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Charles Lemckert

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Overview

The 16th International Workshop on Physical Processes in Natural Waters (PPNW2013)

Crowne Plaza Hotel, Surfers Paradise, Queensland, Australia, July 7 - 11, 2013

The focus of the PPNW workshops is the physics of inland and coastal water bodies and their interactions with the physical and biogeochemical processes that control water quality, ecosystem function, and the services such systems provide. The workshops traditionally cover a broad spectrum of scientific topics. Besides general topics, the Queensland workshop will pay special attention to the coupling of physical and ecology processes and water quality in sub-tropical lakes.

PPNW is an open workshop, actively seeking to expand contacts with neighbouring fields such as physical oceanography, the atmospheric sciences, and engineering. With 42 participants and a small number of invited speakers, the PPNW meetings are characterized by their active workshop atmosphere and a comfortable time frame for presentations and discussion.

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16th International Workshop on Physical Processes in Natural Waters (PPNW2013)
Crowne Plaza Hotel, Queensland, Australia, July 7-11, 2013

PPNW2013 Program Structure

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9:30		Invited Speaker John Patterson Buoyancy driven exchange flows in the nearshore regions of lakes and reservoirs or Natural convection is everywhere!	Serena Lee Sydney Estuary Dynamics - estimation of freshwater inflow from CTD measurements		Richard Woolway A novel method for detecting thermal stratification from surface water temperature measurements in temperate lacustrine systems
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11:30		Rikke Laursen Wind-driven water movements in an Australian subtropical freshwater reservoir	Madis-Jaak Lilover Ice dynamics in relation to wind and currents in the central Gulf of Finland derived from bottom-mounted ADCP	Nicole Gallina Identifying Morpho-Functional Groups for Lake Geneva – A key first step to model phytoplankton dynamic succession	Alexander Forrest Observations of Turbidity Currents in Glacial Lake Ohau, South Island, New Zealand
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Buoyancy driven exchange flows in the nearshore regions of lakes and reservoirs
or
Natural convection is everywhere!

John Patterson

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EXTENDED ABSTRACT

Natural convection is the flow driven by differences in density, and is ubiquitous in nature and industry. It is the source of most environmental flows, and is the basis for almost all industrial heat exchange processes. It operates on both massive and micro scales. It is usually considered as a flow driven by temperature gradients, but could equally be from a gradient in any density determining property – salinity is one obvious example. It also depends on gravity; so magnetohydrodynamics becomes relevant as well. One particular interesting and environmentally relevant flow is the exchange flow in the nearshore regions of lakes and reservoirs. This occurs because of the effects of a decreasing depth approaching the shore resulting laterally unequal heat loss and heat gain during the diurnal cooling and heating cycle. This presentation will discuss some of the results obtained by the Natural Convection Group at Sydney University in analytical, numerical and experimental investigations of this mechanism, and the implications for lake water quality.

Seasonal evolution of the thermal structure of a tropical reservoir

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KEYWORDS

Seasonal evolution, Thermal structure, Tropical physical limnology, Tropical reservoir

EXTENDED ABSTRACT

Introduction: In the tropics, unlike in temperate regions, the seasonal variation of shortwave radiation is much smaller and does not affect much the thermal lake stratification (Lewis, 1987). Air temperature seasonal variability is also small. Hence, the atmospheric heat fluxes do not vary much along the year and the stratification changes must have a different source. The tropical hydrology seasonal variability is ruled by the Inter-Tropical Convergence Zone (ITCZ), distinguishing between dry and wet seasons (Poveda, 2006).

Given the importance of the stratification annual cycle on lake ecosystem, we investigated the stratification annual cycle of a tropical system and its forcing climatology and hydrology in order to detect the main sources of stratification variability. With this, we hope to understand the nutrients pathways as a key element to understand lake functioning.

Methods: La Fe, a tropical reservoir located at 06°06’50”N in Colombia was continuously monitored for over one year with a 14-thermistor chain and a floating meteorological station, and during short field campaigns with a CTDO. La Fe is a small reservoir (1.4 km^2) with a maximum depth of 26 m, and located at 2,140 masl. It regulates a nearly constant withdrawal around 5.0 m^3/s, and it is fed by two natural inflows. A pumped inflow is used when the natural inflows are low. Few NO_3^- and NH_4 samples were collected through the water column. The inflows temperature was measured with single thermistors. Discharges were provided by the reservoir managing company, Empresas Públicas de Medellín.

Short wave and net long wave radiations were directly measured. Latent and sensible heat were calculated using typical bulk heat formulas. The inflows intrusion depth was calculated based in their initial temperature corrected by mixing estimated with simple 1D models.

Results and Discussion: Heat exchange with the atmosphere did not change much over the year and did not introduce significant changes in the thermal structure. The larger variability in atmospheric heat fluxes was due to variations in cloud cover, had a time scale of days and only affected the heat content in the surface layer. The large discharges during the wet season (Fig. 1a) produced the most significant changes in the temperature distribution in the reservoir (Fig. 1d), while the surface heat fluxes remained relatively constant (Fig. 1b). A temperature difference of 2°C degrees in the inflow temperature was enough to change the behaviour of the plumes and lake stratification. In the dry seasons, the inflow water was warm and intruded between 5 and 12m deep (Fig. 1d) generating a thick bottom stagnant layer with long residence time. During the wet seasons, the inflows were cold and filled the reservoir renewing the water in the bottom layer (Fig. 1d). This tropical reservoir reached its maximum stratification during the colder weather due to the cold inflows (Fig. 1c). The changes in inflow dynamics determine two very distinctive nutrient and oxygen distributions in the water column (Fig. 1e,f). Figure 2 summarizes the two contrasting lake conditions.

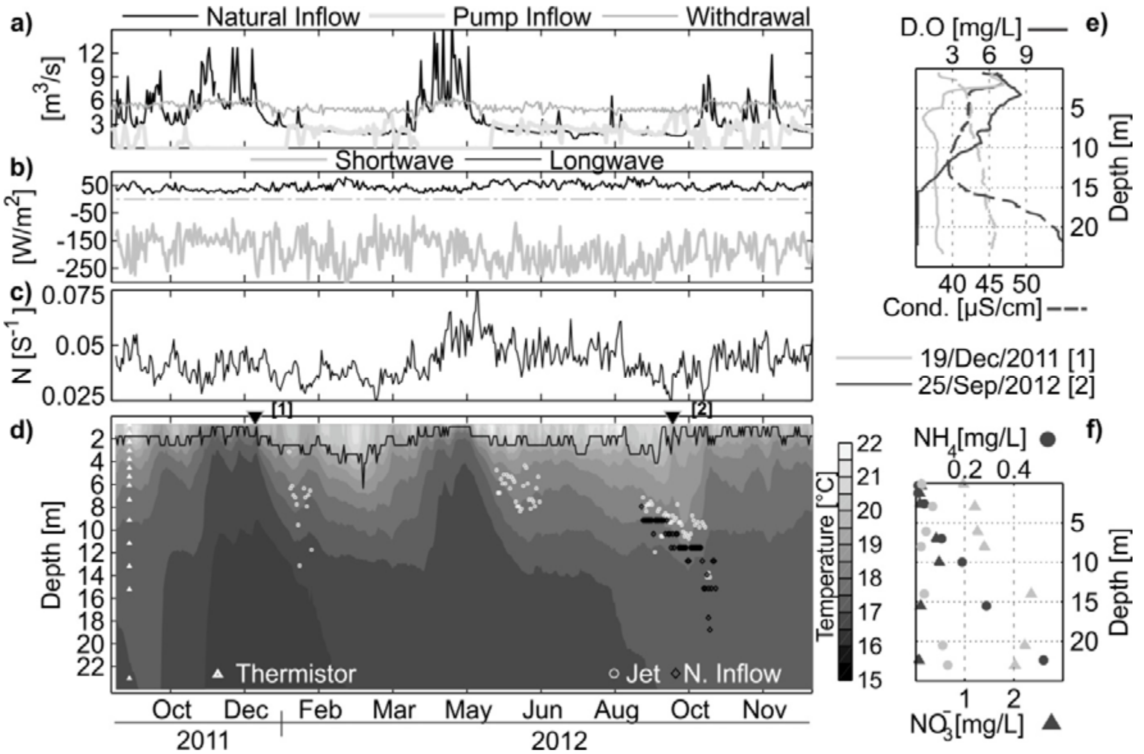

Figure 1. Seasonal evolution of external forcing and thermal structure. (a) Flow discharges, (b) radiative heat flux, (c) maximal buoyancy frequency, (d) water temperature, thermistors location (white triangles), maximum buoyancy frequency depth (black line), natural (white dots) and pumped (black dots) inflows intrusion depth, (e) and (f) typical profiles in wet and dry seasons.

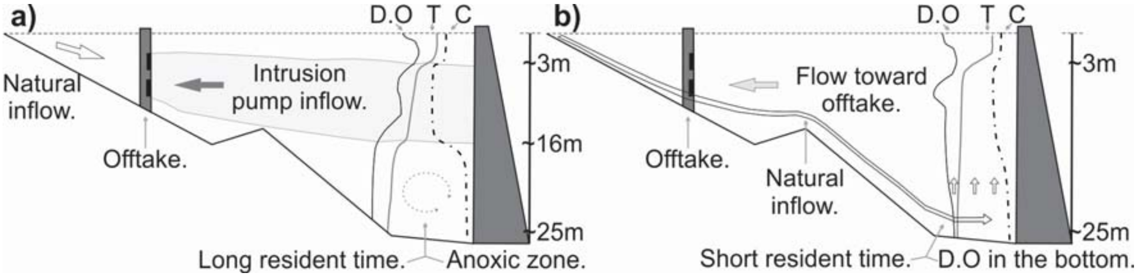

Figure 2. Water motions and typical profiles during the (a) dry and (b) wet seasons

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Wind-driven water movements in an Australian subtropical freshwater reservoir

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KEYWORDS

Hydrodynamics; mixing; reservoir; stratification; wind forcing.

EXTENDED ABSTRACT

Little Nerang Dam (LND, Figure 1a) is a subtropical, warm monomictic, freshwater reservoir, located approximately 80 km south of Brisbane, Australia. LND has a surface area of 0.44 km^2 and full supply capacity of 6,465 ML. Maximum water depth is 36.2 m (avg. 14.8 m). Mixing processes that drive water exchange between the epilimnion, metalimnion and hypolimnion in LND are primarily determined by the wind, inflow and outflow. Due to periodicity of the wind forcing, water movement in LND typically follows a distinct diurnal cycle. This cycle is interrupted by storm events that can dominate mixing processes in the reservoir for short (1-5 days) periods. For water resource management applications an understanding of underlying physical processes that drive mixing, as well as their interactions within a water reservoir, are necessary for effective water quality management (Ji, 2008).

Field monitoring from 2 – 8 February 2011 was conducted in LND during highly stratified conditions (Lake Number, $L_N > 150$) to increase understanding of mixing processes in LND, when wind forcing is the main energy supplier and no major inflows and/or outflows are present. Water temperature data was measured by thermistor chain (MEA WSTCBuoy, T2 in Figure 1a) fitted with MEA2173 thermistors. Climate data was monitored by a Vaisala WXT520 climate station (C2) 2 m above the water surface. Water velocity (v_W) and direction data were at location ADCP2 monitored with an upward looking, bottom mounted Teledyne RDI Workhorse Sentinel (600 kHz). Outliers and noise in the ADCP data were removed via the true three-dimensional phase space method (Goring and Nikora, 2002; Mori *et al.*, 2007) and a centered running average filter (window size 10 min) respectively. Spectral analysis using a fast fourier transformation approach has been conducted on the wind speed, wind direction, isotherms, v_W and flow direction data.

The monitoring data show that in absence of storm events the periodicities of 24 and 12 hours are dominant for the wind forcing (Figure 1b). At the location of ADCP2 the epilimnion is directly exposed to wind forcing from NNE and SSW (Figure 1b, d, e) and this result in relative high horizontal (40 – 80 mm s^{-1}) and vertical (8 – 15 mm s^{-1}) v_W from approximately 2 m depth to the top of the metalimnion boundary (Figure 1d, e). These are speculated to be caused by Langimur circulations which then highly contribute to vertical transport of water, nutrients, organic matter and phytoplankton in the epilimnion of LND. Wind forcing also

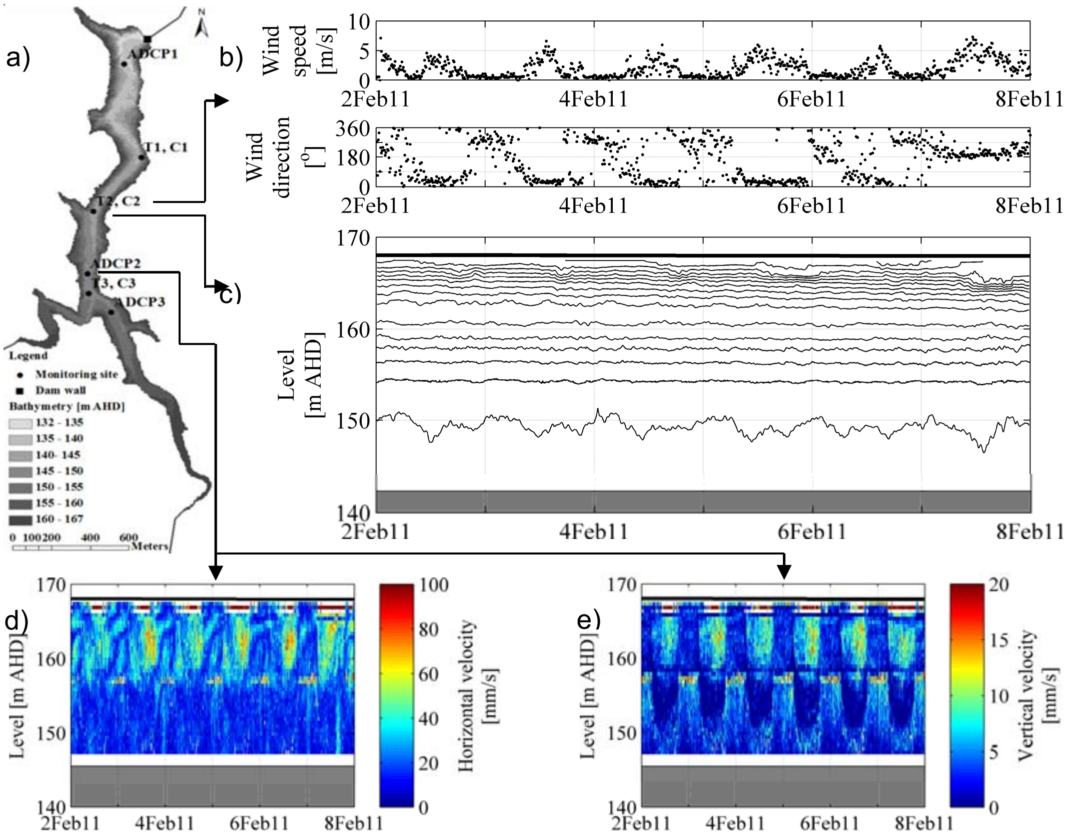

Figure 1. Little Nerang Dam including monitoring sites (a). Wind speed [m s^{-1}], direction [°] (b) and isotherms [°C] (c) monitored 2 – 8 February 2011 by climate station C2 and thermistor chain T2. Isotherm 14.5 °C and 15 – 29 °C with a temperature step of 1 °C are shown. Horizontal (d) and vertical (e) water velocities [mm s^{-1}] monitored by ADCP2 are presented too. Gray shaded areas indicate sediment and thick black lines water surface. The horizontal axis ticks mark midnight.

results in internal wave activity within LND (Figure 1c) where the isothermal displacements generally include frequency periods matching the periods of the wind field. Isotherm 14.5 °C (lowest isotherm analysed) exhibits the largest vertical displacements. This is unexpected as the largest vertical isothermal displacements should occur in the metalimnion region due to the highest density differences (Wetzel, 2001). The 14.5 °C isotherm is located in the hypolimnion (~150 m AHD) below the thermocline (~157 m AHD) it is speculated to whether the large wave amplitude is caused by interaction of reflected waves or a high density chemical stratification layer in the hypolimnion. The cause of the large vertical displacements of the 14.5 °C isotherm requires further investigation, however it is hypothesized that the vertical displacements cause the periodically increased vertical v_W observed in the hypolimnion at the location of ADCP2 after the wind force has decreased (Figure 1e). Spectral analysis of the v_W in the hypolimnion show similar frequency periods as isotherm 14.5 °C (24, 11 and 8 hours cycle^{-1}). Additionally at the location of ADCP3 (data not shown) relative large horizontal and vertical v_W (up to ~400 mm s^{-1} and ~100 mm s^{-1} respectively) have been observed in the hypolimnion. It is hypothesized that this could be a result of breaking of internal waves in this region. The cause of these periodic and relative large horizontal and vertical v_W in the hypolimnion compared to v_W in the rest of the water column require further investigation.

Acknowledgements

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Sensitivity of Thermal Structure to Meteorological Forcing in a Large Temperate Lake

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KEYWORDS

Climate change; ELCOM; hydrodynamic modelling; Lake Erie; lake thermal structure.

EXTENDED ABSTRACT

Introduction

Global warming and the resulting changes in meteorological forcing are anticipated to significantly affect the Laurentian Great Lakes ecosystem in many different ways. With the complexities inherent in modelling and predicting ecological impacts, it is important that we start with an accurate account of the most direct responses of climate variations, notably the thermal structure. In this abstract and during the conference we will investigate the responses of the thermal structure to the possible changes in air temperature and wind speed.

