An Analysis of a Persistent Isotherm Tilt During Early-Spring and Its Effect on the Diatom Bloom: Lake Washington, Seattle, WA.

Kevin A. Schock

A dissertation
submitted in partial fulfillment of the
requirements for a degree of

Doctor of Philosophy

University of Washinton

2008

Program Authorized to Offer Degree:
Department of Civil and Environmental Engineering

University of Washington
Graduate School

This is to certify that I have examined this copy of a doctoral dissertation by

Kevin A. Schock

and have found that is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Chairs of the Supervisory Committee:

Mitsuhiro Kawase

Harry Yeh

Reading Committee:

Mitsuhiro Kawase

Harry Yeh

Sally MacIntyre

Date: January 8, 2008

In presenting this dissertation in partial fulfillment of the requirements for the doctoral degree at the University of Washington, I agree that the Library shall make its copies freely available for inspection. I further agree that extensive copying of the dissertation is allowable only for scholarly purposes, consistent with “fair use” as prescribed in the U.S. Copyright Law. Requests for copying or reproduction of this dissertation may be referred to Proquest Information and Learning, 300 North Zeeb Road, Ann Arbor, MI 48106-1346, to whom the author has granted “the right to reproduce and sell (a) copies of the manuscript in microform and/or (b) printed copies of the manuscript made from microform.”

Signature_____

Date_____

University of Washington

Abstract

An analysis of a persistent isotherm tilt during early-spring and its effect on the diatom bloom: Lake Washington, Seattle, WA.

Kevin A. Schock

Chairs of the Supervisory Committee

Associate Professor Mitsuhiro Kawase
School of Oceanography
and
Professor Harry Yeh
School of Civil and Construction Engineering

A persistent isotherm tilt was observed during the early spring diatom bloom, the isotherms had an upward tilt from north to south. Concurrently, phytoplankton biovolume concentrations showed different concentrations near the northern, central, and southern parts of the lake, phytoplankton concentrations were higher at the central part.

The persistent tilt was caused by frequent northward wind events with wind period being less than one-forth the first mode internal wave period. The Wedderburn Number was generally less than two and often times less than one, which indicated a strong relation between the isotherm tilt and wind stress. Isotherm response was functionally described by the Wedderburn Number. This condition indicated the isotherm response behaved as a forced system. The northward winds maintain the observed isotherm tilt and transported surface water and phytoplankton downwind.

The isotherm tilt created a variable mixed layer depth with deeper mixing at the north end (downwind) and shallower mixing at the south end (upwind). At the north end, the deeper mixing reduced the depth integrated photosynthesis compared to the south end of the lake. At the south end of the lake, hydrodynamics that maintained the tilt also caused bottom water to upwell; the upwelled water was transported

downwind. The upwelled water diluted the phytoplankton biomass and the downwind currents transport them out of the area faster than they could grow. These conditions reduced the effective phytoplankton growth rate at the north and south ends compared to the central region. The bloom occurred when vertical mixing relaxed and the phytoplankton growth rate exceeded vertical diffusive fluxes out of the euphotic zone, but vertical diffusion balanced sinking.

Table of Contents

Page

List of Figures iii

List of Tables xiii

1 Influence of Wind on Isotherm Tilt 1

1.1 Introduction 1
1.1.1 Previous Studies in Lake Washington 2
1.1.2 Other Lake Studies 6
1.1.3 Study Goals and Hypothesis 8
1.2 Methods 9
1.2.1 Field Monitoring Program 9
1.2.2 Atmospheric Observations 13
1.2.3 Analytical Methods 15
1.3 Results 30
1.3.1 PCA Decomposition of Temperature and Velocity Profiles 31
1.3.2 Longitudinal Temperature and Fluorescence Profiles 45
1.3.3 Wedderburn and Lake Numbers and Relations between the Temperature and Velocity Expansion Coefficients 57
1.3.4 Application of Wedderburn Number to Isotherm Deflection 71
1.3.5 Non-linear Wave Dynamics 75
1.3.6 Modal Response for Depth Varying Buoyancy Frequency 75
1.3.7 Effect of Cedar River on Temperature Observations at SWA 79
1.4 Discussion/Conclusion 88

2 Effect of Isotherm Tilt and Hydrodynamics on the Early-Spring Diatom Bloom 90

2.1 Introduction 90
2.2 Methods 91
2.2.1 Field Methods 91
2.2.2 Transport and Kinetic Equations 98
2.3 Field Results 104
2.3.1 Observed Plankton Densities 104
2.3.2 Measured Particle and Phytoplankton Concentrations 106
2.3.3 Photosynthetically Available Radiation and Light Attenuation 113
2.3.4 Phosphorous and Silica Concentrations 114
2.3.5 Vertical Eddy Diffusion K_e 116
2.3.6 Convective Mixing 124
2.4 Advective/Reactive Diffusion Model 126
2.4.1 Configuration of the Advective/Reactive Diffusion Model 128
2.4.2 Model Results 133
2.5 Discussion 144
2.5.1 Relevance of this Study to Other Studies 149
2.6 Conclusions 152
2.7 Future Studies 153

References 155

Appendix A Eddy Diffusion Profiles 164

Appendix B Phytoplankton and Zooplankton Kinetics 172

List of Figures

Figure Number Page

Figure 1. 1. Most abundant species that comprised the phytoplankton population for year 2003. 1

