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Marine downscaling of a future climate scenario for the North Sea

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ABSTRACT

The SRES A1B scenario for the period 2072–2097 with the Bergen Climate Model (BCM) has been downscaled for the marine climate in the North Sea using the Regional Ocean Model System (ROMS). The results are compared to the 20C3M run for the period 1972–1997.

The results show a warming of the North Sea, with a volume average of 1.4 °C, and a mean SST change of 1.7 °C. The warming is strongest in May–June. Geographically the strongest warming in the North Sea is found towards Skagerrak–Kattegat in the surface waters and in the central North Sea at 50 m depth. The downscaling show a weak increase in the Atlantic inflow to the North Sea.

The BCM scenario has a change in the wind stress pattern in the Faeroe Island region. This strengthens the branch of Atlantic Water flowing west of the Faeroes and weakens the flux through the Faeroe–Shetland Channel. As a result both BCM and the downscaling show large changes in the temperature in this area, with weak warming and sometimes cooling south of the Faeroes and strong warming on the north side.

1. Introduction

Climate change and variability affect marine ecosystems and fisheries in several ways. First temperature has a direct influence on metabolism and growth, see for example, Jobling (1996). Climate may also have secondary effects, affecting a species by changes in food availability, competitors or predators. For the North Sea, there are several recent studies on the effects of climate on the cod stock (O'Brien et al., 2000; Clark et al., 2003; Cook and Heath, 2005) and on plankton (Beaugrand et al., 2002; Richardson and Schoeman, 2004).

Temperature change may also act as a proxy for other climate mechanisms such as circulation changes and changes in vertical mixing and stratifications. For the North Sea the inflow of Atlantic water is an important climate variable. In addition to the influence on the temperature, this inflow is a major source of nutrients and zooplankton. The relation between temperature, inflow, plankton and cod is considered by Sundby (2000).

To study the ecological impact of climate change, a consistent scenario of future climate is needed. Such scenarios are produced by global coupled atmosphere–ocean circulation models. However, for shallow shelf seas like the North Sea, the present generation of such global models do not have the necessary resolution to properly resolve the shelf topography. Typically they also lack important shelf sea physical processes like tidal mixing.

This paper uses the technique of dynamical downscaling to regionalize a future global climate scenario for the North Sea. This is done by forcing a shelf sea circulation model with atmospheric forcing and open ocean lateral boundary description from a global climate model. This approach has been validated for the present climate by Ådlandsvik and Bentsen (2007). They document that this procedure works technically and provides added value by increased regional details, more realistic shelf sea stratification, improved winter temperature, and more realistic Atlantic inflow.

There is a large activity on regional ocean modelling of the North Sea, see Jones (2002) and Lenhart and Pohlmann (2004) for recent reviews. This includes hindcast studies forced by atmospheric reanalyses. For future climate, there are downscaling studies on ocean climate including hydrography (Kauker, 1998), and storm surge and wave climate (Debernard et al., 2002; Woth et al., 2005).

2. Methods

2.1. The global scenario

The global scenario is the SRES A1B scenario provided by the Bergen Climate Model (BCM) as input to the 4th assessment report of the International Panel on Climate Change (IPCC).

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The period considered here is 2072–2097. As control run, the 20C3M run for the period 1972–1997 is used. This run also formed the basis for a prior validation study, Ådlandsvik and Bentsen (2007).

The BCM is an atmosphere–ocean general circulation model. The atmospheric component is the ARPEGE model (Déqué et al., 1994) while the ocean component is the Miami Isopycnal Ocean Model (MICOM) (Bleck et al., 1992). The coupling is done with the OASIS coupler (Terray and Thual, 1995). An earlier version of the model system is documented in (Furevik et al., 2003). The present version is run without flux-correction.

2.2. *The regional model*

The regional model used is the Regional Ocean Model System (ROMS), described in Shchepetkin and McWilliams (2005) and Haidvogel et al. (2007). The model is based on the primitive equations and is discretized by finite differences. The vertical coordinate is the terrain-following s-coordinate (Song and Haidvogel, 1994). For these simulations the generic length scale formulation of the Mellor–Yamada vertical mixing closure (Warner et al., 2005) was used. More details on the model configuration and forcing is given in Ådlandsvik and Bentsen (2007).

