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Southern ocean sea-ice variability around the Indian Antarctic stations in the context of climate change using ocean sea-ice modelling

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ABSTRACT

The role of sea-ice physics on ocean state estimate in the Southern Ocean (SO) region [9^0E-78^0E and 50^0S-72^0S] is demonstrated using ocean sea-ice modeling. It is shown that the sea-ice plays an important role in seasonal variability of the salinity and temperature. The sea surface temperature (SST) and sea surface salinity (SSS) around the Indian Antarctic stations is computed and their seasonal variability is studied during 2008-2012. The model simulated values agree well with the observations during ice-melting and ice-formation stages. According to the formation and melting of sea ice, we divided the study domain into ice-affected (above 65^{0}S) and ice-free (below 65^{0}S) zones. During the formation of ice July-August-September (JAS), the seasonal SSS remains high (low) in the ice-affected zone (ice-free zone) whereas a low SST is noted during the same time period. The area-averaged temporal variation of SST and SSS with the available satellite/reanalysis data is also investigated. Apart from this special emphasis is given to see the temperature and salinity variation with depth.

Keywords: Antarctic; Ocean Sea-Ice Model; Southern Ocean

1. INTRODUCTION

Antarctic sea ice is one of the most important and seasonally varying geophysical mediums on Earth. Due to the lack of incoming solar radiation, ocean freezes and produces sea ice in polar region (Gupta, 2015). Because of it's less density it floats on the sea surface and acts as an insulator among water and atmosphere. It immensely affects the climate system by modulating the exchange of heat between ocean and atmosphere. Apart from this, sea ice impacts global heat budget due to its high albedo. The ocean state variables also get affected by the formation and melting of the sea-ice.

Variability of the Antarctic sea ice has been investigated by a number of researchers. The ice melting from oceanic heat flux decreases faster than the ice growth in Southern Ocean, leading to an increase in the net ice production and hence an increase in ice mass and concentration (Zhang 2006). But unfortunately much attention was not paid to figure out the effect of sea ice on SSS, SST and SSHA. To add to this, in-situ observations are severely lacking in spatial and temporal detail (Worby et al. 2008). Lack of observational data in this region forces us to choose modeling as the only viable tool to understand the physics of SO. Different Models have been used for various sensitivities study of Antarctic sea ice, including the effects of surface precipitation (Powell et al. 2005; Atul Srivastava et al. 2015), winds (Stossel et al. 2011), and ice-shelf melt water (Hellmer 2004).

Antarctic sea-ice influences global climate over a range of time scales because of the vast cover (Fletcher 1969, Walsh 1983). Variability of the Antarctic sea ice has been investigated by a number of researchers. Various studies depict that sea ice extent has slowly increased in the Antarctica region during 1979-2010 (Zwally et al. 2002; Comiso and Nishio 2008;Cavalieri and Parkinson 2012) in spite of the increasing surface air temperature and incoming solar radiation.

The zonal wind stress generates a strong eastward flow called the Antarctic Circumpolar Current (ACC) which extends from 45°S to 55°S (Trenberth et al., 1990; Orsi et al., 1995). The large volume transport by ACC is one of the important feature of SO. Apart from ACC, the Antarctic bottom water (AABW) is one of the densest water mass of in the world as well. It is the coldest bottom water which has a significant influence on the movement of world's ocean. AABW is found to occupy the depth range below 4000 m of all ocean basins that have a connection to the Southern Ocean at that level. Prydz Bay (70°E– 80°E) is one of the most important regions of bottom water, which is the third largest shelf region around Antarctica (Orsi et al. 1999). Here we have used an ocean general circulation model with an associated sea ice package to simulate the variability of SSS and SST over the Antarctic region.

