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Regional modelling of the 21st century climate changes in the Irish Sea

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Abstract

An assessment of the complex evolution of climate change signals in the Irish Sea over the 21st century is presented in this paper. Potential impacts of climate change on the local hydrography are explored and interrelationships between fundamental oceanographic shelf sea phenomena investigated. A regional ECOMSED ocean model is used to downscale a 120-year period (1980-2099) of the SRES A1B scenario experiment from a global ocean model. A detailed regional analysis shows that local climate changes may be significantly different from the expected global changes.

This research suggests that in the future the Irish Sea will be warmer with sea surface temperature increase of around 1.9˚C. Maxima and minima annual temperatures will occur around 2 weeks later each year relative to the present climate. Geographically, shallow waters along the coastline and in the eastern Irish Sea will exhibit strongest warming due to increased heat uptake during summer and autumn and reduced heat loss in spring and winter. Warming in the deep channel in the western Irish Sea will be generally weaker with seasonal variability subdued due to a large heat storage capacity. The warming will be largely stored in the surface layer of the water column leading to strengthening of stratification and a considerable decrease in the thickness of the mixed layer. The western Irish Sea gyre will become stronger and result in substantial reinforcement (>30%) of southward currents along the east coast of Ireland. Net northward flow in future climate will be maintained at the current annual rate. Steric sea level is projected to rise by 0.31m during the 21st century, leading to an overall projected sea level rise of approximately of 0.47m.

Future changes to oceanographic parameters, flushing times and hydrodynamics of the Irish Sea are likely to alter the habitat and distribution of marine species; the finding of this research are therefore of great interest to ecologists and the fishery industry.

Keywords: Irish Sea, climate change, numerical model, regional modelling, dynamic downscaling

1 Introduction

The climate changes projected to occur within the next 100 years will have considerable impact on the physical conditions of the Irish Sea (McGrath and Lynch, 2008). Understanding long-term variability in climate parameters is crucial to predicting these impacts. Temperature is one of the most important climate variables. In the Irish Sea, temperature is responsible for seasonal stratification and consequently for circulation patterns (Olbert et al., 2011). These features, however, may change in response to future climate changes with potentially significant effects on the local hydrography. Potential impacts of climate change on relationships between various oceanographic phenomena observed in the Irish Sea and on the hydrodynamics have not yet been the subject of any detailed investigation.

The Irish Sea climate is also important for local ecosystems and regional fisheries. Temperature, winds, vertical mixing, salinity, oxygen and pH directly affect physiology, development rates, reproduction behavior and survival of individual species (Brander, 2010). Climate may also have secondary effects on species through changes in food availability, competitors and predators (Adlandsvik, 2008). Recent studies showed clear evidence of climate change on jellyfish (Lynam et al., 2011), fish (Drinkwater, 2005; Brunel and Boucher, 2007) and phytoplankton (Edwards et al., 2006).

According to the IPCC report (IPCC, 2001), the 20th century was the warmest century in the last millennium. Over the past 50 years the rate of warming was almost double that of the past 100 years (IPCC, 2007). The warming of the oceans in recent decades is an obvious feature of climate change. Since 1850 global average sea surface temperature (SST) has increased by 0.74˚C and this warming has occurred during two main periods of 1915-1945 and 1975-present. Over the same period the SST in the North Atlantic Ocean has risen by approximately 0.49˚C. Hoerling et al. (2001) relates the North Atlantic change to a progressive warming of tropical SST, especially over the Indian and Pacific Oceans.

With regard to the Irish coastal waters, satellite OISST data produced by the National Oceanic and Atmospheric Administration (NOAA) shows a general warming trend of 0.37˚C per decade for the period 1982-2006. The historic dataset of SSTs in the Irish Sea during the period 1850-2007 reveals a warming trend averaging 0.3˚C with the warmest years in the records being 2005, 2006 and 2007. In contrast, the historic dataset from the north of Ireland for 1958-2006 exhibits a linear warming of 0.85˚C (Cannaby and Hüsrevoğlu, 2009), while recent in situ coastal observations in the Irish Sea show trend of up to 0.7˚C (McGrath and Lynch, 2008). These trends of SST in the Irish Sea were also reproduced by Olbert et al. (2011) using a numerical model where a hindcasted increase of 0.35˚C was recorded for the period 1951-2008. The same modelling study predicted a rise in SST of 0.83˚C for the subset 1965-2008 and unprecedented warming of 1.66˚C since 1980. The recent intense warming was explained by the natural variability associated with multidecadal-scale fluctuations (with Atlantic Multidecadal Oscillation (AMO) having greatest contributions) and global warming in equal measure (Cannaby and Hüsrevoğlu, 2009).

Increases in SST can have significant impact on physical and transport processes within the Irish Sea. A study on the long-term variability of the gyre in the western Irish Sea (WIS) showed that an increase of water temperature is followed by strengthening of stratification and, consequently, changes in the gyre structure, circulation patterns and retentive properties of the western Irish Sea (Olbert et al., 2011). Initial investigations into the effect of changes within the western Irish Sea on the entire sea suggested good correlation between strengthening of the gyre and changes to the net flow through the sea.

An increase in SST may also affect the intensity or frequency of cyclones through the resulting increase in atmospheric moisture (Gyakum and Danielson, 2000). Statistical analysis of 56-year storm history over the North East Atlantic and associated extreme surge events in Irish coastal waters demonstrated high likelihood of stronger surges in the future (Olbert and Hartnett, 2010). Brown et al. (2010) postulate that future climate for the eastern Irish Sea will enhance peak surges by up to 40 % as a result of stronger winds combined with sea level rise. This will translate to increased risk of storm damage and flooding (McGrath and Lynch, 2008).

There have been very few attempts to estimate climate change signals in the Irish Sea; so far, efforts have focused on storm surges (Wang et al., 2008; Brown et al., 2010; Lowe and Gregory, 2005), sea level rise (Woodworth et al., 2009; Lowe et al., 2001) and wave climate (Wolf and Woolf, 2006). High resolution studies of the impact of climate change on the hydrography of the Irish Sea have not been carried out to date. All projections of the Irish Sea future climate have been based on global model information, however, local changes may not scale with the anticipated global climate change. Climate is a complex system and while global models are capable of describing essential climatic processes, coarse model resolution introduces uncertainty through an inability to resolve sub-grid scale processes (Wilby et al., 1999). One particular problem is a lack of relevant shelf sea physical processes such as tidal mixing which is of great importance in the case of the Irish Sea. Global model results may not, therefore, be applicable for studying climate change in shelf seas. There are two approaches to deal with this problem: (1) the use of high resolution global models (Cubash et al, 1995), or (2) the use of nested regional models (Giorgi and Mearns, 1999). In this paper both approaches are combined by running a global model with increased resolution over the European continental shelf and then dynamically downscaling results using a high resolution model of the Irish Sea. This method is advantageous in providing a globally consistent simulation and fine-scale shelf physics. Apart from model resolution, another source of uncertainty in predictions of future climate is related to emission scenarios and differences in global climate change simulations (Woth et al., 2006); however, this uncertainty is very difficult to quantify.

Many researchers studying the effects of climate change favour the use of the time-slice approach, where results are derived from contemporary and future climate periods without information for the period between the two. This approach can be a source of error. In this study, a transient simulation approach, covering the full time period, is used. The method is more advantageous than the time-slice approach as it provides consistent timeseries of changes and allows one to distinguish between long-term variability and change signals (Nuemann, 2010). Bearing in mind the broad range of uncertainties associated with model resolution, model selection, simulation scenario and period, this analysis of future climate changes in the Irish Sea is carried out in a way that aims to minimize the potential errors described.

In this paper, a regional ocean model of the Irish Sea is used to downscale a 120-year period (1980-2099) of the SRES A1B scenario experiment from the global MPI-OM model. The main aim of this study is to investigate responses of physical conditions in the Irish Sea to the climate changes in the regional atmosphere as well as in the North East Atlantic. A complex assessment of the future Irish Sea hydrography involves detailed analysis of inter-annual evolution and seasonality of temperature (including horizontal distribution and vertical profile) as well as effects of temperature changes on mixing layer depth, stratification strength, regional circulation patterns and transport through the Sea.

2 Irish Sea hydrography

The Irish Sea is a semi-enclosed body of water located on the North-West European Continental Shelf and designated by coordinates 51N-56N and 2.5W-7W. It is connected to the Atlantic Ocean waters through two openings: the North Channel and St. George's Channel. It's approximate length is 300 km and it's width varies between 75-200 km. The North Channel, with width 30 km and depth exceeding 275 m, is the narrowest and deepest region of the Irish Sea whereas the eastern Irish Sea, with average depths of 30 m, is the shallowest region. More hydrological details can be found in Olbert et al. (2010).

