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ARTICLE

Idealized Large-Eddy Simulations of Sea and Lake Breezes: Sensitivity to Lake Diameter, Heat Flux and Stability

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Abstract Idealized large-eddy simulations of lake and sea breezes are conducted to determine the sensitivity of these thermally-driven circulations to variations in the land-surface sensible heat flux and initial atmospheric stability. The lake-breeze and sea-breeze metrics of horizontal wind speed, horizontal extent, and depth are assessed. Modelled asymmetries about the coastline in the horizontal extent of the low-level onshore flow are found to vary as a function of the heat flux and stability. Small lake breezes develop similarly to sea breezes in the morning, but have a significantly weaker horizontal wind speed component and a smaller horizontal extent than sea breezes in the afternoon.

Keywords Lake breeze · Large-eddy simulation · Numerical modelling · Sea breeze · Thermally-driven circulation · Weather Research and Forecasting model

1 Introduction

Sea and large lake breezes have been studied extensively over the past several decades using observational and numerical approaches (Simpson 1994; Miller et al. 2003), and continue to be actively investigated (e.g., Levy et al. 2009; Papanastasiou et al. 2010; Soler et al. 2011). However, our understanding of these thermally-driven systems remains incomplete (see Crosman and Horel (2010) for a review of the numerical modelling of sea and lake breezes and recommendations for future research). Lake breezes for small lakes, however, have not been extensively studied and are not as well-understood as sea breezes (Segal et al. 1997). In this paper we describe initial findings from a numerical sensitivity study on sea and lake breezes concerning variations in the land-surface sensible heat flux, initial atmospheric stability, and lake diameter.

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As discussed by Crosman and Horel (2010), sea breezes have historically been studied in terms of three widely-used metrics: (1) the horizontal extent l, (2) the horizontal wind speed u, and (3) the depth h of these thermally-driven circulations. A number of scaling analyses using both observational and numerical data have been derived to approximate the environmental controls on these three sea-breeze metrics (e.g., Niino 1987; Dalu and Pielke 1989; Steyn 1998, 2003; Drobinski et al. 2006; Porson et al. 2007). In addition, a few scaling relations have attempted to characterize the differences between sea breezes and the smaller lake breezes and inland breezes resulting from land-surface heterogeneities (e.g., Anthes 1984; Segal et al. 1997; Patton et al. 2005; Courault et al. 2007; Baldi et al. 2008; Drobinski and Dubos 2009; Hidalgo et al. 2010).

Despite the abundance of sea-breeze modelling, scaling, and observational studies, no sensitivity study to our knowledge has modelled the three-dimensional structure of the sea-breeze circulation under a wide range of environmental forcing. In addition, no study has systematically modelled the differences in u, l, and h for small lake breezes versus larger lake and sea breezes. Several studies have noted the differing dynamics of sea and large lake breezes and small lake breezes and inland breezes (Segal et al. 1997; Drobinski and Dubos 2009). Small lake breezes are fundamentally different from sea breezes due to the limited cool boundary-layer air available to the thermally-driven circulation and the limited extent offshore to which the competing mirror circulations can grow horizontally (Crosman and Horel 2010).

In this study we provide new insights into the detailed spatial and temporal characteristics of small lake breezes using large-eddy simulations (LES), where the larger-scale boundary-layer turbulence and the small-scale structure and frontal dynamics of the breezes are resolved. The ability of LES to realistically reproduce a single sea-breeze life cycle has been amply demonstrated (Sha et al. 1991, 1993, 2004; Dailey and Fovell 1999; Rao et al. 1999; Fovell and Dailey 2001; Ogawa et al. 2003; Fovell 2005). Antonelli and Rotunno (2007) were the first to conduct numerical sensitivity studies concerning the sea-breeze onset using LES, and in this study we build on their work.

2 Model and Experiment Design

2.1 Weather and Forecasting Model Configuration

The National Center for Atmospheric Research (NCAR) Advanced Weather Research and Forecasting (WRF) model is a fully-compressible, non-hydrostatic atmospheric model (Skamarock and Klemp 2008; Skamarock et al. 2008) that has been used extensively in LES (Moeng et al. 2007; Rotunno et al. 2009; Catalano and Moeng 2010; Lundquist et al. 2010).

Details on the WRF model configured as a LES model for this study are given in Table 1. The model was run with a horizontal grid spacing of 100 m such that no planetary boundary-layer parametrization was required. In addition, because a dry atmosphere was assumed and surface fluxes were prescribed, no radiation, microphysical, or land-surface parametrizations were used. Surface drag was computed using Monin–Obuhkov similarity theory and subgrid-scale turbulence was modelled using a 1.5-order turbulent kinetic energy closure and the non-linear backscatter anisotropic turbulence subgrid-stress model of Mirocha et al. (2010).

The model domain for the WRF simulations follows the general approach of Antonelli and Rotunno (2007) (Fig. 1). The primary differences between our study and that of Antonelli and Rotunno (2007) are: the simulations reported herein (1) were run for a longer period of

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Table 1 WRF model LES details

Model parameter	Model configuration (WRF namelist selections in italics)
Numerics	WRF Version 3.2, non-hydrostatic, Runge–Kutta 3rd order time-splitting time integration, 5th (3rd) order horizontal (vertical) momentum advection, stress mixing (*diff_opt = 2*)
Grid	Terrain-following hydrostatic-pressure (vertical) and Arakawa C-grid (horizontal)
Parametrizations	Obukhov surface layer (*sf_sfclay_physics = 1*), no radiation, PBL, or land-surface schemes; subgrid-scale turbulence: 1.5 order TKE (*km_opt = 2*) with NBA of Mirocha et al. (2010) (*sfs_opt = 2*)
Domain	230 km (x) $\times$ 5 km (y) $\times$ 5 km (z)
x-grid spacing	100 m (2,300 grid points)
y-grid spacing	100 m (65 grid points)
z-grid spacing	30–150 m stretched (65 grid points)
Boundary conditions	Periodic along-shore; open cross-shore
Timestep	1 s (acoustic timestep 0.166 s)
Simulation length	10 h
Damping	W-Rayleigh layer at model top (500 m deep), coefficient 0.1; numerical diffusion of Knievel et al. (2007) (*diff_6th_factor = 1*)
Prescribed sensible heat flux	According to Eq. 1 over land, zero over water
Fixed initialization parameters	Initial land surface temperature 288.15 K, roughness length over land 0.2 m, roughness length over water 0.0001 m, Coriolis parameter $(f) = 10^{-4}\ \mathrm{s}^{-1}$, initial geostrophic flow zero
CTL simulation	$(H, \mathrm{K\ m\ s}^{-1}) = 0.16$; $(N, \mathrm{s}^{-1}) = 0.01$
Heat flux sensitivity tests	$(H, \mathrm{K\ m\ s}^{-1}) = 0.08$ (LO_H); 0.16 (CTL); 0.30 (HI_H)
Initial stability sensitivity test	$(N, \mathrm{s}^{-1}) = 0.005$ (LO_N); 0.01 (CTL); 0.02 (HI_N)
Lake diameter sensitivity tests	$(d, \mathrm{km}) = 10$ (LK_10); 25 (LK_25); 50 (LK_50); 100 (LK_100); sea (infinite dimension)

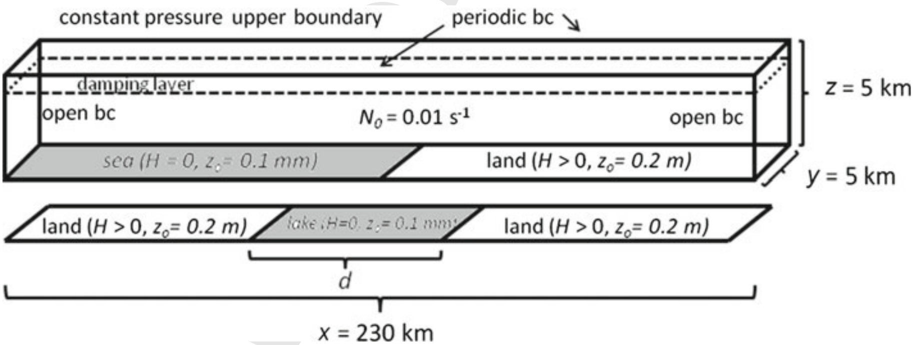

Fig. 1 Schematic diagram of simulation set-up for control sea-breeze simulation (Table 1) (*top*) and lake-breeze cases (*bottom*). H represents the land-surface sensible heat flux, N_o is the initial Brunt–Viasala frequency, z_o is the roughness length, and d is the lake diameter

