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Long-term inter-annual variability of a cyclonic gyre in the western Irish Sea

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Abstract

The western Irish Sea Gyre (WISG) is a cyclonic baroclinic flow around a dome of stagnant water which develops each year during the heating season in the western Irish Sea. Research was carried out to determine long term changes in the strength of stratification within WISG and associated changes in the gyre structure, circulation patterns and retentive properties. Model simulations were carried out for the fifty eight year period 1951-2008. The characteristics of the gyre were quantified by means of potential energy anomaly (PEA), measuring the strength of stratification, and total kinetic energy (KE), reflecting the strength of cyclonic circulation. Additionally, long-term changes in flushing rates within the gyre were assessed. Results show that stratification in the western Irish Sea consistently begins to develop in March, increases linearly from April till June, peaks at the beginning of July and remains at close to maximum level throughout the month of July, before a start of a sharp decline at the beginning of August. The strength of stratification is significantly correlated with averaged summer air temperatures and summer wind speeds. Trend analysis of PEA shows an increase in the stratification strength over the period considered; the increase of PEA peak value is
accompanied by a shortening of the gyre duration and a delay in the timing of the peak value. There is also an increasing trend in the KE value, showing that the thermal stratification plays a crucial role in the hydrography of the region. Flushing analysis shows that the stronger the stratification the lower the residence time and thus the faster the removal of the material from the western Irish Sea. Residence time within WISG shortens on average by 8 days over the 58 year period.

Keywords: Irish Sea; Western Irish Sea Gyre; numerical model; stratification; inter-annual variability

1 Introduction

The Irish Sea is part of the Northwest European Continental Shelf located between the islands of Ireland and Great Britain (Fig. 1a). It is a semi-enclosed body of water connected to the Atlantic Ocean waters through two openings: the North Channel and the St. George’s Channel. The complicated coastline and rapidly varying bathymetry, as shown in Fig. 1(b), induce a high complex tidal regime. Concurrent action of tides entering the sea from north and south (Jones and Davies, 1996), and long-term (sub-tidal) flow comprising of wind-driven (Jones and Davies, 2006) and density-driven (Heaps and Jones, 1969; Horsburgh et al., 2000) components result in unique features affecting the overall circulation in the region. The most characteristic and important phenomenon of the Irish Sea circulation is the Western Irish Sea Gyre (WISG), present each year over the summer season in the western Irish Sea (WIS) region. The WISG consists of baroclinic flow around a dome of stagnant water and has significant implications on the circulation of water within the region (Horsburgh et al., 2000), associated material transport and retention of pollutants (Olbert et al., 2010a; Dabrowski et al., 2010). This cyclonic flow is also relevant to the marine ecosystems; the gyre is a retention mechanism for commercially valuable species such as Norway lobster (Hill et al., 1996) and pelagic juvenile fish (Dickey-Collas et al., 1997). For this reason understanding the WISG hydrodynamics and its
transport properties has important commercial and environmental implications. Although the gyre’s structure and formation mechanisms are well understood, the long-term variability in the strength of stratification and baroclinic currents has not been previously analyzed. Constant density models have improved our understanding of the Irish Sea physical processes (Proctor, 1981; Davies and Aldridge, 1993; Davies and Lawrence, 1994); however, these models were unable to predict the gyre circulation. Along with a development of three-dimensional models, the substantial exploration of baroclinic flows has been made. The mechanism of gyre formation is well recognized now thanks to the work of Hill et al. (1996; 1997) and through the relevance to similar structures observed in other parts of the world (e.g. Gulf of California (Lavin et al., 1997), Yellow Sea (Hu et al., 1991) and Adriatic Sea (Rizzoli and Bergamasco, 1983)). Good reproduction of the WISG was obtained by the application of a three-dimensional model of Horsburgh (1999), Xing and Davies (2001) and Horsburgh and Hill (2003). The effects of seasonal circulation on transport from Sellafield were shown for one-year simulation in Dabrowski and Hartnett (2008) and 7-year hindcast in Olbert et al. (2010a). The latter study has indicated significant effects of inter-annual variability on travel times; it also corroborated strong effects of summer heating on material transport processes within the Irish Sea. Transport in the WIS was also quantified by analysing flushing rates. Dabrowski et al. (2010) illustrated the significant influence of seasonal circulation on flushing of the Irish Sea, whereas Olbert et al. (2010b) showed variations in flushing properties in the water column; seasonal and inter-annual discrepancies were also revealed. The same study further demonstrated strong effects of wind forcing on flushing rates. Understanding changes in density-driven circulation patterns is central to understanding the potential effects of future climate change on the Irish Sea ecosystem. The seasonal nature of many baroclinic flows, and their dependence on horizontal variations in density, implies sensitivity to annual changes in climatic forcing (Horsburgh et al., 2000). Since the gyre characteristics strongly depend on meteorological conditions, climate changes are likely to significantly affect the WISG. The numerical analyses on the WISG to date involve only short-term simulations, which do not give an insight into long-term changes and potential climatic effects. This research focuses on the assessment of changes in circulation and transport patterns within the WISG over the past half a century. The main aim is to establish long-term
variability in the degree of summer stratification and strength of the cyclonic flow around the stratified region. Also, the relationship between these features and material retention within the gyre are investigated. The final objective is to investigate possible relationships between climatic forcing and stratification.

