Sea breezes in along-shore flow: Idealised simulations and scaling

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1. Introduction

- Previous numerical studies have shown that the cross-shore component of the ambient wind strongly modulates the intensity and evolution of the sea breeze (Crosman and Horel 2010)
- The along-shore component has generally been considered of little importance; however, this may be a consequence of the ubiquitous use of 2D or quasi-2D simulations (infinite coastlines)
- We hypothesise that in the case of a finite-length coastline (e.g. a peninsula), the along-shore flow will play a much greater role due to the step-change in heating at the upstream coast
- This hypothesis is tested using idealised numerical simulations performed with the Met Office Unified Model

2. Model Configuration

- 600 x 300 km domain with 1 km grid spacing and 70 levels
- Fixed lateral boundary conditions (LBCs)
- Peninsula represented using a 400 x 100 km island to reduce discontinuities on the outflow boundary (Fig. 1)

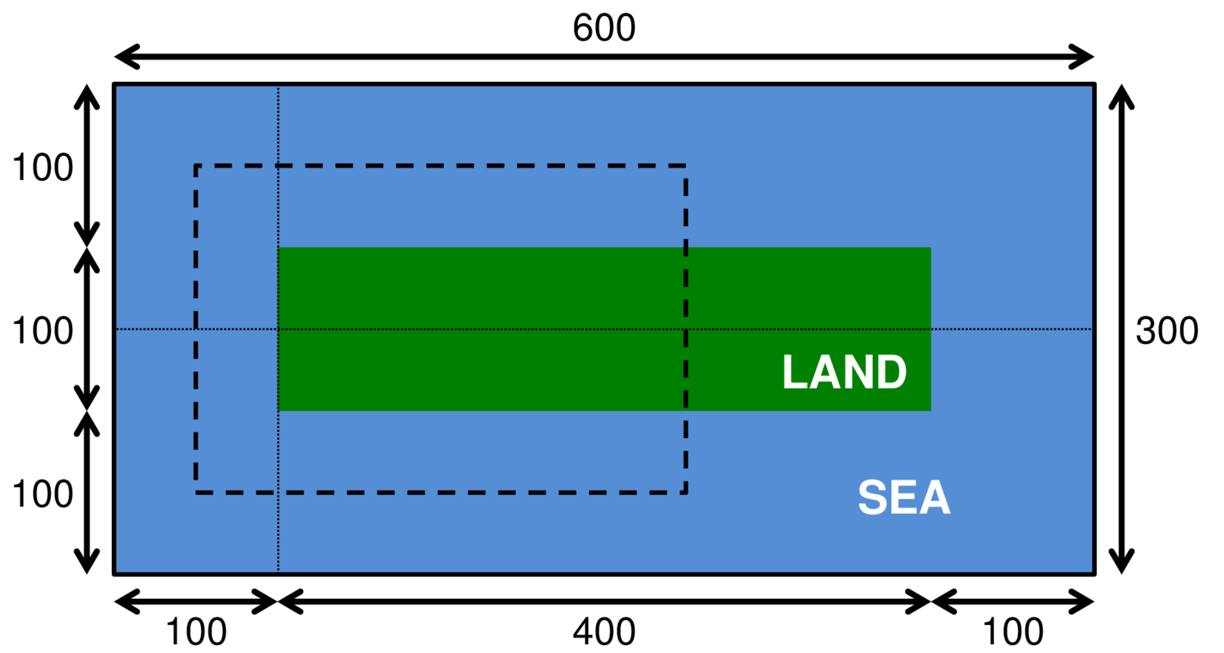

Fig. 1 Schematic of the simulation domain. Dimensions are given in km. The dashed box shows the 300 x 200 km subdomain for which model output is shown.