Figure 1. 2. Temperature profiles (a) and isotherm contours (b) taken March 27, 2003 (JD 85.5) at the NOA (blue), MWY (red), and SWA (green). For the isotherm contours, station locations are noted by the colored vertical lines. 2

Figure 1. 3. Lake Washington study area and field stations NWA, NOA, SR520, MWY, SEW, and SWA. Bathymetric contours are shown to present bottom relief and North is aligned with the page. Yellow lines demark the three general regions of the lake: north, center, and south. 3

Figure 1. 4. Identification of three of the four corrupted temperature channels in the RBR thermistor located at SWA; temperature readings drifted across neighboring temperature readings. Each line is a thermistor at a set depth. 13

Figure 1. 5. Wind roses for the April 2003 period of study. Wind direction and magnitude (a) where north is 0° and east is 90°, wind direction is from the noted degree, and magnitude is denoted by the radial grid, maximum grid is 10 m/s. Directional frequency (b) is denoted by the radial grid, maximum grid is 200 counts. The strong southward winds occurred from April 24th to 29th. 14

Figure 1. 6. Wind roses for the March 2004 period of study. Wind direction and magnitude (a) where north is 0° and east is 90°, wind direction is from the noted degree, and magnitude is denoted by the radial grid, maximum grid is 20 m/s. Directional frequency (b) is denoted by the radial grid, maximum grid is 200 counts. 14

Figure 1. 7. Observed solar radiation (a) and air temperatures (b) for years 2003 (blue) and 2004 (red). The straight lines are the average condition over the given period; year 2004 is red and year 2003 is blue. In 2004, solar radiation and air temperature was higher compared to the same period in 2003. 15

Figure 1. 8. Schematic of a simple two-layer system comprised of the surface layer of depth h_1, density ρ_1, and velocity u_1 and the bottom layer of depth h_2, density ρ_2, and velocity u_2. 16

Figure 1. 9. Schematic of the two-layer model for **(1.1)** (a) and how wind stress enhances the relaxation of the tilt (a) and opposes the relaxation of the tilt (b). The wind stress direction is depicted by the arrow annotated with u_* and the tilt relaxation is denoted by the semi-circular arrow. 20

Figure 1. 12. Density interface tilt that results from a wind stress applied at the water surface. The horizontal line is the static position before the wind stress and the tilted line is the resultant tilt from the applied wind stress. Two thermistor arrays are shown to the north and south of the center of rotation. The two upper and lower thermistors were selected (circles) to estimate the density difference over the depth. 24

Figure 1. 13. Temperature profiles from the SCAMP and RBR on April 10, 2003. SCAMP profiles were taken at NOA (blue), MWY (red), and SWA (cyan) and the RBR profiles were taken at $SR520_C$ (circles) and

SWA (diamonds); thermistors are demarcated by the circles or diamonds. 25
Figure 1. 14. Temperature profiles from the SCAMP and RBR on March 9, March 30, and April 16 of 2004. SCAMP profiles were taken at NOA (blue), MWY (red), and SWA (cyan) and the RBR profiles were taken at NOA (circles) and SWA (diamonds); thermistors are demarcated by the circles or diamonds. 26
Figure 1. 17. April 2003 time series of the averaged density (a) ($\sigma=\rho$-1000 (kg/m^3)) at SR520 and SWA and the corresponding density perturbation (observed less trend) (b). Temperature readings were interpolated to a common depth interval between the two locations. Vertical dashed lines represent periods defined in section 1.3.3.1. 32
Figure 1. 18. April 2003 eigenvector modes for temperature and the north-south velocity component (VN) at SR520 (a), SWA (b), and MWY (c). Percent of variance for the dominant modes is given in Table 1. 6. 33
Figure 1. 19. April 2003 expansion coefficients for the mode one (blue) and mode two (green) eigenvectors presented in Figure 1. 18. SR520 is (a), SWA is (b), and MWY is (c). 34
Figure 1. 20. Observed north-south velocities at MWY (a) and the decomposed PCA mode one (b) and mode two (c) north-south velocities. The mode one and two expansion coefficients are superimposed on the contour plots and centered at the 30-meter depth. Color contours have units of (cm/s) with positive being north. 35
Figure 1. 21. April 2003 temperature contours at SR520 (a) and SWA (b). Isotherms occur at about 0.23 ^{o}C intervals. 36
Figure 1. 22. First (blue) and second (green) mode expansion coefficients plotted against density perturbations (red) shown in Figure 1. 17b. The series have been scaled for better presentation. SR520 is (a) and SWA is (b). 39
Figure 1. 23. March 2004 time series of the averaged density (a) ($\sigma=\rho$-1000 (kg/m^3)) at NOA, MWY, and SWA and the corresponding density perturbation (observed less trend) (b). Temperature readings were interpolated to a common depth interval between the three locations. Vertical dashed lines represent periods defined in section three. 40
Figure 1. 24. March 2004 eigenvector modes for temperature at NOA (a), MWY (b), and SWA (c). Percent of variance for the dominant modes are given in Table 1. 7. 41
Figure 1. 25. March 2004 expansion coefficients for the first and second mode eigenvectors presented in Figure 1. 24. NOA is (a), MWY is (b), and SWA is (c). 42
Figure 1. 26. First (blue) and second (green) mode expansion coefficients plotted against density perturbations (red) shown in Figure 1. 23b. The series have been scaled for better presentation. NOA is (a) and MWY is (b), and SWA is (c). 43
Figure 1. 27. For March 2004, temperature contour plots for location NOA (a), MWY (b) and SWA (c). Isotherms occur at ~0.22 ^{o}C intervals. 44
Figure 1. 28. Temperature profiles at the NOA (blue), MWY (red), and SWA (green) locations for March 27, 2003 (JD 85.5); (a) shows each profile and (b) shows isotherm contours based on the relative distance between locations; blue locates NOA, red MWY and green SWA.