The model domain is shown in Fig. 1. The average resolution in the area is 8 km. In the vertical 32 s-levels has been used. The atmospheric forcing consists of daily averaged fields from BCM using a flux formulation based on Bentsen and Drange (2000). The lateral ocean boundary description is taken from monthly averages from BCM and 8 tidal constituents from Flather (1976). The open boundary scheme is the Flow Relaxation Scheme (Engedahl, 1995) for temperature, salinity and the deviation from the depth averaged current and a combination of the Flather and Chapman schemes (Marchesiello et al., 2001) for sea surface elevation and depth mean current. River input is from climatology, modulated by the BCM precipitation over the area. In addition, a relaxation of sea surface salinity towards the BCM SSS has been used.

3. Results

3.1. *Temperature*

The coarsest temperature indicator is the averaged temperature over the North Sea. For averaging purposes the North Sea is delimited by thick black lines in Fig. 1. In the BCM scenario the averaged sea surface temperature (SST) increased from 8.7 °C for the 1972–1997 period to 9.7 °C for the 2072–2097 period. The mean increase is 1.0 °C and the maximum increase in the monthly averages is 1.5 °C in May. The downscaled fields show stronger surface warming. Here the mean SST increases from 10.5 to 12.2 °C, with a mean warming of 1.7 °C and a peak warming of 2.2 °C in June.

For the marine ecosystem the temperature in the water column may be more relevant than the sea surface temperature. For the same North Sea subdomain, the volume averaged temperature has been calculated. The BCM scenario gives an increase from 7.2 to 8.1 °C, a warming of 0.9 °C with strongest increase in monthly averages of 1.3 °C in April. The average seasonal cycle after downscaling is shown in Fig. 2 for the future scenario and the control run. The averaged temperature is increased from 8.7 to 10.1 °C, a warming of 1.4°C. The warming is significant in that

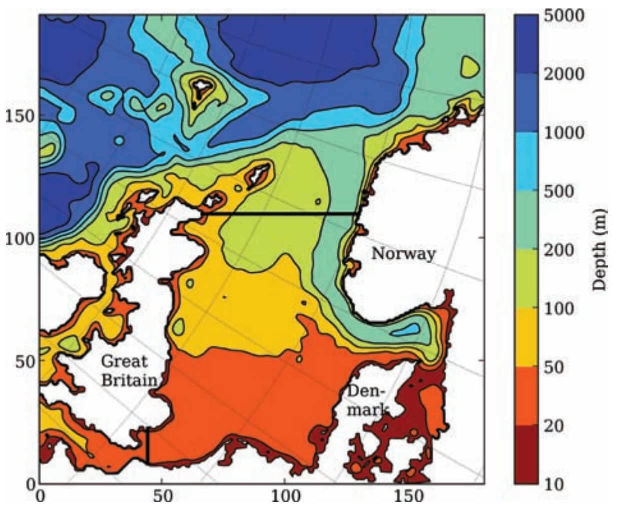

Fig. 1. Model domain with filled contours of bathymetry. Grid lines are given with 5° equidistance for longitude and 2° for latitude. The axis tick labels are grid coordinates. The thick black lines delimits a subdomain for the North Sea used for statistics presented in Section 3.

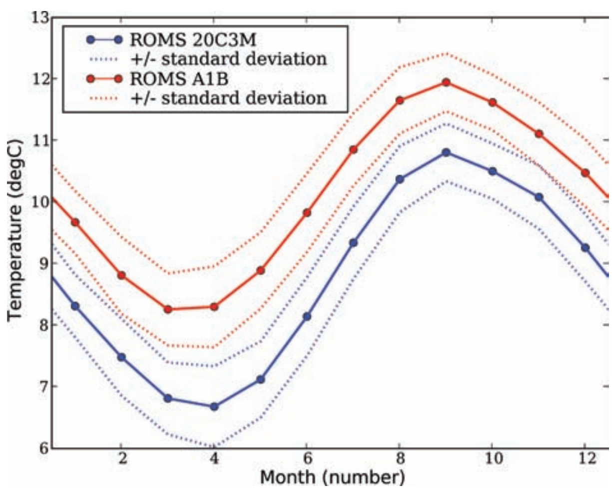

Fig. 2. Seasonal cycle of averaged temperature in the North Sea for the 20C3M and A1B run respectively. The averaging periods are 1972–1997 for 20C3M and 2072–2997 for A1B. The downscaled model results are averaged over the volume of the North Sea subdomain marked in Fig. 1. The dotted lines indicate plus/minus one standard deviation as computed from the monthly averages.

