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CHANGES IN HEAT EXCHANGE BETWEEN THE NORTH SEA AND ADJACENT SEAS DUE TO THE ASSIMILATION OF SATELLITE SEA SURFACE TEMPERATURE

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Abstract

This study investigated the modelled lateral heat transports across the shelf edge and into the Baltic Sea with/without applying data assimilation (DA) of satellite sea surface temperature. The assimilation scheme, i.e., a 3D variational (3DVAR), adopted model error correlations that depend on the water mixing layer thickness derived from a coupled circulation-wave model. The analysis showed, besides the direct change in heat transport due to the DA of water temperature, the indirect change in heat transport due to the significant hydrodynamic response to DA of the model. The largest DA impact was found in the Norwegian Channel, where the dominant process is Eulerian transport, followed by tidal pumping and wind pumping. It is demonstrated that, due to the DA of the water temperature, the along-shelf current at the northern edge of the North Sea is accelerated. This decreased the horizontal pressure gradient from the Atlantic to the North Sea and reduced the Eulerian transport of heat outward the North Sea through the Norwegian Channel.

Keywords: heat budget, advective transport, data assimilation, mechanism analysis

1. Introduction

The interest of the research communities on the ocean temperature has increased with the rising concern of global warming (Dye *et al.*, 2013). The variation (both in space and time) of the seawater temperature has a large relevance to fishery management, coastline protection, ecological balance maintenance, and weather predictions (Kjellstrom *et al.*, 2005; Kirby *et al.*, 2007; Fallmann *et al.*, 2017). To improve the seawater temperature prediction, a data assimilation scheme was often applied to

combine data from observations, such as from satellites, *in situ* measurements, and that from numerical model simulations (Anna and Hargreaves, 1999, Liu *et al.*, 2009, Fu *et al.*, 2011). Meanwhile, other studies focused on the DA technique itself, developed various DA methods with implementing sophisticated mathematical disciplines (Losa *et al.*, 2012, 2014). However, the efforts invested in the impacts of DA on physical processes and the secondary effect of DA are insufficient. This study, in contrast, analyzed the influence of DA on heat transport in the North Sea. Specifically, it explored 'How does the assimilation of SST observations change the different components of the simulated North Sea heat budget, and what are the secondary effects of temperature assimilation on the remaining prognostic model variables that are relevant for the heat budget?'

In this study, a 3-D numerical couple model system NEMO-WAM was employed to assimilate OSI SAF SST satellite measurements. Wave coupling applied in this model resolved the role of turbulent mixing in simulating vertical mixed layer thickness. The latter, which varies over time and space, is an important parameter further applied in the 3-D variational DA analysis technique as the model error covariance matrix. Finally, a harmonic analysis was performed and identified the physical processes that govern the advective heat transport between the North Sea and adjacent seas.

2. Materials and Methods

2.1 Model and observations

The study applied an ocean circulation (NEMO version 3.6, Madec & the NEMO team, 2016) and wave (WAM, the Wamdi Group, 1988) coupled model of the Geesthacht Coupled cOastal model SysTem (GCOAST, Staneva *et al.*, 2019). The model domain, between -19.89°E and 30.16°E and 40.07°N and 65.93°N , covers the Northwest European Shelf, the North Sea, the Danish Straits, the Baltic with a resolution of 3.5 km (Figure 1). The model was spun up and ran for more than three years to reach a relatively balanced state (January 1, 2017). Subsequently, the model ran without DA for one year (denoted as the Free Run). Then the model was restarted on January 1, 2017, and ran with DA for a year. This experiment was denoted as the DA Run.

The modelled seawater temperature was analyzed with OSI SAF SST data. The number of available points of this data changed at different locations due to varying cloud conditions. The SST measurements were compared with Match up Data Bases (MDB) of *in situ* measurements, and only data of high quality were collected for the DA.

