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Wind-driven circulation patterns in a shallow estuarine lake: St Lucia, South Africa

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ABSTRACT

The spatiotemporal structure of wind-driven circulation patterns and associated water exchanges or residence times can drive important bio-hydrodynamic interactions in shallow lakes and estuaries. The St Lucia estuarine lake in South Africa is an example of such a system. It is a UNESCO World Heritage Site and RAMSAR wetland of international importance but no detailed research on its circulation patterns has previously been undertaken. In this study, a hydrodynamic model was used to investigate the structure of these circulations to provide insights into their role in transport and water exchange processes. A strong diurnal temporal pattern of wind speeds, together with directional switching between two dominant directions, drives intermittent water exchanges and mixing between the lake basins. "High speed flows in shallow nearshore areas with slower upwind counter-flows in deeper areas, linked by circulatory gyres, are key features of the circulation". These patterns are strongly influenced by the complex geometry of St Lucia and constrictions in the system. Water exchange time scales are non-homogeneous with some basin extremities having relatively long residence times. The influence of the circulation patterns on biological processes is discussed.

1. Introduction

Wind blowing over the surface of shallow lakes or estuaries can drive flows, surface waves and sediment resuspension. Elucidating the spatiotemporal structure of wind-driven circulation patterns, water exchanges and residence times is an important step towards understanding the bio-hydrodynamic interactions in these systems. Examples include the transport and/or mixing of nutrients and planktonic organisms, and the effects of turbidity and turbulence on biological productivity. Discussion of these issues may be found in Fischer et al. (1979); Bloesch (1995); Dyer (1997); McLusky and Elliot (2004); Scheffer (2004); Wolanski (2007).

Csanady (1973) considered the wind-driven circulation in an idealised long narrow lake with shallow margins and parallel depth contours. He showed that depth integrated flows are in the same direction as the surface wind where depths are shallower than the average depth of the lake, and opposed to the wind where the lake is deeper. This result in a characteristic double gyre circulation pattern referred to as topographical gyres due to their link with bathymetry. In shallower areas, the surface wind stress and bottom friction tend to dominate hydrostatic pressure gradients and therefore the transport is downwind. In deeper areas the axial hydrostatic pressure gradient can dominate the wind stress resulting in an upwind depth integrated transport. The formation of topographic gyres is linked to vorticity generated when the wind stress is perpendicular to gradients in bathymetry (Simons, 1980; Rueda and Vidal, 2009).

Double gyre circulation patterns have been observed in many homogenous lakes or estuaries and in the upper layer of stratified water bodies. The 3D structure of these flows such as the vertical variations associated with the above-mentioned counter-flows, are discussed by Simons (1980); Heaps (1984); Hunter and Hearn (1987). The latter used an idealised long basin approximation to show theoretically that the ratio of depth-averaged velocities to total velocities depends mainly on the bottom roughness and the depth distribution.

The St Lucia estuarine lake in South Africa (Fig. 1) is part of the iSimangaliso Wetland Park, a UNESCO World Heritage site and Ramsar wetland of international importance. It is renowned for its natural beauty and is an important regional source of biodiversity (Perissinotto et al., 2013b). The region has highly variable rainfall and runoff patterns and intermittent droughts occur on decadal time scales. Therefore, the lake is naturally subjected to extreme fluctuations in physicochemical conditions that include

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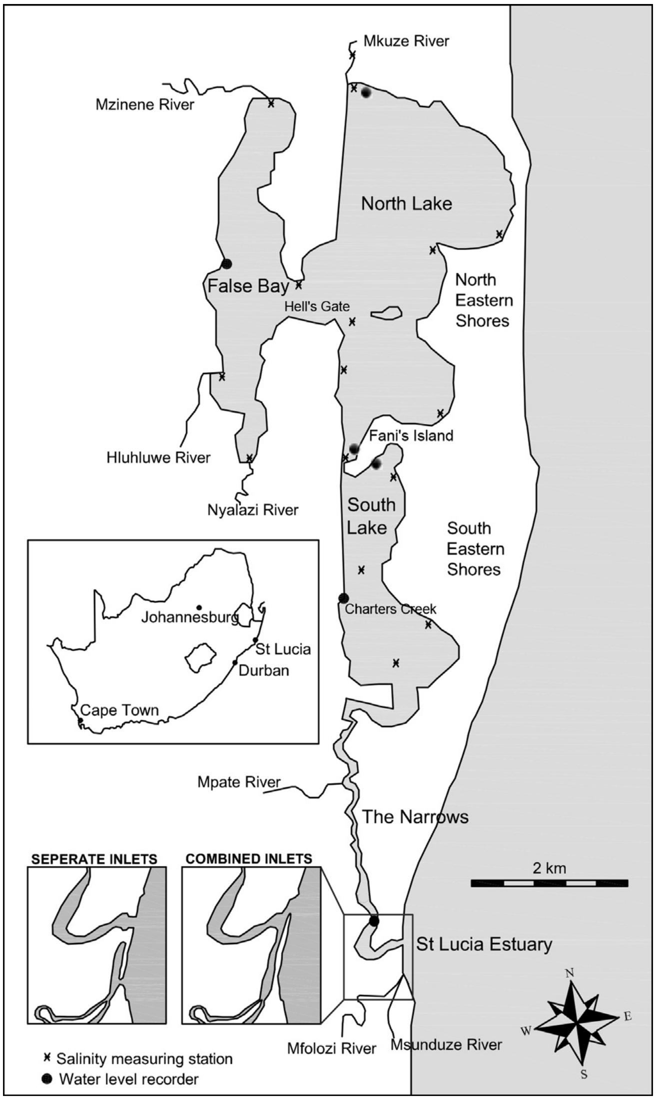

Fig. 1. Location map for St Lucia on the east coast of South Africa (adapted from Lawrie and Stretch, 2011a).

hypersalinity, high turbidity, and variable water levels. Anthropogenic impacts have exacerbated these characteristics and it is anticipated that future climate change will also significantly affect the system. Detailed reviews of these and related issues concerning Lake St Lucia are given by Taylor (2006), Whitfield and Taylor (2009), Lawrie and Stretch (2011a, b), Stretch et al. (2013); Whitfield et al. (2013). The sustainability of important natural resources like St Lucia and other similar systems worldwide requires understanding the forcing mechanisms that control the physico-chemical environment and underpin ecosystem functioning.

In this paper we explore the spatio-temporal structure of wind-driven flows at Lake St. Lucia, which is unusually shallow for its size and has a complex geometry with constrictive connections between its basins (Fig. 1). Strong prevailing winds in the region have been reported to produce a set-up of 0.5 m across the lake (e.g. Taylor, 2006). With an average depth of only 1 m this indicates that wind-driven circulation can transport significant volumes of the lake's water. Salt, nutrients, suspended sediments, and planktonic organisms are also transported by these exchanges, which suggest a key role in the biological functioning of the system.

Wind-driven set-up in Lake St Lucia was previously studied by Hutchison (1976); Hutchison and Pitman (1977); Hutchison and Midgely (1978) in the 1970's. They used a simplified 1D hydraulic model to investigate wind-driven set-up, particularly the development of an equilibrium state due to a constant wind. They showed that the constriction at Fani's Island initially limited the exchange flow between northern and southern basins. They did not estimate the volumes of water exchanged between lake basins nor the spatial structure of the circulation patterns associated with them.

In transient conditions, the flow accelerates as the wind increases until a balance is reached between the wind stress and the hydrostatic forces associated with the water level changes. This equilibrium will be associated with characteristic residual circulation patterns in the lake. However, at Lake St Lucia the winds vary with a diurnal cycle and it is unlikely that equilibrium conditions are attained (Hutchison, 1976). Therefore, the flow in the lake is typically accelerating or decelerating as the wind picks up, dies down and/or changes direction. This can result in more complex circulation patterns than those associated with a persistent constant wind.