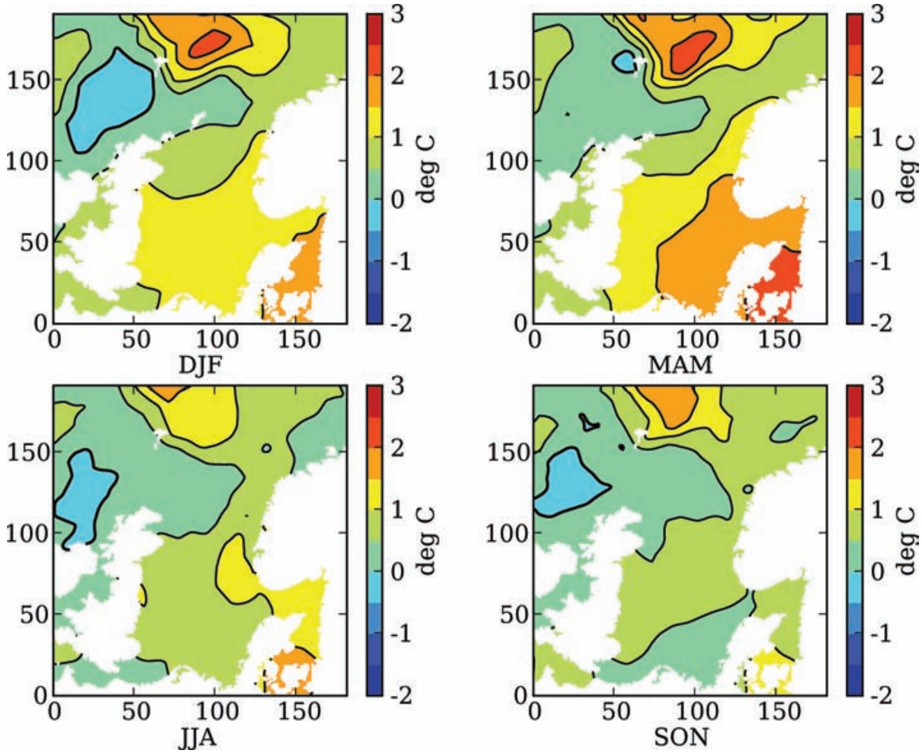

Fig. 3. Sea surface temperature difference between the BCM A1B and 20C3M simulations. The sea surface temperatures are seasonal means for the period 2072–2097 and 1972–1997, respectively. The seasons are three-monthly starting with December–January–February.

the one standard deviation intervals based on the 26 yr series of monthly averages do not overlap. The strongest warming occur in May with 1.8 °C and a minimum in November with 1.0 °C.

For regional details, seasonal maps of temperature changes will be examined. First, the sea surface temperature from the BCM runs are interpolated onto the regional grid. The change in SST is shown in Fig. 3. A common feature for all seasons is the low change in the Atlantic water south of the Faeroe–Shetland channel. The temperature change is less than 0.5 °C. The low warming continues into the Norwegian Sea with temperature changes less than 1 °C. During winter (DJF) the warming is between 1 and 1.5 °C in most of the North Sea, with stronger warming towards Kattegat in east. The strongest changes are found around the Faeroes with more than 2 °C warming on the north side and a large area with cooling on the south side. The same spatial pattern is found in the spring season with stronger warming. The summer and autumn patterns are similar to each other, with warming less than 1 °C in the North Sea. The warming north of the Faeroes is also weakened. The Atlantic cooling area is here closer to Ireland than the Faeroes.