The Irish Sea due to its complex geometry and bathymetry exhibits complicated flow pattern. The circulation within the sea is driven by tides, winds and baroclinc flow. The M2 and S2 tidal constituents are the greatest contributors to barotropic flow. Tides enter the region through both the St. George's and North Channels, with the two paths meeting along a line running westward from south of the Isle of Man (McKay and Pattenden, 1993). The strongest tidal currents of 1.0–1.5 m/s are observed at both entrances and in the vicinity of headlands (over 2 m/s), while the weakest tidal currents occur in the western Irish Sea. Wind action also plays a significant role with the strongest response to wind observed in the shallow eastern Irish Sea (Olbert and Hartnett, 2010) and in the North Channel (Brown and Gmitrowicz, 1995). The wind driven mixing in the Irish Sea results from shear in response to surface wind stress and shear induced by near-inertial oscillations due to sudden changes in wind direction. Sherwin (1987) quantifies mean summer surface and shear-induced mixing power as 7.1 x 10^4 W/m^2 and 2.0 x 10^4 W/m^2, respectively.

Baroclinic flow, controlled mainly by water exchange with the Atlantic Ocean and seasonal heating, is generally northward through the Irish Sea. This flow, however, is periodically disturbed due to wind action and seasonal formation of density gradients. In particular, development of stratification from spring until late summer in the western Irish Sea has results in seasonal changes to the northward flow. This thermal structure, along with persistent slack waters in the region, provides the baroclinicity that drives a geostrophic cyclonic surface flow called the western Irish Sea gyre (WISG). The anticlockwise gyre results in formation of seasonal southward flow along the east coast of Ireland and is therefore responsible for reversing the general northwards net flow. More details on the structure of the flow can be found in Hill et al. (1996, 1997), Horsburgh et al. (2000) and Olbert et al. (2011).

3 Methods

Applying data from a global ocean model at lateral boundaries of a regional model allows resolution of fine-scale processes present in shelf seas but not resolved by the global circulation model. In this research, large scale boundary conditions of a future climate scenario were derived from the ocean MPI-OM and atmospheric ECHAM5 global models developed by the Max Planck Institute for Meteorology, Hamburg. Model forcing for the regional simulations was provided by dynamic downscaling with ECOMSED used as the regional ocean model for downscaling. The downscaling method utilized here is a one-way nesting. In total, 120 years of model simulations (1980-2100) of global ocean conditions (MPI-OM) and the Irish Sea conditions (ECOMSED) under the moderate economic growth SRES A1B emission scenario were performed.

3.1 MPI-OM model

The MPI-OM model has been applied to a wide range of climate change studies including sea level changes (Lenderer et al., 2007), thermohaline circulation (Jungclaus et al., 2006a) and biogeochemical processes (Kloster et al., 2007; Wetzel et al., 2006). A detailed technical description of the model and parameterization can be found in Marsland et al. (2003); for brevity, only the main features of the model pertinent to current analysis are discussed here.

The primitive equations for a hydrostatic Boussinesq fluid are formulated with a free surface (Jungclaus et al., 2006b) and horizontal calculations of vectors and scalars are formulated on a C grid (Arakawa and Lamb, 1977). The continuity equation implies conservation of volume and the prognostic sea surface height field has a zero global mean. Globally-averaged rates of precipitation, evaporation and river runoff are close to zero and the eustatic sources in the simulation are excluded. Therefore, the net global volume change (steric sea level) in the model is due to changes in ocean temperature only (Lenderer et al., 2007) estimated from the local density structure.

The model mesh generated specifically for this research was placed on the bipolar orthogonal curvilinear grid with one of the poles placed over Europe and the other over North America. The average global grid resolution is 1.5˚ with the average resolution over the Irish Sea being approximately 15 km. The model has 239 zonal by 164 meridional lanes; the vertical resolution is 30 z levels, 20 of which are distributed over the upper 800m. The topography was generated from the ETOPO5 dataset (NGDC, 1998). Bathymetry and model meshes are illustrated in Fig. 1(a). The model was forced at the surface by the ECHAM5 (Roeckner et al., 2003) atmospheric model of T63 horizontal resolution and L31 vertical levels. The atmospheric output for the SRESA1B emission scenario was provided on 6-h temporal resolution.

3.2 ECOMSED model

Three-dimensional water temperature and salinity fields computed by the MPI-OM model were used to generate initial and lateral boundary description for the ECOMSED regional model of the Irish Sea. Technical details of the ECOMSED model can be found in Blumberg and Mellor (1987). A previous hindcast model study of the Irish Sea climate (Olbert et al., 2011) using the same models and downscaling approach proved that the downscaling performs well at a 10:1 reduction in grid size.

Computation of the Irish Sea hydrodynamics was carried out on a 2 km by 1.5 km horizontal rectangular grid covering the entire area of the Sea (51.0 – 56.0°N and 7.0 – 2.6°W). The bathymetry was constructed from the Irish National Seabed Survey data and is illustrated in Fig. 1(b). The vertical processes are calculated on the 21 sigma terrain-following layers.

The model was forced by astronomical tides, baroclinic conditions and atmospheric forcing. Tidal input was supplied by a variable surface elevation prescribed at the open boundary. Data for five tidal constituents, K1, O1, M2, N2 and S2, were extracted from the FES2004 dataset (Lyard et al., 2006). Initial and boundary conditions in the form of monthly-averaged temperatures and salinity were specified to the model from the MPI-OM model and river discharges were provided by the ISSG (1990). ECHAM5 output was used to force the model's surface boundary.

4 Results and discussion

4.1 Atmospheric forcing

Air temperature has a significant impact on the development of important hydrographic features of the Irish Sea like stratification and density driven flows, while wind forcing is particularly important in shallow water circulation (e.g. eastern Irish Sea) and on the stability of stratification. Fig. 2 shows expected long-term trends in some atmospheric parameters over the Irish Sea. Over the 1981-2100 period, the 2-m air temperature is projected to rise linearly by an average by 2.2˚C, which constitutes a 19.5% increase with respect to the 1980's value (Fig. 2a). Seasonally, a rise is expected for all four seasons with the highest rate of warming during summer (2.7˚C) and lowest during spring (1.5˚C).

Wind speeds and directions for all four seasons over the Irish Sea are presented in Fig. 2(b) and (c), respectively. The ECHAM5 model under the A1B scenario projects a slight (c. 2%) increase in winter wind speeds and decreases of 1.2, 4.5 and 2.2% in spring, summer and autumn, respectively. These trends are in line with those found from ensemble simulations for Ireland (McGrath and Lynch, 2008) and with observations (Esteves et al., 2011).

With regard to wind direction, the model projects a winter shift of mean wind direction from approximately 195° from north to 215° from north. This means that during winter future winds will be slightly stronger and more westerly than at present. No significant changes to wind directions are expected for other seasons.

4.2 Control run validation

As a prerequisite to applying the downscaling technique for future climate the performance of the global and regional model must be examined in order to determine the extent to which the hindcast control period reproduces past climate conditions. A comprehensive evaluation of the MPI-OM and ECOMSED simulations under atmospheric forcing of NCEP Reanalysis 2 model (Kanamitsu, 2002) was carried out by the Authors and is presented in Olbert et al. (2011). It is not repeated here for reasons of brevity. It was found that both models demonstrated good ability to replicate hydrographic features like temperature profile, stratification and flow fields in the observed Irish Sea marine climate. Thus, when correct meteorological forcing is prescribed the models are capable of simulating ocean physical processes accurately on both temporal and spatial scales. Validation also confirmed that the downscaling procedure is well suited for the Irish Sea and the small-scale advective and convective processes are resolved by the regional model.

In the present study, the ocean models are forced with the ECHAM5 global model output. Verification of the ECOMSED model performance was carried out by comparing physical parameters of this model to the corresponding parameters of the well-validated ECOMSED model forced with the NCEP data. Climatologies of both models are derived for the period 1981-2005. Fig. 3 shows the SST bias of the ECOMSED–ECHAM5 results compared to the ECOMSED-NCEP output. For the whole Irish Sea the SSTs simulated with the ECHAM5 forcing are slightly overestimated compared to the NCEP dataset with annual mean bias of approximately 0.18˚C. Spatially, a maximum warm bias of up to 0.5˚C is found in the shallow waters along the east coast of Ireland, north coast of Wales and around the Isle of Man. In contrast, an annual cold SST bias of approximately -0.25˚C occurs at the south entrance to the Irish Sea.

Overall, the SST biases generated by the ECOMSED model are due to the biases in atmospheric forcing introduced by the ECHAM5 model. The summer cold bias is dominated by the air-sea heat exchange, therefore, it is smaller than the winter warm bias, which is additionally influenced by the stronger inflow of warmer Atlantic water. The biases of water temperature in regional climate studies due to biases introduced by atmospheric models were reported recently by Neumann (2010), Samot et al. (2006) and Dőscher and Meier (2004).

Fig. 4 compares the annual cycle of the 2-m air temperature of the ECHAM5 output and the NCEP dataset. In both cases, minimum and maximum monthly air temperatures occur in February and August, respectively. The ECHAM5 model shows strong winter warm bias of as much as 2.6˚C. The summer temperature is insignificantly underestimated with respect to the NCEP reanalysis data. This misrepresentation of air temperatures by the ECHAM5 model could be due to coarse model resolution (Roeckner et al., 2004; Roeckner et al., 2006) which does not allow correct resolving of the jet stream.

