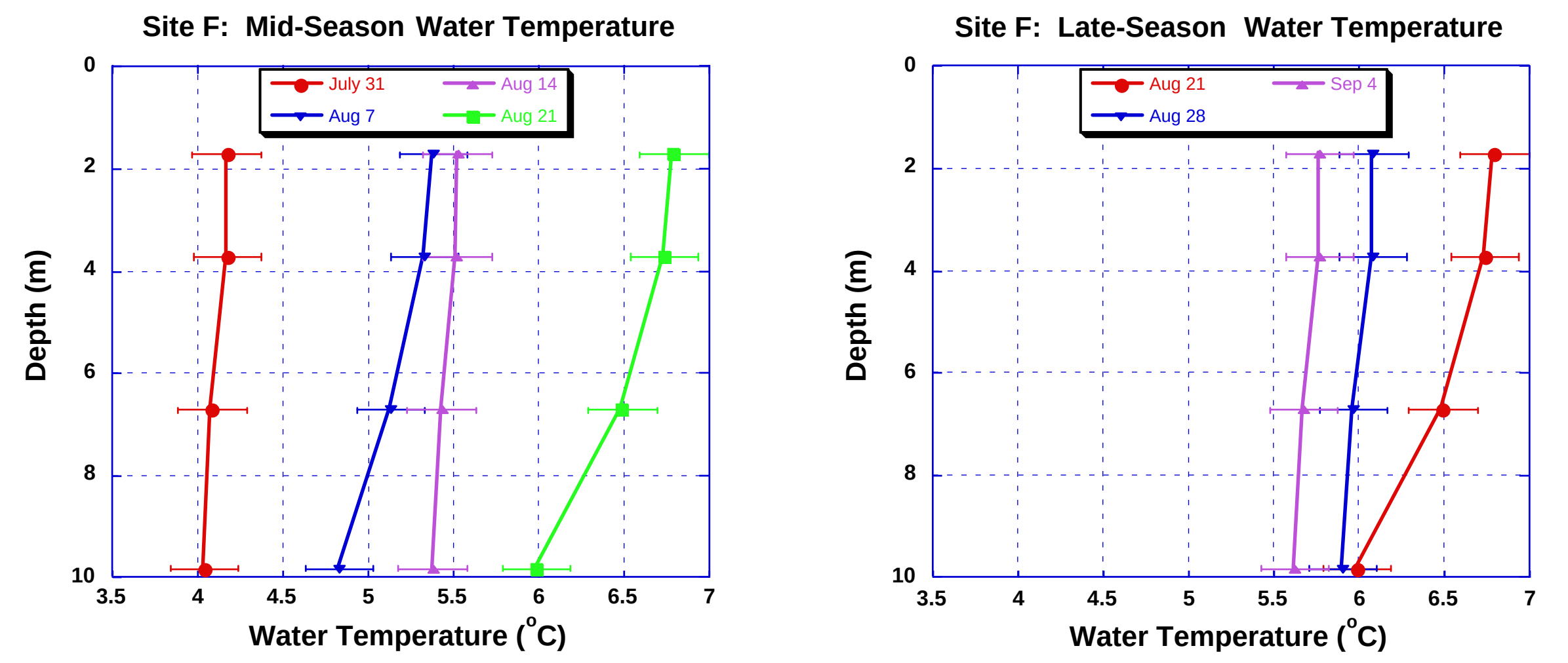
Regular Heating and Cooling

All mooring sites in Lake Linné experience periods of regular heating and cooling. Illustrated below are in-lake temperature data for Site F for a period of warming (Figure 4A) and cooling (4B).

As illustrated in Figure 4A, the surface waters of the epilimnon are heated and this heat then slowly migrates into the metalimnon through the summer season. (The nonconforming data for August 14 are discussed in Figure 5). Lake water develops a typical thermal stratification profile with epilimnon water temperatures rising by up to 2°C per week while metalimnon and hypolimnon temperatures rise by approximately 0.5°C per week.

Regular cooling in the late season ("fall turn-over") is observed by epilimnon temperatures that cool to those of the metalimnon and hypolimnon. Thereafter, all water temperatures cool at equal rates until ice-over.