This study used a numerical hydrodynamic model of Lake St Lucia to address two main objectives: (1) to characterise the spatial structure of wind-driven circulation patterns in a lake of complex morphology, and (2) to quantify the volume that is exchanged between the lake's basins in response to wind forcing. The overall aim is to use the hydrodynamic model to elucidate bio–physical interactions in the lake such as sediment resuspension and turbidity effects, and larval transport or nutrient exchanges between the lake basins. This is the first study to explore the detailed spatial structure of wind-driven circulation patterns in Lake St Lucia.

2. Methods

2.1. The case study site

Lake St Lucia (27°42′ – 28°24′ S, and 32°21′ – 32°34′ E) is a subtropical estuarine lake (Fig. 1) with average surface area of 328 km^2 and average water depth of 1 m (Stretch et al., 2013). The average depth and surface area vary with the lake water level in times of floods and droughts. Water levels are measured relative to estuary mean water level (EMWL), a local datum corresponding to the average water level in the lake when the mouth is open.

The lake comprises three main basins - North Lake, South Lake, and False Bay - that in turn have several morphological sub-basins (Fig. 1). False Bay and North Lake are connected by a shallow constriction at Hell's Gate, while North and South Lake are linked via a laterally constricted channel at Fani's Island.

A statistical summary of the wind characteristics at St Lucia is shown in Fig 2. Prevailing winds with speeds greater than 4 ms^{-1} are predominantly from the northeast and southwest. They are therefore nearly aligned with the long axis of the lake. The lake is 40 km long in its longest dimension and depending on their directions, winds can have a significant fetch over the lake.

There are strong diurnal variations in both wind speed and direction at St Lucia (Fig. 2). Day-time winds in the afternoons are on average stronger than morning or night-time winds with median values about twice as high. Wind directions for day-time winds are mainly from the north-east and night-time winds from the west (for wind speeds <4 ms^{-1}) or south-west (for higher wind speeds). The variability is also highest in the day-time winds.

The lake is connected to the sea via the Narrows, a meandering channel that is approximately 22 km long (Fig. 1). Tidal effects reach 14 km up the Narrows (Wright and Mason, 1993) but the lake itself is not tidal. Until 2002, the inlet from the sea was artificially kept open by management interventions. Therefore, the water level in

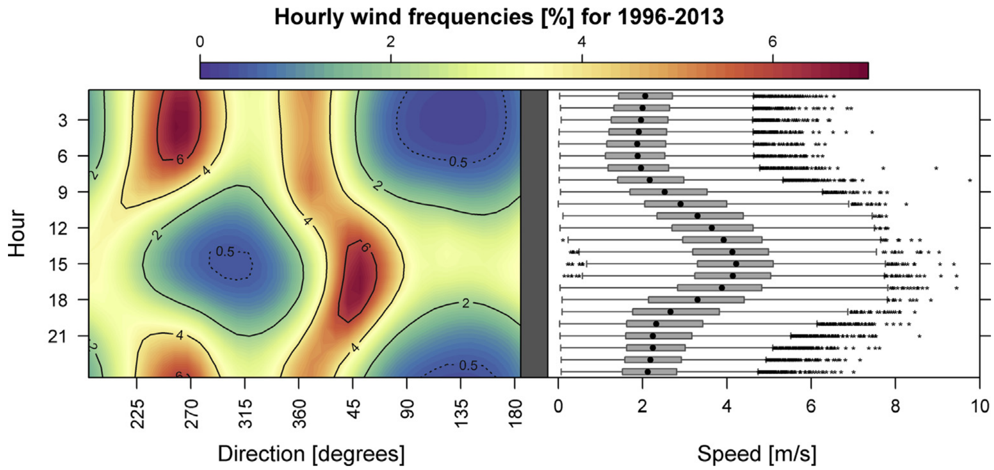

Fig. 2. Statistical characteristics of wind at St Lucia based on data from Charters Creek between 1996 and 2013. The left panel shows diurnal variations of hourly direction frequencies (%). In the right panel wind speed is shown as box-whisker plots with the black dot representing the median, the lower and upper end of the grey box representing the lower (1st) and upper (3rd) quartile, whiskers representing values within the 1.5 interquartile range (3rd − 1st quartile), and stars representing values outside the 1.5 interquartile range. R (R Core Team, 2013) with package metvurst (https://github.com/tim-salabim/metvurst) was used to visualise the wind statistics.

the lake remained near EMWL but had some variability associated with wind-driven setup and episodic flood events. In 2002, the mouth closed, and during the subsequent drought the lake water levels fell to unprecedented low levels. In 2012, a link between the St Lucia estuary and the Mfolozi inlet was partially restored. The restoration of this link together with the ending of the drought led to lake levels rising back to near EMWL. This study focuses on the hydrodynamics of the lake when it is at or near EMWL. Therefore, data from the period 2002–2012 were not considered in this study.

2.2. Lake bathymetry

The lake bathymetry used in this study was measured in 1973 (Hutchison, 1974). Some changes to the bathymetry of the basins are expected to have taken place during the last 40 years but have not been re-measured. However, ad hoc transects in South Lake during April 2013 showed reasonable agreement with the Hutchison bathymetry and provide some confidence in the available data. Furthermore, as will be shown later, the simulated water levels from 2013 agree reasonably well with measured water levels which suggest that the available bathymetric data is adequate for the purposes of the present study.

The distribution of the lake's storage volume between its main basins can influence mixing and exchange time scales in the system, especially when the links between them are constricted (refer §3.5). In this case, the False Bay and South Lake basins have similar volumes while North Lake contains 2 to 3 times as much volume as either of the smaller basins. These proportions vary with water level.

2.3. Wind and water level data

This study considered lake circulations for three different periods during 1973, 1999 and 2013. As noted previously, the volume of the lake basins depends on the water level in the lake. Relative to EMWL, the lake still water levels were approximately −0.25 m, +0.15 m and +0.25 m during the 1973, 1999 and 2013 periods respectively.

Wind and water level data reported by Hutchison (1974) were used for calibrating the model and comprised hourly wind measurements from Listers Point and water levels from six loca- tions across the lake for February and March of 1973 (Fig. 1). Wind data for 1999 and 2013 were obtained from the South African Weather Service (SAWS). Wind speed and direction were measured at five minute intervals by a weather station at Charter's Creek (co-ordinates −28.197763°N, 32.414137°E: refer Fig. 1). Water level data for 1999 and 2013 were obtained from the South African Department of Water Affairs (DWA) and comprised measured hourly water levels at Lister's Point in False Bay (only available for 1999) and Charter's Creek in South Lake.

2.4. Numerical hydrodynamic model

Wind-driven circulation in the lake was modelled using the MIKE hydrodynamic solver developed by the Danish Hydraulics Institute (DHI, 2011). Both vertically averaged (2DH) and 3-dimensional (3D) versions of the model were used but unless stated otherwise all of the results presented here are from 2DH simulations. The lake is very shallow and all the main results presented here showed no significant changes with the inclusion of 3D effects. This is consistent with the theoretical analysis of Hunter and Hearn (1987) who argued that for low bed roughness and variable depths, the depth averaged lateral circulation velocities are the dominant contribution to the total velocities.

The MIKE solver uses a finite volume method to solve the shallow water equations with second order accurate time integration. An unstructured horizontal mesh (Fig. 3) was generated using the Hutchison bathymetry. The mesh comprised 40,489 triangular elements and the maximum area of each element decreased exponentially with depth. The time-step for the numerical solutions is based on the Courant-Friedrichs-Lewy (CFL) number and the size of the smallest element in the grid. In this case CFL <= 1 and the smallest grid element was 1872 m^2. The average element size was 10,870 m^2. The influence of mesh size was explored by simulations with double these resolutions. The 3D simulations added 3 or 5 layers (sigma co-ordinate system) in the vertical. A standard $k - \varepsilon$ turbulence model was used for vertical turbulent transport processes.