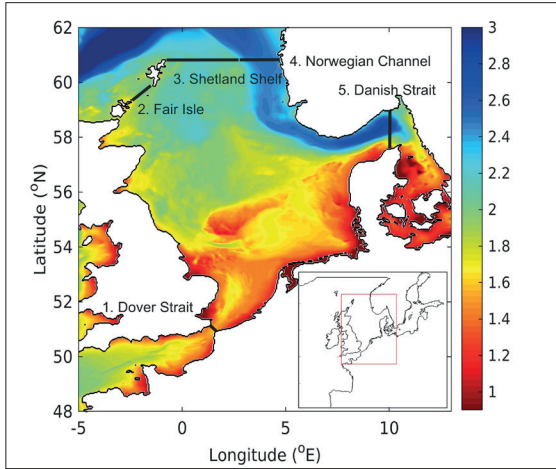


Fig. 1. Model domain with the bathymetry in log10 scale. The locations and names of the transects are shown as well.

2.2 Assimilation scheme

The 3DVAR approach bases on the minimization of a cost function, which was solved using a conjugate gradient method. Moreover, the error covariance matrix in this study is a function of the mixing layer thickness that varies in time and space with the evolution of turbulent mixing. The latter was an output of the numerical model. In the North Sea area, waves play important roles in vertical turbulent mixing, which was also the motivation for using the model that coupled the circulation model and the wave model. The horizontal correlation length of model errors was assumed to be constant both in time and space.

2.3 Heat transport and physical processes

The heat transport across five boundary transects (see Figure 1a) was calculated as:

$$q = \int_A \rho c_p u (T - T_r) dA \quad (1)$$

where dA was the incremental area and u the velocity normal to the transect. The reference seawater density $\rho = 1026 \text{ kg m}^{-3}$ and the heat capacity constant $c_p = 4.19 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$. The reference temperature $T_r = T_{rc} + 273.15$, with $T_{rc} = 60^\circ \text{C}$ (following that of Dieterich et al., (2019)). To gain insight into the mechanisms that induce the heat transport, the current velocities and local areas along the five transects were decomposed by applying a tidal harmonic analysis (Pawlowicz et al., 2002):

$$\begin{aligned} \bar{q} = & \underbrace{\left(\int_A \bar{T}_k \bar{u} d\bar{A} \right)}_{\text{Eulerian}} + \underbrace{\left(\int_A \bar{T}_k \bar{u}^t d\bar{A}^t \right)}_{\text{Stokes}} + \underbrace{\left(\int_A \bar{T}_k \bar{u}^w d\bar{A}^w \right)}_{\text{Wind}} + \underbrace{\left(\int_A \bar{T}_k^t \bar{u}^t d\bar{A} \right)}_{\text{Tidal pumping}} + \underbrace{\left(\int_A \bar{T}_k^t d\bar{A}^t \bar{u} \right)}_{\text{Tidal pumping}} + \underbrace{\left(\int_A \bar{T}_k^t d\bar{A}^t \bar{u}^t \right)}_{\text{Tidal pumping}} \\ & + \underbrace{\left(\int_A \bar{T}_k^t \bar{u}^w d\bar{A} \right)}_{\text{Wind pumping}} + \underbrace{\left(\int_A \bar{T}_k^t d\bar{A}^w \bar{u} \right)}_{\text{Wind pumping}} + \underbrace{\left(\int_A \bar{T}_k^t d\bar{A}^w \bar{u}^w \right)}_{\text{Wind pumping}} + \underbrace{\left(\int_A \bar{T}_k \bar{u}^t d\bar{A}^w \right)}_{\text{Wind-tide interaction}} + \underbrace{\left(\int_A \bar{T}_k \bar{u}^w d\bar{A}^t \right)}_{\text{Wind-tide interaction}} + \underbrace{\left(\int_A \bar{T}_k^t d\bar{A}^w \bar{u}^t \right)}_{\text{Wind-tide interaction}} c_p \rho. \end{aligned}$$

(2) Here, the overbar represented an annual average and superscripts 't' and 'w' indicated harmonic quantity and wind-induced quantity. The temperature T_k was obtained from the model runs.

