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# Cyclonic Circulation in the Western Irish Sea in Future Climate

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## **Abstract:**

*The Irish Sea (IS) is a semi-enclosed body of water on the European Continental Shelf and the Western Irish Sea Gyre (WISG) is a characteristic phenomenon of the Sea. The gyre due to its significant effects on the circulation, transport and retention of pollutants within IS has important commercial and environmental implications.*

*Global ocean MPI-OM model was run in conjunction with high resolution IS model ECOMSED for the period 1990-2090 in order to determine future long-term changes in climate parameters (SST) of the IS as well as in the gyre structure. Potential Energy Anomaly (PEA) and Total Kinetic Energy (TKE) are used to quantify strength of stratification and cyclonic flow.*

*Projected SST exhibits a warming trend of 1.78°C for the 100-year period. A substantial increase in PEA peak value is accompanied by shortening of the gyre duration and retardation of the peak occurrence. An increasing trend in TKE shows that thermal stratification plays a crucial role in the hydrography of the region.*

**Keywords:** Irish Sea, Western Irish Sea Gyre, numerical model, stratification, climate change.

## **1. INTRODUCTION**

Understanding long-term variability in climate parameters like the sea surface temperature (SST) is crucial to monitor effects of climate change. The historic data of SST collected in the Irish Sea during period 1850-2007 shows a warming trend averaging 0.3°C while the historic dataset from the north of Ireland for 1958-2006 exhibits a linear warming of 0.85°C (Cannaby and Hüsrevoğlu, 2009). Olbert et al. (in press) produced a hindcast of SST in the Irish Sea for the period 1951-2008 and found a warming trend of 0.35°C. In the subset 1965-2008 there was a 0.83°C rise in SST and unprecedented warming of 1.66°C since 1980. This recent intense warming may be explained by the natural variability associated with multidecadal-scale fluctuations (AMO has greatest contributions) and global warming.

At the current state of knowledge the analysis of future pattern of the Irish Sea physical parameters is likely to be conducted with a broad range of uncertainty. Woth et al. (2006) relates these uncertainties among others to the emission scenarios and differences in the global climate change simulations. In this study a global ocean model is run for the period 1990-2090 to provide boundary conditions for a high resolution model of the Irish Sea. SRESA1B emission scenario is used to simulate anthropogenic contribution to warming. The numerical results are analyzed in order to project changes in the Irish Sea over the 21<sup>st</sup> century.

## 2. IRISH SEA HYDROGRAPHY AND WESTERN IRISH SEA GYRE

The Irish Sea is a semi-enclosed body of water located on the European Continental Shelf and connected to the Atlantic Ocean waters through two openings: the North Channel and St. George's Channel. It is approximately 300km long and 75-200km wide. The North Channel with width 30 km and depth exceeding 275 m is the narrowest and deepest region of the Irish Sea. The eastern Irish Sea with average depths of 30 m is the shallowest region.

The hydrodynamics of the Irish Sea is driven mainly by tides; the M2 and S2 constituents have greatest impact. Tides enter the region through both the St. George's and North Channels, with the two paths meeting along a line running westward from the south of the Isle of Man (McKay and Pattenden, 1993). The strongest tidal currents are usually observed in the North Channel and St. George's Channel (1.0-1.5m/s) and in the vicinity of headlands (2.0m/s). The annual net flow through the Irish Sea is northward, however, as a result of wind action and seasonal formation of density gradients (mainly in the western Irish Sea) the movement of water is disturbed from spring till late summer and results in formation of a southward flow along the east coast of Ireland. More hydrographical details can be found in Olbert et al. (2010).

The Irish Sea due to its complex geometry and bathymetry exhibits complicated flow patterns that seasonally under certain meteorological conditions lead to development of thermal structure as the western Irish Sea gyre (WISG). The WISG is an important phenomenon of the Irish Sea and only a few similar structures are reported in other parts of the world (e.g. Gulf of California, Yellow Sea and Adriatic Sea). The gyre develops during heating season in the stratified western Irish Sea (WIS) due to a combination of persistent slack water and water depths exceeding 100 m. Weak tides and 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 much warmer upper layer (Olbert et al., in press). A two-layer system develops over a matter of days (Hill et al., 1997) usually around April. The surface layer is 20-40 m thick and up to 7°C warmer than the bottom layer (Horsburgh, 1999). Cold dome of water is flanked on both sides by strong horizontal density gradients. These gradients provide the baroclinicity that drives a geostrophic cyclonic surface flow. Along with the sharpening of density gradients throughout heating season the cyclonic flow increases and reaches up to 20 cm/s. Gradual cooling and strong wind events in early autumn weaken the density structure leading to breakdown of dome around October.

