Reply to the comments of reviewer 2 on the NHESS submission:

'The role of heat wave events on the occurrence and persistence of thermal stratification in the southern North Sea'

The manuscript aims to investigate the contribution of marine heatwaves (MHW) to thermal stratification in the North Sea by using ocean-wave coupled numerical experiments performed during a 8-year period. Comparing with observations (in-situ and remote-sensing), they observed large stratification events in the summers of 2014 and 2018, when large surface-to-bottom differences in water temperature co-occurred with high air temperatures. They argue that in absence of turbulent mixing high air temperatures lead to high SST and intensified stratification, triggered also by the long memory of seawater compared to air to low temperatures in the cooling season (e.g. January-April).

Thermal stratification and MHWs show a well-defined dependency in areas, along the Danish coast, which were not well characterized in the literature as one of the density stratification regimes in the North Sea. The vertical structure of stratification (Ri) shows the water depth as the factor modulating the sensitivity of the stratification to the summer heatwave (max values observed in the middle of the water column).

The work is well developed and well placed within the framework of the scientific open issues about the effect of extreme climate events. The authors use robust analysis and provide an exhaustive physical interpretation of all the results obtained, which address the goals of the study. The publication is recommended.

Here follow some suggestions, which could help improve certain parts of the manuscript.

We thank the Editor and the reviewer for their careful reading of the manuscript and for many constructive comments and suggestions, which were useful to improve the manuscript. Below, we present a point-to-point reply to all comments. The original text of the reviewers is in black and our reply is in italic blue.

General Comments

1. The sensitivity of ocean-wave coupling is addressed in supplementary materials (SM), but either a dedicated Appendix on the wave-induced processes included in the coupling, or an additional Figure in SM on the sensitivity to the wave-induced turbulent mixing, could help the reader to fully understand the results (e.g. Lines 270-275).

We appreciate the reviewer for this suggestion and add added texts in discussion (line 275) to show the mixed layer depth in the southern North Sea during summer months with/without wave-induced processes coupling: "Figure 12 shows the modelled seasonal mean mixed layer depth (MLD) of the

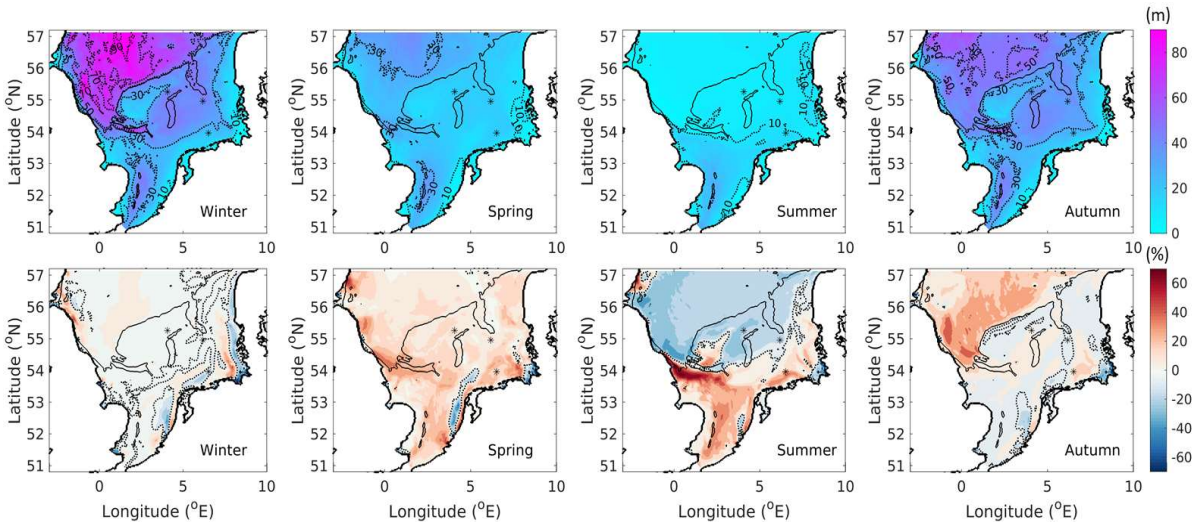

Figure 12. Upper panels: The seasonal mean mixed layer depth (MLD) of the coupled NEMO-WAM model run. Lower panels: The relative changes of MLD when comparing the coupled run with the stand-alone NEMO (uncoupled) run. Dotted lines in the lower panels indicate the 0 % contour.

