



Processes affecting deposition of sediment in a small, morphologically complex lake

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Abstract

Devil Lake is morphologically complex as a result of Pleistocene glacial erosion of the Frontenac Axis of the Canadian Shield. In order to assess the processes causing highly variable sedimentation in the lake, we monitored currents, suspended sediment and temperature in the lake before and during autumn overturn in 2002. Strong summer thermal stratification (stability number to 0.11 s^{-1} declining with the approach of overturn) was insufficient to prevent a dynamic response in the hypolimnion to wind forcing. Superimposed on a gradual increase in suspended sediment concentration in the last weeks of stratification from less than $2 \mu\text{g/l}$ to about $30 \mu\text{g/l}$ were shorter-term rises lasting up to several days. Associated with these events was an increase in particle size of the sediment from a mode of 40–50 to 150–200 μm ascribed to flocculation from primary particles. These events culminated in rapid (<1 h) clearing of the water associated with strong, sustained winds over the lake, especially from the southwest. After overturn, the events were more frequent, and flocculation was unable to develop as well in the more vigorous circulation. However, currents in the hypolimnion occurred throughout the period before, during and after overturn with speed related to wind speed, but direction largely independent of wind direction. The results represent an approach to understanding the nature of sedimentary processes and thus to strengthening the use of sedimentary records as proxy in environmental and paleoenvironmental assessment.

Introduction

In a study of acoustic sub-bottom imagery of the sediments in Devil Lake located in southeastern Ontario (Figure 1), Gilbert (2003) documented the complexity of form of the lake created by Pleistocene glacial processes, including subglacial fluvial erosion, on the Frontenac Axis of the Canadian Shield in eastern Ontario. He showed that the pattern of subsequent lacustrine deposition is highly variable over the lake floor and through time. This variation was ascribed to environmental changes since deglaciation of the region about 12 ka BP and, by inference, to

processes, associated with circulation in the lake. This work also demonstrated that care should be exercised in choosing sites from which to recover cores used in environmental and paleoenvironmental assessment. Even the deepest parts of the lake contain complex and incomplete records which may lead to important mis-interpretation unless the regional and temporal pattern of deposition is assessed.

In this companion paper we report on preliminary measurements of processes in Devil Lake covering the period of thermal stratification in late summer through overturn in autumn and winter 2002–03 in order to provide a basis for

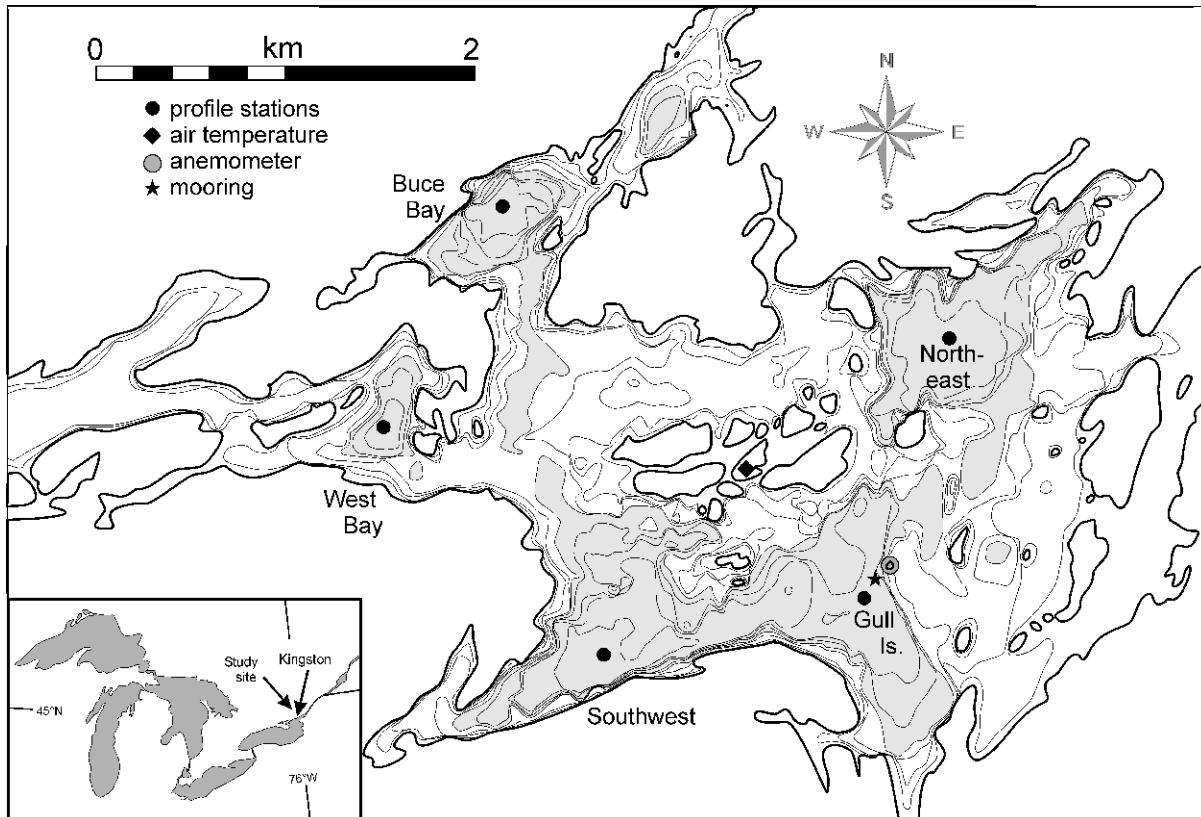


Figure 1. Bathymetric map of Devil Lake prepared from a sub-bottom acoustic survey (Gilbert 2003) showing the locations of measurements presented in this paper. Isobath interval, 5 m; region below 20 m depth is shaded. West Bay and Gull Island are informal names. Inset map shows the regional setting of Devil Lake.

assessment of the relation between physical processes of the lake and the manner in which sediment is delivered to, and deposited on, the lake floor. When we use the physical characteristics of lacustrine sediments as proxy for extra-limnic factors such as climate, hydrology or geomorphology, we may do so without consideration of process; however, such linkages made wholly on the basis of descriptive or inferential statistical associations are at best unsatisfying in that they do not tell us how, for example, rates of accumulation are related to precipitation or runoff, and at worst may be misleading due to spurious correlation.