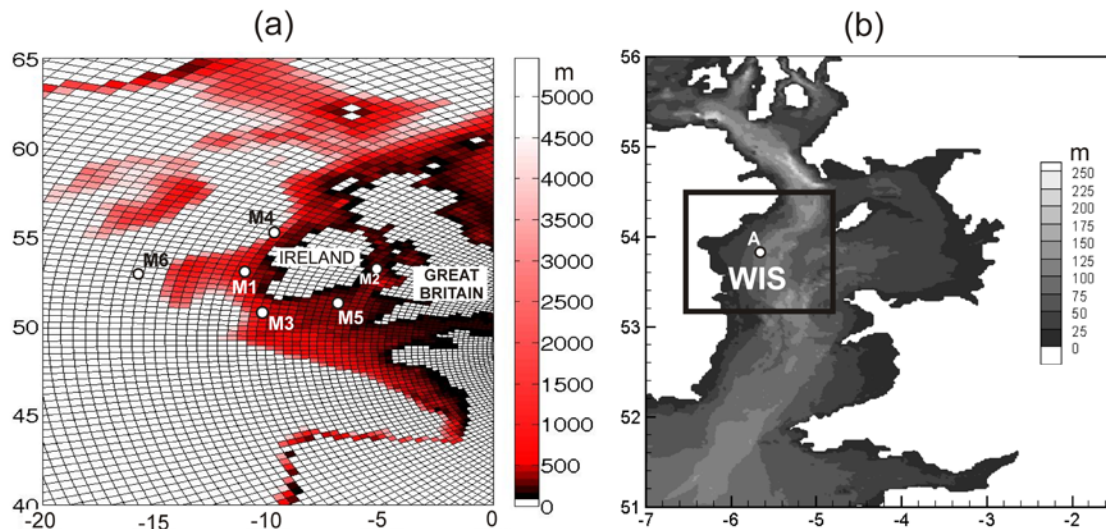


Figure 1 Bathymetry of (a) the MPI-OM model and (b) the Irish Sea model.

### 3. METHODS

#### 3.1. Models

The MPI-OM model developed by the Max Planck Institute for Meteorology, Hamburg is a global ocean model. It is applied mainly for a wide range of climate change studies such as sea level changes, thermohaline circulation and biogeochemical changes in water. Full description of the model can be found in Marsland et al. (2003). The model mesh for this research is placed on the orthogonal curvilinear horizontal grid with two grid poles - one of the poles over Europe, while the other over North America. Such setup provides the highest model resolution over the European Continental Shelf which is an area of interest in this research. The average resolution over the Irish Sea is approximately 15 km. The model has 239 zonal by 164 meridional lanes and 40 vertical levels. The topography is obtained from ETOPO5 dataset interpolated on the NASH15 grid. Bathymetry and model meshes are illustrated in Fig. 1(a). The model is forced by two meteorological datasets: (1) NCEP Reanalysis dataset for the period 1990-2009 and (2) ECHAM5 model output run for SRESA1B emission scenario and period 2010-2090.

Three-dimensional water temperature and salinity fields calculated by the MPI-OM model were used as initial and boundary conditions for the ECOMSED regional Irish Sea model. Technical details of the ECOMSED model can be found in Blumberg and Mellor (1987). 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). Since internal Rossby radius varies typically between 1 to 2 km (Holt and Proctor, 2003), the numerical horizontal resolution should be sufficient to resolve baroclinic features. The model bathymetry was constructed from the Irish National Seabed Survey data. A bathymetric map with depths referred to the MWL and locations of important sites are presented in Fig. 1(b). The vertical processes are calculated on the 21 sigma terrain-following layers.

The model is forced by a variable surface elevation due to tides, baroclinic conditions and atmospheric forcing. At the open boundary a radiation condition relates the normal component of currents to the sea surface elevation accounting for tidal input. Five tidal constituents K1, O1, M2, N2 and S2 along open boundaries were extracted from the global hydrodynamic model FES2004 and interpolated onto the model grid. Initial and boundary conditions as monthly averages of temperature and salinity were specified to the model from the MPI-OM model. River discharges were provided by the ISSG. The same set of meteorological conditions as for the global model was used.

