Validation of three global ocean models in the Weddell Sea

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Abstract

We present a validation of three global z-level eddy permitting/resolving ocean general circulation models against hydrographic observations and remote sensing sea ice data from the Weddell Sea. The Weddell Sea is a region in which complex processes such as water mass formation, sea ice formation and melt, and circulation under ice shelves take place. The representation of these processes is challenging even for the current generation of eddy-permitting ocean models. Simulating the hydrographic structure of this basin is a stringent test for models, notably so when considering the global influence of the regional processes. The performance of OCCAM (at two resolutions), ORCA025 and TPAC are tested regarding water mass properties, sea ice seasonality (OCCAM and ORCA025 only) and volume transport. OCCAM simulates the deep water masses reasonably well in both resolutions. The eddy resolving run is not significantly better than the eddy permitting simulation. ORCA025 and TPAC represent the surface layers and the Weddell Gyre circulation...
better but are generally too warm throughout the water column. All models underestimate Weddell Sea Bottom Water formation. Both OCCAM and ORCA025 struggle to correctly model the sea ice cover: OCCAM overestimates the summer ice extent while little multi-year sea ice remains in ORCA025. TPAC exhibits considerable drift in potential temperature during the model run. The choice of a model for a study has to be made carefully taking into account the model’s performance in the specific area, application and variable of interest. We identify several starting points for improving the models, namely model numerics and parameterisations of subgridscale processes, ensuring more accurate forcing datasets, correct initialisation, and ice-ocean interactions, all of which are likely to have larger benefits than simply increasing the horizontal resolution beyond eddy permitting.

Key words: global ocean model, Weddell Sea, hydrography, sea ice, deep water masses, Southern Ocean

1 Introduction

Various complex processes such as deep and bottom water formation, sea ice formation and melt, circulation under ice shelves and mixing make the simulation of the Weddell Sea a challenge for ocean models. A correct representation of the Weddell Sea is, however, of importance for the simulation of the global oceans (e.g. Hellmer et al., 2005). The dense water masses exported from the Weddell Sea are important drivers of the thermohaline circulation and contribute significantly to the ventilation of the deep oceans (Hellmer and Beckmann, 2001; Jacobs, 2004). They are formed from saline Warm Deep Water (WDW), the Weddell Sea variation of Circumpolar Deep Water, and fresh and very cold shelf waters (Foster and Carmack, 1976; Foldvik et al., 1985; Weppernig et al., 1996). The shelf waters interact with the atmosphere in coastal polynyas, where heat loss to the atmosphere and brine rejection during sea ice formation lead to the formation of High Salinity Shelf Water (HSSW). A second

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form of shelf water modification occurs underneath ice shelves, where supercooling and melt of
the ice shelf base produces the extremely cold and rather fresh Ice Shelf Water (ISW). At the
continental slope, the shelf waters mix with WDW and form Weddell Sea Deep and Bottom
Water (WSDW and WSBW, respectively). The downslope flow of these cold and dense water
masses has been observed along the southern and western Weddell Sea (e.g. Fahrbach et al.,
2004). The sea ice cover in the Weddell Sea is highly seasonal. While the release of freshwater
during the ice melt in summer is important for the modification of Antarctic Surface Waters
(AASW) in the central and northern Weddell Sea, brine rejection during ice formation aids the
formation of dense water on the shelves (Gill, 1973). Ice formation rates are particularly high
in coastal polynyas in front of the ice shelves in the southern and southwestern Weddell Sea
(Renfrew et al., 2002).

Teleconnections between the Southern Ocean and the North Atlantic were previously re-
ported by Hellmer et al. (2005). They used the adjoint method to include high resolution model
results for the Weddell Sea in a global ocean circulation model. They found that improving the
simulation of processes in the Weddell Sea has a major impact on the export of WSDW and
the location and transport of the Antarctic Circumpolar Current (ACC). Colder and relatively
fresh water spreads into the South Atlantic and changes in the North Atlantic are reported.
This reinforces the importance of correctly simulating the Weddell Sea in global ocean and
climate models.

Stand-alone ocean general circulation models (OGCM) are valuable tools to investigate
smaller scales and improve parameterisations, numerics and the overall representation of oceanic
processes. Climate models also benefit from better, higher resolution ocean models (Roberts
et al., 2008). With better codes, parameterisations, topography and forcing datasets, and higher
resolution, OGCMs have greatly improved. However, detailed and correct representation espe-
cially of polar processes which are crucial on a global scale remains difficult. To improve the
simulation of water mass formation and modification in polar regions, sea ice models are cou-
ped to OGCMs. Sea ice models still struggle to realistically represent the ice cover, both in
the Arctic and the Southern Ocean and especially with respect to ice thickness (e.g. Timmer-
mann et al., 2004; Holland and Raphael, 2006; Martin and Gerdes, 2007; Renner and Lytle,
These areas are also important for the heat flux between atmosphere and ocean and the overturning circulation (Marsland et al., 2007) as the ocean loses heat to the atmosphere and shelf waters become cooler. Stössel et al. (1998, 2002) demonstrated effects of Antarctic sea ice on the simulation of a global OGCM. Amongst other aspects, they show how tuning of a parameter such as sea ice salinity changes Antarctic Bottom Water formation. In addition to modelling specific difficulties, validation of the models in polar regions suffers from the scarcity of observational data. Therefore, one of the aims of the World Ocean Circulation Experiment (WOCE) was to obtain a baseline dataset, including hydrographic sections across the Weddell Sea. The recent developments in modelling and observations make this an opportune time to revisit the performance of ocean models in polar regions and in particular in the Weddell Sea.

In this paper, we test the performance of three global ocean general circulation models in the Weddell Sea and suggest possible reasons for the different model behaviours. First, we present the models used in the comparison, followed by a description of the observational datasets. The Weddell Sea hydrography and the sea ice cover in the models are compared between models and with observations in the fourth section. The discussion brings together the similarities and differences of the models and we propose mechanisms leading to the model characteristics. At the end of the discussion, we present key points for improving OGCMs. The conclusion gives an overview of the benefits of each model and suggests the application where each model is most suitable.

2 The Models

For this study we use output of three global ocean models, one of them at two horizontal resolutions. All are z-level models with partial bottom cells, and two include sea ice. This section gives a brief overview of their characteristics, with the main details summarised in Table 1.

