Persistent northerly-to-easterly cold-air outbreaks affected the UK during the winters of 2009–2010 and 2010–2011, with the resulting convection frequently organizing into snowbands over the English Channel and Irish Sea. Sounding data and composite radar reflectivity images from the Met Office Nimrod precipitation radar network reveal that these bands formed along the major axis of each body of water (or sea) when the boundary-layer flow was roughly parallel to each of those axes (along-channel). For both seas, a band was present the majority of times that the 850 hPa flow was along-channel. Of these times of along-channel flow, the 850 hPa wind speed and surface-to-850 hPa temperature difference were significantly greater when bands were present than when they were not. For the English Channel only, the land–sea temperature difference was also significantly greater when bands were present than when they were not. In a real-data Weather Research and Forecasting model (WRF) control simulation of a typical band over the English Channel, a trough develops over the water and offshore air streams from either side converge along it. In the absence of surface fluxes, the trough, convergence and organized precipitation fail to develop altogether. Orography and roughness-length variations are less important in band development, affecting only the location and morphology.

Key Words: lake effect; land breeze; radar; WRF; convection; snowbands; cold-air outbreaks

1. Introduction

During the winters of 2009–2010 and 2010–2011, anti-cyclonic blocking over the North Atlantic led to an anomalous synoptic-scale flow regime over northern Europe, with extremely cold, dry air being advected over the UK from the north and east. With the polar jet typically a long way south, often as far as the Mediterranean Sea, fewer cyclones affected the UK than during a westerly regime and hence synoptic-scale fronts were less of a factor in generating precipitation. Instead, the precipitation during these periods was characterized by clusters of convective cells arriving from the North Sea and organizing around the UK’s coasts (Figure 1). Snow resulting from this convection fell in the same locations for several consecutive days. With temperatures barely rising above freezing during the daytime, snow accumulated as Arctic air flowed over the UK. In January 2010 and December 2010 (the culmination of the blocking in each of the winters), almost the whole country experienced at least eight and twelve days of snow cover, respectively (http://www.metoffice.gov.uk/climate/uk/anomacts/). In both winters, snow depths exceeding 10 cm were widespread around the country with depths up to 50 cm in some locations over higher ground (http://www.metoffice.gov.uk/climate/uk/interesting/). Leading insurance company RSA estimated that the severe winter weather in late 2010 cost the UK economy £1.2 billion per day (http://www.channel4.com/news/snow-chaos-costs-uk-economy-1-2bn-a-day). In the final quarter of 2010, GDP fell by 0.5%, which the Office for National Statistics attributed to the weather...
Figure 1. Met Office Nimrod radar composite for 1000 UTC on 2 December 2010 at 1 km grid spacing, expressed as precipitation rate in mm h$^{-1}$. Note the extensive showers coming in off the North Sea and the banded structures in the English Channel and along the north Cornish coast.

Figure 2. The locations of the radiosonde launch sites at Herstmonceux and Castor Bay, as well as place names referred to in the text.

Figure 3. Examples of bands over the English Channel as observed in Met Office Nimrod radar data (mm h$^{-1}$) at 1 km grid spacing: (a) a single band at 2130 UTC on 6 January 2010; (b) a multiband at 0730 UTC on 18 December 2009.

They formed over each sea when the boundary-layer flow was parallel to its major axis (approximately eastnortheasterly for the English Channel and approximately northnortheasterly for the Irish Sea), hereafter ‘along-channel’. Although they formed over water, parts of these bands regularly came onshore (Figures 3 and 4), leading to snowfall in the same locations for many hours. They were either ‘single bands’, where precipitation organized along a single axis (Figures 3(a) and 4(a)) or ‘multibands’, where precipitation organized along two or more parallel axes (Figures 3(b) and 4(b)). One particular place that was hard hit was Guernsey, an island in the English Channel, where thundersnow occurred (Guernsey Meteorological Office, 2011) as the cold air over warm waters produced the necessary conditions for electrification and snow (e.g. Schultz, 1999; Schultz and Vavrek, 2010).

That such bands form during cold-air outbreaks over water suggests that the heat and moisture fluxes from the water are crucial to their formation. Indeed, shallow convection is generated over warm water when cold air in the boundary layer flows over it (Benard, 1900; Rayleigh, 1916). Over an open ocean, the resulting convection typically takes one of two morphologies—cellular convection or horizontal convective rolls—depending upon the static stability and vertical shear of the horizontal wind (hereafter vertical wind...
obtained a widely varying precipitation distribution when plays a role. To that effect, Andersson and Gustafsson (1994) However, modelling studies over different bodies of water generating lift for the observed banding:

factors is generally concluded to have been responsible for the Baltic Sea (e.g. Andersson and Nilsson, 1990; Andersson (Pike, 1990), over the Sea of Japan (Nagata, 1987) and over England coast (Bosart, 1975), off the north coast of Germany (Asai, 1970; Miura, 1986; Shirer, 1986). Instead of vertical wind shear, many authors use near-surface wind velocity to determine the band orientation. This works well because the two are usually well correlated, but occasionally a situation arises where using the wind direction is a poor predictor of band orientation (e.g. Schultz et al., 2004). In contrast to the open ocean, water bodies that are constrained by land experience a greater variety of structures. Some of the most remarkable form over and downwind of the Great Lakes of North America and produce so-called lake-effect precipitation. Here, three morphologies are common: vortices, widespread coverage and shoreline bands (Laird et al., 2003a,b).

