Changes in atmospheric circulation over the North Atlantic and sea-surge variations along the Belgian coast during the twentieth century

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ABSTRACT: Wintertime (October-to-March period) 99th percentile of sea level (sea surges) at Ostend has increased at a rate of +3 mm/year (+1 mm/year) from 1925 to 2000. Relationships between daily sea surge at Ostend and five weather regimes – Zonal (ZO), East Atlantic (EA), Greenland Above (GA), Blocking (BL), and Atlantic Ridge (AR) – over the northeast Atlantic and Europe (40°W–40°E, 30°–70°N) are analysed during the period of 1925–2000. More than 70% of sea surges ≥65 cm occur during the AR weather regime, ahead of low pressure travelling on a northern track from Iceland to Scandinavia. The relationships between monthly/wintertime frequency of the AR weather regime and 99th percentile of sea surge at Ostend tend to strengthen during the twentieth century: for example, correlation between wintertime frequencies of AR and 99th percentile of sea surge increases from 0.21 in 1925–1950 to 0.74 in 1975–2000. This increase is associated with the pressure rise over the near Atlantic, between (30°W and 15°W), (30°N and 50°N), leading to an increase in the frequency of strong surge-related pressure gradient during AR days. Copyright © 2009 Royal Meteorological Society

KEY WORDS: sea surge; sea-level pressure; weather regime; North Sea; Belgian coast.

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1. Introduction

In low-lying, sandy coastal areas, vulnerability to short-term and long-term rises in sea level is particularly high (Nicholls and Hoozemans, 1996). Recent climate models summarized by the Intergovernmental Panel on Climate Change (IPCC) have predicted a significant warming and global sea-level rise for the twenty-first century (IPCC, 2007), which is expected to increase the flooding risk along low-lying coasts. Several factors may induce sea-level variations at different time scales. On time scales longer than 1 year, regional- and global-scale sea-level variations are associated with volume change due to temperature and salinity variations (Gornitz et al., 1982; Cabanes et al., 2001; Cazenave et al., 2002) and mass change between ocean and continents, including ice melting (Lambbeck, 1990; Cabanes et al., 2001; Cazenave and Nerem, 2004).

On time scales of less than 1 year, the predominant forcing of sea-level variations is mostly related to atmospheric variability (Lamb, 1991; Tsimplis and Josey, 2001; Trigo and Davies, 2002; Wakelin et al., 2003; Tsimplis et al., 2005), including extra-tropical storms (Heyen et al., 1996; Bouligand and Pirazzoli, 1999; Pirazzoli, 2000; Woth et al., 2006; Ullmann et al., 2008). The atmospheric forcing leads to a sea surge defined as the difference between the observed sea level and the astronomical tide. Sea surges are thus important for coastal impacts (i.e. flooding and erosion), especially for low and sandy beaches such as most part of the Belgian coast. The inverse barometer effect is equivalent to a 1-cm sea-level rise per hectopascal (hPa) of surface pressure drop and vice versa but the most important atmospheric factor are the onshore winds associated with moving mid-latitude low-pressure systems (Pirazzoli et al., 2005; Ullmann et al., 2007) and cause water to pile up against the coast.

Our main goal in this paper is to analyse the relationship between sea surge at the Ostend tide-gauge station from 1925 to 2000 and atmospheric variability over the northeast Atlantic and Europe (40°W–40°E; 30°N–70°N). In Section 3.1, we first analyse the inter-annual to multi-decadal variability of sea level and sea surge at Ostend from 1925 to 2000. The atmospheric circulation is then summarized by an objective weather classification using a k-means algorithm (Section 3.2). The weather regimes are defined as persistent large-scale flow patterns that appear repeatedly at fixed geographical locations, and thus organize the behaviour of synoptic systems that affect local-scale weather during several days or consecutive weeks. The 5-cluster solution emphasizing well-known weather regimes already observed in this area (Vautard, 1990; Michelangeli et al., 1995; Plaut and Simonnet, 2002; Moron and Plaut, 2003) is chosen (Section 3.2). The mean sea-surge height during each weather regime is analysed, along with the frequency

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of weather regimes for different sea-surge levels (Sections 3.3 and 3.4). The relationships between sea surge and frequency of each weather regime at inter-annual to multi-decadal time scales are then analysed (Section 3.5). Concluding remarks are provided (Section 4).

