Atmos. Chem. Phys. Discuss., 13, 24785–24807, 2013
www.atmos-chem-phys-discuss.net/13/24785/2013/
doi:10.5194/acpd-13-24785-2013

Atmospheric Chemistry and Physics
Discussions
Open Access

A case study of sea breeze blocking regulated by sea surface temperature along the English south coast

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Received: 6 August 2013 – Accepted: 22 August 2013 – Published: 24 September 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The sensitivity of sea breeze structure to sea surface temperature (SST) and coastal orography is investigated in convection-permitting Met Office Unified Model simulations of a case study along the south coast of England. Changes in SST of 1 K are shown to significantly modify the structure of the sea breeze. On the day of the case study the sea breeze was partially blocked by coastal orography, particularly within Lyme Bay. The extent to which the flow is blocked depends strongly on the static stability of the marine boundary layer. In experiments with colder SST, the marine boundary layer is more stable, and the degree of blocking is more pronounced. The implications of prescribing fixed SST from climatology in numerical weather prediction model forecasts of the sea breeze are discussed.

1 Introduction

A sea breeze is a mesoscale circulation driven by the differential heating of land and sea surfaces. It is characterised by a surface flow from the sea towards the land, and a deeper, weaker return flow aloft. Sea breezes have been extensively studied world-wide due to their daily recurrence in many regions of dense human population. They are particularly of interest to air-quality control bodies and many marine and littoral industries. Miller et al. (2003) review the large range of geophysical factors upon which the sea breeze depends, including surface temperature variation, diffusion of heat, topography, acoustic wave propagation, the Coriolis force, static stability, and the synoptic-scale flow. In this paper we demonstrate the critical dependence of sea breeze structure on sea surface temperature (SST) for a case study on the English south coast.

The land-sea temperature difference is one of the most important factors influencing sea breeze development, and without which the sea breeze would not form. The large amplitude of the diurnal heating of the land surface is well known. However, changes in

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sea surface temperature also play a strong role in air-sea interaction (Kawai and Wada, 2007). Any variability in the sea surface temperature (SST) over timescales of months, weeks, days and even hours impacts the atmospheric boundary layer and may affect sea-breeze formation.

Early numerical studies of the sea breeze demonstrated a relative lack of sensitivity of the sea breeze to SST in low wind conditions (Segal and Pielke, 1985). Arritt (1987) concluded that as long as the surface layer over the water body remains stably stratified, then the water temperature does not make a difference to the sea breeze. More recent studies have concluded that the impact of SST on the sea breeze is stronger than was previously thought. Kawai et al. (2006) investigated the effect on the surface wind field of a diurnal variation in SST within Mutsu Bay, Japan – a semi-enclosed sea. Diurnal SST variation is climatologically high in most semi- to fully-enclosed seas such as the Mediterranean, the Arabian Sea, the Sea of Okhotsk and the Sargasso sea. In conditions of high insolation and weak gradient wind speed the diurnal amplitude of the SST in Mutsu Bay is large, up to 5 K in some areas. Due to this, Kawai and Wada (2007) estimated that the simulated heat flux from the ocean is underestimated by an average of $10\,\mathrm{W\,m^{-2}}$ by midday. Kawai et al. (2006) analysed SSTs from NOAA-AHVRR satellite retrievals and in-situ buoy data and found that for over 80 % of the days between April and September when the diurnal SST signal exceeded 1.0 K the daytime upslope wind speed remained below $5.0\,\mathrm{m\,s^{-1}}$. By comparing numerical simulations of the sea breeze with and without a coupled mixed-layer ocean model, Kawai et al. (2006) demonstrated that while the sea breeze circulation does not change structurally, the circulation was weaker in the coupled diurnally-varying SST run than in the uncoupled fixed SST control run.

Tang (2012) investigated the effect of hourly-updated SST in a convection-permitting numerical model simulation of the sea breeze in the southern UK. The SST from a shelf sea model was on average 1.5 K warmer than the fixed values of a control run in which the SST was initialised with Operational Sea Surface Temperature and Sea Ice (OSTIA; Donlon et al., 2012) data. The consequences of a warmer SST were a weaker sea breeze, a less stable marine boundary layer, and less fog and mist. Tang (2012) presented this case study as evidence that short-term forecasts could be improved if operational regional-scale numerical weather prediction (NWP) models such as the Met Office Unified Model (MetUM) incorporated diurnally-varying SST.