2.1 OCCAM

The Ocean Circulation and Climate Advanced Modelling (OCCAM) project model run by the National Oceanography Centre, Southampton, is a global ocean general circulation model
OGCM) of the Bryan-Cox-Semtner type (Bryan, 1969; Semtner, 1974; Cox, 1984) coupled with a dynamic-thermodynamic sea ice model (Aksenov, 2002). The sea ice dynamics are based on an elastic-viscous-plastic formalism. The thermodynamics use one vertical layer for snow and one or two layers for thin and thick ice, respectively. The ice albedo is set to 0.66. Details are given by Webb et al. (1998), Webb (2000) and Coward and de Cuevas (2005). The model exists in different resolutions, both in the horizontal and the vertical. We use the eddy-permitting 1/4°- and the eddy-resolving 1/12°-versions with 66 z-levels with partial step bottom layer (OCCAM 1/4 and OCCAM 1/12 respectively). This corresponds to a grid spacing of approximately 6 x 9.3 km at 50° S and 2.1 x 9.3 km at 77° S for OCCAM 1/12, 17.9 x 27.8 km at 50° S and 6.2 x 27.8 km at 77° S for OCCAM 1/4, and layer thicknesses of 5 m at the surface to 208 m for the deepest layer for both models. The model runs were forced using 6-hourly winds and heat fluxes from the NCEP/NCAR reanalysis data (Kalnay et al., 1996; Large et al., 1997), and monthly cloud fraction and solar radiation from the International Satellite Cloud Climatology Project. Monthly precipitation is based on Microwave Sounding Unit data and blended with Xie and Arkin (1997) observational data. The bathymetry is constructed from Smith and Sandwell (1997) and DBDB5 (DBDB5, 1983). Sill depths of important straits are checked and adjusted manually (Coward and de Cuevas, 2005). The runs for both resolutions were initialised using WOCE Hydrographic Program Special Analysis Centre (SAC) climatology (Gouretski and Janske, 1996) for potential temperature ($\theta$) and salinity ($S$) with additional data for the Arctic Ocean. Sea ice in the Southern Ocean was set to 1.50 m thickness of sea ice and 0.15 m snow in all cells south of 65.25°S with an ice concentration of 99% in each affected grid cell. Both OCCAM 1/12 and OCCAM 1/4 were run for 20 years corresponding to January 1985 to December 2004 (runs 401 and 103, respectively).

2.2 ORCA025

ORCA025 is a global configuration of the ocean model OPA (Océan PARallélisé; Madec (2006)) coupled with the Louvain la Neuve sea ice model LIM2 (Fichefet and Morales Maqueda, 1997). LIM2 is a dynamic-thermodynamic sea ice model with three layers (one for snow and two for ice) and a viscous-plastic rheology. Ice albedo is parameterised following Shine and
Henderson-Sellers (1985) with modifications (Greenfell and Perovich, 1984). The model run used for this study (run G70) was performed at the Laboratoire des Ecoulements Géophysiques et Industriels (LEGI) in Grenoble. For ORCA025, the global, tripolar Mercator grid has a nominal horizontal resolution of $1/4^\circ$ at the equator. In our study region, the grid spacing therefore varies from $17.9 \times 17.9$ km at $50^\circ$S to $6.2 \times 6.2$ km at $77^\circ$S. The 46 vertical levels have a thickness of 6 m at the surface increasing to 250 m for the lowest level. The model uses partial bottom cells. The setup follows Barnier et al. (2006) except for the vertical mixing where a modified version of the turbulent kinetic energy (TKE) parameterisation for the vertical mixing coefficient was used that includes the effects of long waves, Langmuir cells and the penetration of TKE in depth (Molines et al., 2006, updated 2007).

Run G70 was forced by the Drakkar Forcing Set No. 3 (DFS3; Molines et al. (2006, updated 2007); Brodeau et al. (submitted)). DFS3 is compiled from various sources. Long- and shortwave radiation fields are from CORE (Coordinated Ocean-Ice Reference Experiments) forcing (Large and Yeager, 2004). Precipitation south of $30^\circ$N is from the GXGXS (uncorrected CORE) dataset and CORE north of $30^\circ$N. Air temperature, wind and air humidity are 6-hourly ERA40-reanalysis fields (1958-2001) and ECMWF(2002-2004). River runoff is implemented from Dai and Trenberth (2002) using a new dataset including coastal runoff. For a comparison of G70 with runs using the standard CORE forcing see Barnier et al. (2007). The model bathymetry is regridded from ETOPO2 merged with the Bedrock Mapping Project data (Lythe and Vaughan, 2001) south of $72^\circ$S and GEBCO on the continental shelves (i.e. in depths shallower than 200 m). Additional smoothing and manual editing in key regions has been performed (Molines et al., 2006, updated 2007). $\theta$ and $S$ were initialised from Levitus et al. (1998) in mid to low latitudes and the Polar Science Center Hydrographic Climatology (PHC) v2.1 (Steele et al., 2001) in high latitudes. The initial sea ice state was taken from a previous run after 10 years of spin up (Molines et al., 2006, updated 2007). The model is run for 47 years corresponding to the years 1958 to 2004.
2.3 TPAC

The OGCM of the Tasmanian Partnership for Advanced Computing (TPAC) is based on the Geophysical Fluid Dynamics Laboratory’s (GFDL) Modular Ocean Model (MOM), version 3.1. It is a primitive equation, ocean only model extending from 80° N to 80° S. Horizontal resolution is 1/8° × 1/8° corresponding to 8.9 x 13.9 km at 50° S and 3.1 x 13.9 km at 77° S. In the vertical, the model has 24 z-levels with minimum layer thickness of 22 m at the surface and 489 m at the bottom, with partial bottom cells. Unusual for an eddy-resolving model (and different from OCCAM 1/12), TPAC includes isopycnal mixing by using the Gent and McWilliams (1990) parameterisation. Sea ice is not considered. More details are given by Meijers et al. (2007).

For the run we use in this study, the model is forced by applying hemispheric wintertime boundary conditions to which NCEP-R2 variability and trends (Kanamitsu et al., 2002) were added. Sea surface temperature is constrained to the NOAA Optimum Interpolation Sea Surface Temperature V2 (Reynolds et al., 2002). Surface salinity is adjusted by a salt flux calculated using the NCEP-R2 latent heat flux and precipitation rate. The time scale for both sea surface temperature and salinity restoring is 30 days. The model is initialised from the WOCE Hydrographic Programme SAC atlas (Gouretski and Jancke, 1998) and Levitus (1982) data in the Arctic. The model bathymetry is based on the TerrainBase dataset (Row et al., 1995). Integration time is 20 years, corresponding to 1982-2001, using asynchronous time stepping.

3 The observational datasets and extracted model output

3.1 Hydrographic sections

θ and S data were selected from hydrographic transects made in the Weddell Sea between Joinville Island and Kapp Norvegia onboard RS Polarstern between 1989 and 1998 (Table 2; Fig. 1, Fahrbach et al. (2007)). They were designated section SR04 of the WOCE Repeat Sections Program. Fahrbach et al. (2004) present details of the measurements and instruments as well as a description of the data. Using monthly mean fields, which correspond in time with the
months the CTD data were collected, model $\theta$ and $S$ were bilinearly interpolated from the four nearest grid points onto the location of the CTD casts. As each model has a different vertical resolution, we then linearly interpolated the model data to fit the CTD depth grid (converted to depth from a 2 dbar pressure grid), thereby ensuring consistency between the models when calculating model to CTD differences and statistics.