Methods

The Numerical simulations were conducted using the Estuary and Lake Computer Model (ELCOM, Hodges et al. 2000). The environmental forcing was from field measurements, and the model was validated using mooring data collected in 2008 (Fig.1). The 2008 simulation was taken as the base case, and we varied the observed air temperature by ±1, ±2, and ±4°C (the longwave radiation was adjusted according to Austin and Allen, 2011) and the observed wind speed by ±5%, ±10%, and ±20%. Four metrics are selected to quantify the responses of the thermal structure (Robertson and Ragotzkie, 1990): mean epilimnion temperature, mean hypolimnion temperature, onset and breakdown of stratification, and thermocline depth. We present an original method to define spatially and temporally varying regions for the epilimnion, thermocline, and hypolimnion. The thermocline is defined as the surface of maximum vertical temperature gradient (the black line in Fig.1B). The locations of epilimnion and hypolimnion are based on the thermocline. We propose a criterion based on the relative temperature difference between the surface (or bottom) water and the thermocline (the epilimnion and hypolimnion boundaries are denoted as white lines in Fig.1B).

Results and Discussion

Due to the length limitation only the results from the air temperature analyses are presented. (i) Air temperature change can significantly affect the mean epilimnion temperature (Fig.2A-C). The response is about 0.5-0.7°C with, and 0.4-0.6°C without, the longwave radiation adjustment per 1°C air temperature change. This is similar to the estimates of 0.4-0.85°C from Robertson and Ragotzkie (1990) for Lake Mendota, Wisconsin. (ii) The change of the mean hypolimnion temperature is minimal (Fig.2D,E), because higher air temperature leads to a warmer epilimnion, enhancing the stratification and the stability of the metalimnion, which results in less downward heat flux to warm the hypolimnion. (iii) When air temperature is increased the stratification forms earlier and breaks down later, hence the total duration of the stratified period is extended. This is clearly shown from the plot of total stratified grid-columns as a function of time in the eastern basin (Fig.2F). (iv) The changes in the thermocline depth are small but gradually increase at the end of the season. Higher/lower air temperature raises/deepens the thermocline depth (Fig.2G). Exploiting the power of the three dimensional model to provide more authentic characterization of thermal structure in such large lakes, it is shown that patterns inferred from simple isotherm dynamics, as typically done with one dimensional models, are not always accurate. The present results for Lake Erie show the potential for complicated and interactive effects of climate forcing on important biogeochemical processes, especially hypolimnetic oxygen depletion.

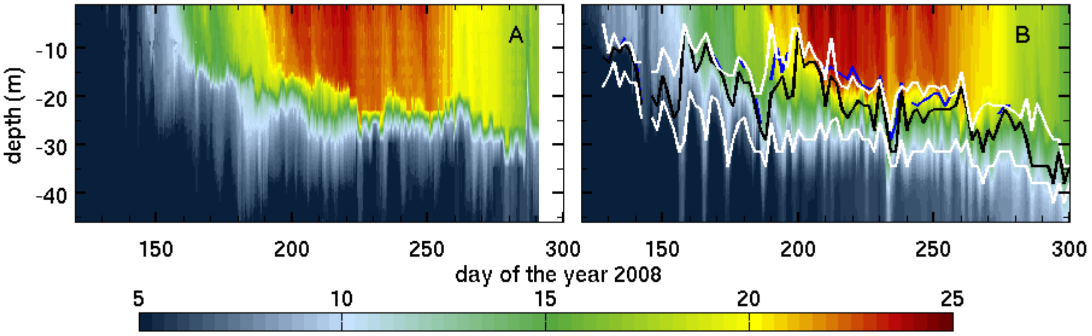

Figure 1. (A) Observed and (B) modelled temperature at station 452 in the eastern basin. Black line: calculated thermocline. White lines: epilimnion and hypolimnion boundaries.

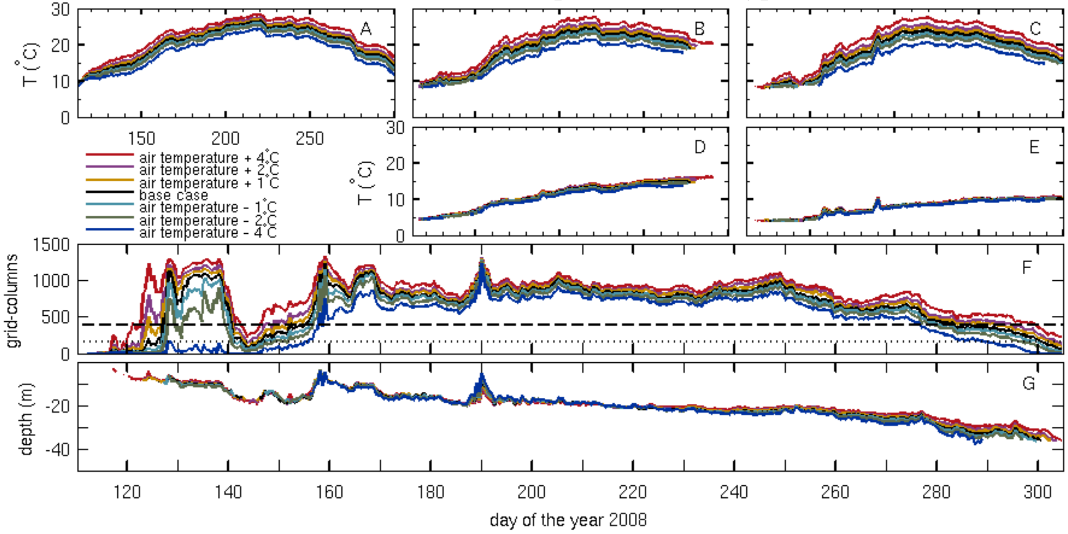

Figure 2. Mean temperature response to the air temperature changes in: (A) western basin, (B) central basin epilimnion, (C) eastern basin epilimnion, (D) central basin hypolimnion, and (E) eastern basin hypolimnion. (F) Total number of stratified grid-columns in the eastern basin. (G) Mean thermocline depth in the eastern basin.

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Characteristics of Lake Baikal's Internal Wave Spectrum

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KEYWORDS

Baikal; internal waves; inertial waves; limnology; time series analysis; wavelets

EXTENDED ABSTRACT

Lake Baikal is the most voluminous and deepest (over 1.6 km) fresh water body on earth holding about 20% of the world's unfrozen fresh water. It is an elongated lake extending about 650 km from the southernmost to the northernmost point and it consist of three sub-basins, the South, Central and North basins. Its size, location and stratification make it a unique system to study internal waves. The top 250 m are seasonally stratified, while the deeper part of the lake has a constant temperature of about 3.4 °C, slightly decreasing with depth with a gradient of 0.03 °C m^{-1}. Exchange of the deep water between the three basins is restricted by the high sills forming the sub-basins. The density stratification in the lake depends almost exclusively on temperature while salinity is nearly constant with depth. Typical values of the squared buoyancy frequency, N^2, vary between 10^{-8} s^{-1} in the deep water to $2 \cdot 10^{-7}$ s^{-1} at the summer thermocline. The local inertial frequency (f) is $1.8 \cdot 10^{-5}$ s^{-1} corresponding to an inertial period of 15 hr 14 min. We are interested in calculating the internal wave spectrum in order to investigate the types of inertial motions propagating in the lake and evaluate their importance to mixing.

The temperature of the lake's South Basin has been systematically monitored for over a decade (since March 2000) with moored stations placed in a triangle close to the northern coast. We are in possession of a temperature time series with a temporal resolution between 10 s and 1 h and a vertical resolution varying between 25m at the surface and the bottom layers and 150m in the mid depths. Additionally, sparse velocity measurements are available, measured by a mechanical current meter placed either in the surface layer or at the bottom.

Throughout the 12-year temperature data set a distinct peak is observed almost at all depths in all moorings close to the inertial frequency (figure 1). In order to visualise the temporal and spatial distribution of the most energetic oscillations we employ the wavelet transform (code developed by Torrence and Combo, 1998) and integrate the spectra in the inertial frequency band for each available depth measurement. The annual differences and similarities between the spectra are investigated and conclusions are drawn on the influence of the wind and stratification on the inertial motions. Internal Kelvin waves at the seasonal thermocline and other possible internal modes are also investigated in this study.

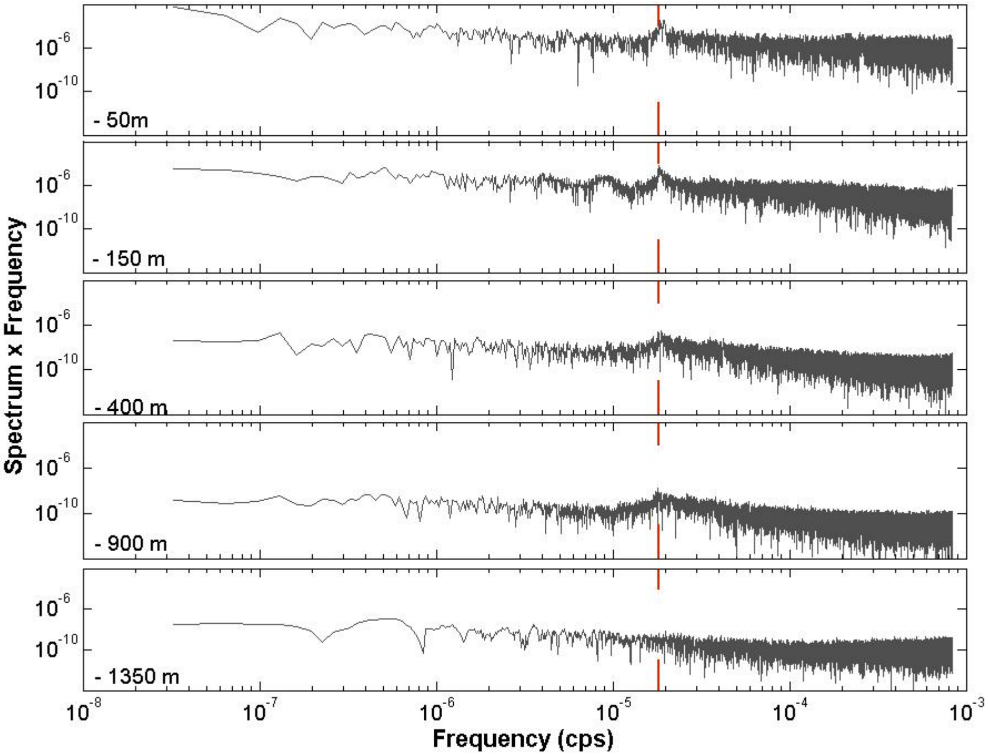

Figure 1. Typical annual spectrum at different depths of the south basin of lake Baikal. The inertial frequency $1.8 \cdot 10^{-5}$ s^{-1} is denoted by the red line.

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Eigen Modes or Internal Gravity Waves? Observations of Current Velocity Structures in a Small Lake

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KEYWORDS

ADCP; current; Eigen Mode; internal gravity wave; limnology; ray wave.

EXTENDED ABSTRACT

Measurements of water currents in a small lake (Willersinnweiher, Ludwigshafen/Germany) were interpreted in Ilmberger et al (2005) in terms of higher mode (5th) internal standing waves. (There are only few reports on more than 2nd mode, e.g. Antenucci et al (2000), Pérez-Losada et al. (2003)). In this contribution another view to the measurements -regard it as **internal ray waves-** is given.

Internal wave motion in a continuous stratified fluid can be described as ray wave. (e.g. Görtler 1943, Turner 1973) There, one regards a small disturbance in a continuous stratified fluid and the wave propagation there after.

Starting with the two dimensional differential equation for the vertical velocity (Turner 1973) we get:

$$\frac{\omega}{N} = \frac{k}{\sqrt{k^2+m^2}} = \frac{k}{\left|\vec{K}\right|} = \cos\varphi \quad (1)$$

That is, the ratio of the horizontal component k and the magnitude of the wave vector $\left|\vec{K}\right|$, which means the direction of the progression of the wave at the angle φ (Fig.1), is fixed through the **existing stratification N** and the **angular frequency of the exciting disturbance ω**. Only if $\omega < N$ we get waves propagating away from the source which can only propagate at: $\pm\varphi,\ \pm(\pi-\varphi)$.

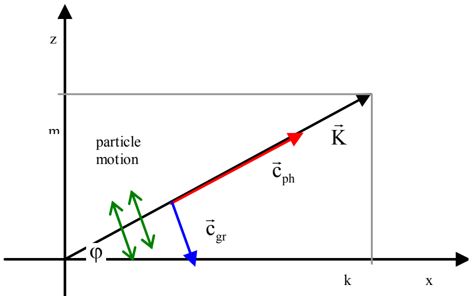

Fig 1: Sketch of the wave vector, group and phase velocity in the x-z-plane. Figure after Turner (1973)

$$\text{The phase velocity is: } \vec{c}_{ph} = \frac{\omega}{\left|\vec{K}\right|}\cdot\frac{\vec{K}}{\left|\vec{K}\right|} = \frac{\omega}{\left|\vec{K}\right|^2}\cdot\ (k\ ,\ m) = \frac{k\cdot N}{\left|\vec{K}\right|^3}\ \cdot\ (k\ ,\ m) \quad (2)$$

$\vec{c}_{ph}$ is in the direction of the wave vector $\vec{K}$, and the magnitude is: $c_{ph} = \frac{k\cdot N}{m^2+k^2}$ (3)

$$\text{The group velocity is: } \vec{c}_{gr} = \left(\frac{\partial\omega}{\partial k}\ ,\ \frac{\partial\omega}{\partial m}\right) = \frac{m\cdot N}{\left|\vec{K}\right|^3}\cdot(m\ ,\ -k) = \frac{m}{k}\cdot\frac{\omega}{\left|\vec{K}\right|^2}\cdot\ (m\ ,\ -k) \quad (4)$$

The group velocity (direction of particle motion) is perpendicular to the wave vector $\vec{K}$

$$c_{gr} = \frac{m\cdot N}{\left|\vec{K}\right|^2} = \frac{m}{m^2+k^2}\cdot N \quad (5)$$

Wind velocity at the lake and 30km afar.

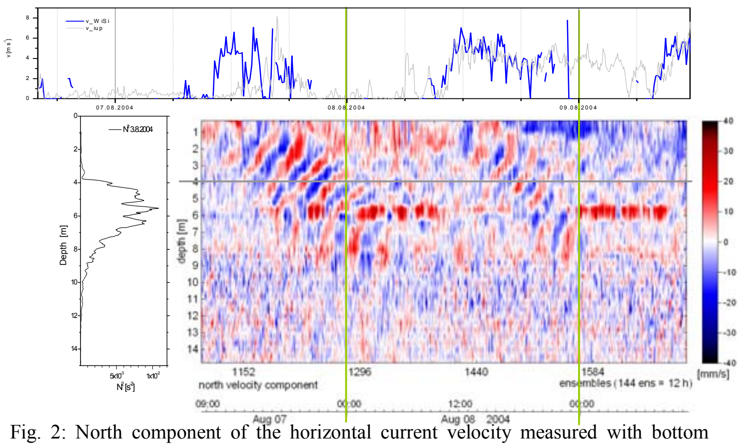

Fig. 2: North component of the horizontal current velocity measured with bottom moored Acoustic Doppler Current Profiler (ADCP) at Willersinnweiher (Germany), Aug. 07 – Aug. 11, 2004. The upper panel shows the wind speed measured at the lake side and for comparison the record of a meteo station 30 km afar. Left panel: Stability N^2 calculated from CTD-measurements at Aug. 3^{rd}.

Results and discussion

Considering the observations as **ray waves** one can calculate characteristic properties. Form figure 2 we can estimate the mean period T=-3.1 h ($\boldsymbol{\omega = 5.6 \cdot 10^{-4}\ s^{-1}}$), the buoyancy frequency **N** from **0.01 to 0.1 s^{-1}** and the mean vertical wave length λ_z=2.4 m (**m = 2.6 m^{-1}**).

***Angle of propagation* φ.** Using relation `(1)`, we can calculate φ for N (0.1 and 0.01 s^{-1}) we get 86.6 and 89.7° respectively. That means in either case the wave propagates nearly vertical.

***Horizontal wavelength* λ_x.** As ω << N, we can simplify equation `(1)` and get: $k \approx m \cdot \frac{\omega}{N}$

with $m = \frac{2\pi}{\lambda_z}$ and $\lambda_x = \frac{2\pi}{k}$ we get $\lambda_x \approx \frac{\lambda_z \cdot N}{\omega}$ Inserting the values, we get λ_x 43 to 430 m (k=0.15…0.015m^{-1}). If we are to use the small value for N, we get a wavelength for the exciting disturbance of around 400 m, which is in the order of the length scale of the lake.

Phase velocity. Using the same simplification we get from `(3)` $c_{ph} \approx \frac{k \cdot N}{m^2}$, which leads to a very low value of 0.0002 m/s (0.8 m/hr)

***Group velocity* c_{gr}.** The group velocity is calculated after equation `(5)` with k << m: $c_{gr} \approx \frac{N}{m}$ Using the estimated values, we get for the magnitude of the group velocity values from c_{gr} = 3.8 to 38 mm/s.

Conclusions

The description of the observed phenomena in terms of ray waves is possible.

As we have a rather high stability compared to the frequency of the disturbance we get rather large horizontal wave length. So we tend to a basin wide wave, which rather resemble a modal description, than a propagating internal ray wave.

The angle of propagation is close to 90°, which means that there is almost no propagation.

So it seams for that specific situation the description of the observed phenomena in terms of modal structure is more appropriate.

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Lake number as a predictor of turbulence generation on a slope

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KEYWORDS

Boundary mixing, Internal waves, Lake number, Turbulence

EXTENDED ABSTRACT

In many lakes, vertical mixing in the thermocline is the result of wind-induced internal waves interacting with the boundaries. Both the strength of the wind forcing required to generate these waves and the ability of these waves to mix fluid at the boundary depend on the stratification and the bathymetry. Because turbulence is difficult to measure, we seek to determine whether turbulence at the boundary can be predicted from standard measurements of meteorological conditions, stratification, and bathymetry. To do so, we investigated the dependence of internal waves and turbulence on the slope on the Lake number, which compares the stabilizing tendency of stratification to the destabilizing tendency of the wind.