The shallowness of Lake St Lucia means that the water column is generally well mixed vertically due to wind-generated waves (often with extensive white-capping) and boundary turbulence (Jones and Monismith, 2008; Perissinotto et al., 2013b). No significant vertical gradients in salinity or temperature have been observed. However, during extreme conditions, such as prolonged droughts,

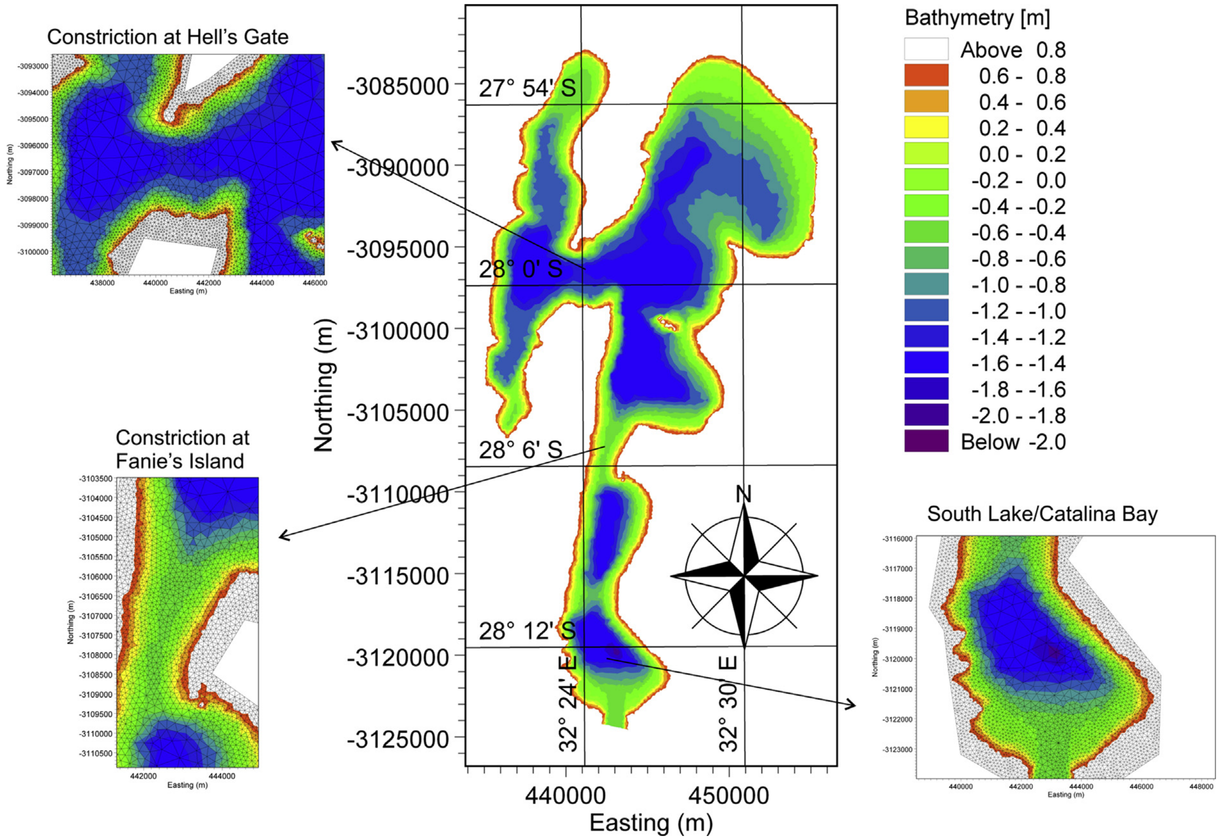

Fig. 3. Bathymetry and samples of the computational mesh geometry for the model set up.

spatial salinity gradients can develop between north and south lake basins (Lawrie and Stretch, 2011b; Stretch et al., 2013). All salinity and temperature variations were omitted from the simulations reported here which therefore limits their applicability to conditions where the effects of salinity/temperature non-homogeneities are small.

The simulations were forced by surface wind stress with an assumed constant friction coefficient C_f. Bottom friction was modelled using a constant Manning's number $M = 48\ \mathrm{m}^{1/3}\ \mathrm{s}^{-1}$ where the drag coefficient at depth h is given by $C_d = g/(M^2h^{1/3})$.

For the main simulations presented here neither horizontal eddy viscosity nor eddy diffusivity was explicitly specified in the model. However, sub-grid scale numerical diffusion has an effective diffusivity $K \sim \Delta s^2/\Delta t \sim u\ \Delta s$ where Δs is a characteristic length scale of the mesh and $u \sim \Delta s/\Delta t$ is a characteristic velocity (since CFL $\sim u\ \Delta t/\Delta s \sim 1$). Therefore, small scale horizontal mixing depends on the resolution of the simulations in this case. Some simulations were also done using a Smagorinski sub-grid mixing model. The different sub-grid scale model changed the small scale irreversible mixing, but there were no significant effects on the main results discussed in this paper.

The local Rossby radius is about 50 km so that Coriolis effects should be negligible at the 5–10 km horizontal scales of the St Lucia basins. This was confirmed using trial simulations with and without Coriolis effects.

All boundaries to the lake were specified as closed for the simulations reported herein. Inflows from the Mzinene, Hluhluwe and Nyalazi rivers into False Bay, and the Mkuze river in North Lake (refer Fig. 1) were therefore neglected. The connection of South Lake to a 22 km channel (the Narrows) linking the lake to the sea, was also assumed to be closed. The purpose of these initial simplifications was to focus on the role of wind-driven circulations only. Inflows from the rivers are generally very small during the dry (winter) season from April to August. The connection to the Narrows is constricted by a shallow sand bar and its role depends on the water levels in the system and the mouth state at the sea, and is also expected to be less significant during dry periods.

The volume exchanges between the north and south basins were calculated as the net amount of water that moved through the constriction at Fani's Island as a proportion of the volume of South Lake at still water level. The volume exchanges between North Lake and False Bay were similarly based on the amount of water flowing through the Hell's Gate constriction as a proportion of the False Bay volume at still water level (Fig. 1).

The dispersion and mixing of a passive tracer was simulated to investigate the time scales for the wind-driven volume exchange flows between North Lake, False Bay and South Lake (Fig. 1). An initial condition was specified with all the tracer in North Lake (with an arbitrary concentration of 1 kg m^{-3}) and no tracer in the other basins. Monitoring the re-distribution of this tracer during the simulations provides an indication of the time scales for the volume exchanges and the associated residence times in different parts of the lake. However, note that small scale irreversible mixing process is not resolved in the simulations presented here and should therefore be interpreted with caution.

3. Results

3.1. Calibration and validation

The model was calibrated using wind and water level data from a 3-week period in 1973 (Hutchison, 1974). During this process small adjustments were made to the surface and bottom friction coefficients in the model to match the measured water levels. Measurements from five locations across the lake are plotted in Fig. 4 together with the simulation results. There is good agreement and the results are comparable to those previously obtained by Hutchison (1976) with a simpler 1D model of the wind-driven setup process.

Fig. 4 shows that water levels in South Lake and North Lake can change by up to 0.5 m due to wind events, increasing downwind and decreasing upwind. Across the constriction at Fani's Island the water level changes are generally out of phase due to the constriction of the channel. Water initially builds up on the upwind end of the channel and is drawn down on the downwind end, which gives rise to a substantial hydraulic gradient across the constriction. Water level variations at Lister's Point in False Bay are notably smaller than those at the other locations.

