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Numerical simulation of the dynamic effects of grounding icebergs on summer circulation in Prydz Bay, Antarctica

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Abstract The Regional Ocean Modeling System (ROMS) is employed to create a three-dimensional numerical model of the summer circulation in the Prydz Bay region, Antarctica. Consistent with the currents measured using an underway acoustic Doppler current profiler during a Chinese cruise, the simulated current field illustrates the major features of the Prydz Bay circulation, including the Antarctic Slope Current (ASC) along the continental shelf break, the cyclonic Prydz Bay Gyre, and the Prydz Bay Eastern Coastal Current (PBECC). The effects of grounding icebergs D15 and B15 on the circulation in Prydz Bay are investigated via numerical simulations. The results indicate that these giant grounding icebergs substantially affect the flows into and within the bay, which may differ with the different grounding locations. As grounding iceberg D15 is located close to the southwestern part of the West Ice Shelf (WIS), it cuts off the coastal current along the outer edge of the WIS, and the ASC can only enter Prydz Bay from the west side of iceberg D15, whereupon it becomes a main source of the PBECC. Iceberg D15 also weakens the circulation in the bay in general. The relatively small iceberg B15 entered Prydz Bay from 2007 to 2009 and grounded on the southwestern section of the Four Ladies Bank. The numerical experiments indicate that iceberg B15 guides the ASC flowing into the bay around its west side and reduces the width of the inflow on the eastern side of the Prydz Bay Channel. The grounding of iceberg B15 has also led to adjustments of the circulation within the bay, among which the most significant is that the outflow along the western flank of Fram Bank has shifted to the west and become more intensive.

Keywords **circulation**, **grounding iceberg**, **numerical simulation**, **Prydz Bay**, **Antarctica**

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1 Introduction

Prydz Bay (Figure 1a), which is located in the Indian Ocean sector of the Southern Ocean, is the third largest embayment around Antarctica behind the Weddell and Ross seas. Following the establishment of Zhongshan Station by China in 1989, the Prydz Bay region has become a focus area of Chinese oceanographic investigations and scientific research (Shi et al., 2013; Gao et al., 2016). To the east of the mouth of Prydz Bay, the Four Ladies Bank (FLB) stretches from northeast to southwest. Icebergs that drift from the east propelled by the Antarctic Slope Current (ASC) often ground on the shallow part of the FLB (depths of <200 m) (Li et al., 2017). For example, iceberg B15 (which has since split into three pieces, B15b, B15r, and B15t) grounded on the southwest corner of the FLB from 2007 to 2009 (Hou and Shi, 2021) (Figure 1b). A grounding tabular iceberg (D15) with an area of 4717 km^2 (Wesche and Dierking, 2015) has grounded on the northwestern side

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of the West Ice Shelf (WIS) since 1991 (Figure 1) (Hou and Shi, 2021). In addition to icebergs originating outside of the bay, icebergs can calve from the Amery Ice Shelf (AIS) in the south end of Prydz Bay. Iceberg D28 calved from the Loose Tooth rift system in the front of the AIS (Zhao et al., 2013) at the end of September in 2019 (Chi and Klein, 2021). It then exited Prydz Bay along the east flank of Fram Bank (Liu et al., 2022). Grounding icebergs affect the local circulation, water mass, and distribution of sea ice. Grounding icebergs in the Weddell Sea have blocked the entry of sea ice and the outflow of the High Salinity Shelf Water (HSSW), changing the local circulation patterns (Markus, 1996; Grosfeld et al., 2001). Icebergs B15 and C19, which calved from the Ross Ice Shelf, had profound impacts on the physical oceanography in the region around McMurdo Station (Robinson and Williams, 2012). Grounding iceberg B15 limited the circulation of the surface water, and iceberg C19 reduced the new ice production and the formation of HSSW as it moved northward. Therefore, it can be inferred that the grounding giant icebergs in Prydz Bay should affect the local circulation. However, no relevant studies have been conducted in this area.