In conclusion, it could be stated that the regional ocean model together with the ECHAM5 atmospheric forcing reproduces present climate reasonably well considering that the models are not tuned to the current climate. It is therefore expected that the hydrodynamic model response to the future climate will also perform well.

4.3 Temporal variations in water temperature

Water temperature is a state variable in the climate change studies. The global mean sea surface temperature simulated by the MPI-OM model is projected to rise by 2.75˚C during the 21st century. This amount of warming agrees very well with multi-model averages under the A1B scenario (IPCC, 2007). However, the rate of warming for future climate is geographically non-uniform, with regional patterns similar to those observed over the past several decades. At large scale basin the greatest warming is expected in the Arctic and along the equator in the eastern Pacific while the lowest warming is projected for the North Atlantic and Southern Ocean. The MPI-OM SST projection for the Irish Sea of 1.93˚C is less pronounced than the global mean. This is partially due to advective transport from the North Atlantic which, for future climate, will exhibit reduced warming (Gregory et al., 2005) caused by a weakening of the Atlantic Meridional Overturning Circulation (MOC) (Dai et al., 2005).

The Irish Sea temperature is controlled mainly by seasonal heating and water exchange with the Atlantic Ocean. Fig. 5 presents annual cycles of the SST over the period 1981-2099. Annual cycles of the depth-averaged temperature are also presented as this parameter is a more comprehensive measure of the Irish Sea climate and is, for many studies (e.g. ecosystem studies), a more relevant parameter than SST. Values are spatially averaged over the whole Irish Sea. The annual cycles, shown as weekly instantaneous values, have a sinusoidal-like distribution with minimum temperatures in February-March and maximums in July-August. As expected the SST shows greater inter-annual variability than the depth-averaged temperature. This is particularly evident during summer time when limited vertical mixing means the summer warming is trapped in the surface layer of the sea. Much stronger mixing processes during other seasons reduce the difference in warming between the surface and whole water column.

Both the SST and depth-averaged temperature show increasing warming over the 21st century. Trends were determined from SST and depth-averaged temperature anomalies using a least-squares fitting method. The goodness of the fit was assessed from the associated regression coefficient and the analysis is statistically significant with a 95% significance level. By the 2090's, the SST and depth-averaged temperature across the Irish Sea will increase above the 1980's values by c. 1.89˚C and 1.79˚C, respectively. These trends are subject to considerable seasonal differences. Autumn accounts for the greatest warming with the highest projected monthly increase occurring in October. In contrast, projected warming is lowest in spring with the lowest monthly increase occurring in May.

Fig. 6(ai) and (bi) show annual maximum and minimum temperatures over the period of 1981-2099; these data are overlain by a linear trend. The regression model displays an increase in maximum SST and depth-averaged temperatures in the Irish Sea of 2.30˚C and 2.05˚C, respectively. The minimum annual temperatures of the surface layer and mean water column exhibit the same warming rate of 1.78˚C and these positive relationships are confirmed by a R^2 of 0.65. Inter-annual variability in the timing of the maximum and minimum temperatures was also considered. As shown in Fig. 6(aii) (and 6bii), a delay in the time of occurrence of the maximum SST (and depth-averaged temperature) is likely to occur; by the end of 2099 the maximum SST is expected to occur approximately 19 days (16 days) later than at the beginning of the time-period considered. The time of occurrence of lowest temperatures is also expected to be delayed with a 12 day delay predicted for both the SST and depth-averaged temperature. Finally, the onset of temperatures above and below a threshold level of 13˚C was investigated (Fig. 6 aiii and biii). Following the general warming trend, the rise of temperatures above 13˚C is projected to occur at an earlier stage of the year while the fall below 13˚C is expected to occur at a later stage of the year. By the end of 2099 it is expected that the SST rise above 13˚C will occur 1 day earlier than at the beginning of the simulated period while there will be a 46-day time lag in the fall below 13˚C. In case of depth-averaged water temperatures by the end of 2099 the rise of temperatures above the 13˚C threshold will occur 25 days earlier relative to the 1980's values while the fall below 13˚C will occur 46 days later.

The above trend analysis shows that the future climate will be warmer than the current climate for all seasons of the year. By 2099, peak temperatures will occur later during a year by about 2 weeks and the period of time during which temperatures exceed 13˚C will be extended by 47 and 71 days for SST and depth-averaged temperature, respectively.

4.4 Regional variations in temperature

The projected rate of warming of the Irish Sea is expected to vary regionally; these regional variations may also change temporarily. The spatial distribution of warming trends over the Irish Sea was examined for four seasons: winter (JFM), spring (AMJ), summer (JAS) and autumn (OND). This analysis is based on a time-slice approach and though it may include undesired contributions from natural climate variability it provides a good indication of the spatial and temporal characteristics of warming.

Differences between the future scenario time-slice (2070-2099) and the control run (1981-2010), shown in Fig. 7, reflect regional patterns of surface warming. The SST increase is generally weaker than that calculated using the long-term linear trend analysis; this could be due to the stabilizing tendency of SST at the end of the 21st century. SST warming is projected to range from 0.5˚C to 1.8˚C and to vary both seasonally and regionally.

During winter the warming is generally between 1.0˚ and 1.5˚C everywhere within the Irish Sea with the highest winter rises in the western Irish Sea (>1.4˚C) and in the central part of the sea and north from the North Channel (>1.3˚C). Spring exhibits the most homogenous spatial pattern. SST trends over the Irish Sea are generally weak and vary between 0.7 and 0.9˚C following slight increases in air temperature during spring. The strongest spring warming is found along the southern boundary suggesting that Atlantic waters will be warmer during future spring seasons. The summer season is characterized by significant warming and the largest regional differences ranging from 1.0˚C in the central Irish Sea to 1.7˚C at the south entrance. Warming >1.5˚C also occurs in shallow waters adjacent to the UK coast and in the western Irish Sea. Finally, the greatest increase in warming occurs during autumn. The highest SST change of 1.8˚C occurs in the eastern Irish Sea and along the Irish and UK coastlines; the lowest increase of 1.2˚C occurs at the north entrance to the Sea.

Geographically, no consistent pattern of warming was found as there is no dominant region where warming is strongest for all four seasons. As expected, the shallow waters of the eastern Irish Sea and along Irish and UK coastlines show strongest warming during summer and autumn, while the central channel of the Irish Sea exhibits strongest warming during winter and spring. These variations are related primarily to the regional atmosphere-ocean heat transfer and secondly to the Atlantic influence. Shallow waters of the eastern Irish Sea, remote from the main south-north channel flow, show an increased heat uptake during summer and autumn and reduced heat loss in winter and spring in accordance with trends in the annual cycles of future atmospheric conditions. The temperature differences in the main channel along the south-north axis exhibit lower seasonal variations due to the larger heat storage capacity of its deeper waters.

The influence of the Atlantic Ocean is mostly confined to the deeper regions outside the Irish Sea where warming is generally weaker. Interestingly, the strong warmer inflows through the south boundary during summer appear to be a surface phenomenon as they are not manifest in the deeper parts of the water column and they seem to have little effect on overall warming in the Irish Sea.

4.5 Vertical temperature profile and mixing depth

Temperature change may also act as proxy for other climate mechanisms such as changes in stratification, vertical mixing and circulation. Olbert et al. (2011) investigated possible connections between SST, stratification and strength of circulations in the western Irish Sea and found significant positive relationships.

In this section future changes in temperature are considered for various depths of the water column. Again, the analysis is based on the 30-year time-slice approach. Fig. 8 illustrates differences in the temperature between the future and control runs for the four seasons at three different locations (see Fig. 1b for map of locations).

Results show that the complete water column gets warmer in the future. Largest differences during autumn (c. 1.6˚C) and smallest during spring (c. 0.9˚C) confirm the findings from the regional analysis. The vertical distribution of temperature differences and, in particular, the seasonal aspects are very interesting. The degree of warming over the water column is uniform during winter at all three locations. This is because winter water tends to be mixed to the bottom due to strong wind energy. In Autumn, homogenous distributions are observed in both the North Channel and the western Irish Sea while a 0.2°C difference between surface and bottom temperatures is observed in St. George's Channel. Spring is characterized by a weaker warming trend near the surface and a gradual increase towards to the bottom. The largest vertical differences in warming occur during summer; the differences vary between 0.4 and 0.8˚C depending on the location. These strong gradients show that more of the warming is stored in the surface layer than the bottom layer. The higher surface warming will consequently affect vertical stratification and mixing depth.

Inter-annual variations of summer mixing depths at three selected locations are presented in Fig. 9. Calculations of the mixed layer depth are based on a delta rho criterion. The summer mixed layer depth shows a strong inter-annual variability and a clear trend. In general, there is a considerable decrease in the thickness of the mixed layer. For St. George's Channel the regression analysis reveals a linear decrease from 44.5 to 33.5 m between 1981 and 2099 giving a decreasing 120-year trend of 11 m. In the North Channel and the western Irish Sea the trends are also decreasing with changes of 8.3 and 3.5 m, respectively.