The objective of this study is to determine the sensitivity of the sea breeze along the English south coast to SST and coastal orography. At present, the Met Office prescribes climatological SSTs with no diurnal variation in their regional-scale operational NWP forecasts. As in Tang (2012), a motivation for performing the analysis described in this paper is to determine what errors in sea-breeze structure result from prescribing fixed SST. To accomplish this goal, hindcasts for a case study day are generated using the MetUM. In a control run, the SST field is prescribed from the OSTIA climatological dataset. Additional experiments are performed using SST fields perturbed from the OSTIA values, with and without coastal orography. Sea-breeze dynamics and characteristics – including timing, strength, direction and depth – are analysed for each hindcast. The paper is organized as follows. The methodology is described in Sect. 2, including a description of the case study region and the design of numerical experiments. An overview of the synoptic conditions on the day of the case study is presented in Sect. 3. In Sect. 4, the sea breeze in a control simulation with unperturbed SST is described, and in Sect. 5 simulations of the sea breeze with perturbed SST, with and without coastal orography, are compared. The results and implications for short-term NWP forecasts are discussed in Sect. 6.

2 Methodology

The design of numerical experiments is described in this section, along with a detailed presentation of the SST and coastal orography in the region of interest.

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2.1 Case study location

The analysis presented in this paper focuses on a stretch of coastline in southern England surrounding Weymouth (58.62° N, 2.62° W). The coastal topography in the vicinity of Weymouth and the locations of two observational platforms, Lyme Bay and Portland Harbour, are shown in Fig. 1a. The platform labelled "Portland Harbour" is located on a breakwater on the southeast side of The Isle of Portland – a large promontory approximately 6 km long and 2.5 km wide extending south of Weymouth (not marked on the map). The orography to the northwest of Weymouth consists of hills of approximately 150 m elevation. To the northeast of Weymouth the topography of the mainland is relatively flat.

Weymouth Bay is shallow, with a maximum depth of 25 m. It faces south-east and is approximately 12.5 km wide. It is not a semi-enclosed sea (like Mutsu Bay that was studied by Kawai et al., 2006), but the shallow depth and small dimensions suggest a potential for large diurnal SST variations (see Sect. 2.2). The prevailing winds are in the south to west quadrant, and occur 61 % of the year (Risien, 2013).

Lyme Bay lies to the west of the Isle of Portland. It is an open bay facing south, approximately 55 km wide. Eastern Lyme Bay, adjacent to the Isle of Portland, has an approximately straight coastline facing south-west. The orography rises steeply to 160 m above sea level.

2.2 Numerical model description

The MetUM version 7.3 is employed for this study. The MetUM solves the fully compressible, nonhydrostatic equations of motion using a semi-Lagrangian, semi-implicit time integration scheme with a fifth-order-accurate spatial differencing scheme on an Arakawa-C grid with a terrain following vertical coordinate (Davies et al., 2005). The model is run with a full suite of parameterization schemes including a mixed phase microphysics scheme (Wilson and Ballard, 1999), the MOSES-II boundary layer scheme (Lock et al., 2000), and the Gregory-Rowntree mass-flux convection scheme (Gregory and Rowntree, 1990). Orography in the model is derived from the GLOBE (The Global Land One-km Base Elevation) dataset.

In this project the MetUM is configured as an atmosphere-only series of nested model runs: a global run, a 12 km horizontal grid spacing run over the North Atlantic European (NAE) domain, a 4 km horizontal grid spacing run over a UK-only domain, and a 1 km horizontal grid spacing run centred on the English Channel, as depicted in Fig. 1b. The presentation of results in Sects. 4 and 5 focus on the simulations run with 1 km grid spacing. In the configuration that uses 1 km grid spacing, the convection scheme is disabled. The larger domains provide the lateral boundary conditions for the smaller domains, with the initial and lateral boundary conditions for the NAE domain sourced from the global run. The NAE domain covers 7200 km by 4320 km with 38 vertical levels; the 4 km grid spacing simulation covers 1600 km by 1120 km across the UK with 38 levels; the 1 km grid spacing simulation covers 600 km by 360 km with 76 levels. The model top is located 39.2 km above ground level. The 12 km grid spacing run begins at 12:00 UTC on 7 August 2010, the UK domain run with 4 km grid spacing begins at 00:00 UTC on 8 August 2010 and the 1 km grid spacing run begins at 06:00 UTC on the same day. The run-times are offset in order to allow for the model at each resolution to "spin up" smaller-scale structures.

Numerical experiments are performed with the 1 km grid spacing configuration using three different SST fields to assess the sensitivity of the sea breeze to changes in SST. Each is derived from the daily 0.5 degree OSTIA dataset interpolated onto the 1 km grid. The three SST fields are (a) the OSTIA SST without perturbation, (b) the OSTIA SST plus a 1 K uniform temperature perturbation, and (c) the OSTIA SST minus a 1 K uniform temperature perturbation. After initialization, SST is constant throughout each model run. Figure 2a shows the unperturbed OSTIA SST field in the 1 km domain. Each of these three experiments is performed both with and without orography. In the experiments without orography, the elevation of the lower boundary is set to 0 m above sea level everywhere in the 1 km domain. A total of six numerical experiments are therefore performed in the 1 km domain. The experiment with unperturbed OSTIA SST

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and unperturbed orography is hereafter referred to as the control experiment and is analysed in Sect. 4. The perturbed experiments are examined in Sect. 5.