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time over a greater horizontal domain (10 h versus 6 h; 230 km versus 100 km), (2) included a time-varying land-surface sensible heat flux (instead of fixed), (3) included idealized lake surfaces, and (4) were conducted over a larger range of the land-surface sensible heat flux and initial atmospheric stability. The model was run in three dimensions, with a volume of dimension 5 km along-coast (y) × 230 km cross-coast (x) × 5 km vertical (z). Assuming a straight coastline parallel to y results in two-dimensional sea-breeze circulations in the x–z plane while simulating the three-dimensionality of individual convective eddies. Periodic boundary conditions were imposed in the y-direction with open boundary conditions in the x-direction. The model was run with a 100-m grid resolution in x and y, and a stretched z grid ranging from ≈30 m at the lowest level to ≈150 m below the model top (Crosman 2011). A damping layer was used at the model top to avoid the reflection of acoustic and gravity waves. The model was run for 10 h using a 1-s timestep (Table 1). The surface boundary conditions were partitioned between land and water (lake or sea) surfaces (Fig. 1). The land-surface sensible heat flux was set to zero over the sea or lake surface, while over the land surface a time-varying land-surface sensible heat flux (H) was prescribed by

$$H(t) = A\sin\left[\left(\frac{\pi}{12}\right)\left(\frac{t}{3600}\right)\right] \quad (1)$$

where t is the time in seconds from model initialization and A is the heat-flux amplitude. The aerodynamic roughness length was prescribed as 0.0001 m over water and 0.2 m over land (Table 1). The transition between the water and land surfaces was modelled with a 300 m gradient in both the surface heat flux and drag. The initial surface temperature was 288.15 K, there was no initial geostrophic flow, and the Coriolis parameter was set to 10^{-4} s^{-1}. The initial atmospheric stability profiles were prescribed to be horizontally homogeneous over land and water.

2.2 Sensitivity Tests

Twenty-five LES were conducted on the sensitivity of the horizontal cross-coast wind speed u, inland extent l of the sea-breeze or lake-breeze front from the coast, and depth h (at the coast unless noted otherwise) of sea and lake breezes to the land-surface sensible heat flux (H, referred to hereafter as "heat flux") and the initial atmospheric stability (N, referred to hereafter as "stability") (Table 1). Various combinations of the three different values of the peak amplitude A of the heat flux ($H = 0.08, 0.16, 0.30$ K m s^{-1}) and stability (Brunt–Viasala frequency $N = 0.005, 0.01, 0.02$ s^{-1}) were prescribed in the simulations of four slab-symmetric (i.e., an elongated lake with two-dimensional symmetry) lakes with diameters of 10, 25, 50 and 100 km and the 'infinite' sea-breeze dimension (Table 1).

The range of heat fluxes used corresponds roughly to low (≈90 W m^{-2}), medium (≈180 W m^{-2}), and high (≈375 W m^{-2}) environmental values (Hsu 1983). The range of stability used also corresponds roughly to a low-stability (0.005 s^{-1}), standard-stability (0.01 s^{-1}) or high-stability (0.02 s^{-1}) atmosphere. In the low-stability atmosphere, the boundary layer over the land surface mixes to near-neutral in the presence of the high heat flux, representing the case of a sea breeze forming in an arid coastal region. Conversely, the high-stability atmosphere (0.02 s^{-1}) would be more representative of a sea breeze forming under a capping inversion, possibly resulting from a pre-existing nocturnal inversion, marine boundary layer, or elevated stable layer.

This study has several limitations that should be noted. First, because there is no land-surface model and the heat fluxes are prescribed in time according to Eq. 1, the model does not simulate interactions between the cool onshore flow and ground temperature. Second,

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the heat flux in this study is set to zero over water surfaces although small negative values are typically observed due to evaporative cooling (Segal et al. 1997). Third, homogeneous initial atmospheric conditions were assumed over the land and water surfaces. Fourth, the simulations were terminated after 10 h (mid-afternoon) to avoid numerical instabilities occasionally observed at the lateral boundaries after that time. Finally, the modelling framework (i.e., quasi-two-dimensional) for lakes in this study does not allow for consideration of coastline curvature effects.

For the purposes of the study, time will be given in hours from the start of a simulation. Thus, hr 6 corresponds to noon local solar time, with hr 10—the end of the simulation—corresponding to mid-afternoon. References to ‘morning’ indicate times prior to simulation hr 6, whereas ‘afternoon’ refers to simulation hrs 6–10.

3 Results and Discussion

3.1 Control Simulation

The overall development of the sea breeze in the control (CTL) run is consistent with previous observational and numerical studies (Reible et al. 1993; Miller et al. 2003; Bastin and Drobinski 2006). The sea-breeze circulation initiates near the coast and expands laterally and vertically during the daytime life cycle (Fig. 2a–c). During the morning, the region of low-level onshore flow with horizontal wind speeds >2 m s^{-1} is confined to within 10 km of the coast (Fig. 2a), and by mid-afternoon the region of low-level onshore flow with horizontal wind speeds >4 m s^{-1} has extended onshore and offshore by over 30 km (Fig. 2c). An afternoon maximum in the cross-coast wind speeds associated with the sea-breeze return flow is noted behind the sea-breeze front between 1 and 2 km above the surface. The horizontal temperature gradient between the coast and the leading edge of the sea-breeze front ($\approx$38 km inland at hr 9) increases from $\approx$2 K at hr 3 to $\approx$4 K by hr 9. The competing effects of turbulent convection, which acts to deepen the internal marine boundary layer (Garratt 1990), and the stable marine onshore flow, which limits the sea-breeze depth are evident. The sea-breeze low-level onshore flow deepens and becomes increasingly turbulent with increasing distance inland during the afternoon (Fig. 2b, c). The sea-breeze low-level onshore flow at the coast remains a relatively constant depth ($\approx$600 m) through the afternoon, while the depth of the low-level onshore flow immediately behind the sea-breeze front increases to $>$900 m (Fig. 2b, c). Vertical motions associated with the sea-breeze front and boundary-layer convection ahead of the front also increase during the afternoon (Fig. 2b, c).

A general weakening of the low-level horizontal temperature gradient through turbulent frontolysis is noted with increasing distance inland (the horizontal temperature gradient near the coast is $\approx$0.25 K km^{-1} as compared to $\approx$0.10 K km^{-1}25 km inland at hr 9). The sea-breeze horizontal wind speeds increase linearly during the morning before levelling off in the afternoon at the coast (Fig. 2d). Similar conditions are observed offshore over the ocean, except that the horizontal wind speeds are smaller until hr 8 when the stronger core of the low-level onshore flow has expanded sufficiently to reach that location. Inland from the coast (4 km), a sea-breeze frontal passage is evident near hr 3, marked by an increase in the horizontal wind speeds, and a flattening of the temperature trace (Fig. 2d, e). Further inland (24 km), the sea-breeze frontal passage is delayed until hr 7, which allows for greater diurnal heating of the prefrontal boundary layer and development of the sea-breeze front, with an associated 1.5 K temperature decrease associated with frontal passage.