#### 3.2. Methodology

The assessment of strength and characteristics of the WISG was based on calculations of the potential energy anomaly and total kinetic energy within the western Irish Sea. The potential energy anomaly (PEA) reflects the vertical density gradients and therefore quantifies the strength of stratification. It is defined as an amount of energy required to vertically homogenise the water column and given by equation (Simpson et al., 1977)

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

Where  $\bar{\rho} (= \frac{1}{D} \int_{-H}^{\eta} \rho dz)$  is the depth-mean density,  $g$  is the gravitational acceleration,  $z$  is the vertical coordinate (positive upward from the bottom,  $z = -H$ , up to the sea surface,  $z = \eta$ ),  $\rho(z)$  is the density profile in the water column of total depth  $D = H + \eta$ .

Strength of the cyclonic gyre is quantified by the total kinetic energy (TKE) budget expressed as

$$TKE = \frac{1}{2} \left( \overline{u^2} + \overline{v^2} \right) \quad (2)$$

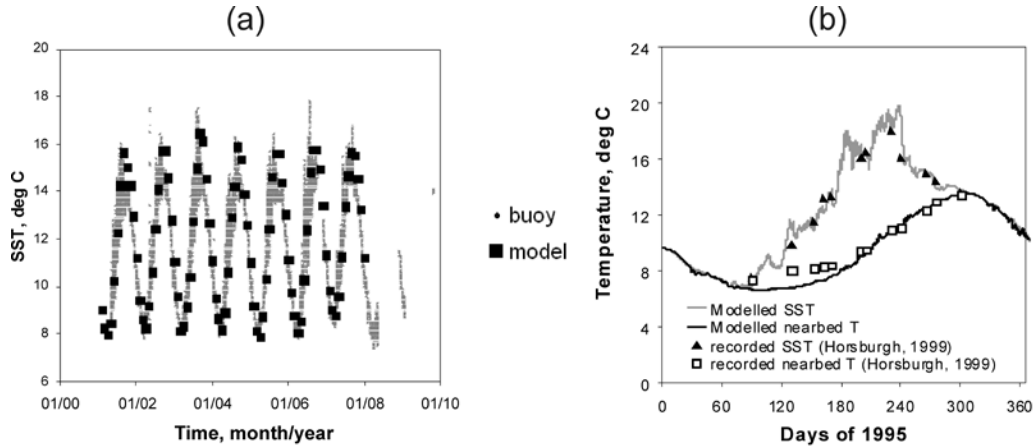
Where  $\overline{u}$  and  $\overline{v}$  are depth-averaged mutually perpendicular orthogonal velocity components.

## 4. RESULTS AND DISCUSSION

### 4.1. MPI-OM model validation

The evaluation of the MPI-OM global model accuracy in predicting hydrodynamics of the Irish waters was conducted in Olbert et al., (in press), and for brevity only selected validation results are repeated here. The comparison of mode-predicted and measured SST at six marine data buoys (see locations of M1-M6 in Fig 1) located around Ireland demonstrates generally good performance of the model. As shown Fig 2 (a) the model results correspond closely to field data in most of locations; some discrepancies were found for M4 site, where model tends to overpredict the annual minimum temperatures. Encouragingly, the modelled SST for M2 location, which is a site of particular interest to this study, is highly accurately predicted.

The ECOMSED hydrodynamic model of the Irish Sea was used previously in Olbert et al., (in press); validation results for surface and nearbed temperatures near the centre of the stratified region are presented in Fig 2 (b). Generally good agreement between modelled temperatures and records was obtained. For the SST the agreement was particularly good; the magnitudes throughout the year were accurately simulated, also timing of commencement and breakdown of stratification were correctly predicted.