In this study, the global numerical model MPI-OM was used in conjunction with a regional model ECOMSED in order to hindcast the hydrodynamics of the Irish Sea and flushing rates for the period 1951-2008. The strength of the gyre was quantified by the potential energy anomaly values and total kinetic energy budget. Trends in the gyre strength and duration were established. A multiple linear regression was used to study effects of meteorological conditions on strength of stratification. Finally, flushing properties of the gyre were quantified using residence time and conclusions from the 58-year analysis were drawn.

2 Western Irish Sea Gyre

The western Irish Sea gyre is an important feature of the western Irish Sea region and significantly affects Irish Sea hydrodynamics. The gyre is formed as a result of thermal stratification due to a combination of persistent slack water and water depths exceeding 100 m as weak tides and relatively deep water produce insufficient vertical mixing to overcome the input of surface buoyancy generated by solar heating (Simpson, 1971). Thermal stratification develops quickly in spring and isolates a dome of cold, dense water beneath a strong thermocline from a much warmer upper layer. The thermocline sharpens during the course of summer and a well-defined two-layer structure develops. The surface layer is 20-40 m thick and up to 7°C warmer than the bottom layer (Horsburgh, 1999). The cold water pool, composed of relict water left over from the previous winter, is flanked on both sides by horizontal density gradients. The transition from vertically well-mixed to stratified water occurs rapidly (over c. 10km) along a tidal mixing front. The frontal region experiences large seasonal heat exchange, and is characterised by strong horizontal temperature gradients. The sharpest front is observed on southern and eastern sides of the WISG where there is a temperature change of approximately 2°C in less than 2 km (Gaffney, 2001). Simpson and Hunter (1974) identified front
locations to be along contours of \( \log(h/u^3) \), where \( h \) is a water depth, \( u \) is maximum tidal surface current and critical value of \( h/u^3 \) controlling the front formation is between 65 and 100. Strong sloping density gradients within this zone provide the baroclinicity that drives a geostrophic cyclonic surface circulation. Drifter studies showed that along-front jets have speeds of up to 20 cm/s and are concentrated in narrow cores at the base of the pycnocline and above the flanks of a well-defined dome of dense water (Horsburgh et al., 2000). As a result of such density-driven flow, the general northward net flow through the Irish Sea is reversed to a south direction. Cyclonic flows increase throughout the heating season as a response to sharpening of density gradients. This is due to suppressed turbulence which leads to a shallower mixed layer and reduced turbulent mixing. Increased turbidity of the mixed layer limits absorption of solar radiation to deeper layers, increasing stratification and thus further shallowing of the mixed layer (Burchard et al., 2006). The density structure weakens typically in early autumn due to atmospheric cooling and strong wind events, until final breakdown in October. Horsburgh et al. (2000) suggests that the baroclinic component of residual flow is of the same order as the maximum tidal currents in the area, and that the gyre dominates the long-term, near-surface circulation during summer months.

3 Methods

Long-term (1951-2008) hindcasts of global ocean conditions and regional Irish Sea hydrodynamic conditions were performed using the MPI-OM and ECOMSED numerical models, respectively. Boundary conditions for the high-resolution Irish Sea ECOMSED model were extracted from the MPI-OM global ocean model using dynamic downscaling. Descriptions of both models and run setups are presented below along with the methods used for the analysis.

3.1 MPI-OM
The MPI-OM global ocean model was developed at the Max-Planck-Institute for Meteorology, Hamburg, Germany. The model’s main applications are climate change studies including thermohaline circulation (e.g. Jungclaus et al., 2006a; Latif et al., 2004), sea level changes (Lenderer et al., 2007) and biogeochemical changes in water (e.g. Kloster et al., 2007; Wetzel et al., 2006). Technical details of the MPI-OM model and the parameterisation can be found in Marsland et al. (2003). The primitive equations for 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 vertical discretization uses irregularly spaced vertical z levels. The Richardson number-dependent scheme of Pacanowski and Philander (1981) was applied for the vertical eddy viscosity and diffusion.

An orthogonal curvilinear horizontal grid allows placement of grid poles accordingly to resolution requirements. In the current study setup, one of the poles is placed over Europe, while the other over North America. As a result highest resolution is obtained on the European continental shelf, with the Irish Sea having a resolution of c. 15 km. The model has 239 zonal and 164 meridional lines and 40 vertical levels. The topography is interpolated from the ETOPO5 dataset (NGDC, 1998). The atmospheric forcing to the model was obtained from the NCEP Reanalysis 2 model (Kanamitsu et al., 2002). Hindcast parameters of wind speed and direction, 2m air temperature, barometric pressure, cloud cover, relative humidity, evaporation, precipitation and shortwave radiation were provided as 6-h instantaneous values.

Predictions of the three-dimensional water temperature and salinity fields obtained from MPI-OM were used to generate initial and boundary conditions for the regional high-resolution three-dimensional model of the Irish Sea.

3.2 ECOMSED

The mathematical formulation of the ECOMSED model can be found in Blumberg and Mellor (1987), HydroQual (2002) and Mellor (2003), and therefore only a brief outline is given here. The model resolves hydrodynamic equations using the hydrostatic assumption and the Boussinesq approximation. It calculates time-dependent distributions of water levels, three components of velocity, temperatures and salinities. Vertical diffusion is determined from transport of the vertical...
turbulence kinetic energy and turbulence macroscale defined by advection-diffusion equations of Mellor-Yamada level 2.5 turbulence closure scheme (Mellor and Yamada, 1982).

The model domain covering a complex area of the Irish Sea and surrounding waters is delineated by the following coordinates: 51.0 – 56.0°N and 7.0 – 2.6°W. Computation was carried out on a 2 km by 1.5 km horizontal rectangular grid constructed from the Irish National Seabed Survey (INNS) data. Twenty one sigma terrain-following layers are specified. A bathymetric map with depths referred to the MWL and locations of important sites are presented in Fig. 1(b).