The similar set of panels for the downscaled SST fields are shown in Fig. 4. As expected from the integrated numbers, the surface warming is stronger than in the BCM results. The panels also show some more regional details, in particular around the Faeroes. As with the BCM results, this area show weak warming and sometimes cooling to the south and strong warming on the north side. In winter and spring there are strong gradients in the warming patterns, caused by a shift of the position of the warm Atlantic Current. The large-scale geographical pattern in the North Sea is similar to BCM results and quite smooth. The warming is strongest towards Skagerrak and Kattegat. There is a change in timing, with strongest warming in spring and summer.

The FRS boundary scheme used in the downscaling should give identical results at the outermost grid cells in Figs. 3 and 4. This does not happen due to a misalignment in time. The effect of this is clearly visible in the autumn (SON) field. However, the problem is confined to the boundary areas and does not affect the North Sea subdomain.

Going deeper, to 50 m, gives only slight changes from the surface pattern in the BCM results. In the ROMS downscaling there is considerable change from the surface pattern, as shown by the 50 m temperature differences in Fig. 5. These patterns are rich in regional detail with strengthened gradients. In the central North Sea there is rather strong warming, with more than 2 °C most of the year. The pattern of cooling Atlantic water south of the Faeroes and warming in the north side is present. These features also seem to be advected with the two branches of the Atlantic Current into the Norwegian Sea. This gives a very strong gradient in the temperature differences where the two branches meet. The gradient is consistent with a westwards shift of the warm Atlantic current, with strong warming on the northwest side and cooling in southeast. In summer and autumn,

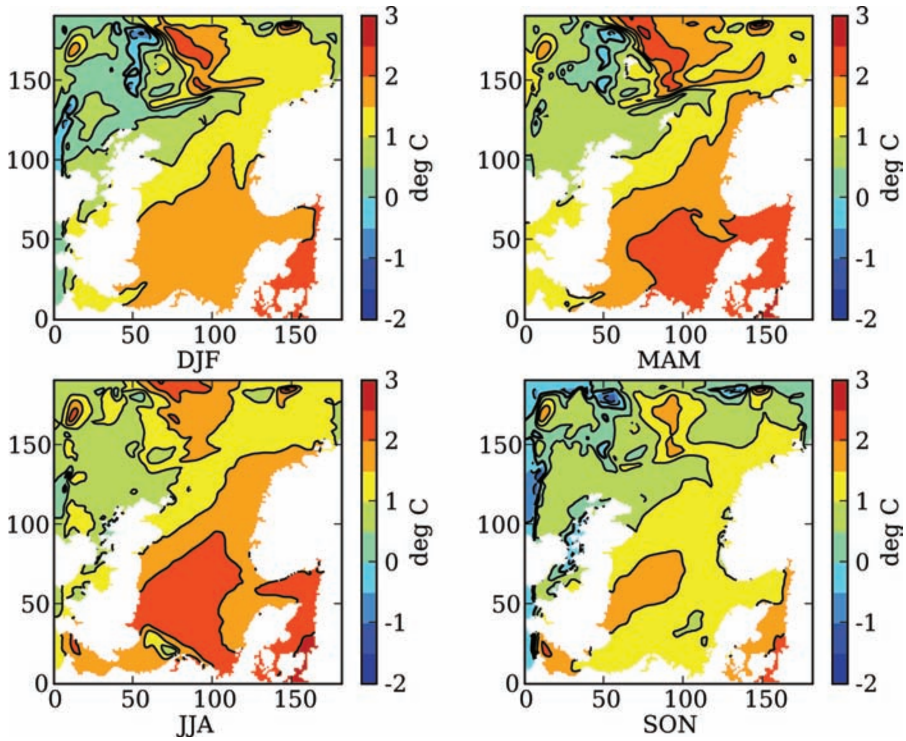

Fig. 4. Sea surface temperature difference between the downscaled A1B and 20C3M simulations. The sea surface temperatures are seasonal means for the period 2072–2097 and 1972–1997, respectively.