After calibration the model was validated by comparing simulations with more recent water level data from 1999 and 2013. Results for Charter's Creek during April 2013 are plotted in Fig. 5 and show good agreement. Water levels for Lister's Point were not available in April 2013. A summary of quantitative model performance measures is given in Table 1 and indicates that the simulated water levels are generally within a few centimetres of measured values. The largest discrepancies between modelled and measured water levels occurred for sites south of Fani's Island (Charter's Creek and Fani's South) in the 1973 simulations (Fig. 4). The average lake water levels were relatively low (−0.25 m) during that period and the discrepancies probably reflect inaccuracies in

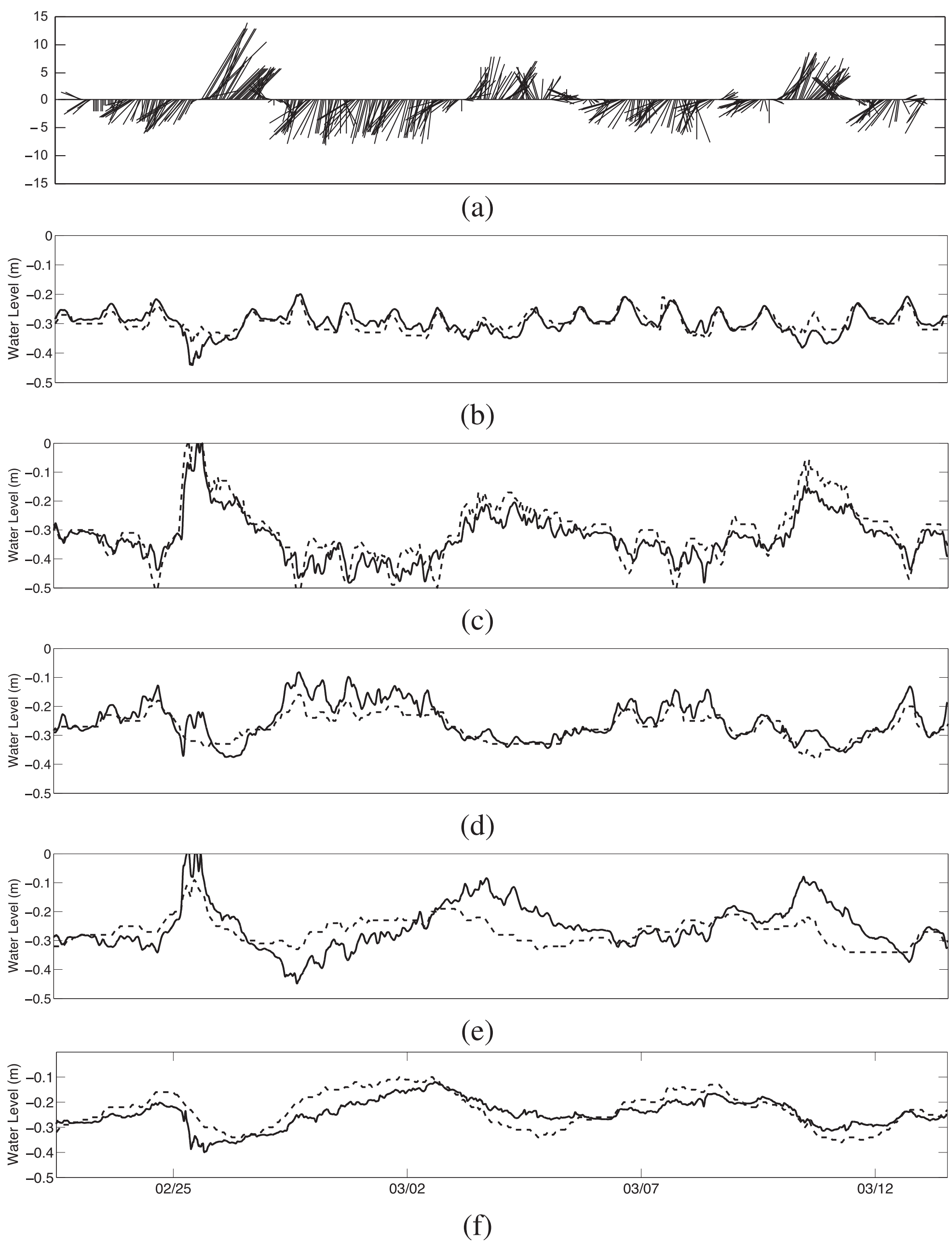

Fig. 4. Measured and modelled water levels at five locations from February 22nd to March 12th, 1973. Wind vectors are shown in (a) while measurements are from (b) Lister's Point (c) North Lake (Mkuze river) (d) Fani's North (e) Fani's South and (f) Charter's Creek. Modelled water levels are shown with solid lines and measured water levels with dashed lines.

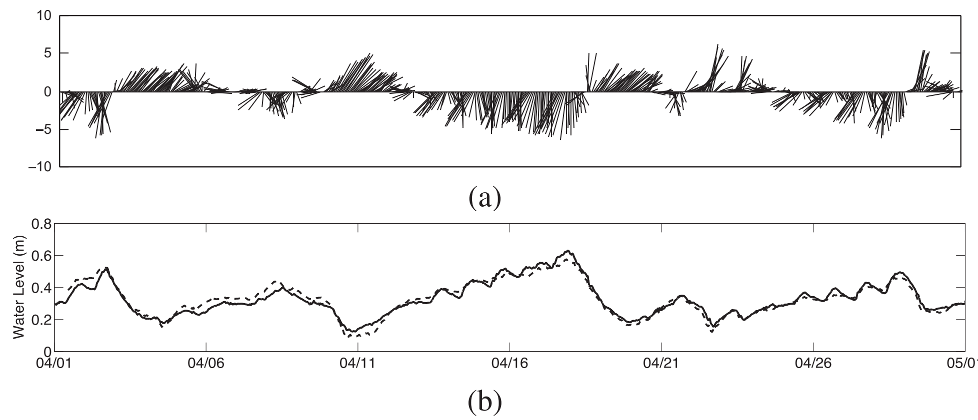

Fig. 5. Measured and modeled water levels for Charter's Creek in April 2013. Wind speeds and directions are shown in (a). Modeled water levels are shown in (b) with a solid line and measured values are shown with a dashed line.

the bathymetry for the Fani's Island channel that become more significant at lower water levels. Note that the simulations for the 2013 period (Fig. 5) show much better agreement when water levels are higher (+0.25 m in this case).

3.2. Steady state circulation patterns and water levels

Under steady wind forcing, the circulation patterns and water levels in Lake St Lucia take 24 h or longer to reach an approximate steady state. Longer times are required at lower water levels and higher wind speeds due mainly to the effect of the constrictions between the basins, particularly at Fani's Island (see §3.4). This time scale is generally longer than that for changes in wind speed and/or direction. For example, there is a strong diurnal cycle in the winds at this site (Fig. 2). This means that the circulation patterns are typically in a transient state and attainment of a steady state is rare. Nevertheless it is instructive to start by discussing results from hypothetical scenarios where the wind forcing is constant.

The steady state circulation patterns and water levels in the lake for constant north-easterly and south-westerly winds are shown in Fig. 6. In these conditions the water levels increase monotonically in the downwind direction across the entire lake. Along the shallow margins of the lake depth-averaged flow velocities are relatively high and in the same direction as the wind while in deeper areas of the lake basins there are typically slower counter-flows that oppose the wind direction. These features occur consistently throughout the lake and are linked to basin scale circulatory gyres that change direction with the wind. These are the “topographical” gyres deduced theoretically by Csanady (1973) and reported by others (e.g. Rueda and Vidal, 2009). The complex geometry of St Lucia with several irregularly shaped basins yields a rich structure with multiple gyres of various sizes and locations (Fig. 6). The main gyres scale on the size of the sub-basins in which they occur and therefore play an important role in the advective transport and mixing in those basins.

During the development of the steady state flows shown in Fig. 6, there are distinctive time-dependent features associated with the narrow constriction between North and South Lake at Fani's Island. Water levels initially increase/decrease on the windward/leeward side of the constriction in response to the wind forcing – examples are evident in water level records in Fig. 4 d, e. The resulting hydraulic gradient drives water downwind through the constriction with no counter-flow circulations occurring initially within the constricted channel. During this phase of the flow development the constriction seems to function as a hydraulic control on the exchange flow through the channel. Hutchison (1976) also reported these effects at Fani's Island and suggested that they make the lake behave as two nearly independent basins. If the wind persists long enough for the system to reach an equilibrium state with no net exchange flow, then a counter-flow occurs in the deeper sections of the channel (Fig. 7).