The work we present here follows a long tradition of understanding the complexities of lacustrine process (Lerman et al. 1995; Hutchinson 1957); it is not definitive but points to some useful prospects for a better comprehension of the link between process and form and so to a more reliable application of lacustrine sediment as a proxy.

Methods

The study was conducted between 12 September and 22 November 2002. During this and the antecedent period, air temperature was recorded at 2-h intervals in a small screen beneath the forest canopy on an island in mid lake (Figure 1) by means of a data logger (Figure 2a). Water temperature was recorded manually at 1-m depth intervals at southwest station (Figure 1) with a thermistor probe calibrated to ± 0.05 °C using high-precision mercury thermometers. Measurements were taken at intervals of 2–20 days between 11 May and 30 November as other duties permitted (dots above Figure 2b), and on several occasions during this period at Buce Bay and West Bay. From these a pattern of lake water temperature was plotted (Figure 2b) and the stability (Brunt-Väisälä) frequency (Imboden and Wüest 1995) was calculated (Figure 2c) based on the sampling interval of 1 m,

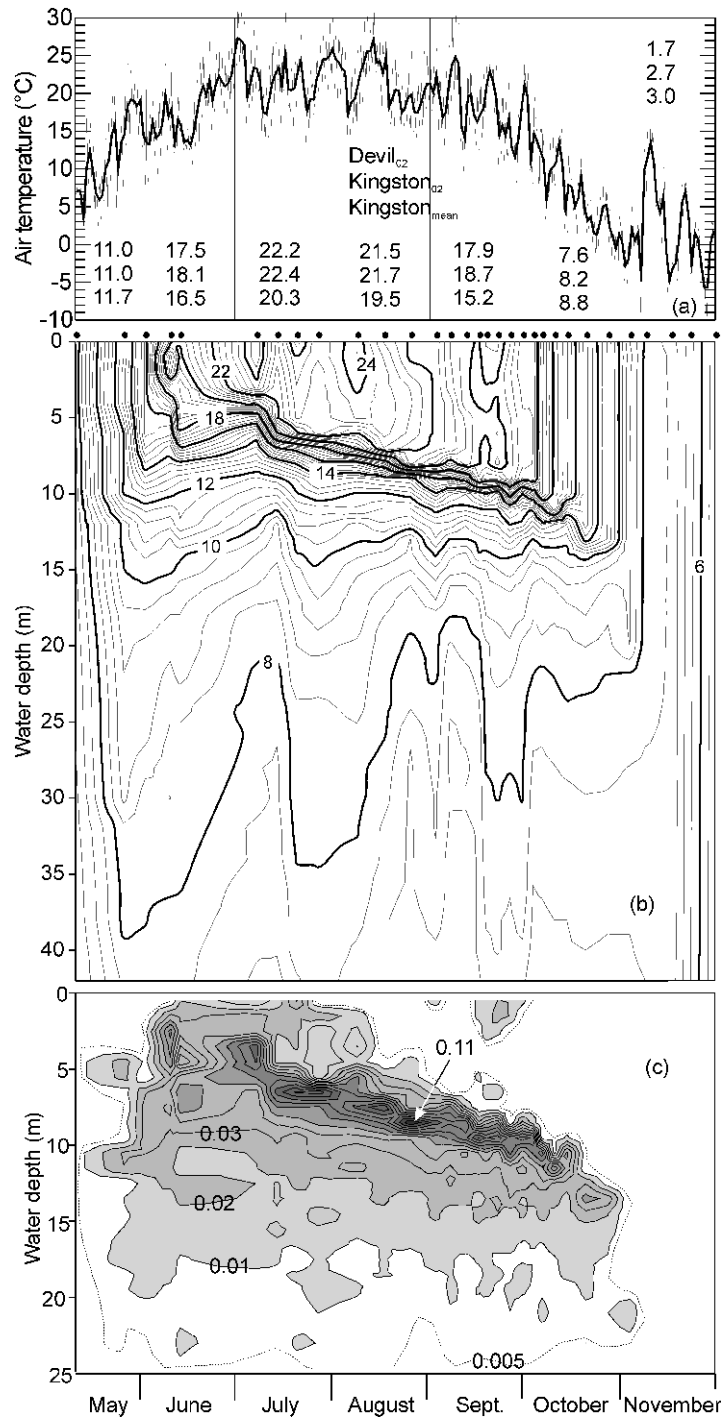


Figure 2. (a) Air temperature at Devil Lake (Figure 1) at 2-h intervals in grey and mean daily in black; (b) water temperature and (c) stability (Brunt-Väisälä) frequency (N) in $\text{Hz (s}^{-1}\text{)}$ (Imboden and Wüest 1995) from profiles taken at times shown by dots above the graph at southwest station (Figure 1) from 11 May to 30 November 2002. Isotherm interval in (b) is $0.5\text{ }^{\circ}\text{C}$; isopleth interval in (c) is 0.01 s^{-1} (solid lines) and 0.005 s^{-1} (dashed line). $N \geq 0$; values below 25 m depth were less than 0.005 s^{-1} at all times. Also shown in (a) are the mean monthly temperatures at Devil Lake in 2002 (Devil₀₂), Kingston in 2002 (Kingston₀₂), and the 30-year normal mean at Kingston (Kingston_{mean}). Kingston is 40 km south of Devil Lake; Kingston data are from Meteorological Service of Canada.

assuming the density of the water was solely the product of water temperature.