Shoreline bands forming along the major axis of a lake are relevant to this study; over the Great Lakes (e.g. Peace and Sykes, 1966; Passarelli and Braham, 1981; Hjelmfelt, 1990) and over the Great Salt Lake (Steenburgh et al., 2000; Steenburgh and Onont, 2001; Onont and Steenburgh, 2001). The single bands in Figures 3(a) and 4(a) (and other single bands identified in this study) are similar to the Type IV lake-effect snowband of Niziol et al. (1995). The crucial difference between bands over lakes and the ones studied here is that a lake has an upwind and downwind shore (in addition to a shore on either side of the flow) and a sea does not. However, wintertime wind-parallel bands arising from land–water contrasts have also been studied along the New England coast (Bosart, 1975), off the north coast of Germany (Pike, 1990), over the Sea of Japan (Nagata, 1987) and over the Baltic Sea (e.g. Andersson and Nilsson, 1990; Andersson and Gustafsson, 1994). Some combination of the following factors is generally concluded to have been responsible for generating lift for the observed banding:

- thermally driven land breezes;
- frictional differences between land and sea;
- deflection of air around orography.

However, modelling studies over different bodies of water garner different results on the extent to which each of these plays a role. To that effect, Andersson and Gustafsson (1994) obtained a widely varying precipitation distribution when altering the geometry of the coastline around the Baltic Sea, coining the terms ‘coast of departure’ and ‘coast of arrival’. Thus, the unique geography of each body of water implies that each warrants its own investigation into how bands form there.

The precipitation band over the Irish Sea has been given a name by weather enthusiasts: the Pembrokeshire Dangler. There is some discrepancy over how the band forms, however. For example, one source attributes the band formation to convergence produced by deflection of flow around the Pembrokeshire peninsula (Figure 2: http://weatherfaqs.org.uk/node/216), whereas another attributes the band to northerly flow through the North Channel meeting converging land breezes, forcing convergence the length of the Irish Sea (http://en.wikipedia.org/wiki/Pembrokeshire Dangler). Given the lack of agreement over the origins of these bands, how they form would seem to be a topic ripe for investigation.

To date, there has not been a comprehensive description of such bands around the UK in the open scientific literature. The nearest candidate is the investigation of Browning et al. (1985), who identified wind-parallel cloud bands over the North Channel (Figure 2) and Irish Sea. This study was followed up by Monk (1987) and Monk et al. (1990); their results were not published in a scientific journal but images from Monk (1987) appeared in Bader et al. (1995, Section 6.2.4). These studies first called attention to these features and Monk (1987) identified the three lifting mechanisms itemized above as possible causes.

As far as we know, the scientific literature contains neither a climatology of atmospheric conditions associated with these UK bands nor a modelling sensitivity study of them. Thus, the extent to which the mechanisms forming the snowbands resemble those of lake-effect bands or those referred to over other bodies of water around the world remains unknown. This article aims to address these issues. The availability of precipitation radar observations of these bands and high-resolution mesoscale models to simulate them allows us to study these bands in a way not done to date.

The remainder of this article is organized as follows. Section 2 outlines the data and methods. Section 3 gives a case study of a typical band over each sea during the winters in question. In section 4, synoptic composites are presented for the times when bands initiated. In section 5, a climatology of sounding data is presented. In section 6, reanalysis simulations are presented for a band over the English Channel. In section 7 we discuss the results and compare them with previous literature. In section 8 we summarize the findings.

## 2. Data and method

Met Office precipitation radar (Nimrod) composites were examined for every day during periods of ‘snow and low temperatures’, as defined on the Met Office’s website (http://www.metoffice.gov.uk/climate/uk/interesting/). These were from 17 December 2009–15 January 2010, 25 November 2010–9 December 2010 and 16–26 December 2010. Radar data were unavailable from 20 December 2010 onwards due to a data-processing error at the Met Office. Therefore, 49 days were available for analysis.
Times were recorded at which bands initiated along the major axis of each sea, excluding those that formed roughly along a synoptic-scale front. This approach identified 14 bands over the English Channel and 19 over the Irish Sea. In each case, the low-level winds were broadly along-channel; synoptic composites of these initiation times are presented in section 4.

To establish why bands sometimes did not form, given favourable wind direction, the study identified the times during these 49 days when the 850 hPa flow was along-channel. These times were diagnosed from sounding data from Herstmonceux and Castor Bay, which are located near the upwind end of the English Channel and Irish Sea, respectively (Figure 2). For the English Channel, a sounding from Herstmonceux and Castor Bay, which are located near the upwind end of the English Channel and Irish Sea, respectively (Figure 2). For the English Channel, a sounding from Herstmonceux and Castor Bay, which are located near the upwind end of the English Channel and Irish Sea, respectively (Figure 2). For the Irish Sea, the requirement was that the 850 hPa wind direction over Castor Bay be between 0° and 45° (i.e. between northeasterly and easterly), which we hereafter term eastnortheasterly or ENE flow. For the Irish Sea, the requirement was that the 850 hPa wind direction over Castor Bay be between 0° and 45° (i.e. between northerly and northeasterly), which we hereafter term northnorthwesterly or NNE flow. These criteria led to 19 times of ENE flow over the Irish Sea and 16 times of NNE flow over the Irish Sea. For each of these sounding times, the corresponding radar precipitation image was studied to establish whether a band was present or not and, if so, whether it was single or multiband.

2.1. Nimrod data

Nimrod composite maps are constructed from the radar reflectivity measurements from 18 5.6 cm wavelength radars, evenly distributed around the British Isles (http://www.metoffice.gov.uk/weather/uk/radar/tech.html). The data from each radar are sent to the Met Office headquarters and converted into a 1 km × 1 km grid of reflectivity values (Z, in mm$^6$ m$^{-3}$), which are then converted to precipitation rate ($R$, in mm h$^{-1}$) using the equation in Table 1 of Harrison et al. (2009):

$$Z = 200R^{1.6}.$$  (1)

An example is plotted in Figure 1.