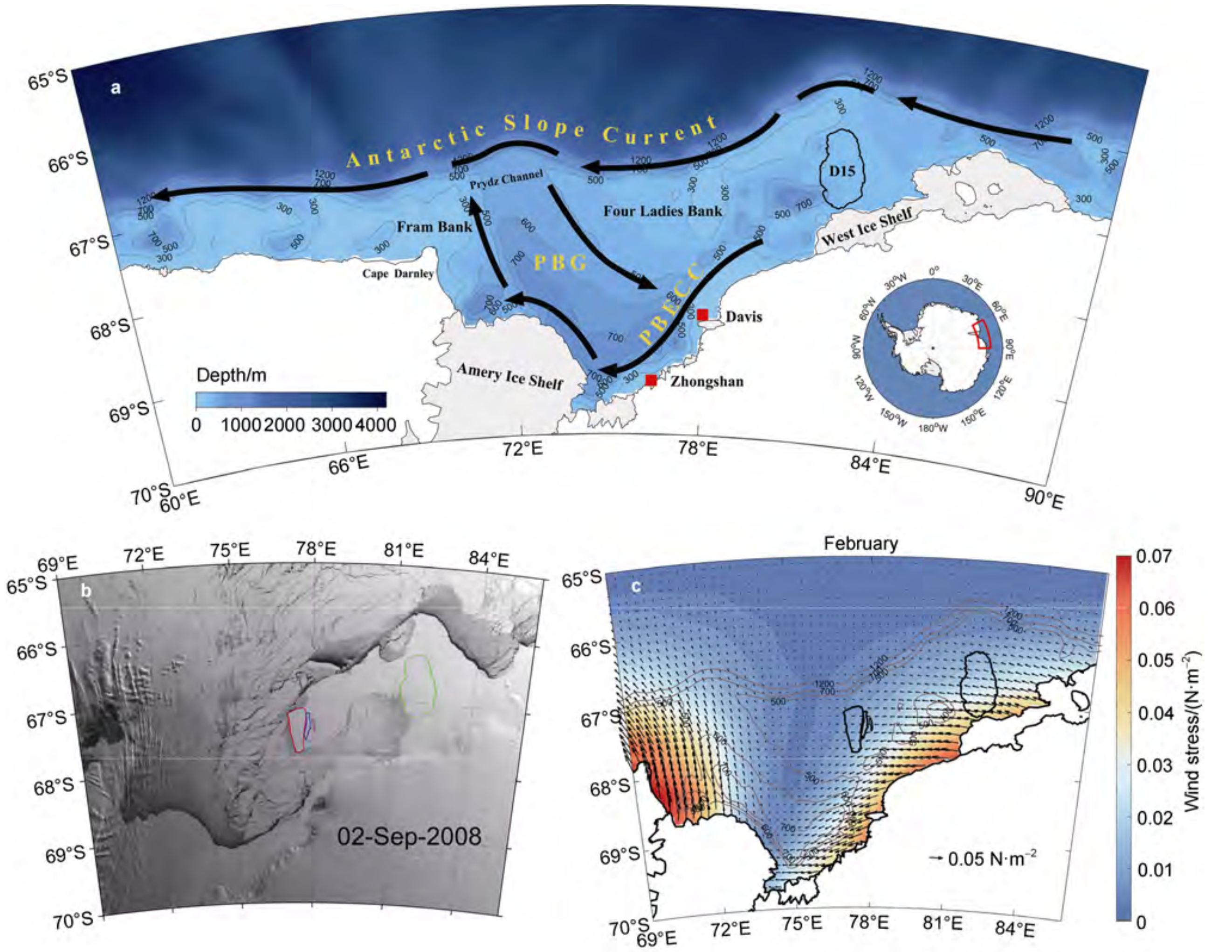


Figure 1 **a**, Bathymetry of Prydz Bay. The black arrows indicate the schematic circulation. The thin black line is the outline of giant grounding iceberg D15. The red squares indicate the research stations. **b**, MODIS visible image acquired on September 2, 2008. The green line is the outline of iceberg D15, and the other three colored lines in the center of the bay represent the outlines of icebergs B15b, B15r, and B15t from left to right. **c**, Wind stress in February averaged from 2013 to 2018. The brown contours are isobaths.