Temperatures increase from south to north (a) and isotherms have an upward tilt from north to south (b). 46
Figure 1. 29. Fluorescence profiles at the NWA (blue), MWY (red), SWA (green) locations for March 27, 2003 (JD 85.5); (a) shows each profile and (b) shows fluorescent contours based on the relative distance between locations; blue locates NOA, red MWY, and green SWA. Fluorescence increased slightly from south to north (a) and contours have an upward tilt from north to south (b). 47
Figure 1. 30. Temperature profiles at the NOA (blue), MWY (red), SEW (green), SWA (cyan) locations for April 10, 2003 (JD 99.5); (a) shows each profile and (b) shows isotherm contours based on the relative distance between locations; blue locates NOA, red MWY, green SEW, and cyan SWA. Temperatures increase from south to north (a) and isotherms have an upward tilt from north to south (b). 47
Figure 1. 31. Fluorescence profiles at the NWA (blue), MWY (red), SEW (green), SWA (cyan) locations for April 10, 2003 (JD 99.5); (a) shows each profile and (b) shows fluorescent contours based on the relative distance between locations; blue locates NOA, red MWY, green SEW, and cyan SWA. Fluorescence increased from south to north (a) and contours have an upward tilt from north to south (b). 48
Figure 1. 32. Temperature profiles at the NOA (blue), MWY (red), SEW (green), SWA (cyan) locations for May 1, 2003 (JD 120.5); (a) shows each profile and (b) shows isotherm contours based on the relative distance between locations; blue locates NOA, red MWY, green SEW, and cyan SWA. Temperatures increase from south to north (a) and isotherms have an upward tilt from north to south (b). 48
Figure 1. 33. Temperature profiles at the NWA (blue), NOA (red), MWY (green), SEW (cyan), and SWA (magenta) locations for March 2, 2004 (JD 61.5). Observed profiles (a) and isotherm contours based on the relative distance between locations (b), vertical lines identify station location. Temperature increased from south to north (a) and isotherms have an upward tilt from north to south (b). 51
Figure 1. 34. Fluorescence profiles at the NWA (blue), NOA (red), MWY (green), SEW (cyan), and SWA (magenta) locations for March 2, 2004 (JD 61.5). Observed profiles (a) and fluorescence contours based on the relative distance between locations (b); vertical lines identify station location. 52
Figure 1. 35. Temperature profiles at the NWA (blue), NOA (red), MWY (green), SEW (cyan), and SWA (magenta) locations for March 9, 2004 (JD 68.5). Observed profiles (a) and isotherm contours based on the relative distance between locations (b); vertical lines identify station location. Temperature increased from south to north (a) and isotherms have an upward tilt from north to south (b). 52
Figure 1. 36. Temperature profiles at the NWA (blue), NOA (red), MWY (green), SEW (cyan), and SWA (magenta) locations for March 16, 2004 (JD 75.5). Observed profiles (a) and isotherm contours based on the relative distance between locations (b); vertical lines identify station location. Temperature increased from south to north (a) and isotherms have an upward tilt from north to south (b). 53
Figure 1. 37. Fluorescence profiles at the NWA (blue), NOA (red), MWY (green), SEW (cyan), and SWA (magenta) for March 16, 2004 (JD

75.5). Observed profiles (a) and fluorescence contours based on the relative distance between locations (b); vertical lines identify station location. 53
Figure 1. 38. Temperature profiles at the NWA (blue), NOA (red), MWY (green), SEW (cyan), and SWA (magenta) locations for March 30, 2004 (JD 89.5). Observed profiles (a) and isotherm contours based on the relative distance between locations (b); vertical lines identify station location. Temperature increased from south to north (a) and isotherms have an upward tilt from north to south (b). 54
Figure 1. 39. Fluorescence profiles at the NWA (blue), NOA (red), MWY (green), SEW (cyan), and SWA (magenta) for March 30, 2004 (JD 89.5). Observed profiles (a) and fluorescence contours based on the relative distance between locations (b); vertical lines identify station location. 54
Figure 1. 40. Temperature profiles at the NWA (blue), NOA (red), MWY (green), SEW (cyan), and SWA (magenta) locations for April 6, 2004 (JD 96.5). Observed profiles (a) and isotherm contours based on the relative distance between locations (b); vertical lines identify station location. Temperature profiles indicate a slight south to north tilt..... 55
Figure 1. 41. Temperature profiles at the NWA (blue), NOA (red), MWY (green), SEW (cyan), and SWA (magenta) locations for April 9, 2004 (JD 99.5). Observed profiles (a) and isotherm contours based on the relative distance between locations (b); vertical lines identify station location. Temperature profiles indicate a neutral thermocline position..... 55
Figure 1. 42. Temperature profiles at the NWA (blue), NOA (red), MWY (green), SEW (cyan), and SWA (magenta) locations for April 13, 2004 (JD 103.5). Observed profiles (a) and isotherm contours based on the relative distance between locations (b); vertical lines identify station location. Temperature increased from south to north (a) and isotherms have an upward tilt from north to south (b). 56
Figure 1. 43. Temperature profiles at the NWA (blue), NOA (red), MWY (green), SEW (cyan), and SWA (magenta) locations for April 16, 2004 (JD 106.5). Observed profiles (a) and isotherm contours based on the relative distance between locations (b); vertical lines identify station location. Temperature increased from south to north (a) and isotherms have an upward tilt from north to south (b). 56
Figure 1. 44. Fluorescence profiles at the NWA (blue), NOA (red), MWY (green), SEW (cyan), and SWA (magenta) locations for April 16, 2004 (JD106.5). Observed profiles (a) and fluorescence contours based on the relative distance between locations (b); vertical lines identify station location. 57
Figure 1. 45. Calculated Wedderburn and Lake Numbers for year 2003. 60
Figure 1. 46. Wind velocity vectors (a) and mode one expansion coefficients (blue lines) for SR520 (b), SWA (c), and MWY_{VN} (d); friction velocity is also shown (green line). Positive wind values mean it blows to the north. The Wedderburn Number (green line) and the period for a V1H1 internal seiche (blue line) are shown in (e). Red lines indicate instances when the wind stress shifted and complemented the density adjustment. 61
Figure 1. 47. Normalized mode one expansion coefficients for SWA temperature (blue) and MWY north-south velocity (green) (a) and