coupled NEMO-WAM model run in 2018 and the relative changes when comparing the fully coupled run with the uncoupled run, i.e., $(MLD_{coupled} - MLD_{uncoupled})/MLD_{coupled} \times 100\%$***.***

Following the annual cycle of water temperature, MLD in the southern North Sea decreases from winter to summer and develops again in autumn. The MLD changes quicker in deeper regions than in shallow coastal areas. There is almost no seasonal cycle along with the German Bight coast. The large difference in MLD between the coupled and uncoupled run is found from spring to autumn, when stratification develops with the changing air temperature. In summer, the MLD of the coupled run is approximately 20~ 40% larger than that of the uncoupled run in the southern North Sea, whereas it is approximately 20% smaller north to the 54°N. In autumn, the stratification disappears in the southern North Sea, where the MLD differences drop to -10~10%. In the north, where water depth is larger than 50 m, the MLD of the coupled run is approximately 20% larger than the MLD of the uncoupled run. The wave-induced processes change also the heat fluxes at the water surface (Figure 13). The net heat flux is overall positive (from air to the sea) in spring and summer and from sea to the air in winter and autumn The importance of wave forcing for ocean predictions in the North Sea has been demonstrated by Staneva et al., 2017. The wave-induced processes impact the distribution of the heat

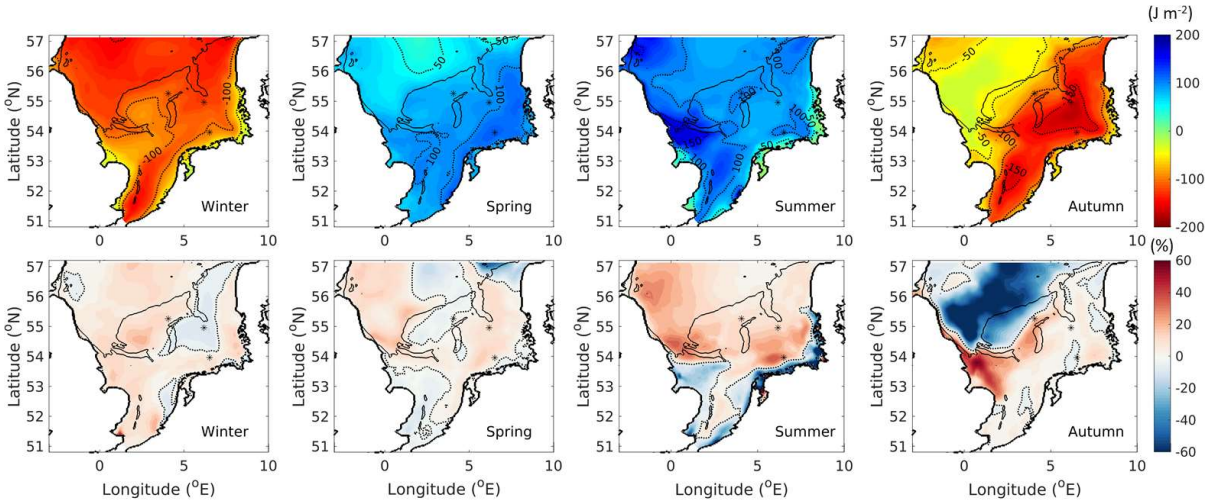

Figure 13. The same as Figure 12, but for the surface heat fluxes. In the upper panels, positive values denote net fluxes from the air the sea.

fluxes. In summer, in the southern North Sea, the fluxes increase by about 20-40% while along the coastal, well-mixed area of the German Bight is the opposite and a reduction of 20 -50% is observed.

2. The quality of the graphics and Figure captions could be improved (look at specific comments).

We thank the reviewer for this suggestion and corrected the figures accordingly.

Specific Comments

Introduction

Line 17: the reference IPCC, 2012 should be updated to AR6

The reference is updated.

Line 26: "In the North Sea …" - rephrase.

Now it is rephrased as "The North Sea is predicted to be warming …" and shifted to line 33-35.

Line 55: "who showed…" – rephrase.

The revised sentence reads: "Recently, Klonaris et al. (2021) developed a state-of-the-art three dimensional hydrodynamic model based on ROMS and showed accurately reproduced thermohaline variations in the southern North Sea.".