3. Results

The heat transport at the five selected transects was calculated using eq.1 for the year 2017 (Figure 2). It was found that the North Sea gains heat through advective heat transport at the Dover Strait, the Fair Isle, and the Shetland Shelf, and loses heat at the Norwegian Channel. The heat transport at the Danish Strait was negligible. In total, the North Sea gained 18.32 TW (17.78 TW) of heat and lost 16.32 TW (15.04 TW) in the Free Run (DA Run). In 2017, a net heat content accumulated in the North Sea through the advective heat transport, with a value of 2.02 TW in the Free Run and 2.74 TW in the DA Run.

Contributions at each transect to the total heat transport were related to the amount of water volume through the transects (not shown). For instance, in the Free Run, the net volume transports were 0.09 Sv at Dover Strait, 0.04 Sv at the Danish Strait, 0.48 Sv at the Fair Isle and the Shetland Shelf, and -1.27 Sv at the Norwegian Channel. These values were consistent with the finding of earlier observations and model studies (Prandle *et al.*, 1996; Otto *et al.*, 1990; Hjollo *et al.*, 2009).

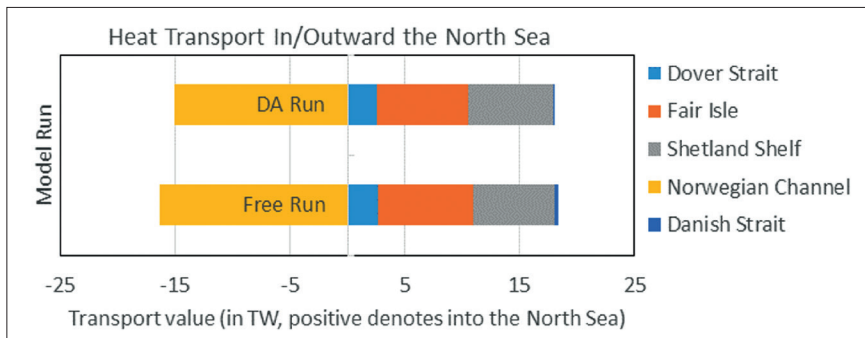


Fig. 2. Annual mean heat transport through the five selected transects. Positive/negative denotes into/out the North Sea.

Figure 2 further showed that the main difference between the Free Run and the DA Run occurred at the Norwegian Channel. Through this transect, the heat transport reduced from the North Sea to the Atlantic after DA. To gain further insight into the DA impact, the physical processes that dominate heat transport were investigated (see section 2.3) in more detail. As shown in Figure 3, the features of the heat transport at each open boundary were different. At the west side (Dover Strait), the Eulerian transport and the Stokes transport were two mechanisms at the dominant order. At

the north boundary, i.e., Fair Isle, Shetland Shelf, and Norwegian Channel, the major heat transport was the Eulerian term. At the east side (Danish Strait), tidal pumping and wind pumping of heat acted as the dominant process for the advective heat transport. Moreover, it was worth noting that the Norwegian Channel transect and the Danish Strait transect were both inside the Norwegian Trench. Hence, they shared some similarities in transport mechanisms, i.e., tidal pumping and wind pumping also played a role at the Norwegian Channel transect.

When comparing the Free Run and the DA Run, Figure 3 revealed the Eulerian transport as the main changed term, implying a reduced outward volume transport through the Norwegian Channel. Figure 4 illustrated a mean current field of one month (hence, the dominant tidal components were removed, e.g., M2). The pattern in other months was similar and thus not shown. The contours indicated the relative difference in the dynamic energy between the DA Run and the Free Run per unit water mass, i.e., $\epsilon=0.5(u_a^2-u_f^2)/0.5(u_a^2+u_f^2)$. When $\epsilon=1$, the water current was generated by the DA, whereas $\epsilon=-1$ DA removed the water current locally. The case $\epsilon=0$ implied that DA does not change the local velocity field. The larger change of the vertical mean current due to DA occurred in the area with deeper water depth. The largest dynamic changes occurred inside the Norwegian Channel and outside of the shelf sea. Current velocities in the Atlantic were enhanced along the northern side of the North Sea shelf because of DA. As a result, the branch-current along the western side of the Norwegian Channel increased, and in consequence compensated the net outward current of the North Sea.