SWA mode two temperature with MWY mode one north-south velocity (b). Vertical lines assist in showing phase relations between temperature and velocity. 64
Figure 1. 48. Calculated Wedderburn (blue) and Lake (green) Numbers for year 2004. 66
Figure 1. 49. Wind velocity vectors (a) and mode one expansion coefficients (blue lines) for NOA (b), MWY (c), and SWA (d); friction velocity is also shown (green line). Positive wind values mean it blows to the north. The Wedderburn Number (green line) and the period for a V1H1 internal seiche (blue line) are shown in (e). Red lines indicate instances when the wind stress shifted and complimented the density adjustment. 69
Figure 1. 50. NOA temperature time series for 2004 with calculated isotherm deflections (red-dashed line) using **(1.19)** for k=0.27. The red-dashed line estimates the deflection of the isotherms; it does not represent a particular isotherm. 74
Figure 1. 51. SWA temperature time series for 2004 with calculated isotherm deflections (red-dashed line) using **(1.19)** for k=0.27. The red-dashed line estimates the deflection of the isotherms; it does not represent a particular isotherm. 74
Figure 1. 52. Buoyancy frequency (a) and first and second modes for the normalized eigenvector for the vertical velocity profile (b) at MWY for April 10, 2003. The strongest thermal structure is located near the 35 meter depth. The unit rad is radians. 77
Figure 1. 53. Buoyancy frequency (a) and first and second modes for the normalized eigenvector for the vertical velocity profile (b) at SEW for April 10, 2003. The strongest thermal structure is located near the five meter depth. The unit rad is radians. 77
Figure 1. 54. Buoyancy frequency (a) and first and second modes for the normalized eigenvector for the vertical velocity profile (b) at MWY for March 9, 2004. March 9 is shown because it is near the start of the RBR thermistor date range. The unit rad is radians. 78
Figure 1. 55. Buoyancy frequency (a) and first and second modes for the normalized eigenvector for the vertical velocity profile (b) at MWY for April 6, 2004. April 6 is shown because it is near the end of the RBR thermistor date range. The unit rad is radians. 79
Figure 1. 56. Standardized observations for the averaged temperature at SWA (blue) and Cedar River Temperature (green) for April 2003. The red line is the 24 hour moving averaged for SWA and the dark green line is the 24 hour moving average for the Cedar. 85
Figure 1. 57. Standardized observations for the averaged temperature at SWA (blue) and Cedar River Temperature (green) for March 2004. The red line is the 24 hour moving averaged for SWA and the dark green line is the 24 hour moving average for the Cedar. 86

Figure 2. 1. An acceptable fit between theoretical Bachelor spectrum (red line) and the sharpened spectrum (blue line) with 95th confidence intervals (green dashed line). The sharpened spectrum is little affected by noise (lower blue line) and lies just above the unadjusted spectrum (black dashed line). The temperature gradient signal has a wave structure with small undulations about 2 to 4 cm in length, which