- No moisture or radiation included
- Coriolis force specified using an f-plane with $\phi = 50°$
- Roughness length specified as 0.0002 m over sea and 0.1 m over land
- Temperature profile specified with a surface value of 288.15 K (15°C) and three layers of constant static stability:

$$\frac{\partial \theta}{\partial z} = \begin{cases} 0 \text{ K km}^{-1} & \text{for } z < 1 \text{ km} \\ 5 \text{ K km}^{-1} & \text{for } 1 < z < 10 \text{ km} \\ 15 \text{ K km}^{-1} & \text{for } z > 10 \text{ km} \end{cases}$$

- Geostrophic momentum forcing used to represent a uniform pressure gradient (specified with vertical profiles of u_g and v_g)
- Imposed wind profiles adjusted to surface friction using a 10-day run on a 100 x 100 km all sea domain with periodic LBCs and an initially uniform zonal wind of speed U_g
- Diurnally varying surface sensible heat flux with amplitude $H_{\max}$ specified over land
- Simulations integrated for 24 h with heating applied during the final 12 h (12 h of spin up to allow winds to adjust over land)

3. Control simulation

- Sea breezes form on the north and south coasts (Fig. 2)
- Near the upstream coast, the sea breeze fronts (SBFs) form quasi-stationary arcs; further downstream they are straight, move inland and eventually collide
- Slight north–south asymmetries exist due to the Coriolis force