The Irish Sea hydrodynamic model is driven by a variable surface elevation due to tides, baroclinic conditions and meteorological forcing. At the open boundary a radiation condition relates the normal component of currents to the sea surface elevation accounting for tidal input. Tidal spectrum consisting of 5 constituent (K1, O1, M2, N2 and S2) was extracted from the FES2004 dataset (Lyard et al., 2006). Initial conditions for temperature and salinity as well as monthly averages of salinity and temperature along open boundaries were specified to the model from the MPI-OM model. Fresh water inputs along the British and Irish coasts were provided by the ISSG (1990). The same set of meteorological conditions as for the global model was used.

3.3 Methodology

The analysis of inter-annual variability of the WISG is based on calculations of potential energy anomaly and total kinetic energy within the gyre. The potential energy anomaly (PEA) is used as a measure of stratification strength reflecting vertical density gradients. Physically, $PEA$ defines the amount of energy per volume that is required to vertically homogenise the entire water column. It is given by Simpson et al. (1977) as:

$$ PEA = \frac{1}{D} \int_{-\eta}^{\eta} g(z)(\bar{\rho} - \rho)dz $$

with the depth-mean density

$$ \bar{\rho} = \frac{1}{D} \int_{-\eta}^{\eta} \rho dz $$

(1)

(2)
where $g$ is gravitational acceleration, $z$ is the vertical coordinate (positive upward from the bottom, $z = -H$, up to the sea surface, $z = \eta$), $\rho$ is the density profile in the water column of total depth $D = H + \eta$.

The strength of the cyclonic flow around a dome of stagnant water is quantified by the total kinetic energy (KE) budget within the gyre expressed as

$$ KE = \frac{1}{2} \left( \bar{u}^2 + \bar{v}^2 \right) $$

where $\bar{u}$ and $\bar{v}$ are depth-averaged mutually perpendicular orthogonal velocity components.

The inter-annual variability of the WISG is also considered through flushing characteristics of the region. Residence time is defined as an expected time during which material resides in a region under consideration. The average residence time ($\tau$) of a water body is computed by integrating a remnant function $r(t)$

$$ \tau = \int_0^\infty r(t) dt $$

Takeoka (1984) defined $r(t)$ as the ratio of the mass of material within a water body at a given time, $M(t)$, to the initial mass of this material, $M_0$. For a water body in steady state, $r(t)$ can be defined as the ratio of the material concentration $c(t)$ at time $t$ to its initial concentration $c_0$.

$$ r(t) = \frac{M(t)}{M_0} = \frac{c(t)}{c_0} $$

Murakami (1991) showed that in most cases $r(t)$ can be well approximated by the exponential function:

$$ r(t) = \exp(-At^B) $$

where $A$ and $B$ depend on the shape of the tracer decay curve.

The average residence time ($\tau$) is then calculated by fitting a remnant function representing an exponential distribution (Eq. 6) to the actual decay curve (Eq. 5) using the least squares method, and integration over a time range from 0 to infinity according to Equation 4.
4 Results and Discussion

4.1 Assessment of MPI-OM in Irish waters

Comparisons of MPI-OM model results with observations in the North Atlantic are presented in Marsland et al. (2003). In this study, an assessment of the model performance is carried out for the Irish coastal waters. The MPI-OM model reproduces the sea temperatures in the Irish waters with a high degree of accuracy. A comparison between the model-predicted and measured SST at six marine buoys M1-M6 (Fig. 1a), located off the eastern, southern and western Irish coasts and also off the continental shelf, is presented in Fig. 2. The model predictions correlate well with the temperatures recorded by the instruments; only at location M4, off the north-west coast, the model slightly overestimates the annual minimum temperatures by up to two degrees. The inter-annual variations in sea surface temperatures are also well predicted, for example, temperatures in the summer of 2003 at location M1 are more than 1°C higher than the temperatures in the summer of 2002. It should be noted that the model predicts SST at location M2 highly accurately despite the complex hydrography of the Irish Sea (Dabrowski and Hartnett, 2008; Dabrowski et al., 2010), the importance of tidal mixing on temperature distribution (Simpson, 1981; Simpson and Hunter, 1974) and the coarse model resolution (the average grid size in the Irish Sea is 0.27 deg). M2 buoy is located in the stratified region of the WIS, which is an area of interest to this research.

The model also reproduces vertical distributions of water temperatures well. Fig. 3 presents a comparison between predicted summer temperature profiles in the upper 200 m of the water column and profiles obtained from temperature recorders attached to 12 seals inhabiting the Atlantic waters off the west coast of Ireland. The temperatures were averaged over the months of June, July and August and over the area extending from 52 – 57.9°N and 6.2 – 11.2°W, where all tagged seals resided. The strength and depth of the thermocline are properly represented by the model. The differences between model predictions and field data are likely to result from averaging over an extensive area and nonuniform distribution of seals throughout the region.
4.2 Assessment of regional model

Extensive hydrographic surveys were carried out in the WIS during 1995 (Horsburgh, 1999; Horsburgh et al., 2000; Horsburgh and Hill, 2003; Young et al., 2004); available data includes surface and nearbed temperatures recorded near the centre of the stratified region between April and October (location A in Fig. 1b). Fig. 4 presents comparisons of recorded temperatures with predictions from the regional high resolution Irish Sea model for both sea surface and near bed. In general, good agreement between data and the model output can be observed despite the fact that at the onset and over the first c.80 days of stratification time period the model underpredicts the nearbed temperatures by c.1°C. Although the potential energy is biased by the deep water temperature, the PEA is not unduly affected by the uncertain skill of the model to represent bottom temperature (as shown in Figure 7).