As equipment returned from other projects it was deployed in Devil Lake. Between 11 September and 30 November temperature profiles were also recorded at the times shown in Figure 2 at Buce Bay, southwest station and Gull Island, and on several occasions at West Bay and northeast station (Figure 1) using a Hydrolab Datasonde[®] logging at depth intervals of 0.1–0.3 m depending on the rate of descent. Several profiles were also recorded in winter 2003 from the ice cover on the lake. Between 12 September and 27 November a Sequoia LISST-100[®] was used to record temperature, sediment concentration and particle size distribution at 15-min intervals at 20 m depth on a mooring near Gull Island in mid lake (Figure 1) in 32 m water depth. Location of the mooring was governed in part by need to limit interference with the extensive sport fishery in the lake. On 28 September the instrument was raised to 18 m depth. On 27 October it was lowered to 20 m depth and an Alec Electronics Compact EM[®] current meter logging at 30-min intervals was installed above it at 19 m depth. Both instruments also recorded water temperature to ± 0.01 °C. In addition, Onset Tidbit[®] data loggers installed on the mooring line recorded temperature to ± 0.2 °C at 30-min intervals at depths of 3, 10 and 15 m. Between 3 October and 22 November a Davis Industrial anemometer was installed 5.0 m above the surface of Gull Island (about 7 m above the water surface) logging mean wind velocity in 10-min intervals. Based on similar patterns of wind at Kingston and Devil Lake during the period of observation, data from Kingston were used to extend the record between 12 September and 3 October, before the anemometer was installed at Devil Lake.

Antecedent conditions

Figure 2 shows that Devil Lake is dimictic with stratification developing through May 2002, following ice-off which occurred on 9 April. During this period, stratification was weak as evidenced by values of the stability (Brunt-Väisälä) frequency (Imboden and Wüest 1995), $N < 0.03$ s⁻¹, although a warm period at the end of May increased N

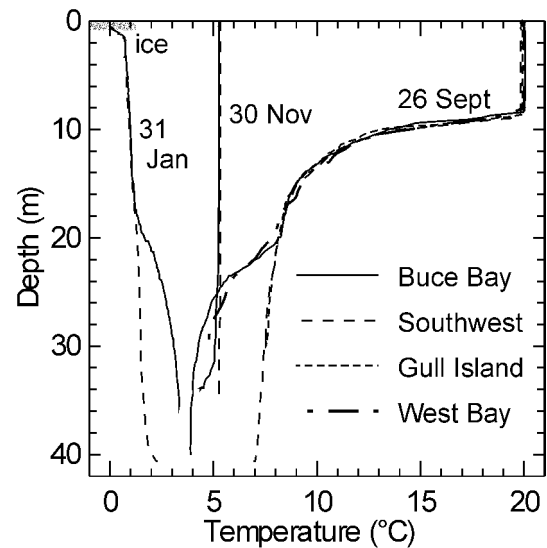


Figure 3. Temperature profiles recorded on 26 September 2002, 30 November 2002 and 31 January 2003. For locations, see Figure 1.

briefly to 0.06 s⁻¹. Very warm conditions persisted with short interruptions from late June to September with the result that the lake became strongly stratified ($0.08 < N < 0.11$ s⁻¹) as the thermocline deepened from 7 to 10 m between mid July and late September. Discussion of the breakdown of thermal structure during the study period is presented below.

Temperature in the epilimnion reached a maximum of 24.7 °C on 7 July and exceeded 24 °C on two other occasions in the summer in response to maximum air temperatures above 30 °C, although exact comparison of water and air temperature is difficult because of the sampling period and because the profiles were not recorded at the same time each day. Temperature in the hypolimnion decreased from about 10 to about 7 °C with depth during this period, although it fluctuated by about 0.5 °C at any particular depth. Similar temperature patterns were observed earlier in nearby Upper Rock Lake (Agbeti et al. 1997), although in this much smaller (0.7 km²) and more sheltered lake the thermocline occurred between 4 and 6 m depth.

In the main body of the lake, as seen in profiles from southwest station, Gull Island (and northeast station not shown in Figure 3) the temperature declined to about 7 °C at the bottom. However, in protected Buce Bay and West Bay a second

thermocline occurred about 22 m depth and hypolimnic temperature decreased to a minimum of 3.9 °C. The difference in these profiles is associated with the larger fetch in the main body of the lake compared to a limited fetch (see Discussion below) and hills to 30 m above the lake in the immediate vicinity. More vigorous circulation in the main lake continued as the lake warmed in the spring, mixing warmer water to the greatest depths and spreading that influence above a bathymetric barrier about 20 m deep (Figure 1) into the protected bays. However, vertical circulation in these areas is precluded by the difference in density between this and the cold bottom water in the absence of vigorous overturn as occurs in the open lake, even though the stability frequency of the lower thermocline is much less ($0.02 < N < 0.04 \text{ s}^{-1}$) than that of the main thermocline.

Data are not available from the period before 11 May. However, data from winter 2003 (Figure 3) indicate that the winter temperatures were below 2 °C throughout the main part of the lake, while remaining up to 3.5 °C at the bottom in protected regions such as Buce Bay. The warmer temperatures in the hypolimnion during summer may be accounted for by mixing in near isothermal (and thus isopycnal) conditions between ice-off and the onset of thermal stratification. Similarly, the colder temperatures in late autumn and winter represent mixing after overturn and before ice-on.

Through September, epilimnion temperatures at all sites were very nearly the same (Figure 3) and changed by less than 0.1 °C through depth (Figure 2), indicating that the epilimnion is well mixed both laterally and through depth. Similarly, temperatures were nearly identical everywhere through the metalimnion and into the hypolimnion to about 20 m depth.