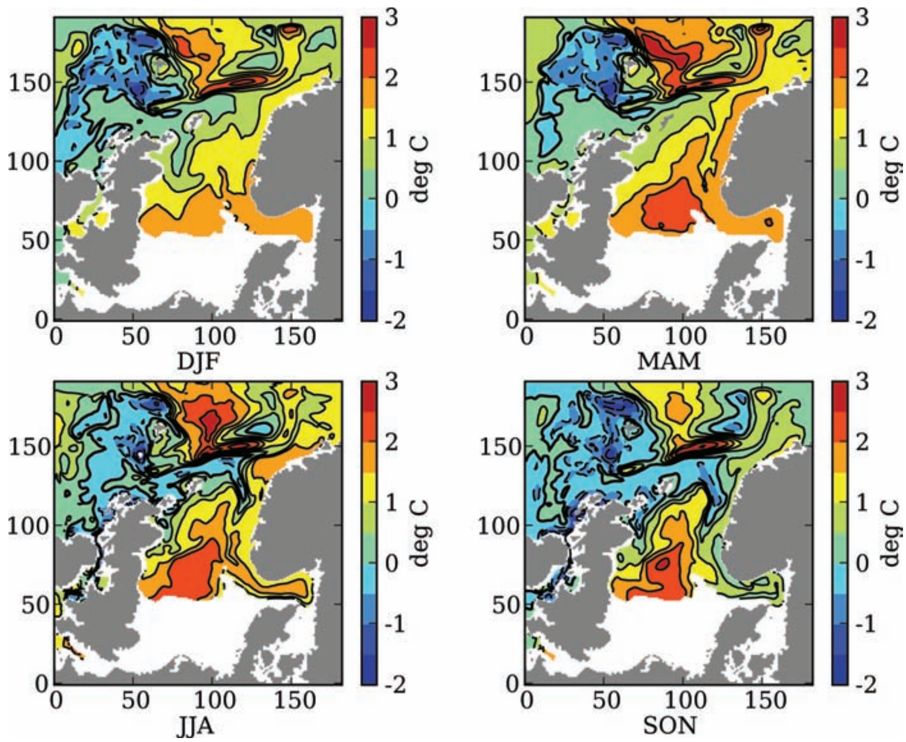

Fig. 5. Temperature difference at 50 m between the downscaled A1B and 20C3M simulations. The temperatures are seasonal means for the period 2072–2097 and 1972–1997, respectively.

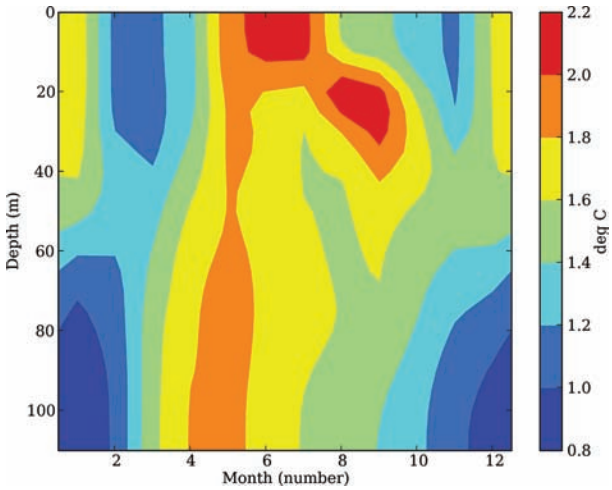

Fig. 6. Seasonal cycle of temperature difference between the downscaled ROMS A1B and 20C3M scenarios at grid cell (100, 100) in the central northern North Sea. Averaging periods are 2072–2097 and 1972–1997, respectively.