Importantly, the SST and the timing of both the commencement and breakdown of the stratification are predicted accurately. Previous modelling efforts of the western Irish Sea thermal stratification were characterised by the premature mixing of the water column. The models developed by Horsburgh (1999) and Dabrowski et al. (2010) predicted this breakdown to occur at the end of September, whereas the in-situ data suggests that the stratification breakdown occurs during the second half of October. These authors postulated possible reasons of the error that included application of the meteorological forcing originating from terrestrial station, where air temperatures tend to fluctuate more when compared to locations over the sea (Horsburgh, 1999), overestimation of vertical mixing in the model in a response to the intensified wind shear stress and inaccurate prescription of vertical profile of temperatures at the open sea boundaries (Dabrowski et al., 2010). This study shows that the application of accurate vertical profiles of water temperatures at the open sea boundaries from the MPI-OM global model results in improved predictions of water temperatures in the WIS particularly the nearbed temperatures at the latter stages of stratification.
4.3 Seasonal and inter-annual variations in stratification

An examination of the vertical temperature profile in the WIS shows that the region remains well-mixed over winter with gradual development of stratification starting from spring. Differences between surface and bottom temperatures, shown in Fig. 4, reflect the structure of the WISG where a sharp thermocline separates a dome of cold water from warm water at the surface. As the strength of stratification is a response to meteorological conditions, some seasonal and inter-annual variability in the 58-year simulation is expected. In this section, the scale of short-term (seasonal) variability and long-term (inter-annual) variability of WISG properties is discussed.

The instantaneous values of potential energy anomaly at 7-day intervals for 1951-2008 averaged over the WIS region (the region is marked in Fig. 1b) hindcasted by the model are presented in Fig. 5. The onset of stratification is observed in March, though some non-zero PEA are observed frequently in February (this may however be associated with river runoff and salinity stratification). Thermal stratification develops over spring and summer to reach the maximum value between day 154 in 1978 and 224 in 1969. The maximum weekly instantaneous value computed was 43.6 J/m$^3$ in year 1955, followed by 41.5 J/m$^3$ (1975) and 41.4 J/m$^3$ (2006). In contrast, the lowest maximum annual values were 28.6, 29.1, 29.5 J/m$^3$ and these were obtained respectively for years 1961, 1956 and 1974. The process of de-stratification proceeds faster then stratification and is more homogenous in time. By mid-October the average PEA value in the region is less than 1 J/m$^3$.

The seasonal and inter-annual variability of PEA is also expressed as the annual time series for 1951-2008 climatologies in the WIS region (Fig. 6). The curve has Gaussian shape with values close to zero approximately in the first two and last two months of the year. Significant seasonal stratification begins to develop during March, increasing almost linearly from April till June and reaching the maximum sometime in July. The PEA climatology peaks (31 J/m$^3$) at the beginning of July (day 190) and remains at comparably high levels throughout the month of July (until day 210) before a start of a sharp decline at the beginning of August. Typical standard deviation of $\pm 3$ J/m$^3$ occurs from late-spring to early-autumn with the largest standard deviation of $\pm 8$ J/m$^3$ in July.
The shape of the long-term weekly stratification curve is in good agreement with SST profile for the same region and period, as demonstrated in Fig. 7. The computed PEA time series is correlated to the computed SST time series with a correlation factor of 0.98 and the relationship is statistically significant (correlation coefficients throughout the paper are given at the 95% significance level). Such high correlation is characteristic of a coastal region and demonstrates that stratification events are primarily related to increasing thermal stratification and less influenced by salinity distributions.

4.4 Spatial extent of gyre and stratification

A map of model-predicted residual circulation in the western Irish Sea during late July of 2006 is shown in Fig. 8(a). Southward flowing surface currents have magnitudes between 15-20 cm/s, while northward flowing currents are generally weaker with magnitudes typically in range 10-15 cm/s. Lowest velocities are observed in the centre of the gyre, which is a region characterized by strongest potential energy anomaly as shown in Fig. 8(b). These highest mean summer PEA values of c. 80 J/m$^3$ are observed in the central part of the stratified region and the lowest values of less than 10 J/m$^3$ occur outside the gyre. Strong horizontal gradients arise from complex interactions between tides, winds, bottom friction and surface heating and the amount of turbulent mixing that these processes generate. Tidal motions in the WIS generate strong frictional stresses at the seabed, resulting in turbulent stirring. Since this stirring has a spatial distribution controlled by tidal dynamics, levels of vertical mixing vary greatly over the region. Xing and Davies (2005) imply that a reduction in tidal mixing associated with a decrease in tidal current from near shore shallow water to deeper offshore regions is the dominant feature which leads to a cold water bottom-dome formation and density gradients throughout the region. Stronger vertical mixing in shallow waters due to the tidal stirring is additionally amplified by bottom friction mixing because of greater flow velocities.

In summary, tidal stirring controlled by tidal dynamics and wind mixing controlled by water depth compete with the buoyancy inputs from surface heating to determine the pattern of density stratification in the region (Simpson, 1998). In shallow coastal regions, the turbulent mixing due
to tidal stirring, bottom friction and wind stress exceeds surface heating input, and hence well-mixed vertical structure is observed. Whereas reduced tidal stirring and deeper water in the centre of the WIS are conducive to weaker vertical mixing and stronger stratification (Simpson, 1971).