Since Prydz Bay is frozen during the winter, *in situ* observations in Prydz Bay are mostly limited in summer. Early studies have provided a preliminary understanding of the circulation in Prydz Bay using the geopotential height anomaly calculated from the limited temperature and salinity profiles (e.g., Smith et al., 1984; Nunes Vaz and Lennon, 1996). The circulation pattern in Prydz Bay is characterized by the westward flow of the ASC along the continental shelf break and the cyclonic Prydz Bay Gyre (PBG) within the bay. Middleton and Humphries (1989) regarded the ASC as a current that has reached an approximate geostrophic balance and is driven by the easterly wind. The PBG mainly consists of the inflow into the bay that crosses the shelf break on the east side of the

Prydz Channel and the outflow leaving the bay on the west side, which skirts around the shallow Fram Bank (Nunes Vaz and Lennon, 1996). Nunes Vaz and Lennon (1996) reported more details about the PBG. In the upper layer (shallower than 200 m), the inflow mostly comes from the coastal current in the vicinity of the WIS. Whereas at greater depths, the flow comes from the continental shelf break on the western FLB.

Through the application of numerical circulation models, our understanding of the circulation in Prydz Bay has improved. Various numerical model simulations have produced similar results, including the cyclonic PBG and ASC (Shi et al., 2000, 2002; Aoki et al., 2010; Galton-Fenzi et al., 2012; Liu et al., 2017, 2018), which are consistent with those obtained from the geopotential height anomaly. Shi et al. (1995) and Sun et al. (1995) simulated the summer circulation in Prydz Bay using a three-dimensional baroclinic numerical model, and their results indicate that the topography is a dominant factor controlling the circulation pattern. Liu et al. (2017) identified a strong southwestward current along the coastline from 75°E to 82°E in their simulation, and they named this current the Prydz Bay Eastern Coastal Current (PBECC). The PBECC originates from a series of branches of the ASC on the north side of WIS, and it likely carries the modified Circumpolar Deep Water (mCDW) into the cavity under the AIS, which has potential consequences for the basal melting of the AIS (Liu et al., 2017, 2018). However, these branches pass through the location of grounding iceberg D15, and iceberg D15 was not included in their model. In this study, the effects of the presence of grounding icebergs on the circulation in Prydz Bay were analyzed through numerical simulations.

2 Model configuration

The Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005) was employed in this study. The ROMS is a free-surface ocean model based on hydrostatic and Boussinesq approximations, which has been widely used to simulate inshore circulation. The ROMS uses orthogonal curvilinear coordinates (Arakawa C) in the horizontal directions and the stretched, terrain-following coordinate in the vertical direction, so it is suitable for use in regions with large topographic variations, such as Prydz Bay.

The model domain (60°E–90°E, 65°S–70°S) covers the Prydz Bay region. The zonal model resolution is 0.15°, and the grid spacing ranges from ~5.7 km at the southern boundary (70°S) to ~7.1 km at the northern boundary (65°S). The meridional resolution of the grid spacing is the same as the zonal resolution to obtain an isotropic grid. There are 10 layers in the vertical direction, and the upper layers have a higher resolution (Figure 2a). The eastern,