In areas away from the Fani's Island constriction the basic circulation patterns in the lake are set up in a relatively short time of about 6 h and then remain essentially unchanged. However, it can take several days for the water levels to equilibrate to the state shown in Fig. 6.

Table 1
Model performance indicators for calibration and validation simulations of water levels. There was no water level data available at Listers Point for 2013.

Dates	1973	1999	2013
Lister's Point			
RMS error (cm)	2.5	1.8	–
Error range (cm)	−11–5.1	−8.1–7.7	–
Mean abs. error (cm)	2.0	1.4	–
Agreement index[a]	0.86	0.84	–
Model efficiency[a]	0.34	0.51	–
Charter's Creek			
RMS error (cm)	4.6	2.9	2.9
Error range (cm)	−9.5–16	−7.8–7.8	−7.3–6.8
Mean abs. error (cm)	3.8	2.3	2.3
Agreement index[a]	0.86	0.94	0.98
Model efficiency[a]	0.60	0.81	0.93

[a] The Nash-Sutcliffe index of efficiency and Wilmott index of agreement (Nash and Sutcliffe, 1970; Wilmott, 1981).

3.3. Unsteady circulation patterns

For unsteady wind forcing the circulation patterns continually change with the wind speed and direction. It is evident from the wind vectors shown in Figs. 4 (a) and 5 (a) that the wind can blow persistently from either of the prevailing directions for several days at a time before switching direction but wind speeds tend to change diurnally. When wind blows persistently from the southern sector, the circulation patterns resemble those in Fig. 6 (a) but flow velocities scale with wind speed. Similarly winds from the northern sector drive patterns similar to those in Fig. 6 (b). The switches from one prevailing wind direction to another are associated with complex transitions in the flow field. The main circulatory gyres change direction, as do the shallow water jets, and considerable large scale differential advection and mixing can occur during the

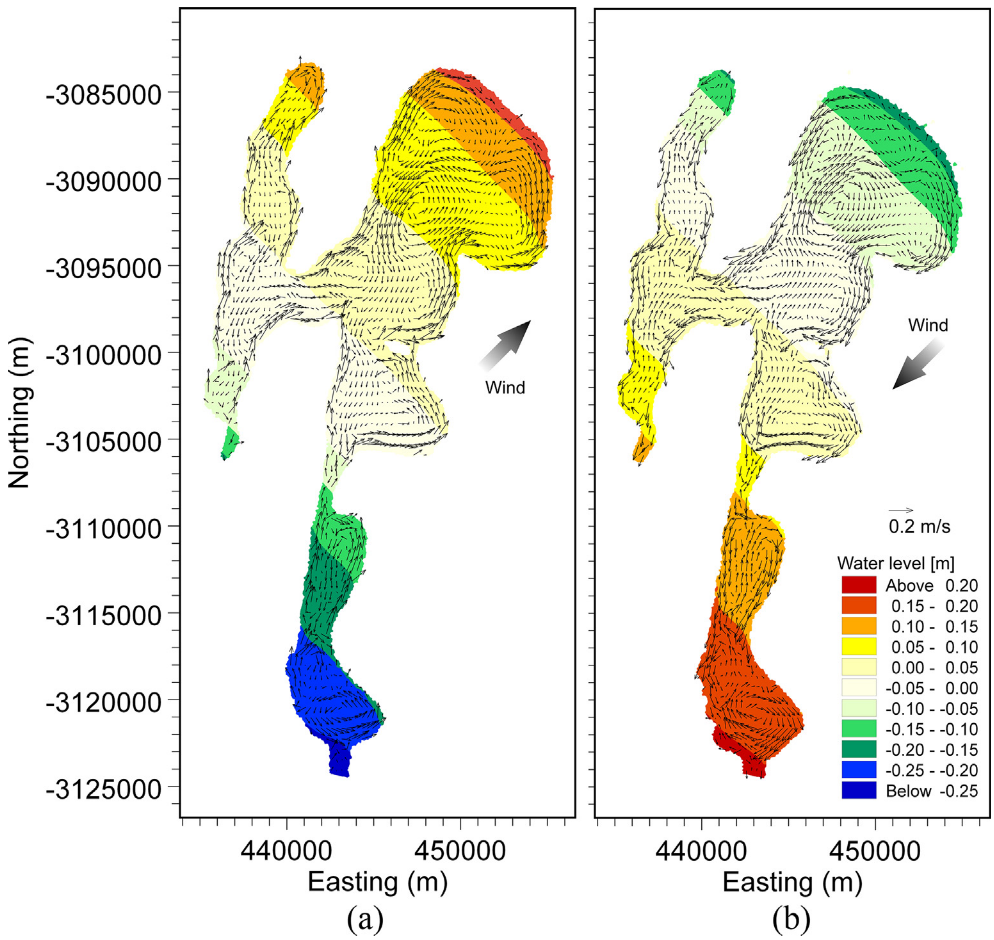

Fig. 6. Steady state circulations and water levels in Lake St. Lucia due to a (a) south-westerly wind (225°), and (b) north-easterly wind (45°). The plots show the situation after 168 h of constant wind with speed 4 m s^{-1} and with the still water level at EMWL.

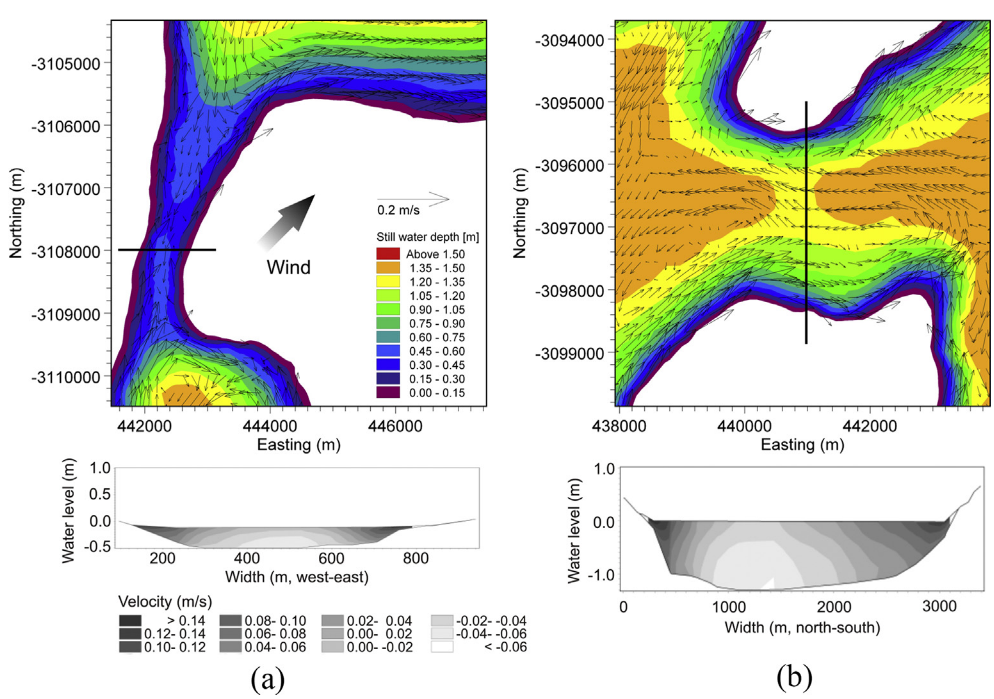

Fig. 7. Details of the flow within the two main constrictive inter-basin links at (a) Fani's island, and (b) Hells Gate during persistent south-westerly winds. The cross-sections (lower panels) show the vertical structure of the flows in the constrictions from 3D simulations.