The considerable changes in the mixing depth clearly reflect strengthening of the thermal stratification associated with a surface warming. The increased heating, and weaker wind speeds, over summer suppress turbulence causing a sharpening of density gradients and an increasing stability of stratification. This in turn leads to reduced turbulent mixing and shallower mixed layers. Additionally, increased turbidity of the mixed layer limits absorption of solar radiation to deeper layers, causing further strengthening of stratification and thus a shallowing of the mixed layer (Burchard et al., 2006).

4.6 Circulation pattern

According to the 4th assessment report of the IPCC and ECHAM5 results for the A1B scenario, the climate of the Irish Sea will become warmer during the 21st century whereas winds (except winter) will be slightly milder with a shift in direction. Since the circulation within the Irish Sea is driven by tides, winds and baroclinc flow, effects of future changes in temperature and wind characteristics may interact with each other (counteract or amplify) with possible impacts on the evolution of circulation patterns in the Irish Sea.

Olbert et al. (2011) showed that summer stratification strengthens in the western Irish Sea with increasing air temperature and decreasing wind speeds. The Authors further quantified strong positive relationships between SST and potential energy anomaly and between potential energy anomaly and residual flows through the region. Wind effects in the Irish Sea are more problematic to measure and are usually discussed in the context of surge development (Jones and Davies, 1998, 2006; Olbert and Hartnett, 2010) but wind contribution to circulation in shallow waters and stability of vertical structures is recognized.

Fig. 10(a) presents maps of seasonally-averaged surface residual flows for the control run. The simulated currents within the Irish Sea are in good agreement with observations (Hill et al., 1996; Simpson and Hunter, 1974) and previous modeling efforts (Horsburgh et al., 2003; Olbert et al., 2011). Winter residual flow is northward with a supply of warmer, saline water from the Atlantic Ocean. From March onwards, along with the seasonal formation of stratification in the western Irish Sea, the density-driven gyre develops. This cyclonic circulation results in a disturbance of the northward flow and formation of a southward current along the east coast of Ireland. The gyre is strongest in July and starts to decline in August until it finally breaks in October. From October until the following March the residual flow through the central Irish Sea is northward again.

Seasonal differences in the surface currents expressed in a relative form as future-to-control current ratios are shown in Fig. 10(b). Although the effects of wind stresses and temperatures are difficult to separate, the impact of changes in wind signal is noticeable. This is particularly true during winter, when residual currents in shallow coastal regions are predicted to increase on average by 25 - 40% and the western component of the current vectors becomes more pronounced (due to the westerly shift in winter winds). Summer sharpening of stratification (discussed in the previous section) will result in strengthening of the gyre circulation in the western Irish Sea. Consequently, the southward branch of the flow adjacent to the coast of Ireland will be reinforced with magnitudes exceeding those from the control run by 30%. In autumn, the generally prevailing northward flow will strengthen.

4.7 Transport through the Irish Sea

Polewards flowing waters off and along the west and south coasts of Ireland are composed of two water masses: flow from the south along the continental margin originating in the Bay of Biscay and flow along the western slope fed by the North Atlantic Current waters (Pingree et al, 1999). The most important aspect of the physical oceanography of the Irish Shelf, however, is the presence of coastal jets (Brown et al., 2003) flowing along the southern and western coastlines of Ireland. Hill et al. (2008) recognize that density-driven frontal jets are the most significant contributor to seasonal shelf transport and show the importance of thermohaline circulation of shelf seas. Future changes to the pathways of sub-polar and sub-tropical North Atlantic gyres may modulate the North Atlantic Current with implications for the water masses on the Irish Shelf. Projections for the North Atlantic Current foresee increased northward heat transport (Hu et al., 2004). Therefore, changes in the position and strength of current systems, such as North Atlantic Current, the European slope current and frontal jets, may modify hydrodynamic conditions in the Irish Sea.

Overall changes in the Irish Sea flow pattern and inflow from the Atlantic are assessed based on the strength of flow through the Irish Sea. The stream function used in this assessment integrates the meridional velocity in zonal direction from the western coast to the eastern coast of the Irish Sea along the section A (shown in Fig. 1b) and vertically integrates from the bottom to the surface of the sea.

Fig. 11(a) quantifies the circulation changes between the control run and the future scenario run. In both cases the 30-year average flow remains northward throughout the year, however, the level of inter-annual variability is high. The process of averaging masks the seasonal variability that often leads to development of southward flow at some time between July and September. From the annual cycle of the 30-year climatology it can be seen that the strongest inflow through St. George's Channel occurs in February. It then starts to gradually decline to reach the lowest level in July after which it rises again in the second half of the year to match the December inflow of the control run.

The annual cumulative volume of water advected into the Irish Sea through the southern boundary is shown in Fig. 11(b). In comparison to the control run the northward flow in the future run is weaker in the first half of the year but significantly stronger in the second half of the year; the total volume of water transported northward annually is quite similar in both cases at 1420.2 and 1416.4 km^3 for control and future run, respectively. This is supported by the regression analysis of 120 years of weekly flows, which shows no clear trend of weakening of the northward flow.

Two main conclusions arising from this analysis are: (i) in the future, northward flow will be maintained at an annual rate almost identical to that of the current climate and (ii) the intra-annual flow distribution will resemble the control run flow pattern, however, the flow rates will be different.

4.8 Steric sea level rise

Global mean sea level changes due to changes in ocean mass or changes in ocean density. In this analysis sea level rise is constructed from the changes in ocean density only (steric change); eustatic mass sources are not included in the MPI-OM simulation. The global mean changes in density are dominated by the thermal expansion (thermosteric) (Gregory et al., 2001); salinity variations (halosteric) play only a minor role (Bindoff et al. 2007). Local changes in sea level may vary from the global mean. In large-scale basins, a change in ocean circulation pattern and intensity results in substantial redistribution of water mass properties and significant differences in regional sea level responses (Landerer et al., 2007). Thus, the change of sea level gradients is a direct measure of large-scale circulation change (Gregory et al., 2001). There have been many studies showing the relationship between sea level change and thermohaline circulation (Levermann et al. 2004; van der Shrier et al. 2004). Thorpe et al. (2001) defines the mechanisms of MOC response to climate change as air-sea buoyancy fluxes and the advection of salt and temperatures anomalies. According to Schmittner et al. (2005), projected weakening of the Atlantic MOC by 25% over the 21st century will result in sea level changes in the North Atlantic. Due to its direct proximity to the Atlantic, the Irish Sea is likely, therefore, to be subjected to an additional increase in sea level on top of the global mean sea level.

Time series of seasonal global sea level variations under the SRES A1B emission scenario is presented in Fig. 12(a). The model projects a sea level rise of 0.24 m and this result is in line with climate model ensemble projections for the A1B scenario (IPCC, 2007). Seasonal variability due to expansion and contraction of the water column resulting from air-sea heat exchange decreases considerably in the future climate run with standard deviations of 10.3mm and 4.0mm for periods 2010-2020 and 2090-2099, respectively.

On top of the thermosteric effect there is additional steric sea level rise attributed to changes in ocean dynamics. This local change is calculated as a difference in steric change between the Irish Sea and global mean. As shown in Fig. 12(b), the local sea level in the Irish Sea is projected to rise at an annual rate of 0.73 mm. Thus, over the 21st century the total steric sea level, combining the contributions of global mean thermosteric sea level and local sea level, is expected to rise at rate of 3.1 mm/yr. This can be compared to 69-year tidal records from Liverpool of estimated sea level trend of 1.8 mm/yr (Woodworth et al. 2009). The increase simulated by the model, although much larger than the 20th century observation does not include the eustatic signal. Katsman et al. (2008) calculated rates of sea level changes due to changes in the Atlantic Ocean mass and proposed the following contributions: glaciers (0.101m), Greenland (0.011m), Antarctica (0.021m) and terrestrial water storage (0.020m). Adopting these values, the total sea level increase consisting of steric and eustaic sources amounts to 0.466 m by 2100.

5 Conclusions

In this study a global ocean model was run in conjunction with a regional high resolution model in order to assess evolution of the climate change signals in the Irish Sea over the 21st century. In total, 120 years of model simulations (1981-2100) under the SRES A1B scenario were performed. Dynamic downscaling was used to force the regional ECOMSED model with the large-scale controlling conditions derived from the MPI-OM global model.

The research presented in this paper is the first model-based projection of the Irish Sea future climate and in this regard it is the most comprehensive study of this region. The paper explores potential impacts of climate change on the local hydrography as well as providing an understanding of the complex interrelationships between various oceanographic phenomena. The changes of local atmospheric conditions over the Irish Sea for the future climate are translated into long-term variability and trends in the key climate parameters, including SST and depth-averaged temperature, and their direct effects on fundamental shelf sea processes such as vertical mixing, stratification, baroclinicity and circulation. The main conclusions that have emerged from this research are summarised as follows:

- Future sea temperatures will be warmer during all seasons everywhere within the Irish Sea. Projected warming trends in the SST and depth-averaged temperature throughout the basin are 1.89˚C and 1.79˚C, respectively, with the highest warming occurring in autumn and the lowest occurring in spring. There will be a time shift in the annual temperature cycle: maxima and minima annual temperatures for the future climate will occur approximately 2 weeks later each year.