To examine details of the inter-annual variability and persistence of stratification the basic statistics of standard deviation (Fig. 8c) and variation coefficient (Fig. 8d) were computed. As expected, the highest PEA inter-annual variability of up to 7 J/m$^3$ is observed in the region of strongest stratification. Variations in the potential energy of the density field lead to the release of different amount of kinetic energy, and hence to the modification of the circulation. Nonetheless, very low coefficients of variation in the stratified region indicate rather stable structure of the gyre on the inter-annual scale. Variation coefficients of 0.4 in the near shore area are attributed to the greater sensitivity of shallow water column to tidal and wind straining and heating due to short-wave radiation.

4.5 Effects of atmospheric conditions on stratification

In the WIS the stratification and de-stratification processes are primarily controlled by the heat flux and wind mixing. In autumn the net heat flux is directed towards the atmosphere. During winter, wind mixing is so intense and solar radiation so low that the region remains well mixed. In summer, a reduction in wind strength and an increase in solar heating trigger stratification in the deep water region. However, the inter-annual variability in onset and strength of stratification can be large (Xing and Davies, 2001). It is reasonable, therefore, to expect that inter-annual variability in surface heating and wind stress are the main drivers of this variability.

The wind driven mixing is both through shear in response to surface wind stress and shear induced by near-inertial oscillations attributed to sudden changes in wind direction. In the Irish Sea the energy available for internal mixing from the observed oscillation may have been as much as 80 J/m$^2$, compared with 150 J/m$^2$ from wind induced surface mixing (Sherwin, 1987). This corresponds to mean summer surface and shear-induced mixing power of $7.1 \times 10^4$ W/m$^2$ and $2.0 \times 10^4$ W/m$^2$, respectively. Whilst the surface mixing is well reproduced on temporal and
spatial scale by the M-Y 2.5 turbulence closure scheme (Mellor and Blumberg, 2004), the mixing within the interior of the water column due to near-inertial oscillation is not explicitly represented by the model. To compensate for missing sources of turbulence the model includes background diffusivity (Rippeth, 2005). By doing this, the model provides sufficient levels of vertical mixing, however, this does not represent inter-annual variability of vertical mixing. Also, the 6-hour temporal resolution of wind fields may be not sufficient to simulate the effect of phasing, direction and duration of winds on mechanical mixing due to near-inertial oscillation (Rippeth et al., 2009). For this reason the effect of wind-induced mixing on stratification strength cannot be fully quantified. The analysis shown below provides, however, good insight into relationships. Higher frequency of wind data and better representation of near-inertial oscillation by the model is likely to improve the reliability of similar studies in the future.

Relationships between WIS stratification and meteorological conditions have not yet been developed. Sherwin (1987) quantified mixing power from wind-induced surface mixing and inertial oscillations, while Rippeth et al. (2009) explained mechanism of shear-induced thermocline mixing in the WIS. Horsburgh and Hill (2003) identified important interactions between wind and density fields that could modulate the cyclonic flow around the stratified region during the heating season. Wind direction can determine the location of the strongest horizontal density gradients, and therefore can determine where the fastest baroclinic currents are located. The importance of wind stress in sea surface mixing, in particular, in the breakdown of the thermal stratification in the WIS in autumn, was recognized by Xing and Davies (2001). Their model study showed that the exclusion of wind forcing on short timescales (of the order of two days) or strong winds is likely to yield poor predictions of surface mixing. Properties of the gyre were also investigated by Olbert et al. (2010b) where significant effects of wind forcing on a flushing rate were demonstrated. With regard to air temperature, Olbert et al. (2010a) observed a link between this parameter and concentration of the radionuclide Tc-99 on the east coast of Ireland that suggested strong effects of the temperature on WISG formation and hence transport processes within the Irish Sea.

In this section, effects of atmospheric conditions on stratification strength are analyzed. PEA values averaged over the months of June, July and August were compared to 3-months averages of air temperature and wind speed for each of the simulation years. Multiple linear and
polynomial regressions were performed and best estimates for a combination of these two independent variables isolated. PEA was best predicted from a linear combination of air temperature \((\text{airT} \text{ in } ^\circ\text{C})\) and wind speed \((Wsp \text{ in } \text{m/s})\) using the following equation:

\[
PEA = 10.439 + 1.85 \times \text{airT} - 1.657 \times Wsp
\]  

(7)

Results from the linear regression analysis imply that the summer stratification strengthens with an increase in the air temperature and a decrease in the wind speed.

Fig. 9 presents correlation between PEA simulated by the numerical model and PEA calculated using the linear regression model (Eq. 7); this is also accompanied by basic statistics. The linear trend line yields slope and y-intercept values of 0.47 and 14.2, respectively. There is a good agreement between both PEA values; this is supported by high Pearson correlation coefficient \(R\) of 0.68 and small statistical errors. Statistics shows standard deviation error (SDE), root-mean-square difference (RMSD) and root-mean-square error (RMSE) between two datasets of 0.234 J/m³, 0.058 J/m³ and 0.233 J/m³ for \(N=58\).