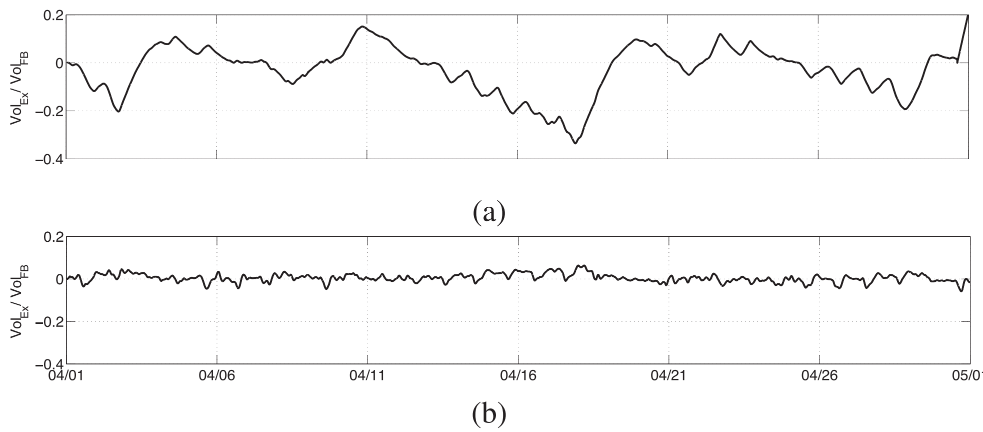

Fig. 8. Volume exchanges in April 2013 for (a) north – south through Fani's Island as a proportion of the volume of South Lake, and (b) east – west through Hells Gate as a proportion of the volume of False Bay. Wind data are shown in Fig. 5 (a).

transitions. Flow patterns within the main basins become re-established after about 6 h while the water level adjustments are slower and may not attain equilibrium conditions at all.[1]

3.4. Volume exchanges between the lake basins

Wind-driven water exchanges between the lake's main basins are fundamental to the overall mixing of the lake. A constant or accelerating north wind drives water southward and vice versa. A decelerating wind can be associated with net water transport in the opposite direction due to residual unbalanced hydrostatic forces.

Fig. 8 (a) shows the water volumes exchanged between North and South Lake due to varying wind forcing in April 2013. Water levels at Charter's Creek increase when the wind accelerates from the northeast and vice versa for wind from the southwest. Northward flow is positive in Fig. 8. During the interval April 11–17 in 2013 the volume of water in South Lake increased by nearly 50% due to wind-driven exchanges with North Lake. This event started when a south wind began to decelerate on April 11th and changed direction on April 12th. An event of this magnitude clearly has significant implications for mixing between the basins.

East – west volume exchanges between False Bay and North Lake at Hell's Gate are shown in Fig. 8 (b) and are generally much smaller than the exchanges between North and South Lake. This is attributable to misalignment with the prevailing wind directions, and because water tends to move in both directions at the same time due to the circulation patterns described in §3.2.

3.5. Tracer re-distribution

Circulation and mixing in and between the basins is further elucidated by results from passive tracer simulations for the periods January to July 2013. Samples of the results are shown as concentration maps in Fig. 9.[2]

The tracer movements between the basins reflect features of the flow fields discussed in §3.2. Initially the tracer penetrates False Bay and South Lake basins around the shallow margins where the wind-driven depth-averaged flow velocities are highest. Subsequently the tracer becomes mixed by the advection effects of the gyre circulations in the basins and smaller (sub-grid) scale mixing process. It is interesting to note that during the transient mixing events, significant concentration gradients can occur between the shallow nearshore areas and the deeper areas of the basins. This feature of the inter-basin exchanges may be relevant to biological processes.

Extended simulations (not shown here) indicate that it takes 3–4 months to fully distribute the tracer over the whole lake when water levels are at EMWL or above. This time increases as water levels decrease due to the constriction at Fani's Island. It is further evident in Fig. 9 that the extremities of False Bay and North Lake basins are the slowest to be exchanged and therefore have the longest residence times.

Time histories of the average tracer concentrations in False Bay and South Lake are plotted in Fig. 10 for a 3-month period during 2013 and for three different water levels. At relatively higher water levels the mixing between North Lake and South Lake is significantly stronger than that between North Lake and False Bay. This reflects the volume exchange results discussed in §3.4. However, the North-South exchanges are more severely affected by reductions in water levels. Therefore, at lower water levels, the volume of water exchanged between South Lake and North Lake becomes more comparable to that exchanged between North Lake and False Bay due to the more severe constriction at Fani's Island than at Hells Gate.

4. Discussion

The case study at St Lucia illustrates how wind-driven transport and mixing processes can manifest themselves in a large, shallow, multi-basin lake of complex geometry and provides a framework to develop new insights into bio-hydrodynamic interactions in this type of system.

The diurnal character of the wind forcing as well as the regular directional changes associated with two prevailing wind directions plays an important role in the wind-driven mixing of the system. They drive the main volume exchanges between basins and the associated differential advection, stretching and folding of fluid volumes that underpin the mixing process. Wind-driven chaotic advection processes are a generic feature of all shallow systems driven by variable wind speeds and directions (Kranenburg, 1992; Liang et al., 2006a, b, amongst others).

The basic features of the circulation patterns at St Lucia have been observed at many other systems worldwide (e.g. Simons, 1980; Rueda and Vidal, 2009). However the shallowness and

[1] An animation of the vector field is provided at https://drive.google.com/file/d/0BxyJNLgBZOGvODhWbmRuODFHRE0/edit?usp=sharing.

[2] An animation of the tracer field is provided at https://drive.google.com/file/d/0BxyJNLgBZOGvSkpySWxrNjhlbGc/edit?usp=sharing.