Radar data, however, have their limitations. Problems arise at long ranges because, due to the curvature of the Earth, each radar can only observe precipitation some distance above the surface. For example, precipitation may evaporate below the lowest elevation scan, leading to an overestimate of precipitation at the surface. Also, the radar beam may pass over the top of low-lying clouds, understimating precipitation. As shown in section 3, this underestimate may be occurring with these bands because of the shallow convection.

Another common error is the bright band, in which the high reflectivity of droplets detected at the level where snow is melting returns strong echoes, leading to an overestimate of intensity. However, the vast majority of the radar echoes observed in this study were from precipitation that reached the surface as snow and so this is unlikely to have occurred.

In this study, we are primarily concerned with the morphology, as opposed to intensity, of precipitation. Bands were manually identified from criteria for orientation, length, width and intensity in Table 1. Additional criteria were applied to determine multibands (Table 2). Multibands usually consisted of one longer band accompanied by one or more shorter bands. Thus, to qualify as a multiband, the threshold for length was less for any additional parallel bands. Any band satisfying the criteria in Table 1 but not Table 2 was considered a single band.

These criteria led to 10 times at which a band was observed over the English Channel (from the 19 times of ENE flow at 850 hPa) and 10 times at which a band was observed over the Irish Sea (of the 16 times of NNE flow at 850 hPa). Of these, 8 over the English Channel and 4 over the Irish Sea were multibands. A climatology of sounding data, using these times of along-channel flow, is presented in section 5.

2.2. Sea-surface temperatures

Sea-surface temperatures (SSTs), taken from Met Office buoys and light vessels over the two seas, were also used to inform the climatology. At each time of ENE and NNE flow, the mean SST was calculated. The surface temperature taken from the sounding was subtracted from this mean SST to obtain the local land–sea temperature difference, $\Delta T$, and thus assess the impact of thermally driven circulations on the generation of bands. Similarly, the 850 hPa temperature taken from the sounding was subtracted from the mean SST to obtain the surface-to-850 hPa temperature difference and thus assess boundary-layer stability over the water. Following Braham (1983), a surface-to-850 hPa temperature difference of about 13 K is sufficient for free convection as this corresponds to the dry adiabatic lapse rate. However, as shown in section 3, some cloud bases for these bands were

<table>
<thead>
<tr>
<th>Parameter</th>
<th>English Channel</th>
<th>Irish Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>A line or curve of approximately eastnortheasterly orientation</td>
<td>A line or curve of approximately northnorthwesterly orientation</td>
</tr>
<tr>
<td>Length</td>
<td>At least half the distance between the Dover–Calais and Penzance–Brest midpoints (Figure 2)</td>
<td>At least half the distance between Douglas and the Penzance–Cork midpoints (Figure 2)</td>
</tr>
<tr>
<td>Width</td>
<td>≤ 50 km at all points along length</td>
<td></td>
</tr>
<tr>
<td>Intensity</td>
<td>≥ 1 mm h$^{-1}$ at regular intervals along identified line or curve</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Orientation</th>
<th>Length</th>
<th>Width</th>
<th>Intensity</th>
<th>Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>As in Table 1 for at least two parallel bands</td>
<td>As in Table 1 for at least two parallel bands</td>
<td>As in Table 1 for at least two parallel bands</td>
<td>As in Table 1 for at least two parallel bands</td>
<td>≥15 km between parallel bands where intensity is continuously, or near-continuously, ≤ 1 mm h$^{-1}$</td>
</tr>
</tbody>
</table>

Table 1. Threshold criteria for single bands identified from Nimrod images.

Table 2. Threshold criteria for multibands identified from Nimrod images.
3. Case studies

To illustrate typical band development and decay, two case studies are presented: one over the English Channel (section 3.1) and one over the Irish Sea (section 3.2).

3.1. English Channel

A band developed and decayed over the English Channel on 30 November and 1 December 2010 (Figure 5). A zonally elongated high over Scandinavia and a zonally elongated low over western Europe led to parallel, near-zonally oriented isobars across the UK (Figure 6). The Met Office analysis also features multiple troughs, predominantly over water, the longest of which is along the English Channel (Figure 6). The Herstmonceux sounding at 0000 UTC on 1 December indicates northeasterly flow below 500 hPa (Figure 7). Temperature and dew-point temperatures in the boundary layer were below 0°C with a capping inversion at 750 hPa overlying a shallow cloud deck about 100 hPa thick (Figure 7).

Radar echoes began to organize along the English Channel about 0800 UTC on 30 November. At 1200 UTC, as the band was beginning to form (Figure 5(a) and (e)), the 850 hPa wind speed was 11.8 m s⁻¹, up from 8.2 m s⁻¹ at 0000 UTC, and eastnortheasterly (Table 3). Initially, the echoes exhibited a multibanded structure of eastnortheast–westsouthwest orientation, occupying only the western half of the English Channel (Figure 5(a)). Visible
Table 3. Evolution of variables as diagnosed from SST data over the English Channel and sounding data at Herstmonceux during the development and decay of a band over the English Channel.