2. Data and methods

As the highest sea surges occur in winter, only the October-to-March period (‘winter’ hereafter) is analysed for each variable.

2.1. Sea surge

This work analyses the daily maximum time series of sea-level height measured at Ostend station along the Belgian coast [(02°54'E), (51°13'N); Figure 1] for the winter periods from October 1925 to March 2000. Sea-level data are expressed in centimetres relatively to the same altimetric reference, the Tweede Algemene Waterpassing (TAW). Time (hours and minutes) of daily maximum sea level is also available. For each daily maximum sea level, the corresponding astronomical tide (in TAW) has been computed in a previous study by Technum-IMDC-Alkyon (2002). The daily surge height has been computed as the difference between the observed sea level and the astronomical tide at the same moment. As daily surges are derived from the daily maximum sea level, they always correspond to surges occurring during high tide, which is particularly interesting from an impact perspective. The study of the inter-annual to multi-decadal variability of surge height led to the decision to separate the problem of the mean sea level (MSL) trend and the problem of the isolated spikes (the surges) (Pirazzoli et al., 2005; Ullmann et al., 2007). In other words, sea-level variability associated with atmospheric circulation (i.e. sea surges) needs to be separated from sea-level variability associated with volume changes due to temperature and salinity variations and mass change between ocean and continent. Therefore, for each year, the value of the yearly mean of daily maximum sea level is removed from daily surge heights. The different climatic aspects estimated this way are kept independent as much as possible, and inter-annual variability to long-term trend of surge can be separated from ocean volume variations (Pirazzoli et al., 2005).

2.2. Sea-level pressure SLP data

The MSL pressure available from the National Center for Atmospheric Research (NCAR) at 1 PM UTC from October 1, 1925 to December 31, 1939 and at noon UTC from January 1, 1940 to March 31, 2000 has been extracted from the NCAR web site (http://dss.ucar.edu/). No attempt has been made to fill the missing entries in the NCAR data or to remove the seasonal cycle. The sea-level pressure (SLP) data are not available at the exact time of sea-surge records, but the weather regimes are persistent large-scale patterns, and it is expected that the one observed at noon or 1 PM is usually the same all day long (Ullmann and Moron, 2008).

2.3. Weather classification

Weather classification has been extensively used to summarize the extra-tropical atmospheric circulation (Vautard, 1990; Michelangeli et al., 1995; Plaut and Simonnet, 2002; Ullmann and Moron, 2008). The NCAR SLP standardized anomalies of the 93.9% of days without missing values are weighted by the cosine of latitude and compressed onto the 11 leading empirical orthogonal functions (EOFs) that account for 90% of the total variance. The standard k-means algorithm (Diday and Simon, 1976) is applied to the 11 principal components to extract five clusters, in accordance with previous studies (Vautard, 1990; Michelangeli et al., 1995; Plaut and Simonnet, 2002; Moron and Plaut, 2003; Ullmann and Moron, 2008). Two hundred cluster analyses were performed with random seeds, and the classifiability index (Michelangeli et al., 1995; Plaut and Simonnet, 2002) that measures the average similarity within the 200 sets...
of clusters is used to select the best partition. In this way, each day of the period 1925–2000 is classified into one of the five clusters. The 4.6% of days, where all grid points are not available, are classified in the cluster that minimizes the squared Euclidean distance with its centroid, considering only the available grid points. 1.2% days of the whole sample have no SLP data at all and are not considered in the following analyses.

3. Results

3.1. Sea-level and sea-surge variability in the twentieth century

Wintertime 99th percentile of daily maximum sea level and of daily sea surge has been computed at Ostend from 1925 to 2000. Note that 99th percentile values are computed from a polynomial curve fit (6th order) to the empirical cumulative distribution function (cdf). Wintertime 99th percentile of maximum sea level shows an increasing trend of +3 mm/year, significant over 99% level of confidence with a Student’s t-test (Figure 2(a)). During the same period, the wintertime 99th percentile of daily sea surge has increased at a rate of +1 mm/year ($p > 99\%$) and especially from ~1955-1960 to 1980 (Figure 2(b)). Moreover, the mean wintertime (October to March) sea level in the southern North Sea and along the Belgian coast has risen with a mean speed of $\sim +2$ mm/year during the twentieth century (Van den Eynde et al., 2007). To summarize, long-term increase in wintertime 99th percentile of sea-level height at Ostend (i.e. extreme sea levels) during the twentieth century could be explained as the superposition of (1) the increase in wintertime 99th percentile of sea surges, partly associated with increase in onshore NW winds and storminess in the southern North Sea, especially between 1960 and 1980 (Alexandersson et al., 2000; Weisse et al., 2005), and on (2) the slow MSL rise, mostly linked with thermal expansion (Nerem and Mitchum, 2001; Cazenave et al., 2002).