The conditions described above may be similar to those in most years in Devil Lake. The mean monthly temperature (Figure 2a) is comparable to that at Kingston, 40 km south on the shore of Lake Ontario averaging 0.5 °C cooler during the study period, probably due more to the location of the sensor under the forest canopy than to regional temperature differences. The mean temperatures at Kingston in 2002 were below the long-term mean in May (−0.7 °C) but rose to 3.5 °C above the mean by September before dropping below again in October (−0.6 °C) and November

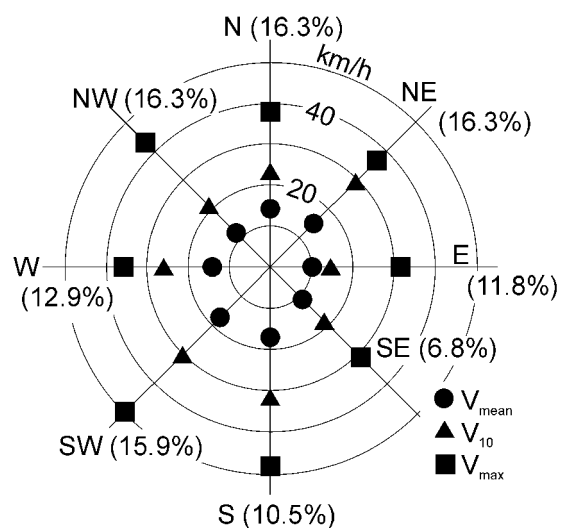


Figure 4. Summary of wind velocity by cardinal direction in 10-min intervals between 3 October and 30 November 2002. Shown are the mean wind velocity (V_{mean}), the velocity exceeded 10% of the time (V_{10}), the maximum recorded velocity (V_{max}), and the per cent of time the wind blew from each direction. Calm conditions occurred only 0.05% of the time. Location of instrument is shown on Figure 1.

(−0.3 °C). Thus, it is probable that the thermal structure persisted several weeks longer in September and deteriorated somewhat more rapidly in October and November than normal. Clearly, other meteorological conditions, including wind as described below and insolation also affected the thermal pattern in the lake.

Conditions during the study period

The study period covers the end of strong thermal stratification, decay of stratification through isothermal conditions of overturn (Figure 2) until about 1 week before the lake became frozen over. Ice formed near shore and in the inter-island areas beginning on 3 November, expanding irregularly to about 20% of the water surface on 1 December, with complete ice-over by 4 December when air temperature reached −17 °C. We choose this study period because wind is normally strongest during autumn storms (AES 1984), which with overturn of the lake water, we expected would produce the most vigorous circulation in the lake.

Moderate northwest to northeast winds predominated (49% of the time) during the study period (Figure 4). The mean wind speed (14.1 km/h) was

lower than the long-term mean at Kingston for October (17.9) and November (19.8) (AES 1984). The strongest recorded winds (49 km/h) were from the south and southwest during a storm on 5 October before the instrument was damaged by wind and repaired 18 h later. During this time, wind at Kingston exceeded 30 km/h for 19 h and reached a maximum mean hourly speed of 48 km/h with a maximum gust of 61 km/h. The long-term extreme data for Kingston indicate that mean hourly winds stronger than 61 km/h occur only 0.04% of the time (Gilbert 1999), making this storm one of the larger on record. Calm conditions prevailed only 0.05% of the time at Devil Lake.

The observations are presented below for the period 12 September to 26 October, and 27 October to 22 November, the latter during which the current meter was in operation.

12 September to 26 October

During September, the upper epilimnion responded to daily air temperature cycles with up to 2° warming at 3 m depth (Figure 5a). In the lower epilimnion a more complex pattern is seen. Between 12 and 20 September small, irregular fluctuations occurred in response to circulation by wind of warmer surface water to depth (Figures 2 and 5a); an event on 13 September in response to sustained 28–30 km/h southwest winds (Figure 5, event 1) is conspicuous. From 21 to 28 September these events became more pronounced with fluctuations in 0.5–6-h periods of up to 4 °C, for example event 3 in response to sustained south winds of 18–28 km/h, and event 4 as two decreases in sediment concentration over 18 h in dominantly north-east winds of 11–22 km/h. Both of these events were associated with significant temperature fluctuations in the metalimnion. Merian's formula indicates that the period of a unimodal internal seiche on the thermocline would have been about 7–8 h at this time (cf. Hutchinson (1957), p. 338). The frequency of the temperature fluctuations on 13 October was 6.5 h, suggesting the fluctuations may have been due to an internal seiche. On 28 September the sensor was placed at the top of the hypolimnion (13 m: Figure 2b) to record the deterioration of the thermal structure of the lake.

During this period, the maximum stability number (Figure 5c) remained near the maximum values

recorded during summer (Figure 2c). Nevertheless, there were significant fluctuations in the hypolimnion. These are poorly detected by temperature because the variation though the hypolimnion was much smaller than in the epilimnion (Figure 2b), although small fluctuations (especially events 3 and 4) are seen, as the hypolimnion responded to conditions in the epilimnion. Most remarkable are the fluctuations in concentration and particle size of suspended sediment in the hypolimnion. Superimposed on a gradual increase in suspended sediment concentration in the last weeks of stratification from less than 2 µg/l to about 30 µg/l (Figure 5c) were shorter-term rises lasting up to several days. Associated with these events, the relative distribution of particle size of the material (Figure 5d) shifted to larger diameter, with the peak centred on 150–200 µm, over periods of up to 4 days. During much shorter periods of a few hours (events 1–4) the concentration decreased as the water cleared substantially, and many of the coarser particles were lost from the water column. Event 2 is poorly recorded in the thermal record of the epilimnion, although it appears to have occurred in response to sustained south winds reaching 13–26 km/h.