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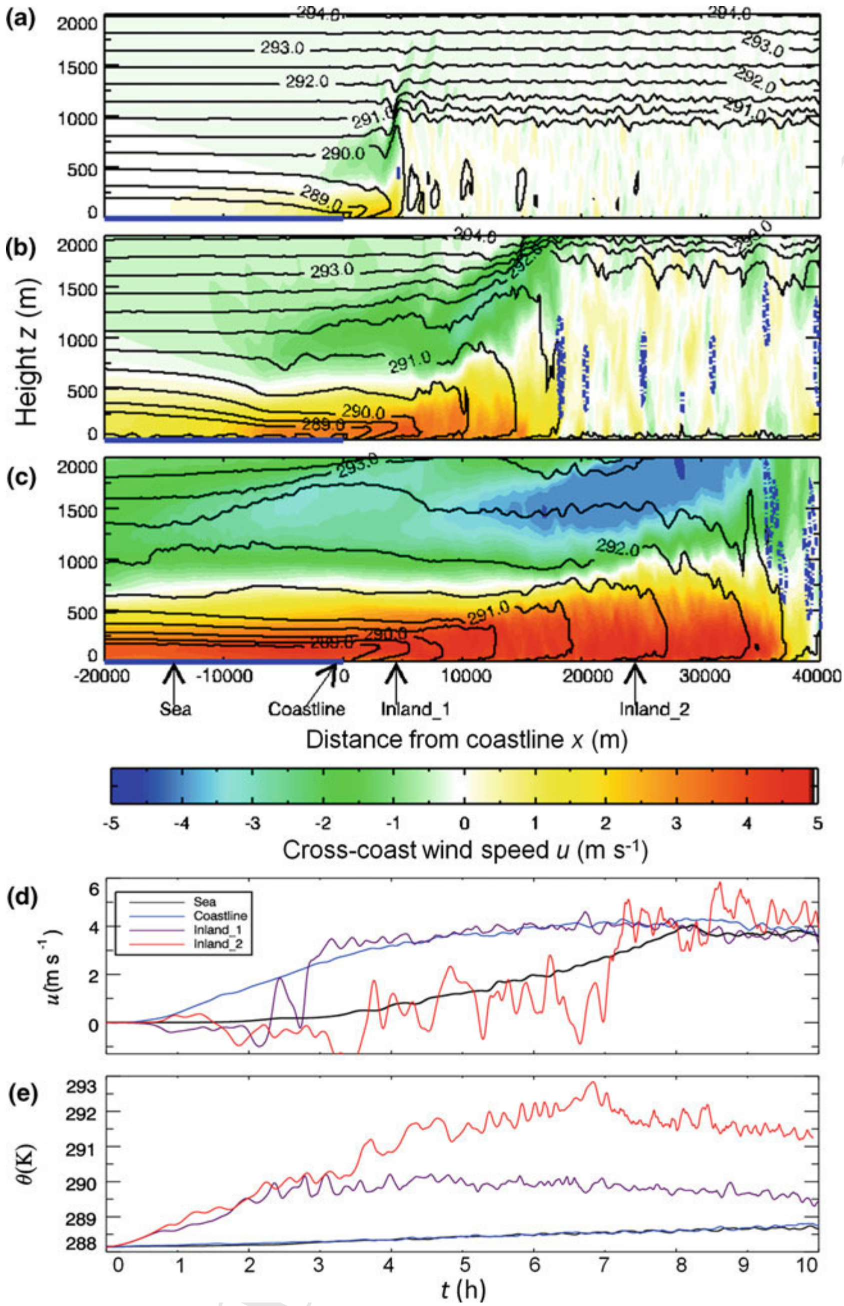

Fig. 2 **a–c** Vertical cross-sections of the *y*-averaged sea-breeze circulation for the CTL simulation (see Table 1) at hr **a** 3, **b** 6, and **c** 9 (time is hours after simulation start, i.e., sunrise). *Colours* represent the cross-coast wind speed (u, m s^{-1}) and *solid contours* represent potential temperature (θ, K). Regions of upward vertical motion greater than 0.5 m s^{-1} are contained within the *dashed blue line*. The sea surface is represented by *solid blue line*. The approximate locations of near-surface time series of **d** cross-coast wind speed u (m s^{-1}) and **e** potential temperature θ (K) are indicated with *arrows* in **c**

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3.2 Sensitivity to the Land-Surface Sensible Heat Flux and Atmospheric Stability

In this section we summarize the effects of variations in the heat flux and stability on the structure of mature (mid-afternoon) sea-breeze and small lake-breeze ($d = 25$ km, hereafter referred to as lake unless otherwise noted) circulations. Several new findings on sea and lake breezes not previously reported in the literature are observed. First, horizontal asymmetries in the wind speed of the lake-breeze and sea-breeze onshore low-level flows are observed as a function of the heat flux and stability (Figs. 3, 4). Second, the highest wind speeds associated with the lake-breeze onshore low-level flow are noted immediately inland from the coastline (Figs. 3c, d; 4c, d). Other lake-breeze and sea-breeze responses to variations in the heat flux and stability are generally as expected: the horizontal cross-coast wind speed (for both the low-level onshore flow and the return flow aloft), vertical wind speed, circulation width, land-water temperature contrast, and depth of the lake and sea breezes in a high heat-flux environment generally increase relative to a low heat-flux environment (Fig. 3a–d), while a high stability atmosphere significantly decreases the depth of both the low-level onshore flow and the return flow aloft, in addition to damping the near-surface horizontal and vertical wind speeds (Fig. 4a–d). Relatively weak sea-breeze fronts are evident in the simulations, consistent with a lack of background flow to drive frontogenesis (Reible et al. 1993). The thermodynamic effects of variations in the heat flux are small near the shore since the increase in heating is largely offset by increased advection of marine air inland. Consequently, the near-shore surface temperature is similar for low and high surface heat fluxes, with the surface temperature 20 km inland from the coast ≈2 K higher in the high heat-flux environment (Fig. 3a, b).

3.2.1 *Asymmetry of the Lake-Breeze and Sea-Breeze Circulations*

For sea breezes, the region of maximum wind speeds associated with the onshore low-level flow is notably more asymmetric about the coastline for the low heat-flux and high stability cases (Figs. 3a, 4b) than for high heat-flux and low stability simulations (Figs. 3b, 4a). In the low heat flux and high stability cases, the horizontal extent of maximum wind speeds associated with the sea-breeze low-level onshore flow is approximately twice as far onshore as offshore (Figs. 3a, 4b). For the high heat-flux and low stability cases, the horizontal extent of maximum wind speeds within the sea-breeze low-level onshore flow is comparable in the onshore and offshore directions (Figs. 3b, 4a). For lake breezes, the offshore extent of the circulation is constrained to the middle of the lake due to the competing mirror circulations forming on either side of the water body. Thus, the lake breeze becomes increasingly asymmetric with increasing inland extent of the circulation. In the low stability and high heat-flux environments the inland extent of the lake breeze low-level onshore flow is roughly twice the offshore extent (Figs. 3d, 4c). In addition, the strongest lake-breeze horizontal wind speeds within the low-level onshore flow are generally observed within 10 km inland from the coast for both low and high heat-flux and stability environments (Figs. 3c, d; 4c, d).

In addition to the noted asymmetry in the horizontal extent of the low-level onshore flow, the overall horizontal shape of the lake-breeze and sea-breeze circulations is also asymmetric about the coast, with the low-level onshore flow observed to be deeper and to have a higher vertically-averaged horizontal wind speed over the land than over the sea. The horizontal wind speed of the return flow is also notably stronger over the land than over the sea (Figs. 3, 4). These findings are consistent with the observations of Drobinski et al. (2006) who found that sea-breeze circulations were “far from the toroidal circulation found in the textbooks.”