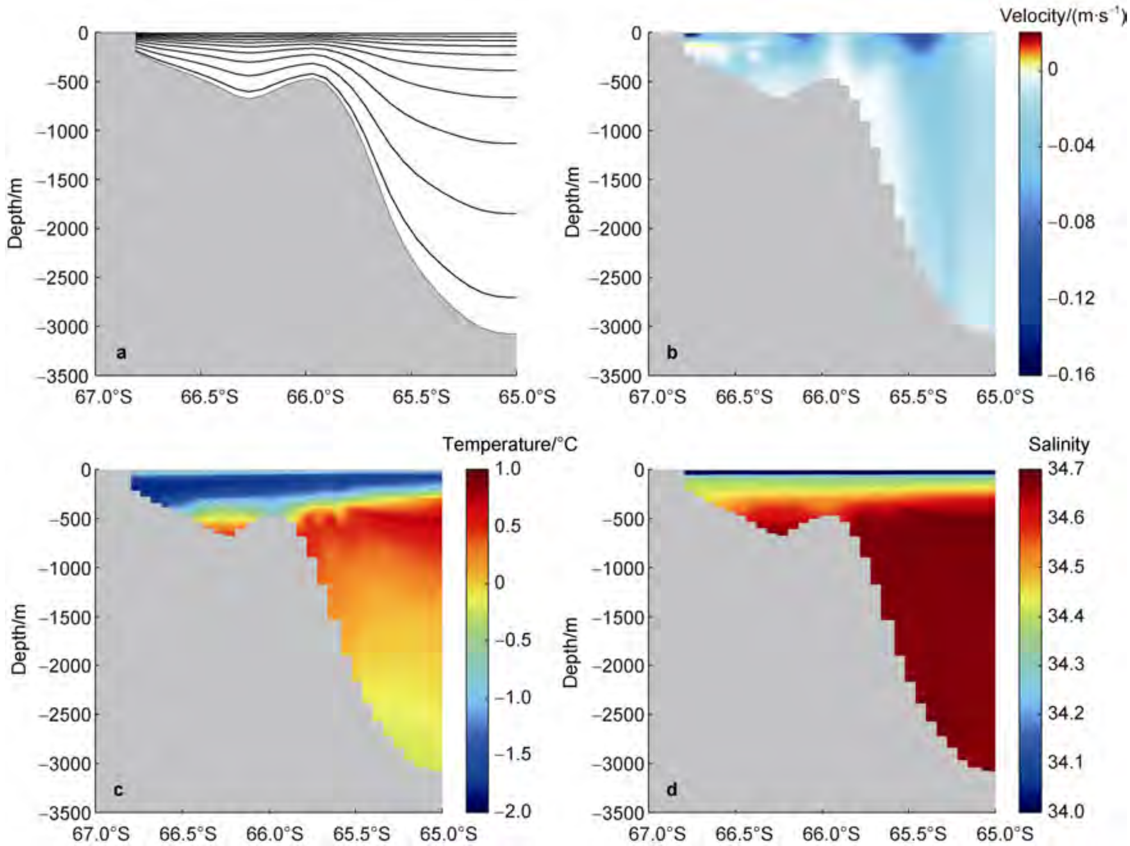


Figure 2 Sections on the eastern boundary. **a**, Distribution of the 10 vertical layers in the vertical direction; **b**, Zonal velocity (positive eastward); **c**, Potential temperature; **d**, Salinity, the grey region represents the seabed.

western, and northern boundaries are set as open boundaries located far away from Prydz Bay to minimize their effects on the circulation in the bay.