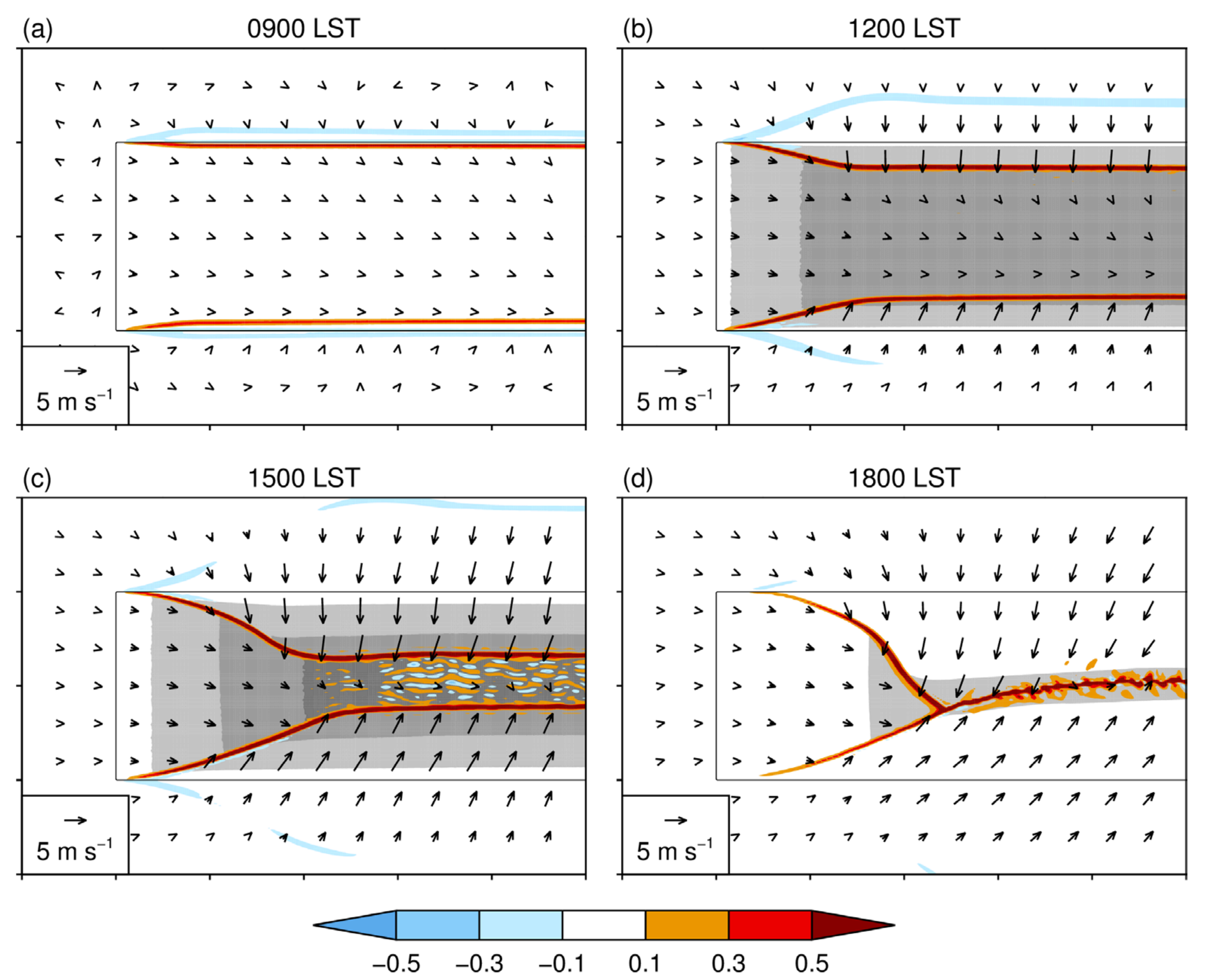

Fig. 2 Evolution of the control simulation (U_g = 5 m s^{-1} and $H_{\max}$ = 200 W m^{-2}). Variables shown are θ' on the lowest model level (grey shading, 1 K intervals), w at 600 m (colour shading, m s^{-1}), and $\mathbf{u}'$ at 60 m (vectors); primes indicate perturbations from the initial state. Tick marks on the axes are every 50 km.

4. Sensitivity to wind speed and heat flux

- Four sensitivity tests performed with U_g and $H_{\max}$ increased and decreased by 50 %
- Both parameters strongly influence the evolution of the SBFs (Fig. 3)