3.2. Weather regimes

The first weather regime (Figure 3(b)) is close to the climatological mean SLP (Figure 3(a)), with a strengthening of the Icelandic low and a strengthening and a north-eastward shift of the Azores High centred over southern Europe. This pattern is hereafter referred to as the ‘Zonal’ (ZO) weather regime. The second pattern (Figure 3(c)) shows an anomalous high pressure shifted over continental Europe. It is referred to as an ‘East Atlantic’ regime (EA) (Plaut and Simonnet, 2002; Ullmann and Moron, 2008). The third weather regime exhibits an anomalous
anticyclone over Greenland and a deep low pressure centred around 48°N–50°N over the eastern North Atlantic (Figure 3(d)). The flow allows synoptic perturbations to reach Europe but on a more southerly track than usual (Rogers, 1997). This pattern is referred to as the ‘Greenland Above’ (GA) regime. The next weather regime (Figure 3(e)) shows typical blocking extended from Eastern Atlantic to Scandinavia and Eastern Europe and a deep cold trough over western Europe and NW Mediterranean Sea (BL for ‘Blocking’). For this weather type, synoptic perturbations can be shifted towards the extreme northeast North Atlantic, but they can travel over the Mediterranean Sea (Plaut and Simonnet, 2002). The last pattern (Figure 3(f)) is characterized by a weak ridge over the mid-eastern Atlantic, followed by a trough stretching from Scandinavia to Eastern Mediterranean sea. This weather regime is called the ‘Atlantic Ridge’ (AR) regime with reference to previous studies (Michelangeli et al., 1995; Plaut and Simonnet, 2002; Moron and Plaut, 2003; Ullmann and Moron, 2008). These five weather regime are almost equal to those found by Ullmann and Moron (2008) in the period 1905–2002.

3.3. Sea surges and weather regimes: mean relationship

Each day is categorized into one of the five weather regime, and Table I displays the mean and standard deviation of sea surge at Ostend for each weather regime over the 1925–2000 period. The highest sea surges are clearly observed for AR, while EA is associated with the lowest sea surges (Table I). AR are potentially associated with low pressure travelling on a northern storm track, between Iceland and Scandinavia, that leads to strong onshore winds in the southern part of the North Sea (Figure 3(f)).

Nevertheless, the standard deviation is quite large, especially for AR, implying that there is considerable variability in sea surges relative to the mean for each
Table I. Mean and standard deviations (in cm) of daily maximum sea surges at Ostend for each weather regime (ZO, ‘zonal’; EA, ‘East-Atlantic’; GA, ‘Greenland Above’; BL, ‘Blocking’ and AR, ‘Atlantic Ridge’) and for the climatology (i.e. the mean and standard deviation of all the days).

<table>
<thead>
<tr>
<th>Weather Regime</th>
<th>Mean sea surge (cm)</th>
<th>Standard deviation of sea surge (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZO</td>
<td>−4.8</td>
<td>24.0</td>
</tr>
<tr>
<td>EA</td>
<td>−13.0</td>
<td>19.0</td>
</tr>
<tr>
<td>GA</td>
<td>−4.9</td>
<td>20.5</td>
</tr>
<tr>
<td>BL</td>
<td>−3.4</td>
<td>22.9</td>
</tr>
<tr>
<td>AR</td>
<td>15.8</td>
<td>27.7</td>
</tr>
<tr>
<td>Climatology</td>
<td>−3.7</td>
<td>24.2</td>
</tr>
</tbody>
</table>

Table II. Column 2 (column 3): frequency of weather regimes when sea surge at Ostend >65 cm (in all data) in the October-to-March period from 1925 to 2000.