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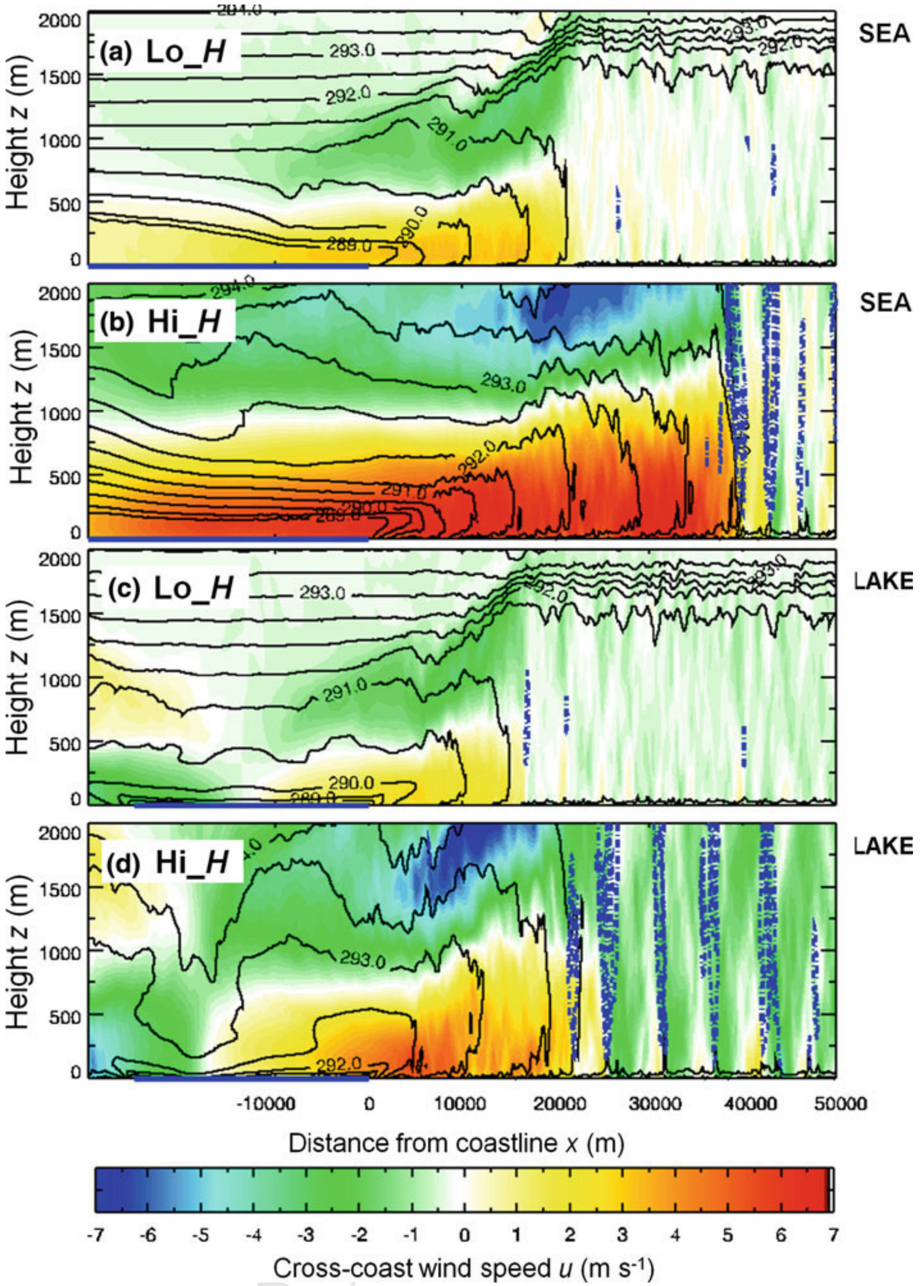

Fig. 3 Vertical cross-section of the *y*-averaged circulations at hr 8 (time is hours after simulation start) for experiments **a** LO_*H* and **b** HI_*H* for the sea-breeze case and **c** LO_*H* and **d** HI_*H* for a 25 km lake. *Colours* represent the cross-coast wind speed (u, m s^{-1}) and *solid contours* represent potential temperature (θ, K). Regions of upward vertical motion greater than 0.5 m s^{-1} are contained within the *dashed blue line*. The sea or lake surfaces are represented by *solid blue lines*

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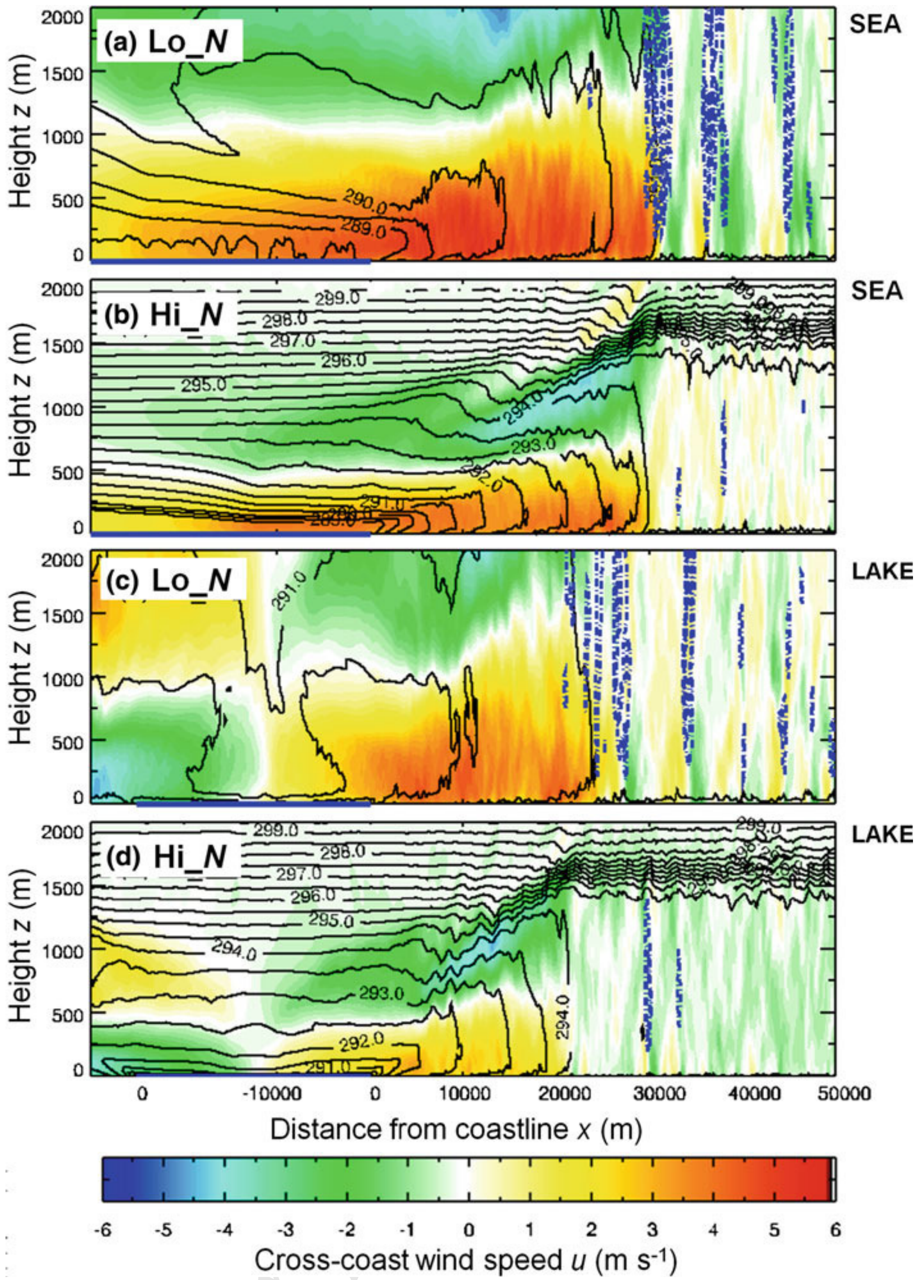

Fig. 4 Vertical cross-section of the y-averaged circulations at hr 8 (time is hours after simulation start) for experiments **a** LO_N and **b** HI_N for the sea-breeze case and **c** LO_N and **d** HI_N for a 25 km lake. *Colours* represent the cross-coast wind speed (u, m s^{-1}) and *solid contours* represent potential temperature (θ, K). Regions of upward vertical motion greater than 0.5 m s^{-1} are contained within the *dashed blue line*. The sea or lake surfaces are represented by *solid blue lines*