Following Fahrbach et al. (2004) we calculate the area occupied on the sections by WDW, WSDW and WSBW, as well as the average $\theta$, $S$ and depth for each water mass. We use the same criteria as Fahrbach et al. (2004): WDW is the water below the mixed layer with $\theta > 0^\circ$ C, WSDW lies below that and has $-0.7^\circ C < \theta \leq 0^\circ$ C, and WSBW is at the bottom of the water column with $\theta \leq -0.7^\circ$ C.

In addition to the sections across the Weddell Sea Fahrbach et al. (2004) use for their analysis, we include the section SR04e (April 1998) to maximise the available validation data. Since the section does not extend all the way onto the shelf in the eastern Weddell Sea, the derived water mass properties (average $\theta$, $S$, depth and occupied area) are biased and cannot be compared directly with the results from the previous sections. For example, $\theta$ and $S$ will be lower than in the other sections as water is transformed while flowing on and along the continental shelf and slope by interaction with ice shelves and sea ice formation.

Observations in regions such as the Weddell Sea are often compromised by circumstances encountered during the cruise and by time limitations. Station spacing therefore varies between the different occupations of the SR04 section. When directly comparing a CTD section to the model section at the respective time, we extract and interpolate the model data onto exactly the set of CTD station positions of each of the five sections. For the timeseries of water mass properties we show the range of values for the four sets of stations excluding the station set of section SR04e. Representative of the five occupations of the SR04 transect, we present the full depth section and the $\theta - S$ diagram of the spring section SR04b in Figs. 2 and 3.

3.2 Sea ice data

Sea ice has been observed from satellites using passive microwave radiometry since the 1970s (e.g. Parkinson, 2004). For this study, we use monthly sea ice concentrations derived
using the Bootstrap algorithm from brightness temperatures measured by Special Sensor Mi-
crowave/Imagers (SSM/I) (Comiso, 1990, updated 2007), available from the National Snow
and Ice Data Center. We restrict the region considered for extent and area calculations to the
Weddell Sea, namely from the east coast of the Antarctic Peninsula and east of 58.5° W to
10° W (Fig. 1a)). Ice extent is defined as the area of all grid boxes covered by ice whereas ice
area is the area of the grid boxes covered by ice multiplied by the respective ice concentration.
As satellites struggle with recognising very low concentrations, we use a threshold value of 15%,
below which concentrations are not considered for calculations of ice extent and area.

4 Results

4.1 OCCAM 1/12

OCCAM 1/12 captures the general features of the Weddell Sea hydrography (Figs. 2 and 3):
The AASW lies above WDW below which \( \theta \) decreases again with depth through WSDW and
WSBW. There are, however, several deviations from the observations. In general, the depth of
the pycnocline and thereby the mixed layer is too deep and too cold in summer. In the CTD
sections, the surface mixed layer (ML; defined as the layer from the surface to the depth where
the gradient in potential density is greater than 0.02 kg m\(^{-3}\) per 10 db) extends down to 50 to
100 m in the central Weddell Sea (Fahrbach et al., 1992). In OCCAM 1/12, the average ML
depth in the deep Weddell Sea (i.e. bathymetry deeper than 4000 m) ranges from approximately
140 m at the start of the run to around 230 m after 15 model years and extends to 300 m in
the western part of the Weddell Sea.

Beneath the mixed layer on the eastern side of the section, the modelled \( \theta \) is colder then
the observations to a depth of 2500 m (Fig. 2). This signal can be attributed to the opening
of a polynya in the Maud Rise region shortly after the beginning of the model run. Following
the opening of the polynya in the OCCAM 1/12 sea ice cover in July 1985, a patch of water
characterised by a low WDW \( \theta_{\text{max}} \) appears in the eastern Weddell Sea in August 1985. The
polynya persists until early summer when the sea ice retreats. It recurs in 1986 and the WDW
\( \theta_{\text{max}} \) decreases further. In the following model years, the cold water signal slowly moves around
the Weddell Gyre.

Averaged over the entire WDW layer along the section, $\theta$ is higher than observed (Fig. 4). As the mixed layer is too thick, the area occupied by WDW is smaller than observed. Above the continental slope, both in the western and the eastern Weddell Sea, the downward slope of the thermocline is less pronounced than in the observations leading to a core of water up to $1^\circ$C warmer situated above the 1000–3000 m isobaths. The cold water plume of newly formed WSBW on the western continental slope which is visible in the CTD sections (Fahrbach et al., 2001) is not resolved in the model (Fig. 2).

The area covered by WDW is underestimated in OCCAM 1/12 in all sections. After a decrease in WDW area percentage during the first five years of the model run, the amount of WDW increases again after 1990 but does not reach the initial level (Fig. 4). Average $\theta$ and $S$ increase slightly during the run. The increase of the average depth is more pronounced. Contrary to WDW, the area percentage of WSDW increases in 1985-1990 and decreases after that (Fig. 5). WSDW is overestimated at the cost of WDW. The area percentage of WSDW remains greater than observed. Average $\theta$ and depth are fairly constant but $S$ increases over the model run. The area occupied by WSBW in OCCAM 1/12 is very close to observations, as is the average depth. $\theta$ is on average about 0.03$^\circ$ C warmer in the model, excluding the last section SR04e (April 1998). For this section, the CTD data show much lower average $\theta$ and $S$ as the warmer and saltier eastern Weddell Sea is not included completely. Bottom water production in the southern and western Weddell Sea leads to an asymmetric distribution of WSBW with more WSBW in the western part. Although this pattern is present in OCCAM 1/12 as well, it is rather weak, which indicates underestimated bottom water formation. The total amount of WSBW along the section line fits the observations well though. It decreases during the model run (Fig. 6). As for WDW and WSDW, the average WSBW $S$ increases. WSBW also becomes warmer and deeper.

The seasonal cycle is most visible in the sea ice cover (Figs. 7 and 8). In OCCAM 1/12, the climatological minimum ice extent occurs in February, agreeing with observations, and the maximum is in August, a month earlier than observed in the SSM/I climatology. Although the annual cycle in the model agrees well temporally with the observations, the extent of the ice
cover is far overestimated by OCCAM 1/12 (Fig. 7 a). The ice extent at its minimum reaches $2.2 \times 10^{12}$ m$^2$, almost 70% more than observed. Instead of a small area of high concentration of sea ice in the southwestern Weddell Sea and near the Antarctic Peninsula, the ice spreads over the entire Weddell Sea (Fig. 8). However, the summer ice cover is different in OCCAM 1/12 before and after 1994. In the first part of the run the ice extent reaches a summer minimum of $5.5 \times 10^{10}$ m$^2$ in 1990 (Fig. 7 b). After 1994, the seasonal variations are small and ice concentration and extent remain high even in summer. During winter, ice concentrations are at 99%, the maximum value allowed in the model, over most of the Weddell Sea. Only at the ice edge, which is too far north, and close to the coast at the tip of the Antarctic Peninsula and the South Shetland Islands, is the ice less dense (Fig. 8). Concentrations remain too high near the coast in the central Weddell Sea and prevent the formation of coastal polynyas such as that observed in front of the Ronne-Filchner ice shelf (e.g. Renfrew et al., 2002).

