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A regional coupled atmosphere-ocean model system REMO/HAMSOM for the North Sea

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A regional coupled atmosphere-ocean model system REMO/HAMSOM for the North Sea

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1 Research goals and purpose of cooperation

We aim at providing climate projection time series for the North Sea to the Kliwas project using the regional coupling system (REMO/HAMSOM). The coupled REMO/HAMSOM system was established by Prof. Schrum and other colleagues (Schrum, et. al., 2001, 2003). However this coupled system applied bulk formula to calculate the heat fluxes, which is nowadays replaced by exchanging fluxes of heat, momentum and freshwater. In this cooperation, we developed a new high resolution regional coupled atmosphere-ocean model via heat flux coupling. We aim to better resolve coastal processes, study air-sea interaction and provide long-term simulations. By this means, we are able to improve the prediction of climate change impacts in the North Sea. In addition, the advantage of using interactive coupling is evaluated by validating coupled and uncoupled hindcast experiments with long-term observations.

During the project, we cooperated intensively with BSH, MPI-M and CSC partners. BSH provided the observations and the guiding research lines. They also were involved in the interpretation of the data and model results. The MPI-M group provided the results of a global coupled ocean-atmosphere-ice model, which were used as atmospheric forcing. The global ocean model MPIOM also provided data sets for the open boundaries of the regional ocean model HAMSOM. The CSC group cooperated with us to establish the regional coupling model system and interpret the results of the regional climate model REMO.

2 Model setup

2.1 Model configuration

REMO (Fig. 1 blue color) is a regional climate model which is based on the Europa-Modell from the German Weather Service (DWD). It is based on the primitive equations in a terrain-following hybrid coordinate system. The finite-difference equations are written in advective form on an Arakawa C-grid. To avoid numerical instabilities the vertical advection, as well as the vertical turbulent fluxes are treated implicitly. More details about REMO can be found in Jacob and Podzun (1997) and Jacob et al. (2001). The model runs in a horizontal resolution of 37 km and has 27 vertical pressure levels. The area cover by Remo is shown in Fig. 2 (blue color).

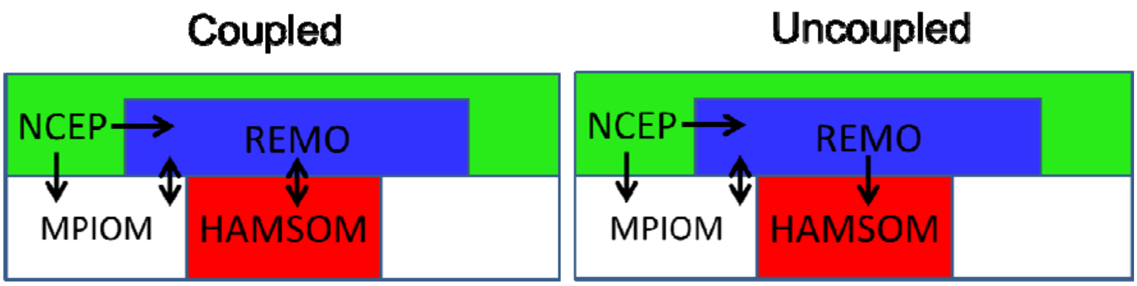

Fig. 1: Schematic plots of coupled (left) and uncoupled (right) hindcast runs (1986 - 1999). The upper boxes refer to the atmospheric components of the coupled system, while the lower boxes refer to the oceanic part. Arrows indicate the direction of information flow from one compartment to the other. Since the REMO domain is much larger than the respective HAMSOM area the oceanic boundary conditions in these areas are provided by the regionally coupled MPIOM run.