Throughout October the pattern continued as the thermal structure of the lake weakened. Events 5 and 6 represent a minor clearing of the water column and relative loss of coarse particles in response to persistent dominantly southwest winds of 11–30 km/h the previous day, and very strong southwest winds to 49 km/h, respectively. The former has no signal in the metalimnion temperature records; the latter is characterized by several large internal waves of period 7.0 h. Merian's formula suggests the period of an internal seiche would have been about 8–9 h at this time as the difference in density between the epilimnion and hypolimnion was decreasing. Throughout this period the stability of the metalimnion remained high with $N > 0.08 \text{ s}^{-1}$. However, on 13 October (event 7) the thermal structure weakened substantially ($N < 0.05 \text{ s}^{-1}$). Event 7 occurred in response to sustained southwest winds to 31 km/h which also generated large internal waves of mean period 7.2 h. At this time the water column cleared significantly, although not as much as occurred earlier in the study period. On 19 October the thermocline passed 13 m depth (cf. Figure 2); stability

continued to decline slowly, but in relatively light winds of less than 18 km/h dominantly from the northwest to northeast the lake was relatively quiet.

27 October to 22 November

On 27 October, a current meter was installed on the mooring at 19 m depth. The results of this and the data acquired with the other instruments are shown in Figure 6. Temperature in the epilimnion continued to decline and the thermal stability of the lake decreased until overturn occurred on 7 November as a result of northwest winds reaching 43 km/h and very cold air temperature (-10°C) in the early morning hours (event 16). Light to moderate winds from the northeast, then the southwest generated currents from the south southeast, parallel to the orientation of the sub-lacustrine topography in this area (Figure 1). The best correlation between wind and currents occurred when the winds were from the southwest to west. When the wind was north to northeast, currents were reduced, probably because the shallower water to the north and east (Figure 1) protected the mooring site. For brief periods on four nights during this period when winds decreased and became southwest, this pattern was interrupted with weak currents from the northwest to northeast.

Concentration of suspended sediment decreased from the most turbid water which occurred on 31 October ($27\ \mu\text{g/l}$) in a series of events preceded by events of moderate to strong winds and currents, although the correlation between specific events is not always clear. Events 9, 10, 14, and 15 were associated with strong southwest winds but events 11 and 12 were associated with moderate southeast winds and nearly calm conditions, respectively. Each of these clearing events resulted in a loss of coarser particles ($>100\ \mu\text{m}$) and an increase in the finer component (Figure 6f).

Between 7 November and 13 November air temperature increased significantly and strong, dominantly southwest winds mixed and very slightly warmed the entire lake before cold conditions with strong (to 36 km/h) north and northeast winds began on 14 November, cooling the entire lake until temperatures moderated and winds decreased on 19 November. Current direction switched dramatically to the north, gradually

backing to west southwest through this period. Events of increased sediment concentration during this period were associated both with stronger winds (events 17 and 18) and light to moderate winds (events 19–22). Following 14 November the concentration remained low with a few excursions to higher values and coarse-grained particles were much less abundant. In all cases, there appears not to be a strong relation between current velocity and the events of increased in the turbidity of the water column.

Discussion

Our results are preliminary and tentative. However, they do indicate that the complex bathymetry and shape of Devil Lake (including the numerous islands in mid lake) give rise to a complex pattern of limnological processes and therefore sedimentary deposits. Figure 7 illustrates the maximum effective fetch of the lake determined by the procedure of Håkanson and Jansson (1983) and Gilbert (1999), having consideration for the shelter effect (across 100–180 m) caused by the relatively high land around weather (upwind) shores of the lake (Ottesen-Hansen 1978). The shelter effect of the lee shore ($<100\ \text{m}$) is not considered in these calculations because waves and their influences travel downwind with little or no modification through this relatively narrow zone to reach the shore. The largest effective fetches (up to 1.93 km) are in the northeast, south and southwest of the lake where the sheltering effect of islands is least. A smaller area occurs in the northwest but because southeast winds are generally lighter than those from other directions (Figure 4), the effect of this region is less.

According to Sinclair and Smith (1972), an effective fetch of 1.9 km results in a maximum significant wave height of 0.6 m in 60 km/h winds and 0.95 m in 100 km/h winds. Sustained wind of significantly less than 1 h is required to generate a fully developed sea in these conditions (CERC 1973). Such conditions may generate surface currents of 8 and 12.5 cm/s, respectively, as water is driven downwind, and wave base of about 6 and 11 m, respectively (Norrman 1964; Johnson 1980).

The complex morphology of the lake creates two mixing environments during spring and autumn