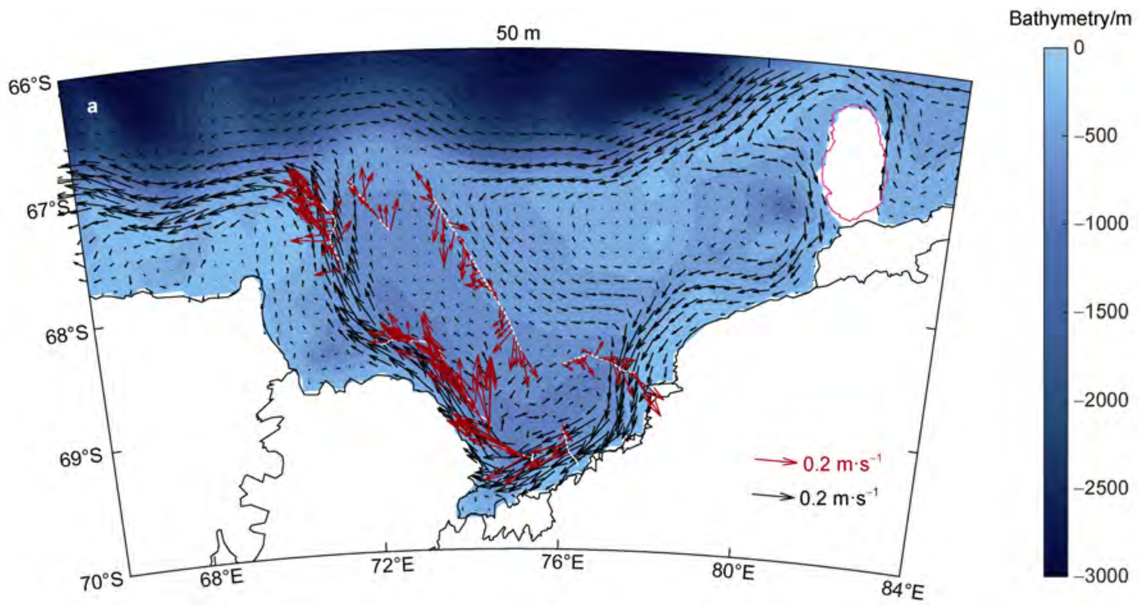
To highlight the effects of icebergs on the circulation, the circulation in February when Prydz Bay is almost ice-free was simulated, so sea ice was not included in the model. The bathymetry was obtained from a high-resolution global 30 arcseconds Refined Topography dataset (Rtopo-2). In order to improve the stability of the model, the water depth was smoothed. The ice shelves and grounded icebergs in the model were treated as land for the circulations in cavities under ice shelves have limited effects on the circulations in upper layer and the space between the base of iceberg and the sea bed is too small to allow effective ocean currents. To avoid the blowing-up phenomenon caused by the “big wall” at the closed boundary, the maximum water depth at the front of the ice shelves and in the vicinity of the icebergs was limited to 150 m. The temperature and salinity data used for the open boundaries and model initialization were derived from the World Ocean Atlas 2018 (WOA2018) climatological monthly mean data. Sections of temperature and salinity on the eastern boundary indicate the existences of the warm and salty Circumpolar Deep Water and the cold Shelf Water, as well as the Antarctic Slope Front between them (Figures 2c, 2d). The velocities at the open boundaries were interpolated from the Southern Ocean State Estimate (SOSE) data in February averaged from 2013 to 2018. The strong westward jet along slope shown in the section of zonal velocity on the eastern open boundary represents the ASC (Figure 2b). Since the atmospheric thermodynamic forcing in summer continuously heats the ocean, making the model unstable, only the wind stress was applied to force the summer circulation model. Using an empirical formula, the wind stress was converted from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis-Interim (ERA-interim) wind speed at a height of 10 m in February averaged from 2013 to 2018 (Figure 1c). With a time step of 300 s, the model simulation reached an approximate steady state after integration of about 30 months.

As giant icebergs barely melted in Prydz Bay (Hou and Shi, 2021), their thermodynamic effects on circulation are negligible and their outlines are fixed in our model. The outline of iceberg B15 was obtained from a Wide Swath Mode Advanced Synthetic Aperture Radar (ASAR) image acquired on July 2, 2008. The outline of iceberg D15 was obtained from a Moderate Resolution Imaging Spectroradiometer (MODIS) visible image. Iceberg D15 has been grounded on the WIS since 1991 (Hou and Shi, 2021), and it was included in the Standard Run.