A comparison of the numerical experiment SST values and the observations for the case study day is shown in Fig. 2b. The observations of the Weymouth waverider buoy – located on the western shore of Weymouth (see Fig. 1a) – measured SST during the day ranging from 290.2 K to a maximum of 290.5 K. The OSTIA value is slightly cooler than the observations. It should be noted that the model SST values shown in Fig. 2b apply only to the gridbox nearest the waverider buoy, and the relative differences between observations and model may not hold across the entire domain. Figure 2c presents the observed SST over two years at this buoy. Monthly variations are typically about 2 K, and the diurnal variation occasionally exceeds 1 K. The 2 K range of SST values prescribed in the numerical experiments performed in this study is therefore representative of the SST error that may result when SST is prescribed using diurnally-fixed climatological values.

3 Case study overview

Synoptic and in-situ meteorological observations for the case study are described in this section. The surface pressure analysis chart for 00:00 UTC is shown in Fig. 3a. The synoptic situation on 8 August 2010 was characterised by an area of high pressure to the southwest of the UK, with an associated ridge that extended towards both Scotland and western France. The geostrophic wind for Weymouth on the English south coast was light northerly. The synoptic-scale pressure gradient weakened slightly during the day (not shown).

A visible satellite image of the southern UK at 15:00 UTC on the case study day indicates a sea breeze on the south coast (Fig. 3). This image shows cloud cover over most inland areas of England. Some cirrus existed over the south-west of the UK in the early morning, with shallow cumulus clouds developing after sunrise. When a sea-breeze circulation is established the sea-breeze inflow rises at the sea-breeze front

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generating convective cumulus clouds; the descending air of the return flow is dry, causing clear skies over the sea. The clear air over the English Channel adjacent to the coast is indicative of a sea-breeze circulation with a sea-breeze front likely to be present at the boundary between the clear skies and the cumulus clouds. The inshore extent of the sea breeze can be estimated by the width of clear skies from the shoreline towards inland areas along the south coast.

4 Control simulation

Model output for the control experiment shows a clear sea breeze signal along the south coast on 8 August 2010. The dynamics and characteristics of the sea breeze are examined in this section.

Figure 4 depicts the 10 m above ground level (a.g.l.) surface winds in a subdomain of the 1 km grid domain around Weymouth. The 11:00 UTC wind field (Fig. 4a) shows the beginning of the sea-breeze circulation. An area of light winds of variable direction exists off the coast. Inshore at Weymouth there is a south to south-westerly flow at the coast. This inflow is met by a weaker but more uniform north-north-westerly flow over the land. The line of convergence of these two flows is the sea-breeze front.

At 15:00 UTC (Fig. 4b) the sea breeze is well established, with both the offshore and inshore extent increased. The inland penetration of the sea breeze front is approximately 15–20 km at most locations along the coast. Offshore, the sea breeze is nearly uniform south-westerly flow as the circulation strengthens, deepens, and aligns perpendicular to the land mass of England rather than localised land features. The sea-breeze strength is reasonably consistent across the sea with one notable exception in Lyme Bay. The exception is a narrow region of weaker surface winds located immediately offshore. This feature is hereafter referred to as the "calm zone" and will be examined later in this section.

Figure 5 presents a comparison of 10 m a.g.l. wind time series between observations and simulations at the grid points nearest to Portland Harbour and Lyme Bay. Although

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the time series for all six numerical simulations are shown in this figure, discussion of the perturbation experiments is deferred to Sect. 5. At both locations, the wind speed and direction both prior to and following the sea breeze onset are very similar in the observations and control simulation. The wind strength behind the sea breeze front is twice as strong at Portland Harbour (approximately 6 $m s^{-1}$) as at Lyme Bay (approximately 3 $m s^{-1}$). The reduced wind speed at Lyme Bay, seen in both observations and simulation, is due to the presence of the calm zone near the shore (see Fig. 4b). The most discernible difference between the control simulation and observations is seen in the timing of the sea breeze onset. At both locations, the sea breeze front in the simulations leads the observations by approximately 45 min.

5 Simulations with perturbed SST and smoothed orography

The effect of SST and coastal orography on the sea breeze is examined in this section. As discussed in the previous section, Fig. 5 presents 10 m a.g.l. winds in Portland Harbour and Lyme Bay in observations and in the three experiments with perturbed SST and unperturbed orography. The numerical experiment with the warmest SST field (red curves) has the latest sea breeze onset time, and the experiment with the coolest SST (blue curves) has the earliest. At Portland Harbour, the perturbation of SST affects the sea breeze onset time but does not have a very strong effect on the wind strength and direction after the passage of the front. At Lyme Bay, which lies within the calm zone (see Fig. 4b), the simulations with warmer SST produce a *stronger* wind than the simulations with cooler SST. In other words, a larger land-sea temperature contrast results in a weaker wind speed at Lyme Bay following the passage of the sea breeze. This counterintuitive result is a consequence of the sea breeze circulation being partially blocked by the coastal orography, as will be demonstrated in the remainder of this section. The degree of blocking is determined in part by the static stability of the marine boundary layer. A cooler SST implies a more stable marine boundary layer,

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which permits a greater degree of blocking, which results in weaker winds immediately offshore.