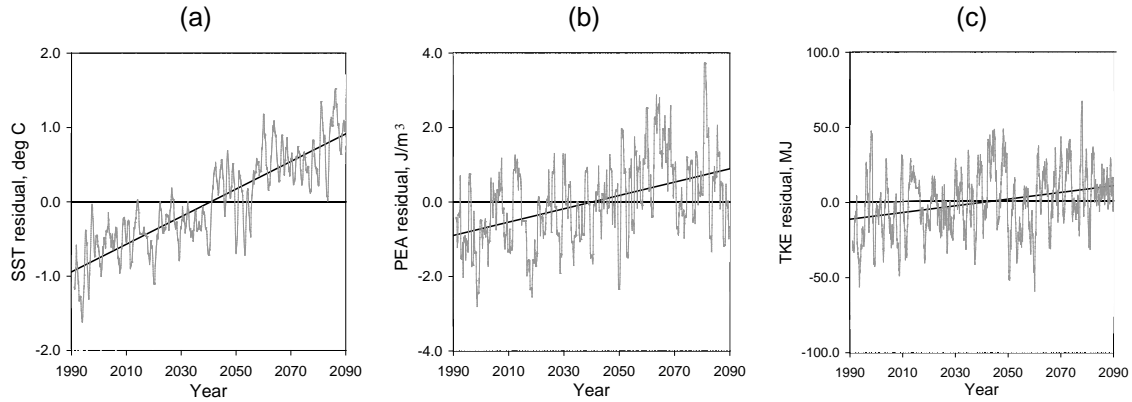


**Figure 2 (a) Comparison between SST recorded at M2 data buoy and modelled by the MPI-OM model, (b) comparison of recorded and modelled temperatures at location A in WIS.**

### 4.2. Trends in SST

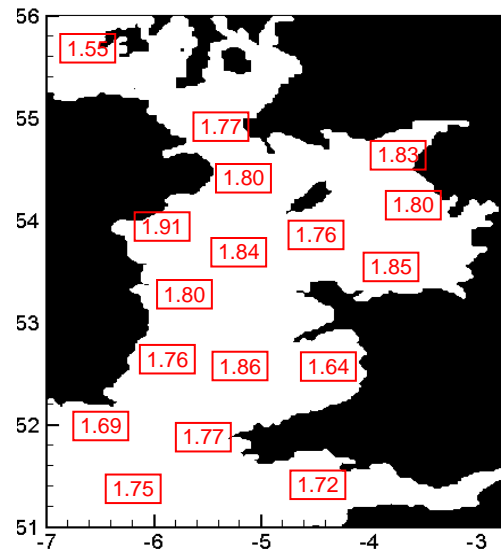
In this study the SST in the Irish Sea was modelled for the period 1990-2090. The SST anomaly shown in Figure 3(a) was calculated by subtracting best-fit sine curve from SST time series; strong correlation between simulated SST and fitted sine curve was found ( $R^2=0.88$ ). Linear trends were calculated using least-squares fitting method. The forecasted SST in the WISG exhibits a warming trend of  $1.86^\circ\text{C}$  for the 100-year period. Since long-term warming trend is a non-linear function of time resulting from non-linearity of greenhouse gas emission, the SST anomaly timeseries is unlikely to exhibit a linear trend too. Interestingly, the SST timeseries

shows a cyclic pattern of a relatively rapid increase followed by a 15-year plateau and a rapid decrease. Each cycle is approximately 20 years long and over the 100-year period four full cycles were observed. Also, a plateau of a subsequent cycle is higher than the previous one. The periodicity may be explained by a natural variability while the evident warming may be related to increasing CO<sub>2</sub> emission in accordance with A1B scenario.



**Figure 3 One-year running mean of (a) SST, (b) PEA and (c) TKE residual timeseries averaged over the WIS region and overlain by a linear trend.**

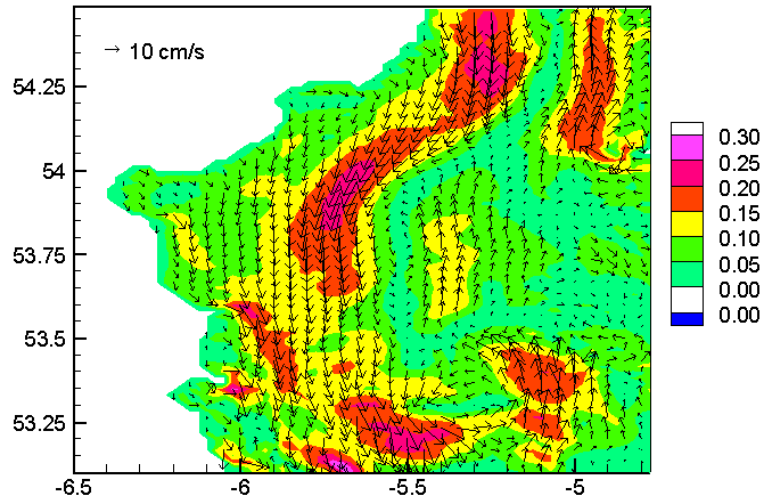
The spatial distribution of warming trend over the Irish Sea was also examined. Figure 4 shows a linear trend over a 100-year period for 17 locations uniformly distributed over the Sea. In general, the rise of temperature is similar at each location (average of 1.78°C); highest values are observed in the western and eastern Irish Sea while lowest value of 1.55°C at the north entrance to the Sea.