The high-resolution 3-D baroclinic, free surface, shallow water equation model HAMSOM is applied as the regional oceanic component in the present system. The use of relatively long time-steps is possible in HAMSOM since terms limiting the time-step are treated implicitly (details see Backhaus (1985)). This advantage enables HAMSOM to perform long-term simulations, and is thus suitable for climate studies. HAMSOM has been intensively validated in the North Sea (Pohlmann, 1996, 2006). The horizontal resolution of HAMSOM is ~ 3 km and it has 30 vertical levels, and includes tidal constituents. In the coupled experiments only M2 tides are included because they are the major component. Temperature, salinity and sea level data are provided at the open boundaries (northern boundaries, English Channel and Baltic outflow) by data from MPIOM run 215 under inflow conditions for the scenario runs. In case of the hindcast simulations the boundary conditions for temperature, salinity and sea level are taken from MPIOM run 253. Adaptive boundary conditions have to be applied under outflow conditions (for details of the adaptive open boundary conditions see Chen et al. (2013). Freshwater supply through the rivers is taken from climatological data (Damm, 1997). The hydrological cycle is kept constant throughout the scenario runs. The reason for using a climatological data set for the river runoff instead of data from the hydrological model used during the MPIOM simulation is to avoid problems with the freshwater balance in the model due to different biases in the models. However, the constant hydrological cycle has to be taken into account when analyzing the near coastal salinity distributions.

MPIOM is the ocean component of the Max-Planck-Institute for Meteorology Earth System Model (MPI-ESM). It is a free-surface ocean general circulation model formulated on an Arakawa-C Grid and a z-coordinate system in the vertical (Jungclaus et al., 2013). Details of the model equations and physical parameterizations can be found in Marsland et al. (2003). The A1B scenario simulations from the regionally coupled set–up of MPIOM/REMO (run215, in the NASH6 setup of the model) were used as open boundary value for HAMSOM. For details of the MPIOM simulations we refer to the final report of the MPIOM group (Kliwas Schriftenreihe, MPIOM final report in prep., 2014).

The regional coupling system includes a regional ocean model (HAMSOM), a regional atmospheric model (REMO) and coupler (OASIS3). The global climate model MPI-ESM provides the boundary conditions for regional coupling system.

The coupler in the system is OASIS3 (Valcke et al., 2004). At run-time, OASIS3 acts as a separate executable mono process, which main function in our experiments is to synchronize the model components. OASIS could also provide an interpolation of the ocean and atmosphere model grids on the respective other component, but since tested interpolation routines already existed for HAMSOM/REMO this was not necessary.

The oceanic coupling domain is within the North Sea, while the REMO domain is much larger than the North Sea (Fig. 2). One reason for choosing such are large domain was to keep the model setup similar to the MPIOM runs performed in the KLIWAS cooperation. Additionally we choose the large REMO domain with 37 km resolution, because 1) most storms influenced the North Sea are generated in regions close to the Labrador Sea; 2) the grids ratio between REMO and NCEP/ECHAM is not too large. For the A1B scenario simulation the SST outside the North Sea region is provided by the global coupled REMO/MPIOM model results (run 215). In the hindcast experiments, the lateral boundary values of REMO are provided by NCEP/NCAR re-analysis data. The lateral boundary conditions for the ocean in this case are provided from the respective hindcast simulation by MPIOM (run 253). In the scenario experiments, the lateral boundary values of REMO are provided by ECHAM5 (ECHAM5_T63L31 MPI-OM_GR1.5L40 SRESA1B run no.3). Coupling time step is 3 hours. At each coupling time step, REMO provided heat fluxes, turbulent fluxes (wind stress) and water fluxes (precipitation-evaporation) to HAMSOM. HAMSOM exchanges SST to REMO. The coupled model is running in super computer (DKRZ) with 96 processors (3 nodes), and the clock time on the computer 12 hours for 1 model year.