A comparison of the 10 m a.g.l. winds in the six experiments with perturbed SST and orography is presented in Fig. 6. The presence of a calm zone offshore in Lyme bay is only evident in the runs with orography (left column, Fig. 6). The runs without orography (right column, Fig. 6) produce a more uniform wind field offshore and there is no evidence of a calm zone. The run with the coolest SST and orography (Fig. 6a) produces a calm zone that is broader and more pronounced than in the control run (Fig. 6c) or in the run with warmest SST (Fig. 6e). The effect of SST alone on the surface structure of the sea breeze in the absence of orography is not very pronounced, as can be seen by comparing the perturbed SST experiments without orography (compare panels Fig. 6b, d, f).

The time of sea breeze onset as a function of distance from shore along the sections through Lyme Bay and Portland Harbour marked in Fig. 4b is presented in Fig. 7, along with snapshots of 10 m a.g.l. wind speed along these sections at 15:00 UTC. The time of sea breeze onset is defined at each point in the section as the first time when wind speed exceeds 2 $\mathrm{m\,s^{-1}}$. Changing the value of the threshold between 1 and 3 $\mathrm{m\,s^{-1}}$ does not change the speed or uniformity of the offshore propagation (not shown), although the onset time is delayed; this is due to the large gradient in wind speed at the sea-breeze front. (The inland propagation speed of the sea breeze can be defined as the speed at which the sea-breeze front advances inland, Finkele 1998.) The speed of the extension of the sea breeze circulation can be inferred from the slope of the curves in Fig. 7a, c and appears approximately constant in each direction from the gridbox of earliest onset. However, the sea-breeze spreads more rapidly offshore than inland. The reasons for this are not clear and to the authors' knowledge have not been investigated in the literature, but are likely due to the inherent differences between the sea-breeze front (which exhibits gravity current behavior) and the broader, weaker, rearward side of the circulation.

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The wind speeds at 15:00 UTC in the Lyme Bay and Portland Harbour sections are shown in Fig. 7b, d. In the Portland Harbour section, the sea breeze front is advanced farther inland and the offshore wind speed is approximately $1\,m\,s^{-1}$ stronger in the experiments with orography compared to those without orography. In the Lyme Bay section, the calm zone is evident within the first 10 km offshore in the experiments with orography. The calm zone is stronger in the runs with colder SST. In the runs without orography, no such decrease in offshore wind speed is evident. Changing the SST does not lead to a significant change in the overall strength of the sea breeze, but it can significantly modify the structure of the sea breeze, as demonstrated below.

Figure 8 presents vertical cross sections of the sea breeze circulation through Lyme Bay. In all experiments, the sea breeze circulation is characterized by a region of inflow near the surface and a return flow aloft. The top of the leading edge of the sea breeze front is elevated. In the experiments without orography (Fig. 8b, d, f), the height of the interface slopes gently downwards for the first 10 km or so behind the elevated sea-breeze front. In the experiments with orography (Fig. 8a, c, e), there is a secondary jump in the elevation of the interface in the vicinity of the shoreline. This secondary jump is associated with airflow over the coastal topography. Furthermore, a shallow region of reduced wind speeds (i.e., the calm zone) is evident immediately offshore which is not present in the runs without orography. This shallow region of stagnation is more pronounced in the run with cold SST (Fig. 8a) than in the run with warm SST (Fig. 8e).

Stagnation of flow on the windward side of an obstacle can be understood in terms of the Froude number $Fr = U/(HN)$, where N is the Brunt-Väisällä frequency, U is the speed of the flow approaching the obstacle, and H is the height of the barrier. The Froude number characterizes the relative importance of the flow inertia versus the resistance to lifting imposed by the static stability. A Froude number less than 1 is associated with blocking. A stronger flow would discourage blocking, whereas a stronger static stability would encourage blocking. For all of the experiments shown in Fig. 8, the onshore flow is approximately $6\,m\,s^{-1}$ (see also Fig. 7d). However, the static stability varies significantly between the cold and warm SST experiments (for the runs with orography). The vertical temperature gradient in the cold experiment (inferred from Fig. 8a) is approximately 5 K/(100 m) in the lowest 100 m; in the warm experiment the gradient (inferred from Fig. 8e) is approximately 2 K/(100 m). The corresponding Froude numbers are estimated to be approximately 1 in the cold SST experiment (i.e., right at the blocking threshold) and 1.5 in the warm SST experiment. Consequently, the calm zone that exists in Lyme Bay is consistent with partial flow blocking by orography enhanced by colder SST.