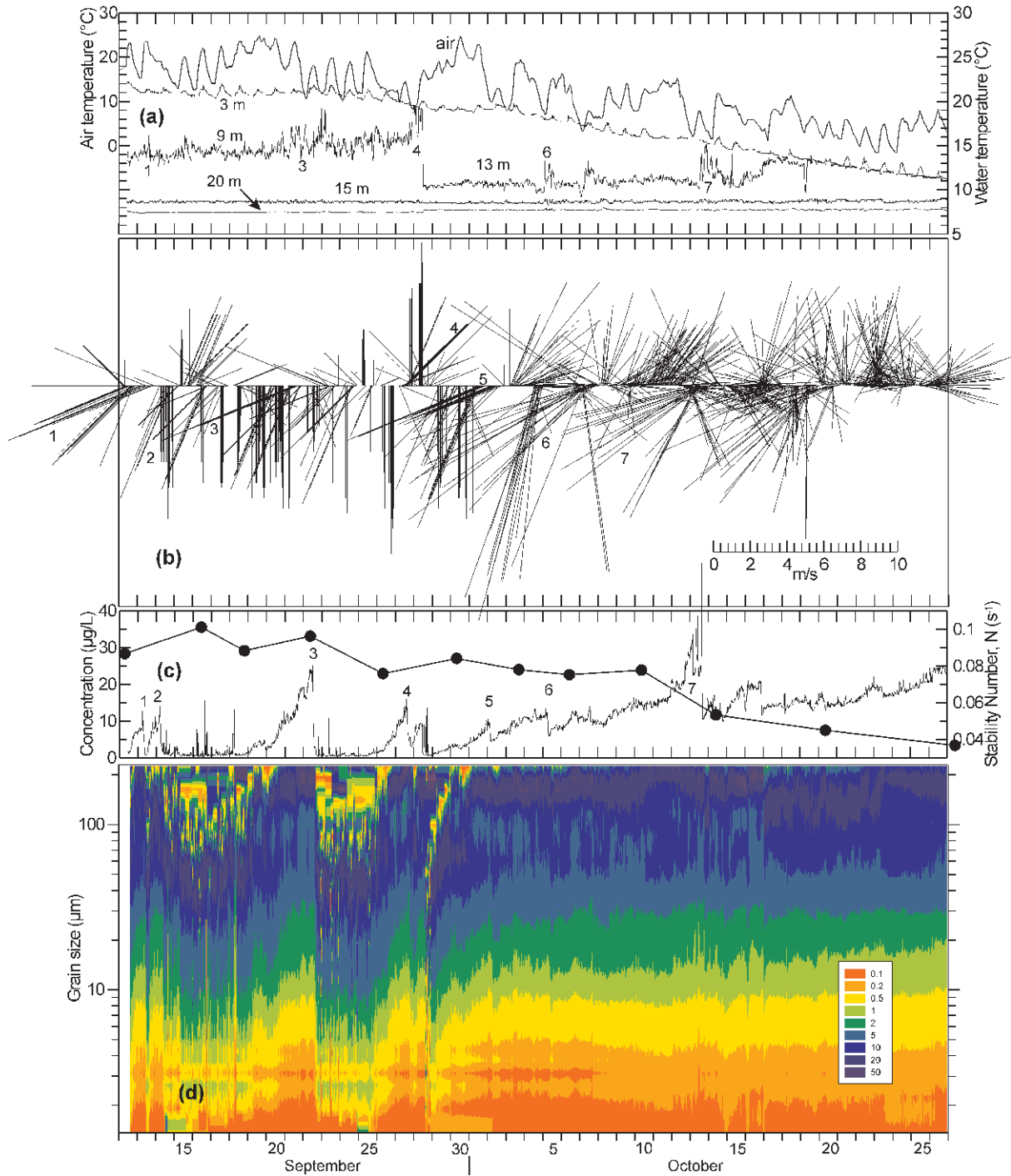


Figure 5. Summary of data between 12 September and 26 October 2002: (a) air temperature at 2-h intervals and water temperatures at the mooring at 30-min intervals at 3 m depth, 9 m (moved to 13 m depth on 28 September), 15-m (all with resolution, 0.2 °C) and at 15-min intervals at 20 m depth (resolution, 0.01 °C), (b) mean hourly wind velocity from Kingston before 3 October (except between 00:00 and 05:00 h) and afterward at Devil Lake, (c) suspended sediment concentration at 20 m depth at the mooring and the maximum stability (Brunt-Väisälä) frequency from profiles at southwest station, and (d) relative particle size distribution of suspended sediment as per cent in 0.24 ϕ intervals at 20-m depth at the mooring. Numbers refer to discussion in text. For locations, see Figure 1.