4.2 OCCAM 1/4

The representation of the central Weddell Sea in OCCAM 1/4 resembles that of OCCAM 1/12. The main water masses are present with similar properties to those of OCCAM 1/12 (Figs. 2–6) and their properties fit the observations well. As in OCCAM 1/12, the mixed layer is too deep (Fig. 2) and gets deeper during the model run. During the first nine years of the model run (1985-1993), OCCAM 1/4 is more saline in the mixed layer than OCCAM 1/12. Also, while in OCCAM 1/12 the upper two layers experience a warming over the entire section in summer during that period, OCCAM 1/4 does not show this behaviour. After 1994 the surface layers warm significantly only twice (in summer 1999/2000 and 2001/2002), and on these occasions the warming is visible in both resolutions but only over the continental shelf and slope. In OCCAM 1/4, the surface layer is at or close to the freezing point at the times of all sections.

The amounts of WDW (WSDW) in OCCAM 1/4 show only a small increase (decrease) from 30 to 35% (58 to 57%) during the model run. Only WSBW significantly decreases: the occupied area drops from 11% to below 7%, a reduction by more than a third of the initial amount. The WSDW is slightly deeper in the lower resolution version, occupies less area along
the section than in OCCAM 1/12 and is warmer. WSBW is also deeper in OCCAM 1/4, but
\( \theta, S \) and the amount of WSBW are similar to OCCAM 1/12.

The different behaviour of the two runs in the surface layer coincides with differences in
the ice cover. The seasonal cycle in the sea ice of OCCAM 1/4, although present, is far less
pronounced than in the satellite observations (Fig. 7a). The climatological minimum ice extent
in February is \( 3.2 \times 10^{12} \text{ m}^2 \), a reduction of less than 30\% of the August maximum. The
observations show a far larger seasonal cycle where in summer the ice cover is reduced by about
70\% of the winter extent. As with the higher resolution version, OCCAM 1/4 produces dense
pack ice with maximum ice concentrations in winter (Fig. 8). In contrast to OCCAM 1/12, the
sea ice concentration remains high even in summer. As in the surface water properties, the two
versions of OCCAM become more similar in the sea ice evolution after 1994 (Figs. 7a and 7b).
The seasonal sea ice cycle in OCCAM 1/4 is consistent throughout the model run; the abrupt
change observed in OCCAM 1/12 does not appear. The polynya in the OCCAM 1/12 ice cover
in 1985 and 1986 does not appear in OCCAM 1/4 and the propagation of colder water around
the Weddell Sea as observed in OCCAM 1/12 is not visible in OCCAM 1/4.

4.3 ORCA025

ORCA025, the other 1/4\(^{\circ}\)-model in our comparison, is generally too warm and, except in
the uppermost layer and above the shelves, slightly too saline (Figs. 2 and 3). In summer, the
surface layer is up to 2.8\(^{\circ}\)C warmer than measured. At the shelf break, both temperature and
salinity are lower than in the CTD data. The modelled descent of the isolines starts further
away from the shelf over a deeper part of the continental slope and is less steep in the model.
Towards the end of summer (sections S04a and SR04e, not shown), the surface layer becomes
too saline. Overall, the salinity gradient from the surface to the salinity maximum in the WDW
is less steep than observed. The mixed layer depth is stable throughout the run at around 100
m. However, the average depths of the deeper water masses increase (Figs. 4-6). In ORCA025,
the average temperatures of WDW are 0.3\(^{\circ}\) C too high. WDW warms substantially during the
first ten model years. The warming is slower during the rest of the run (Fig. 4). In ORCA025,
WDW occupies a larger area along the sections (on average 43.9\% in the sections) than in the
CTD measurements (28.6%) and the average depth is 285 m deeper. Consequently, WSDW and
WSBW are deeper as well (Fig. 5,6). The WSDW salinity is overestimated by 0.005 (Fig. 5).
Average θ for WSDW matches the observations quite well, but the coldest deep water in the
model only just qualifies for WSBW and reaches a minimum of −0.719° C in the austral spring
section of 1989 (SR02). As in the OCCAM runs, the plume of newly formed WSBW along the
western continental shelf is not visible.

The Weddell Sea in ORCA025 becomes warmer during the model run. As the temperature
increases, the area occupied by WDW becomes larger and spreads deeper while the average
depth of WSDW and WSBW increases and the area occupied by WSBW decreases (Fig. 4-6).
At the same time, salinity increases too. Eventually, the entire water column is so warm that
from 1994 onwards no water fulfills Fahrbach et al. (2004)'s criterion for WSBW. The average
area, temperature and salinity of WSDW vary only a little.

The sea ice in ORCA025 is very different from the simulations by OCCAM (Fig. 8,7).
The timing of minimum and maximum ice coverage and the annual mean ice extent agree
with SSM/I data (Fig. 7). In winter, the ice concentrations are closer to the observations than
in both OCCAM versions (Fig. 8). However, although ORCA025 manages to simulate lower
concentrations close to the coast, they are still too high. The climatological maximum extent
is slightly overestimated but still below the values for OCCAM 1/12 and OCCAM 1/4. In
summer, almost all sea ice disappears and the ice extent decreases to $6.8 \times 10^{10}$ m$^2$, an order
of magnitude less than observed. Only a very small amount of low concentration multi-year ice
remains in the southern Weddell Sea.

4.4 TPAC

TPAC is, like ORCA025, too warm (Figs. 2 and 3). At the surface, θ drops to below −1.4°
C during September to December while during the rest of the year and particularly in late
summer and early autumn θ reaches values of more than −0.4° C. In the CTD data, θ remains
close to the freezing point at −1.8° C in the upper 10 m in all sections except for the summer
section SR04d where θ reaches 0.5° C near the Antarctic Peninsula (not shown). In the model,
cold and fresh Antarctic Surface Water occupies only the uppermost model layer and the mixed
layer is far too shallow at just over 30 m, which corresponds to the upper two model layers. The surface layer and the waters below down to 150 m are too saline in all sections. Only over the continental slope both in the eastern and western Weddell Sea is the model colder and fresher than observed, indicating that the downward sloping of the isopycnals is too far away from the coast. The plume of cold fresh water flowing down the western continental slope is not reproduced.

TPAC is the only model in our comparison that is overall too saline in all of the sections. While the maximum salinity ($S_{\text{max}}$) in the CTD section is between 34.693 and 34.706 in the WDW, even the average salinity in the WDW exceeds these values reaching 34.714 to 34.738 and $S_{\text{max}}$ is 34.793 in section SR04b (Figs. 3 and 4). The WDW is on average more than 0.2°C warmer than observed. As the entire water column is too warm in TPAC, the area occupied by WDW is also overestimated. The water warms further during the model run and the WDW area percentage increases while WSDW decreases. WDW gets warmer and saltier but remains slightly colder than in ORCA025. As the area occupied by WDW increases, so does the average depth. The WSDW area decreases during the run (Fig. 5). The salinity of the deep water corresponds to the observations, but $\theta$ is too high from the beginning of the run. The coldest bottom water in TPAC is far too warm at $-0.45^\circ$ C (Fig. 3). Using Fahrbach et al. (2004)’s criteria, TPAC does not simulate any WSBW at all (Fig. 6). As even in the first month of the model run (January 1982) no WSBW is present, this suggests that the initialisation dataset is too warm. TPAC shows a clear drift in both $\theta$ and $S$. The increase during the run is similar to ORCA025 but occurs over a far shorter period of time (20 years cf. 47 years).