<table>
<thead>
<tr>
<th>Time &amp; Date</th>
<th>’Instability’</th>
<th>$U_{850}$</th>
<th>$\Delta T$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K)</td>
<td>(m s$^{-1}$)</td>
<td>(K)</td>
</tr>
<tr>
<td>Pre-initiation</td>
<td>00 UTC 30 Nov</td>
<td>19.2</td>
<td>8.2 (60°)</td>
</tr>
<tr>
<td>Developing</td>
<td>12 UTC 30 Nov</td>
<td>20.9</td>
<td>11.8 (80°)</td>
</tr>
<tr>
<td>Decaying</td>
<td>00 UTC 1 Dec</td>
<td>22.1</td>
<td>16.4 (60°)</td>
</tr>
<tr>
<td>Decaying</td>
<td>12 UTC 1 Dec</td>
<td>22.2</td>
<td>18.0 (40°)</td>
</tr>
</tbody>
</table>

Variables are surface-to-850 hPa temperature difference (‘instability’), 850 hPa wind ($U_{850}$) and land–sea temperature difference ($\Delta T$). Whether the band had not yet initiated, was developing, decaying or no longer visible is indicated at the time of each sounding.

Between 1200 UTC on 30 November and 0000 UTC on 1 December, eastnortheasterly flow strengthened, reaching 16.4 m s$^{-1}$ at 850 hPa (Table 3). Although the intensity of the radar echoes did not increase, the band became better defined and lengthened, occupying the full length of the English Channel by 0200 UTC (Figure 5(b)). The separate parallel bands became less distinctive and gradually merged into one wider band (Figure 5(b)). The infrared imagery at this time shows distinctive cloud along part of the English Channel (Figure 5(f)), but it is not until the visible imagery becomes available at 0800 UTC that the reduction to a single band is seen on satellite (Figure 5(g)), at which time the radar shows the band still well defined and spanning the full length of the English Channel (Figure 5(c)). At this time, the location of the band corresponds exactly to the trough on the surface pressure analysis (Figure 6), the latter likely drawn by a Met Office forecaster observing the location of the cloud and radar echoes.

Between 0000 UTC and 1200 UTC on 1 December, 850 hPa wind speed further increased to 18 m s$^{-1}$ but became more northerly, no longer quite parallel to the English Channel (Table 3). During this time, the band steadily dissipated (observe the transition from Figure 5(b) to Figure 5(d)). The band gradually rotated anti-clockwise throughout its evolution (observe the transition from Figure 5(a) to Figure 5(d)), roughly following the direction of the wind. During its decay, the band regained its multibanded structure (Figure 5(d) and (h)).

Throughout the band’s development and decay, the surface-to-850 hPa temperature difference was between 20.9 and 22.2 K (15.7–17.6 °C km$^{-1}$, thus absolutely unstable) and the land–sea temperature difference was between 11.9 and 13.5 K (Table 3). However, there was no marked change in these variables during development or decay (they both increased very gradually during both development and decay).
3.2. Irish Sea

A band developed and decayed over the Irish Sea on 6–7 January 2010 (Figure 8). High pressure over the North Atlantic induced northerly flow along the Irish Sea and again troughs were analyzed, including over the Irish Sea (Figure 9). Near-surface dewpoints were around −5°C at Castor Bay, implying little moisture, and in this case the cloud top was only at about 800 hPa (Figure 10), suggesting shallower convection than in the English Channel case.

Radar echoes began to organize along the Irish Sea about 2300 UTC on 6 January (Figure 8(a)). At 0000 UTC on 7 January, the 850 hPa wind was 9.8 m s\(^{-1}\) and northerly (Table 4). Initially, a multiband lay just south of Douglas (Figure 2), its two constituent bands of different orientation from one another (Figure 8(a) and (e)).

Thereafter, the multibands merged and, until about 0900 UTC, steadily lengthened but did not widen or intensify, by which time the single band spanned almost the full length of the Irish Sea (Figure 8(b) and (f)). Sounding data are unavailable until 1200 UTC, at which time the 850 hPa wind was 15°, still parallel to the Irish Sea, but its speed had plummeted to 4.1 m s\(^{-1}\) (Table 4). Indeed, at this time and thereafter, the band was steadily decaying (Figure 8(c) and (g)). Although not detected on radar (Figure 8(c)), the visible imagery at 1600 UTC shows that the band had separated into two parallel cloud streets (Figure 8(g)).

The final radar echoes and infrared cloud signatures were observed at about 2200 UTC on 7 January (Figure 8(d) and (h)). At 0000 UTC on 8 January, the 850 hPa wind was still along-channel but its speed had further decreased to 3.6 m s\(^{-1}\) (Table 4).

The surface-to-850 hPa temperature difference was between 16.3 and 18.1 K (11.2–12.9°C km\(^{-1}\), thus absolutely unstable) and the land–sea temperature difference was between 10.9 and 11.6 K throughout the band’s development and decay (Table 4). As in the English Channel case, there was no great variability in these variables (surface-to-850 hPa temperature difference, in fact, gradually decreased throughout).

3.3. Synthesis

Both bands formed in strong along-channel winds (about 12 and 10 m s\(^{-1}\) at 850 hPa for the English Channel and Irish Sea, respectively). In the English Channel case, the 850 hPa wind speed continued to increase during the decay but its direction changed, no longer along-channel. In the Irish Sea case, the 850 hPa wind remained along-channel but slowed to about 4 m s\(^{-1}\). In both cases, the surface-to-850 hPa temperature difference and land–sea temperature difference were high, implying an unstable boundary layer and large differential heating between land and water. However, there was no marked increase in these variables during development or decrease during decay. Thus, in both cases, the evolution of the wind field appears to have controlled the development and decay of the bands.