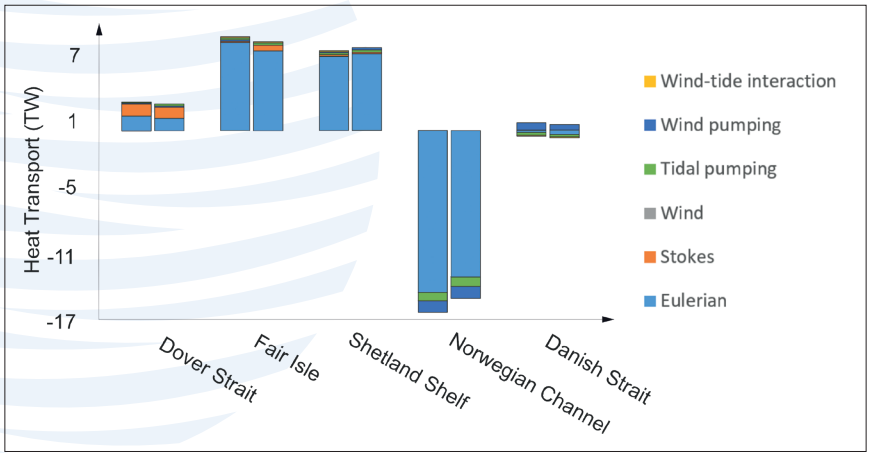


Fig. 3. Annual mean heat transport due to different physical processes through the five selected transects for the Free Run (left column) and the DA Run (right column). Positive/negative denotes into/out the North Sea.

4. Conclusions

The study investigated the impact of the satellite SST assimilation on the modeling of heat transport in the North Sea. The DA scheme implemented a 3DVAR with model errors correlated with the length of the mixing layer. It was demonstrated that DA not only affected the heat transport through the direct change of seawater temperature but also affected the heat transport through the secondary impact on the current velocity. The largest secondary impact of the DA was at the Norwegian Channel, where the lateral heat transport outward decreased from 16.32 TW to 15.04 TW.

Further decomposition of the heat transport with a harmonic analysis revealed that the dominant mechanism of the heat transport at the Norwegian Channel was the Eulerian transport, followed by tidal pumping and wind pumping at a higher order of magnitude. The decreased outward heat transport through the Norwegian Channel was due to the decreased Eulerian volume transport. Further analysis revealed an acceleration of the along-shelf current at the northern edge of the North Sea due to DA, which compensated the outward currents, in consequence, decreased the flux from the North Sea to the Atlantic.

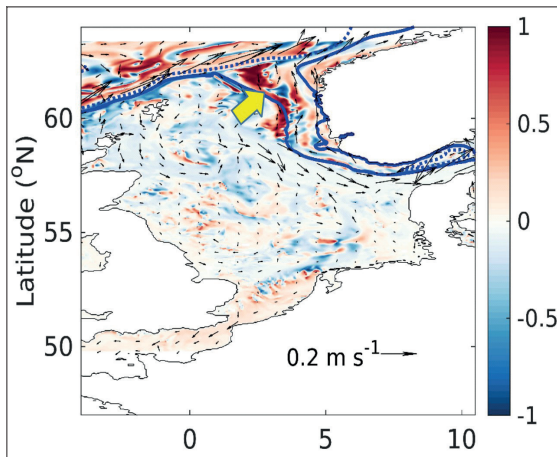


Fig. 4. Vertical mean current averaged over a one month period in 2017. Arrows are velocities of the DA Run, and the contours denote the relative changes in dynamic energy from the Free Run to DA Run. Positive/Negative values represent the increasing/decreasing energy due to DA. Blue solid (dotted) line indicate the sea bottom 250 m (500 m).

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