- Geographic variations in warming are attributed primarily to the regional atmosphere-ocean heat transfer; Atlantic inflow is of secondary importance. Shallow waters along the coastline and in the eastern Irish Sea, separate from the main south-north channel flow, will exhibit the strongest warming (>1.7˚C in summer and autumn). This is associated with an increased heat uptake during summer and autumn and a reduced heat loss in spring and winter following the trend in the annual cycle of future atmospheric conditions. Warming in the main deep channel will be generally weaker with reduced seasonal variability due to the relatively large heat storage capacity.
- The water column in the future will be generally warmer with the highest and lowest differences between the future and control periods likely to occur in autumn and spring, respectively. The strongest vertical gradients in warming will occur during summer, showing that the largest portion of warming is stored in the surface layer. Suppressed turbulence strengthens stratification and reduces turbulent mixing leading to a considerable decrease in the thickness of the mixed layer.
- Climate change signals will significantly modulate the circulation patterns of the Irish Sea. A summer sharpening of the stratification will result in strengthening of the western Irish Sea gyre and also, consequently (by more than 30%), the southward current along the Irish coast. In winter, the impact of future changes to wind stresses will be more pronounced with a 25-40% increase in residual current magnitudes and considerable changes in flow directions.
- Water transport through the Irish Sea exhibits an annual cycle with the highest inflow from the Atlantic in February and lowest in July. For the future climate, it is predicted that northward flow will be maintained at an annual rate equal to that of the current climate, though the flow will be weaker in the first half of the year and stronger in the second half.
- Steric sea level is projected to rise by 0.31m in the 21st century due to thermal expansion and changes in local dynamics; an overall sea level rise of approximately 0.47m is forecast.

The detailed regional analysis presented in this paper shows that local climate changes may be substantially different from the expected global changes. The A1B scenario, for which this research is carried out, is a realistic hypothesis given current economical and geo-political circumstances. Nevertheless, ensemble simulations are needed to fully assess the validity of these findings.

The conclusions of this research may be greatly beneficial not only to the scientific community but also to marine management organizations and institutions in the context of their applications to marine health and safety. Given the changes forecast for residual seasonal flows flushing characteristics are likely to alter significantly. Further, travel times of pollutants discharged into the Irish Sea, for example from Sellafield (UK) to the east coast of Ireland, are also likely to change. These issues need further investigation.

Since the changes to oceanographic parameters and hydrodynamics of the Irish Sea may alter habitats and distribution of marine species, this research provides a large range of information on parameters and processes required to investigate the effects of climate change on marine ecosystems; as such this research should also be of great interest to ecologists and the fishery industry, amongst others.

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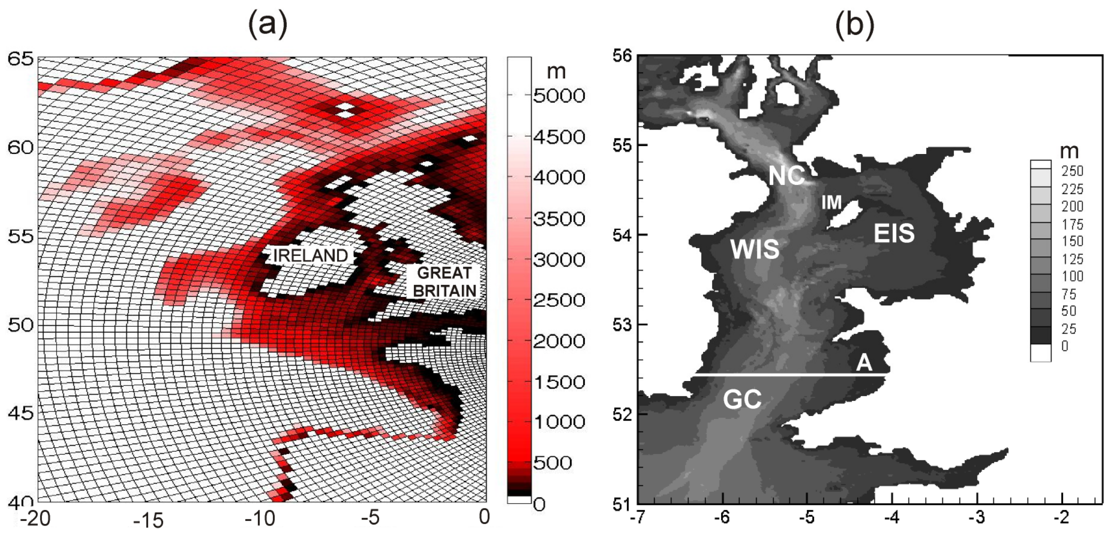


Fig. 1. Bathymetry of (a) the MPI-OM model and (b) the Irish Sea model. Abbreviations: NC – North Channel, IM – Isle of Man, WIS – Western Irish Sea, EIS – Eastern Irish Sea, GC – St. George's Channel

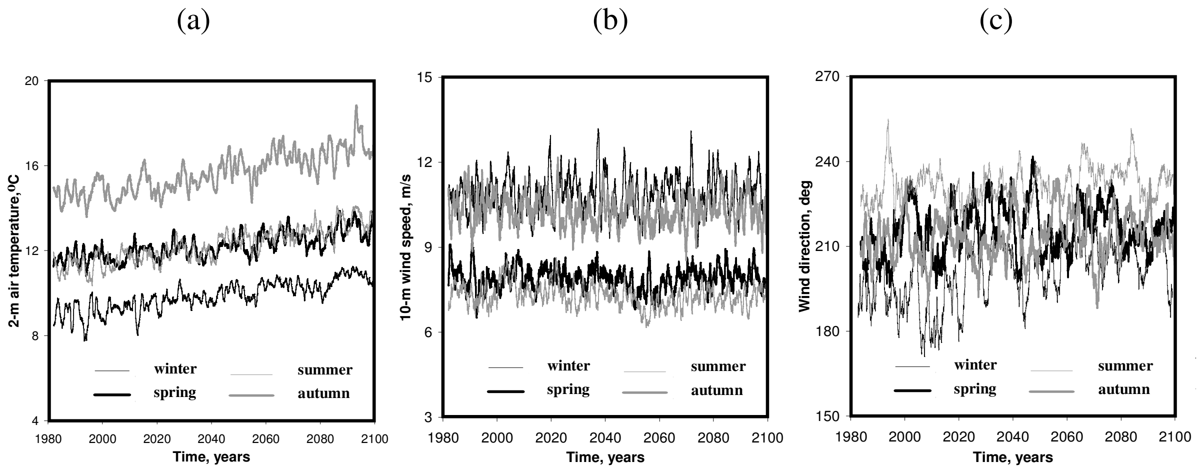


Fig. 2. Projected three-month seasonal running means of air temperature (a), wind speed (b) and wind direction (c) over the Irish Sea

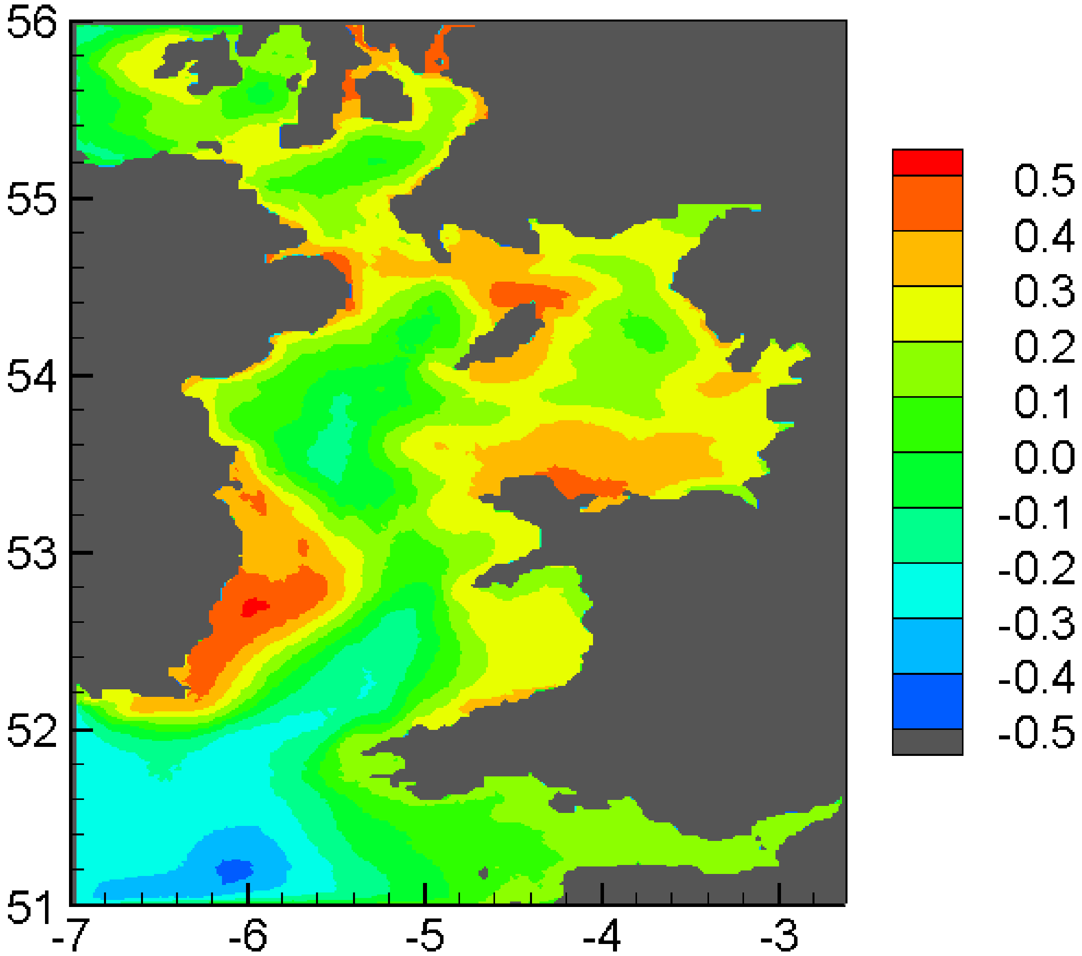


Fig. 3. SST (˚C) difference between ECOMSED models forced with ECHAM5 output and NCEP dataset