**Figure 4 Linear trends of SST in °C at selected locations within the Irish Sea.**

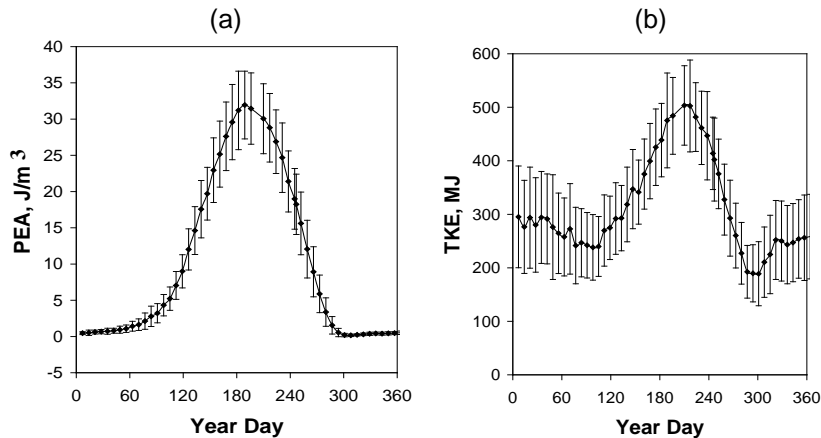
### 4.3. Seasonal variability in WIS

Modelled spatial extend of the gyre in the western Irish Sea is shown in Figure 5 (see Figure 1 for region bounds). Southward surface currents along the east coast of Ireland of up to 20cm/s are stronger than the northward currents. The flow has the shape of a cyclonic along-frontal jet. Center of the gyre is characterized by stagnant stratified water. The transition between stratified and well-mixed waters occurs quickly (c. 10 km) along a tidal mixing front. Highest PEA values (c. 80 J/m<sup>3</sup>) occur in the centre of the gyre while lowest in the coastal well-mixed zone (< 10 J/m<sup>3</sup>).



**Figure 5 Model-predicted surface residual circulation in the WIS at 30 July 2006.**

Figure 6(a) presents annual PEA time-series for 1990-2090 climatologies in the WIS. The peak value of 33 J/m<sup>3</sup> occurs at the beginning of July and is accompanied by the highest standard deviation ( $\pm 6$  J/m<sup>3</sup>). No stratification is observed in the first two and last two months of the year. The peak value of TKE (c. 500 MJ), shown in Figure 6 (b), lags behind the PEA peak by approximately 30 days. The lags results from a delay in response between development of stratification and gyre formation. The annual pattern of both PEA and TKE shows evident seasonal variability and can be approximated by the Gaussian curve.