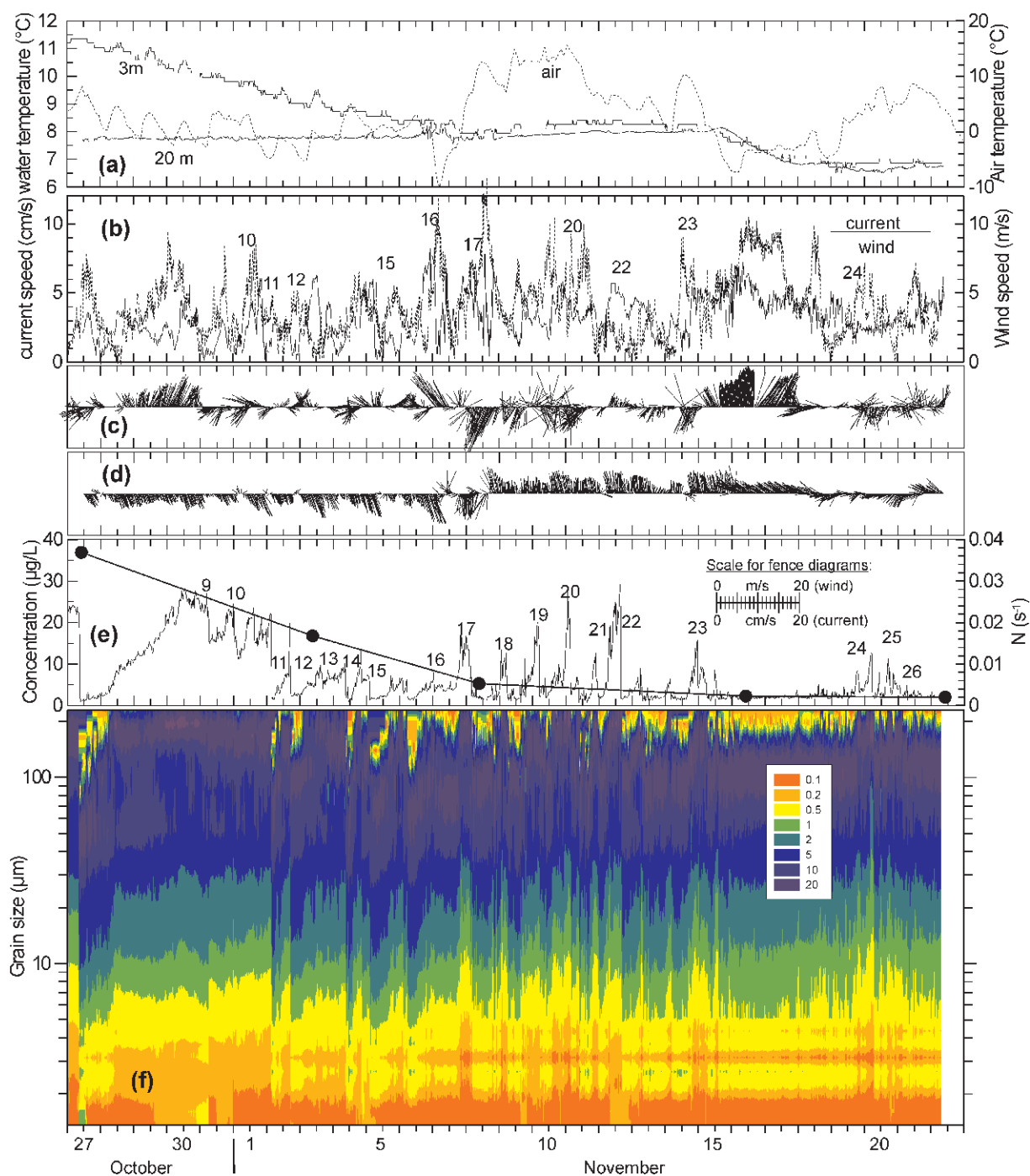


Figure 6. Summary of data between 27 September and 22 November 2002: (a) air temperature at 2-h intervals and water temperatures at the mooring at 30-min intervals at 3 m depth, 13 m, 15 m (all with resolution, 0.2 °C) and at 15-min intervals at 20 m depth (resolution, 0.01 °C), (b) mean wind speed at 10-min intervals and water current speed at 19-m depth at 30-min intervals, (c) mean wind velocity at 10-min intervals expressed in m/s to facilitate comparison to current velocities, (d) current velocity at 19-m depth at 30-min intervals (e) suspended sediment concentration at 20 m depth at the mooring and the maximum stability (Brunt-Väisälä) frequency from profiles at southwest station, and (f) relative particle size distribution of suspended sediment as per cent in 0.24ϕ intervals at 20-m depth at the mooring. Numbers refer to discussion in text. For locations, see Figure 1.

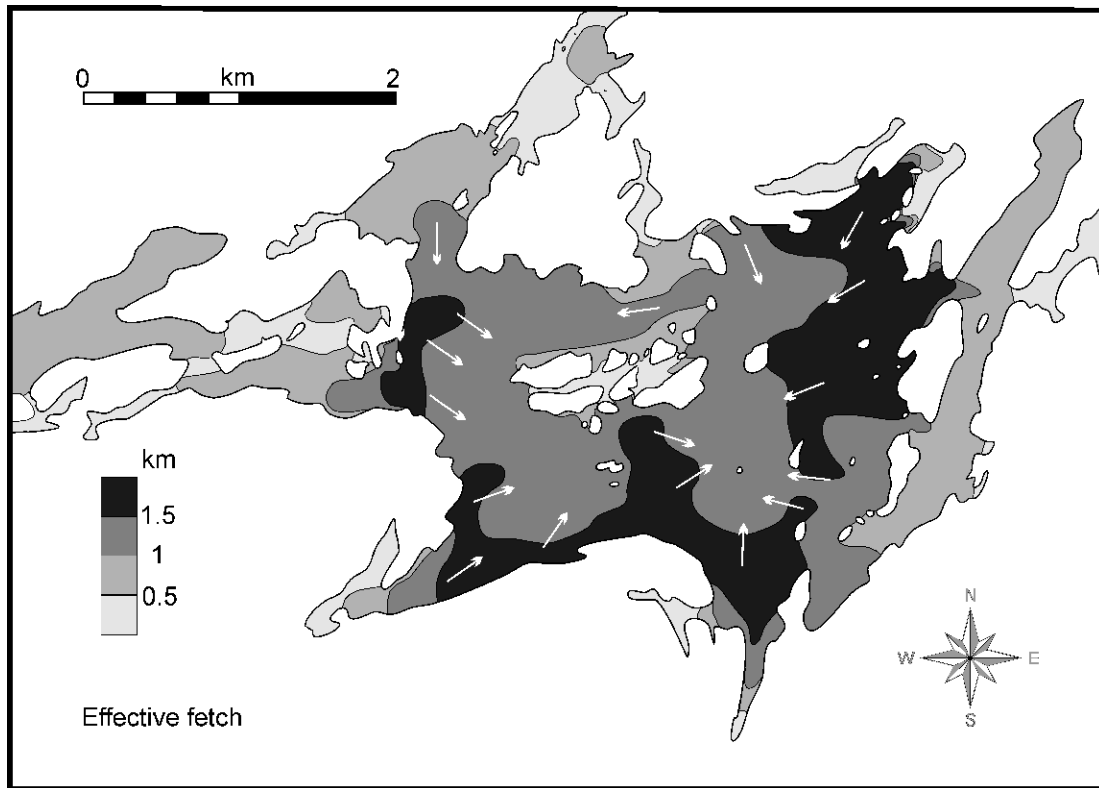


Figure 7. Maximum effective fetch in Devil Lake determined according to Håkanson and Jansson (1983) and Gilbert (1999) from points in a 200-m grid on the lake surface. Arrows on selected grid points indicate the direction of maximum effective fetch (opposite in direction to the associated wind).

overturn. In the larger area of the open lake, isopycnal circulation continues in spring, warming the water column to about 8 °C and in the autumn, cooling the water column to less than 2 °C. This more vigorous circulation extends the period during which sediment may be delivered to the deepest portions of the lake, and even potentially reworked from existing benthic deposits. This circulation drives water laterally into sheltered embayments in the west and northwest of the lake, above the lake floor which forms a sill at 17–19 m depth (Figure 1). However, there is insufficient energy in these regions to overcome the stability of higher density water at greater depth and so a second metalimnion is formed below about 20 m (Figure 3). Water in the hypolimnion experiences more limited direct connection to the epilimnion with the result that sedimentation occurs in a quiet environment with little mixing due to currents. Examination of Figure 4c in Gilbert (2003) shows that the sill in the

northwest between the main body of the lake and the protected bays has less than 2 m of Holocene sediment deposited on it. The still between the northeast and southwest of the lake is also largely devoid of sediment.