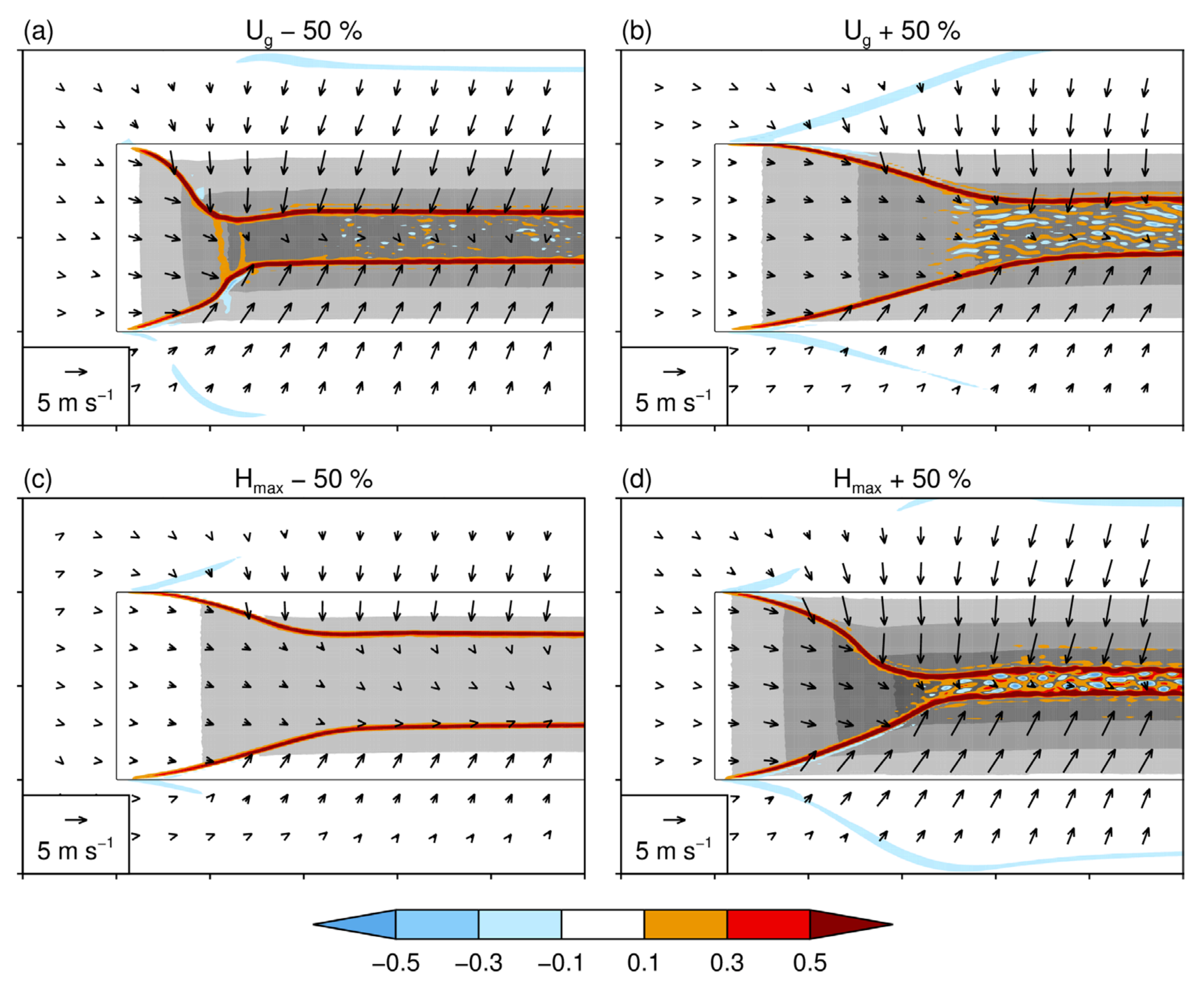

Fig. 3 As in Fig. 2 but for a single time (1500 LST) in the sensitivity runs with (a) U_g = 2.5 m s^{-1} and $H_{\max}$ = 200 W m^{-2}, (b) U_g = 7.5 m s^{-1} and $H_{\max}$ = 200 W m^{-2}, (c) U_g = 5 m s^{-1} and $H_{\max}$ = 100 W m^{-2}, and (d) U_g = 5 m s^{-1} and $H_{\max}$ = 300 W m^{-2}.

5. Sea breeze scaling

- Based on the pure sea breeze scalings of Steyn (1998, 2003), Tijm (1999), and Porson et al. (2007), we let $v_{sb} = \alpha v_s$ where

$$v_s = \left(\frac{g\hat{H}}{\rho c_p T_0}\right)^{1/2}$$

is the scaling velocity, with g the acceleration due to gravity, $\hat{H}$ the time-integrated surface sensible heat flux, ρ the air density (taken as 1.2 kg m^{-3}), c_p the heat capacity of air at constant pressure, and T_0 a reference temperature (taken as the prescribed surface temperature)

- We then assume a linear relationship between the sea breeze velocity and the SBF velocity, of the form $v_{sbf} = \beta v_{sb}$
- The constants α and β are determined through linear regression
- The integrated heat flux must be computed along the west-to-east trajectory defined by the background flow – at time t and downstream distance x, it is given by

$$\hat{H}(x,t) = \hat{H}(x - \delta x, t - \delta t) + \frac{\delta t}{2}\left[H(x - \delta x, t - \delta t) + H(x,t)\right]$$

where δt is the time interval (set as 60 s), $\delta x = U\delta t$ is the space interval, and U is the low-level along-shore flow speed (set as $0.855U_g$ through experimentation to minimise errors in y_{sbf}; see below)

- The SBF position y_{sbf} can then be determined through integration, again along the trajectory defined by the background flow:

$$y_{sbf}(x,t) = y_{sbf}(x - \delta x, t - \delta t) + \frac{\delta t}{2}\left[v_{sbf}(x - \delta x, t - \delta t) + v_{sbf}(x,t)\right]$$

- This relation is able to predict the structure and inland movement of the SBFs remarkably well (Fig. 4), although it cannot capture the north/south asymmetries which are more pronounced with large U_g