3 Results and analysis

3.1 Validation of model results

To verify the reliability of the model, the simulated flow field was compared with the currents observed with an underway acoustic Doppler current profiler (ADCP) during the 31st Chinese National Antarctic Research Expedition (CHINARE) in the austral summer of 2015 (Figure 3). Since the 38 kHz ADCP can only obtain reliable data in regions with water depths of shallower than 800 m where it can track the seabed, the high quality ADCP data used for the comparison were mainly concentrated in the shelf region within the bay. ADCP data for the deep layers were not available due to a lack of suspended reflectors in the deep water, so the validation of the model results was mainly based on a comparison of the circulation in the upper layers.



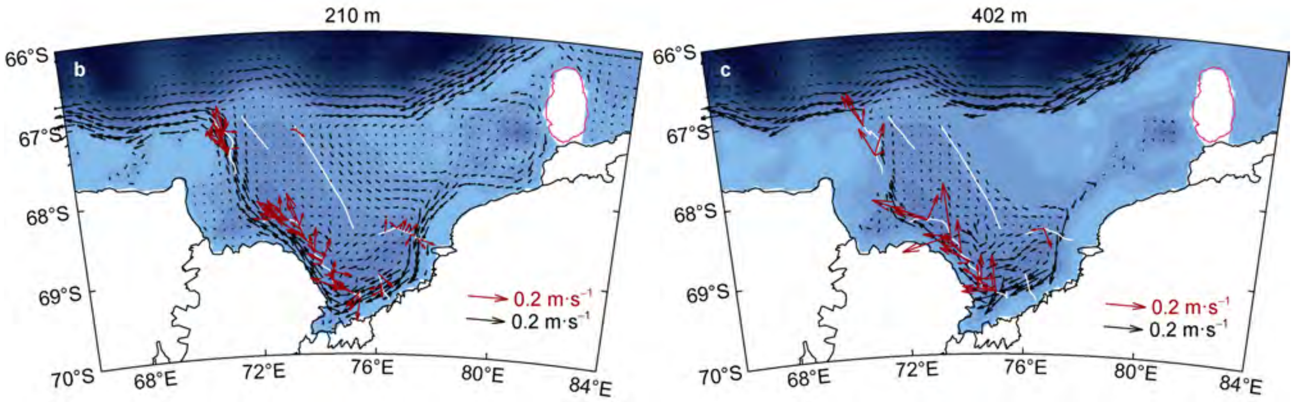


Figure 3 Comparison of simulated circulation at different depths with ADCP data collected during the 31st CHINARE: 50 m (**a**), 210 m (**b**) and 402 m (**c**). The colors represent the bathymetry. The black and red arrows represent the simulated results and the ADCP data, respectively. The white line is the trajectory of the research vessel. The solid magenta line is the outline of iceberg D15.

In general, the simulation results are in good agreement with the ADCP observations, providing the major features of the circulation within Prydz Bay, i.e., the cyclonic PBG (Figure 3). The PBG is strongest at the surface and decreases with depth until it reaches the bottom layer, which is generally consistent with previous model results (Shi et al., 2000; Aoki et al., 2010; Liu et al., 2017). Both the model and ADCP results indicate that inflow into the bay occurs along the east flank of the Prydz Channel, which is consistent with the simulation conducted by Liu et al. (2017). The inflow observed using the ADCP is mainly in the southwest direction, while the simulated inflow turns from southeast to east on the east side of the ADCP observation track. This difference may be due to the deviation of the ADCP observation track from the core of the inflow, and it may also reflect the interannual variability of this inflow. In addition, the ADCP data near the southwestern tip of the FLB suggest the presence of southeastward flow, implying that part of the inflow moves towards the southeast, which is consistent with the model results. The simulation results show that the inflow merges with the PBECC when it reaches the coastal area, forming the eastern branch of the PBG. The nearshore ADCP data (especially near Zhongshan Station) confirm the existence of the strong southwestward coastal current observed in the simulation. The coastal current exists throughout the water column and decreases with depth, with a speed about 0.2 $m\cdot s^{-1}$ at 50 m (Figure 3a). After encountering the AIS, the coastal current turns northwest along the eastern front of the AIS, and it finally leaves the bay along the east flank of Fram Bank. During this process, its velocity does not decrease and can even increase. This simulated flow is consistent with the ADCP observations, the results of dynamic height calculations (Smith et al., 1984; Nunes Vaz and Lennon, 1996), and previous numerical simulations (Shi et al., 2000; Aoki et al., 2010; Liu et al., 2017).