2. METHODOLOGY

The MIT general circulation model (MITgcm) with sea-ice physics is used to realistically simulate the southern ocean state variability. We use the model with hydrostatic and boussinesq approximations. The built in sea-ice package provides dynamic and thermodynamic interactive sea ice model. The spherical polar grid and no slip bottom-boundary conditions are used in the experiment. The line successive over relaxation (LSR) solver is use to solve sea ice dynamics. The ice concentration and thickness, snow and enthalpy are advected by conservative advection schemes with flux limiters. We kept the horizontal resolution of 15 km, whereas, the vertical model resolution varies from 5 m near the surface to 500 m near the ocean floor. In this way, the ocean is divided into 28 vertical levels. The NCEP/NCAR daily varying near surface zonal and meridional wind, air temperature, precipitation, evaporation, specific humidity, and downward shortwave and long wave radiation is used as external forcing. The model uses the open boundary conditions on all sides. The initial and boundary conditions for temperature, salinity, zonal and meridional current is taken from the Estimating the Circulation and Climate of Ocean (ECCO) state estimates (Alok Kumar Mishra et al. 2015). The sea- ice initial conditions are taken from the Southern Ocean State Estimation (SOSE). The bathymetry data is taken from Smith and Sandwell's bathymetry. The model is spin up for 3 years from 2005- 2007 to get stable initial conditions. We choose the region of interest around [9^0 E-78^0 E, 72^0 S- 50^0 S]. It includes the only two active Indian Antarctic stations, Maitri [11.7^0 E, 70.7^0 S] and Bharti

[76.1^0 E, 69.4^0 S] where scientific research expeditions are carried out on a regular basis. The model result is stored on a daily basis for further analysis. The thermodynamics of sea ice model for simulating the sea ice concentration and sea ice thickness is based on Hibler (1979). Snow is simulated as per Zhang and Hibler (1997).

3. RESULTS AND DISCUSSION

To check the quality of model mean state we compare in Figure 1, the SST and SSS climatology with the corresponding values from the advanced very High Resolution Radiometer (AVHRR) and Southern Ocean State Estimate (SOSE) reanalysis for the aforesaid period. From the figure it is clear that simulated SST and SSS agree well with the observation. The SST keeps on decreasing south of 50^{0}S, whereas, SSS exhibits nearly opposite nature. This is happening as a result of dominant sea-ice dynamics at the higher latitudes. However, the SSS from the model is underestimated in the sea-ice regions near the poles. In order to check the variability of surface hydrographic variables in the region of study, we compute the standard deviation of the SST and SSS. We show in Figure 2, the standard deviation of the model and compare it against the corresponding values from the observations. The model very well captures the SST variability. However, the SSS variability is poorly represented in model simulation. The model shows much higher SSS compared to the observation.

To assess the quality of model's seasonal variability, the seasonal SST maps from the model and corresponding SST observations obtained from the AVHRR satellite has been drawn in figure 3. Sea surface temperature (SST) depends on a number of factors like surface air temperature, upwelling due to zonal or meridional wind, incoming solar radiation, amount of frozen ice(a special case of SO) etc. The seasons chosen for this purpose are Jan-Feb-Mar (JFM), Apr-May- Jun (AMJ), Jul-Aug-Sept (JAS), and Oct-Nov-Dec (OND). The seasonal variability exhibited by the model matches very well with the AVHRR observations. The highest SST is obtained during the JFM, whereas, the lowest SST during JAS. The SST during AMJ and OND remains intermediate. The increments of SST in JFM suggest that the insolation increases.

Evaporation, precipitation and formation of sea ice are the major factors for variation of surface salinity. Together with temperature, salinity is used for determination of water density and thus is intimately linked with the global ocean circulation. We show in Figure 4,the seasonal SSS variability and compare it with the SOSE reanalysis data. We see from figure that the model underestimates the SSS throughout the domain for every season. The highest differences in the SSS are observed during the melting season (JFM) in which the model is not able to simulate correct values of the SSS. During the sea-ice formation stage, the ice ejects brine leading to increase in the surface salinity. On the other hand, during the summer the surface is flooded by plenty of freshwater due to the melting of ice, thereby lowering the salinity. This periodical change in the values of the SSS is captured by the model.