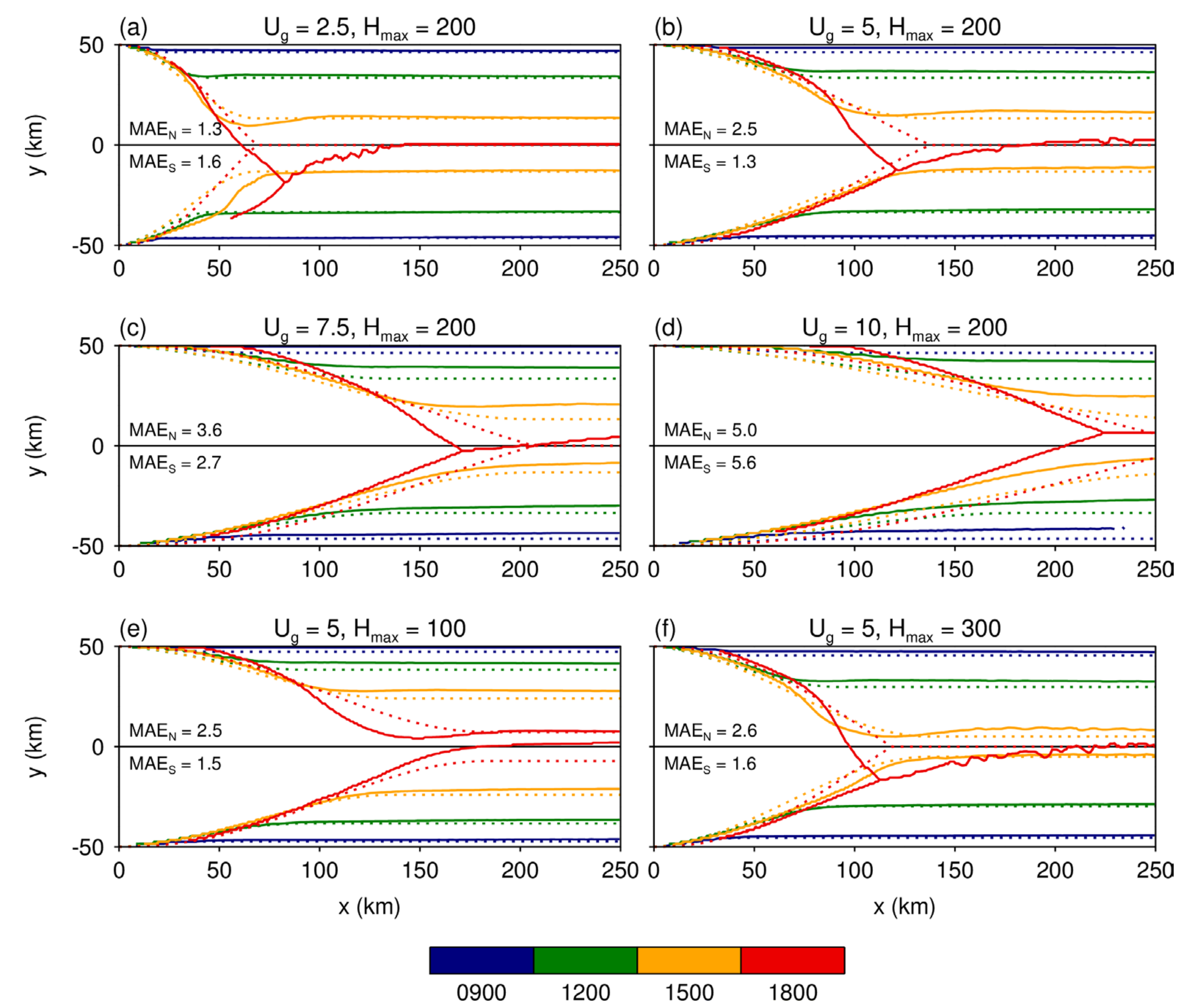

Fig. 4 Simulated (solid) and scaling-derived (dotted) SBF positions y_{sbf} as a function of time (colours, LST) for simulations with (a) U_g = 2.5 m s^{-1} and $H_{\max}$ = 200 W m^{-2}, (b) U_g = 5 m s^{-1} and $H_{\max}$ = 200 W m^{-2}, (c) U_g = 7.5 m s^{-1} and $H_{\max}$ = 200 W m^{-2}, (d) U_g = 10 m s^{-1} and $H_{\max}$ = 200 W m^{-2}, (e) U_g = 5 m s^{-1} and $H_{\max}$ = 100 W m^{-2}, and (f) U_g = 5 m s^{-1} and $H_{\max}$ = 300 W m^{-2}. Mean absolute errors (MAE; km) for the north (N) and south (S) coast SBFs are given in each panel.

6. Asymmetric peninsula

- Runs performed with south coast angled 15° w.r.t north coast
- With U = 10 m s^{-1} and $H_{\max}$ = 200 W m^{-2}, the south coast sea breeze is significantly weaker and the north coast SBF moves inland much more slowly and stalls around 20 km from the coast (Fig. 5)
- This is reminiscent of SBFs over the UK Southwest Peninsula under southwesterly flow which can initiate flash flood–producing quasi-stationary convective systems (Golding et al. 2005; Warren et al. 2014)