Line 56 “Considering the interface …” – rephrase.

The revised sentence reads: “Models investigate thermodynamic air-ocean interface processes by coupling the interactions between the air-sea system (Ho-Hagemann et al., 2017; Stathopoulos et al., 2020).”

Section 2

Line 99: Check the reference GEMORAR, 2019

Now it is corrected to GEOMAR, 2019

Line 102: omit “for the location”.

Corrected.

Section 3

Line 158-159: rephrase. Something like: “The results were further compared with satellite data. Figure 4 shows an annual variation in the modelled and remote sensed SST at the NSB III platform location in 2018.

We thank the reviewer for the suggestion and we updated the sentence accordingly in the revision.

Line 194: multi-year mean.

Corrected.

Section 4

Line 232: “….the number of days when the water …”

Corrected.

Line 265: “…down to the bottom”: it is hard to distinguish max Ri values at the bottom, and the statement is in contrast with the sentence at Lines 267-268. Consider rephrasing.

This sentence is revised in the new manuscript as: “Moreover, at the Dogger Bank and NSB III, the maximum R_i shifted from the upper water layers to the bottom during the early stage of the warming season.”

Line 277-295: It could be shorter and move to the conclusions.

We agree with the reviewer to shorten this paragraph. However, we decided to keep the text in this section because these texts discussed the potential hydrodynamic response of the southern North Sea to the occurrence of extreme MHW events rather than the main finding of this work. The new texts now read:

"Apart from circulation-wave coupling, stratification itself also influenced circulation. Baroclinic circulation, a result of the balance between baroclinic forcing and friction, is more pronounced with stronger current velocities (larger vertical shear) in warmer climate conditions when the turbulent eddy viscosity is eliminated by the increased stratification. Huang et al. (1999) showed an enhancement of water transport from a weakly stratified situation in spring to a strongly stratified situation in summer in the Bohai Sea. In the North Sea, relations between the cycle of thermal fronts and baroclinic circulation were analyzed at different ranges of timescales (Lwiza et al., 1991; Luyten et al., 1999). Decreased vertical turbulent mixing reduces the magnitude and horizontal shear of the baroclinic currents. This was found to be important feedback from turbulent mixing to the frontal temperature gradients and baroclinic circulation (Luyten et al., 2003). These mechanisms would be further pronounced in case extreme events occur. By analyzing 40-year data, Schrum et al. (2003) identified unusual stratification due to wind and volume transport in the 1990s. Recently, Chen et al. (2021) investigated the heat budget of the North Sea. They demonstrated the modification of SST affected advective water and heat transport in the North Sea. Comparatively, extreme events, i.e., summer heatwaves, had more intensive influences on SST but within a relatively shorter timescale. Exploring the reaction of the regional water circulation to extreme events in the southern North Sea is an interesting topic and deserves further study."

Comments about Figures

Figure 2:

The bottom panel should be either described in the manuscript or removed.

We add the following text in Line 149: "The differences in water temperature between the model and the measurements are in the range of ±2◦C. The model error is smaller during the winter months than in the summer months"

Caption

"Bottom panel: the differences …".

The sentence is revised as: "The water temperature differences between the model and the in-situ measurements at the surface and the bottom."

Figure 3

The text in the caption should be improved.

The updated caption reads: "The in-situ measured and the model simulated water temperatures (in◦C) in July. At the Dogger Bank, measurements are obtained by the CTD profiler during the Poseidon campaign and at the MARNET stations NSB III and FINO-1, temperatures are measured at fixed water layers."

Figure 4

The text in the caption should be improved.

The updated caption reads: "Annual variation of SST (in◦C) at the NSB III platform in 2018. Apart from the satellite measurement (yellow curve) and the model simulation (purple curve), the 10th- and 90th-percentile SSTs from the multiyear statistic are shown as well. Based on the 10th/90th-percentile, one cold-spell and two MHWs are detected.".

Figure 6

Check the unit (see palette). The text in the caption should be improved describing clearly what is displayed on the background. It is hard to distinguish between dashed and solid black lines.

Change to J m^{-3} in $\log_{10}$ scale

Thank you. We have revised the figure following your suggestions.

Figure 9

What about the solid line? See relevant comment for Figure 6.

We add the following sentence: "The thin solid line indicates the location of 50 m depth. "

Figure 10

See previous comments.

We revised the caption accordingly.