Two thermistor chains and a Lake Diagnostic System (LDS) manufactured by Precision Measurements Engineering were deployed in the south basin of Ada Hayden Lake in Ames, Iowa, USA, and a Nortek HR Aquadopp, a high resolution pulse coherent acoustic Doppler current profiler, was placed on a slope in the metalimnion of the lake for three deployments of 13, 15, and 8 days in July, September, and October 2008 respectively. Ada Hayden Lake (Figure 1) is an abandoned rock quarry that is used as a secondary water supply for Ames. The larger, deeper south basin has has a surface area of about 0.3 km^2 and a maximum depth of about 17 m. The lake has steep sides except for a few areas; the southern slope, where the Aquadopp was placed, has a more moderate slope ranging between 5 and 10%. The Aquadopp measured velocity profiles in upward looking mode in the bottom 1.5 m of the water column.

The Lake number L_N can indicate whether boundary mixing from seiching and breaking internal waves should be present in Ada Hayden Lake. The Lake number compares the strengths of the stratification and the wind, which can cause the stable density structure to overturn, essentially extending the concept of the Wedderburn number to account for arbitrary stratification and bathymetry. A Lake number of 1 implies upwelling conditions. Low Lake numbers ($L_N < 10$) indicate that the wind stress is sufficient to generate wind setup throughout the water column (Imberger and Patterson 1990). A time series of the Lake number was computed using the data from the LDS.

The time series of the rate of dissipation of turbulent kinetic energy was computed from the Aquadopp data using the structure function method developed by Wiles et al. (2006), as this method has successfully been used in the oscillatory bottom boundary of a lake (Lorke 2007, Lorke et al. 2008). This method uses the spatial correlations of velocity along a beam to estimate the dissipation.

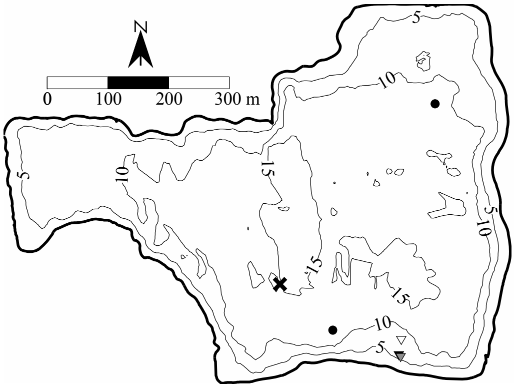

Figure 1. Bathymetric map of Ada Hayden Lake with contour intervals in meters. The locations of the LDS ×), the T-chains (•), and the Aquadopp (Δ). The black, gray, and white indicate the location of the Aquadopp during the July, September, and October deployments, respectively. The Aquadopp was almost in an identical position in July and September. Two

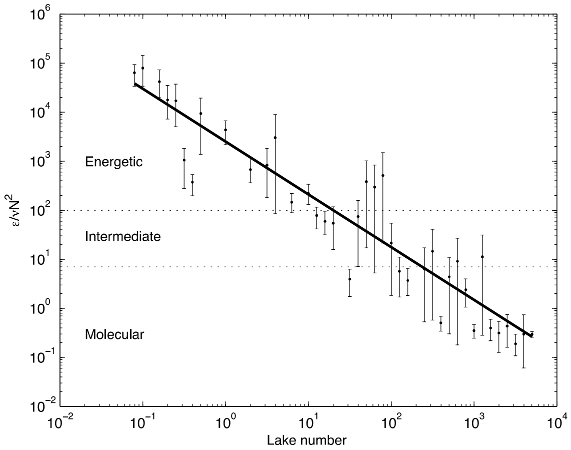

Figure 2. The turbulence intensity as a function of Lake number. The regimes defined by Shih et al (2005) are denoted. The thick line is the power

Dissipation rates of turbulent kinetic energy are just one element that determines whether mixing will occur. In less stratified environments, less turbulent production is needed to generate the same amount of mixing. The three study periods each had different stratification, so to compare the Lake number to turbulence generation and mixing, we use the dimensionless $\varepsilon/\nu N^2$. Shih et al. (2005) classified the turbulence as diffusive, transitional or energetic based on $\varepsilon/\nu N^2$. For $\varepsilon/\nu N^2<7$ (the diffusive regime), the diffusivity is molecular. For $7< \varepsilon/\nu N^2<100$ (the transitional regime), the mixing efficiency was constant and coincided well with the typical value used in eddy diffusivity parameterizations in lakes and the ocean; the mixing efficiency decreased as $\varepsilon/\nu N^2$ grows above 100 (the energetic regime).

For each measurement of dissipation, the Lake number at the closest measurement time was used for comparison. In Figure 2, we show all the data from the three deployments. The data was sorted by Lake number and divided into bins of 1/10th of a decade and then bootstrapped to determine the mean and 95% confidence intervals. Combining all the mean data points together, we can compute a power law between the two variables. With the current data, this yields $L_N\sim(\varepsilon/\nu N^2)^{-1.1}$, implying an almost linear relationship between Lake number and turbulence intensity. If other factors that may affect the spread of the measurements can be constrained, there is potential for predicting boundary mixing within an order of magnitude with commonly measured lake parameters.

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Modeling circulation and residence time in western Lake Erie

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KEYWORDS

Circulation, Lake Erie, residence time

EXTENDED ABSTRACT

In 2011, Lake Erie experienced the largest harmful algal bloom in its recorded history, with peak intensity over three times greater than any previously observed bloom. To investigate the role of lake circulation in encouraging the bloom, we apply 3D hydrodynamic (Beletsky and Schwab, 2001) and particle transport models in 2011 and two preceding years as well. The particle transport model is developed by David Schwab (University of Michigan) and is described in Michalak et al. (2013). Simulations show that western basin monthly circulation is characterized by a broad west-east flow that exits the basin via three channels (North, Middle, and South), with low current magnitudes correlated with increased residence times. All simulated years exhibit relatively low-magnitude currents during summer months (May – August), but 2011 had an extended period with weak currents (consistent with weaker winds) from late winter through summer (February – July). The residence times in the western basin during this period were 46 and 36 % longer than in the previous years (2009 and 2010 respectively). Furthermore, residence times of Maumee River water (the largest source of nutrients in the basin) in June 2011 were 53% longer than previous years and 77% longer (>90 days) than the estimated mean hydraulic residence time of the western basin. Simulations also show that the long residence times were accompanied by a "short-circuiting" of Detroit River waters, leading to minimal mixing between the Detroit and Maumee River waters along the western and southern shores of the basin, thus diminishing dilution of nutrient-rich Maumee River waters. Although some mixing occurs near the islands between the western and central basins during April-August, Detroit and Maumee waters primarily leave the western basin through the North and Middle/South Channels, respectively. Location and timing of bloom initiation is consistent with simulated advection of the elevated late spring Maumee runoff, suggesting that the water mass present at the first stages of the bloom initiation likely originated from the Maumee River close to June 1.

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Modeling international variability of general circulation and thermal structure in the Great Lakes with FVCOM

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EXTENDED ABSTRACT

An unstructured Finite Volume Coastal Ocean Model (FVCOM) was applied to all five Great Lakes simultaneously to simulate circulation and thermal structure from 1993 to 2008. Model results are compared to available observations of currents and temperature and previous modeling work. Maps of climatological circulation for all the five Great lakes were constructed. An EOF analysis was applied to each season to derive the dominant patterns of the circulation and temperature. The temperature profile during the summer is well simulated when a surface wind-wave mixing scheme is included in the model. Main features of the seasonal and international variability of water temperature, such as reverse stratification during the winter, the spring and autumn overturn, the thermal bar, and the stratification during summer are well reproduced. The lakes exhibit significant interannual variations in current speed and temperature. These patterns are linked to the atmospheric circulation teleconnection patterns associated with ENSO and North Atlantic Oscillation.

Optimizing withdrawal from a tropical hydropower reservoir for improved water quality in downstream wetlands

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EXTENDED ABSTRACT

Large reservoirs in the tropics act as efficient nutrient traps and often develop hypoxic conditions in the hypolimnion. Withdrawing hypolimnetic waters may have severe implications for aquatic ecosystems, such as hypoxic conditions in the downstream rivers posing toxic risks, and reduced nutrient loads limiting primary production in downstream riparian agriculture and in natural wetlands. This case study on Itezhi-Tezhi Reservoir (Zambia) aims at defining optimized turbine withdrawal to prevent hypoxia and to relieve nutrient deficits in the downstream Kafue Flats floodplain. A biogeochemical model simulating reservoir-internal processes and water quality in the outflow was used for estimating dissolved oxygen (DO) concentrations and inorganic nitrogen and phosphorus loads in the outflow. The water depth of turbine withdrawals was varied in a set of simulations to optimize outflow water quality.

Releasing hypolimnetic water was shown to result in lower average outflow DO concentrations of 4.1 to 6.8 mg l^{-1} compared to the current 7.6 mg l^{-1}. More importantly, the outflow will remain hypoxic during up to ~190 days. Meanwhile, by withdrawing nutrient-rich hypolimnetic water, such scenarios were most effective in compensating for nutrient losses to the sediment. Both outflow DO concentrations and nutrient output could be optimized in the scenario with 50% epilimnetic turbine discharge originating from ~13 m depth. In this optimal scenario, hypoxia was prevented permanently, and average DO concentrations decreased moderately to 5.2 mg l^{-1}. Additionally, five-times higher dissolved inorganic N and dissolved inorganic P loads resulted in comparison to the current dam operation.

A comprehensive investigation into the distribution of salinity and turbidity in the Brisbane River estuary, Australia

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EXTENDED ABSTRACT

The Brisbane River estuary not only plays a vital role in ecosystem health, but is also of importance for people who live nearby. The estuary experiences high turbidity and salinity throughout most of the year. A comprehensive investigation into the salinity and turbidity distributions was conducted both in the long- and short-term. Based on ten years of field data, the distributions of salinity and turbidity in the estuary were examined during both wet and dry seasons (under non-significant flood event circumstances). The results revealed that the typical salinity value at the river mouth was estimated to be 31.7 and 32.8 ppt during wet and dry seasons, respectively. The surface longitudinal salinity then decreased along the estuary, with the highest decreasing rate, 0.65 ppt/km, occurring within the mid-estuary. During the wet season, the length of the turbidity maximum was approximately 35 km, which was three times as long as in the dry season. Although the surface distribution of salinity and turbidity varied significantly between the two seasons, the vertical distribution patterns tended to be similar: salinity fairly well mixed but turbidity significantly stratified. Further analysis focused on the variations in salinity and turbidity during a tidal cycle, using a verified numerical model. It was found that the upstream turbidity distribution was relatively less impacted by the tide and the turbidity remained at a high level during the tidal cycle. In contrast, the turbidity in the mid-estuary was significantly influenced by the tidal condition. At the downstream reach, the combined effects of relatively clean coastal water and asymmetry of tidal currents during the flood and ebb tides resulted in small changes in turbidity. Particular emphasis was given to the application of satellite remote sensing techniques for accurate estimation of the turbidity distribution in the estuary immediately following significant flood events. A linear relationship between satellite observed surface reflection and the surface turbidity in the estuary was proposed and validated. This proposed relationship allows the ecosystem condition to be immediately evaluated after severe flood events. The results acquired from this comprehensive investigation would be useful for further hydrological study in the estuary.

Sydney Estuary Dynamics - estimation of freshwater inflow from CTD measurements

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EXTENDED ABSTRACT

The Sydney Estuary drains a small catchment of around 500 sq km. Four main tributaries and a complex stormwater system with numerous outlets drain the catchment. Presently only one tributary is monitored, as a consequence freshwater flow is mostly undescribed. Stormwater runoff is currently the main source of pollution to the Sydney Estuary. Describing rainfall runoff and freshwater flow into the estuary is vital to manage this concern and monitoring the numerous outlets is presently unfeasible so a new technique, utilising CTD measurements throughout the waterway and numerical modelling of the estuary was developed to estimate freshwater flow from the catchment under high-precipitation conditions. Using this methodology it has been shown that the SCS-CN method for calculating runoff provides a close estimation of freshwater runoff.

Beach profile changes around a wave-dominated tidal inlet entrance

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KEYWORDS

Beach profile evolution; Currumbin Creek; Tidal inlet entrance;

EXTENDED ABSTRACT

INTRODUCTION

Tidal inlet is an opening in a beach face which is mostly controlled by tidal forces and exhibits periodic exchange of water between an inland water body and the ocean water. The second important features of a typical tidal inlet system are offshore and/or inland deltas. The excess sediment accumulation at these deltas, which sometimes fully blocks the natural passage of water, is one of the common issues of a tidal inlet entrance. The so called excess sediments can be provided by different sources; for instance littoral drift, beach wash over materials, unsuccessful beach nourishment and so on (Castelle, 2007).

In this study, parts of the results of an extensive filed measurement to explore the dynamics of the Currumbin Creek (Figure 1) are presented and the changes in the beach profile around the creek are considered for detail investigation. Currumbin Creek entrance is one of the highly popular tourist attractions in the south-eastern Queensland, Australia which also had a very old history of maintenance operations. In the past 30 years, there has always been annual dredging campaigns to keep the creek entrance open. Nevertheless, the entrance became shoaled, soon after each dredging.

The inlet entrance is mostly located in the east-west direction. At the immediate inland side of the entrance channel, a lagoon is situated which also hosts the inland (flood) shoal (delta). This shoal is the main focus of the annual dredging work and it is believed to be the main reason for making navigation difficulties (Strauss, 2011). The effect of littoral drift, sediment bypass and erosion of the adjacent beaches were proved to be significant in making spatial changes of the ebb and flood shoals (D'Agata, 2002). However, this is also hypothesized in this research that the shore faces of the lagoon and the creek can, likewise, have a share in providing the sediment supply.

Figure 1. Currumbin Creek aerial photo (Copyright: GCCC 2011/03/25)

METHOD

From the entire 5km of the surrounding beach, the measurements were just limited to some 141 particular lines which were surveyed from Dec. 2012 to Mar. 2013 in a weekly manner. Each line was perpendicular to its local shoreline, extending from the dry part of the beach to a depth (normally) 0.5m lower than the lowest low water mark. Every single line also divided to couple of subsections (based on any abrupt changes in elevation or just a maximum section length of 7m), at each end of that, the coordinates and elevation were measured. In terms of environmental forces, during this period there were a number of sever stormy wave incidents and also a very long and heavy rainy period. Based on recorded data available from Australian Government, Bureau of Meteorology (2013), the total amount of rainfall during the measuring period were about 55% of the total 2012 rainfalls. Also the highest significant wave height ($H_{s,max}$) and the longest storm period (incoming significant waves exceeding 3m) are derived to be about 7.5m and 48hrs.

RESULTS AND DISCUTION

In total, about 54100 points have been collected during 16 weeks of data collection with the total length of all surveys as about 134 km. Figure 2 shows profile nos. 33 and 43 as samples. For better distinction, only data of week 1 and other even weeks are presented. Although some profiles show build-up of beach material by time (like no. 33), there are others which show massive erosion (like no. 43). Comparing profiles in group of 3-4, also suggested that whether lost materials of a profile were added to the consequent lines or even just transferred offshore to the main littoral process. It is also concluded that all lines around the entrance channel exhibited erosion. In contrast, most lines around the lagoon, showed a slight build-up (except for those which were subjected to nourishment). The lines, more upstream the creek (which also contains cohesive materials), were about the same during the measuring period.

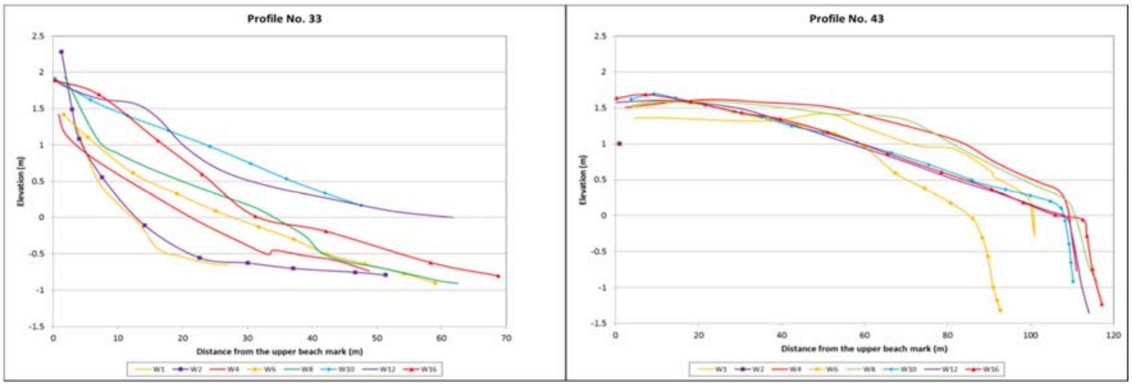

Figure 2. Elevation changes along profile nos. 33 & 43

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How to detect Regime Shifts and their causes in the European Seas?

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KEYWORDS

Breakpoints, linear trend, regime shifts, statistical methods.

EXTENDED ABSTRACT

INTRODUCTION

During the late 1980s air and sea surface temperature increased in many European regional Seas (Baltic Sea, North Sea, Mediterranean Sea). This was accompanied by a longer growing season and by increases in phytoplankton biomass as well as changes in the zooplankton and fish communities. By many authors these changes are considered to represent regime shifts in the ecology of the Baltic Sea, the North Sea and the Mediterranean Sea (Alheit *et al.* 2005, Conversi *et al.* 2010). Further some authors speculate that the regime shift in the Baltic Sea and the North Sea could be caused by a related sign change in the North Atlantic Oscillation index (NAO).