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3.2.2 Difference Between Lake-Breeze and Sea-Breeze Circulations

Lake-breeze circulations are expected to be smaller and weaker than the corresponding sea-breeze circulations (Segal et al. 1997). The LES of the lake breezes have decreased horizontal cross-coast wind speeds and a smaller horizontal extent compared to the corresponding sea breezes (Figs. 3, 4). First, the difference between the lake-breeze and sea-breeze inland extent increases with increasing heat flux (Fig. 3). Second, the highest observed wind speeds in the low-level onshore flow and horizontal temperature gradients associated with lake breezes are limited to the near-shore environment, while sea breezes have larger temperature gradients and wind speeds in the onshore low-level flow that extends further inland (Figs. 3, 4). The low-level horizontal temperature gradient associated with the small lake breeze also remains relatively invariant with increasing heat flux (Fig. 3c, d). Finally, lake breezes appear to be more sensitive to variations in stability than sea breezes, as the differences between lake-breeze low-level onshore flow wind speeds, inland extent, and depth between high and low stabilities are larger than the relative changes in sea breezes between high and low stabilities (Fig. 4a–c). A physical hypothesis for some of these differences will be discussed in Sect. 3.5.

3.3 Temporal Dependence

The temporal evolution of the lake-breeze and sea-breeze horizontal wind speeds at the coast, inland extent, and depth of the low-level onshore flow at the coast for five different environments is given in Fig. 5. The sea-breeze horizontal wind speed, inland extent, and depth in a high heat-flux environment is approximately twice that observed in a low heat-flux environment (Fig. 5a, c, e). For a low heat flux, the horizontal wind speed increases through late morning and remains relatively constant during the afternoon. For a medium and high heat flux, the sea-breeze horizontal wind speed increases through early afternoon before decreasing. The inland penetration speed of the sea-breeze front (i.e., the time rate of change of the inland extent of the sea breeze) is also sensitive to the heat flux. For a low heat flux, the inland penetration speed is $\approx$5 km h^{-1} during the entire simulation (Fig. 5c). For the medium and high heat fluxes, there is a notable afternoon increase in the inland penetration speed to 7.5 and 10 km h^{-1} respectively. These values qualitatively agree with the observed inland penetration speeds of 3–5 km h^{-1} (6–8 km h^{-1}) modelled by Tijm (1999) and Physick (1980) for low (high) heat-flux environments, as well as the sea-breeze observations of Simpson (1994) and Bastin and Drobinski (2006). In addition, several studies have confirmed the afternoon acceleration of the sea-breeze front (Physick 1980; Ogawa et al. 2003). The lake-breeze and sea-breeze horizontal wind speeds are insensitive to stability until hr 5, after which point a weak dependency on stability exists (Fig. 5a, b). The inland extent of sea breezes is virtually independent of stability (Fig. 5c), while the lake-breeze and sea-breeze depths vary significantly as a function of stability (Fig. 5e, f).

3.3.1 Comparison with Sea-Breeze Scaling Estimates

Figure 6 summarizes the changes in the three key metrics (u, h, and l) at mid-afternoon resulting from doubling the heat flux and stability in the LES. The impact of doubling those quantities (i.e., from low to medium and medium to high as defined in Table 1) are expressed in terms of the fractional change in the breeze metrics to 100 % increases in the magnitudes of the heat flux and stability. For example, the cross-coast horizontal wind speed at the coast in the sea-breeze LES increases by 50 % when the heat flux is increased from low to medium with roughly similar increases found when the heat flux is doubled again (Fig. 6a). Also shown

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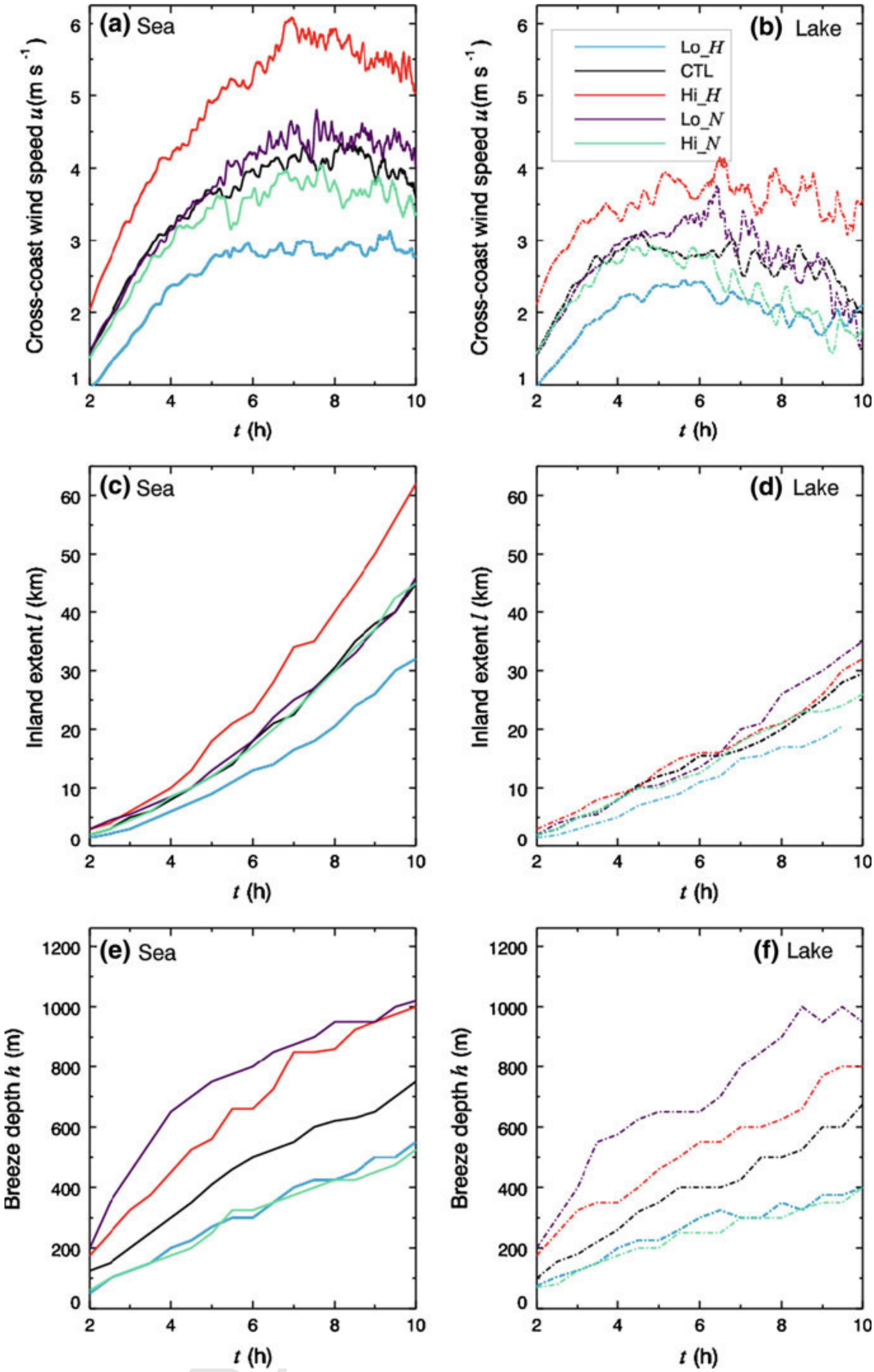

Fig. 5 Time series of **a**, **b** cross-coast wind speed u (m s^{-1}) at the coast (30 m a.g.l.), **c**, **d** inland extent l (km), and **e**, **f** depth h (m) at the coast for low, medium, and high values of the land-surface sensible heat flux and initial atmospheric stability (see Table 1 for more info). **a**, **c** and **e** refer to sea-breeze simulations while **b**, **d** and **f** refer to a 25-km diameter lake. Time on the *horizontal axis* refers to hours after simulation start