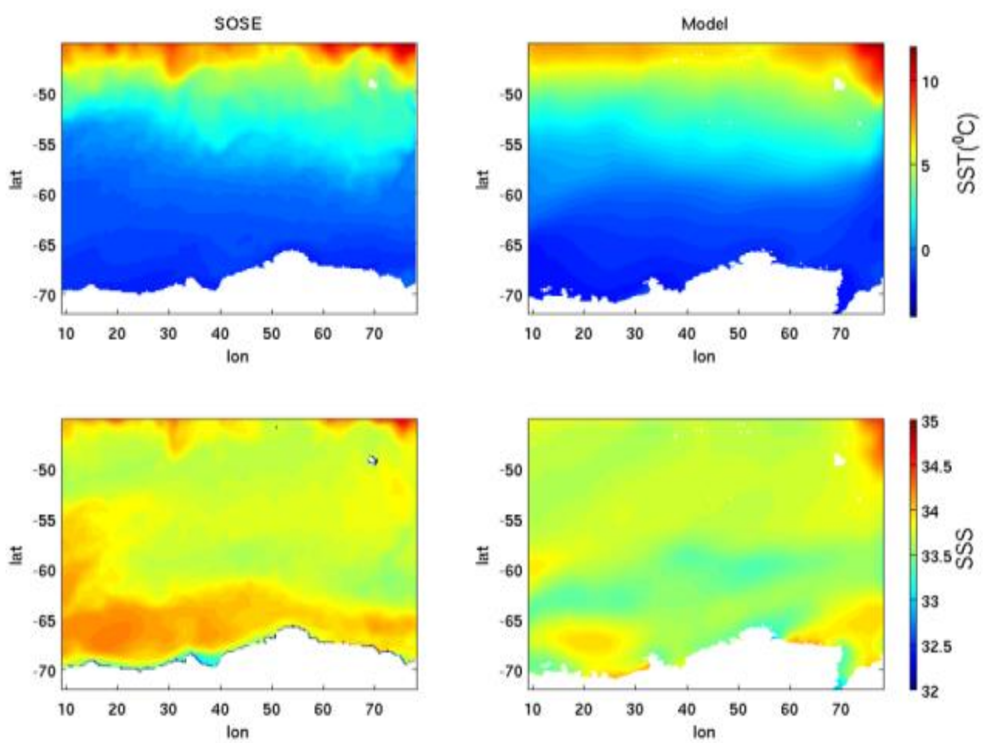

Figure 1 Climatology of the SST (upper panel) and SSS (lower panel)

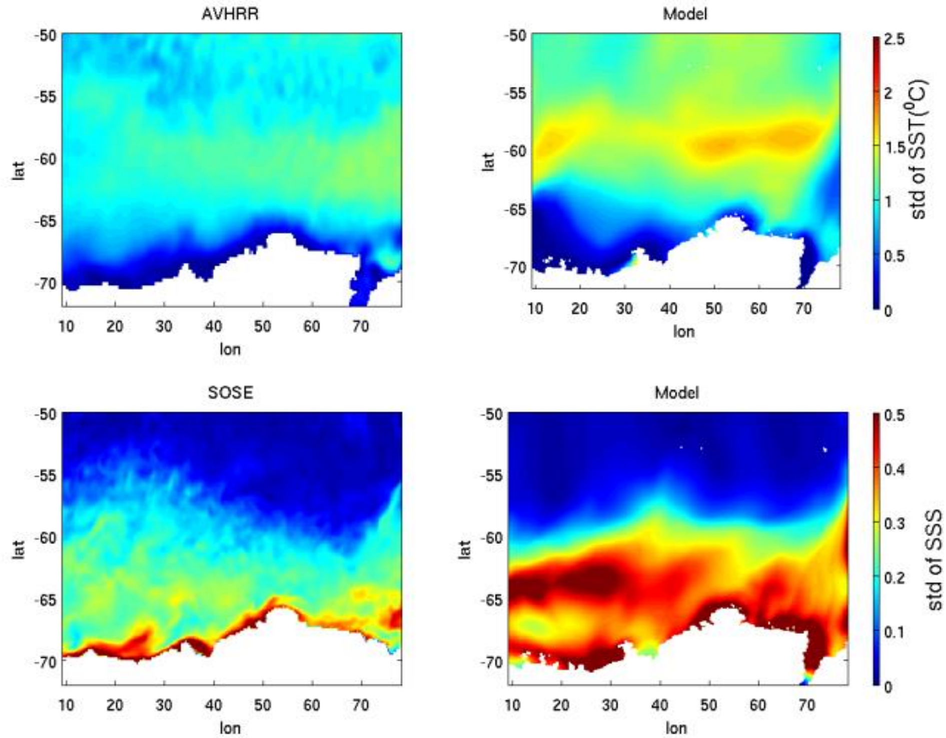

Figure 2 Standard deviation of the SST (upper panel) and SSS (lower panel)