4.5 Error statistics

In order to quantify the model performance in reproducing the observed hydrography and sea ice cover in the Weddell Sea, we calculated the basic statistical properties of observed and modelled variability, correlation, and root mean square error (RMSE) for observed and modelled $\theta$ and $S$ along the sections, and sea ice extent and area in the Weddell Sea (Table 3). The equations for the statistical variables are given in Table 3.

Figure 9 combines the various measures in a single diagram (Taylor, 2001). We use the CTD
measurements and the remote sensing sea ice observations as the reference datasets, marked
by the point labelled “reference” at standard deviation ($\sigma$) = 1 and correlation coefficient (R) = 1. To include $\theta$ and $S$ from all sections and the sea ice data, we use the normalised standard
deviation $\sigma_{\text{norm}}$, that is $\sigma_{\text{norm}} = \sigma_{\text{data}}/\sigma_{\text{obs}}$ for both model and observational data. The better
the correlation of the modelled data to the observations, the closer the corresponding model
marker will be to the x-axis. Similarly, the better the standard deviation (i.e. the variability)
fits the observed value, the closer the marker will be to the dashed black line marking the unit
circle. The red dotted semi circles mark how good the fit is taking into account equally both
correlation and agreement of variability. This “goodness of fit” corresponds to a centred pattern
root mean square error (RMSE), where a general bias in the model data is not considered.

The models are rather spread out on the diagram, i.e. they simulate some sections well
and some badly (Fig. 9). Generally, the models simulate $\theta$ along the sections better than $S$.
In OCCAM 1/12, the spatial variability of $\theta$ along the sections is close to the observations
and $\sigma_{\text{norm}}$ is close to 1. However, the patterns observed are not represented very well and R
is below 0.8 for all sections except S04a. The spatial distribution of $S$ correlates better to the
observations but $\sigma_{\text{norm}}$ is higher and the RMSE larger. The seasonal cycle of the sea ice extent
is more poorly simulated than in OCCAM 1/4 and ORCA025 due to the offset of the annual
cycle.

OCCAM 1/4 matches the patterns and the distribution of the observed $\theta$ better than the
high resolution OCCAM 1/12. The RMSE of $S$ varies between the sections from as low as 0.036
to a maximum of 0.61 (centred RMSE = 0.60). The temporal development of the sea ice extent
is closer to observations than in OCCAM 1/12, but the persistent summer ice cover and the
strong underestimation of the seasonality lead to very low $\sigma_{\text{norm}}$ (0.45).

Both for $\theta$ and $S$, the correlation is better in ORCA025 than in the other models: R varies
between 0.80 and 0.95. $\sigma_{\text{norm}}$ is larger though which suggests an overestimation of the spatial
variability in both variables. The centred pattern RMSE for $\theta$ is much lower than the standard
RMSE (difference of more then 0.1 in all sections) which confirms that ORCA025 is biased
towards high $\theta$. The correlation of the sea ice extent in the model to the observations is very
high at R=0.98, but $\sigma_{\text{norm}}$ is well above 1 as well which is caused by the strong seasonality and
the underestimation of the summer sea ice in ORCA025.

TPAC shows the lowest correlations for $\theta$ and $S$ of all the models. It also has the highest standard RMSE for both variables. As in ORCA025, the centred RMSE for $\theta$ is much lower than the standard RMSE, a sign of the warm bias of the model.

5 Discussion

Although all three models are global primitive equation z-level models, they behave very differently. There are no systematic biases common to all the models in the region. Two resolutions of the same model (OCCAM) also produce different results. Nevertheless, OCCAM 1/4 and OCCAM 1/12 have common issues. Both model versions display a too deep and too cold mixed layer (Fig. 2). This is linked to an extensive sea ice cover (Fig. 8). Very high ice concentrations prevent heat uptake through solar radiation during the summer months, thus preventing a warming of the ocean surface. In winter though, the lack of open water reduces heat loss from the ocean to the atmosphere. In both OCCAM 1/12 and OCCAM 1/4, the first effect seems to be stronger and helps to produce a very cold, deep mixed layer. The high ice concentrations also reduce ice production. In the real oceans, ice formation in particular in coastal polynyas (that do not appear in OCCAM at all) is an important factor as the process is closely linked to salinification, HSSW formation (Renfrew et al., 2002; Foldvik et al., 2004) and hence WSBW formation. The formation of coastal polynyas in OCCAM is compromised by the weak wind forcing applied to both resolutions, and the missing offshore winds (Fig. 10).

A cold anomaly in the WDW $\theta_{max}$ moving cyclonically around the Weddell Sea appears only in OCCAM 1/12 and is not seen in the observations. The cold water is produced in a large polynya in the Maud Rise region which is present in the model in the austral winter in 1985 and 1986, when the sea ice cover has diverged from the initial state. Travel times for anomalies associated with the Antarctic Coastal Current around the entire perimeter of the Weddell Sea are in the range of a few years (Beckmann et al., 1999; Schodlok et al., 2001). The cold water signal which appears on the inner Weddell Sea side of the Antarctic Coastal Current travels much slower in OCCAM 1/12. It takes two years for it to move from the Greenwich Meridian to the hydrographic section at Kapp Norvegia. By the time corresponding to the last section
(SR04e, April 1998), the cold anomaly in OCCAM 1/12 has reached the western end of the section at the Antarctic Peninsula. An indication of the weak Antarctic Coastal Current and the slow circulation of the Weddell Gyre in both OCCAM versions is the small difference of sea surface height (SSH) between the Antarctic Peninsula and the minimum SSH in the middle of the gyre. Fig. 11 (upper panel) shows that OCCAM 1/12 and OCCAM 1/4 have a much weaker gyre than ORCA025 and TPAC. This is due to the weak wind forcing in OCCAM compared with the much stronger winds in ORCA025 (Fig. 10). The OCCAM wind stress is higher than ORCA025’s in the central Weddell Sea while ORCA025 winds are much stronger north of 65°S and along the Antarctic coast. The weak Weddell Gyre in OCCAM may contribute to the extensive sea ice cover: the slow currents lead to long residence times of water in cold regions and prevent faster heat transport into the Weddell Sea by inflow of warmer ACC water. Although still weak, the Antarctic Coastal Current is faster in OCCAM 1/12 than in OCCAM 1/4 even though the forcing is the same. The difference between the two resolutions could be explained by the Gent and McWilliams (1990) parameterisation (GM90) used in OCCAM 1/4. GM90 is used to remove baroclinic instabilities for numerical stability and, although the Antarctic Coastal Current is mostly stable, GM90 reduces the horizontal density gradients across the current and weakens the Coastal Current (Beckmann, pers. comm.). Also, the very dense and mostly land-fast sea ice pack in OCCAM 1/4 with concentrations of > 95% reduces momentum transfer from the wind to the upper ocean. The lower sea ice concentrations in the higher resolution version allow for stronger wind forced currents.