corresponds to the Kolmorgorov length (L_K = 3.3 cm); eddies at the Bachelor scale would be superimposed on L_K and of length near 1.2 cm. The observed segment has an energy dissipation of $1.2x10^{-9}$ (m^2/s^3) and Chi of $3.1x10^{-9}$ ($^oC/m)^2/s$. 95
Figure 2. 2. An unacceptable fit between theoretical Bachelor spectrum (red line) and the sharpened spectrum (blue line) with 95th confidence intervals (green dashed line). The sharpened spectrum is slightly affected by noise (lower blue line) and lies just above the unadjusted spectrum (black dashed line). The Bachelor spectrum lies too much outside the 95th confidence intervals of the adjusted spectrum. 96
Figure 2. 3. Averaged eddy diffusion segments (K_e, red bars) obtained from average energy dissipation segments (ε, red bars) and buoyancy frequency (N, cyan line) for NWA on Apr. 13, 2004. The average energy dissipation was obtained from the two FP07 thermistors. The bars indicate regions where mixing is active or measurable, the length of the bar represents the magnitude of mixing (K_e) or energy dissipation (ε), and the width of the bars represents the depth of turbulent activity. 98
Figure 2. 4. Growth regimes predicted by the advective/reactive diffusion equation for phytoplankton initially uniform in the vertical for sinking rate w_s and mixing depth H. The shaded region of the plot indicates where phytoplankton populations will grow over time. In the unshaded areas, populations will decay. The six growth regimes are defined: (A) exponential decay over time, (B) exponential growth, (C,D) as Pe increases so must G to compensate for sinking, (E) decays monotonically over time, and (F) biomass increases initially but decays completely by time t_s=H/w_s, (reproduced from O'Brien et al. 2003). 100
Figure 2. 5. Simple hydrodynamic representation of upwelling and downwind advection that occurs at SWA (a). Upwelling and horizontal transport in the red dashed box (a) is approximated by the multi-layered box in (b). The horizontal (U) and vertical (W) velocities are driven by the surface wind (U_{wind}); vertical velocity increases towards the surface ($W_1<W_2<\ldots<W_8$) as more flow from each layer is upwelled. The vertical velocity distribution was approximated by an exponential distribution. 102
Figure 2. 6. Most abundant species that comprised the zooplankton (upper panels) and phytoplankton (lower panels) populations for year 2003. Note, org/l is organisms/liter. The zooplankton count is the average from zero to 20 meters. 104
Figure 2. 7. Most abundant species that comprised the zooplankton (upper panels) and phytoplankton (lower panels) populations for year 2004 (note the larger scale for the central phytoplankton). The zooplankton count is the average from zero to 20 meters. 105
Figure 2. 8. Measured LISST particle and phytoplankton biovolume concentrations at NOA, MWY, and SWA for year 2004. The 75 and 119 μm particle concentration increased with time while the 5 and 16 μm tracked more with the *A. subarctica* concentrations. Note scale change for MWY. 107
Figure 2. 9. Temporal evolution of the four particle groups at MWY for year 2004; NOA and SWA had similar results. Each profile is

proportionally offset from the previous observation based on a cumulative concentration. Each profile is related to the initial concentration by the vertical blue line, which represents the depth average concentration for the first profile taken March 2, 2004. 108
Figure 2. 10. The combined LISST particle concentrations (5+16 μm) at NOA, MWY, and SWA for year 2004..... 109
Figure 2. 11. Comparative plots between LISST particle concentrations (upper) and SCAMP fluorescence (lower) for year 2004 at NOA, MWY, and SWA. Chlorophyll *a* at MWY (circles) is also shown on the April 20 fluorescence plot, but it has been reduced by 3.95 so the 5-meter Chl *a* sample aligns with the 5-meter fluorescence reading..... 111
Figure 2. 12. Particle and temperature (red line) profiles at the NOA (a), MWY (b), and SWA (c) location for March 30, 2004 (JD 89.5). The green line is the 5 μm and the cyan line is the 16 μm diameter. The dashed horizontal line represents the potential convective mixing depth given in Table 2. 12. 112
Figure 2. 13. Normalized fluorescence (o), LISST 5+16 particles (+), and chlorophyll *a* (□) profiles for the corresponding profiles in Figure 2. 11. Each profile was divided by the maximum observed value (X_{max}) for that profile. Fluorescence always decreased at a faster rate towards the surface; on April 20, the MWY chlorophyll *a* (□) and 5+16 μm particle (+) profiles correlate well but fluorescence (o) decreased significantly towards the surface. 113
Figure 2. 14. Eddy diffusion (K_e) (red rectangles) and centered displacement length scale (L_c) (green line) for March 16, 2004 (JD 75.5). Locations are NWA (a), NOA (b), MWY (c), SEW (d), and SWA (e). 117
Figure 2. 15. Turbulent mixing patches in the water column at MWY for October 30, 2003. Blue segments are the instantaneous observations and the red segments represent the areas that experienced turbulent mixing. Profile times are given for each cast and percent of segment depth covered (h_{mix}/h_{total}) is given on the abscissa: where h_{mix} is summed patch depths and h_{total} is the water depth at MWY..... 118
Figure 2. 16. Temperature profiles for the first (red) and last (blue) profile at the MWY location for October 30, 2003. The STL extends to about 18 meters. 119
Figure 2. 17. Combined eddy diffusion observations at NOA (a), MWY (b), and SWA (c) for 2004 sample dates noted in legend. The red stars are the geometric average over a five-meter interval (star centered on the interval). The red lines were linearly interpolated lines between the red stars (Table 2. 11). 121
Figure 2. 18. Peclet Numbers calculated for each segment within the STL and assuming a sinking velocity (w_s) of 0.86 (m/s). Red asterisks represent each segment ($P_e=w_s l_e/K_e$, where l_e is the segment length) and blue squares represent the geometric mean of group..... 124
Figure 2. 19. Heat flux at the surface of Lake Washington for year 2004. Negative values indicate heat loss from the water surface (filled green). 127
Figure 2. 20. NOA particle concentrations predicted by the model (blue) compared to observed concentrations (cyan), which combined 5 μm and 16 μm particles. Initial concentrations are represented by the red line, the green line is the STL depth, and sample day is on the right..... 134