Figure 4: Temperature profiles at Site F during mid-season (A) and late-season (B) periods

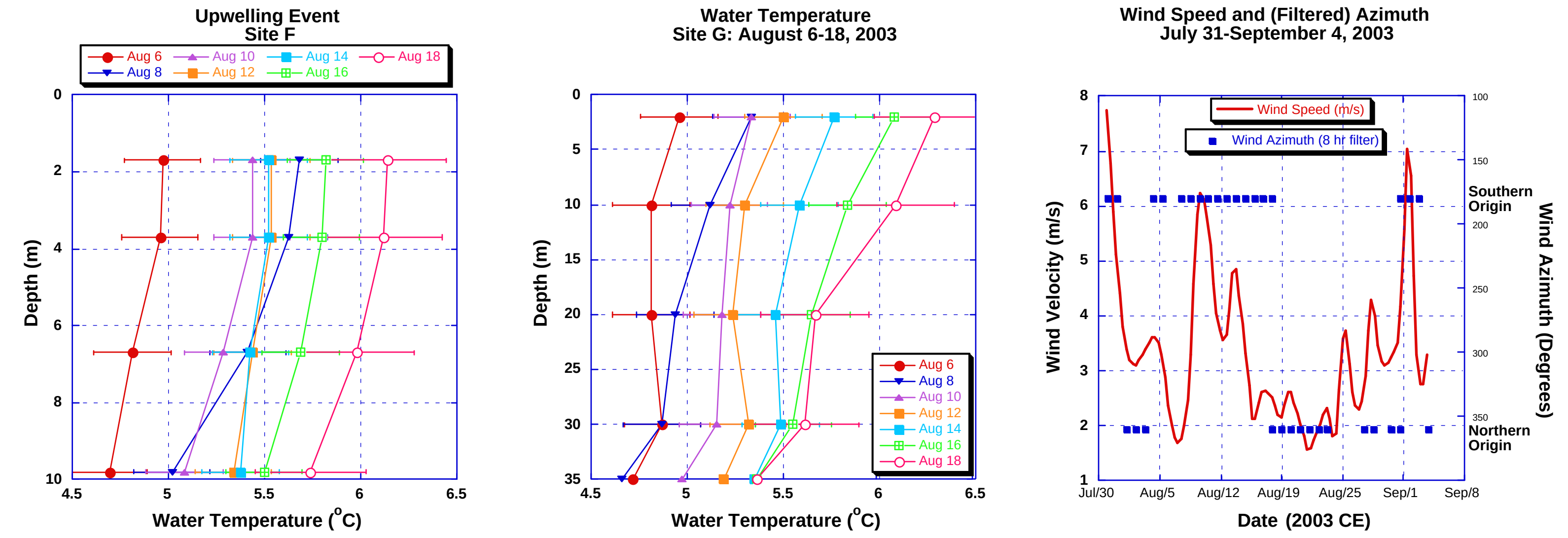


(A) (B)

Upwelling (Irregular Heat Transfer)

Lake Linné shows characteristics of irregular heat transfer during times of increased wind velocity. Temperature profiles at sites F and G are presented in Figure 5A and 5B, respectively, for the period between August 6 and 18. Although irregular, heating continues throughout the period at Site G. Site F, however, experiences a significant decline in water temperature at all depths between August 10 and August 14. Analysis of wind velocity and azimuth (Figure 5C) indicates the period of irregular heating and cooling corresponds to a period of prolonged, strong southerly winds. Thus, a significant upwelling event is implied.

Figure 5: Upwelling evidence-- temperature profiles at Site F (A) and Site (B) and wind data (C)



(A) (B) (C)