OCCAM 1/12 also does not seem to have reached equilibrium in the Weddell Sea. While the ACC transport through Drake Passage seems to be stable soon after the start of the model run (Fig. 11b), the mixed layer depth in the central Weddell Sea continues to increase as does the depth of $\theta_{\text{max}}$ in the WDW. This indicates problems with the surface fluxes. OCCAM 1/4 on the other hand does appear to have reached equilibrium.

In ORCA025, the absence of multi-year ice facilitates too strong warming of the mixed layer, the exact opposite to OCCAM. The warming is enhanced by a low baroclinic ACC transport (Fig. 11b). In the form of a feedback loop, the strength of the baroclinic ACC transport is linked to the bottom water formation in the Weddell Sea: a weak ACC relates...
to a weak meridional surface buoyancy gradient. This means that warmer surface water can penetrate further south and thereby lateral heat transport into the Weddell Sea is enhanced which reduces bottom water formation. This in turn reduces the stratification which weakens the thermohaline forcing component of the ACC (Olbers and Wübben, 1991; Cai and Baines, 1996). The initialisation of the model is a major reason for the missing summer sea ice: the final state of a ten year spin up run has been used which had almost no sea ice left in the Weddell Sea (J.-M. Molines, pers. comm.). The ice cover did not recover during the model run. One likely explanation for this is the high sea surface temperature observed throughout the Weddell Sea during the first month of the model run. In January 1958, the first month of the model run, the surface temperature is only at the freezing point beneath existing sea ice; elsewhere in the Weddell Sea it is up to 2°C. The almost complete loss of the highly reflective ice cover during summer allows for large heat uptake by the ocean through solar radiation and therefore strong warming. In winter, strong winds in the ECMWF forcing (Fig. 10) can quickly advect any sea ice out of the Weddell Sea and thereby promote a faster decrease to the very low summer concentrations. This export of freshwater would also explain the increase in salinity over the ORCA025 model run.

In our comparison, TPAC is the only ocean model that is not coupled to a sea ice model. Combined with the loose constraining of sea surface temperature and salinity to hemispheric wintertime conditions, this can explain the high salinities. Excluding sea ice means that the influence of sea ice formation, melt and drift on the freshwater budget is missing. The constraint to wintertime conditions probably leads to overestimation of the surface salinities because the input of freshwater due to sea ice melt in summer is ignored. The missing sea ice cycle also affects the modification of shelf waters, so that dense water formation is heavily restricted and bottom water missing. The baroclinic ACC transport decreases during the model run. This allows increasing entrainment of warm water into the Weddell Sea, leading to the increasing water temperatures, the increase of WDW and the decrease of WSDW. TPAC shows a large drift which demonstrates the need for suitable forcing (possibly with stronger relaxation of sea surface temperature and salinity to climatology) or coupling to a sea ice model.

Model validations using observations always struggle with the snapshot-like nature of most
observational data. Often, model results are compared with either observations from a single point in time or a very short period (e.g. a hydrographic section), or long-term climatologies. While the first approach neglects the fact that variability in the real world and in the model do not necessarily coincide, the latter neglects the spread caused by exactly that variability. Using repeat sections provides information on the temporal variability. Sampling the models at the different sets of stations demonstrates variations due to station spacing. Hydrographic sections are measured over several weeks and include short-term features such as eddies. Ocean models cannot exactly reproduce the observations but aim to capture the level of natural variability over the course of the model run. The models considered in this study manage to simulate a certain level of variability which covers some of the changes seen in the observations, e.g. area percentage, $\theta$, and $S$ of WDW in OCCAM 1/4, $\theta$ of WSDW in OCCAM 1/12, OCCAM 1/4 and ORCA025, and WSBW area percentage and depth in OCCAM 1/12 and OCCAM 1/4 (Figs. 4, 5, and 6, respectively). They are, however, often in disagreement with the observed mean values. This is most pronounced for the deep water masses and in ORCA025 and TPAC where both models fail to reproduce the observed amounts and the characteristics of WSDW and WSBW. During the entire model runs, the average depth of the WSDW layer was 200 to 400 metres too deep, $\theta$ of WSDW in TPAC 0.1°C too warm, and WSBW completely missing in TPAC. The WSBW layer in ORCA025 disappears after 38 years of the model run. Less drastically, both OCCAM versions struggle as well and the WSBW in both resolutions is too fresh and too warm. They do however simulate all major features of the Weddell Sea hydrography. Using the repeat sections in relation to the entire model runs shows that the model biases are consistent for each model, e.g. for all sections, the area percentage of WDW is too low in OCCAM 1/12 and too high in ORCA025, but there are exceptions, notably for section S04a.

Although the models are set up differently and use different forcings, general conclusions emerge by comparing their performances:

1. **Increasing resolution is not a panacea.** As noted by Barnier et al. (2006), model numerics thoroughly tested at coarse resolutions may require reformulation for higher resolution. Moving to higher resolution, both horizontally and vertically, can improve model simulations significantly (Lee et al., 2002; Thoma et al., 2006). However at the level of resolution in eddy-
permitting and eddy-resolving models, better parameterisations and model numerics are just as important. Examples are better advection schemes, improved and suitably chosen subgridscale parameterisations, and use of partial bottom cells (Lee et al., 2002; Legg et al., 2008; Penduff et al., 2007). It seems that the step from coarse 1° or 2° models to eddy-permitting models was a much more vital one in terms of improving model hydrography and large-scale circulation than going from eddy-permitting to eddy-resolving. The absence of major differences between our OCCAM 1/12 and OCCAM 1/4 results demonstrate this. Within the range of resolutions in the models presented in this paper, we do not find one to perform better than the others. Very high resolution, such as OCCAM’s 1/12° or POP 1/10 as used by Maltrud and McClean (2005), becomes important when examining processes that are strongly influenced by eddies, where currently used subgrid parameterisations in eddy-permitting models are still insufficient (e.g. Legg et al., 2006). In high latitudes however, model grids of nominally eddy-permitting models such as the ORCA025 grid (Madec and Imbard, 1996) can provide high enough resolution to include the effects of eddies.