It is remarkable that the hypolimnion is dynamic throughout summer and early autumn stratification as seen in the fluctuation of summer temperature (Figure 2), transmissivity, grain size and current velocity. A series of slow deteriorations in water clarity and increases in the coarse-grained component of the particle size distribution is followed by rapidly clearing water and shifting of the particle size distribution to the finer sizes. Most are linked to wind forcing by strong winds (>30 km/h) from the southwest. The particle size distributions (Figures 5d and 6f) provide a clue to the processes that are occurring.

Figure 8 shows typical particle size distributions before and after a clearing event. In this case (event 3

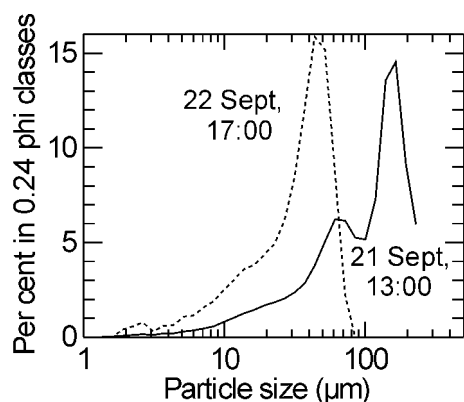


Figure 8. Particle size distributions before and after event 3 (Figure 5).

described above), 37% of the particles are between 140 and 195 μm before and 43% between 37 and 51 μm after. The distribution before is typical of freshwater flocculation where individual microflocs (Eisma 1991) of up to 200 μm diameter settle very slowly in the water column due to the very low effective density of the floc (Droppo et al. 1997). We suggest that the clearing events represent enhanced mixing and turbulence in the water column at this depth (20 m) and the breakup of flocs to primary particles (Eisma 1991), or the flushing or dilution of the flocculated sediment and introduction of dominantly primary particles delivered perhaps from the epilimnion where the higher energy environment above wave base reduces the potential for flocculation. The abundance of Precambrian marble in the drainage basin of Devil Lake (Kingston et al. 1985) creates a hard-water environment with total dissolved sediment of about 100 mg/l which facilitates the process of flocculation.

It is also remarkable that there are significant currents in the hypolimnion during the period of strong thermal stratification. Mean current speed in the period before overturn was less than after (Figure 9), but the highest velocities occurred before overturn. In both cases the current speeds were about 0.5–1% of the sustained wind speed, comparable to the speeds of up to 8 cm/s in winds of 60 km/h predicted by the equations of Sinclair and Smith (1972). Despite events with winds approaching 50 km/h (14 m/s) during the second period (Figure 6), current speeds never exceeded

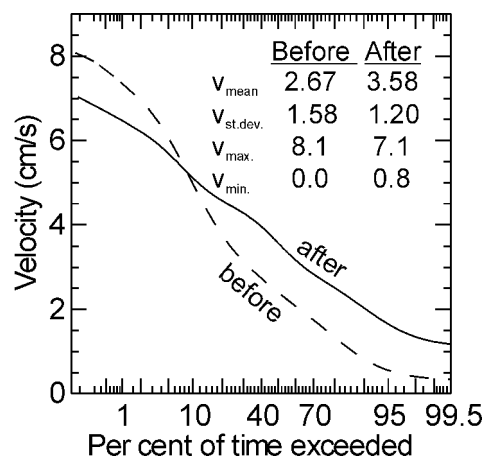


Figure 9. Duration series of current velocities before overturn (27 October to 7 November 2002) and after overturn (8–22 November, 2002). Inset are mean, standard deviation, maximum and minimum velocities in cm/s.

8.1 cm/s which is about one half the velocity necessary to erode fine sand and about one-third the velocity necessary to erode silt (Hjulstrom 1935). While our period of record is very short and does not include rare, more extreme events to which the lake has undoubtedly been exposed, it does suggest that distribution of sediment in the deep basins of the lake is dominantly controlled by processes occurring before initial deposition rather than by secondary processes of particle-by-particle erosion of the lake floor. And because slumping and other catastrophic subaqueous colluvial processes appear to be rare in Devil Lake (based on acoustic evidence – Gilbert 2003), we are encouraged that the use of cored sediment for paleoenvironmental assessment in lakes similar to Devil is, despite its morphological complexity, likely to reflect a relatively un-interrupted depositional sequence. However, our evidence does suggest that deposition on a scale of days to weeks is episodic. Where rates of accumulation are small (e.g., <1 mm/a in Devil Lake – Gilbert 2003) this is not an issue because such events occur at too small a scale to be observed in cores. Where rates are higher, the application of microscale image analysis (Saarinen and Petterson 2001) may provide evidence of the frequency of these events and another proxy of environmental change, especially in an energized environment where storms are more frequent and more intense.

Current direction in the hypolimnion before overturn was almost entirely from the southeast, regardless of wind direction. On several days in early November current velocity demonstrated an approximately diurnal pattern with light and variable currents in the night building to 5–8 cm/s by afternoon before decaying rapidly to light during the night. Winds during this period ranged from strong southwesterly to strong northwesterly to northeasterly. After overturn, current velocity switched to the north then over almost 2 weeks backed to the southwest, again apparently without regard to wind direction. Without a more extensive array of current meters, it is not possible to assess the pattern of currents in the lake, the role of the Coriolis effect in governing currents or the effect of the complex morphology of the lake in the pattern of currents.

Conclusions

The data show that this moderately deep, morphologically complex lake is a very dynamic environment, and that the hypolimnion is not isolated from atmospheric influences, especially wind forcing, even during strongly developed summer stratification. They also indicate that currents and circulation are sufficient to induce significant short-term changes in the sedimentary environment of the lake, and thus have a signal associated with primary deposition which may be read as a measure of intra-annual events, including the frequency and magnitude of storms. These events are also probably sufficient to determine the highly variable depositional environments that occur throughout the lake, although complete assessment of this awaits a larger array of instrumentation in the lake over a longer time period. However, even in the significant storms observed in our study, the currents are insufficient to erode sediment that has been deposited, and thus secondary depositional processes associated with these events are of little or no importance below wave base.

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