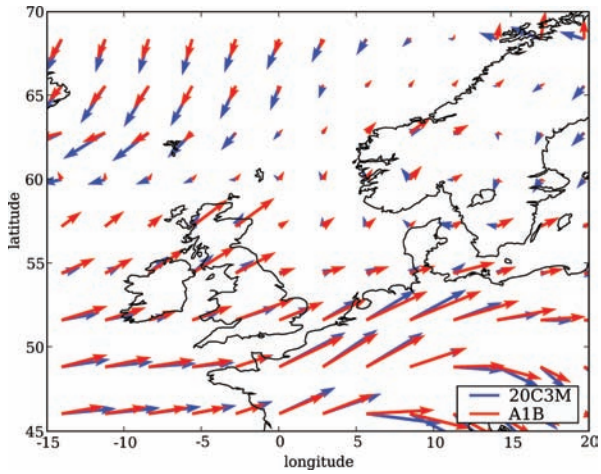

Fig. 7. Wind stress from BCM averaged over the period 1972–1997 from 20C3M (blue arrows) and 2072–2097 from A1B (red arrows).

the cooling region reaches the inflowing areas in the northern North Sea.

For a closer look of the vertical structure, Fig. 6 shows the seasonal development of the vertical temperature column at a location in the central northern North Sea. The whole water column is warmed from the 20C3M to the A1B period. The strongest warming is found with more than 2 °C in June–July near the surface and August–September at 20–30 m. This shows a deepening of the warm surface layer in the late summer. The deeper parts have strongest warming in April–May. The weakest warming is found near bottom during the winter season.

3.2. *Circulation*

The regional circulation depends strongly on the wind stress from the ARPEGE component of the BCM. The mean wind stress over the area is shown in Fig. 7. Both scenarios show strong westerly winds about 45–50°N. The mean wind stress over the North Sea is rather weak. In the north western corner there is a rather strong wind stress from north to northeast. The main difference between the scenarios is a decrease in the A1B scenario in the northerly wind stress in the area north and west of the Faeroes. The wind is strengthened over Great Britain and the southern North Sea while there is a change in direction over the rest of the North Sea.

The mean surface circulation from the regional ocean model is given in Fig. 8. The most notable feature in both scenarios is the Atlantic Current into the Norwegian Sea. The 20C3M run shows a strong jet trough the Faeroe–Shetland channel, while the future A1B run shows a strengthened Atlantic flow around the Faeroes and an increased Atlantic Current where the branches meet. In the North Sea both runs show a cyclonic circulation with signs of

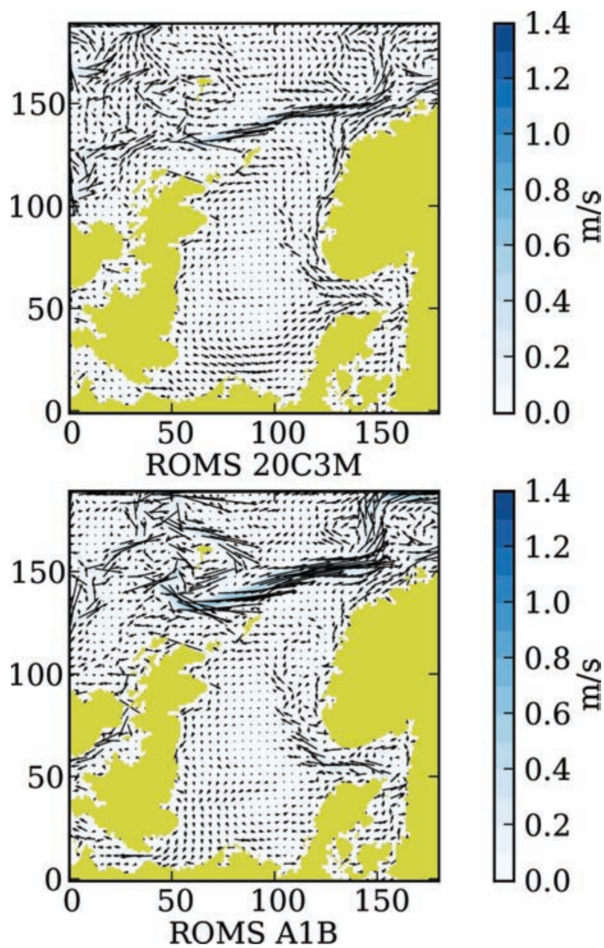

Fig. 8. The mean surface current from the downscaled simulations. Every fourth vector is plotted. Upper panel from 20C3M with average period 1972–1997. Lower panel from A1B averaged over 2072–2097. Filled contours of velocity in m s^{-1}.