6 Conclusions

The effect of SST and coastal orography on the sea breeze along the south coast of England has been investigated in a set of convection-permitting numerical simulations with the MetUM. The previous studies of Tang (2012) and Kawai et al. (2006) demonstrated that warmer SST leads to a weaker sea breeze. Elaborating on these previous studies, it has also been shown that the interaction of the sea breeze with coastal orography results in a narrow region of decreased wind speeds immediately offshore. Termed the "calm zone", the decreased winds are a consequence of partial blocking of the onshore sea-breeze circulation by the orography. The existence of the calm zone was verified by observations. The calm zone only formed in those model runs with coastal orography. Furthermore, the extent of blocking was most pronounced in those model runs having the coldest SST. Although a colder SST would normally generate a stronger sea breeze circulation – an effect which by itself would discourage blocking of the flow – a colder SST also results in a more stable marine boundary layer, and the increased static stability of the onshore flow encourages blocking. In the simulations presented in this study, the increased static stability dominated the effect of increased onshore sea-breeze winds and, as a consequence, blocking was more pronounced for the colder SST experiments.

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The perturbation SST of ±1 K used in this study is representative of the SST errors that are likely to occur in operational NWP forecasts that do not incorporate diurnally-varying SST. As Tang (2012) demonstrated, the errors can indeed be much larger locally (e.g., 4 K as seen in Fig. 2c). The study presented in this paper has emphasized that even a small SST perturbation can have dramatic consequences for the structure of the sea breeze circulation on small scales. Small changes in SST can be amplified due to the strong regulating influence of static stability in the marine boundary layer on the sea breeze structure, such as in the case of onshore winds interacting with coastal topography. We therefore conclude that inclusion of the diurnal cycle of SST is essential for correct representation of the sea breeze in regional scale NWP forecasts, particularly when the Froude number is near unity. Accurate forecasts of the sea breeze are critical to many end users including those in the marine, littoral, and air-quality control industries.

The study presented in this paper focussed on a single case study along the south coast of England. The conclusions drawn from this investigation are likely to be relevant to other coastal locations in the midlatitudes that have coastal orography and modest diurnal SST variation. Nevertheless, analysis of additional cases in different locations is required to determine how frequently the sea breeze is blocked by coastal topography and whether the characteristics of this blocking are sensitive to the details of the synoptic-scale flow. Additionally, a more detailed analysis of boundary-layer processes is required to elucidate the precise manner by which the SST and sea-breeze inflow interact to modify the structure of the marine boundary layer.

Acknowledgements. The authors thank Yongming Tang for discussions that led to the formulation of the experiments presented in this paper. Jeffrey Chagnon is supported by the National Centre for Atmospheric Science (NCAS) under the Weather Directorate.

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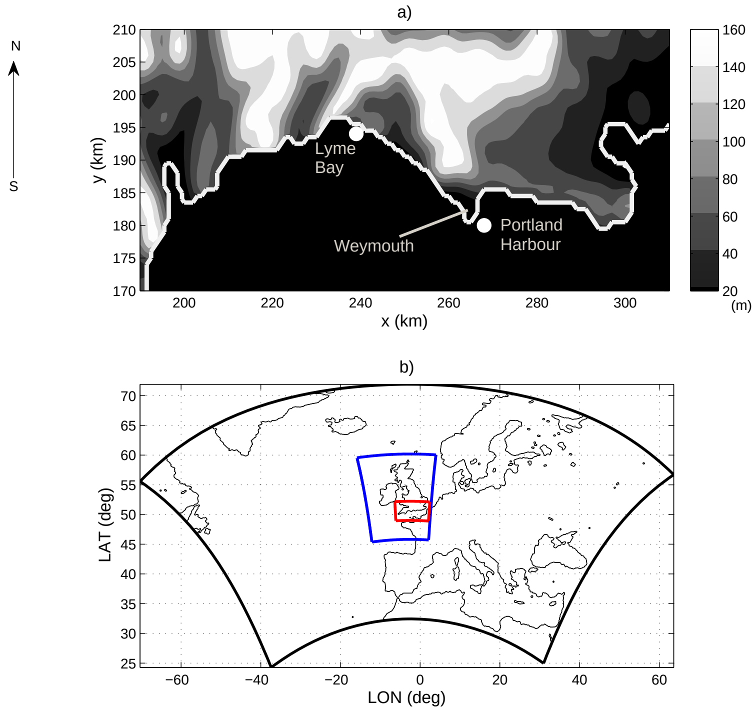

Fig. 1. (a) Orography in the vicinity of Weymouth as used in the 1 km grid spacing MetUM simulation (note this is a subregion of the full domain used in the 1 km simulation). **(b)** The location of the nested model domains. The area enclosed by the black border is the 12 km grid spacing North American European (NAE) domain, the blue is the 4 km grid spacing UK domain, and the red is the 1 km grid spacing English Channel domain. The locations of the Portland Harbour and Lyme Bay observational platforms are depicted by the white circles in **(a)** (data shown in Fig. 5).