The aim of this investigation is to inspect relevant physical and ecosystem variables for trends and structural breakpoints in the time series using sound statistical methods that include confidence tests at the 5% error probability level.

METHOD AND DATA

For estimating structural breakpoints in time series regression models we apply the method developed by Bai and Perron (2003). This method is implemented in the statistical software **R** package *strucchange*. An introduction to the method with examples is presented in Zeilies *et al.* (2003). The **R** statistical software and the mentioned package can be freely downloaded from the Comprehensive R Archive Network (CRAN, http://cran.r-project.org/).

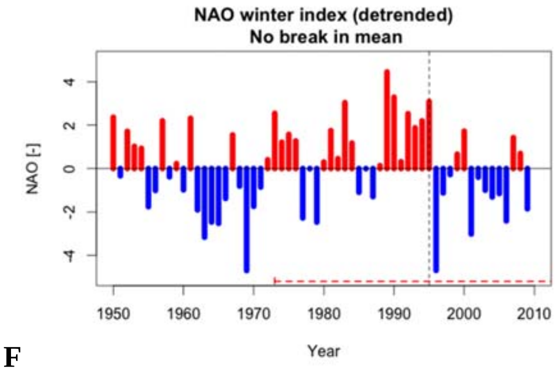
When applying this statistical method to data generated so that they have a significant linear trend and added white noise than in most cases a significant breakpoint is detected. Doing 10000 Monte Carlo simulations we found that time series with a significant trend do have in about 90% of the cases also a significant breakpoint (actually caused by the locally changing mean as a consequence of the trend). To exclude such spurious breakpoints resulting from the applied methodology, data with a significant trend must therefore be detrended before doing the analysis.

For this purpose we investigated a broad range of physical variables including air temperature, wind speed, sea surface temperature, ice cover, precipitation, oxygen as well as ecosystem variables such as phytoplankton biomass, zooplankton and several fish species from the different European regions. For the North Atlantic Oscillation index we used the version from the Climatic Research Unit of the University of East Anglia http://www.cru.uea.ac.uk/cru/data/, see Hurrell (1995).

RESULTS AND DISCUSSION

We found that most of these time series do exhibit a statistical significant linear trend. But tests for structural breakpoints in these time series reveal only for some investigated variables the existence of a breakpoint in the 70-80ties of the last century. In contradiction to the seemingly well established “regime shift” in the different Seas no clear breakpoint can be identified in many physical variables and also not in most ecosystem variables including fish. Finally also the proposed reason for the supposed ecological regime shift in the European Regional Seas, the change of the NAO sign at around 1987, is not statistically significant. The NAO time series from 1950 to 2005 does have a small significant increasing trend of 0.041 (±0.03) per year. The breakpoint analysis of the original data does result in a breakpoint at 1971 (±9) that is corresponding to the most significant sign change in this time series. As the linear trend in the NAO data is significant we must remove it before the breakpoint analysis. The result of this analysis is presented in Figure 1.

In summary we conclude that most physical and ecosystem time series data from the European Regional Seas are statistically best described by a linear trend and not by a regime shift. The underlying dynamics of a system cannot be revealed by a pure statistical analysis. Statistics can help us to question or support our hypothesis but advanced geophysical and ecosystem modeling is needed to understand the system dynamics.



F ex. After removing the significant trend no breakpoint can be identified.

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Ice dynamics in relation to wind and currents in the central Gulf of Finland derived from bottom-mounted ADCP

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KEYWORDS

Baltic Sea; Gulf of Finland; bottom-mounted ADCP; wind forcing; ice dynamics.

EXTENDED ABSTRACT

The Gulf of Finland has elongated form – 330 km long and 80–100 km wide with the main shipways along the Gulf for the tanker traffic and across the Gulf for the passenger ship traffic. The presence of ice cover sets special limitations for navigation as in many cases merchant ships need icebreaker assistance. Operating of several ships simultaneously in the abovementioned circumstances would require the knowledge of local ice dynamics and therefore we concentrate our study on this issue in the frame of EU project SAFEWIN which is dedicated to ice compression study.The ice dynamics causing rapid changes in compressive forces determines the navigation conditions on relatively small timescale. This study aims to describe the high resolution sea ice dynamics in relation to wind forcing by using bottom-track facility of the ADCP (Acoustic Doppler Current Profiler). ADCP detects the presence and movement of the ice pack locally at installation site with high temporal resolution of 10 minutes. Those kinds of measurements are very rare in the Baltic Sea as well as in the Gulf of Finland which is known as an arena for very intensive ship traffic.

The ADCP measurement site in the middle of the Gulf of Finland (59°42.09 N, 26°24.23 E; depth 63 m) located in south-eastward extension of the deep basin towards the Kunda Bay at about 15 km from the coast. A 307.2 kHz broad-band ADCP (Workhorse Sentinel, RD Instruments) was deployed onto the bottom with a trawl-resistant platform and configured to measure in the bottom-track (BT) mode. The relevant wind data, which mainly force ice drift, were obtained from meteorological station on island of Vaindloo (59°49.66 N 26°21.60 E) about 7 miles to the north from the location of ADCP.

The bottom mounted ADCP's bottom-track option in upward looking mode enables to follow the sea surface i.e., the reflected signal from the underside of the ice can be used to determine the ice velocity. The BT output includes velocity components, error velocity (characterizing the instrument performance and data quality) and depth (distance from the instrument's head to the sea surface). The BT error velocity is a main parameter describing the presence of ice cover as well the quality of the ice drift speed. For the low-frequency analysis all data series were filtered with low-pass filter (cutoff 36 hours) to remove the inertial (period 13.9 h) and seiche-driven oscillations with typical periods in the Gulf of Finland of about 26 h as well as other frequencies higher than the seiche variability.

Ice cover periods derived from ADCP and MODIS data

The primary feature to be determined in the measured data series with ice-covered and ice-free sea surface is the periods with lower and higher variability of BT error velocity. We found that rms of error velocity for ice-covered periods was about five times smaller than that for ice-free periods. Altogether five ice-covered episodes with duration of 6−12 days occurred, which makes approximately 60% of the full ‘ice season’. The alteration of ice conditions was in a good accordance with variations of wind in the gulf and was confirmed by the available cloud free MODIS (MODerate Imaging Spectrometer, NASA) images.

Ice drift velocity in relation to wind speed

Vector correlation coefficient introduced into physical oceanography by Kundu (1976) and the scatter plots of ice drift versus wind speeds were used to elucidate the response of the ice drift to the wind forcing during the five discovered ice cover periods. The magnitude of the vector correlation coefficient measures the overall correlation of ice drift and wind vector series and phase angle between these two vectors displays the average phase angle between ice drift vector and wind speed vector. For five ice cover periods the averaged ratio of the ice drift speed to the wind speed was 0.03, which is about two times greater than usually estimated ratio of current speed to wind speed. These ice/wind speed ratios are in accordance with earlier estimates. Typically, the ratio may vary between 0.02 and 0.035 depending on the ice roughness: the low value represents a deformed ice cover with frequent pressure ridges and the high value a smooth ice surface (Leppäranta, 2005). For comparison, the ice/wind speed ratio of 0.03 was estimated in the northern part of the Bothnian Bay (Björk *et al*., 2008). The average correlation between the wind and ice drift vectors was very high: 0.84. The veering of the ice drift vector to the right of wind speed vector was 15 degrees on the average. Typically the value of the angle is 30º in case of free ice drift (Thornike and Colony, 1982). As the extension of the Gulf of Finland, especially its width is not large, the free drift could be very short-termed and the most of the time morphometry of the coast plays a major role in the local ice dynamics, so in our measurement site as well. Similar measurements made in the Bothnian Bay gave the ice drift veering from wind direction around 10º (Björk *et al*., 2008). The scatter plots for the whole ice cover period revealed that the correlation between the wind and ice speed was higher than between ice speed and current speed at 5m depth, 0.85 and 0.69 respectively.

The study concludes that 1) the main forcing for the ice drift was wind, whereas the mean ice to wind speed ratio was about two times higher than the mean water to wind speed ratio 2) the bottom-track option of the ADCP applied for detecting the ice cover and its dynamics appeared to be a reliable tool for ice monitoring.

Acknowledgments

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Sub-tropical Water Supply Reservoirs: A Monitoring-Modelling-Management Response to Emerging Issues

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KEYWORDS

Water quality monitoring, hydrodynamic model, drought, purified recycled water (PRW).

EXTENDED ABSTRACT

Introduction

Sub-tropical water supply reservoirs are under increasing pressure from population driven demand for water resources, transformation and degradation of terrestrial catchments, climate variability and associated increased frequency and severity of extreme weather events (both drought and flood cycles). To mitigate the potential negative impacts of these pressures water resource managers often adopt a monitoring-modelling-management (M-M-M) approach to improve the information on which decisions are based. An overview of the application of a M-M-M approach to address extreme drought in a large sub-tropical water supply reservoir is provided to highlight some challenges and opportunities that the M-M-M approach presents. The study focused on Lake Wivenhoe (27.394022 °S, 152.609334 °E), a sub-tropical, warm monomictic, freshwater reservoir, located 40 km west of Brisbane, Australia. The Lake's surface area and storage capacity are approximately 10,940 hectares and 1,165,000 Ml respectively at full water supply capcity with an additional 1,450,000 Ml of flood storage. Maximum and average depths are 50 m and 10 m respectively at full water supply capacity. The main catchment inflow is from the 5,438 km^2 Upper Brisbane Catchment. The Lake also receives significant inflows via releases from Somerset Dam (located immediately upstream of Lake Wivenhoe on the Stanley River system) and the Splityard Creek hydro-power station (a pumped storage hydroelectric facility that drives both inflows and outflows). Average rainfall and evaporation are approximately 940 mm y^{-1} and 1,872 mm y^{-1} respectively [Seqwater, 2005]. The extent of groundwater interactions with the Lake is largely unexplored.

Investment in a Monitoring-Modelling-Management (M-M-M) framework

During the 2004-2007 drought water levels in the Lake decreased below 20% of full supply (**Figure 1**) exposing the region to risk of loss of water supply. A large-scale indirect wastewater reuse scheme to introduce purified recycled water (PRW) into Lake Wivenhoe was proposed as a solution. The reservoir manager (Seqwater) established partnerships with research institutions, based on a M-M-M approach, to understand the potential changes PRW might induce, particularly the potential effect of increased dissolved nutrient load associated with PRW. Investigations to support the development of numerical modelling tools to explore potential physical, chemical and biological changes to the Lake as well as to communicate results were initiated. Key outcomes included: i) renewed investment in continuous water quality monitoring; ii) collection of the first hydrodynamic measurements (Lemckert et al, 2010); iii) first process investigations into sediment nutrient supply, food web dynamics and greenhouse gas emissions; and iv) renewed investment in harmful algal bloom research. Outcomes were successfully combined with numerical simulations of PRW mixing (Gibbes et al 2009) and predictions of ecosystem response allowing management authorities and regulatory agencies to assess the PRW scheme with an unprecedented level of information. Whilst this model-driven monitoring process was highly successful, the hydrodynamic model's performance could not be validated on previous long term monitoring data or if this was done it required numerous caveats, thus reducing confidence in the modelled outcomes.

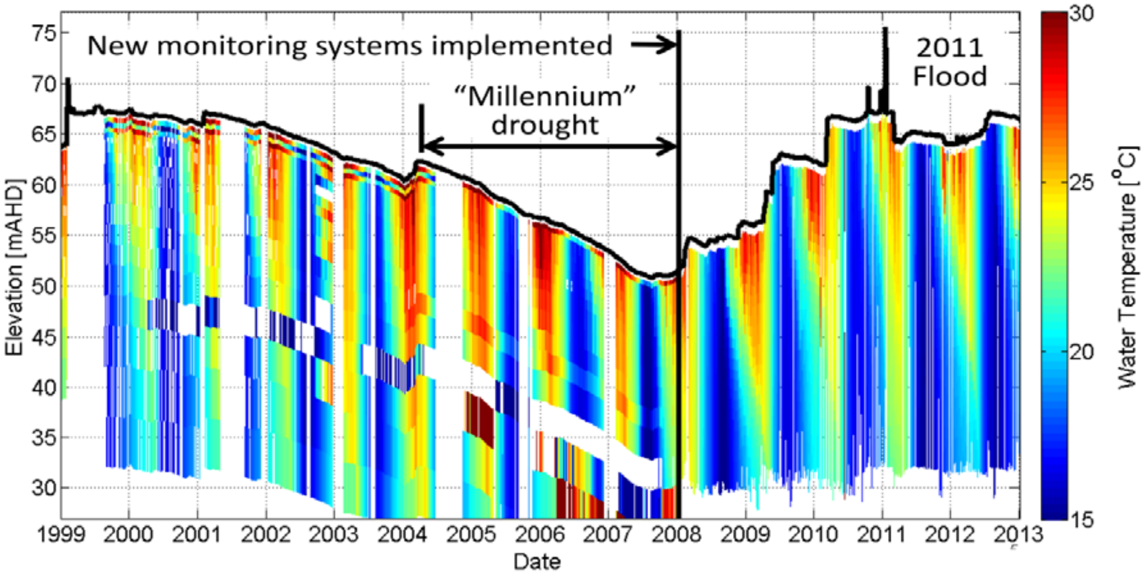

Figure 1. Evolution of water temperature and water level in Lake Wivenhoe 1999-2013. Data values outside the range 0-50 °C have been removed, otherwise data is presented as collected. Significant improvement in data capture rates and ability vary depth of sampling are evident following the introduction of new monitoring systems in late 2007.

Outcomes and on-going improvement

A series of rain events from early 2008 to 2010 triggered the indefinite postponement of the PRW scheme. On reflection a repeat of the millennium drought phase would likely result in a greatly improved predictive modelling process given the availability of improved monitoring data under current monitoring practise. These outcomes highlight the need for investment in research and monitoring as routine expenditure despite there being no apparent management need at the time. Experience with the project has shown that, even where quite intense monitoring programs exist they, may not be suitable for model development and validation – thus limiting the potential return on investment in monitoring. Explicit consideration of model data requirements during the design and review of routine monitoring programs would better position management agencies and their associated research partners to more rapidly and effectively deal with emerging issues.

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Seasonal variability of sediment and contaminant transport in Lake Maggiore, Italy

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KEYWORDS

Intrusion; Lake Maggiore; river plume; seasonal variability; sediment transport

EXTENDED ABSTRACT

INTRODUCTION

Field research and hydrodynamic modeling are used to determine the seasonal impact on the fate of sediment and DDT in Lake Maggiore, Italy. Lake Maggiore is a deep (370m), elongated (65km long, 4km wide), holo-oligomictic, subalpine lake contaminated by DDT. The lake is roughly aligned North-South with a large bay, Pallanza Bay, on its western side. The source of DDT has been traced back to a tributary, the Toce River, at the westernmost tip of Pallanza Bay. Heat fluxes, winds, river inflows and rotational effects drive the large-scale lake hydrodynamics. Additionally, the temperature structure in the lake varies significantly over the course of the year due to summer heating and winter cooling.

The suspended sediment concentration observed throughout the water column within Pallanza Bay is dominated by intermittent large river inflow events, and resuspension of sediment is relatively weak. Therefore, the path of the river largely determines the fate of sediment throughout Pallanza Bay. This may be altered by factors including inflow temperature, inflow velocity, lake temperature, and even the basin shape and width (Alavian et al., 1992). The purpose of this study is to investigate the seasonal variability of river inflow dynamics by and its effect on sediment transport, and in particular, spatial variability of sedimentation.

METHODS

Three moorings, each consisting of a thermistor chain, an Acoustic Doppler Current Profiler (ADCP), and two Acoustic Doppler Velocimeters (ADVs), were deployed in Pallanza Bay from October 2012 through mid-December 2012 to measure temperature and currents. Suspended sediment concentrations were approximated using backscatter intensity measured by the acoustic instruments. The ADVs backscatter measurements were calibrated for suspended sediment concentration in the laboratory using sediment samples from the site.

During the experiment, the lake experienced cooling, multiple large river inflow events and a significant wind event. Temperature and velocity data from the wind event and a large storm event are used to calibrate a hydrodynamic model of Lake Maggiore using the three-dimensional, unstructured-grid SUNTANS model (Fringer et al., 2006).

A river inflow event was modeled using SUNTANS for both fall and spring stratification. The fall stratification was derived from measurements made during the fieldwork discussed above and the spring stratification was taken from measurements made by Laborde et al., (2009) at a nearby alpine lake. The model grid encompassed the entire lake with finer resolution inside Pallanza Bay (50m) and coarser resolution outside of the bay (250m). The model was forced with a pulse river inflow that lasted for two days and corresponded to a flow rate of approximately 300 m^3/s (the largest flow rate during the October-December field work). The river enters from the upper left side of Figures 1b and 1c shown below. The simulations do not include wind forcing. The settling velocity was set to be 2×10^{-4} m/s, which corresponds to the approximate settling velocity of silts.

RESULTS AND DISCUSSION

The difference in the initial temperature structure for the two seasons is shown in Figure 1a below. In the spring, the water column is relatively well mixed, whereas in the fall, the water column is stratified from recent summer heating. The normalized depth-averaged SSCs throughout Pallanza Bay at the end of the weeklong simulation are shown for the spring and fall stratifications in Figures 1b and 1c, respectively. For both conditions, the SSC is highest along the southern end of the lake owing to deflection of the river plume to the right owing to Coriolis effects. During the fall, the depth of the intrusion is shallower than that in the spring case due to the stratification. This causes the sediment to travel father out of the bay and even into the main portion of the lake (Figure 1c). In contrast, for the spring case, the sediment is largely contained within the bay and settles before reaching the bay mouth.