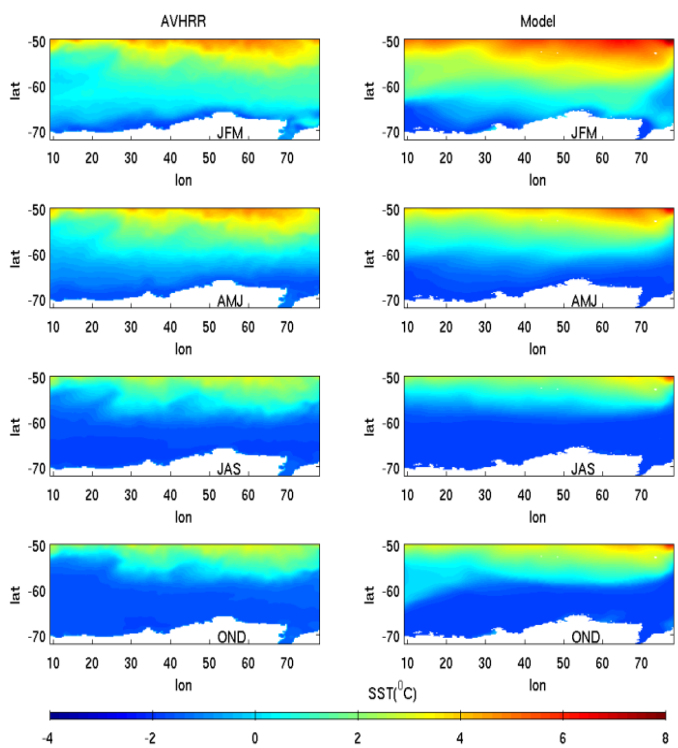

Figure 3 Seasonal variation of SST

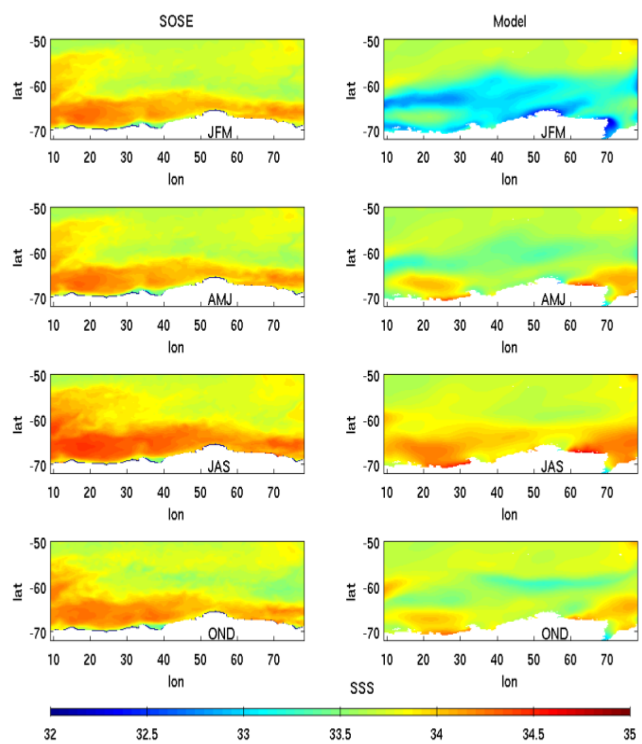

Figure 4 Seasonal variation of SSS

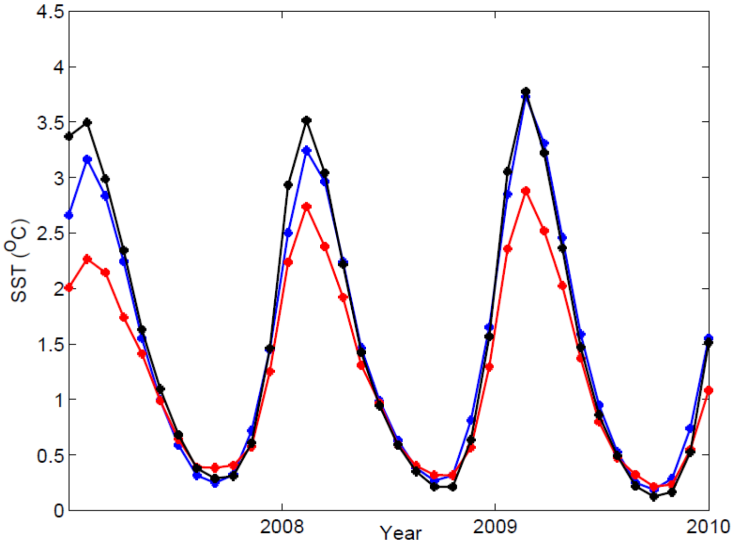

Figure 5 Monthly time series of the SST of SOSE (black), model (blue) and AVHRR (red) averagedover the region [9^{0}E-78^{0}E; 50^{0}S-72^{0}S] in the Southern Ocean during 2008-2012.