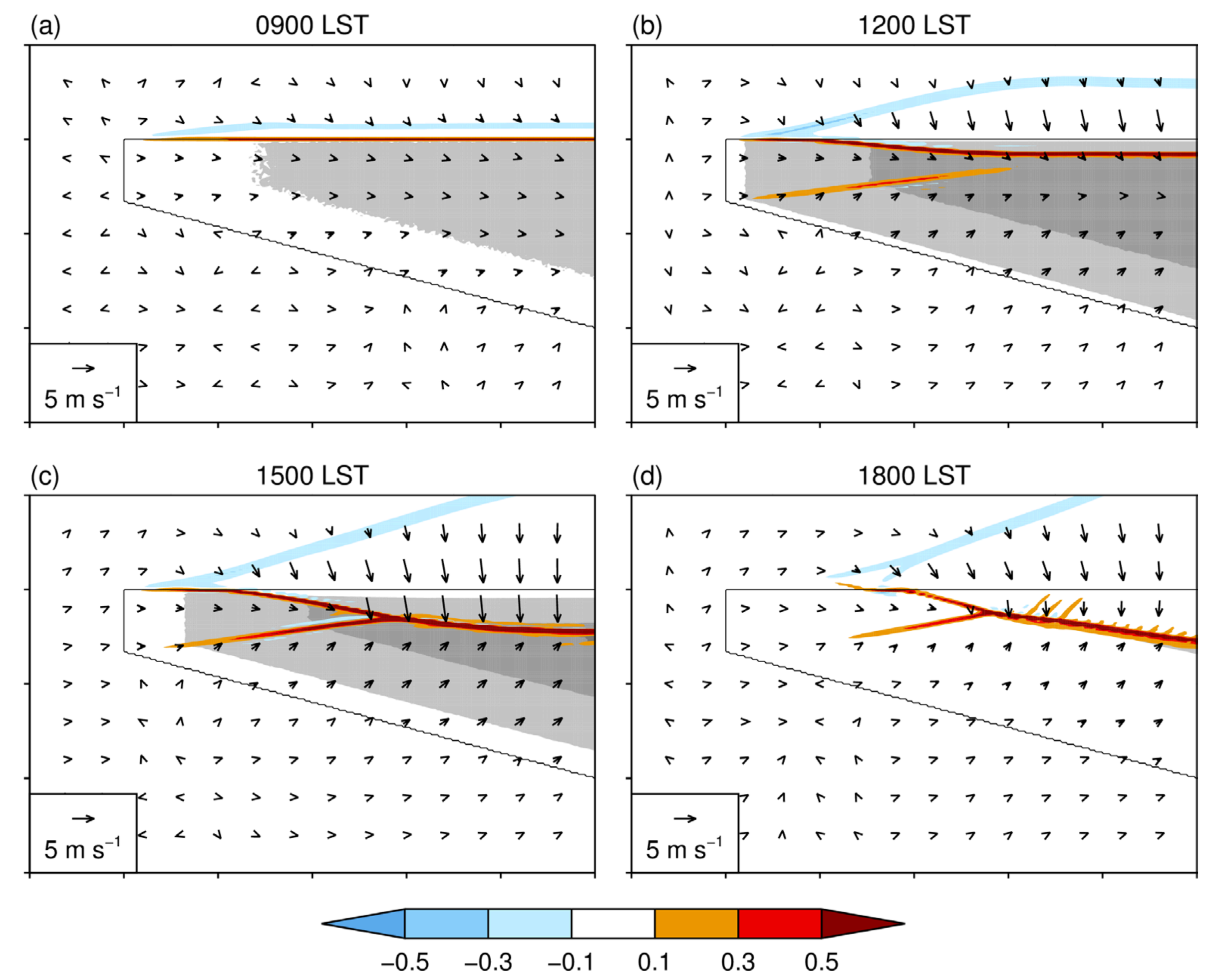

Fig. 5 As in Fig. 2 but for a simulation with U_g = 10 m s^{-1} and $H_{\max}$ = 200 W m^{-2} and an angle of 15° between the north and south coasts.

7. Conclusions

- The along-shore component of the ambient wind plays a significant role in sea breeze evolution over a peninsula (or elongated island)
- As the sea breeze moves inland it is advected downstream, resulting in quasi-stationary SBFs near the upstream end of the peninsula; these may provide a mechanisms for repeated convective initiation
- The evolution of the SBFs as a function of downstream distance is strongly influenced by both the wind speed and the surface heat flux
- A modified scaling for pure sea breezes reproduces this behaviour very well; however, it cannot represent asymmetries associated with the Coriolis force
- The evolution is notably changed when the peninsula is asymmetric
- Possible future work: modify the scaling to deal with a non-zero cross-shore flow component

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