The two cases were also similar in that they both initiated as poorly defined multibands. Over about 12 h, the multibands merged to form a single smooth, almost perfectly straight band, spanning the length of the relevant sea. Subsequently, the single band became increasingly patchy and re-formed multibands, dissipating over about 12 h. Many other single bands over both seas during the winters in question started and ended as multibands. However, some single bands did not evolve from or into multibands and some multibands did not evolve into single bands.

4. Synoptic composite analysis

To illustrate the synoptic-scale weather patterns associated with band formation, synoptic composites are created from reanalysis data from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) (Kalnay et al., 1996) using the compositing web site created by the
Composites were constructed from the daily mean data at the time of initiation of 14 cases in the English Channel and 19 cases in the Irish Sea as determined in section 2. These 14/19 cases for the English Channel/Irish Sea were used, as opposed to the 10/10 times that a band was present during along-channel flow (section 2.1), in order not to make any assumptions about the flow environment (namely wind direction) associated with bands.

Composite sea-level pressure patterns are similar for both types of bands (Figure 11(a) and (b)). A high-pressure system is centred west of Iceland and an elongated low-pressure system is centred over western Europe. The high does not extend as far equatorward in the composite for bands forming over the English Channel, favouring surface geostrophic flow from the northeast over the UK. This pressure pattern is surmounted by a 500 hPa ridge over the Irish Sea and a trough over western Europe, with a slightly more positive tilt to the trough in the English Channel composite (Figure 11(c) and (d)).

Closer to the UK, a local maximum of wind shear magnitude exceeding 8 m s\(^{-1}\) km\(^{-1}\) is present over the southwestern UK in both composites (Figure 11(e) and (f)). The direction of the shear is northeasterly in the English Channel composite and northnortheasterly in the Irish Sea composite. The composite lapse rate at 925 hPa (Figure 11(g) and (h)) indicates small lapse rates over Europe (as low as 2–3 °C km\(^{-1}\), representing absolute stability), consistent with the surface anticyclone, and increasing lapse rates westward over the water (as high as 7–8 °C km\(^{-1}\), representing conditional instability). Thus, both the English Channel and Irish Sea bands occur in a region of locally strong near-surface wind shear roughly parallel to the sea and low-level conditional instability.

Synoptic composites derived from a set of null cases where soundings revealed along-channel flow but bands did not form (not shown) are similar to these composites. Details of the flow pattern will now be investigated to determine the factors controlling band formation.

5. Climatology

Section 4 illustrates the synoptic-scale environment in which the observed bands formed. However, as stated, bands failed to form at other times in a similar synoptic-scale environment. Indeed, for both seas, banding was present only a slight majority of times that the 850 hPa wind direction was along-channel (Table 5). We thus turn our attention to differences between times at which bands were present and times at which they were not.

Over both seas, the mean surface-to-850 hPa temperature difference was greater at times of banding than at times of no banding (Table 5). This difference is greater over the English Channel than over the Irish Sea (3.4 K compared with 1.3 K). However, in both the English Channel and Irish Sea cases this is significant at the 95% level, using a one-sided two-sample t-test (e.g. Wilks, 1995, pp122–124; hereafter just ‘t-test’).

Over both seas, the mean 850 hPa wind speed was greater than 4 m s\(^{-1}\) greater at times of banding than at times of no banding (Table 5). For both seas, this difference is significant at the 95% level using the t-test.

For the English Channel, \(\Delta T\) was just 1.4 K greater at times of banding than at times of no banding (Table 5), but this is significant at the 95% level using the t-test. However, for the Irish Sea, \(\Delta T\) was 4.4 K greater at times of no banding than at times of banding, which is significant at the 95% level using the t-test. We are unable to offer an explanation for this unexpected result.

The variables in Table 5 were also compared between times at which single and multibands were observed. No significant results were obtained to distinguish between the two, however.

6. Real-data simulations

According to the ingredients-based approach, moist convection requires the simultaneous presence of instability, moisture and lift (e.g. Johns and Doswell, 1992). Table 5 demonstrates that the lower atmosphere was sufficiently unstable for the formation of these bands and, despite the relative dryness of the cold-air outbreaks, their formation over relatively warm water explains the origin of the moisture. Thus, the lifting mechanisms responsible for the observed bands are now investigated.

From Table 5, bands were favoured by faster winds and, for the English Channel, by greater land–sea temperature contrast. How did these factors lead to convergence and lift? To examine the extent to which each of the three lifting mechanisms itemized in section 1 was responsible for the observed bands, model simulations of one such band were conducted (that which occurred over the English Channel between 30 November and 1 December 2010, presented in section 3.1).

6.1. Model setup

Simulations were performed with version 3.3.1 of the Weather Research and Forecasting (WRF) model with
Figure 11. Synoptic composite of the initiation of 14 bands over the English Channel (left) and 19 bands over the Irish Sea (right) from daily averaged NCEP–NCAR Reanalysis data. (a), (b) Sea-level pressure every 2 hPa. (c), (d) 500 hPa geopotential height every 60 m. (e), (f) 925 hPa wind shear magnitude (m s$^{-1}$ km$^{-1}$, shaded according to the scale) and direction (vectors). (g), (h) 925 hPa lapse rate shaded according to the scale and contoured every 1°C km$^{-1}$. Figure constructed from images provided by the NOAA/ESRL Physical Sciences Division, Boulder, Colorado, from their web site at http://www.esrl.noaa.gov/psd/data/composites/nssl/day.