<table>
<thead>
<tr>
<th>NCAR October 1925–March 2000</th>
<th>% When sea surge &gt;65 cm</th>
<th>% In total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZO</td>
<td>8.3</td>
<td>20.0</td>
</tr>
<tr>
<td>EA</td>
<td>5.7</td>
<td>25.2</td>
</tr>
<tr>
<td>GA</td>
<td>5.0</td>
<td>15.5</td>
</tr>
<tr>
<td>BL</td>
<td>11.0</td>
<td>17.3</td>
</tr>
<tr>
<td>AR</td>
<td>70.0</td>
<td>22.0</td>
</tr>
</tbody>
</table>

weather regime (Table I). It is interesting to reverse the analysis and to investigate the mean frequency of each weather regime associated with a class of sea surge at Ostend. It is clear that the mean weather regime for AR is associated with the highest sea surges (Table II). A sea surge >65 cm at Ostend (i.e. the wintertime 99th percentile of sea surges in the period 1925–2000) almost never occurs during GA, but could rarely occur during ZO and also BL (Table II). In summary, every AR day is not associated with a sea surge, but a large sea surge at Ostend occurs almost exclusively during this weather regime.

3.4. Weather regime and sea surge during ‘Atlantic Ridge’ days

Every weather regime describes a consistent, large-scale mean atmospheric state but there are regional-scale variations in the SLP pattern within each weather regime. As shown in Section 3.3, sea surges ≥65 cm at Ostend occur mostly during AR phases. Figure 4 shows the mean SLP for AR weather regimes when the sea surge <0 cm at Ostend (Figure 4(a)) and ≥65 cm at Ostend (Figure 4(b)). The SLP patterns are, by definition, consistent at the large scale, but there are clear regional-scale variations. In AR, sea surges ≥65 cm are associated with a deep low pressure <995 hPa covering Scandinavia between 55° N and 65° N and high anticyclonic conditions over the near Atlantic between 30° N and 50° N (Figure 4(b)). A strong southwestward pressure gradient then leads to a northwesterly flow that acts to increase the sea surge along the Belgian coast (Figure 4(b)). However, when the sea surge <0, the deep low pressure is centred between Iceland and British Islands and the high pressure shows a southerly shift (Figure 4(a)). The southward pressure gradient on Western Europe vanishes and shifts southward (Figure 4(a)). In summary, a strong southwestward pressure gradient across the northern part of western Europe in relation with a low (high) pressure centred over Scandinavia (over the near Atlantic between 30° N and 50° N) is the main atmospheric forcing for a rising sea surge ≥65 cm at Ostend, the frequency and amplitude of this eastward pressure gradient being itself modulated by the weather regime.

The possible influence of the length of a persistent spell on the occurrence and amplitude of sea surges is studied. Maximum sea-surge height has been averaged for different duration of AR, expressed in consecutive days. Sea-surge height taken on the last day only of AR’s episodes of different duration has also been averaged over the full analysis period 1925–2000. There is a clear relationship between the length of the sequence of AR and the maximum height of sea surge observed during the sequence (Figure 5). Nevertheless, it is clear that maximum sea-surge heights are not reached on the last day of the sequence of AR (Figure 5). In other words, the peak sea surge does not occur on the last day of AR but on the day when optimum conditions of low SLP and northwesterly winds at Ostend occur. To summarize, a long sequence of AR weather regime increases the occurrence probability of westward shifts of AR’s low-pressure system, from between British Islands

![Figure 4](image-url)
and Iceland to Scandinavia (Figure 5), which favours sea
surges along the Belgian coast.

3.5. Weather regime and sea surges: inter-annual to
multi-decadal variability

The analysis of long-term variability uses the monthly
and wintertime 99th percentile of daily sea surge at
Ostend since 1925 to focus on the highest sea surges
that have the largest potential coastal impact. Consider-
ing the mean monthly/wintertime values leads to similar
results (not shown).