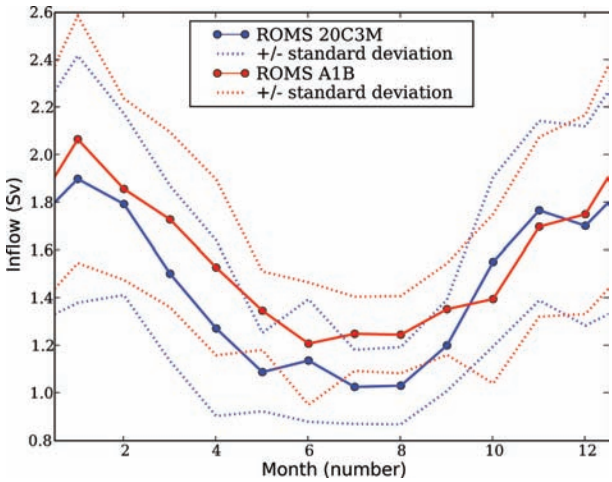

Fig. 9. Seasonal cycle of inflow to the North Sea from north over the upper boundary of the subdomain in Fig. 1. The cycle is based on monthly averages from the period 1972–1999 for the 20C3M and 2072–2097 for the A1B case. The dotted lines show plus/minus one standard deviation of the monthly means.

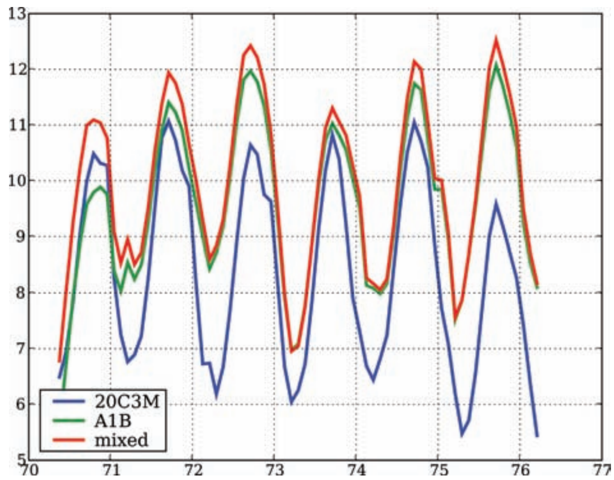

Fig. 10. Time series of volume integrated temperature for the North Sea subdomain. The blue curve is from the 20C3M downscaling, the green curve from the A1B downscaling, while the red curve is from the mixed downscaling with 20C3M ocean and A1B atmospheric forcing.

the Norwegian Coastal Current. In the A1B run the circulation in the southern North Sea has changed direction resulting in a weaker Jutland Current along the Danish west coast.

As mentioned in Section 1, the inflow to the North Sea is an important climate variable. The mean seasonal cycle of this inflow from north with standard deviation from the downscaled scenarios is given in Fig. 9. The mean inflow is increased from 1.4Sv to 1.5Sv (Sv = Sverdrup = 10^6 m^3 s^{-1}) from the control to the future scenario. The maximum increase is found in May with 0.3 Sv and the minimum is a decreased inflow of 0.2 Sv in October. The increase in inflow is less significant than in temperature, as indicated with the overlap of the standard deviation intervals.

3.3. Lateral boundary description

To examine the influence of the ocean lateral boundaries for the downscaled North Sea climate, a mixed downscaling were performed. Here the atmospheric forcing is taken from the future BCM A1B results for a 6-yr period starting May 2070. The initial state and the lateral ocean boundaries were taken from the 20C3M run, starting in May 1970. The time evolution of the volume averaged North Sea temperature for the first 6 yr from this run is presented in Fig. 10 together with the corresponding series from the 20C3M and A1B simulations. The mixed run starts out as the 20C3M run, but gets warmer in the summer. Already in the first winter it becomes quite similar to the A1B run. After the spin-up time, from 72 on the mixed run and the A1B are almost identical most of the year, with a tendency for the mixed run to be warmer in summer.