Figure 2. 21. MWY particle concentrations predicted by the model (blue) compared to observed concentrations (cyan), which combined 5 μm and 16 μm particles. Initial concentrations are represented by the red line, the green line is the STL depth, and sample day is on the right. 134
Figure 2. 22. SWA particle concentrations predicted by the model (blue) compared to observed concentrations (cyan), which combined 5 μm and 16 μm particles; results include upwelling effects. Initial concentrations are represented by the red line, the green line is the STL depth, and sample day and W_N are on the right. 135
Figure 2. 23. SWA particle concentrations predicted without (2.19); the model (blue) compared to observed concentrations (cyan), which combined 5 μm and 16 μm particles; results include upwelling effects. Initial concentrations are represented by the red line, the green line is the STL depth, and sample day and W_N are on the right. 136
Figure 2. 24. Example of eddy diffusion profiles used during model calibration (abscissa is log scale). The STL depth was 20 meters for these profiles. The exponential decay profile in the STL (a) used ϕ=0.45, φ=0.07, ψ=1.0; the step-like profile used ϕ=0.3, φ=0.6, ψ=0.5; and the uniform profile used ϕ=1.0, φ=1.0, ψ=1.0. 137
Figure 2. 25. NOA particle concentrations using a step profile (blue) with ϕ=0.3, φ=0.6, ψ=0.5 and g_{max}=2.0. Observed concentrations (cyan) combined 5 μm and 16 μm particles. Initial concentrations are represented by the red line, the green line is the STL depth, and sample day is on the right. 138
Figure 2. 26. NOA particle concentrations using a uniform K_e profile (blue) but with K_e varying temporally; ϕ=1.0, φ=1.0, ψ=1.0 and g_{max}=1.38. Observed concentrations (cyan) combined 5 μm and 16 μm particles. Initial concentrations are represented by the red line, the green line is the STL depth, and sample day is on the right. 138
Figure 2. 27. Normalized *A. subarctica* and *S. niagarae* (□) biovolume concentrations and observed eddy diffusion (★). All observations were normalized for better presentation of relative changes between phytoplankton response and eddy diffusion. 139
Figure 2. 28. MWY particle concentrations for a temporally constant K_e=0.004 m^2/s (blue) compared to observed concentrations (cyan), which combined 5 μm and 16 μm particles. Initial concentrations are represented by the red line, the green line is the STL depth, and sample day is on the right. K_e varied with depth with ϕ=0.45, φ=0.07, and ψ=1.0. 139
Figure 2. 29. MWY particle concentrations for a temporally constant K_e=0.0002 m^2/s (blue) compared to observed concentrations (cyan), which combined 5 μm and 16 μm particles. Initial concentrations are represented by the red line, the green line is the STL depth, and sample day is on the right. K_e varied with depth defined by ϕ=0.45, φ=0.07, and ψ=1.0. 140
Figure 2. 30. Simulated particle concentration (phytoplankton) at MWY for three different eddy diffusion time series; the observed series (□), a constant eddy diffusion of 0.002 m^2/s after JD 89.5 (o), and a constant eddy diffusion of 0.004 m^2/s (★). Results are the depth-averaged concentration from 0 to 10 meters. 141

Figure 2. 31. Normalized observations for daily-averaged light (yellow bars), three-day running-average light (dashed) , LISST 5+16 μm particle concentrations (o), Ke (★), and simulated particle concentrations (□). All data has been normalized for better presentation. 141
Figure 2. 32. Three phases A, B, and C of the diatom bloom in 2004. The phases are characterized by changes in the hydrodynamic regime shown by the average density at NOA and SWA. Isotherms tilt upward from north to south in Phase A; the isotherm tilt seesaws during phase B; and the isotherms resume an upward tilt from north to south in phase C. 146
Figure 2. 33. Theoretical predator/prey response for a predator that has no incubation period. The time scale can be represented as Lagrangian transport t=x/u, where x is distance and u is horizontal velocity. 148

Figure A. 1. Eddy diffusion (K_e) (red rectangles) and centered displacement length scale (L_c) (green line) for March 9, 2004. Locations are NWA (a), NOA (b), MWY (c), SEW (d), and SWA (e). 164
Figure A. 2. Eddy diffusion (K_e) (red rectangles) and centered displacement length scale (L_c) (green line) for March 23, 2004. Locations are NWA (a), NOA (b). 165
Figure A. 3. Eddy diffusion (K_e) (red rectangles) and centered displacement length scale (L_c) (green line) for March 30, 2004. Locations are MWY (a), SEW (b), and SWA (c). 166
Figure A. 4. Eddy diffusion (K_e) (red rectangles) and centered displacement length scale (L_c) (green line) for April 6, 2004. Locations are NWA (a), NOA (b), MWY (c), SEW (d), and SWA (e). 167
Figure A. 5. Eddy diffusion (K_e) (red rectangles) and centered displacement length scale (L_c) (green line) for April 9, 2004. Locations are NWA (a), NOA (b), MWY (c), SEW (d), and SWA (e). 168
Figure A. 6. Eddy diffusion (K_e) (red rectangles) and centered displacement length scale (L_c) (green line) for April 13, 2004. Locations are NWA (a), NOA (b), MWY (c), SEW (d), and SWA (e). 169
Figure A. 7. Eddy diffusion (K_e) (red rectangles) and centered displacement length scale (L_c) (green line) for April 16, 2004. Locations are NWA (a), NOA (b), MWY (c), SEW (d), and SWA (e). 170
Figure A. 8. Eddy diffusion (K_e) (red rectangles) and centered displacement length scale (L_c) (green line) for April 20, 2004. Locations are MWY (a), SEW (b), and SWA (c) 171

Figure B. 1. Photosynthesis verses irradiance curves including respiration for (B.2) and (B.4) applied to the productivity data for *Melosira (A) italica* obtained from Knoechel and Kalff (1978): April 25 are red solid squares, May 4 are green solid circles, May 14 are blue solid triangles, and May 24 are cyan solid diamonds. Dashed lines are the PvE curves (B.8) - (B.10). 176
Figure B. 2. Growth rates for *A. subarctica* as determined by Gibson and Foy (1988) as circles and Knoechel and Kalff (1974) as squares. The Knoechel and Kalff data was converted from carbon uptake to carbon growth rates and then adjusted for an equivalent series of light:dark cycles used in the Gibson and Foy data. The Gibson and Foy data was adjusted from a 3:21 LD to a 18:6 LD growth rate. 180