In summary, the simulated circulation agrees well with the ADCP data in terms of both the circulation structure and the magnitude of the velocity, verifying the reliability of the simulation results.

3.2 Numerical simulations of the effects of grounding icebergs on ocean circulation

Two numerical experiments were set up to study the effects of grounding icebergs D15 and B15 on the circulation in Prydz Bay (Table 1). Since iceberg D15 has grounded at its current location for at least 30 years, it was included in the Standard Run (SR) but was removed from Experiment 1 (E1). The comparison between the E1 and SR simulation results allowed us to analyze the effect of iceberg D15 on the circulation. Iceberg B15 grounded in Prydz Bay during 2007–2009. Experiment 2 was designed to analyze the effect of iceberg B15 on the circulation by adding it into the domain of the SR.

Table 1 Setup of the numerical experiments

Model design	Iceberg D15	Iceberg B15
Standard Run (SR)	Y	N
Experiment 1 (E1)	N	N
Experiment 2 (E2)	Y	Y

3.2.1 Standard Run

In addition to the cyclonic gyre described in Section 3.1, the westward ASC along the continental shelf break at 67°S was also simulated well in the SR. The simulated ASC is dominated by the barotropic component with a slight decrease in velocity with depth (Figures 3a–3c). Horizontally, the ASC exhibits a strong-weak-strong structure from east to west. The current in the Prydz Channel is weakest, with a core velocity of 0.04 $m\cdot s^{-1}$, while the upstream and downstream currents are stronger, with a maximum speed of about 0.15 $m\cdot s^{-1}$ at 66°E–71°E and 85°E–89°E. This structure matches that in the simulations conducted by Aoki et al. (2010) and Liu et al. (2017).

The simulation results show a coastal current in eastern

Prydz Bay, which originates in the vicinity of the WIS (Figure 4), similar to the results obtained from geopotential anomaly by Yabuki et al. (2006). The coastal current originates from several branches of the ASC in the troughs on the continental shelf break between 78.5°E and 80.5°E. These branches turn to the east due to the influence of the topography of the FLB. After encountering iceberg D15, they converge into a southward flowing current along the western side of iceberg D15. Finally, this current reaches the shore at 81.3°E and becomes the PBECC. The PBECC has a velocity of about 0.1 m·s^{-1} at a depth of 50 m, and its velocity increases to about 0.2 m·s^{-1} north of Davis Station after merging with the inflow from Prydz channel (Figure 3a). At shallower depths (less than 210 m), the inflow of the PBG mostly comes from the coastal current originating in the vicinity of the WIS (Figures 3a, 3b). At greater depths, the inflow comes from the continental shelf break on the western FLB (Figure 3c), which is consistent with the conclusions of Nunes Vaz and Lennon (1996).