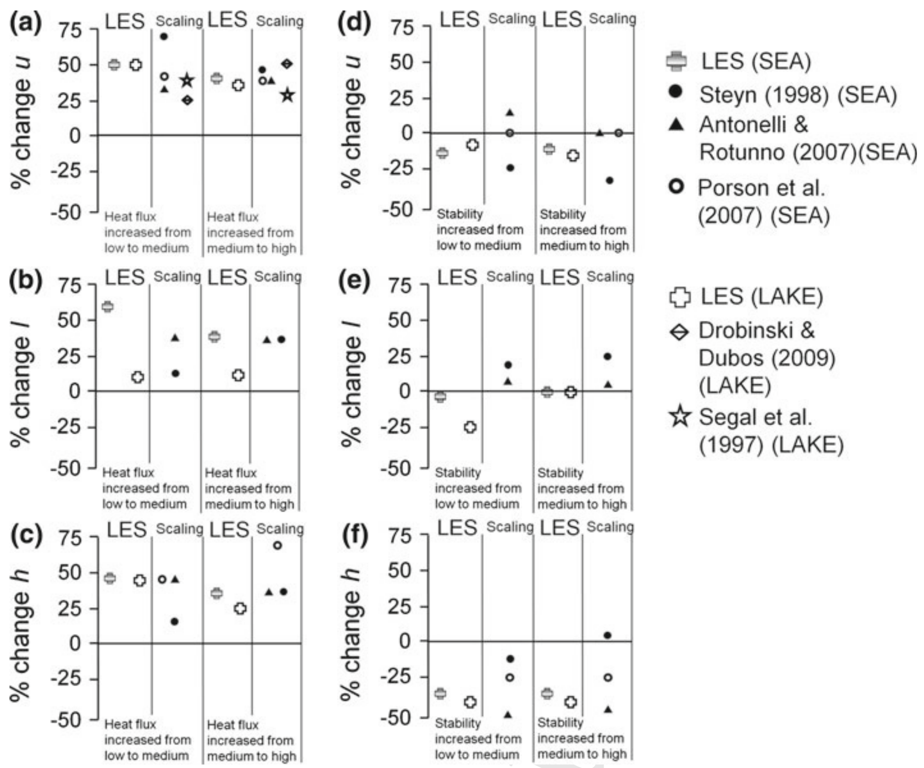

Fig. 6 Impact of a 100 % increase in the heat flux and stability (from low to medium and from medium to high values) on the mature mid-afternoon (hr 8) sea-breeze and lake-breeze circulations as observed in sea-breeze and 25-km diameter lake-breeze LES as well as according to several widely-used scaling estimates. **a** and **d** Cross-coast wind speed u (m s^{-1}), **b** and **e** inland extent l (km), and **c** and **f** depth h (m) expressed as the fractional change (change divided by original value)

in Fig. 6 are estimates of the changes in these metrics expected from multiple scaling relations developed for sea and lake breezes. The scaling technique is outlined by Steyn (1998) and reviewed by Crosman and Horel (2010). In general, the sea-breeze scaling relations appear to capture the LES' response to variations in the heat flux and stability. A doubling of the heat flux results in substantial increases in the sea-breeze horizontal wind speed, depth, and inland extent (Fig. 6a–c). A doubling of the stability results in small changes in the sea-breeze horizontal wind speeds and inland extent and large decreases in depth (Fig. 6d–f).

However, there are several notable discrepancies between the LES and the scaling estimates. These discrepancies bring into question the 'universality' of these scaling laws for the wide range of environments simulated. The scaling estimates for changes in depth with variations in stability by Steyn (1998) and Porson et al. (2007) are less than those of Antonelli and Rotunno (2007) and the LES in this study (Fig. 6f). The Steyn (1998) scaling estimates for the horizontal wind speed and inland extent also disagree with the model simulations in several instances, possibly due to the use of an instantaneous rather than integrated heat flux used in the Steyn (1998) scaling estimates (Drobinski et al. 2006).

Finally, the scaling relations for inland (Drobinski and Dubos 2009) and lake (Segal et al. 1997) breezes for the horizontal wind speed are examined for the 25-km lake LES (Fig. 6a).

The inclusion of lake diameter in the scaling for wind speed appears to be of secondary importance relative to the heat flux, which is further supported by the similar sensitivities to heat flux between the lake and sea LES. However, scaling estimates of the inland extent should depend on lake diameter since the lake-breeze and sea-breeze horizontal length scales respond differently to increases in heat flux and to a lesser extent stability (Fig. 6b, e).

3.3.2 *Difference Between the Lake-Breeze and Sea-Breeze Evolution*

The horizontal wind speed, inland extent, and depth of small lake breezes in many cases show similar sensitivities to variations in the heat flux and stability as for sea breezes (Fig. 5b, d, f). However, there are some notable differences between lake breezes and sea breezes:

- the lake-breeze characteristics are similar to sea breezes through mid-morning;
- the afternoon lake-breeze horizontal wind speed and inland extent are significantly less;
- there is no inland acceleration of the lake-breeze front in the afternoon;
- the lake-breeze inland extent is less sensitive to the heat flux;
- the relative decrease in lake-breeze depth with respect to the sea breeze is less than the relative decrease in the horizontal wind speed and inland extent.

A discussion of possible reasons for some of these differences is given in Sect. 3.5.

3.4 Sensitivity to Lake Diameter

The analysis to this point has focused on a comparison of sea breezes with a 25-km diameter lake. A natural question that follows from this discussion is: how does the comparison between sea and lake breezes vary as the lake size is changed? It is generally agreed that for large lakes (d = 100 km), the lake-breeze characteristics are similar to those for sea breezes, and the results of our study confirm this (Fig. 7). A comparison of the LES lake-breeze evolution for a large lake (Fig. 7a–c) with Keen and Lyons (1978) Lake Michigan breeze shows similar horizontal wind speeds (≈4 m s^{-1}) and depths (≈500–800 m).

However, the horizontal wind speed, inland extent, and depth of lake breezes are observed to decrease with decreasing lake diameter for small- to medium-sized lakes, d = 10–50 km (Fig. 7a–c). The sensitivity of these lake-breeze metrics to lake diameter is highest in the afternoon. Through mid- to late morning, the horizontal wind speed, inland extent, and depth of lake breezes (except for the smallest case d = 10 km) show virtually no dependence on lake diameter (Fig. 7).

The response of lakes breezes to variations in the heat flux and stability is also modulated by the lake diameter (Fig. 7d–f). The mid-afternoon horizontal wind speed and inland extent of medium and large lakes are more sensitive to variations in the heat flux than small lakes. The difference in horizontal wind speed and inland extent between lake breezes for small and large lakes is highest for a high heat-flux environment (Fig. 7d, e). For example, the difference in lake-breeze horizontal wind speed between small and large lakes is ≈1.5 m s^{-1} under a low heat flux and increases to ≈4 m s^{-1} for a high heat flux. Similarly, the inland extent of small and large lakes differs by ≈6 km under low heat-flux conditions and increases to ≈17 km under high heat-flux conditions. For a low heat flux, the lake-breeze depth is relatively insensitive to lake size, while for a medium and high heat flux, the depth is dependent on the lake diameter (Fig. 7f). Variations in stability weakly modulate the response of lake breezes to lake diameter (Fig. 7d–f). The relative differences in horizontal wind speed, inland extent, and depth for lake breezes between 10- and 50-km diameter lakes are greater in a low stability environment than a high stability environment.