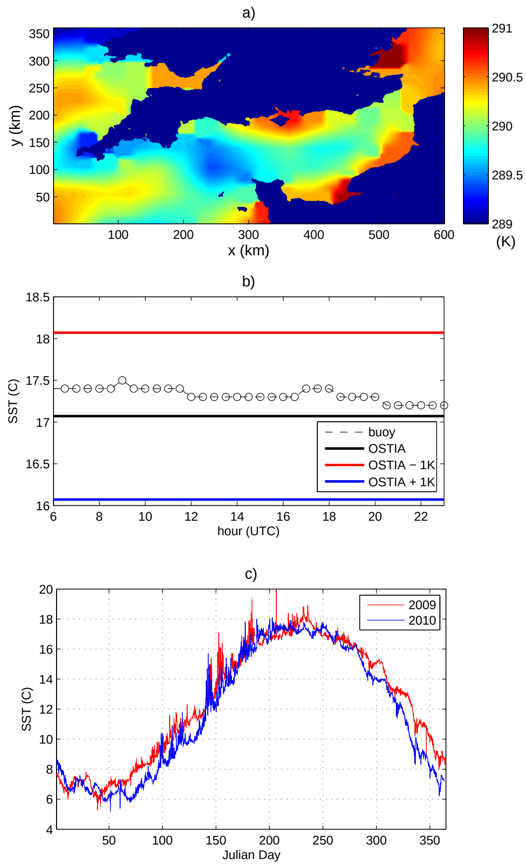

Fig. 2. (a) OSTIA SST in the 1 km MetUM domain. **(b)** Observed SST from the Weymouth Waverider buoy (black circles) and SST used in simulations (solid lines) as a function of time on the day of the case study. **(c)** Observed SST during the years 2009 and 2010 from the Weymouth Waverider buoy. (Waverider buoy data supplied by the Channel Coastal Observatory.)

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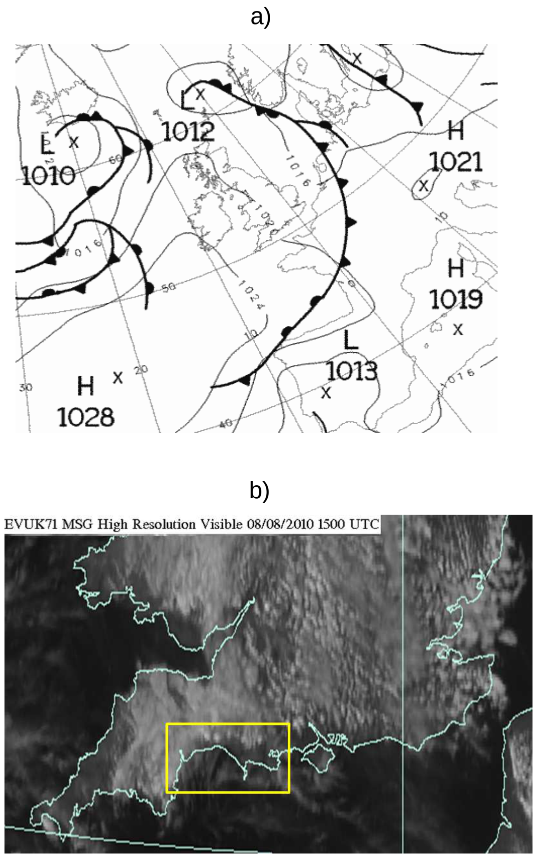

Fig. 3. (a) Met Office surface analysis valid at 00:00 UTC on 8 August 2010. **(b)** Visible satellite image over southern UK at 15:00 UTC 8 August 2010. The yellow box in **(b)** corresponds to the domain of the MetUM simulations run with 1 km grid length that are presented in Sects. 4 and 5. Images courtesy of the Met Office (Crown Copyright).

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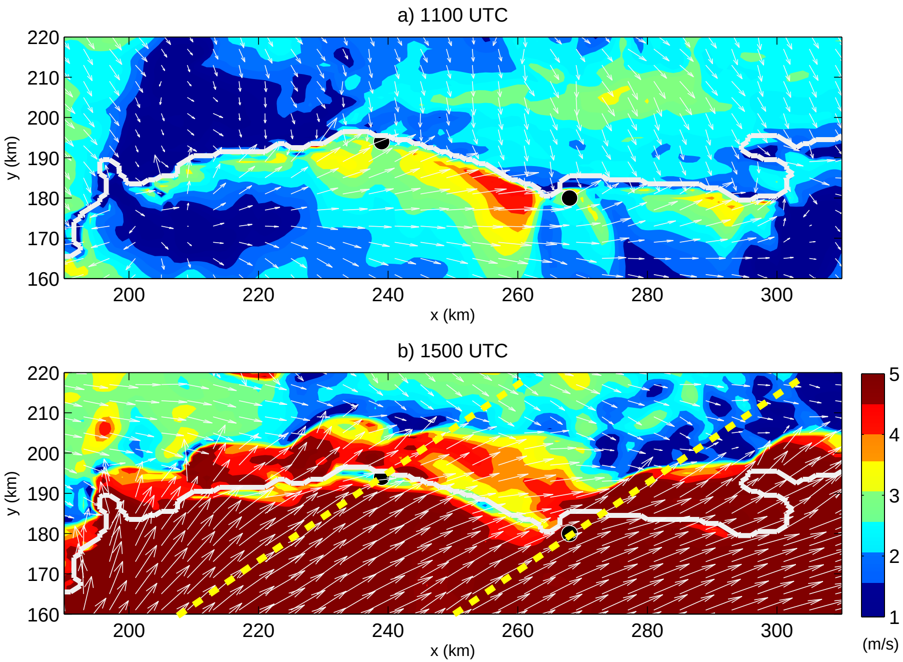