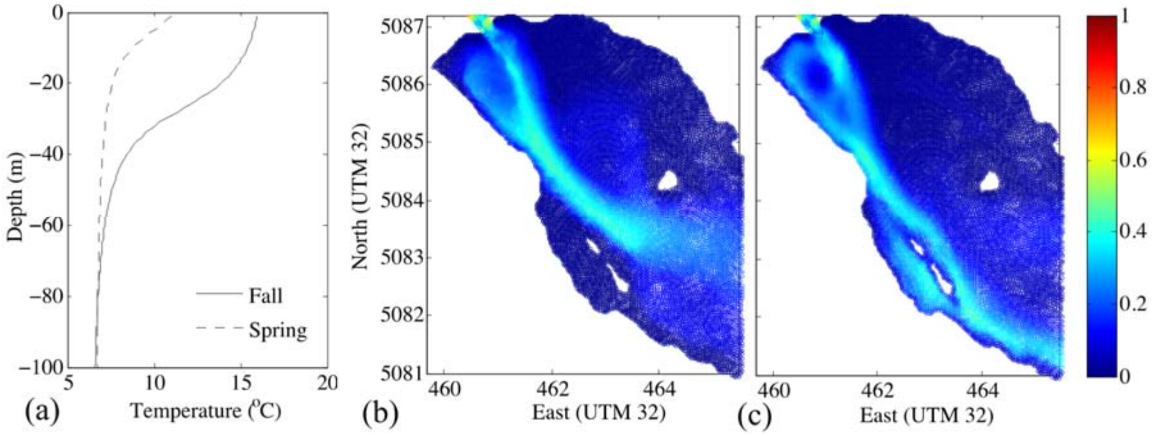

Figure 1. (a) Stratification for the spring and fall simulations and normalized depth-averaged sediment concentration after a one-week simulation with spring (b) and fall (c) stratification.

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Interactions of stream inflows with lake transport processes: Effects on nutrient limitation status of phytoplankton

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EXTENDED ABSTRACT

High–frequency sampling and a three–dimensional hydrodynamic–ecological model application were used to examine how dynamic variations in water, nutrient and sediment transport in a stream inflow influenced water quality in the receiving waters of a eutrophic lake during a five–day period of high rainfall in summer. Wind–driven horizontal circulations in the lake caused deflection of the inflowing stream, strongly influencing water quality in the littoral zone over distances > 1 km from the stream mouth. The nutrient limitation status of phytoplankton varied both temporally and spatially within the lake in relation to nutrient transport processes and, potentially, with changes in assemblage composition and environmental history. Nutrient limitation was the norm in surface waters in the central lake basin but was strongly alleviated in the littoral zone adjacent to the inflow. Comparison of concentrations of suspended sediments and dissolved nutrients measured in the transition zone with those estimated assuming only conservative mixing between the stream and the lake allowed for characterisation of spatial variations in the relative occurrence of active uptake (e.g., deposition) or accumulation (e.g., resuspension) processes in the water column. Dilution of lake water by the stream inflow strongly affected the spatial distribution of chlorophyll *a* although 'hot spots' within the nutrient–rich plume contributed to fine–scale (≈10–30 m) patchiness in the transition zone when phytoplankton at a pelagic site were nutrient limited. Our results point to the complexity of nutrient limitation in the pelagic zone of lakes. There is potential for large spatial and temporal variations in the nature (e.g., N vs P) and magnitude of nutrient limitation, driven by discharge and composition of stream inflows, as well as interactions of stream inflows with lake transport processes and physiological status of phytoplankton in the lake basin.

Identifying Morpho-Functional Groups for Lake Geneva – A key first step to model phytoplankton dynamic succession

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EXTENDED ABSTRACT

Predicting the stochastic pattern of the phytoplankton community remains a challenging task when modeling lake ecosystems due to their extremely diverse behavior. Grouping phytoplankton into functional groups not only has the advantage to better represent their ecological behavior and succession, but moreover reduces the number of assessing entities allowing a more representative overview of the entire community. This study represents a first dynamic modeling approach of functional groups of the phytoplankton community in deep, mesotrophic Lake Geneva using the General Lake Model (GLM) – Framework for Aquatic Biogeochemical Model (FABM). Lake Geneva plays an important environmental role as it is the largest lake in central Europe in the peri-Alpine region, representing an essential resource for drinking water supply. It is hypothesized that climate change will affect the phenology of the phytoplankton communities and promote an increase in biomass. Furthermore, the emergence of potentially toxic cyanobacteria is forecasted, with potential to contribute to considerable deterioration of water quality. Our aim was to produce an accurate predictive management tool for Lake Geneva and to assess the ecological state of the lake under present as well as under future climatic conditions, with focus on the phytoplankton community and its successional sequence. For this purpose, morpho-functional groups of phytoplankton specific for Lake Geneva were identified. Beforehand, a clustering method was applied, based upon species having similar occurrence patterns. The resulting groups were separated based on their functional ecological behavior but also on their morphology, as well as links to abiotic seasonal conditions. The groups were also compared to those derived for similar lake ecosystems. Physiological parameters were defined for each of the groups, with morphological traits (e.g., surface area to volume ratio) being an important consideration in the selected parameter values. The simulations demonstrated the close relationship of successional sequences of functional groups with mixing and stratification in Lake Geneva, which were strongly seasonally driven. Morpho-functional groups appear to be an appropriate level of state variable representation in this type of modeling approach to enable valuable insights into emerging environmental drivers such as climate change.

Spatial Heterogeneity of Plankton Communities in Aquatic Systems: The coupling of Physical and Biological Process at a Multiscale Level

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EXTENDED ABSTRACT

Patchiness of planktonic microorganisms may have important implications in microbial communities not only at small scale within habitats but also at large scales within lake basins and districts in landscapes, and within oceanic regions and biogeographical provinces. However, studies are generally limited to one specific planktonic entity (bacterio-, phyto-, or zooplankton) or one spatial scale and extent (across oceans or freshwater systems, or within systems), and there is still no functional perspective on multiscale patchiness patterns of microbial communities and their generative processes. This review presents some of the key aspects of plankton spatial heterogeneity including concepts, patterns, and processes in the context of a multiscale perspective. The ecological significance of spatial heterogeneity for planktonic microorganisms is presented with a functional perspective relating distribution patterns to environmental processes. The importance of abiotic and biotic forces and that of the biophysical coupling in structuring microbial community in aquatic systems at scales relevant to ecological states or processes of organisms, populations, and ecosystems is discussed. The importance of the application of new and advanced technology, as well as statistical approaches is presented and their spatial relevance discussed.

Dynamics and distribution patterns of dissolved methane in lakes: How accurate are the current estimations of methane emissions to the atmosphere?

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KEYWORDS

Littoral zone, methane release, methane emissions, spatial and temporal distribution, surface waves

EXTENDED ABSTRACT

Lakes and reservoirs have been identified as an important source of atmospheric methane in global methane budgets. Methane is a major product of the carbon metabolism in lakes. Anaerobic carbon mineralization in terms of methanogenesis in anaerobic sediments can account for up to 50% of the overall carbon mineralised in freshwater lakes. A large proportion of the produced methane gets oxidised by methanotrophic bacteria at oxic water and sediment interfaces. The main emission pathways of methane from the water body to the atmosphere are summarised by Bastviken et al. (2004): ebullition from anaerobic sediments, diffusive flux across the air-water interface, plant mediated flux from littoral sediments, and the flux of methane stored in the anoxic water body during the stratification period that is rapidly released during overturning and mixing. The proportion of the individual pathway to the overall lake emission is highly dependent on lake characteristics, e.g., lake size, stratification pattern, nutrient load, and plant cover.

In the past, most of the investigations were focused on profundal sediments as source of methane, internal cycling, and methane oxidation in the water column. Methane produced in epilimnetic sediments is considered as important source for ebullition and the plant mediated flux that cause direct fluxes to the atmosphere. On the other hand, diffusive fluxes from shallow littoral zones were considered to be less important than fluxes from the anoxic profundal sediments.

The main differences between littoral and profundal sediments are the warmer water and sediment temperatures in the littoral during summer that favour higher methane production rates, but also the exposure to surface waves (Hofmann et al. 2008). In the absence of waves the exchange of dissolved methane above the sediment-water interface is dominated by molecular diffusion that limits the flux of methane to the water column and that is accompanied by high methane oxidation rates at the sediment-water interface. Waves cause intense oscillating currents (Hofmann et al. 2008) that accelerate the flux of methane above the sediment-water interface by advective sediment pore-water exchange (wave pumping) (Precht and Huettel 2003) and by resuspension (Hofmann et al. 2011) that breaks up the upper sediment layer.

Simultaneous, high-resolution measurements of the surface wave field, wave-induced currents, the acoustic backscatter strength, and the concentration and distribution of dissolved methane were conducted in oligotrophic Lake Constance. In Lake Constance not only wind-generated, but also ship-generated surface waves contribute significantly to the surface wave field by generating a regular and periodic wave pattern (Hofmann et al. 2008). The measurements revealed that the passage of ship-generated wave groups cause single burst-like releases of methane into the water column that were directly connected to sediment resuspension (Hofmann et al. 2011). During these wave events, methane concentrations in the littoral zone were 50% higher than in the absence of waves. Hence, surface waves are an important trigger for the release of methane and increase the dissolved methane concentration in lake littoral zones, especially during the day when methane production in the sediments is high.

Experiments on the spatial distribution of dissolved methane revealed that near-shore as well as near-surface dissolved methane concentrations were higher compared to the open and deep water throughout the whole season (March-October) and especially during summer (Hofmann et al. 2010; Hofmann accepted). Hence, shallow (nearshore) zones are the predominant source of dissolved methane in lakes. Methane produced and released from the littoral sediments and thereafter transported horizontally to the open water leads to offshore-directed gradients of the dissolved methane concentration. But the dissolved methane concentrations also vary substantially in the littoral zone. These spatial gradients lead to heterogeneous distribution patterns in the open-water dissolved methane concentration and hence the diffusive flux to the atmosphere.

The comparison of diffusive fluxes from different offshore sampling stations reveals that single-point measurements are not necessarily sufficient to estimate lake-wide emissions to the atmosphere accurately. Spatially and temporally resolved lake-wide surveys that account for heterogeneous distribution patterns of methane in lakes are a time-intensive task. However, spatially resolved measurements of methane emissions that cover seasonality are needed at least for a selection of lakes with different trophic state and latitude to assess the uncertainty of emission estimates due to the spatial heterogeneity of the emissions. This would help to evaluate the reliability of the current estimates, and the incorporation of the additional data sets may improve the estimates of the contribution of methane from lakes to the global methane budget.

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Wind-driven sediment porewater mixing drives nitrogen cycling in a shallow coastal lake

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KEYWORDS

Coastal lake; dissolved inorganic nitrogen; sediment porewater; resuspension.

EXTENDED ABSTRACT

The dominant source of nitrogen loading to coastal lake systems in generally assumed to be direct input from point source discharges or diffuse catchment sources. Little consideration is given to loading from the sediment zones within these systems and the contribution from physical mixing of sediment porewaters due to wind-driven resuspension is relatively unknown. The field site chosen for this study was Lake Cootharaba, a large (surface area 38 km^2), shallow (mean depth 1.3 m) sub-tropical coastal lake located at the head of the Noosa River estuary in Queensland, Australia. Annual average wind speed is over 15 km h^{-1} making it a model system to investigate the likely importance of physical mixing in coastal lakes. The study period spans a 7 year period from 2001 to 2008, which was during the "Millenium Drought'. During this period catchment diffuse loading is likely to have been minimal and the only point source of nitrogen is from the small township of Boreen Point with a total population of under 300. Monthly monitoring of water column total and dissolved nitrogen concentration was undertaken at 3 sites forming a longitudinal transect across the lake over a 7 year period (2001 to 2008). In 2008 a series of field and laboratories studies were untaken to better characterise nitrogen cycling within the lake. Firstly, 8 sites were sampled for water column (surface and bottom depths) and sediment total and dissolved nutrients to determine the relative magnitude of nitrogen pools within the system. This was followed by a laboratory study in which sediment cores were used to simulated calm and windy conditions. Magnetic stirrers were used to simulate windy conditions where stirring speeds for simulated sediment resuspension was defined as the slowest speed required to move surface sediment particles. Detailed methodology for field sampling and laboratory incubations can be found in Green et al. (2012). To better understand the likelihood of wind driven sediment porewater mixing over the long term monitoring period it was assumed this would occur during sediment resuspension. Conditions favouring sediment resuspension were defined to occur when surface wavelength was greater than double the water depth and calculated following Chapra, (1997).

Monthly monitoring of from 3 sites within the lake revealed the system undergoes rapid changes in water column total nitrogen both at the monthly and annual scales (Fig. 2). Magnitude of the increase in total water column nitrogen pool can exceed 20 tonnes nitrogen

in a single month (November to December 2007, Fig. 1), requiring a significant source of nitrogen during this period.

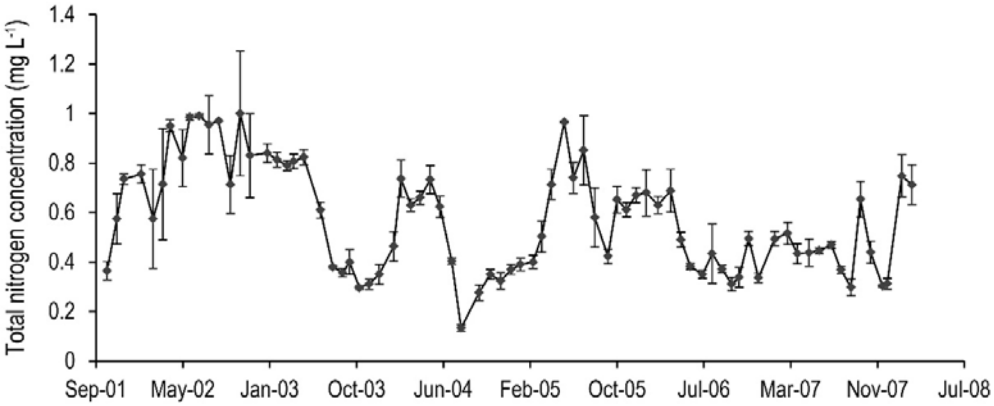

Figure 2. Monthly changes in water column total nitrogen concentration over a 7 year. Values indicate average ± standard error from 3 sites across Lake Cootharaba.

Field surveys estimated upper sediment layers contained a large pool of organic nitrogen (1200 ± 119 tonnes N) relative to the water column (22 ± 0.5 tonnes N) and sediment porewater dissolved inorganic nitrogen concentrations were at least 10 times higher relative to surface waters. Using wind speed data during the long term monitoring period, conditions favouring sediment resuspension and subsequent porewater mixing were likely to occur between 20–50% of the year. Laboratory flux studies demonstrated sediment resuspension increased DIN release from sediments by a factor of 16 compared with calm conditions (Fig. 2). Extrapolation of these elevated flux rates across the lake would account for 20 tonnes N monthly increase in approximately 10 days.

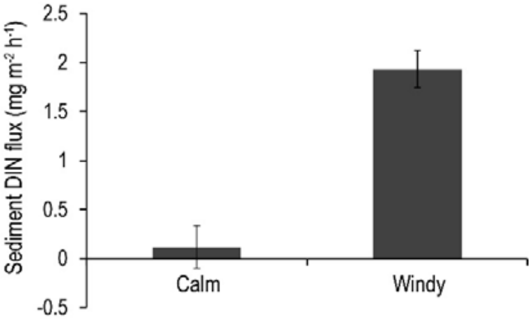

Figure 2. Dissolved inorganic nitrogen flux rate from sediment to water column during simulated resuspension experiment.

Together these findings suggest wind-driven mixing of sediment porewaters to be a major source of nitrogen loading to lake surface waters especially during low inflows. Conditions favouring sediment porewater mixing occur across the lake for significant periods during the annual cycle. Based on these findings the contribution of physical process that mix porewater should be considered in studies of nitrogen loading in similar shallow lake systems.

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Modelling spatial and temporal variation of bubble-plume induced oxygen demand in a eutrophic water supply reservoir

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KEYWORDS

Coupled model; hydrodynamic model; oxygenation; sediment oxygen demand; sediment-water interface; turbulence

EXTENDED ABSTRACT

Introduction

Hypolimnetic oxygenation systems (HOx) are commonly used in lakes and reservoirs to combat hypoxia in the hypolimnion while preserving thermal stratification. Increases in sediment oxygen demand (SOD) often observed during HOx operation have been shown to be positively correlated with the applied HOx gas flow rate (Gantzer *et al.*, 2009). While effective at adding oxygen to the hypolimnion, HOx also transfer energy to the surrounding water, generating currents and increasing near-field turbulence. Recent studies (Bryant *et al.*, 2010, 2011) have shown that the flux of oxygen into the sediment is diffusion-limited and controlled by the thickness of the diffusive boundary layer (DBL) at the sediment-water interface (SWI), which is in turn affected by near-sediment turbulence. As turbulence increases, the DBL thickness (δ_{DBL}) decreases, and SOD increases. Because of the inherent spatial and temporal variation in turbulence, SOD is therefore potentially subject to similar variability. Current HOx design methods cannot accurately predict the changes in SOD as a result of HOx operation, and there is a need for an improved understanding of how bubble plumes induce turbulence and how this in turn influences SOD. Once this relationship is quantified, it can be incorporated into a coupled bubble-plume and 3D hydrodynamic lake model. This model can be used to determine how current bubble plume installations affect turbulence, oxygen distribution, and SOD, and could also be used to optimize the design of future HOx systems.