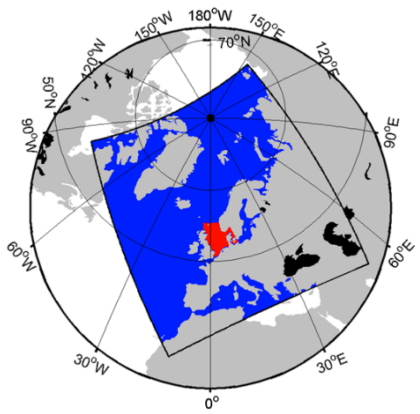

Fig. 2: Coupled domains of the model system. The blue color refers to the domain of REMO, while the red color refers to the domain of HAMSOM.

2.2 Experiments

We chose 1985 - 1999 as the period for sensitivity experiments, because 1) it is the purpose of these experiments to explore the benefits of coupled versus uncoupled experiments and not to investigate the decadal variability in the North Sea, 2) the REMO/MPIOM hindcast run before 1985 was showing exaggerated ice dynamics with associated drift in temperatures (see Bülow et al., Kliwas Schriftenreihe, Band 27, 2014). The purpose of the hindcast experiments is to investigate the advantages of interactive coupling in regional climate downscaling. Therefore, the coupled (run ID 201) and uncoupled (run ID 123) runs in the hindcast period are compared. For the uncoupled hindcast experiment (run 123) the ocean model was driven directly by heat fluxes from the atmosphere because of the limited extent of the simulation (15 years). In longer time simulations the accumulation of small imbalances in the heat budget will lead to unstable model behavior.

A coupling experiment for A1B scenario (run ID 202) is also performed. Boundary conditions are provided by MPIOM run 215. The simulation period is from 1950 to 2099. As mentioned above it would not be possible to perform an uncoupled run for the whole A1B scenario period (150 years) by forcing directly with heat fluxes because of the accumulation of imbalances in the heat budget that would grow over time unrestrained in the uncoupled mode. In order to perform a stable long-term run for the uncoupled A1B scenario bulk formula were applied. The bulk formula for the sensible heat flux involves the temperature difference between air and water and thus provides a feedback between the ocean and the atmospheric forcing data. The main focus of the analysis of the A1B runs in the cooperation is to investigate the climate change signal and the inherent decadal variability and therefore we are not focusing in this report on the advantages of the interactive coupling.

3 Work performed

3.1 Model validation

The validation was done by comparing the hindcast experiments with the SST observations (Janssen climatology and SST data provided by BSH). In Figure 3 we are showing the data from the Janssen climatology (Janssen et al., 1999) for comparison with the model results, although the climatological mean is created from a much longer time period (1900-1996) than the model mean (1986-1999). Comparison with the independent BSH data set of sea surface temperatures for the period 1986-1999 shows that the temporal differences are not too large and the main focus of the analysis here is on the spatial patterns. Additionally the Janssen climatology provides a better spatial resolution than the satellite based SST data set provided by BSH. We found that the coupled model reproduces observed pattern significantly better (Fig. 3). The major improvements are found in the southern North Sea and in particular in the coastal regions. In winter, SST in the uncoupled run at the southern coastal is about 3 ^{o}C colder than the observations. In summer, the spatial SST distribution in the southern North Sea is much closer to the observations in both experiments. More details about the HAMSOM hindcast runs and a comparison to the corresponding MPIOM runs can be found in Su et al. 2014.