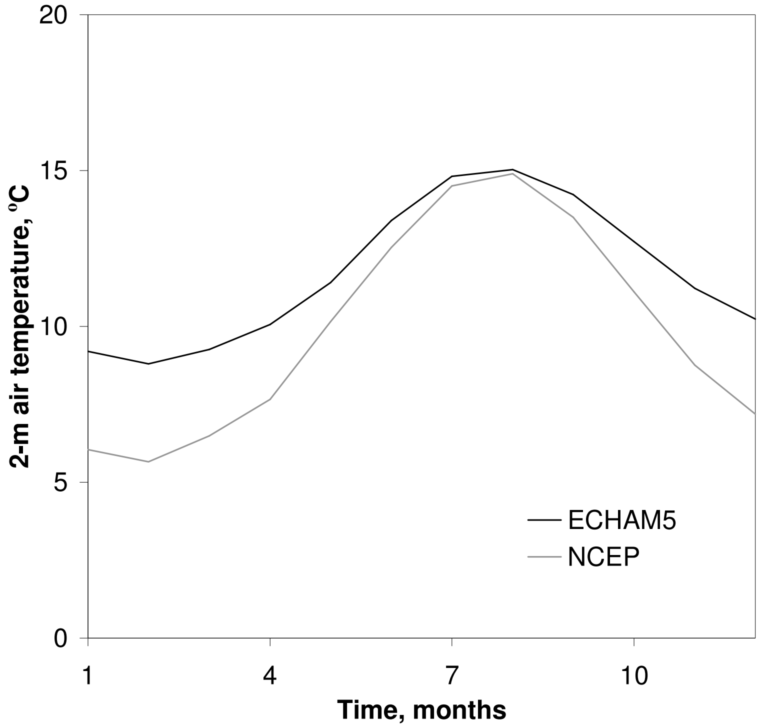


Fig. 4. Comparison of 2-m air temperature between NCEP reanalysis 2 dataset and ECHAM5 outputs over the Irish Sea region. Climatology based on the 1981-2005 period

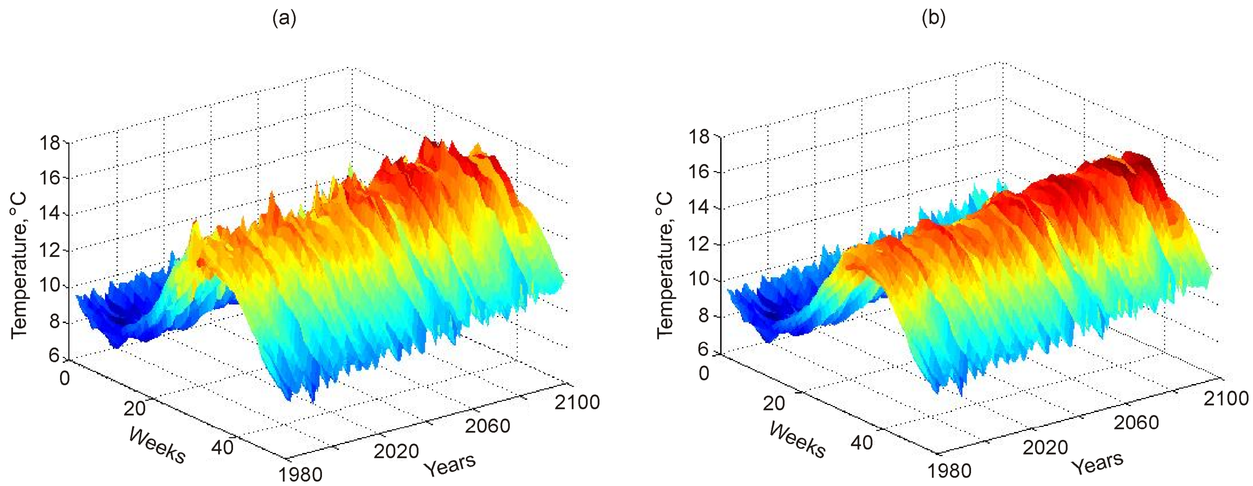


Fig. 5. SST (a) and depth-averaged temperature (b) of the Irish Sea over 120 years of simulation

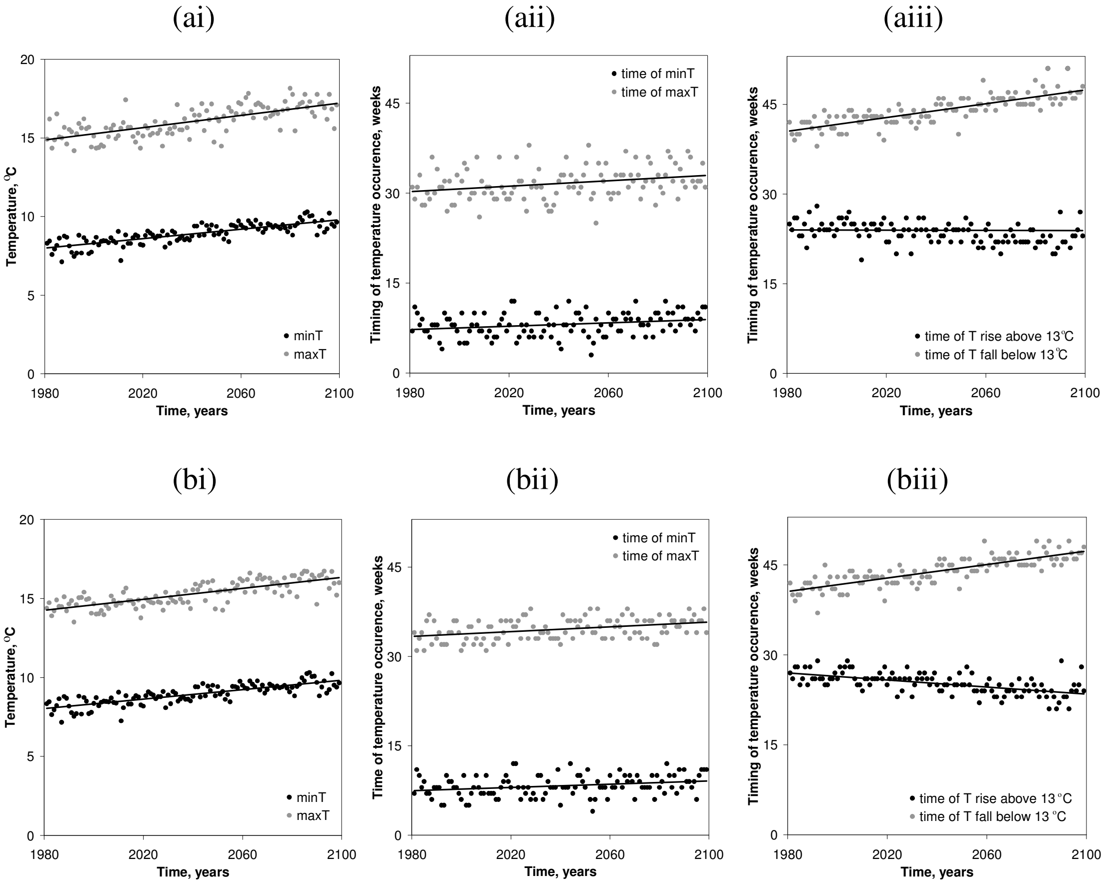


Fig. 6. Time series of SST (a) and depth-averaged temperature (b) shown as (i) minimum and maximum annual temperatures, (ii) timing of maximum and minimum temperature and (iii) timing of temperature rise above 13 ˚C and fall below 13˚C