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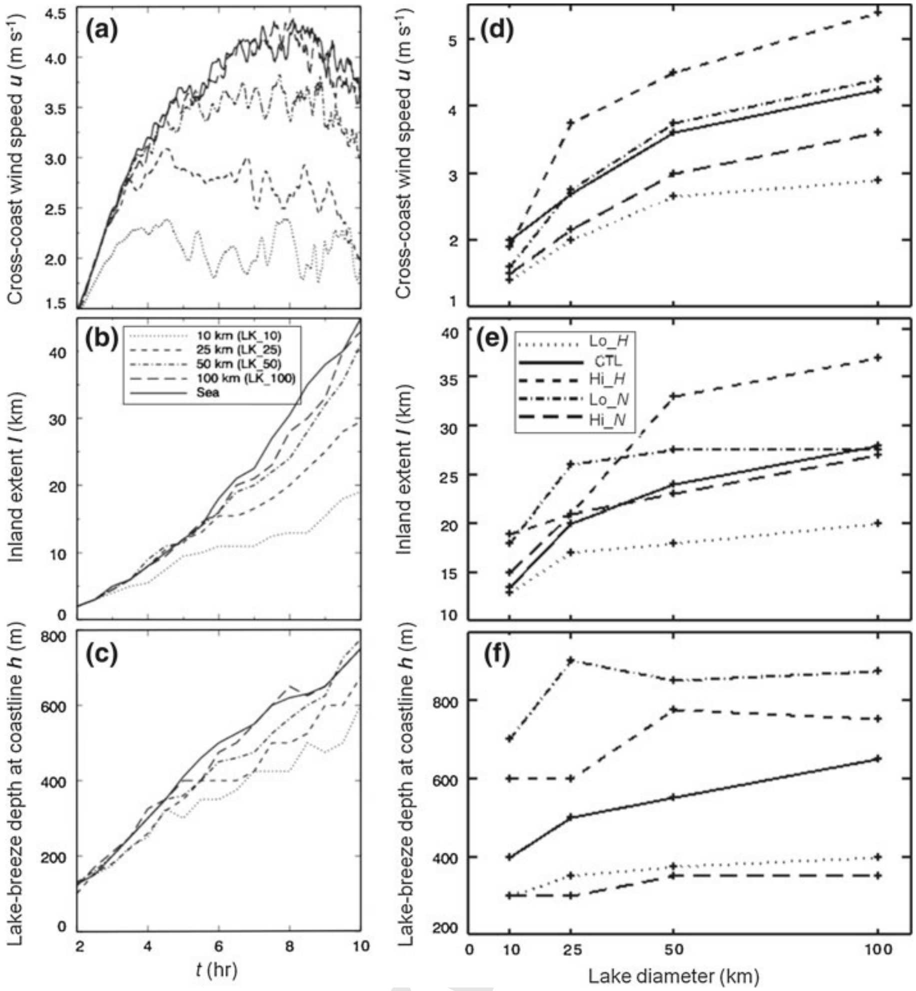

Fig. 7 Lake-breeze and sea-breeze **a** cross-coast wind speed *u* (m s^{-1}) at the coast (30 m a.g.l.), **b** inland extent *l* (km), and **c** depth *h* (m) at the coast for lakes of diameter 10, 25, 50 and 100 km and the sea-breeze case. Time on the *horizontal axis* refers to hours after simulation start. The sensitivity of **d** *u*, **e** *l*, and **f** *h* as a function of lake diameter at simulation hr 8 for low, medium, and high values of the land-surface sensible heat flux and initial atmospheric stability

3.4.1 Variations in the Lake-Breeze and Sea-Breeze Aspect Ratios

Motivated by the comparison of sea-breeze and inland-breeze aspect ratios (inland extent/depth) reported by Drobinski and Dubos (2009), we provide a brief overview of the modelled lake-breeze and sea-breeze aspect ratios as a function of lake diameter, heat flux, and stability. The 10-, 25- and 50-km diameter lakes in this study are likely in the 'transitional regime' between very small land-surface heterogeneities and sea breezes (Drobinski and Dubos 2009). Similar to the findings of Drobinski and Dubos (2009), the aspect ratio is smaller for small lake breezes than for sea breezes (Fig. 8). The modelled sea-breeze aspect ratios are lower than those observed by Drobinski et al. (2006) because the inland extent

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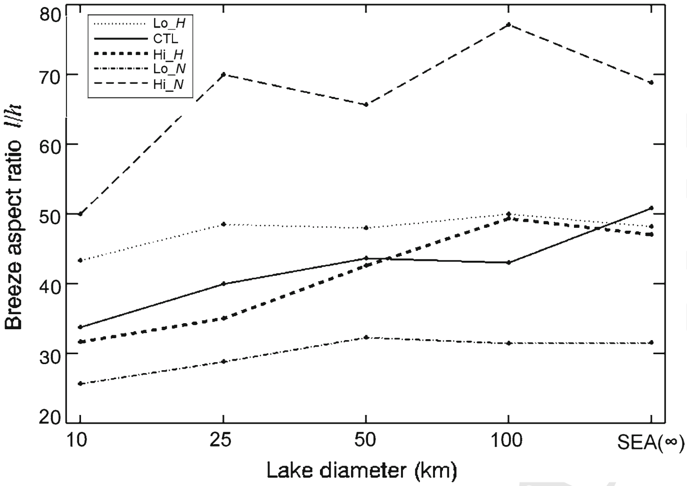

Fig. 8 Aspect ratio (inland extent l divided by depth h at the coast) of sea-breeze and lake-breeze circulations observed at mid-afternoon (hr 8) for low, medium, and high values of the land-surface sensible heat flux and initial atmospheric stability

is computed at mid-afternoon rather than in early evening when the sea-breeze front has progressed further inland. The aspect ratio at mid-afternoon is observed to vary strongly as a function of the land-surface sensible heat flux and stability. For a low stability atmosphere the aspect ratio is much smaller than for a high stability atmosphere. For a low land-surface heat flux, the aspect ratio is relatively uniform for all lake diameters, while the sea-breeze aspect ratio for a high land-surface heat flux is over 50 % greater than that of a lake breeze associated with a 10-km diameter lake.

3.5 Physical Mechanisms Influencing Lake Breezes

Two physical mechanisms are known to weaken lake breezes relative to sea breezes. First, there is a limited supply of cool air available over the lake for the developing lake-breeze circulations, and second, the lake-breeze circulations around the lake compete for the available cool air and horizontal space in which to grow laterally offshore (Crosman and Horel 2010). In addition, for a small lake with a diameter of a few km, surface friction becomes increasingly important in the breeze dynamics (Drobinski and Dubos 2009).

The comparison of small lake and sea breezes to this point has shown that, in the morning, lake-breeze circulations associated with small lakes are typically similar to sea breezes while in the afternoon small lake breezes have weaker winds speeds in the low-level onshore flow and lake-breeze fronts that do not penetrate inland as rapidly as sea-breeze fronts. In addition, the strongest lake-breeze low-level onshore flow and horizontal temperature gradients have been shown to remain fixed near the coast and not extend inland as in the case of a sea breeze.

An analysis of the LES shows that the depletion of cool air over small and medium-sized lakes and the limiting offshore extent for the lake-breeze circulations to expand horizontally influence the evolution of the lake breeze. Because of a combination of depletion of the cool air over the lake and subsidence warming at the intersection of the two lake-breeze circulations in the centre of the lake, the boundary layer over the lake surface in the afternoon is much warmer than that over the sea (Fig. 9). The warming of the lake boundary layer by