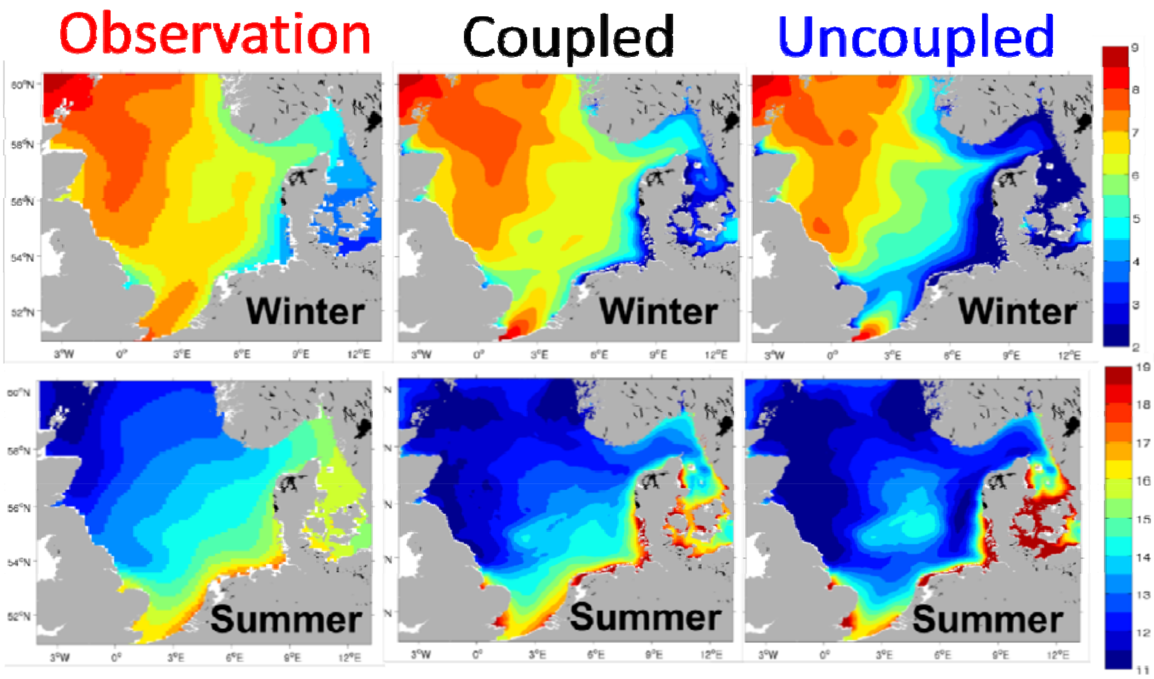

Fig. 3: Multi-year mean SST of the climatology (left, Janssen, 1999), coupled (middle column, run 201) and uncoupled (right column, run 123). Model results in winter are shown in the upper panel and summer in the bottom panel. The Janssen climatology represents a mean for 1900 to 1996, both coupled and uncoupled model results are mean values for 1986-1999.

3.2 Analysis of difference between the coupled and uncoupled model results

In the southern coastal region, particularly the Wadden Sea, the coupled and uncoupled hindcast experiments both were colder in winter and warmer in summer comparing with the observations. In addition, the largest differences between coupled (run 201) and uncoupled (run 123) hindcast experiments were also found in this region, which can be further confirmed by root mean square difference (RMSD) results (Fig. 4). The spatial RMSD distribution of SST between two experiments confirmed that the southern coastal areas exhibited the major difference, which could be up to 5°C. In summary of the spatial comparison, the coupled model simulation showed much reduced deviations from observations, while the uncoupled experiment results deviated from observations in the southern coastal waters.

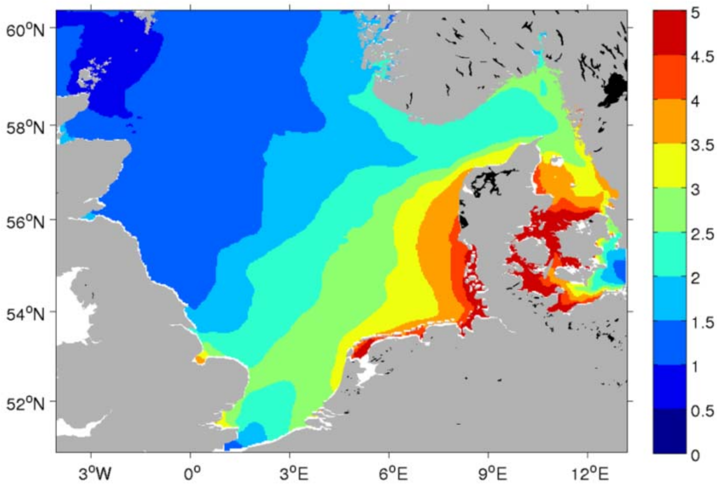

Fig. 4: Root mean square difference (°C) between coupled and uncoupled model results (based on daily output).