Figure 6 shows the time series of the frequency of each
weather regime with the long-term variation computed
with a recursive low-pass Butterworth filter retaining
only periods longer than 1/30 cycles per year. The long-
term increase in sea surge has no real counterpart in
any of the weather regime frequencies (Figure 6(a)–(e)).
Following the relationship between sea surge at Ostend
and AR weather regimes (Section 3.3), the stationarity of
the wintertime frequency of AR days in the 1925–2000
period (Figure 6(e)) should be associated with stationary
wintertime frequency of daily sea surge. In fact, if no
changes in the occurrence of the surge-related optimum
conditions of low SLP and northwesterly winds along the
Belgian coast associated with AR weather regimes occur
during the period 1925–2000, there is no clear reason
to have an increase in surge height at Ostend. However,
as shown in Section 3.1, the wintertime 99th percentile
of sea surge at Ostend has increased in the 1925–2000
period. Such similar paradoxical long-term variability has
also been found by Ullmann and Moron (2008) between
increase in sea surges in the Mediterranean Sea and
‘Greenland Above’ weather regime.

Correlations between wintertime frequency of AR
weather regimes and 99th percentile of daily sea surge
are computed for the whole period and for three sub-
periods of 25 years (Table III). Correlations are given
for raw time series and low-pass filtered time series
(referred to as LF hereafter), which are residuals from
a recursive low-pass Butterworth filter retaining only
periods longer than 1/30 cycles per year to analyse long-
term variability only. The correlation between LF sea
surge and AR weather regime frequencies is significant
for the full period 1925–2000 (Table III). Considering
the three sub-periods, it is interesting to note that the
correlation is significant only for the last sub-period
1975–2000 (Table III), implying that the relationship
between surges at Oostende and AR weather regime is
not stable. Figure 7 shows the running correlations between
the monthly frequency of AR weather regime and the

Table III. Correlation between wintertime (October–March)
frequency of ‘Atlantic Ridge’, AR weather regime, and the
wintertime 99th percentile of daily maximum sea surge at
Ostend for the whole 1925–2000 period (columns 1–2) and
three sub-periods (columns 3–8).

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>Raw LF</td>
<td>0.32**</td>
<td>0.42***</td>
<td>0.21</td>
<td>0.22</td>
</tr>
<tr>
<td>LF</td>
<td>0.18</td>
<td>0.11</td>
<td>0.74***</td>
<td>0.76***</td>
</tr>
</tbody>
</table>

One, two and three stars indicate the two-sided 90, 95 and 99% level
of significance according to a random-phase test (Janicot et al., 1996;
Ebisuza, 1997).
Figure 6. Wintertime (October–March) frequency (in %) of (a) ‘Zonal’, ZO; (b) ‘East Atlantic’, EA; (c) ‘Greenland Above’, GA; (d) ‘Blocking’, BL and (e) ‘Atlantic Ridge’, AR days (line with circle) for the period 1925–2000, with the low-pass variations retaining periods longer than 30 cycles per year as bold line.

The variation in the relationship between sea surge and weather regime frequencies could be explained by several factors. A first possible factor is that low-frequency variability in running correlations, particularly between indices of inter-annual modes of climatic variability (like between our 99th percentile value of surge and frequency of AR), may be affected by pure stochastic
A statistical test is performed for measuring the probability to achieve the deviations amongst the three correlations computed on sub-periods (Table III). Raw and LF time series of wintertime frequencies of weather regimes and 99th percentiles of daily sea surge are randomly permuted by pairs 1000 times, and the correlations are recomputed on the permuted pairs using the same three sequences as those shown in Table III. The computed correlations are then sorted in ascending order. The standard deviation of the correlations between raw and LF time series of wintertime frequency of AR and 99th percentiles of daily sea surges is outperformed by less than 1% of the permuted pairs in the 1975–2000 period.

The variation in the correlation between sea surge and AR weather regime frequency could also be associated with atmospheric changes. Such a change has been also observed in other parts of northern Europe using other data and methods (Wakelin et al., 2003; Jevrejeva et al., 2005). We observed that the highest sea surges are associated with a strong southwestward pressure gradient between near Atlantic [(30°W–15°W), (30°N–50°N)] and Scandinavia [(15°E–30°E), (55°N–65°N)] (Figure 4(b)). Figure 8 displays the low-pass filtered evolution, retaining periods longer than 1/30 cycles per year of some of the components of this SLP pattern during AR days only. Figure 8(b) shows a clear increase in the SLP over the near Atlantic between 30°N and 50°N, particularly from ~1960 to 1980, synchronous with the increase in the Azores high and the positive deviation of the North Atlantic Oscillation shown in previous studies (Hurrell and van Loon, 1997; Machel et al., 1998). The linear trend computed on the whole available period shows a mean rate of +0.026 hPa/year with over 99% confidence according to a Student’s t-test. The behaviour of the SLP over Scandinavia stays statistically stationary in spite of an important multi-decadal variability (Figure 8(a)). The wintertime frequency of daily barometric gradient between both sectors clearly increases since ~1960 at a rate of +0.12%/year with a level of confidence over 99% (Figure 8(c)), synchronous with the SLP rise over the near Atlantic between 30°N and 50°N (Figure 8(b)).