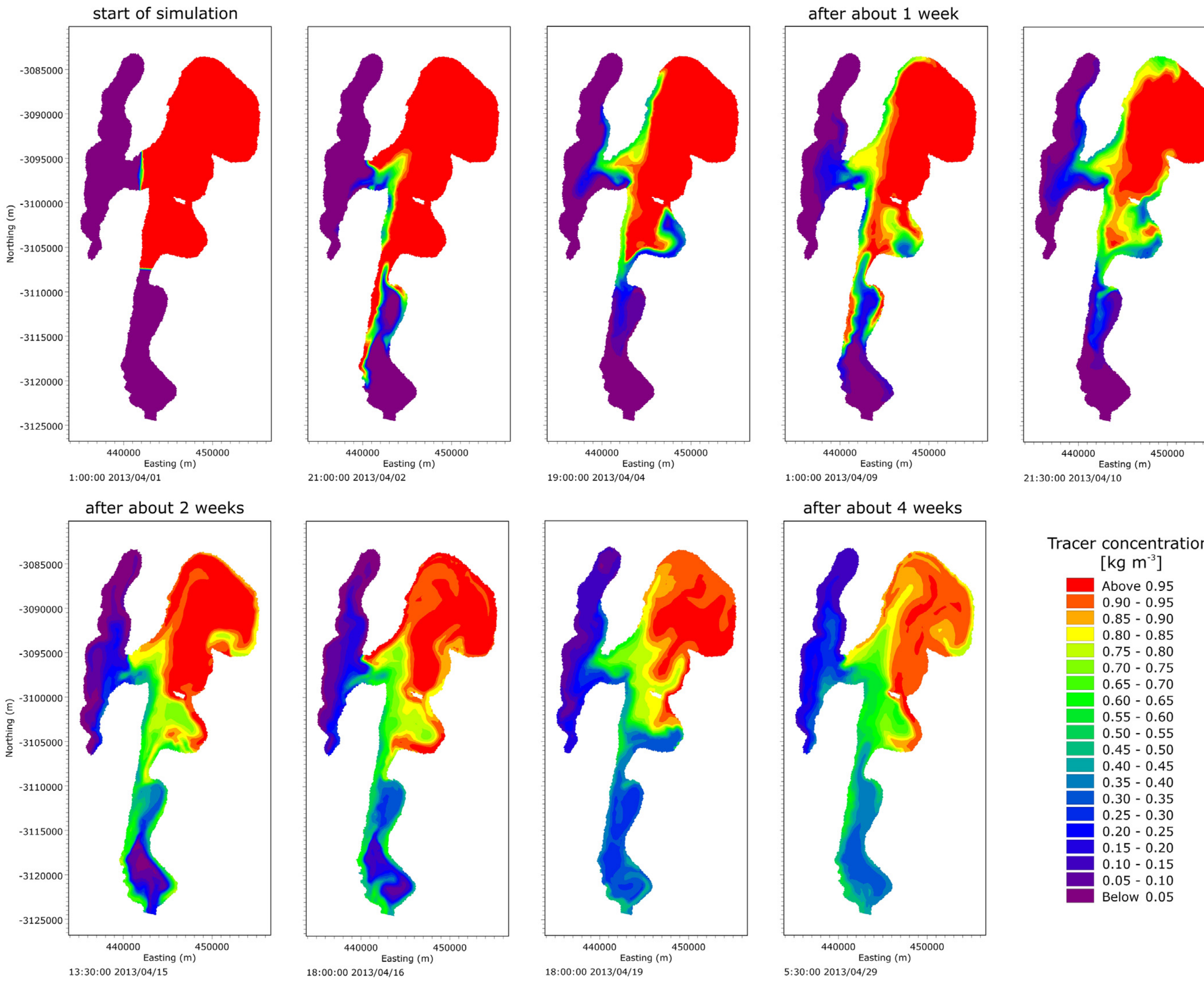

Fig. 9. A time series of tracer concentration images from 2DH simulations for April 2013 at water levels of +0.25mEMWL. The initial conditions (top left) had all tracer concentrated in North Lake. The mixing into False Bay and South Lake are depicted at subsequent irregularly spaced time intervals increasing left to right in each row of images.

complex morphology of St Lucia are unusual and influence the number, location and scale of circulatory gyres in the lake basins. Water exchange time scales are non-homogenous with the tracer simulations showing that the extremities of North Lake and False Bay take longer to mix. Additionally, wind-driven exchange flows along the shallower margins of the lake generally have relatively high velocities, while deeper areas in the middle of the basins have lower velocities and therefore relatively longer residence times.

The role of constrictions at St Lucia is also noteworthy since they can control the volumes exchanged between the main basins. Geyer (1997) has previously reported observations of how constrictions can alter the wind-driven flushing in estuaries by controlling and limiting the flows.

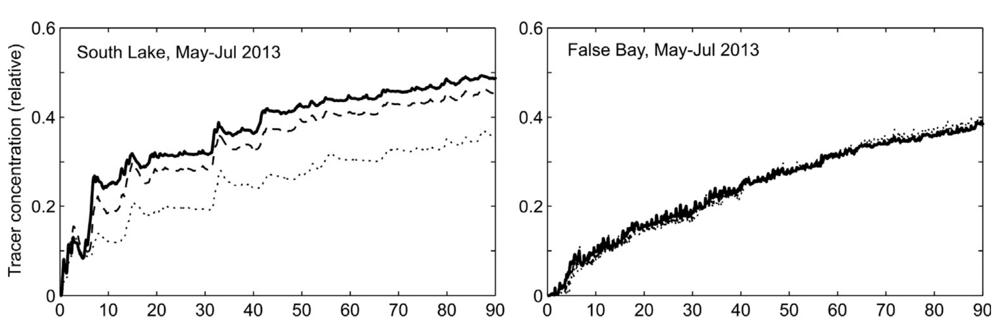

Fig. 10. Tracer distribution over time in South Lake (left panel) and False Bay (right panel) for the period May–Jul 2013 and for three water levels: −0.25mEMWL (dotted lines), 0.00mEMWL (dashed lines), +0.25mEMWL (solid lines).

Water circulation is responsible for moving dissolved and particulate materials such as nutrients, salt, plankton, and suspended sediment between the basins of Lake St. Lucia. Studying circulation can therefore help us understand the spatio-temporal structure of biophysical interactions in the system, including those associated with recovery from extreme conditions such as floods or droughts. The frequency and intensity of such extreme conditions are predicted to increase with future climate change (refer Mather et al., 2013, for a review of these issues). One such extreme event was a severe drought between 2002 and 2012 when the northern basins (False Bay, North Lake) experienced very low water levels, including desiccation and extreme hypersalinities, while becoming disconnected from South Lake. These conditions resulted in disappearance of nearly all macro-zoobenthos from northern areas and major shifts in trophic structure (Pillay and Perissinotto, 2008; MacKay et al., 2010; Cyrus et al., 2011; Chrystal and Scharler, 2013). Environmental conditions were less harsh in the southern parts of the lake system and these areas are thought to act as refugia from which re-colonisation can emanate when conditions improve (Taylor, 2006; Cyrus et al., 2011).

Dispersion of benthic invertebrates can take place during different phases of their life stage: as larvae, juveniles or adults. Lightweight planktonic larvae are most suitable for long distance transport (several km) by wind-driven currents (Lundquist et al., 2004). Our model shows that large amounts of water can be exchanged between South Lake and North Lake within a few days under certain conditions (strong wind, high water level). These exchanges are likely to strongly enhance distribution of bivalves and other organisms within Lake St Lucia. The time scale for recolonisation of the northern basins from refugia sites in South Lake depends on the diurnal changes in wind speed and/or direction and the resulting transient state of the circulation patterns, as well as on the settling behaviour of different organisms. The circulation model provides a basis for further detailed investigations of these processes.

Another potentially important effect of wind-driven flows is their role in the distribution of phytoplankton that can develop into algal blooms. Algal blooms have not been a threat to the system so far, but they might become a problem with increasing nutrient loads of the rivers in the catchment area and more frequent extreme climatic events. Two major blooms were recorded in the recent history of the lake, both occurring in False Bay and North Lake. A dinoflagellate bloom was observed over 3 months in winter 1969 (Grindley and Heydorn, 1970) and a cyanobacteria bloom in winter 2008 lasting over 3 years until 2011 (Muir and Perissinotto, 2011; Perissinotto et al., 2013a, b). Several causes of these blooms were discussed including effects of wind driven flow. Our simulations show that False Bay and North Lake, in particular their extremities, mix slowly and have the longest residence times suggesting that these regions are more prone to the development of algal blooms than the southern basins of Lake St. Lucia. Their relative isolation from South Lake at low water levels may also play an important role.

In summary, it is evident that the hydrodynamic model and further developments thereof have the potential to substantially improve our understanding of bio-hydrodynamic interactions at St Lucia and other similar systems.

5. Conclusions

Wind-driven circulation patterns and associated volume exchanges and residence times can play an important role in the bio-hydrodynamic interactions of large shallow estuarine lake systems such as St Lucia. In this paper we have used a hydrodynamic model to provide the first insights into the spatiotemporal structure of these flows at St Lucia and their effects on mixing in the lake. This can form a basis for exploring the bio-hydrodynamic functioning of the system in detail.

The strong diurnal temporal pattern of wind speeds together with directional switching between two dominant directions, drives significant intermittent water exchanges and mixing between the basins. Shallow water downwind jets along the shoreline and deeper water counter-flows interlinked by circulatory gyres are key features of the circulation patterns. The sense of rotation of the gyres switches with changes in the wind direction. The flow patterns are strongly influenced by the complex geometry of St Lucia. The scale and location of multiple topographical gyres are controlled by the geometry. Water exchange time scales are non-homogeneous with some basin extremities having relatively long residence times. The constrictive link between the main north and south basins of the lake plays an important role in modulating the water exchanges, both in terms of quantities and time scales.

There were several modelling simplifications used in this study and the implications should be explored in future work. Examples include the effects of (a) high river inflows into the lake, particularly during floods; (b) exchange flows between South Lake and the Narrows; (c) spatial variations in the wind field; (d) improved accuracy and resolution in the bathymetry; (e) wind-generated surface waves and variable bed forms and sediments; (f) spatial non-homogeneities in the salinity during extreme conditions.

Integrating an ecological model with the hydrodynamic model can provide detailed insights into how circulation and mixing impact spatio-temporal evolution of ecological communities in St Lucia and other similar systems.