4.6 Trends in stratification

Understanding variability in WISG energy budget is crucial to detect and monitor the effects of climate change. Historic data of SST in the Irish Sea indicate a general warming trend, which, when superimposed on significant inter-annual to multidecadal-scale variability, seems to be related to oscillations of the ocean-atmosphere system. Cannaby and Hüserevolu (2009) found that the dominant modes of low-frequency variability in SST records correspond to the Atlantic Multidecadal Oscillation (AMO), East Atlantic Pattern and North Atlantic Oscillation index, respectively, accounting for 23, 16 and 9% of the total variance in the dataset. The same study also showed that the recent intense warming, evident in the SST records, can be explained by the sum of natural variability associated with AMO-scale fluctuations (60 year phase) and changing climate in almost equal measure.
SST time series collected in the Irish waters between 1850 and 2007 exhibit a warming trend of approximately 0.3˚C (Cannaby and Hüsrevoğlu, 2009). In this study, linear trends were calculated using a least-squares fitting method. The SST residual presented in Fig. 10(a) was obtained by fitting a sine curve to the SST time series and later subtracting the best-fit curve from the time series. The sine curve correlates with simulated SST time series with a strong fit ($R^2=0.93$). The negative SST residuals are present frequently from late 1970s through 1980s till mid 1990s; from the late 1990’s onwards a warming period is observed with a significant rate of increase over the recent past. The hindcast SST exhibits a warming trend of 0.35˚C in the period of 1951-2008. It is interesting to consider how this trend varies for different subsets of the 58 years under analysis. Between the years 1965 and 2008 there is a 0.83˚C rise in temperature and during the period 1980-2008 there is a 1.66˚C rise in temperature. The long-term warming trend is a non-linear function of time considered to be associated with the non-linear emissions of greenhouse gases.

Following the SST increasing trend, it is expected that stratification in the 58-year period considered will exhibit some trends as well. The inter-annual variability of stratification strength is considered by calculating PEA residual which is the difference between PEA time series averaged over the WISG region and Gaussian curve fitted to this time series. Fig. 10(b) presents one-year running mean of residual of PEA weekly instantaneous value overlain by a linear trend. An overall increase in the strength of stratification in the WIS is observed, although the rate of 0.37 J/m$^3$ in 58 years is insignificant.

A detailed analysis of long-term variability of PEA was also conducted. The PEA annual curve for each year in the period considered can be approximated by a Gaussian 3 parameter equation of the following form:

$$f = a \cdot \exp \left( -0.5 \cdot \frac{(x-x_0)^2}{\sigma^2} \right)$$  \hspace{1cm} (8)

where $x$ is the time, $a$ represents the peak value, $\sigma$ the spread of the distribution and $x_0$ the time of the peak occurrence. This curve has been fitted to the data for each year of the simulations. In total, 58 PEA curves were constructed and the parameters describing these curves ($a$, $\sigma$ and $x_0$) are presented in Fig. 11. Linear trends of PEA parameters were
calculated using a least-squares fitting method and the significance of the fit was based on calculation of the associated $R^2$ values. As can be seen in Fig. 11(a), there is an increasing trend in stratification strength, though this is not supported by a high correlation coefficient value. The linear regression model suggests an increase of PEA peak value by 3.9 J/m$^3$ per 100 years, which is equivalent to approximately 12% of a 58-year mean of the parameter $a$. Interestingly, a positive trend in annual peak value is followed by a decrease in $\sigma$. This shows that as the stratification strengthens, the duration of stratification period shortens. This negative relationship is confirmed by the coefficient $R^2=0.33$. Finally, the inter-annual variability in the timing of onset of stratification using high temporal resolution was considered. As shown in Fig. 11(c) the time of the peak occurrence ($x_{ii}$) tends to be later and by the end of 58-year period the peak is expected to occur approximately 4 days later than at the beginning of this period. The trend analysis shows that the differences from one year to another can be substantial and this is confirmed by high standard deviations of all parameters; nonetheless, statistically weak long-term linear trends are observed.

Based on the above analysis it can be stated that over second half of the 20th century there were some trends in the characteristics of the WISG; a 12% increase of peak value in 100 years is accompanied by shortening of the gyre duration and the delay of peak occurrence. Nonetheless, the results from this study cannot be extrapolated to the future because of non-linear effects of climatic changes. Extension of the time series into the future and to the period prior to 1951 is currently being addressed.

In this study relationships between PEA and the circulation within the WIS were also investigated. For this analysis PEA and residual flows calculated over two tidal cycles were computed across section B-C for the years 1961 and 1975. The year 1961 is characterized by the lowest summer PEA values in the 58-year dataset; this is in contrast to year 1975 categorized as the year of strongest stratification. PEA levels along the transect B-C (shown in Fig. 1b) within the western Irish Sea region are shown in Fig. 12(a). Fig. 12(b) illustrates corresponding transport through the transect over the two years considered. Negative values represent southward transport while positive values represent northward transport. Flows in both directions increase throughout the heating season in a response to sharpening density gradients. The strongest flows are observed in July and August and they compose a cyclonic
gyre around the stratified region. Both northward and southward flows during 1975 are shown to be stronger, more consistent and more stable than the flows during 1961. The footprint of the 1975 flows that are greater then 12000 m$^3$/s is approximately twice the flow width of that magnitude for 1961. Comparing the PEA levels for the two years with corresponding transport through the section, it can be clearly seen that greater stratification generates stronger cyclonic circulation.

4.7 KE budget of WISG

Holt and Proctor (2003) state that the complicated residual flows in the WISG are generated by tides, winds and density gradients. The sloping density surfaces bounding the dome of cold water in the WIS can be maintained in geostrophic balance only by the cyclonic surface layer flow (Hill et al., 1996; Hill et al., 1997; Horsburgh, 1999; Horsburgh et al., 2000). This flow has the form of a cyclonic along-frontal jet that generates kinetic energy of levels corresponding to horizontal density gradients. As horizontal density gradients intensify, the baroclinic flow becomes stronger. Thus, the modulation of density fields causes an alteration of the amount of kinetic energy generated, and hence circulation strength.