The wintertime frequency of such daily barometric gradient is significantly lower in the period 1925–1975 than in the period 1975–2000, synchronous with the weakest correlation between the wintertime frequency of AR days and the wintertime 99th percentile of daily sea surge at Ostend (Table III).

These changes could modify the sensitivity of sea surges’ variability along the Belgian North Sea coast to the variation in the weather regime frequency. This is illustrated in Figure 9. The pair of monthly frequency of AR and 99th percentile of daily sea surge on the running 10-year period is ordered according to the frequency of AR. The means, corresponding to the lower (i.e. less AR than 10-year mean) and upper (i.e. more AR than 10-year mean) halves are then computed. The mean frequency of AR is almost stationary in the 1925–2000 period (not shown, but mean of upper and mean of lower half of %AR shown in Figure 9 are already almost stationary). The long-term increase in the mean 99th percentiles of sea surge for both samples is associated with the increase already observed (Figure 2(b)). The mean 99th percentile of daily sea surge associated with the frequent AR [AR(+)◦] increases from ~1960 to 1980, synchronous with the pressure rise over the near Atlantic between (30°W–15°W), (30°N–50°N) shown before. During the same period, the mean 99th percentile of sea surge associated with the rare AR [AR(−)◦] is almost stationary (Figure 9). It helps to understand how the pressure rise over the near Atlantic could increase the sensitivity of sea surges when AR is more frequent than the mean conditions. This asymmetric evolution (Figure 9) contributes to the increase in the correlation between winter AR frequency and 99th percentile of daily sea surge (Table III and Figure 7).
4. Conclusion

From 1925 to 2000, wintertime (October-to-March period) 99th percentile of daily maximum sea level at Ostend shows an increasing trend of +3 mm/year (Figure 2(a)). During the same period, the wintertime 99th percentile of daily sea-surge height has risen at a rate of +1 mm/year (Figure 2(b)). The relationship between daily sea surge at the Ostend tide gauge station and five weather regimes over the northeast Atlantic and Europe is analysed over the 1925–2000 period. Overall, AR is associated with the highest sea surges, while EA
is associated with the lowest ones (Table I). More than 70% of sea surges ≥65 cm occur during AR weather regimes, ahead of low pressure travelling on a northern track from Iceland to Scandinavia associated with strong onshore surface winds over the Belgian coast. Nevertheless, the occurrence of this weather regime is not necessarily associated with a high sea surge. In particular, the sea surge <0 cm when the low-pressure system in AR stays stationary between British Islands and Iceland (Figure 4(a)). These features emphasize regional-scale, SLP differences within each weather regime. High sea surges are systematically associated with a strong south-westward pressure gradient across Western Europe that leads to a northwesterly onshore flow and low SLP over the Belgian coast.

Sea surges’ heights at Ostend show an increase from 1925 to 2000, which is apparently not related to slow variations in the frequency of AR weather regimes. Beyond this long-term rise, there is an increase in the correlation between 99th percentiles of daily sea surge at Ostend and frequency of AR weather regimes (Figure 7 and Table III). This variation does not seem to be explained by pure stochastic processes. Possible factors could be long-term changes in the mean SLP field. For example, the long-term increase in the surface pressure over the near Atlantic, between Spain and British Islands (Figure 8(b)), and the frequency of a high southwestward pressure gradient over western Europe (Figure 8(c)) could induce a stronger sensitivity of the sea surge to the AR weather regime at the end of the twentieth century when it occurs frequently (Figure 9). This slow change needs to be considered in any climate change study using future large-scale atmospheric conditions to infer regional-scale and local-scale variations (i.e. Von Storch and Reichardt, 1997), such as sea surges and extreme sea levels along the Belgian coast.

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