Methods

Carvins Cove reservoir (CCR) is a eutrophic, water-supply reservoir located in southwestern Virginia, USA, and is the main drinking water source for the city of Roanoke. It has a linear bubble-plume diffuser which bubbles pure oxygen gas into the hypolimnion during the summer months to prevent hypoxia. During July and August 2011, a broad suite of equipment was installed in CCR to collect *in situ* measurements of temperature and DO profiles in the water column, current velocity in the bottom boundary layer, and DO microprofiles at the SWI. The DO microprofiles provide hourly measurements of SOD and are paired with corresponding measurements of turbulent energy dissipation (ε), calculated from current velocity measurements. Using these paired measurements, a new model for estimating SOD as a function of near-sediment turbulence is being developed.

Using this field data, a coupled 3D hydrodynamic reservoir and bubble-plume model has been applied to CCR. The hydrodynamic model currently uses a uniform zero-order value for SOD, based on a recently published model (Müller *et al.*, 2012) and calculated as a function of mean hypolimnion depth.

Results and Discussion

The HOx in CCR was turned off for two days during the first week of sampling in 2011, during which the DO at the SWI dropped to zero. After returning the HOx to normal operation, oxic conditions improved, although they did not return to the conditions established prior to HOx operation. The SOD and ε measurements are closely correlated, with SOD ranging from 0.4 – 6.6 mmol O_2 m^{-2} d^{-1}, and ε ranging from $8.3\times10^{-17} - 5.1\times10^{-14}$ W kg^{-1}.

Data collected during the 2011 campaign was used to apply the coupled model to CCR, including bathymetry data, surface forcing, HOx system location and operation, and initial conditions in the reservoir. Initial model runs using the zero-order SOD value based on mean hypolimnion depth (SOD = 0.6 g O_2 m^{-2} d^{-1}) show DO accumulation in the hypolimnion to be quite rapid, much more so than observed in the field measurements, meaning that the current SOD model underestimates the observed SOD.

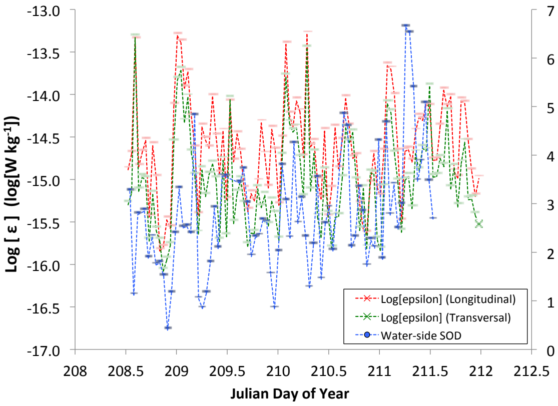

Figure 1. Timeseries of SOD and turbulence (ε) measurements from CCR 2011. Data points are at roughly 50 minute intervals

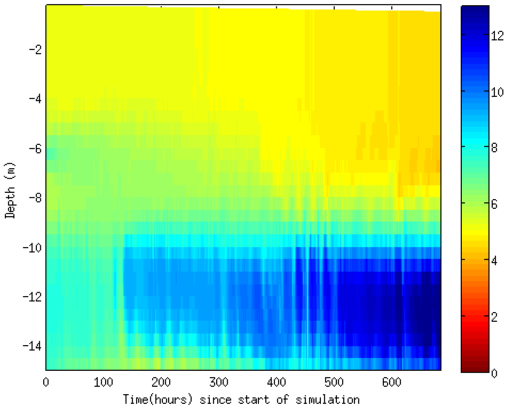

Figure 2. Coupled bubble-plume/3D hydrodynamic reservoir model simulation showing oxygen addition in the hypolimnion. Color scale shows DO in units of g m^{-3}.

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Variability in estimates of wind stress on the water surface of a small coastal lagoon

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KEYWORDS

Limnology; logarithmic boundary layer; wave height; coastal lagoon.

EXTENDED ABSTRACT

Introduction

Wind forcing is recognised as one of the key drivers for water movements in lakes, lagoons and reservoirs. Many numerical models simulate wind-induced hydrodynamics by approximating air-water boundary shear stress (wind stress τ_0) using empirical coefficients and wind speed data such that $\tau_0 = \rho_a C_D U_{10}^2$ [M L^{-1} T^{-2}] where ρ_a [M L^{-3}] is air density, C_D [-] (≈ 1.3 × 10^{-3}) is a drag coefficient in the presence of low wind speeds and small wind-waves and U_{10} [L T^{-1}] is measured wind speed at 10 m above the water surface. The dependence of C_D on both wind speed and surface water wave conditions is widely reported but rarely accounted for in numerical simulations. Wind stress can also be estimated assuming a logarithmic velocity profile such that $\bar{U}_B(z) = u_* / \kappa \ln(z/z_0)$ where $\bar{U}_B(z)$ is mean the wind velocity [L T^{-1}] at elevation z [L] above the air-water boundary, κ [-] (≈ 0.4) is the von Karman constant, z_0 [L] is the roughness height and u_* [L T^{-1}] is the friction velocity (e.g., Belcher and Hunt, 1998). Friction velocity is generally proportional to the surface water-wave height although much smaller and is often expressed as $\tau_0 = \rho_a u_*^2$ [M L^{-1} T^{-2}] (Monismith and MacIntyre, 2009). Potential variability between these types of estimates are explored using data collected from wind sensors located close to the water surface of a small coastal lake. Motivation for the research was to better understand the indicative range of uncertainty in measurement derived estimates of boundary shear stress when compared with estimates derived from empirical wind speed relationships. Such variability could be adopted in future modelling studies which seek to explore the propagation of this uncertainty through simulation results of surface mixed layer dynamics.

Methods

Measurements were collected on 17 December 2012 from three anemometers (Kestrel 4500 self-logging weather meter) located at fixed heights (0.3 m, 0.71 m and 1.31 m) above the mean water surface in Blue Lagoon, a small, shallow (mean depth ≈ 2.8 m, maximum depth ≈ 7 m), freshwater coastal lagoon located near the east coast of Moreton Island, Australia (27.092492°S, 153.440376°E). Concurrent measurements of high frequency (6 Hz) water surface fluctuations were collected (RBR 450XR CTD instrument). Measured wind speed data was used in combination with a logarithmic boundary layer assumption to estimate roughness height scale z_0 and wind shear stress τ_0. The logarithmic velocity profile equation was rewritten in the form of a linear equation, $\ln(z) = \bar{U}_B(z)(\kappa/u_*) + \ln(z_0)$, where the gradient m = κ/u_* was used to estimate the friction velocity u_* and y-axis intercept c = $\ln(z_0)$ was used to estimate the roughness height scale. Shear stress estimates derived from this data ($\tau_0 = \rho_a u_*^2$, where ρ_a ≈ 1.1673 kg m^{-3} based on average temperature and dewpoint of 27.5^{o}C and 22.5^{o}C respectively) were compared to estimates derived from the same field data and commonly used wind speed relationships ($\tau_0 = \rho_a C_D U_{10}^2$, where $C_D \approx$ 1.3 × 10^{-3}, U_{10} derived from the upper most wind sensor using the logarithmic wind profile law with literature derived roughness length scale of 0.0002 m water surface (Masters, 2004)). A comparison of measured wave height derived from water surface fluctuations and the estimated roughness height scale were also made.

Results and discussion

Measured wind speed ranged from 0.5–9.0 m s^{-1} while wave amplitudes in the order of 0.01–0.09 m derived from water surface fluctuations using a simple zero crossing approach (with correction for sensor depth – amplification factor +1.75) were observed. Data analysis results suggest that shear stress estimates based on commonly applied wind speed relationships are likely to underestimate shear stress when compared to estimates based on field data similar to that collected at the study site (**Figure 1(a)**). The results also indicate that the range of the roughness length scale, as derived from analysis of field data, are larger when compared to the measured wave amplitude (**Figure 1(b)**) than routinely expected, although further work is required to develop an improved relationship. These results are consistent with other studies that have noted an increase in shear stress τ_0 and roughness height z_0 when compared to measurements made in 'deep water' (e.g., Shabani et al., 2011).

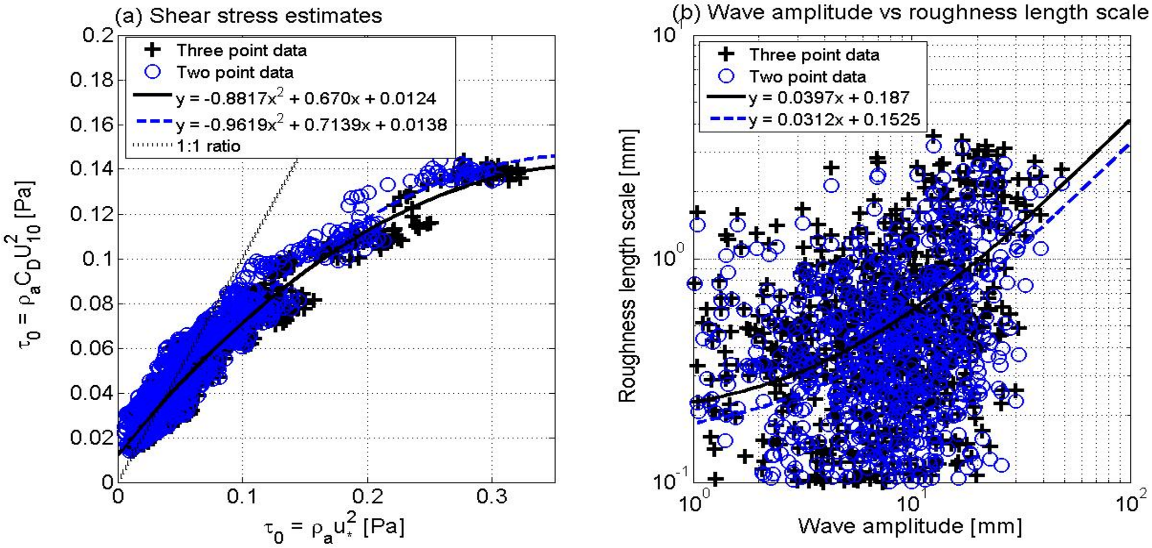

Figure 1. (a) Comparison of shear stress estimates derived from log law analysis of field data and empirical wind speed relationships; and (b) Comparison of measured wave amplitude and estimated roughness length scale. Estimates based on both a three point and a two point (upper and lower sensors) are presented for 10 minute moving average data.

These results have implications for numerical modelling investigations which seek to propagate uncertainty in shear stress estimates through a given set of simulations. More insightful results are likely to be gained by varying shear stress non-linearly with wind speed. Methods using constant drag coefficients ($C_D \approx 1.3 \times 10^{-3}$) are likely to underestimate shear stress in shallow lagoon systems, which in turn has implications for simulation of the surface mixed layer. The consideration of roughness length scales that span a range that is an order of magnitude larger than those commonly adopted from literature for water surfaces ($z_0 \approx$ 0.1-3.0 mm cf. 0.2-0.6 mm in literature) are also likely to be important in such investigations. The variation of results from those obtained from commonly applied methods suggest further work is required to better characterise wind stress in shallow lagoon and lake systems.

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Enhanced vertical mixing by salt fingers in the shelf waters off Kangaroo Island, South Australia

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EXTENDED ABSTRACT

Salt-fingering is a form of double-diffusive convection and plays an important role in the vertical mixing of different water masses in ocean regions where warm-salty waters overlie cool-fresh waters. Using CTD and turbulence microstructure data collected during a cruise in February 2012, we demonstrate the existence of salt-fingering in the shelf region of South Australia. Estimates of the size of salt fingers and associated nutrient flux are given and the implications for phytoplankton dynamics are presented. Salt fingering provides a newly discovered mechanism for vertical mixing of nutrients in the Kangaroo Island cold pool region and may play a significant role in supporting the enhanced primary production observed during the summertime upwelling period.

Hervey Bay - A Low-Inflow Intermittent Hypersaline and Inverse Coastal System

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EXTENDED ABSTRACT

Australia's climate is one of the driest in the world. Year-to-year rainfall variability is high and prolonged drought conditions are common. As a consequence, many estuaries and bays can be characterised as low inflow systems, often featuring hypersalinity and inverse circulations. Examples of these are the Spencer Gulf, Shark Bay, many tropical estuaries during the dry season, the hypersaline coastal waters of the Great Barrier Reef, and Hervey Bay on Queensland's south east coast. Hervey Bay's classification, as a low-inflow intermittent hypersaline and inverse system, is based on hydrographic surveys conducted from 2004 to 2008 and an analysis of the historical water balances. Hypersalinity is a climatological feature of this large bay and its estuary and is not limited to the dry season of the year. Yet, significant storm events such as the high rainfall and river runoff event during February 2013 erode the near shore hypersaline zone temporarily and in consequence, the bay and its estuaries exhibit the features of a classical estuarine system. Simple analytical salt balances and complex three-dimensional hydrodynamic modelling indicate that the physical system responds quickly in restoring prevailing pre-storm conditions and without further significant freshwater input, hypersalinity rapidly returns. Data from an October 2012 and a February 2013 hydrographic survey will be discussed and new insight into the physical oceanography of the bay presented.

Reconstruction of surface water temperature based on air temperature: a comparison among different lakes

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KEYWORDS
Water temperature; lake; air temperature; heat budget; climate change.

EXTENDED ABSTRACT

Introduction
The temperature of surface water is a crucial factor for lakes hydrodynamics and ecology, and its accurate estimation usually requires a significant amount of information that is not always available or reliable. In this work, we present the results of a simple lumped model that has been developed to estimate water temperature in the well-mixed surface layer (epilimnion) as a function of air temperature only.

Methods
The model *air2water* (described in detail in Piccolroaz *et al.*, 2013), which is based on the simplification of the complete heat budget of the well-mixed surface layer, is set up in terms of an ordinary differential equation comprising a few parameters (whose number varies from 4 to 8 depending on the different formulations). Being related to physically based assessable quantities, the range of variation of the parameters is limited, so they can be easily calibrated using two long-term series of air and water temperatures. Moreover, the model is able to provide a qualitative estimation of the depth of the epilimnion during the annual stratification cycle. Given the simplicity of the model, a Monte Carlo calibration can be performed using a large number of randomly chosen sets of parameters (10^8 realizations in the examined cases).

Results and discussion
Four lakes characterized by different morphological features and mixing regimes have been examined: Lake Superior and Lake Erie (USA-Canada), Lake Garda (Italy) and Lake Mara (Canada). For all of them, a satisfactory reproduction of both seasonal and inter-annual fluctuations of water temperature has been achieved (e.g., in terms of the Nash-Sutcliffe efficiency index) over decadal periods. Figure 1 shows an example of the validation of the model applied to Lake Superior, where we note that the difference between cold and warm seasons is correctly reproduced (e.g., between years 2009 and 2010).

In particular, the model is able to properly account for the thermal inertia of the water mass and thus to follow the hysteresis between air temperature and water temperature. In Figure 2 the annual average cycles of Lake Superior (left panel) and Lake Erie (right panel) are compared. The qualitative difference between the first lake, deep (average depth 147 m), and the second one, shallow (average depth 19 m), is clearly and well reproduced even in the simplest version (4 parameters) of the model, with only some minor deviations that are characteristic of buoy measurements (they are not present in the satellite-reconstructed temperatures).

The analysis of the results, and of the values of the model's parameters, allows for the characterization of the behaviour of each lake subjected to varying atmospheric conditions. In this way, the differences among the different lakes can be highlighted, appreciating for instance the different response of the lakes to variations of the air temperature. In this way, some suggestions can be drawn about the expected modifications to surface water temperature due to future changes in climate.

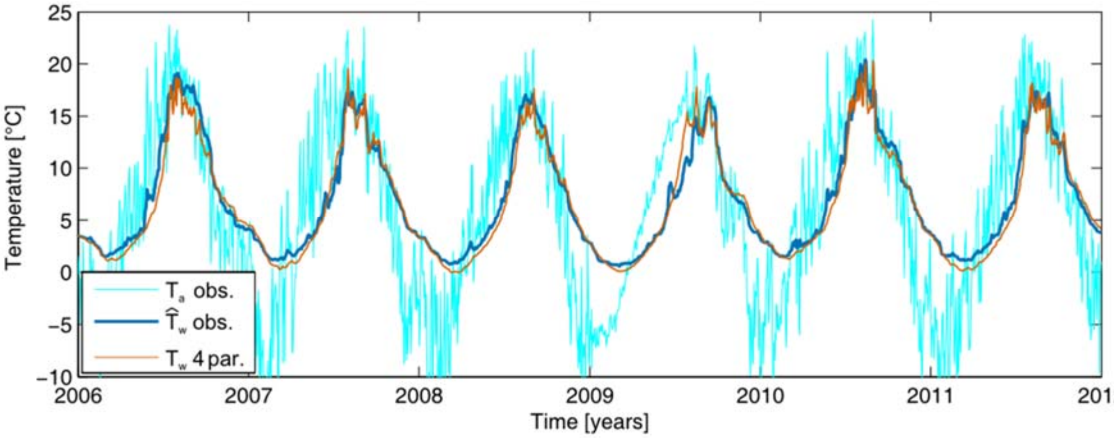

Figure 1. Validation of the model results (water temperature T_w, model with 4 parameters) against the observed surface water temperature ($T_{w\ obs.}$, satellite data) in Lake Superior; air temperature $T_{a\ obs.}$ is also indicated (modified from Piccolroaz *et al*., 2013).