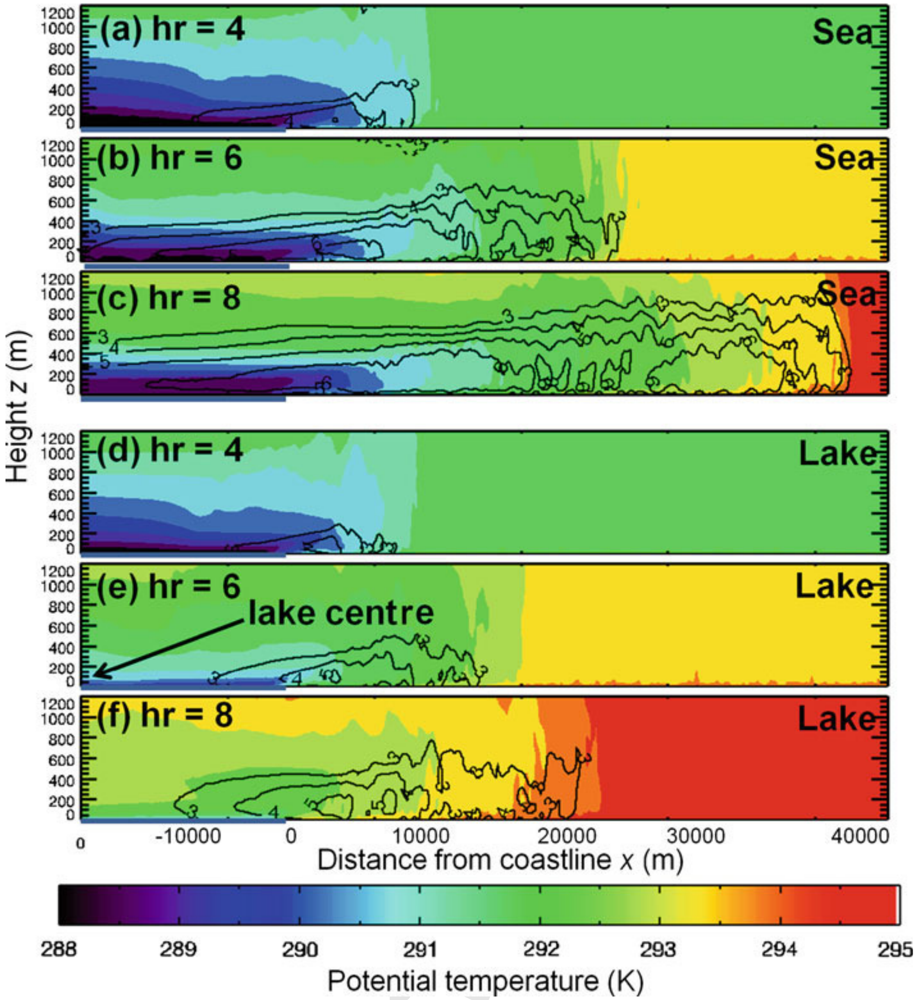

Fig. 9 Vertical cross-sections of the *y*-averaged low-level component of the sea-breeze circulation for the HI_*H* simulation for **a**–**c** the sea-breeze case and **d**–**f** 25 km diameter lake breeze at **a** and **d** hr 4, **b** and **e** hr 6, and **c** and **f** hr 8 (time is hours after simulation start, i.e., sunrise). *Colours* represent the potential temperature (θ, K) and *solid contours* outline cross-coast wind speed (u, m s^{-1}) greater than 3 m s^{-1}. The sea or lake surfaces are represented by *solid blue lines*

≈4 K between mid-morning and mid-afternoon results in a temperature difference between the air above the lake and land surfaces of ≈3.5 K, roughly half the horizontal temperature difference between the air above the land and the sea. Consequently, the mid-afternoon sea-breeze low-level onshore flow is enhanced both in its horizontal extent (the sea-breeze inland extent is roughly three times the lake-breeze inland extent) and wind speed relative to the lake breeze (Fig. 9c, f). The similar magnitude of the horizontal temperature gradient at mid-morning for sea and lake breezes explains why the morning development is similar for both lake and sea breezes, as the heating is not yet sufficient to deplete the cool lake air. The maximum horizontal temperature gradient and associated low-level onshore flow occurs immediately inland from the coast for a lake breeze. Consequently, boundary-layer

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convection and the resultant turbulent frontolysis acting on the smaller horizontal temperature gradient associated with the lake-breeze onshore low-level flow reduces the afternoon inland penetration of the lake-breeze front compared to the sea-breeze front (Figs. 5c, d; 9).

Another difference noted between lake and sea breezes is that the lake-breeze horizontal wind speeds fluctuate more in time than do the sea-breeze horizontal wind speeds (Fig. 5a, b). These fluctuations are observed to be associated with periodic weakening and strengthening of the horizontal temperature gradient, similar to that described by Bastin and Drobinski (2005) for a sea breeze. These fluctuations appear to be magnified by the limited amount of cool air available over the smallest lakes.

The rate of depletion of the cool lake air for small and medium-sized lakes is modulated by the magnitude of the heat flux. Specifying a higher heat flux leads to the lake breeze consuming the available cool air more rapidly. Consequently, the mid-afternoon land-water temperature difference for high values of the heat flux remains similar to the temperature gradient observed for a low heat flux for small lake breezes (Fig. 3c, d). This modulation of the rate of depletion (cold air rapidly depleted in the smallest lakes under a high heat flux) is also hypothesized to be the reason that the difference in wind speed and inland extent between small and large lake breezes is most pronounced in a high heat-flux environment (Fig. 7d, e).

Finally, the decreased static stability of the low-level onshore flow for lake breezes versus sea breezes (sea-breeze air is colder) is hypothesized to result in deeper lake breezes than would be expected if the depth were simply scaled to decrease at a similar rate as the horizontal wind speed and inland extent. Consequently, the lake-breeze depth is less sensitive to changes in lake diameter than the horizontal wind speed and inland extent (Fig. 7c).

4 Summary and Future Work

Idealized numerical studies have been conducted on the sensitivity of sea and lake breezes to variations in the heat flux and stability. Our analysis is the first to explore the effects of perturbations in the heat flux and stability on the spatio-temporal characteristics of lake breezes. The results for sea breezes are generally consistent with prior scaling analyses and modelling studies (Fig. 6). Similar to the results of Porson et al. (2007), the sea-breeze horizontal wind speed and inland extent are largely controlled by the heat flux, while the sea-breeze depth is controlled by stability and heat flux. The key conclusions of our study are as follows:

- horizontal asymmetries about the coast in the wind speeds associated with the sea-breeze and lake-breeze onshore low-level flows are observed as a function of heat flux and stability;
- the largest wind speeds within the lake-breeze low-level onshore flow are generally confined immediately inland from the coast;
- lake-breeze circulations develop similarly to sea-breeze circulations through mid-morning but weaken significantly in the afternoon;
- there is no afternoon acceleration of the inland-moving lake-breeze front; hence, scaling laws for lake breezes that capture the differing dynamics controlling lake-breeze horizontal length scales is needed;
- lake-breeze circulations are less sensitive (more sensitive) to variations in heat flux (stability) than is the case for sea-breeze circulations;
- The lake-breeze and sea-breeze aspect ratios vary as a function of the heat flux and stability.

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The modelled dependence of sea and lake breezes on variations in the heat flux and stability has been presented in terms of simple metrics of sea and lake breezes: the vertical depth and horizontal length and speed scales. However, there exists a plethora of additional information within the LES that will necessitate more sophisticated analysis methods in the future. Additional simulations remaining to be analyzed have also been conducted on the sensitivity of sea and lake breezes to variations in the synoptic flow. Levy et al. (2011) find a strong, persistent downdraft occurring within a sea breeze immediately onshore from the coastline due to the combined effects of convergent horizontal rolls and synoptic flow. These persistent downdrafts are not observed in the current LES with zero geostrophic flow, and it will be interesting to determine whether the LES with non-zero geostrophic flow are able to reproduce such downdrafts. In addition, future simulations will be conducted to ascertain the sensitivity of small to medium-sized lake breezes to variations in the Coriolis parameter and surface friction.

Future work will also require a scaling analysis of the simulations to contribute to current sea-breeze scaling relations and to derive a scaling relation for lake breezes using approaches similar to those for inland breezes (e.g., Drobinski and Dubos 2009; Hidalgo et al. 2010). For sea breezes, developing scaling relations for the vertical wind speeds associated with the sea-breeze front and return flow wind speeds and depth would likely be of interest to the scientific community. However, the spatio-temporal variability of lake and sea breezes captured by these LES illustrates the need for new scaling estimates that include the sensitivity to dependence on distance from the coast, time of day, and season as well as the difficulty to describe these thermally-driven systems with simple scaling relations.

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