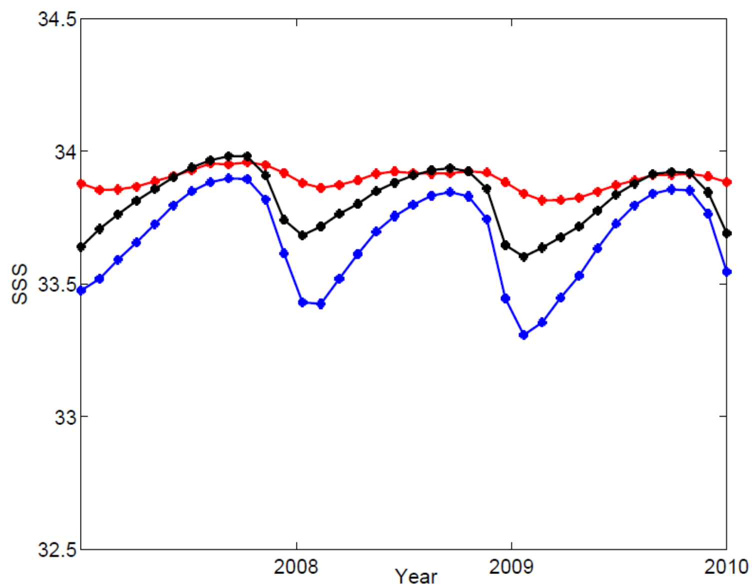

Figure 6 Monthly time series of the SSS of SOSE (black), model (blue) and ORAS4 (red)averaged over the region [9^{0}E-78^{0} E; 50^{0}S-72^{0}S] in the Southern Ocean during 2008-2012.

To see the temporal variation of the SST in the sea-ice region, we show in Figure 5, the spatially averaged monthly SST time series in the region [9^{0}E-78^{0}E; 50^{0}S-72^{0}S] during 2008-2010. The corresponding time series from the AVHRR and SOSE are also shown. The correlation of SST between model and SOSE is 0.99, whereas, the correlation between model and AVHRR is 0.99. These correlations are significant at 99.9 % level. The SST values are high in the sea-ice onset phase, whereas, low SST values are obtained in the ice-melting season. The annual variability of the SST is nearly periodic. Similarly, the temporal variation of the SSS in this study region is shown in Figure 6. The spatial average is made over the region [9^{0}E-78^{0}E; 50^{0}S-72^{0}S]. The correlation of model SSS with SOSE and ORAS4 reanalysis data is found to be 0.98 and 0.81 respectively (significant at 99.9% level).