The Advanced Research WRF (ARW) dynamical core (Skamarock et al., 2005). Three model domains were set up using Lambert conformal mapping (Figure 12) with two-way nesting, grid spacings of 25, 5 and 1 km and time steps of 150, 30 and 6 s. 58 model eta levels were used. European Centre for Medium-Range Weather Forecasts (ECMWF) analysis data (ECMWF, 1994) at 0.5° latitude–longitude grid spacing were used for input into the model every 6 h. NOAA SST analysis data (Reynolds, 1988) at 0.5° latitude–longitude grid spacing, available every 24 h, were interpolated for input into the model at the same times.
Simulation were started at 1200 UTC on 28 November 2010, about 48 h before the band initiated. The finish time was 0000 UTC on 2 December, about three hours after the band dissipated. Grid-scale noise was removed by adding sixth-order numerical diffusion.

A full-physics control run was performed, followed by a run in which surface heat and moisture fluxes were switched off to establish the importance of differential heating between land and sea. Then, simulations were performed in which orography, land–sea frictional differences and surface fluxes were removed cumulatively. In the case of orography, land–sea frictional differences, a constant value of roughness length to establish the importance of differential heating between land and sea. Then, simulations were performed in which orography, land–sea frictional differences and surface fluxes were removed cumulatively. In the case of orography, land–sea frictional differences, a constant value of roughness length, \( z_0 = 0.2 \text{ mm} \) (that of open sea), was set. Thus, five simulations were performed (Table 6), the results of each of which are described in turn.

### 6.2. Control run

A sea-level-pressure trough forms over the English Channel (Figure 13(b)). At 0600 UTC on 30 November (42 h into the simulation), as the radar shows the band initating (Figure 13(a)), winds turn towards the trough in the model simulation as air flows over southern England (Figure 13(b)). Winds across the north coast of France also flow into the trough, meeting the air from southern England. A mesoscale vortex thus lies over the trough, slightly to the west of where it appears to be from radar (Figure 13(a)). Multiple convergence zones (Figure 13(b)) and reflectivity bands (Figure 14(b)) surround the vortex, arising from the confluence of the two air streams. Greater wind speed over water than land further intensifies the convergence. These bands of convergence correspond to bands of divergence higher up, with maxima at about 850 hPa and fading away at about 550 hPa (not shown). Land–surface-station observations also capture the turning of winds over England and convergence over the English Channel (Figure 13(a)).

Subsequently the trough becomes more uniform and 12 h later, at 1800 UTC, the orientation of the isobars is much the same along the length of the English Channel (Figure 15(b)).

The 10 m wind field evolves into a uniform confluence at the downwind end of the English Channel of the two air streams from the north and south, which is also exhibited by the land-surface-station wind vectors (Figure 15(a)). Thus, in the model, the reflectivity is organized into a smooth single band along the downwind end of the English Channel (Figure 15(b)), similar to that on radar (Figure 15(a)), although this single-band transition occurs slightly earlier than in the radar imagery (the morphology is more distinctively multibanded in the radar imagery than in the model at this time).

### 6.3. No surface fluxes

In the absence of surface fluxes, the trough does not develop at 0600 UTC (Figure 14(c)) or 1800 UTC (Figure 15(c)). There is still a turning of winds towards low pressure as they cross the east coast of England (Figure 13(c)) and the airflow offshore from southern England is not much different visibly from that in the control run. However, there is no offshore flow across the north coast of France and the confluence observed in the control run does not develop. Thus, the 10 m wind field remains uniform throughout. There is no banding in the reflectivity at 0600 UTC (Figure 14(c)) or 1800 UTC (Figure 15(c)).

### 6.4. No orography

The trough and vortex develop over water (Figure 13(d)), as in the control run. The isobars are more meridionally oriented at the upwind end of the English Channel, so there are subtle differences from the control run in the location and orientation of the convergence zones (Figure 13(d)) and reflectivity bands (Figure 14(d)). However, the essential pattern of air from southern England meeting air from northern France and forming the vortex is much the same.

Twelve hours later, the trough is more uniform and the wind field evolves into a single confluence zone (Figure 15(d)), as in the control run. The isobars are still more meridionally oriented, however, leading to stronger flow off the north coast of France than in the control run. The band is further north, over the south coast of England, and more cellular than in the control run, much less closely resembling the radar image (Figure 15(a)), but is of similar intensity to both.

### 6.5. Constant \( z_0 \)

The trough develops over water, but the air stream across the east coast of England turns less markedly towards it (Figure 13(e)). Due to constant roughness length over the domain, the winds no longer accelerate over water (notice the faster winds over land than in the other panels of Figure 13). However, the distribution and intensity of convergence (Figure 13(e)) and reflectivity (Figure 14(e)) are similar to the control and no-orography runs.

Twelve hours later, the reflectivity is primarily over the south coast of England as in the no-orography run (compare Figure 15(d) and (e)). However, the band in the constant-\( z_0 \) run is not so concentrated over the south coast of England and weak multibands are over the English Channel.

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Table 6: A summary of all simulations, indicating whether each of orography, \( z_0 \) variations and surface heat and moisture fluxes was left active (Y) or turned off (N).

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Orog.</th>
<th>( z_0 ) var.</th>
<th>Sfc. fluxes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>No surface fluxes</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>No orography</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Constant ( z_0 )</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>All removed</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>
6.6. All removed

As in section 6.3, the removal of surface fluxes prevents convergence (Figure 13(f)) and organized precipitation (Figures 14(f) and 15(f)) from forming. The main difference between this run and the no-surface-fluxes run (in which orography and frictional variations remained) is that there is no turning of the winds towards low pressure to the south as they cross the east coast of England. However, this is immaterial because, as demonstrated by the no-surface-fluxes run, this effect alone is insufficient to generate convergence over the English Channel.