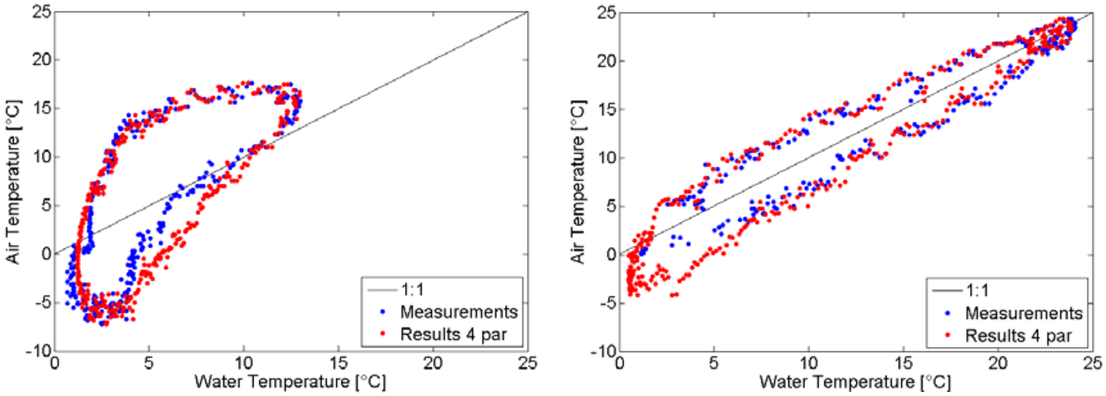

Figure 2. Average annual cycle of the temporal variation of air and water temperature: the model results (4 parameters) are compared with measurements collected at buoys. Note the wider hysteresis cycle in the deeper Lake Superior (left) with respect to the shallower Lake Erie (right).

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A novel method for detecting thermal stratification from surface water temperature measurements in temperate lacustrine systems

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KEYWORDS

Diel; Lake; Stratification; Temperature; Wavelet.

EXTENDED ABSTRACT

Introduction

Thermal stratification is a natural phenomenon that occurs in lakes and reservoirs during summer which results in a vertical partitioning of the water column and plays an important role in ecosystem functioning. The strength of stratification varies significantly among lakes, leading to the onset, duration, and breakdown of stratification varying on global and regional scales. Several modeling approaches have been used to predict the onset of thermal stratification in lakes, coastal seas, and reservoirs (e.g. Etemad-Shahidi *et al*., 2010). Such numerical process-based models, however, require detailed time series of meteorological data to drive them. As such detailed and comprehensive data sets are not always available, we introduce a methodology for detecting the onset of thermal stratification from surface water temperature measurements alone. In the following we present two methods for detecting the onset of thermal stratification (i) according to the observed diel surface temperature range, and (ii) from the diel wavelet power (i.e. variance) of surface water temperature measurements.

Methods

Water temperature profiles were analyzed for Windermere, United Kingdom. The onset of thermal stratification was defined according to top minus bottom temperature difference (Jones and Maberly, 2008) and then by (i) the power of the diel cycle as identified by the Continuous Wavelet Transform (CWT, Torrence and Compo, 1998); and (ii) the observed diel surface temperature range measured between 0600 and 1800. The thresholds for stratification were considered as when the power spectra exceeded 1 and the observed temperature range exceeded 1 °C. In order to avoid the detection of transient stratification events, we only defined a stratified period as when the criterion mentioned were maintained for at least a period of 48 hours. The theoretical surface temperature range was calculated based on the change in lake heat content, driven by volume of water in the surface mixed layer, and surface heating. The surface heat flux was calculated as the sum of surface fluxes following the methods described in Verburg and Antenucci (2010) which were corrected for atmospheric stability and measurement height.

Results and Discussion

The theoretical temperature range (Figure 1) was shown to correlate well with both the observed temperature range and the wavelet power. The onset of thermal stratification was accurately detected from both surface temperature methods although these methods were not able to accurately detect stratification throughout the summer.

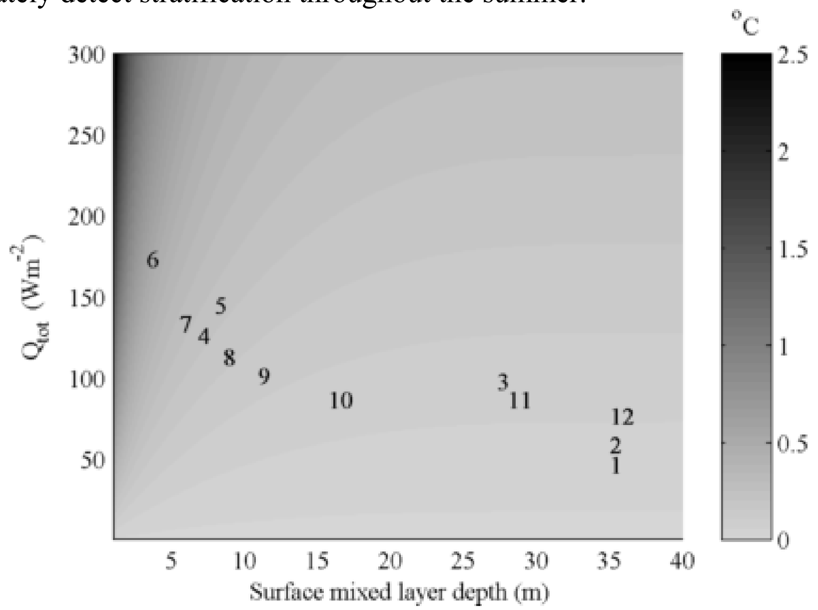

Figure 1. Contour plot of the theoretical ΔT in Windermere where the different numbers refer to the month of the year where the monthly averaged diurnal mixed layer depth and surface heat fluxes were calculated.

It was evident that during periods of large surface heating and small surface mixed layer depth, such as during the onset of thermal stratification, surface water temperatures had a defined 24 hour cycle. However, during periods of small surface heating and large surface mixed layer depth, the climatic signal was generally filtered through the water column thus no longer being significantly detected by the surface water temperature measurements. There surface temperature methods were successfully applied to 6 further lakes located in the United Kingdom, New Zealand, and the United States of America.

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Express analysis of sea radiance coefficient spectra obtained by remote sensing for coastal waters

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KEYWORDS

Light absorption and backscattering of sea waters, sea radiance coefficient, main natural sea-water admixtures concentration, spectrophotometry

EXTENDED ABSTRACT

Coastal ocean regions as well as inland and marginal seas generally differ from the open ocean in terms of their water admixtures concentration and often exhibit significant regional peculiarities because of their confined nature and strong interactions with the continent. To estimate the distribution of water admixtures in the coastal areas some express methods are required. We suggest using passive optical remote sensing from board a ship or a flying vehicle, which makes it possible to calculate the sea radiance coefficient spectra. After processing of such spectra we can retrieve the water content in the explored region.

Sea radiance coefficient depends on some optical properties of sea waters (absorption and backscattering), so it can be used to estimate concentrations of the main water admixtures influencing water transparency. We showed (Matushenko *et al*., 1996) that the optical spectra of the sea radiance coefficient can be operatively measured from board a moving ship or a flying vehicle with a three-channel spectrophotometer. The first channel is for the upward radiation from the sea surface (B_{sea}), the second one is for the solar radiation incident on the sea surface, which is measured as a white screen brightness (B_{ws} - downward radiation). In the third channel the radiance of the adjacent sky area (B_{sky}) is obtained. Using the last value one can exclude from the upward radiation the light reflected by the water surface. The sea radiance coefficient is calculated as follows:

$$\rho = \frac{B_{sea} - 0,02 \cdot B_{sky}}{B_{ws}}$$

Some examples of typical spectra of the sea radiance coefficient show the great variety of this characteristic depending on water content.

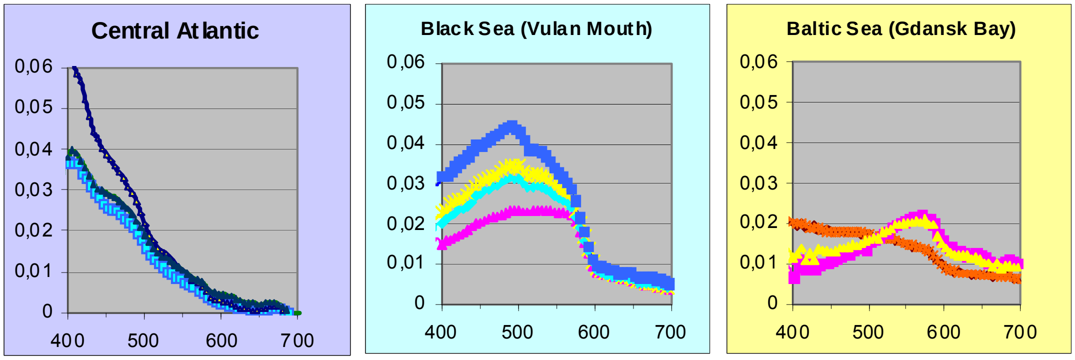

Figure 1. Various examples of the sea radiance coefficient spectra in the band 400-700 nm.

However, sea radiance coefficient spectra calculated from the remote sensing data are affected by the weather conditions such as cloudiness, wind velocity and sea roughness and need some calibration. It was shown that all the spectra of sea radiance coefficient have some common peculiarities despite the content of sea water admixtures. These peculiarities can be explained by the spectrum of pure sea water absorption. Taking this into account a new calibration method was developed. In the spectrum of pure sea water absorption in the visible some narrow spectral bands were selected, where water absorption changes far more rapidly than absorption in the neighboring bands as well as absorption and scattering of the main sea water admixtures. That causes some typical peculiarities in the appropriate places of the sea radiance spectrum, using which the spectra of sea radiance coefficient can be calibrated.

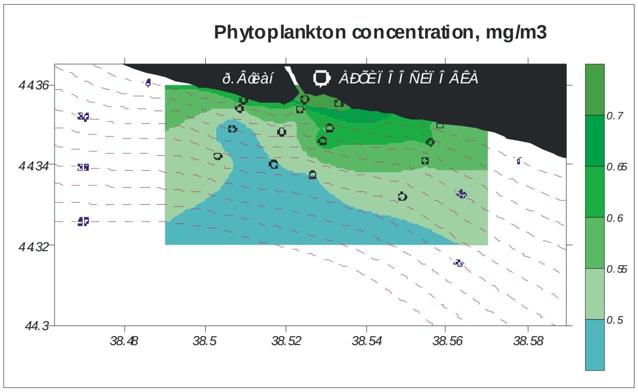

Figure 2. The distribution of the phytoplankton concentration at the Vulan mouth (the Black Sea)

The calculations were carried out for the spectra of sea radiance coefficient obtained at the north-east coast of the Black Sea with the portative spectrophotometer AVANTES from board a ship “Ashamba” (Rostovtseva et al., 2011). The suggested calibration enables to get the sea radiance coefficient spectra independent from the weather and measurement conditions.

After that it was possible to retrieve absorption spectra of sea water admixtures from the remote sensing data. As is known, there are three main natural admixtures in sea-water influencing the water absorption: phytoplankton with its chlorophyll pigment, dissolved organic matter and suspended matter. Using their specific spectra (Wozniak and Dera, 2007) we estimated the admixtures concentration. That allowed us to visualize the distribution of the sea-water natural admixtures in the area of interest. As an example, one of the high resolution maps giving the chlorophyll concentration in the study area is shown.

Thus, the suggested method of express analysis of water content in the coastal waters consists of three stages: firstly, passive remote sensing of the aquatorium from board a moving vehicle with a portative device, secondly, calculation and calibration of the sea radiance spectra using the original methodic and thirdly, estimation of the main natural admixtures concentrations and visualizing their distribution over the examined area.

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Temperature stratification and geothermal heat flux into deep caldera lakes Shikotsu, Kuttara, Tazawa and Towada

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EXTENDED ABSTRACT

Wind forcing has been recognised as one of the key drivers for water movements in lakes, lagoons and reservoirs. Many numerical models that simulate the hydrodynamics of these systems rely on simple equations that relate wind speed at a given height to wind stress at the water surface via the use of empirical coefficients. The potential variability associated with these types of estimates are explored using data collected from a vertical array of wind sensors located close to the water surface of a small coastal lake. Measurements were collected from three anemometers located at fixed heights (0.7 m, 1.0 m and 1.3 m) above the mean water surface in Blue Lagoon, a small, shallow (mean depth ≈ 2.8 m, maximum depth ≈ 7 m), freshwater coastal lagoon located near the east coast of Moreton Island, Australia. Concurrent measurements of high frequency (10 Hz) water surface fluctuations were also collected. Wind speed during the sampling period ranged from 0.5–9.0 m s^{-1} while wave amplitudes in the order of 0.01–0.09 m were observed. The measured wind speed and wave height data was used in combination with a common logarithmic boundary layer approach to estimate the shear velocity and wind shear stress. These values were also compared to wind shear stress estimates derived from commonly used wind speed relationships. Variations between approaches along with the implications of measurement error are discussed.

Observations of Turbidity Currents in Glacial Lake Ohau, South Island, New Zealand

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KEYWORDS

ADCPs; glacial lakes; paleolimnology; sedimentology; turbidity currents

EXTENDED ABSTRACT

Laminated sediment cores extracted from the distal end of Lake Ohau (70m water depth) likely represent seasonal variation in sediment input and are thought to represent a paleo-inflow record for the past 17,000 years. To place observations from these cores in context of the physical mixing within the lake, a detailed dataset was collected (Nov. 2011–Jan. 2013) using thermistor chains, acoustic Doppler current profilers (ADCPs), and turbidimeters moored at the proximal end of the lake (25m and 50m isobaths).

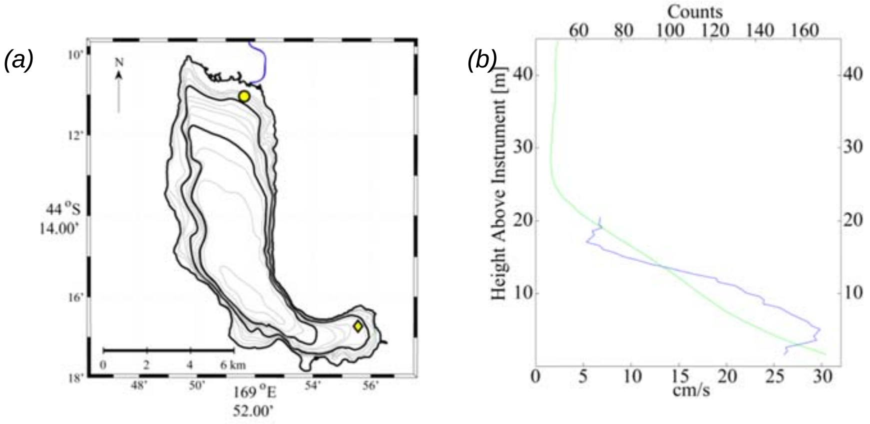

Figure 1. (a) Bathymetric map of Lake Ohau (gray lines are 10m contours and black lines are 50m contours); location of moorings (yellow circle), sediment core (yellow diamond), and main inflow (blue line) at the head of the lake (b) Vertical profile of velocity magnitude (blue line) and acoustic backscatter (green line) on January 1, 2013 at 2200 UTC at the 50m mooring. Note the ADCP could not profile velocity the full depth of water.

Inflows of increased magnitude (highlighted with grey boxes in Fig. 2) enter the lake on an episodic basis. During these inflow events, the bulk of the mass is transported along the bed of the lake as a turbidity current to at least the 50m isobaths at a distance 500m from the mouth of the inflow (Fig. 1a), as evidenced by vertical profiles of velocity and acoustic backscatter (Fig. 1b). During these events, near-bed current velocity of 15–55 cm/s are sustained for 1 hr. periods at both moorings (Fig. 2c), with an associated current direction due south (Fig. 2d); although there is some variation in direction. A strong downward component of velocity is observed at the 25m isobath, while the vertical velocity at the 50m isobath is close to zero and even slightly positive in some cases (Fig. 2e). These observations suggest inflows enter the lake primarily as turbidity currents. However, complexities are highlighted by conductivity-temperature-depth profiles acquired in June 2012 after a winter inflow event, and turbidimeter data, suggesting that sediment is transported to the distal end of the lake (~13 km from the mouth of the inflow).

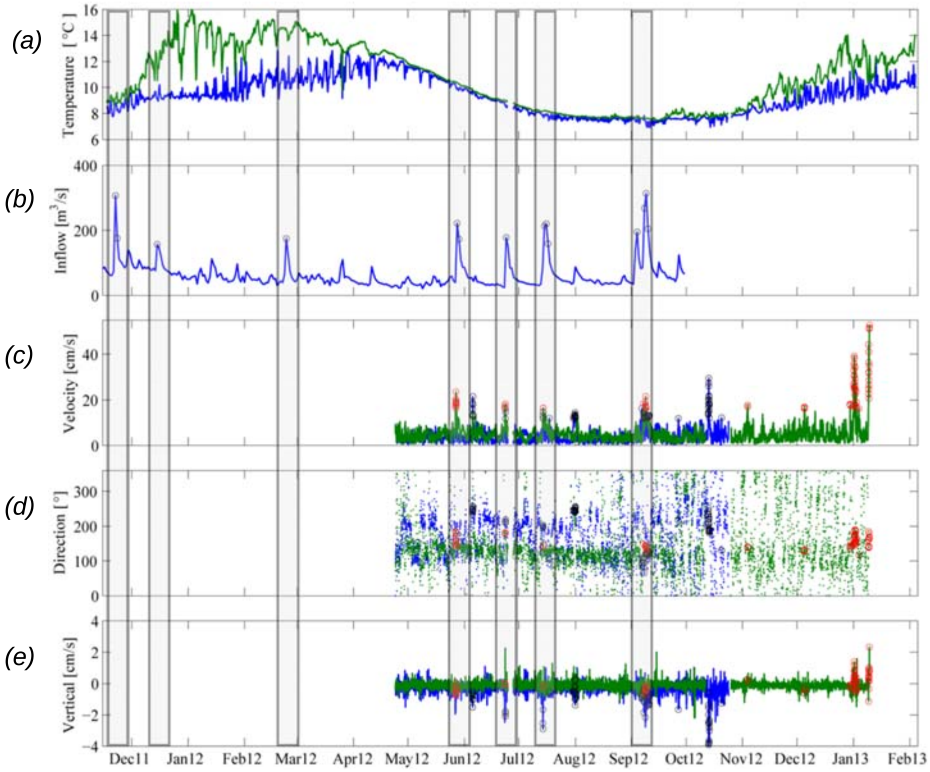

Figure 2. Time-series of (a) 6 hr. bin-averaged near surface (green) and near bed (blue) temperature at 50m mooring (b) Estimated daily inflow magnitude; black circles represent data 3 standard deviations from the mean (c) 1 hr. bin-averaged velocity magnitude (d) 1 hr. bin-averaged velocity direction and (e) 1 hr. bin-averaged vertical velocity. For (c-e) Blue lines are data from the 25m mooring at a location 4m above the instrument; Green lines are data from the 50m mooring at a location 5 m above the instrument; Black and red circles represent velocity magnitudes at 3 standard deviations from the mean at the 25m and 50m moorings, respectively.