Figure B. 3. Optimal fits for (B.2) and (B.4) to the whole data sets from Gibson and Foy (blue circles) and Knoechel and Kalff (red squares); (B.4) is shown by the green squares with dashed 95th confidence intervals, and (B.2) is shown by the red triangles with dotted 95th confidence intervals. 181
Figure B. 4. Sensitivity of photosynthesis rate (P) to the photosynthesis term (α) under a range of light intensities and initial slopes. The potential error decreases with increasing light intensity. While the error may appear large, the potential error is multiplied by a relatively small number. The potential error is more sensitive to light intensity than the initial slope. 184
Figure B. 5. Sensitivity of photosynthesis rate (P) to the photoinhibition term (β) under a range of light of intensities. The potential error is linearly dependent on light intensity. 185
Figure B. 6. Sensitivity of photosynthesis rate (P) to the local maximum growth rate under a range of local maximum growth rates (P_S). The potential error is inversely dependent on the growth rate. 186
Figure B. 7. Growth rate as a function of temperature; data was taken from Figure 3 of Foy and Gibson (1993). The solid line is the fitted temperature response given by (B.6) for parameters given in Table B. 8. 187
Figure B. 8. Theoretical resource ratio gradient for diatom species A ,B. and C. 189
Figure B. 9. Most prevalent zooplankton species in Lake Washington at the Madison Park sampling location, which is offshore from Madison Park in Seattle, Washington. Observations are for years 2003 and 2004 as indicated. 190

List of Tables

Table Number Page
Table 1. 1 Water depths at each monitoring location. 11
Table 1. 2. RBR thermistor array operating depth ranges (meters) at the associated field stations. 12
Table 1. 3. Conversion between Julian Day and Gregorian Calendar. 15
Table 1. 4 Mean value of the three stress terms (u_*^2, u_B^2, and $\partial u/\partial z$) calculated from observed wind and water velocities from the March 2003 observations. Statistics for the velocity shear are based on the absolute value of the observations. 18
Table 1. 5. Internal wave response for combinations of W_N and L_N. Information obtained from Stevens and Imberger (1996) and Imberger and Patterson (1990). 22
Table 1. 6 Percent of total variance explained by each PCA mode for temperature and north-south velocity component at each station for April 2003. 37
Table 1. 7 Percent of total variance explained by each PCA mode for temperature and north velocity component at each station for March 2004. 40
Table 1. 8 Mixed layer depth based on Fluorescence and Temperature for 2003. The mean depth approximates the depth of the thermocline. Depths were based on coincident inflection points in the fluorescence and temperature profiles. 49
Table 1. 9 Mixed layer depth based on Fluorescence and Temperature observations for 2004. The mean depth approximates the depth of the thermocline. Depths were based on coincident inflection points in the fluorescence and temperature profiles. 57
Table 1. 10. Upper layer depths used to calculate the Wedderburn Number. The two values were used to determine the linear variation of h_1 over time for years 2003 and 2004. 58
Table 1. 11. Station distances from the center of the lake. Based on SCAMP temperature contour plots, MWY station could be slightly north of center. 72
Table 1. 12. Isotherm deflections and Wedderburn Number used for determining k in (1.19). The deflection was based on the depth of the noted isotherm at each location for the given Julian Day (JD). 73
Table 1. 13. First mode periods estimated from the eigenvalue problem for the 2003 observations at four locations. 77
Table 1. 14. First mode periods estimated from the eigenvalue problem for the 2004 observations at four locations. 78
Table 1. 15. Flow statistics for the Cedar River for the study period in 2003 and 2004. The geometric mean flow (μ) and one-standard deviation (σ) are given. 83
Table 1. 16. Correlation coefficient and P-values between the standardized observations at SWA and the Cedar River; the correlation was between the averaged temperature time series and Cedar River temperature series. Statistics for the observed series and the 24 hour moving average (MA) are presented. 84
Table 1. 17. Potential wind-driven flows for depth and time-averaged velocities obtained at SR520 and MWY during the 2003 field program.

For windy events during years 2003 and 2004, the larger wind events obtained wind speeds of approximately 8 (m/s). A Cedar River flow (Q_{Cedar}) of 26 (m^3/s) is used to determine the temperature effect from the Cedar River at SWA. 85
Table 1. 18. Momentum length scale (l_M) for average temperatures in the Cedar River (T_{Cedar}) and Lake Washington at SWA (T_{SWA}). Flows from the Cedar River (Q_{Cedar}) represent the mean plus one standard deviation (Table 1. 15) and momentum (M_{Cedar}) and buoyancy (B_{Cedar}) terms are per unit width of the river. 86
Table 1. 19. Estimated flow rates and time scales that could produce the longitudinal isotherm adjustments observed in Lake Washington. Travel was defined as the distance from the Cedar mouth to the MWY location. 87