6.7. Later initialization times

The same simulations were performed with various other initialization times (not shown). In control runs initialized later, the location and morphology of the band in its organized stage much more closely resembled the radar imagery than in Figure 15(b). However, the corresponding sensitivity experiments differed little from the control run, due to insufficient spin-up time. Thus, because the purpose of this article is to investigate the physics of the snowbands rather than to produce the most accurate simulation possible, we have presented the simulations with sufficient spin-up time for each sensitivity simulation to evolve distinctly. We maintain that the larger differences between the observed and modelled bands with the earlier initialization time do not change the conclusions that can be drawn from these simulations. Instead, we have attempted to provide an overview of the identified physical processes (orography, z₀ variations, surface fluxes) involved in band formation.

6.8. Irish Sea

The band documented over the Irish Sea in section 3.2 was also simulated with the same domains (but without the
inner 1 km domain), similar spin-up time and equivalent settings (not shown). A full-physics run produced mid-sea convergence and organized precipitation, similar to the English Channel case. A simulation with surface fluxes switched off also matched that of the English Channel, with the surface convergence failing to form and the 10 m wind field remaining uniform.

7. Discussion

7.1. How does the wind speed affect band formation?

Bands form over open water in strong winds and cold advection. The following three examples illustrate that such bands require lower-tropospheric wind speeds of about 10 m s$^{-1}$ or more. Firstly, observed bands formed in surface winds exceeding 10 m s$^{-1}$ over the Baltic Sea (Andersson and Nilsson, 1990). Secondly, in idealized experiments over Lake Michigan, Hjelmfelt (1990) found that a wind speed of 10 m s$^{-1}$ produces a band for all simulated $\Delta T$ and lapse rates but smaller wind speeds only produce a band for certain $\Delta T$ and lapse rates. Thirdly, in an idealized elongated body of water, Alestalo and Savijärvi (1985) used a wind speed of 10 m s$^{-1}$ to produce a single band. In the present study, although statistical tests did not reveal a critical wind speed for either sea, the 850 hPa wind speed was above 10 m s$^{-1}$ for 9 of the 10 times at which bands were observed in along-channel flow over the English Channel. For the Irish Sea, the 850 hPa wind speed was above 10 m s$^{-1}$ at only 5 of the 10 times but was 6.7 m s$^{-1}$ or greater at 9 of the 10 times. For both seas, the 850 hPa wind speed was significantly greater when bands were present than when they were not present. In particular, the band documented over the Irish Sea developed in an 850 hPa wind speed of 9.8 m s$^{-1}$ but decayed when the wind speed dropped below 4 m s$^{-1}$.

Rather than wind speed, the ratio of ambient wind speed $U$ to fetch length $L$ determines lake-effect morphology for an idealized circular lake (Laird et al., 2003a). When $U/L$ is less than 0.02 m s$^{-1}$ km$^{-1}$, mesoscale vortices form. When $U/L$ is between 0.02 and 0.09 m s$^{-1}$ km$^{-1}$, bands form. For $U/L$ greater than 0.09 m s$^{-1}$ km$^{-1}$, lake-effect convection takes the form of widespread coverage. For elliptical lakes
with an aspect ratio of 9:1 (roughly that of the English Channel and Irish Sea) and flow parallel to the long axis, the threshold for bands is lowered to 0.017 (Laird et al., 2003b). Given that the English Channel and Irish Sea are both roughly 500 km long, $U/L = 0.09$ corresponds to 45 m s$^{-1}$. This value is rarely exceeded at low levels over the UK and indeed widespread coverage has not been documented over the English Channel and Irish Sea. However, $U/L = 0.017$ corresponds to 8.5 m s$^{-1}$. Thus, there is a rough consistency between the observational results in this study and the criteria in the Laird et al. studies. Additional observational and modelling studies could further refine these criteria for the waters around the UK.

7.2. How does the lower boundary condition affect band formation?

Previous studies of similar bands have discussed the relative importance of orography and land–sea frictional differences. For example, Andersson and Gustafsson (1994) found that coastal orography was of secondary importance to forming snowbands over the Baltic Sea, and Onton and Steenburgh (2001) found that the orography was not responsible for band formation over the Great Salt Lake but merely altered the distribution of the snowfall. In our simulations of the snowband over the English Channel, the removal of orography resulted in the band being composed of more cellular convection but did not alter its existence.

Even without the orography, some authors have found land–sea frictional differences to be of primary importance in forming convergence for quasi-stationary bands over water. For example, using an idealized hydrostatic model, Alestalo and Savijärvi (1985) found that a geostrophic wind of 10 m s$^{-1}$ along the major axis of an elongated body of water was sufficient to induce convergence due to frictional difference alone, even when the land and sea are the same temperature and the atmosphere is neutrally stratified. Roeloffzen et al. (1986) also found frictional convergence alone to be sufficient to produce a quasi-stationary cloud band parallel to an idealized coastline. In our simulations, setting the roughness length $z_0$ as a constant caused winds crossing the east coast of England to turn less towards the trough over the English Channel than in the control run. The constant-$z_0$ run also produced multibands at a later
time, with a less well-defined reflectivity maximum than in the control and no-orography runs. Thus, our simulations show that frictional differences enhance band intensity but their absence does not preclude band formation.

7.3. Are the bands caused by land breezes?

Given that the classic land breeze is a circulation resulting from the diurnal variation in heating under relatively benign synoptic situations, particularly during the warm season, we question its applicability to these snowbands. Our interpretation is based upon the following evidence.

(1) No diurnal cycle in the initiation of the observed snowbands was evident.
(2) The land–sea temperature difference changed little during the band’s development and decay (the temperature difference gradually increased; see Table 3), implying that the band was not diurnally driven.