The annual mean SST over the North Sea (calculated over the same domain as BSH SST data) in the coupled hindcast experiment is in good agreement with BSH SST data (with an average offset < 1°C, Fig. 5). In the uncoupled simulation, a continuous drift from observations occurred which reached a maximum in 1997 (~ 4°C colder). As it was stated above the imbalances in the heat budget accumulate over time when the uncoupled ocean model is forced with the heat fluxes and errors grow over time. From Fig. 5, we conclude that the coupled model simulation showed less deviation from observations over decades, thus it can serve as a tool for a free climate-model run. For more details we refer to the paper by Su et al. 2014.

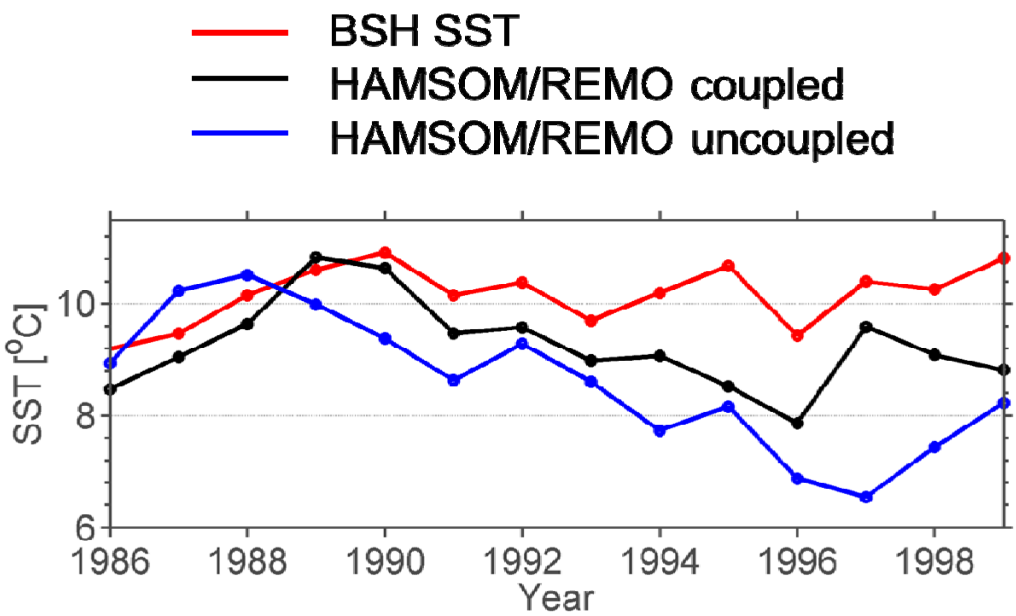

Fig. 5: Time series of the annual mean SST averaged over the North Sea in hindcast runs 123 (uncoupled) and 201 (coupled).

We further explored model data from 1997 with particularly large deviations from the observations to focus on mechanisms by which the coupled model is able to correct the SST fields. For this we use the SST distributions in August 1997 (Fig. 6) and explored the heat fluxes one month earlier in July 1997 (Fig. 7). The monthly mean SST in August 1997 in uncoupled simulation showed that the North Sea is dominated by a basin wide cold water mass (Fig. 6 right), which confirmed the drift we found in Fig. 5. This cold water mass did not occur in the coupled experiment (Fig. 6 left).