4. Summary and discussion

A future climate scenario has been downscaled for the North Sea marine climate. The scenario minus control gives, after downscaling, a volume mean warming of 1.4 °C and a surface warming of 1.7 °C. Without downscaling, the global coupled climate model gives a volume averaged warming of 0.9 °C and a surface warming of 1.0 °C.

The North Sea temperature is in general higher in the regional model. As explained in Ådlandsvik and Bentsen (2007) this is partly due to the increased and more realistic Atlantic inflow and partly due to differences in the heat exchange with the atmosphere caused by the different vertical coordinate systems in the ocean models. The regional ROMS results also show a strengthened warming. This is not due to the Atlantic inflow, as the inflow is not changing very much from the control run and the warming is strongest in the southeastern North Sea and not in the inflow areas. The increased warming is therefore most likely a consequence of different responses to the atmospheric forcing in the models.

The downscaling leads to stronger difference between the SST and the volume averaged temperature. The warming also follows this pattern with increased surface to volume warming ratio after downscaling. The regional model have a more realistic shelf sea stratification than the global model. More of the warming can therefore be trapped in the surface mixed layer, giving a higher surface warming than volume averaged. The isopycnal model tends to be mixed to the bottom in winter time over the whole shelf, reducing the difference between surface and volume averaged warming.

All geographical patterns show strong temperature changes in the waters around the Faeroes, with low warming or cooling on the south side and strong warming on the north side. This can be explained by the changed circulation, with stronger warm Atlantic inflow to the Norwegian Sea west of the Faeroe Islands and less Atlantic influence on the south and east side. The shift in the Atlantic inflow is caused by a major change in the wind stress pattern with decreased wind stress from north in the area.

The SST warming is larger in the downscaled model than in the BCM, but the large-scale patterns are similar. This is probably due to the same coarse atmosphere seen by the regional model and the global MICOM model in BCM. Going deeper, the regional model is less constrained by the scale of the forcing, and develops stronger gradients by its own dynamics.

The downscaling uses both oceanic and atmospheric forcing from the BCM. For the limited North Sea area the atmospheric forcing is most important. This is shown by the mixed sensitivity run presented in Fig. 10. After the spin-up period the results follow the A1B run with the same atmosphere and shows no connection with the 20C3M run. The influence of the lateral boundary conditions are mostly confined to the deeper regions outside the North Sea shelf. The mixed run gets warmer than the A1B run in the summers. This is due to differences in the pattern of the Atlantic inflow to the Norwegian Sea. The mixed run have more Atlantic water east of the Faeroes, giving slightly warmer inflow to North Sea.

There are two reasons for the weak influence of the open boundary description. The first is the semi-enclosed nature of the North Sea with essentially only one open boundary parallel to the shelf edge current. Secondly, the boundaries in the regional model domain has been choosen far enough away from the North Sea to allow the regional model to control the exchange with the deeper North Atlantic and Norwegian Sea (Ådlandsvik and Bentsen, 2007). The North Sea is a special case and the relative importance of atmospheric and lateral ocean forcing is likely to be different for other shelf seas.

It is difficult to judge if the stronger warming in the regional model represents an improvement over the BCM results on the integrated scale. The main area where the downscaling provides added value is by delivering a consistent higher resolution future scenario as input to effect studies by marine ecological models. The improved vertical stratification is important for phytoplankton modelling. The more detailed circulation and improved Atlantic inflow should be useful for all kinds of spatially resolved biological models.

The downscaling experiment could be refined in several ways. Going from approximately 80 km resolution in the global model to 8 km in the regional gives a factor of 10 in grid size reduction. This may be large and a two-step procedure with an intermediate ocean model might be used. However, for a semi-enclosed shelf sea like the North Sea the one-step downscaling procedure works. From the smoothness of the SST-patterns it seems likely that the coarse resolution in the atmosphere is a more important limiting factor. The marine downscaling would probably benefit by using downscaled atmospheric forcing.

This is only one downscaling of one IPCC scenario from one global atmosphere–ocean general circulation model. Therefore the results cannot be regarded as 'truth' and should be used carefully. A broader ensemble of regionalized scenarios is necessary to give more reliable assessment of the future ocean climate in the North Sea and the uncertainties involved.

5. Acknowledgments

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