2. The choice of the forcing datasets is important. Barnier et al. (2007) use various forcings for the same model and show the large impact of the different datasets on the model simulations. Their experiments led to the development of a coherent set of forcing variables (Brodeau et al., submitted). In the Weddell Sea, errors in the freshwater and heat flux forcings can have considerable impact on the ocean by altering sea ice production and melt and the density of shelf waters. Demonstrating the sensitivity of the ocean to wind forcing, Saenko and Weaver (2001) and Saenko et al. (2002) found that wind induced sea ice motion is important for the formation of Antarctic Intermediate and Bottom Water and ocean ventilation. The differences in our model simulations support the importance of realistic wind forcings. The weak NCEP wind forcing is at least partly responsible for the build-up of the very dense sea ice pack and the weak Weddell Gyre in the OCCAM runs. Gnanadesikan et al. (2004) demonstrated how observations such as Levitus et al. (1998) used for restoring models did not allow deep water masses to outcrop at the surface and hence restricted the formation of deep and bottom waters in the Ross and Weddell Seas. Surface restoring of temperature and salinity cannot therefore replace the accurate simulation of the underlying processes in order to produce the right water
masses.

3. Sea ice models need to be improved. The lack of a sea ice model in TPAC makes a realistic simulation of the processes in the Weddell Sea difficult. The missing bottom water, the warming of the entire water column, and the low salinities above the continental shelf and slope show the necessity of the inclusion of sea ice formation and melt processes for a correct model hydrography. The relaxation using salt flux derived from latent heat and precipitation is not sufficient to ensure adequate bottom water formation without the sea ice processes. From the ORCA025 run, we learn that the initialisation of the ice cover can impact the entire model run. Kerr et al. (2009) analysed ocean model runs with and without a coupled sea ice model. They found that the effect of the sea ice model on the ocean is complex. Having used a 1° model, they conclude that both refined resolution and improved parameterisations of physical processes are necessary to simulate ice-ocean interactions and the hydrography in the Weddell Sea. Hellmer (2004) and Wang and Beckmann (2007) showed that including ice shelves in a coupled sea ice-ocean model improves the simulation of the sea ice cover and alters the hydrography in the Weddell Sea with global effects. None of the models discussed in this paper include ice shelves.

A previous model intercomparison study suggested biases specific to z-level models. As part of the DYNAMO (Dynamics of the North Atlantic circulation) project, Willebrand et al. (2001) compare three models at 1/3° horizontal resolution with different vertical coordinate schemes (z-level, sigma and isopycnic). They find that the z-level model suffers from the steplike representation of the topography combined with insufficient resolution (30 vertical levels). Combined with inadequate numerical algorithms for advection and mixing, this leads to excessive diapycnal mixing and poor representation of downslope flows. Similarly, investigating the performance of two z-level models including an earlier version of OCCAM 1/4 in the Scotia Sea, Thorpe et al. (2005) suggest that low vertical resolution, poor representation of the bathymetry, and issues with the vertical mixing schemes lead to errors in the circulation and loss of Antarctic Bottom Water. In this paper, we have shown that the new version of OCCAM 1/4 with the higher vertical resolution and partial bottom cells is much improved and capable of simulating Weddell Sea deep water masses. In ORCA025 and TPAC, however, with fewer vertical levels and different vertical mixing schemes, WSBW is lost rapidly during the model run or is not
present at all, suggesting both the parameterisation and the vertical resolution are not suf-
ficient. All our models are too warm and too saline in the bottom layer of the Weddell Sea
suggesting that further improvements can be made with the representation of bottom water
formation processes including the simulation of cold overflows.

6 Conclusions

Comparing the output of three global OGCMs with observational data and with each other,
we find significant differences. The results of the same model with different horizontal resolution
(OCCAM 1/12 and OCCAM 1/4) are very similar but the higher resolution in OCCAM 1/12
and the different approach to vertical mixing lead to different behaviour in the upper ocean and
the sea ice model. Qualitatively, the results of ORCA025 and TPAC are close to each other but
very different from OCCAM. The mismatches between models and observations are genuine
and not an artefact of the snapshotlike nature of the hydrographic sections. The models are at
high enough resolution to reproduce some variability due to station location, but struggle with
the average values or fail to simulate the deep water masses correctly.

Ocean models are often used and developed to study specific areas or regions, for example
the North Atlantic overturning circulation or the Agulhas retroreflection. They are tuned to
represent those regions well, while other regions might be less well simulated, as long as on a
global scale, results seem reasonable. As the models in this comparison produce very different
results for different parameters, it is not possible to choose “the best model”. Instead, the choice
should be made according to the application. We find that for analyses regarding deep water
mass properties, ORCA025 and TPAC perform poorly and OCCAM does best. However, the
seasonality of the sea ice cover and the surface of the ocean is very limited in OCCAM. The high
resolution of OCCAM 1/12 allows for much more detail as eddies are explicitly resolved and
topography is more precise. Thompson and Heywood (2008) demonstrate how higher resolution
in observations changes our understanding of processes in regions with narrow jets and the same
can apply to model analyses. For processes which are closely linked to the growth and retreat of
sea ice, for example assessing the spring phytoplankton bloom or air-sea CO$_2$ fluxes, ORCA025
is more suitable. Problems can arise where the existence of multi-year ice is of importance.
Reasons for the different model performances include the use of different forcing datasets, different initialisations and different parameterisations of vertical mixing and other subgrid-scale processes. When using a global model for a regional study, the choice has to be made carefully; our study has shown how models can be suitable for specific applications such as outflow of bottom water, ocean-topography interaction, or ecological studies. It is difficult to say, which improvements to OGCMs are most likely to be the most effective. Comparisons to previous studies have shown the effect of better mixing and advection parameterisations and the benefit of vertical resolution and partial bottom cells. Eddy-permitting OGCMs are being tested to be used in the new generation of coupled climate models (e.g. Shaffrey et al., 2008, early online release; WCRP, 2009). Keeping this in mind, we suggest that at least for global models the focus should be on improving vertical mixing and horizontal advection schemes, better parameterisations of processes at the ice-ocean interface and in the sea ice models, and on more self-consistent and realistic forcing datasets, and not on increasingly higher resolutions.

Acknowledgements

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Error statistics for ocean model - observation comparison following Taylor (2001). RMSEs for $\theta$, and sea ice extent are given in $^\circ$ C and m$^2$, respectively.
Table 1
Summary of the main characteristics of the models under validation. References for the bathymetry datasets are given in the text.