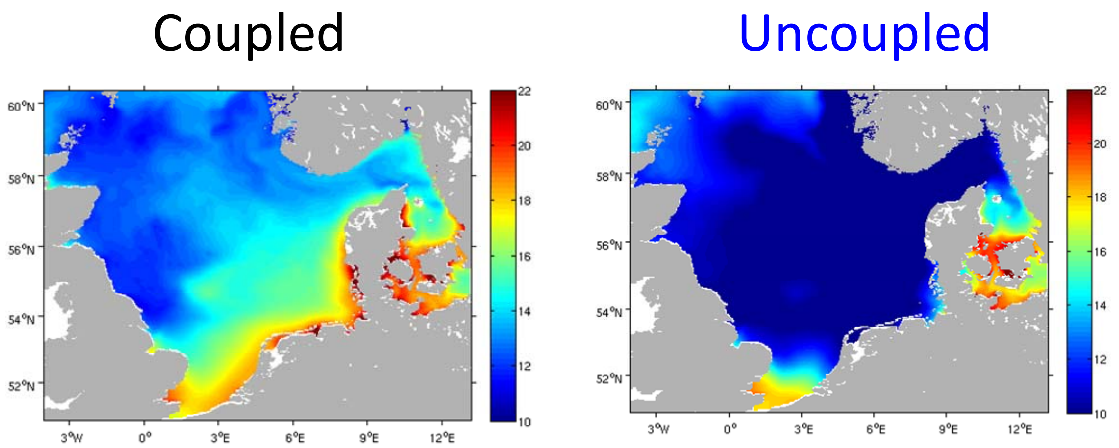

Fig. 6: SST (^{o}C) of coupled (left) and uncoupled (right) hindcast simulations in Aug 1997.

The different heat flux components in July 1997 are shown in Fig. 7. Surprisingly, shortwave radiation flux exhibited the major difference between the both experiments (Fig. 7, upper left panel, ~ 60 Wm^{-2} in the northern North Sea). The other three heat flux components did not show such a large difference. The surface shortwave radiation flux must relate to the cloudiness fraction.

The spatial REMO results of cloudiness and shortwave radiation in July 1997 were shown in Fig. 8. In the uncoupled experiment, it is obvious that the lower shortwave radiation patch at the northeastern North Sea was due to the higher cloudiness. Therefore, the interactive coupling corrects the accumulative errors of heat fluxes via cloudiness. The mechanism will be further investigated by our partners in REMO group.

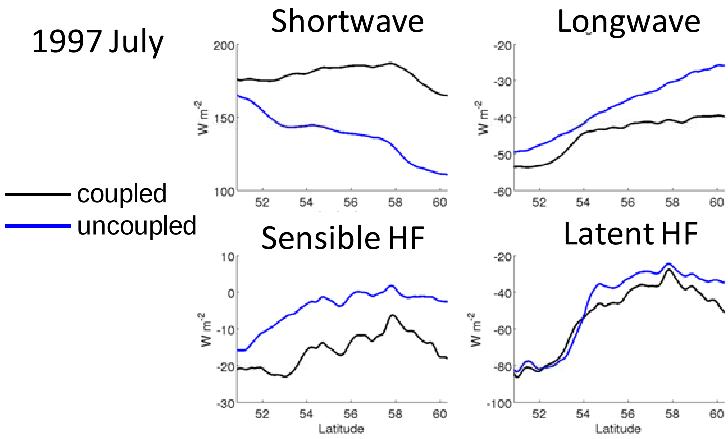

Fig. 7: Zonal mean heat flux components (W m^{-2}, also over land) of coupled and uncoupled runs in July 1997. The positive value indicates downward direction. Black and blue lines refer to the results from coupled and uncoupled experiments, respectively.