Fig. 4. Wind speed (filled contours) and wind vectors at 10 m a.g.l. in the control simulation valid at **(a)** 11:00 UTC and **(b)** 15:00 UTC. The black circles depict the location of the Portland Harbour and Lyme bay observational platforms (Fig. 1a), and the yellow dashed lines correspond to the sections in Figs. 7 and 8.

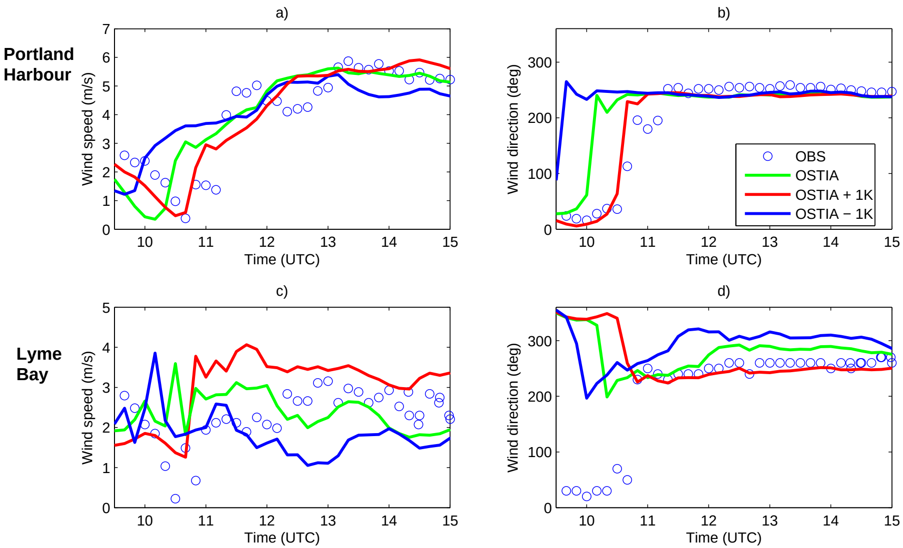

Fig. 5. A comparison of observed and simulated 10 m wind speed and direction at the Portland Harbour and Lyme Bay observational platforms. Modelled and observed data are plotted at 10 minute intervals. (Data supplied by the Channel Coastal Observatory.)

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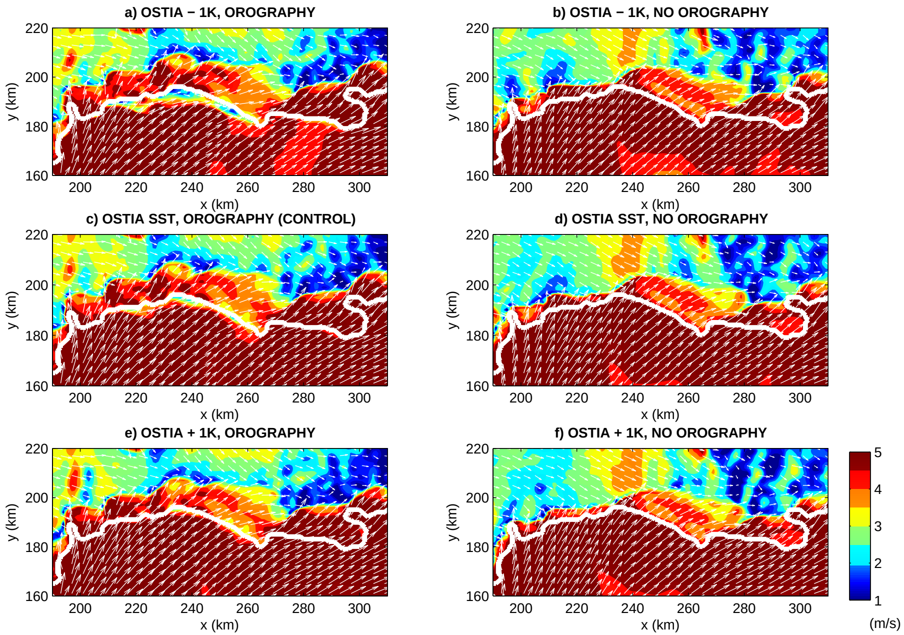

Fig. 6. Wind speed (filled contours) and vectors at 10 m a.g.l. at 15:00 UTC (as in Fig. 4) for the perturbed-SST experiments, with and without orography. **(c)** is identical to Fig. 4b but is included to enable direct comparison with the perturbed experiments.