The density-driven flows are frequently affected by wind stresses and tidal currents. With the onset of stronger winds, warm water above the thermocline may be advected into a regime where it rapidly becomes vertically mixed. As a result a stronger density contrast with coldest water beneath the thermocline is formed. With regard to tidal flows, in a semidiurnal regime the density field can be modulated by the spring-neap cycle; as tidal currents increase, increased density gradients develop along with associated baroclinic flow (Horsburgh and Hill, 2003). Assuming that M2 is the strongest contributor to tidal currents, the 3-month average of total kinetic energy will not be affected by tidal currents at an inter-annual timescale (barotropic kinetic energy will remain on the same level), so wind stress and solar heating are considered as the primary contributors to the long-term KE variability.

Since most of the kinetic energy is contained in mesoscale eddies, which have a role in creation and destruction of the gyre, the question arises whether the model resolution is sufficient to
adequately resolve baroclinic features. In the current model set-up (grid resolution 1.5x2km) the
model is eddy-permitting. That implies that smaller eddies are likely to be grid constrained, which
may results in the underestimation of kinetic energy budget. Although a smaller grid size is likely
to improve model results (but substantially increase computational effort) it is believed that the
findings from the trend analysis presented below are not affected by the model resolution.
Annual patterns of the 1951-2008 total KE climatologies in the WIS predicted by the model are
shown in Fig. 13. Likewise PEA, the KE annual time series is approximated by a Gaussian
distribution, though the peak of the KE lags behind the peak of the PEA. The lag corresponds to
the response time between development of stratification and gyre formation. The peak KE in the
region amounts to c.480 MJ at that time, and is approximately three times higher than typical
winter values of approximately 160 MJ.
The annual time series of modelled total KE residual in the western Irish Sea region is presented
in Fig. 10(c). KE values have been averaged horizontally over the entire region of WIS and
vertically over water column. The procedure of fitting the Gaussian curve and extracting KE
residual is identical to the PEA analysis. A linear increase of 14.7 MJ in the period 1951-2008 is
observed.
The results from fitting KE annual curves to the Gaussian 3 parameter equation (Eq. 8) are
shown in Fig. 14. The KE peak value (a) shows an increase of 34.2 MJ over years 1951-2008.
This amount constitutes around 8.8% of mean peak value in the period considered or over
15% in 100 years if the same rate of change is assumed. Similar to the conclusions from the
PEA analysis, an increase in the peak values yields shortening of the period in which higher KE
values occur (11% decrease in 58 years). This means that over the period considered the gyre
becomes stronger but it persists over a shorter time. As can be seen in Fig. 14(c) by the end of
58-year period the peak value is expected to occur over 6 days later than at the beginning of this
period.

4.8 Flushing of WIS
The importance of the retentive character of the gyre on material transport and marine organism
entrainment has also been examined. Research undertaken by Dabrowski et al. (2010) revealed
that the WISG is responsible for a twofold increase in the value of residence time of the region. A
study by Olbert et al. (2010b) also reveals strong retentive properties, particularly when the wind speed is low. In this section the long-term variability of the gyre flushing properties is analysed in a similar manner to that of PEA and KE variability. Effects of baroclinic, barotropic and wind-driven flows on the WISG retentive characteristics are investigated indirectly through flushing analysis. A well-mixed conservative tracer within the region of WIS (see Fig. 1b for region bounds) is used to examine residence times. Since the fully developed gyre is a summer feature, tracer release was performed on the 1st of June for each of the 58 years. Levels of the tracer in the domain were analysed in three-day intervals for a period of 5 months. Variability in the effects of inter-annual circulation and stratification patterns were considered by calculating residence times for the WIS and statistical analysis.

Residence times calculated according to Eq. (4-6) indicate high discrepancies from one year to another; they range from a minimum 123 to a maximum 191 days, with mean value of 153 days and standard deviation of 14.5 days. A simple trend line analysis of residence time over the period considered finds an 8-day decrease between 1951 and 2008, though $R^2$ is low. The apparent inter-annual variability within the WIS is primarily due to the inter-annual differences in meteorological conditions and hence is likely impacted by climate change. Tidal conditions at the start of simulation are found to have very little effect on flushing. A coefficient of variation for residence times calculated for various scenarios of tidal conditions is approximately 0.03.

Fig. 15 presents results from the regression analysis between residence time and PEA and KE values. There is a medium strength negative correlation ($R^2=0.33$) between residence time and PEA, and weak negative correlation between residence time and KE ($R^2=0.16$). These relationships suggest that the flushing rate increases with the strengthening of the gyre. Comparing residence time with parameters of PEA and KE distributions, it can be seen that there is a negative correlation between residence time and parameter $\alpha$ of PEA and $\alpha$ parameter of KE (Fig. 15 aii and bii), and a positive relationship with $\sigma$ parameter of PEA and KE (Fig. 15 aiii and biii). Bearing in mind the fact that the duration of stratification period shortens...
with strengthening of stratification, it is suggested that the tracer flushes out quicker when the
gyre is strong but of shorter duration, and retention is longer for a weaker but longer lasting gyre.