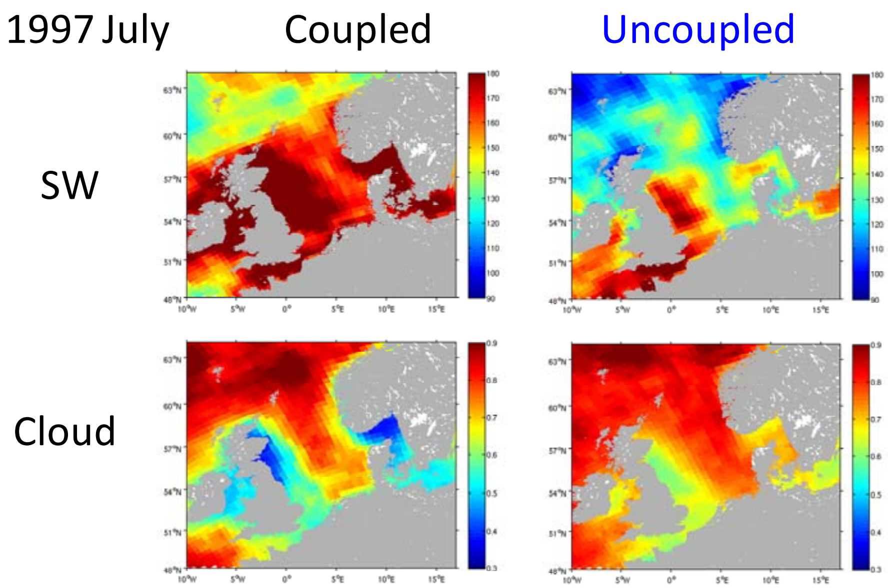

Fig. 8: Upper panel: comparison of shortwave radiation flux between coupled (left) and uncoupled (right) experiments (W m^{-2}) in July 1997. Positive direction is downwards. Bottom panel: comparison of cloudiness (percentage) between coupled (left) and uncoupled (right) hindcast experiments.

4 The A1B scenario run

A detailed discussion of the A1B results will be given in the joint report of all three modelling groups which is in preparation (Bülow et al., Kliwas Schriftenreihe, Band 27, 2014) and only some comparisons to the bias corrected A1B run (Mathis and Pohlmann, 2013) are given here.

The time series of the regional and annual mean SST of the A1B scenario run, taken over the whole HAMSOM area is illustrated in Fig 9. As discussed above the uncoupled runs with direct heat flux forcing showed model drift due to accumulation of errors from the heat budget (see Fig. 5) and could not be run for an extended period. Hence, we compared coupled run with a bias corrected uncoupled run applied bulk formulae to calculate the heat fluxes (for details of this uncoupled run please see Mathis et al. (2013) and Mathis and Pohlmann (2013)). The main purpose of this comparison is not to demonstrate the advantage of interactive coupling, but to study the inter-decadal variability in the coupled run since ocean feedback to the atmosphere is a slow process. During the control period (1950 - 2000), SST is colder than the mean state of observation in both runs. In particular, the warming trend after 1990 can’t be captured. After 2007, SST in coupled run is higher than that in uncoupled run. This inter-decadal variability should be further investigated in other studies.

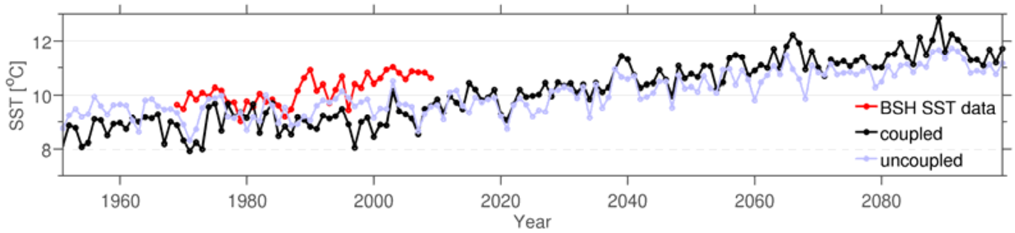

Fig. 9: Time series of the annual mean SST in the North Sea in the A1B scenario run. Please note that the uncoupled run is performed outside the KLIWAS cooperation and published in Mathis and Pohlmann (2013).

5 Results in terms of key messages

1) The coupled model simulation shows no major deviation from observations, thus it can serve as a tool for a free climate-model run.
2) In the uncoupled model simulation, we found a drift from observations when integrating the model for more than 10 years. This drift is due to the accumulation of heat flux errors.
3) The interactive coupling could damp these errors in a long-term simulation.

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