Some authors have interpreted the land-breeze concept more broadly as a thermally driven offshore flow superimposed on an along-shore ambient wind, free from any diurnal influence, and have attributed along-shore snowbands to the collision of these land breezes from opposing shores (e.g. Passarelli and Brahman, 1981; Savijärvi, 2012). In accordance with this relaxed definition, the American Meteorological Society (AMS) Glossary states that the land breeze ‘usually’ blows at night (http://amsglossary.allenpress.com/glossary).

In our simulation of the band over the English Channel, there was indeed strong offshore flow across the north coast of France that failed to develop in the absence of surface fluxes and was essentially the same in the no-orography and constant-2σ runs. Thus, this aspect to the flow was largely thermally driven and qualifies as a land breeze as defined by the above authors and in the AMS Glossary. However, there was no major difference in the flow from southern England in the control run and no-surface-flux runs.

This asymmetry between the two coastss may be explained by Atlas et al. (1983). They found that, during cold-air outbreaks, a bay that is concave in the downwind direction leads to offshore convergence downwind because the part of the air stream that has had a shorter trajectory over the warm water experiences less heating than the other trajectories. Thus, there is differential heating and the higher pressure air that has travelled less distance over water flows towards the lower pressure air further offshore. For this case, the north coast of France is divided into two such bays that are concave facing downwind (east and west of the Cherbourg Peninsula, Figure 2) and along each of these there is strong turning of the winds towards the air that has travelled further over water (to the right). This was also observed over the English Channel in the modelling experiments of Monk (1987). The south coast of England, on the other hand, is almost a straight line, which does not allow for this effect.

Combining the evidence from sections 7.1, 7.2 and 7.3, the snowband is the mesoscale response to surface heating of cold-air advection over warm water, as first described by Lavoie (1972). The roles of orography and frictional differences may affect the timing or location of the band but do not fundamentally alter its occurrence.

8. Conclusions

Quasi-stationary wind-parallel snowbands formed along the major axis of the English Channel and Irish Sea during cold-air outbreaks in the winters of 2009–10 and 2010–11. These bands bear similarity to those in other parts of the world: Great Lakes, Great Salt Lake, New England, off the north coast of Germany, Sea of Japan and the Baltic Sea. They were studied using the analysis of observational data (e.g. radar imagery, satellite imagery, surface and upper-air data), synoptic composites, climatology and real-data numerical modelling. Two different morphologies of bands were identified: single bands and multibands. Unfortunately, the climatology in section 5 was unable to identify distinguishing characteristics between these two morphologies, suggesting that the environmental factors tested in this study (e.g. wind direction, land–sea temperature difference) were not responsible for the single or multiband morphology.

However, case studies over both seas in section 5 indicated that multibands occurred during the formation and decay stages of mature single-band cases, which was commonly (although not always) observed during the winters in question.

The case studies showed that bands formed over the English Channel and Irish Sea when winds were greater than about 10 m s$^{-1}$ and nearly parallel to the long axis of the water body. The surface-to-850 hPa temperature difference exceeded 18 K and the land–sea temperature difference exceeded 10 K. The band over the English Channel decayed when the wind direction was no longer along-channel. The band over the Irish Sea decayed when the wind speed decreased markedly.

Synoptic composites showed that bands formed with a ridge over Greenland and a trough over western Europe at 500 hPa. A surface anticyclone was centred west of Iceland and a zonally elongated cyclone was centred over western Europe. Synoptic composites were similar, however, for times at which bands were not present, demonstrating that band occurrence depends on the finer details of the flow environment. In support of this, surface-to-850 hPa temperature difference and 850 hPa wind speed were both found to be significantly greater at times of banding than for no banding. Thus the observed bands formed when convection resulted from pronounced instability over water, with that convection organized into bands for sufficiently strong winds.

Model sensitivity experiments were performed for one such band over the English Channel. In the control run, a trough in sea-level pressure formed over the English Channel and surface winds turned cyclonically towards the trough as they passed from the North Sea over the east of England. Over the English Channel, these winds met an air stream offshore from northern France, forming a mesoscale vortex and strong convergence zones over the English Channel. Precipitation bands formed over the convergence lines. Over the course of about 12 h, the trough intensified, forming a single convergence line and precipitation band at the downwind end.

Removing the orography and setting the roughness length constant across land and sea produced a weaker trough and differences in the timing, location and intensity of the band, but the band was still present, despite less turning of the winds over southern England towards the trough. The removal of surface heat and moisture fluxes, both with
and without orography and \( z_0 \) variations, resulted in the complete failure of convergence and organized precipitation to develop. We therefore conclude that these fluxes are the major factor in generating the observed snowbands.

Acknowledgements

The Nimrod data used in this study were provided by the Met Office through the British Atmospheric Data Centre (BADC). ECMWF analyses were obtained using the ECMWF Meteorological Archive and Retrieval System (MARS) software. Sounding data were provided mainly by the Department of Atmospheric Science, University of Wyoming, but some were only available through BADC. Meteosat images and MIDAS land-surface-station data were also accessed through BADC. We thank Karen Barfoot of the Met Office for providing SST data, NOAA/ESRL Physical Sciences Division for construction of the composites in Figure 11 from their web page and Bogdan Antonescu and Hugo Ricketts for use of their script to process the raw Nimrod data. We also thank the anonymous reviewers and Keith Browning, who all provided helpful comments on the initial version of the manuscript. Jesse Norris is a NERC-funded student through the DIAMET (DIAbatic influences on Mesoscale structures in ExTratropical storms) project, NE/I005234/1.

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