The potential sediment transport mechanisms are still under investigation but two hypotheses are proposed: (1) turbidity currents detach below the 50 m isobath and sediment is transported by internal motions in the lake; or (2) there are multiple intrusions and a near surface intrusion transports sediment by either advection and/or convection processes. The initial mixing and propagation of the currents will play a role in how much sediment can be transported throughout the lake. These observations are important in order to develop statistical models that relate physical characteristics from the sediment core to inflow magnitude and regional climate.

Surface Mixed Layer in a Tropical Shallow Lake

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KEYWORDS

surface mixed layer, tropical shallow lakes, turbulent kinetic energy, vertical distribution of phytoplankton biomass

EXTENDED ABSTRACT

The surface mixed layer is an essential component of lake ecosystems, directly interacting with the external meteorological forcing, i.e., being actively mixed by the wind-induced turbulence as well as surface heat exchanges. From the biological point of view, the thickness of the surface mixed layer (SML) can determine the light intensity experienced by phytoplankton and hence primary production. A diurnal cycle of stratification and de-stratification has been observed in a tropical shallow lake, Kranji Reservoir with an average depth of about 6.7 meters (1˚25'N, 103˚43'E) in Singapore. We investigate the behaviour of the surface mixed layer as well as its impact on biological processes in the context of a thermal dynamics of a shallow, tropical lake.

Two common ways to describe the SML are the depth (a) at which the temperature first decreases to $T_{surface} - \Delta T$ and (b) at which the maximum density gradient occurs (Brainerd and Gregg, 1995; Rochford and Hurlburt, 2000). Here we calculate the depth of SML by the temperature difference $\Delta T = 0.02°C$ that is also chosen for Lake Victoria, East Africa (MacIntyre, Romero *et al.*,2002) and the maximum temperature gradient, using data collected from three 24-hr series of SCAMP microstructure profiling in July 2012.

Both definitions reflect the diurnal variation in the SML depth, with a thin SML of about 0.5m to 2m observed during the daytime stratification and a thicker SML observed during night time cooling (Figure 1). To further evaluate the value of these two different definitions, we use the turbulent kinetic energy (TKE) budget to simulate night time SML deepening (Fischer,1979). The evolution of SML identified by the maximum temperature gradient (represented by solid lines with dots in Figure 1.) matches the results of TKE budget model (denoted by red lines with open circles), giving a deepening of the SML to about 6 meters or deeper beneath the surface. The temperature difference method matches the TKE model during the first 24 hr SCAMP profiling but tends to give a thinner layer of about 4 meters for the latter two measurement periods. This observation indicates that a constant ΔT may not be suitable for defining the SML in Kranji Reservoir where the strength of stratification varies significantly as a function of time on daily scales. Thus, we conclude that the maximum temperature gradient may give a better estimation of the surface mixed layer depth.

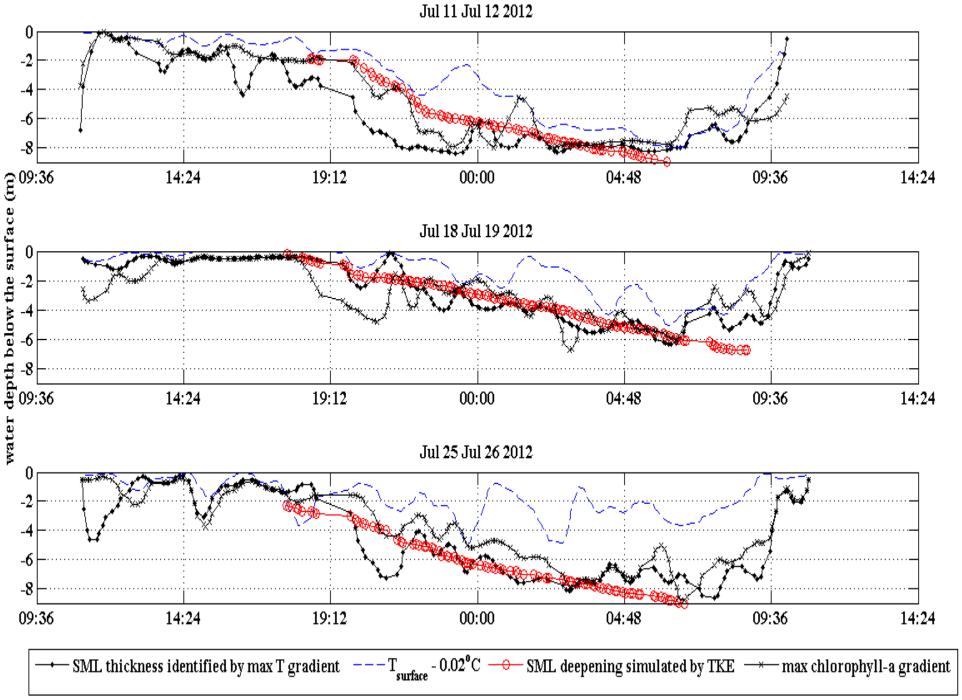

Figure 1. Surface mixed layer in Kranji reservoir: SML given by max temperature gradient (black solid line with dots) and by temperature difference (blue dash line); TKE simulated SML deepening (red line with circles) and max chlorophyll a gradient (black solid lines with crosses)

We next investigate the correlation between the SML behavior and the vertical distribution of phytoplankton biomass. Both the maximum temperature gradient depth and the TKE budget modelled depth track the max chlorophyll-a concentration gradient (black lines with crosses in Figure 1.) as well, suggesting the importance of convective cooling in shaping the vertical distribution of phytoplankton biomass.

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Autonomous Data Mining Of Vertical Profilers Readings To Predict Manganese Content In Water Reservoirs

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EXTENDED ABSTRACT

Continuously monitoring and managing Manganese (Mn) concentrations in drinking water supply reservoirs is paramount for water suppliers: high concentrations of Mn create a metallic odour and discoloration of potable water supplied to the customers. Traditional Mn management approaches typically involve manual sampling and laboratory testing of raw water from supply reservoirs on a regular basis, and then treatment decisions are made based on the soluble Mn level exceeding an allowable threshold level. Often Mn testing is conducted all year, but in the sub-tropical Gold Coast City region where Hinze Dam is located, high Mn concentrations only occur for a brief period during the dam destratification process which occurs in winter. High concentrations of Mn in water entering the water treatment plant are usually treated by chlorine or potassium permanganate.

Recently, the introduction of the vertical profiling systems (VPS) enabled a real-time data collection of many water parameters, such as water temperature, dissolved oxygen, pH, conductivity and redox potential. Despite the abundance of data collected by the VPS, they cannot directly measure a range of water quality parameters including Mn concentrations, thus manual sampling and testing is still the norm.

Given that prior studies have shown significant links between the parameters collected by VPS and Mn concentrations, there are opportunities to create prediction functions that can utilise VPS parameters as inputs to autonomously generate Mn values with a high degree of confidence. Successfully achieving the development of an autonomous and intelligent tool for the data mining of VPS parameter datasets to predict levels of Mn will significantly reduce laboratory costs while concurrently enhancing corrective action decision times.

Analysis of collected data verified a strong relationship between water column temperature and Mn concentrations in the epilimnion, where the water is drawn. As a consequence, a multiple linear regression model predicting the water column temperature one week ahead was integrated with a data-driven equation able to reliably predict the occurrence of the Mn peak event on an independent test set. The model can also display the results in form of probabilities, since it was found to be a better output for the dam operators.

Mangroves without Mosquitoes: An interdisciplinary approach – but, who's in the team?

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EXTENDED ABSTRACT

Saltwater mosquitoes breed profusely in mangrove basin forests across the tropics and sub-tropics. Mosquito control in these ecosystems relies on application of expensive larvicide chemicals, repeated whenever breeding occurs. Alternative, habitat based, control approaches exist – particularly in the USA – but involve substantially modifying the system hydrology, for example, by impounding the mangrove basin and controlling water levels through pumping and managing flow through culverts. This has an adverse effect on natural ecosystem values. In Australia, protection of coastal ecosystems has meant that there are no habitat-based alternative control strategies that can be applied in mangroves. Nor is there any regulatory framework to guide the use of such an approach. Our research is addressing these gaps by developing a mosquito control strategy that is modelled on the existing mangrove system structure and function combined with knowledge of the mosquito's use of the habitat. Our approach is focussed on minimal environmental impact, maintaining or improving existing ecosystem functions, values and services (e.g., water quality, mangrove health, fishery) while controlling mosquitoes.

In this talk we present an outline of our mosquito habitat modification research, including describing a pilot project where we have modified the hydrology of the mangrove basin. We also discuss the range of physical and biogeochemical issues that have arisen and that require further research. We also describe a model and framework we have developed that identifies the research and knowledge requirements across a wide range of disciples. This then requires a team also with a wide range of expertise. To work together effectively the team must be collaborative and the environment must be collegiate.

Environmental sustainability: water in watersheds

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KEYWORDS

Framework; indicator; life-cycle assessment; measure; orientor; system dynamics

EXTENDED ABSTRACT

Environmental sustainability exists within a broader context that includes social and economic sectors. All sectors or subsystems must ultimately be simultaneously addressed for sustainability to be achieved (Figure 1). We focus on the environmental subsystem, including direct effects of humans on ecosystems and indirect effects of humans on other humans via the environment. For the management of water in watersheds, this entails human activities impacting water quantity or quality that subsequently impacts ecosystems and humans.

Sustainability assessment is a rapidly growing field where one or more measures are used within an assessment framework to evaluate and compare alternative actions. Although the rigor of the assessment process depends upon a defensible quantification of sustainability, a broad suite of environmental sustainability measures and assessment frameworks is being used with little agreement or standards. The majority of existing measures for evaluating water-related environmental sustainability focus on water use at the national level or impacts on water from product manufacturing or transport. A few applications have focused on infrastructure such as wastewater treatment plants. Yet the watershed is one of the most fundamental units of analysis for water resources (Figure 2), and we argue that sustainability must be quantified at that level to be useful in decision-making processes that occur at similar scales, such as urban planning.

We review existing assessment frameworks (ecological footprint, environmental impact assessment, material flow analysis, process life-cycle assessment, input-output life cycle assessment, and system dynamics) before categorizing current watershed-relevant measures according to several dimensions including non-integrated measures (physical, chemical, and biological; midpoint versus endpoint; spatially explicit; temporally explicit; and absolute versus relative) and integrated measures that use a "common currency" (monetary valuation, energy, and risk). Unfortunately, spatial explicitness is rare and important watershed components are often overlooked. A complete assessment will likely require the use of both existing and new measures. A critical area for research is therefore integrating and further developing existing approaches into a unified and comprehensive framework that can be extended to include economic and social subsystems (Figure 1).

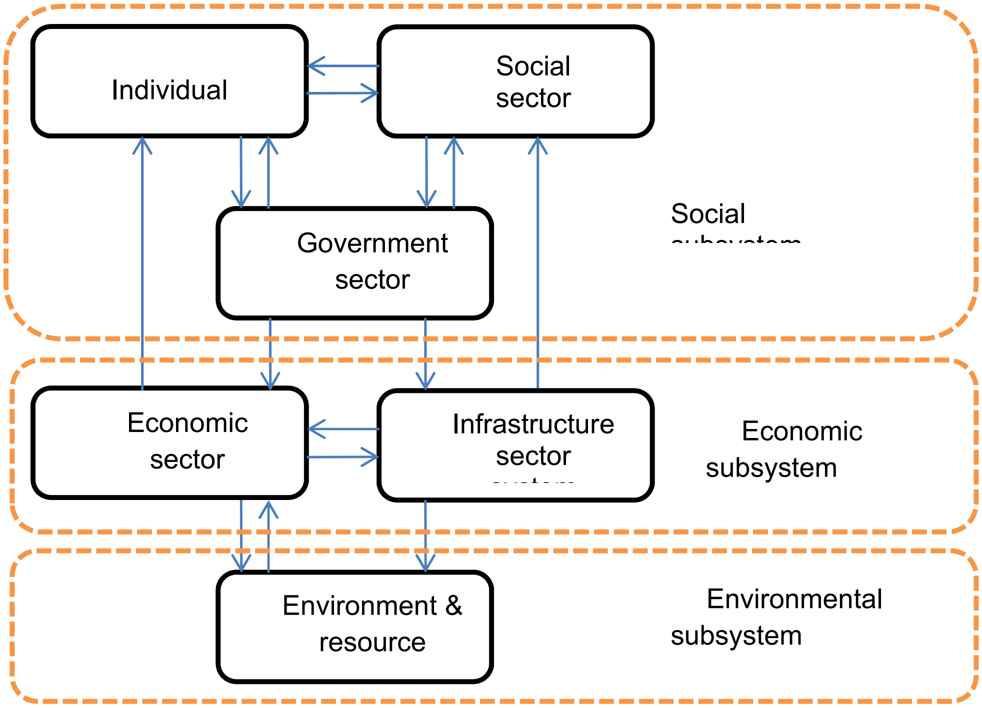

Figure 1. Six sectors of a societal system, and their major interrelationships, with aggregation into the three classic subsystems of sustainability.

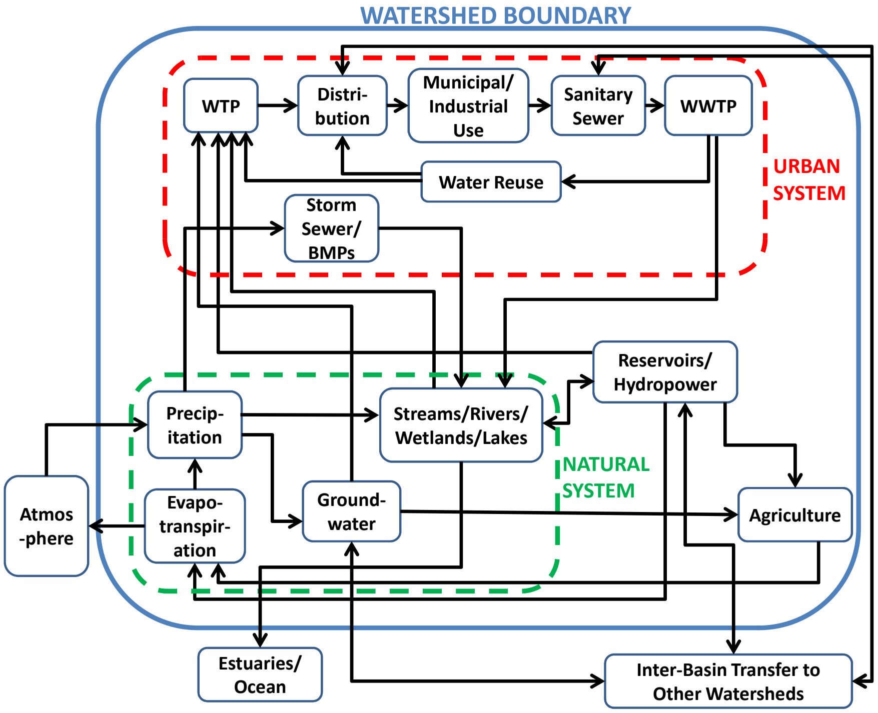

Figure 2. Example components of watershed hydrologic cycle for environmental sustainability assessment. Arrows are drawn for major processes only. WTP=water treatment plant; WWTP=wastewater treatment plant; BMPs=best management practices.

Modeling spread of invasive species by lake currents

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KEYWORDS

Larval transport, Lake Michigan, invasive species

EXTENDED ABSTRACT

Aquatic invasive species (AIS) are a key stressor impacting biodiversity and ecosystem function in the North American Great Lakes. One of the ways AIS spread in the Great Lakes is by lake currents (Beletsky et al., 2007) which can have significant velocities (especially in the epilimnion) both nearshore and offshore (Beletsky et al., 1999; Beletsky and Schwab, 2001). Dispersal of two AIS (ruffe and limnoperna) in Lake Michigan is studied with a 3D particle transport model. The model is developed by David Schwab (University of Michigan) and is described more fully in Michalak et al. (2013). Particles are assumed to be passive and neutrally buoyant. Advection fields for the particle transport model are obtained from the 1998-2007 currents modeled by Beletsky and Schwab (2008).

We are predicting larval transport from ballast release points located along the major shipping lane that runs the length of Lake Michigan (to determine safest ballast exchange locations), ports, and major tributaries. Release time and maximum drift duration is specie specific. Ruffe larvae released at surface daily during spring-summer (March-August) and tracked for 30 days while limnoperna larvae released daily during summer-fall (June-November) and tracked for 70 days. Settlement at coast is targeted initially and is currently being expanded to cover nearshore areas. For ballast releases, both species show a tendency to drift eastward (reflecting prevailing surface currents) and colonize more or less the same area on the east coast but due to seasonal and drift duration differences limnoperna is expected to survive/spread better because 62% of limnoperna particles reached shore versus only 20% for ruffe. For port releases, settlement rates (percentage of particles reaching shore in time allowed) are close (82-89%) but limnoperna spreads over much larger area. Ruffe spread is very localized near source ports while limniperna spreads much more around east coast (mostly due to drift from Chicago and Milwaukee).

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