5 Conclusions

A global ocean model MPI-OM was run for a 58-year period and used to provide boundary
conditions for a high resolution regional Irish Sea ECOMSED model in order to predict long-term
changes in the structure of WISG. Inter-annual variability in the gyre features was analysed over
the period of 1951-2008. Characteristics of the region were quantified by means of PEA,
measuring stratification strength, and by levels of KE, reflecting the strength of cyclonic
circulation around the dome of stagnant water. Additionally, long-term changes in flushing
properties of the gyre were assessed. This research has helped further knowledge of this
important oceanographic feature in the Irish Sea and the main conclusions that have emerged
are summarized below:

- Modelling carried out in this research presents consistent results that compare well to
data and, therefore, may be used to draw conclusions about long-term trends in the
western Irish Sea. The 58-year analysis of seasonal development of the gyre
corroborates existing knowledge based on short-term observations and simulations.
Further, this research demonstrates that the WISG develops approximately at the same
time of each year and it is a stable, consistent structure. Stratification in the WIS begins
to develop in March, increases almost linearly from April till June, peaks at the beginning
of July and remains close to maximum levels throughout the month of July before a start
of a sharp linear decline at the beginning of August.

- Relationship between PEA time series and SST time series is quantified in this
research. The strength of stratifications rises linearly with the SST increase and
correlation between both parameters is very high (R=0.99). This confirms previous
findings that thermal stratification dominates summer circulation in the WIS.

- Effects of atmospheric conditions on stratifications are estimated. The strength of
summer stratification is significantly correlated with averaged summer air temperatures
and summer wind speeds in the WIS. PEA strengthens with increasing air temperature and decreasing wind speed. It should be realized, however, that the numerical model does not fully account for mechanical mixing due to wind-driven near-inertial oscillation.

- A novel approach to the quantification of long-term trends of PEA is developed. This approach facilitates analysis relating changes in PEA to characteristics of the WISG. Trend analysis shows an increase in stratification strength of 2.2 J/m$^3$ in the period considered, constituting 7% of the 58-year mean value. An increase of PEA peak value is accompanied by shortening of the gyre duration and retardation of the peak occurrence.

- The long-term trend analysis methodology used for PEA is also used to estimate long-term variability of KE. Trend analysis shows an 8.8% increase of mean KE peak value, 11% shortening of the period in which higher KE values occur and a 6-day delay of the peak occurrence in the period considered.

- Relationships between stratification strength and residual flow in the WIS have been clearly demonstrated. Transport in the gyre is positively correlated with PEA indicating that greater stratification generates stronger cyclonic circulation around the stratified region.

- Finally, in this research inter-annual variability of WISG is determined from flushing characteristics of the gyre. Strength of stratification in the region proves to play an important role in the transport processes. Negative correlation between residence time and PEA and KE suggest that the stronger the stratification the lower the residence time and thus the faster the removal of the material from the WIS.

It has to be stressed out at this point that the wind-induced inertial oscillation generating approximately 30 % of energy available for wind mixing is not explicitly represented by the model. Although background diffusivity compensates for missing sources of turbulence, the inter-annual variability in vertical mixing is not fully represented.

In conclusion, the 58-year analysis shows that the WISG, by and large, remained stable and consisted structure during the period considered. From the trend analysis it can be seen, however, that gyre characteristics have been modulated, in a statistically significant sense, over the analysis period. Initial results from future climate simulations (2000-2100) suggest changes
in temperature which are likely to further modulate gyre characteristics. The authors are currently investigated these effects.

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Fig. 1. Bathymetry of (a) the European continental shelf on MPI-OM grid with M1-M6 data buoy locations and (b) the Irish Sea with marked western Irish Sea (WIS) region
Fig. 2. Comparison between SST recorded at M1-M6 data buoys and modelled by the MPI-OM model. See Fig. 1(a) for M1-M6 locations.

Fig. 3. Vertical profiles of recorded and modelled summer water temperatures off the west coast of Ireland.
Fig. 4. Comparison of recorded and modelled water temperatures at location A in the WIS.

Fig. 5. Weekly PEA (J/m$^3$) values in WIS over period 1951-2008.
Fig. 6. Annual patterns of the 1951-2008 PEA climatology in the WIS predicted by the model
Fig. 7. Correlation between PEA and SST climatologies (1951-2008) during April-August period. The correlation coefficient and least square fit are shown.
Fig. 8. Model-predicted (a) surface residual circulation in the WIS at 30 July 2006, (b) mean summer PEA, (c) standard deviation from summer PEA and (d) variation coefficient.

Fig. 9. Correlation between summer 3-month averages of PEA obtained from a numerical model and calculated using equation 7.
Fig. 10. One-year running mean of (a) SST, (b) PEA and (c) KE residual time series averaged over the WIS region and overlain by a linear trend

Fig. 11. PEA annual curve parameters (a) peak value $a$, (b) spread of distribution $\sigma$, and (c) time of the peak occurrence $x_0$ overlain by a linear trend
Fig. 12. Map of (a) PEA and (b) residual north-south flow along the transect B-C during year (i) 1961 and (ii) 1975. See Fig. 1(b) for position of transect B-C
Fig. 13. Annual patterns of the 1951-2008 PEA and KE climatologies in the WIS predicted by the model

Fig. 14. KE annual curve parameters (a) peak value $a$, (b) spread of distribution $\sigma$ and (c) time of the peak occurrence $x_0$ overlain by a linear trend
Fig. 15. Regression analysis between residence time and (ai) PEA, (aii) $a$ parameter of PEA and (aiii) $\sigma$ parameter of PEA, (bi) KE, (bii) $a$ parameter of KE and (biii) $\sigma$ parameter of KE