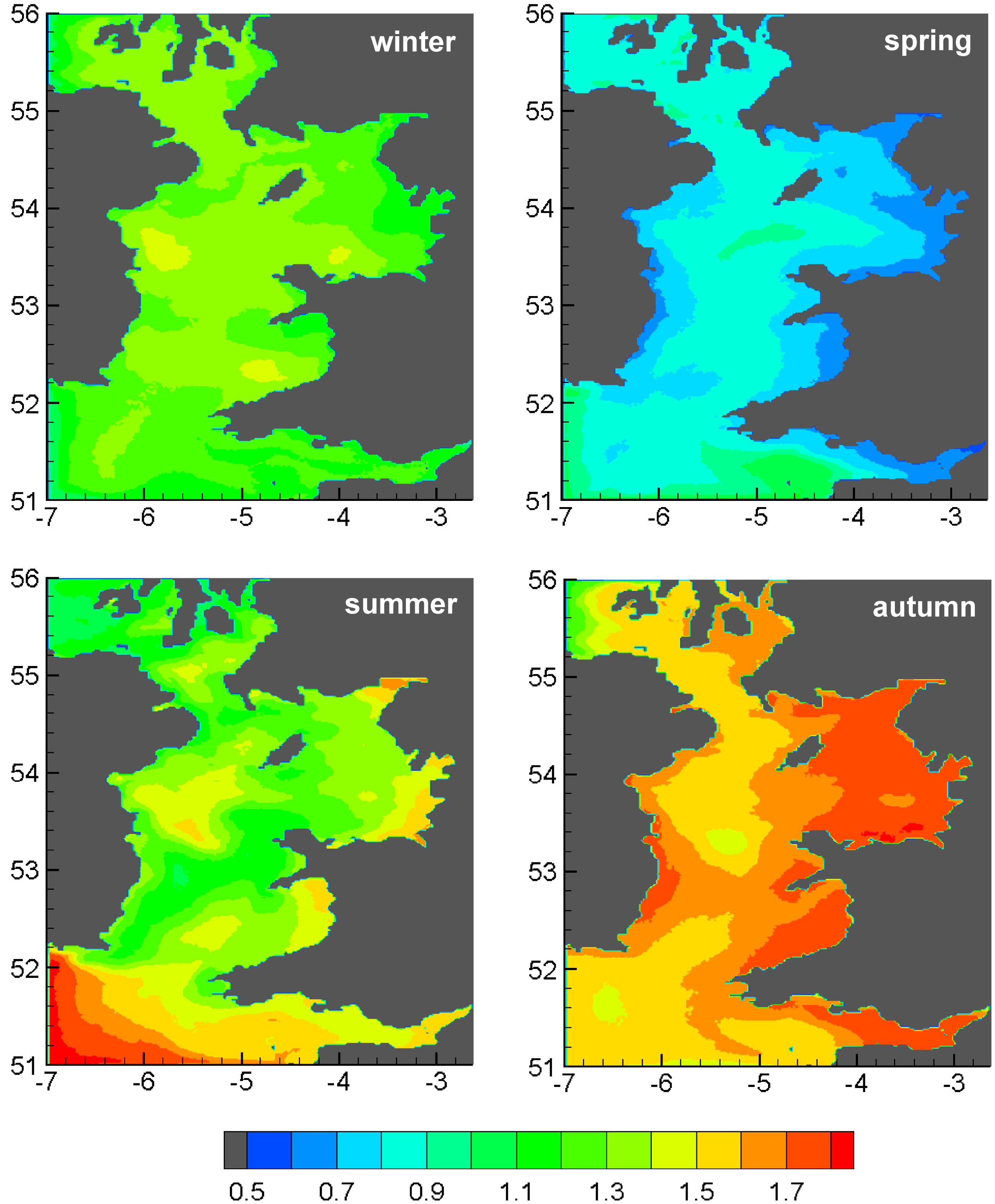


Fig. 7. Regional trends of SST (˚C) within the Irish Sea at four seasons

(a) (b) (c)

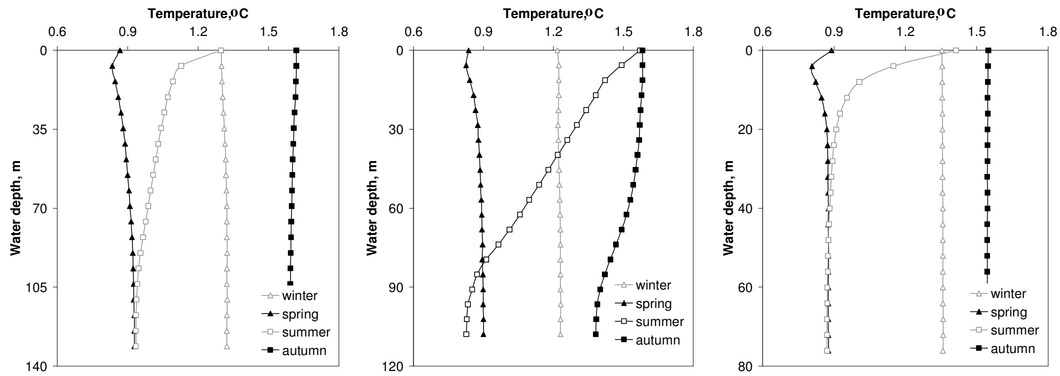


Fig. 8. Water column temperature difference between future and control run for four seasons and three locations: North Channel (a), St. George’s Channel (b) and WIS (c)

(a) (b) (c)

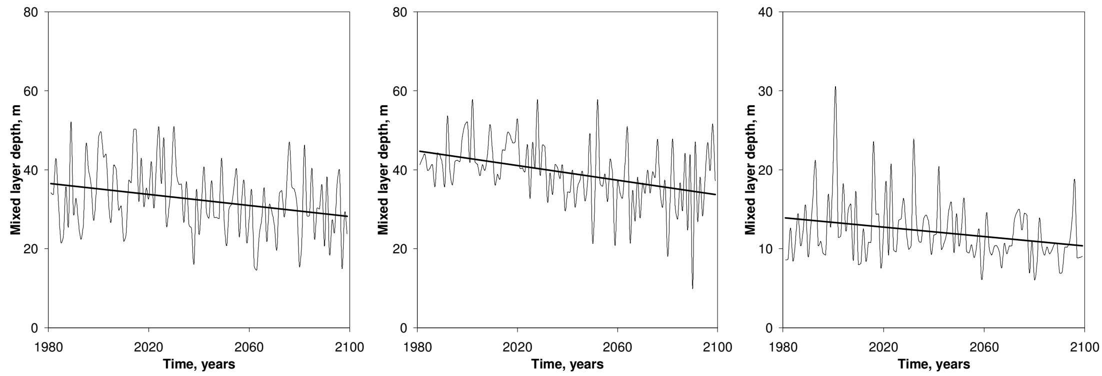
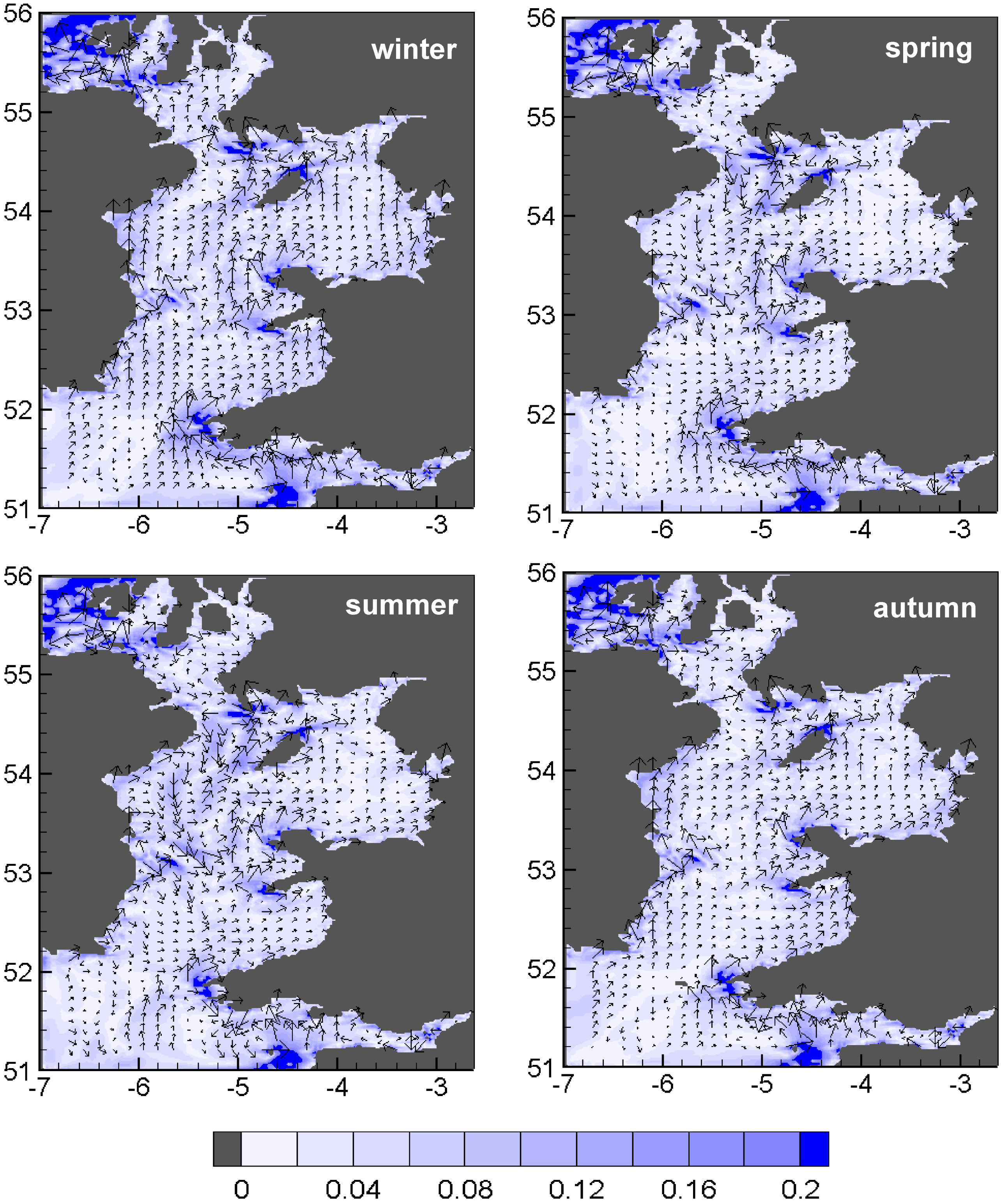