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References

Bloesch, J., 1995. Mechanisms, measurement and importance of sediment resuspension in lakes. Mar. Freshw. Res. 46, 295–304.
Chrystal, R.A., Scharler, U.M., 2013. Network analysis indices reflect extreme hydrodynamic conditions in a shallow estuarine lake (Lake St Lucia), South Africa. Ecol. Indic. 38, 130–140.
Csanady, G.T., 1973. Wind-induced barotropic motions in long lakes. J. Phys. Oceanogr. 3, 429–438.
Cyrus, D.P., Jerling, H.L., MacKay, F., Vivier, L., 2011. Lake St Lucia, Africa's largest estuarine system in crisis: combined effects of mouth closure, low levels and hypersalinity. S. Afr. J. Sci. 107 (3/4), 59–71.
DHI, 2011. MIKE 21 & MIKE 3 Flow Models - hydrodynamic and Transport Module: Scientific Documentation. http://www.mikebydhi.com.
Dyer, K.R., 1997. Estuaries: a Physical Introduction, second ed. Wiley.
Fischer, H.B., List, E.J., Koh, R., Imberger, J., Brooks, N., 1979. Mixing in Inland and Coastal Waters. Academic Press, New York.
Geyer, W.R., 1997. Influence of wind on dynamics and Flushing of shallow estuaries. Estuar. Coast. Shelf Sci. 44, 713–722.
Grindley, J.R., Heydorn, A.E.F., 1970. Red water and associated phenomena in St. Lucia. S. Afr. J. Sci. 66, 210–213.
Heaps, N.S., 1984. Vertical structure of currenst in homogeneous and stratified waters. In: Hutter, K. (Ed.), Hydrodynamics of Lakes, CISM Courses and Lectures. Springer-Verlag, New York, pp. 153–207. No. 286.
Hunter, J.R., Hearn, C.J., 1987. Lateral and vertical variations in the wind-driven circulation in long, shallow lakes. J. Geophys. Res. 92 (C12), 13106–13114.
Hutchison, I.P.G., 1974. St Lucia Lake and Estuary - hydrographic Data. Report No. 3/74, Hydrological Research Unit. University of the Witwatersrand, Johannesburg, South Africa.

Hutchison, I.P.G., 1976. Lake St Lucia: Mathematical Modelling and Evaluation of Ameliorative Measures. Report No. 1/76, Hydrological Research Unit. University of Witwatersrand, Johannesburg, South Africa.
Hutchison, I.P.G., Pitman, W.V., 1977. Lake St Lucia: mathematical modelling and evaluation of ameliorative measures. Civ. Eng. S. Afr. 19 (4), 75–82.
Hutchison, I.P.G., Midgely, D.C., 1978. Modelling the water and salt balance in a shallow lake. Ecol. Model. 4, 211–235.
Jones, N.L., Monismith, S.C., 2008. The influence of whitecapping waves on the vertical structure of turbulence in a shallow estuarine embayment. J. Phys. Ocean. 38, 1563–1580.
Kranenburg, C., 1992. Wind-driven chaotic advection in a shallow model lake. J. Hydraul. Res. 30 (1), 29–46.
Lawrie, R.A., Stretch, D.D., 2011a. Anthropogenic impacts on the water and salinity budgets of St Lucia estuarine lake in South Africa. Estuar. Coast. Shelf Sci. 93, 58–67.
Lawrie, R.A., Stretch, D.D., 2011b. Occurrence and persistence of water level/salinity states and the ecological impacts for St Lucia estuarine lake, South Africa. Estuar. Coast. Shelf Sci. 95, 67–76.
Liang, Q., Borthwick, A.G.L., Taylor, P.H., 2006a. Wind-induced chaotic advection in shallow flow geometries. Part I: circular basins. J. Hydraul. Res. 44 (2), 170–179.
Liang, Q., Borthwick, A.G.L., Taylor, P.H., 2006b. Wind-induced chaotic advection in shallow flow geometries. Part II: non-circular basins. J. Hydraul. Res. 44 (2), 180–188.
Lundquist, C.J., Thrush, S.F., Oldman, J.W., Senior, A.K., 2004. Limited transport and recolonization potential in shallow tidal estuaries. Limnol. Oceanogr. 49, 386–395.
MacKay, F., Cyrus, D., Russell, K.-L., 2010. Macrobenthic invertebrate responses to prolonged drought in South Africa's largest estuarine lake complex. Estuar. Coast. Shelf Sci. 86, 553–567.
Mather, A.A., Stretch, D.D., Maro, A.Z., 2013. Climate change impacts. In: Perissinotto, R., Stretch, D.D., Taylor, R.H. (Eds.), Ecology and Conservation of Estuarine Ecosystems: Lake St. Lucia as a Global Model. Cambridge University Press.
McLusky, D.S., Elliot, M., 2004. The Estuarine Ecosystem. Ecology, Threats and management, third ed. Oxford University Press.
Muir, D.G., Perissinotto, R., 2011. Persistent phytoplankton bloom in Lake St. Lucia (iSimangaliso Wetland Park, South Africa) caused by a cyanobacterium closely associated with the genus *Cyanothece* (*Synechococcaceae*, *Chroococcales*). Appl. Environ. Microbiol. 77, 5888–5896.
Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I — a discussion of principles. J. Hydrol. 10 (3), 282–290.
Perissinotto, R., Bate, G.C., Muir, D.G., 2013a. Microalgae. In: Perissinotto, R., Stretch, D.D., Taylor, R.H. (Eds.), Ecology and Conservation of Estuarine Ecosystems: Lake St. Lucia as a Global Model. Cambridge University Press.
Perissinotto, R., Stretch, D.D, Taylor, R.H. (Eds.), 2013b. Ecology and Conservation of Estuarine Ecosystems: Lake St. Lucia as a Global Model. Cambridge University Press.
Pillay, D., Perissinotto, R., 2008. The benthic macrofauna of the St. Lucia Estuary during the 2005 drought year. Estuar. Coast. Shelf Sci. 77, 35–46.
R Core Team, 2013. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL: http://www.R-project.org/.
Rueda, F.J., Vidal, J., 2009. Currents in the upper mixed layer and in unstratified water bodies. In: Likens, G.E. (Ed.), Encyclopedia of Inland Waters: Hydrodynamics and Mixing in Lakes, Reservoirs, Wetlands and Rivers. Academic Press, pp. 568–582.
Scheffer, M., 2004. The Ecology of Shallow Lakes. Kluwer Academic., pp. 357.
Simons, T.J., 1980. Circulation models of lakes and inland seas. Can. Bull. Fish. Aquat. Sci., 146.
Stretch, D.D., Chrystal, C.P., Chrystal, R.A., Main, C.M., Pringle, J.J., 2013. Estuary & lake hydrodynamics. In: Perissinotto, R., Stretch, D.D., Taylor, R.H. (Eds.), Ecology and Conservation of Estuarine Ecosystems: Lake St. Lucia as a Global Model. Cambridge University Press.
Taylor, R.H., 2006. Ecological Responses to Changes in the Physical Environment of the St Lucia Estuary. Unpublished PhD Thesis 2006. Norwegian University of Life Sciences, Department of Plant and Environmental Sciences, Aas, Norway, pp. 172.
Whitfield, A.K., Taylor, R.H., 2009. Case studies and reviews: a review of the importance of freshwater inflow to the future conservation of Lake St Lucia. Aquat. Conserv.: Mar. Freshw. Ecosyst. 19 (7), 838–848.
Whitfield, A.K., Bate, G.C., Forbes, T., Taylor, R.H., 2013. Relinkage of the Mfolozi River to the St. Lucia estuarine system — urgent imperative for the long-term management of a ramsar and world heritage site. Aquat. Ecosyst. Health Manag. 16 (1), 104–110.
Willmott, C.J., 1981. On the validation of models. Phys. Geogr. 2, 184–194.
Wolanski, E., 2007. Estuarine Ecohydrology. Elsevier.
Wright, C.I., Mason, T.R., 1993. Management and sediment dynamics of the St Lucia estuary mouth, Zululand, South Africa. Environ. Geol. 22, 227–241.