Seasonal Dynamics: Model

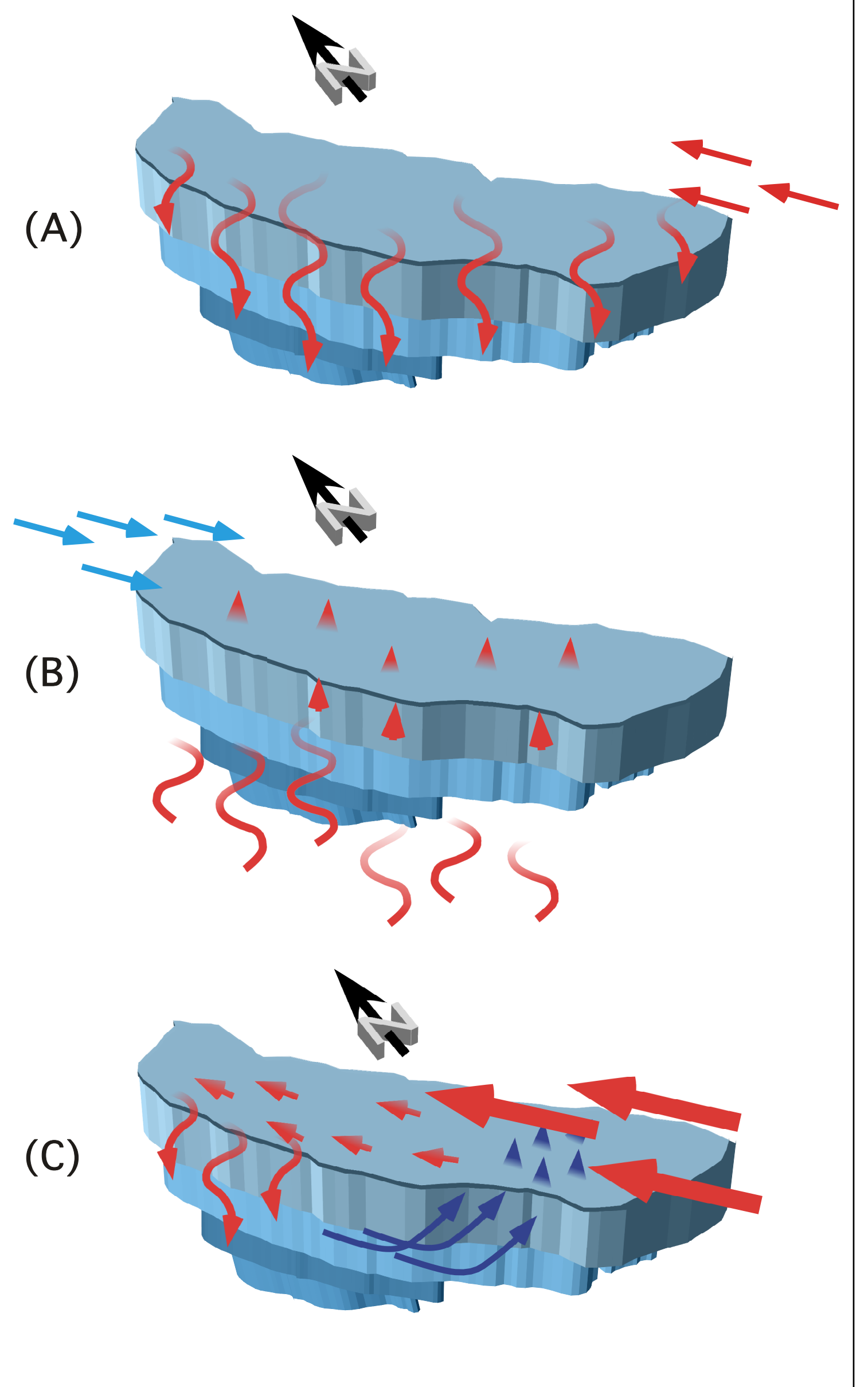
Based on this analysis of water and climatic data from July 30 through September 4, 2003, we propose a three component heat budget and circulation model for ice-free conditions in Lake Linné. Figure 6 illustrates the three highly stylized end-member components of the model.

Component 1, Normal Heating. By mid-season, the primary source of heat to the epilimnon is wind-related mixing with warm (i.e., >6°C) air overlying the lake. Heat is transferred from the epilimnon to deeper waters by normal turbulence. An important consideration of Component 1 is that winds associated with warm air over Lake Linné may be northerly or southerly; however, the winds from either direction are generally calm (i.e., < 4 m/s) during this phase of warming.

Component 2, Normal Cooling. Lake Linné is a "deep lake": Sixty percent of the lake volume exists below 10 m. Consequently, this volume serves as a large heat sink during periods when the epilimnon is cooled by low-temperature air masses. In our data, one such air mass arrived on August 20. Within five days of an air temperature drop of 4°C, epilimnon water temperature equilibrated with metalimnon water temperature. The hypolimnon is not an inexhaustible source of heat: Once thermal stratification is lost, continued cooling of the epilimnon works downward and causes all levels of the lake to cool simultaneously (at the rate heat can be dissipated from the hypolimnon).

Component 3, Upwelling. During periods of strong southerly winds, upwelling events occur. See Figure 6C. Warm surface water from the southern shelf is moved into deep water. Cold water from metalimnon and hypolimnon underlying bathyal portions of the lake is then moved up onto the edge of the shelf. In our data, modest wind speeds of only 5-8 m/s sustained over a period of as little as 16 h were required to initiate upwelling. If these are the average conditions that initiate upwelling in Lake Linné, then it appears susceptible to many, far more intense upwelling events-- a condition that deserves additional study.

Figure 6: Lake Linné heat and circulation models for periods of normal heating (A), normal cooling (B), and upwelling events (C)



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Acknowledgments

We thank Dr. Al Werner, Mount Holyoke College and Dr. Steve Roof, Hampshire College, for developing and directing the Svalbard REU. Thanks also to Ms. Edith Jaurrieta, Svalbard REU participant, for use of her streamflow data. Funding was provided by the National Science Foundation support of the Svalbard REU and Minnesota State University, URC Scholar Support Program (to Schimek).