Table 2. 1. Reduction of particle sizes into four representative groups; each group represents a range of diameters. 106
Table 2. 2. Typical cell dimensions for *A. subarctica* and *S. niagarae*; *Asterinonella formosa* and *Fragilaria crotonensis* are also presented..... 107
Table 2. 3. Relative proportions that the 5 and 16 µm particles contributed to the total particle concentration over year 2004. The percentages represent the average for NOA, MWY, and SWA. 109
Table 2. 4. Normalized measures for 5+16 µm and chlorophyll *a* (Chl *a*) concentrations and fluorescence. Each measure (X_i) was divided by the maximum measure (X_{max}) of the group. Depths 1, 2, 4, and 6 meters were used for April 16 and depths 1, 2, 3, 4, and 5 meters were used for April 20. Results are plotted in Figure 2. 13..... 110
Table 2. 5. Light attenuation coefficient (k_d) obtained for NOA, MWY, and SWA for year 2003. 114
Table 2. 6. Light attenuation coefficient (k_d) obtained for NWA, NOA, MWY, SEW, and SWA for year 2004. 114
Table 2. 7. Phosphate concentrations (mg/l) for years 2003 and 2004; concentrations are the average for sample depths 0 to 10 meters. 115
Table 2. 8. Silica concentrations (mg/l) for years 2003 and 2004; concentrations are the average for sample depths at 1 and 2 meters. 115
Table 2. 9. STL depth averaged eddy diffusion $\langle K_e \rangle$ and energy dissipation $\langle \varepsilon \rangle$ for each profile taken on October 30, 2004 at MWY. The STL depth was about 18 meters. 119
Table 2. 10. STL depth-averaged eddy diffusion at NWA, NOA, MWY, and SWA for year 2004. The segment-weighted values were determined over the STL (h_{STL}), which was determined from particle and fluorescence distributions. 120
Table 2. 11. Eddy diffusion values obtained from the linearly interpolated lines presented in Figure 2. 17. Values were obtained at the surface, intercept, and bottom. Lines were interpolated to the geometrically averaged points (Figure 2. 17) over the ranges specified; lower interpolation ranges were the depths below the upper ranges. 122
Table 2. 12. Potential convective mixing depths based on daytime temperature profiles and the following night's heat flux (the effective temperature decrease is given in parentheses in ^oC). At NOA on JD 89.5, the 19-meter mixing depth was driven by a large tilt in the isotherm structure, Figure 1.24. 126

Table 2. 13. Travel time between the MWY and NOA locations for various depth-averaged velocities. For windy events for the 2003 and 2004 periods, typical wind speeds were approximately 8 (m/s). 128
Table 2. 14. Profile shape parameters used in the eddy diffusion profile equation (2.27); ϕ, φ and ψ were determined by calibration and provided the best visual fit between simulated and observed phytoplankton profiles. 129
Table 2. 15. Depth intervals that were used to calculate an average concentration that defined bottom concentrations in the model. 130
Table 2. 16. Adult *D. (L.) ashlandi* densities sampled near MWY. Adults comprise males and females. 132
Table 2. 17. Parameter values that produced the best model fit to observed particle concentrations. 133
Table 2. 18. Phytoplankton growth limitations based on the observed hydrodynamic and environmental conditions at NOA, MWY, and SWA for days noted. Light and temperature limits are the depth-integrated photosynthesis effect on growth, and Z_{STL} is the depth of the STL (Table 2. 10). 143

Table B. 1. Carbon uptake and irradiance productivity measures for *Melosira (A) italica*; data was taken from Figure 3 of Knoechel and Kalff (1978). Irradiance has units ($\mu E/m^2/sec$) and carbon uptake has units (g $Cx10^{-15}/\mu m^{-3}/h$). Shaded cells indicate data used in estimating respiration. 175
Table B. 2. P v E parameter values derived from the productivity measures given in Table B. 1. 176
Table B. 3. Growth rate verses irradiance for *Aulacoseira subarctica* for a 3:21 LD cycle at a constant 16°C; values taken from Figure 1 of Gibson and Foy (1988). Growth Rate = ln(2)(doubling/day)(1 day). 178
Table B. 4. Changes in ash-free dry weight over a 24-hour period under a 6:18 LD cycle at 16 ^{o}C; data taken from Figure 8 of Gibson and Foy, (1983). The 18:6 LD cycle is obtained from the 6:18 LD by multiplying the 6 and 24 hour observations by 1.15. 179
Table B. 5. Optimal PvE parameter values for the adjusted Knoechel and Kalff and the adjusted Gibson and Foy irradiance and growth rate data. 181
Table B. 6. Potential error or uncertainty in the photosynthesis rate (ΔP) for a given parameter error $\Delta\alpha$, $\Delta\beta$, or ΔP_S at the specified irradiance. 186
Table B. 7. Growth measures verses temperature for *A. subarctica* taken from Figure 3 of Foy and Gibson (1993); Growth rate = (doublings/day)ln(2). 187
Table B. 8. Optimal parameter values for (B.6) fitted to the data given in Table B. 7. 187
Table B. 9. Relative position of various diatoms along the resource gradients for Si:N and N:P. The relations were obtained from works by Kilham et al (1996) and Interlandi et. al. (1999). 188
Table B. 10. *D.(L.) ashlandi* filtering rates obtained from Bowers (1980), Hartmann (1985), and Richman et al (1980). 192

ACKNOWLEDGEMENTS

The author wishes to thank Dr. Daniel Schindler at the University of Washington Zoology Department for providing the quantitative zooplankton data, the collection of which was funded by a Andrew Mellon Foundation grant.

DEDICATION

To my wife Rima, who sacrificed her time for me to pursue this degree and to my daughter Ariana who has only known her dad to be a student.