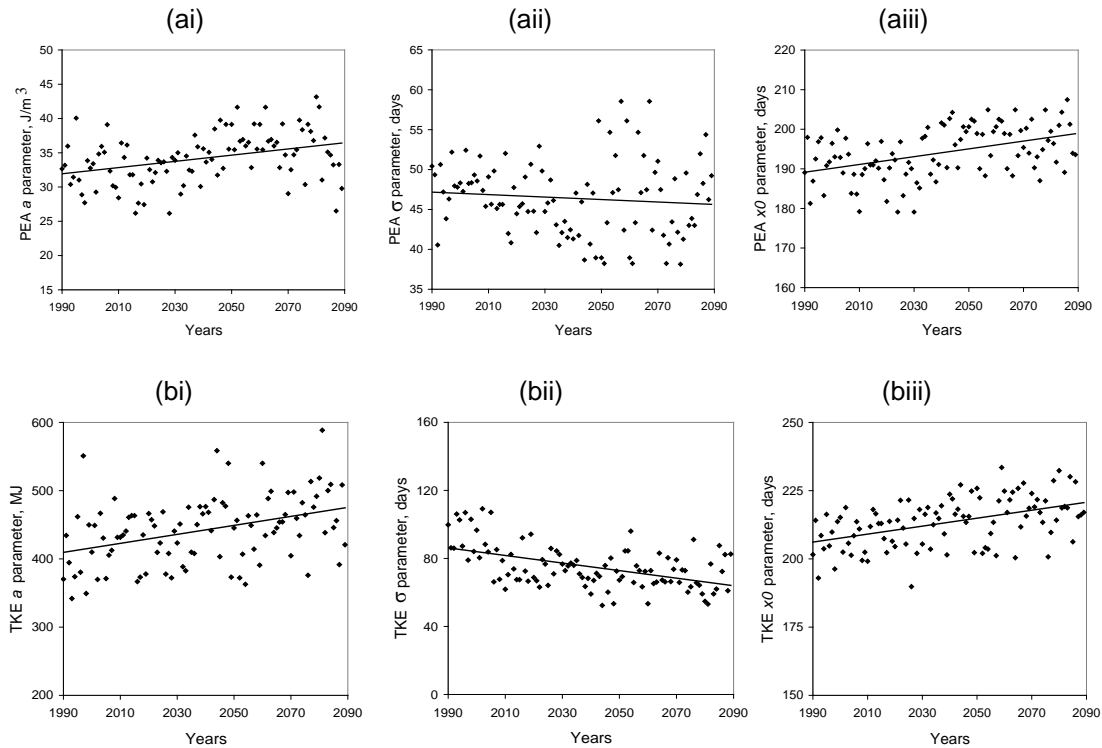


**Figure 6 Annual patterns of the 1990-2090 climatology of (a) PEA and (b) TKE.**

#### 4.4. WISG in future climate

A detailed analysis of the long-term variability of PEA and TKE in the WIS was also conducted. Annual curves were best-fitted to the Gaussian distribution, and residuals were extracted in the same manner as the SST. The 100-year time series of PEA and TKE residuals overlain by a linear trend are shown in Figure 3 (b-c). The increase in the period 1990-2090 of  $1.79 \text{ J/m}^3$  and  $19 \text{ MJ}$  for PEA and TKE, respectively, is projected.

For each of the annual Gaussian curve in the 100-year period considered 3 parameters describing the curve were identified. These are the peak value ( $a$ ), the spread of the distribution ( $\sigma$ ) and the time of the peak occurrence ( $x_0$ ). The analysis shown in Figure 7 (a) suggests an increase in strength of stratification by  $6.8 \text{ J/m}^3$  and shortening the period of stratification ( $\sigma$  decreases by approx. 3 days by 2090). The time of peak PEA occurrence is shifted so the peak in 2090 is expected to occur almost 10 days later than in 1990 (Figure 7aiii). Similar analysis was conducted for the TKE and results are presented graphically in Figure 7 (b). The TKE peak value is expected to increase in 100 years by  $69 \text{ MJ}$  (Figure 7bi). This positive trend is followed by a decrease in the spread of the distribution by 22 days (Figure 7bii) and a delay of TKE peak value occurrence by 14 days (Figure 7biii).



**Figure 7 (a) PEA and (b) TKE annual curve parameters overlain by a linear trend. Parameters (i)  $a$ , (b)  $\sigma$ , and (c)  $x_0$ .**

#### 5. CONCLUSIONS

A 100-year hindcast of hydrodynamic conditions within the Irish Sea was performed using the global MPI-OM model and regional ECOMSED model in order to project long-term variability in the SST, PEA and TKE of the Irish Sea and consequently changes in the WIS gyre structure. The forecasted for the 21<sup>st</sup> century SST exhibits a likely warming trend of  $1.86^\circ\text{C}$  in the WISG and  $1.78^\circ\text{C}$  in the entire Irish Sea; however, no correction for the multi-decadal scale variability is



applied to this analysis. A cycle of approximately 20-year periodicity in the SST anomaly time series was detected. Trend analysis of PEA shows an increase in stratification strength. An increase in PEA peak value of  $6.8 \text{ J/m}^3$  is followed by shortening of the gyre duration and retardation of the peak occurrence (10 days). In case of TKE a 69 MJ increase of peak value accompanied by a decrease in spread of distribution by 22 days and a retardation of peak value by 14 days is expected. These results suggest that the likely changes in hydrodynamic conditions of the Irish Sea over the 21<sup>st</sup> century are greater than anticipated from a hindcast analysis (1951-2008) conducted by Olbert et al. (in press). However, it has to be stressed that uncertainties associated with climate natural variability, model simulation and emission scenario are not quantified in this research.

## 6. ACKNOWLEDGMENTS

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