Fig. 9. 120-year timeseries of summer mixed layer depth overlain by a linear trend in North Channel (a), St. George’s Channel (b) and WIS (c)

(a)


winter
spring
summer
autumn
56
55
54
53
52
51
-7
-6
-5
-4
-3
0
0.04
0.08
0.12
0.16
0.2

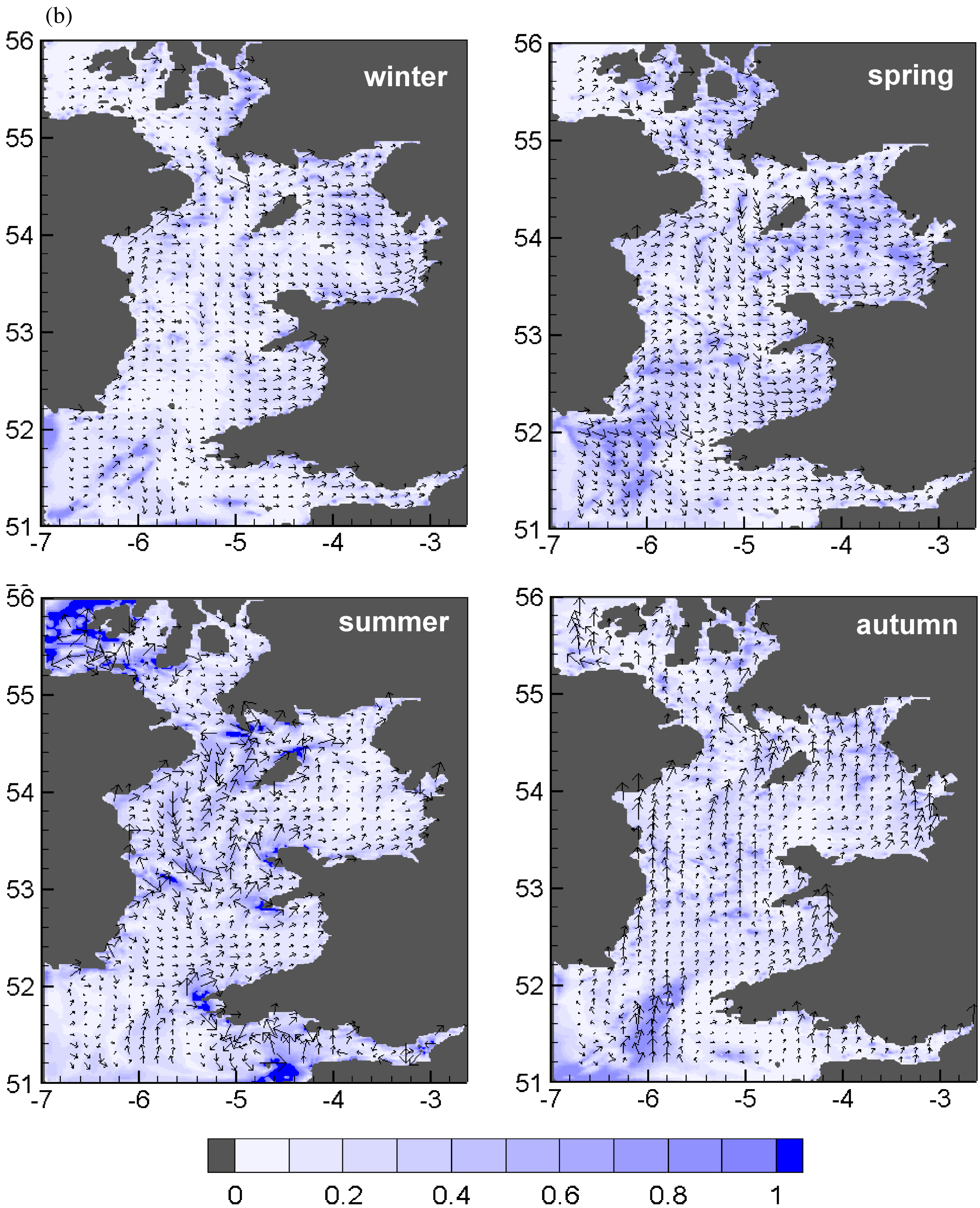


Fig. 10. Seasonal surface residual currents (m/s) in the Irish Sea averaged over control run (a) and relative differences in currents between future and control run (b)

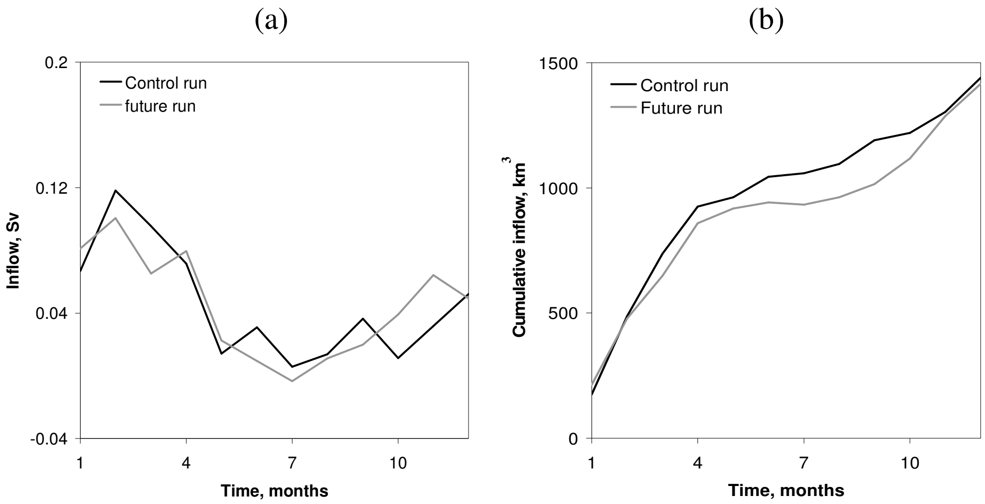


Fig. 11. Annual pattern of 30-year residual flow climatology (a) and cumulative volume of water transported (b) through section A

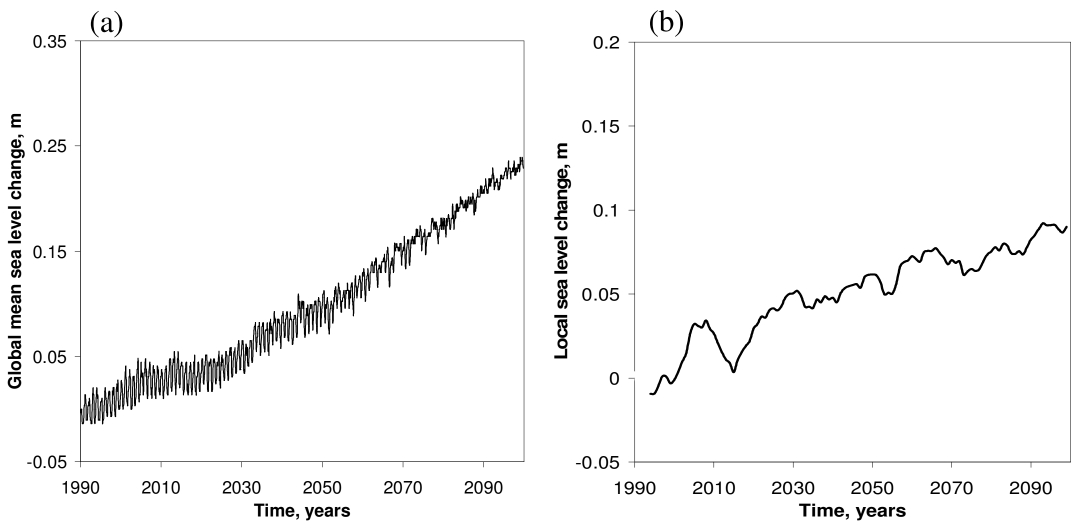


Fig. 12. Weekly changes of global mean sea level (a) and 5-year running mean of local sea level changes in the Irish Sea (b).