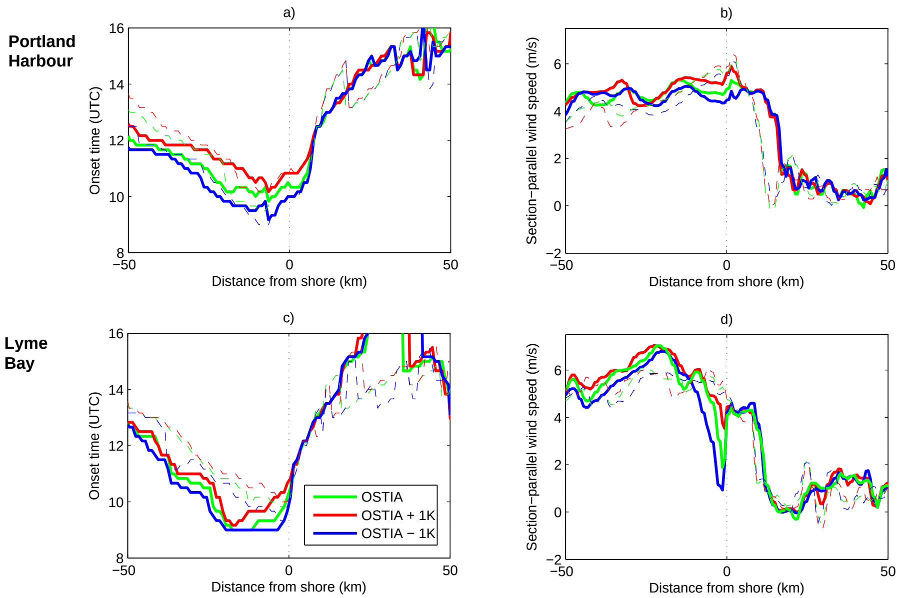

Fig. 7. Sea breeze onset time (left column) and 10 m southwesterly wind component at 15:00 UTC (right column) along SW-NE oriented sections passing through Portland Harbour (first row) and Lyme Bay (second row). Experiments with orography are indicated by the solid lines, and experiments without orography are indicated by the dashed lines. The locations of Lyme Bay and Portland Harbour are shown in Fig. 1a, and the location of the cross-sections are shown in Fig. 4b. Lines plotted using model output with 10 min temporal and 1 km horizontal spacing. Positive distance is inland and negative distance is offshore.

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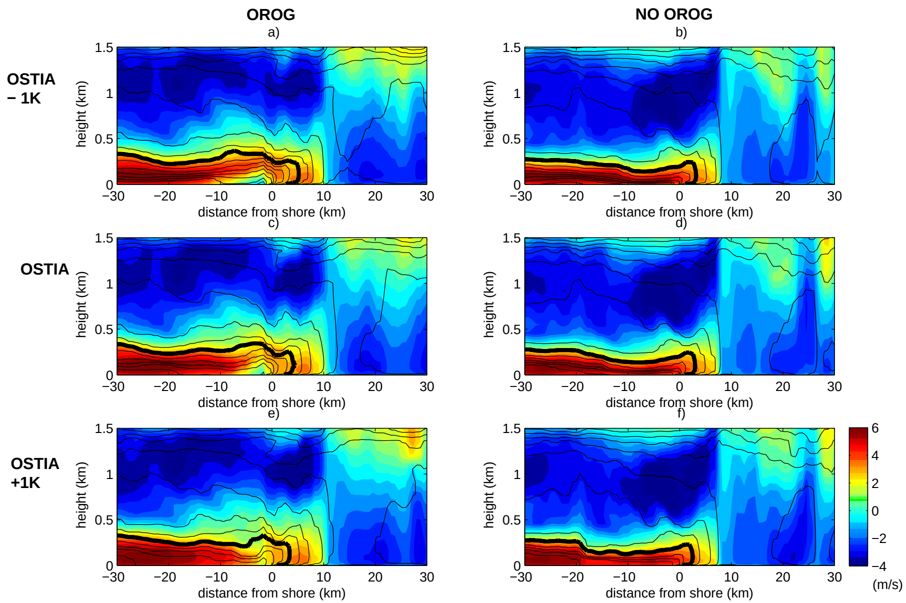

Fig. 8. Vertical cross-sections along a SW-NE transect through Lyme Bay at 15:00 UTC. The section-parallel wind component (filled contours) and isentropes (black contours, every 0.5 K) are shown for each of the perturbed-SST simulations with and without orography. For reference, the thick black contour is the 291 K isentrope. Height corresponds to the terrain following model coordinate.

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