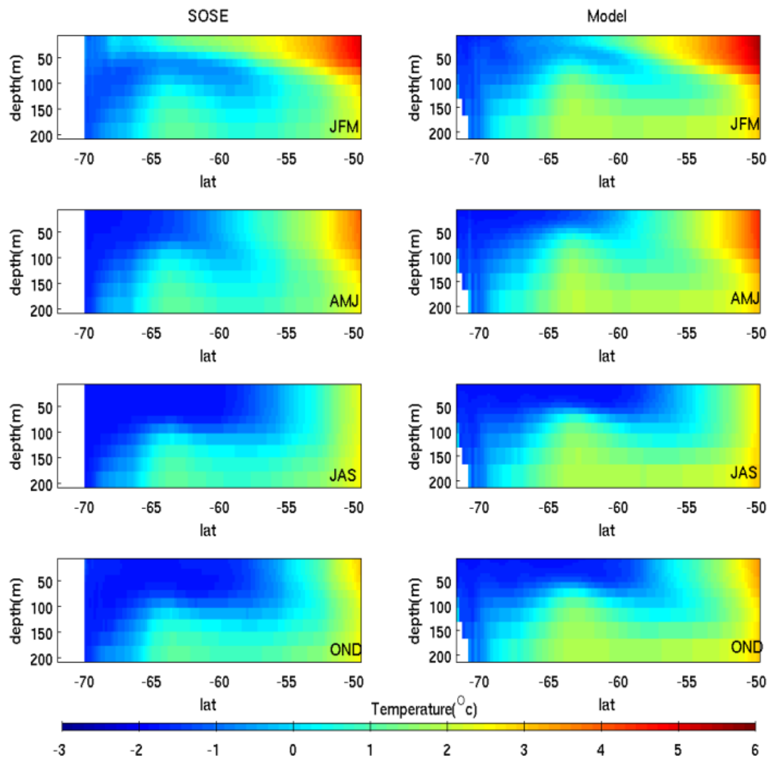

Figure 7(a) Temperature with lattitude and depth

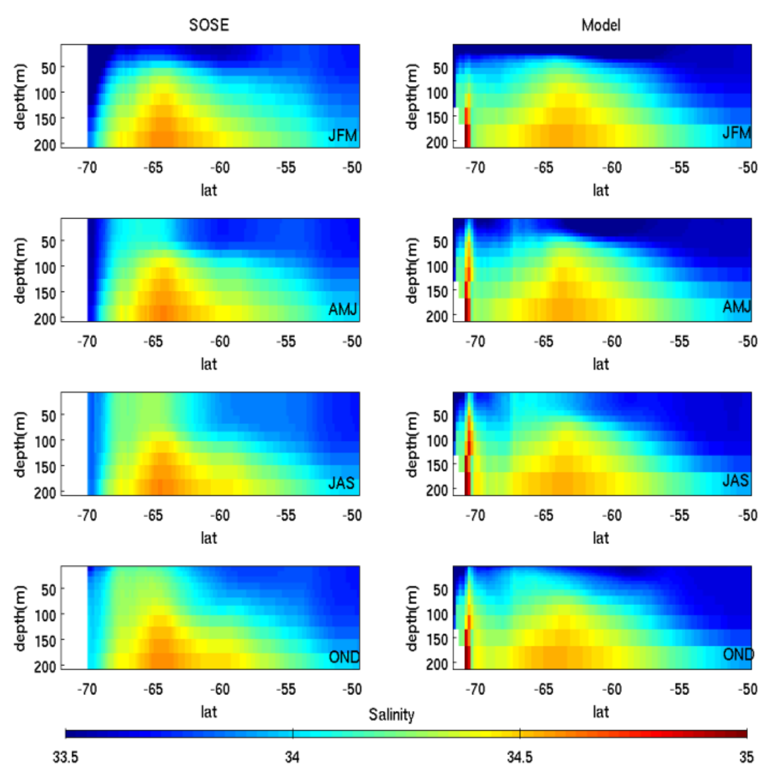

Figure 7(b) Salinity with lattitude and depth

4. SEASONAL VARIATION OF TEMPERATURE AND SALINITY WITH DEPTH

We have also quantified the effect of ice in the sub-surface region by analyzing seasonal climatology of temperature and salinity in upper 200 meter from the surface. From figure 7, we can infer that temperature profile remains low in the higher latitude throughout the year but in the lower latitude high temperature water mass dominates the region. On the other hand, very little seasonal changes (0.1 to 0.2 psu) of salinity take place in comparison to temperature in the higher latitude. Seasonal variation of mixed layer depth (MLD) has also been captured in this figure. We can depict that MLD become thick (shallow) during austral winter (summer). The low saline and high temperature water mass present in the lower latitude (below 55^0S) carries the mark of ACC, which is considered to be one of the mightiest currents in the world. From these figure it is clear that high salinity band is captured by model at between 59^0S to 69^0S for all season with respect to depth. It is because of presence of sea ice during each season at higher latitudes. The ice formation leads to brine rejection, which increases salinity at higher latitudes.

5. CONCLUSION

We analyzed the seasonal variations of temperature and salinity in the region of interest for the year 2008 to 2012. The seasonal variability as well as climatology and standard deviation of different model variables compares very well with observations though with the exception of seasonal variability of SSS in the ice-melting phase. High seasonal variations of SST and SSS are prominently seen especially in the regions of sea-ice formation. The model SST decreases from lower to higher latitudes, which is also supported by the observations. The model simulated SSS captures overall spatial pattern of observations but magnitudes are slightly underestimated. There is not enough seasonal variation of sea surface salinity and sea surface temperature in ice-free zones (above 60^0S) but in the ice-zone (below 60^0S), the variation is pervasive which is controlled by melting and freezing of ice. With the freezing of sea-ice during the winter season, the SST decreases while the SSS increases and vice-versa for the melting (summer) season. The model also realistically simulates the variation of temperature and salinity with depth in the presence of strong ACC.

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