<table>
<thead>
<tr>
<th>Model</th>
<th>Ocean component</th>
<th>Vertical mixing scheme</th>
<th>Surface salinity restoring</th>
<th>Sea ice component</th>
<th>Horizontal and vertical Resolution</th>
<th>Bathymetry source</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCCAM 1/12</td>
<td>Bryan-Cox-Semtner type</td>
<td>No isopycnal mixing scheme</td>
<td>Relaxation of surface grid box salinity to Levitus et al. (1998) at timescale of 30 days</td>
<td>Aksenov (2002); dynamic thermodynamic with elastic-viscous-plastic rheology (Semtner, 1976; Hunke and Dukowicz, 1997)</td>
<td>1/12° × 1/12°; 66 vertical levels</td>
<td>Smith &amp; Sandwell v6.2 with DBDB5 south of 72° S; sill depths checked manually</td>
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<tr>
<td>(Coward and de Cuevas, 2005)</td>
<td>As OCCAM 1/12; eddy-permitting</td>
<td>Isopycnal mixing scheme (Griffies, 1998) with Gent and McWilliams (1990) parameterisation</td>
<td>As OCCAM 1/12</td>
<td>As OCCAM 1/12</td>
<td>1/4° × 1/4°; 66 vertical levels</td>
<td>As for OCCAM 1/12</td>
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<td>ORCA025</td>
<td>OPA9 (Madec, 2006): hydrostatic primitive equation model with free surface; eddy permitting</td>
<td>Modified TKE parameterisation</td>
<td>Relaxation to Levitus et al. (1998)/PHC at timescale of 60 days for the upper two vertical levels</td>
<td>LIM2 (Fichefet and Morales Maqueda, 1997): dynamic thermodynamic, viscous-plastic rheology (Hibler, 1979)</td>
<td>1/4° Mercator grid; 46 vertical levels</td>
<td>ETOPO2 with Bedrock south of 72° S and GEBCO on the continental shelves; additional smoothing, editing in key areas</td>
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<td>(Barnier et al., 2006)</td>
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<td>TPAC</td>
<td>MOM 3.1: primitive equation model; eddy-resolving</td>
<td>Isoneutral mixing in form of the Gent and McWilliams (1990) subgrid-scale mixing</td>
<td>Relaxation using NCEP-R2 latent heat flux and precipitation rate, timescale 30 days</td>
<td>No sea ice included</td>
<td>1/8° × 1/8°; 24 vertical levels</td>
<td>TerrainBase</td>
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Table 2
Overview of WOCE hydrographic sections used for the model validation

<table>
<thead>
<tr>
<th>Section name (Cruise name)</th>
<th>Date</th>
<th>Colour in Fig. 1a</th>
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<tr>
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</tr>
<tr>
<td>SR04b (ANT IX/2)</td>
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<tr>
<td>SR04d (ANT X/7)</td>
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<td>SR04e (ANT XV/4)</td>
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<tr>
<td>-----------------------</td>
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1 a) CTD stations. Colour key to individual transects is given in Table 2. The bathymetry shown is from Smith and Sandwell V10.1. The white dashed line marks the western limit north of the Antarctic Peninsula for sea ice extent calculations. b-d) model bathymetries: b) OCCAM 1/12 (dashed line: OCCAM 1/4 coastline in the Weddell Sea), c) ORCA025, d) TPAC.

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3 $\theta$ - $S$ diagram for section SR04b (Nov/Dec 1990). The dotted lines are contours of constant potential density anomaly (kg m$^{-3}$).

4 Properties of WDW in OCCAM 1/12, OCCAM 1/4, ORCA025 and TPAC (left to right) averaged along the SR04 section line. From top to bottom: Percentage of area along section covered by WDW; average WDW $\theta$; average WDW $S$; average WDW depth. The grey shading indicates the variation due to the different station spacing of the hydrographic sections (excluding the set of stations of SR04e). The triangles indicate the values derived from the CTD sections, the circles the values from the corresponding model sections. Filled markers denote full sections, the open markers section SR04e which does not extend over the entire eastern margin of the Weddell Sea. Note the extended x-axis for ORCA025.

5 Fig. 4 but for WSDW.

6 Fig. 4 but for WSBW.

7 Sea ice extent in the Weddell Sea: a) climatological annual cycle (1988-2002), and b) monthly means.
8  Climatological sea ice concentrations for the years 1988-2002 in February (upper panel) and September (lower panel) for SSM/I observations, OCCAM 1/12, OCCAM 1/4 and ORCA025 model results (TPAC does not include sea ice).

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10 Annual mean wind stress magnitude (N m$^{-2}$) for OCCAM, ORCA025, and from NCEP Reanalysis 2 for TPAC (from left to right). The NCEP Reanalysis 2 wind field is on the original 2° resolution grid instead of the TPAC model grid because only snapshots of the forcing were stored during the model run.

11 a) Difference of sea surface height (SSH) between the tip of the Antarctic Peninsula (63.45° S, 55° W) and the SSH minimum in the Weddell Sea. b) Monthly mean baroclinic ACC transports through Drake Passage (referenced to the bottom).
Fig. 1. a) CTD stations. Colour key to individual transects is given in Table 2. The bathymetry shown is from Smith and Sandwell V10.1. The white dashed line marks the western limit north of the Antarctic Peninsula for sea ice extent calculations. b-d) model bathymetries: b) OCCAM 1/12 (dashed line: OCCAM 1/4 coastline in the Weddell Sea), c) ORCA025, d) TPAC.
Fig. 2. Section SR04b, Nov-Dec 1990. Uppermost panel: CTD observations for $\theta$ (left) and $S$ (right). Below: differences between model and CTD for $\theta$ (left) and $S$ (right), from second panel to bottom panel: OCCAM 1/12, OCCAM 1/4, ORCA025, and TPAC. The upper 500 m are expanded to allow for more detail. The white lines on the x-axis indicate CTD station positions. The black lines on the right hand side of the difference plots indicate the model depth levels.
Fig. 3. $\theta$ - S diagram for section SR04b (Nov/Dec 1990). The dotted lines are contours of constant potential density anomaly (kg m$^{-3}$).
Fig. 4. Properties of WDW in OCCAM 1/12, OCCAM 1/4, ORCA025 and TPAC (left to right) averaged along the SR04 section line. From top to bottom: Percentage of area along section covered by WDW; average WDW $\theta$; average WDW $S$; average WDW depth. The grey shading indicates the variation due to the different station spacing of the hydrographic sections (excluding the set of stations of SR04e). The triangles indicate the values derived from the CTD sections, the circles the values from the corresponding model sections. Filled markers denote full sections, the open markers section SR04e which does not extend over the entire eastern margin of the Weddell Sea. Note the extended x-axis for ORCA025.
Fig. 5. Fig. 4 but for WSDW.

Fig. 6. Fig. 4 but for WSBW.
Fig. 7. Sea ice extent in the Weddell Sea: a) climatological annual cycle (1988-2002), and b) monthly means.

Fig. 8. Climatological sea ice concentrations for the years 1988-2002 in February (upper panel) and September (lower panel) for SSM/I observations, OCCAM 1/12, OCCAM 1/4 and ORCA025 model results (TPAC does not include sea ice).
Fig. 9. Taylor diagram for $\theta$ (+), $S$ (○), and sea ice (*) statistics. Dark blue markers represent OCCAM 1/12, red markers OCCAM 1/4, grey markers ORCA025 and cyan markers TPAC.

Fig. 10. Annual mean wind stress magnitude (N m$^{-2}$) for OCCAM, ORCA025, and from NCEP Reanalysis 2 for TPAC (from left to right). The NCEP Reanalysis 2 wind field is on the original 2° resolution grid instead of the TPAC model grid because only snapshots of the forcing were stored during the model run.
Fig. 11. a) Difference of sea surface height (SSH) between the tip of the Antarctic Peninsula (63.45° S, 55° W) and the SSH minimum in the Weddell Sea. b) Monthly mean baroclinic ACC transports through Drake Passage (referenced to the bottom).