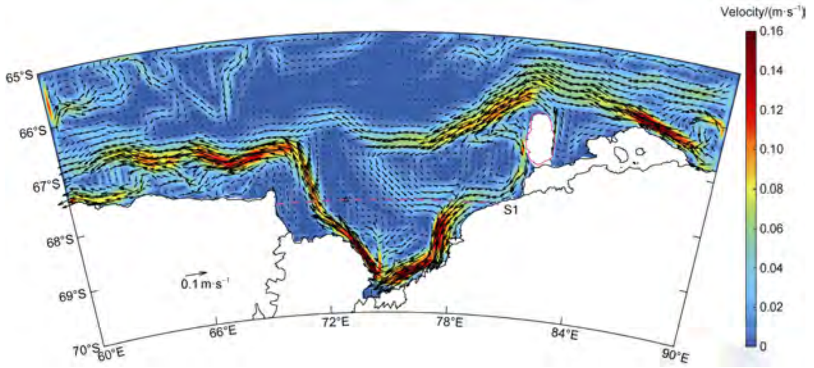


Figure 4 Depth-averaged velocity of Standard Run. The purple dashed line along 68°S indicates the sections used to calculate the volume transport. The black triangle indicates the position separating the inflow and outflow. The solid magenta line is the outline of iceberg D15.

3.2.2 Effect of iceberg D15 on circulation

To investigate the effect of iceberg D15 on the circulation in Prydz Bay, iceberg D15 was removed from the model topography in E1. Similar to the results of the SR (Figure 4), the simulation results of E1 also show the westward ASC, the cyclonic PBG and the southwestward coastal current along east coast of the Prydz Bay between 75°E and 81°E (Figure 5a). However, the origin of the coastal current in E1 is the two branches of the ASC at 82°E and 85°E, which differs from that in the SR. Without the grounding iceberg blocking the current, the branch at 85°E is able to flow southwestward along the outer edge of the WIS and then along the coastline, becoming the PBECC named by Liu et al. (2017). Another branch at 82°E flows southward along the east side of the FLB until it reaches the outer edge of the WIS where it merges with the PBECC.

To visualize the changes in the circulation, the depth-averaged velocity of E1 was subtracted from that of the SR to obtain the difference (Figure 5b). The largest changes mainly occur around iceberg D15. The velocity at the junction between the south side of iceberg D15 and the WIS is lower than in the SR, while the velocity on the other sides of the iceberg is higher than in the SR, reflecting the significant effect of the iceberg on the circulation near its grounding location. First, grounding iceberg D15 cuts off the ASC branch that originates at 85°E and flows along the outer edge of the WIS. In addition, the source of the PBECC changes to the ASC branches between 78.5°E and 80.5°E. Moreover, the flow velocity on the three sides of iceberg D15 that meet the ocean significantly increases. Since the northern end of D15 is located close to the continental shelf break, the ASC between 80°E and 82.5°E is enhanced, with a velocity increase of approximately 0.05 m·s^{-1}. In addition to the local effects, grounding iceberg D15 also weakens the overall circulation in Prydz Bay, especially in the high-speed regions on the southern side of the WIS, along the east coast of Prydz Bay, and of the east side of Fram Bank (Figure 5b). The volume transported into the bay across the 68°S section (Figure 4) in E1 and SR is about 1.43 Sv and 1.40 Sv, respectively, which indicates that the grounding of iceberg D15 resulted in a decrease of 2% in the volume transported into Prydz Bay.

3.2.3 Effect of iceberg B15 on circulation

Experiment 2 was conducted to investigate the effects of the short-term grounding of an iceberg on the circulation. Iceberg B15 drifted into Prydz Bay in September 2007 and grounded on the southwestern part of the FLB (Figure 1b) where it remained until February 2009 (Hou and Shi, 2021).

In the SR without iceberg B15, there are several inflows to the bay at the shelf break east of the Prydz Channel. The inflows at 74°E–75°E are stronger, with a maximum velocity of 0.05 m·s^{-1}; while the east inflow is very weak, with a velocity of less than 0.02 m·s^{-1} (Figure 4). After iceberg B15 grounded, creating a physical barrier, the surrounding flow field changed significantly. The northern end of iceberg B15 was close to the shelf break, and it induced the ASC to generate a southward branch that flowed into the bay along the west side of the iceberg (Figure 6a). Thus, the original weak flow in this area was strengthened (Figure 6b), making

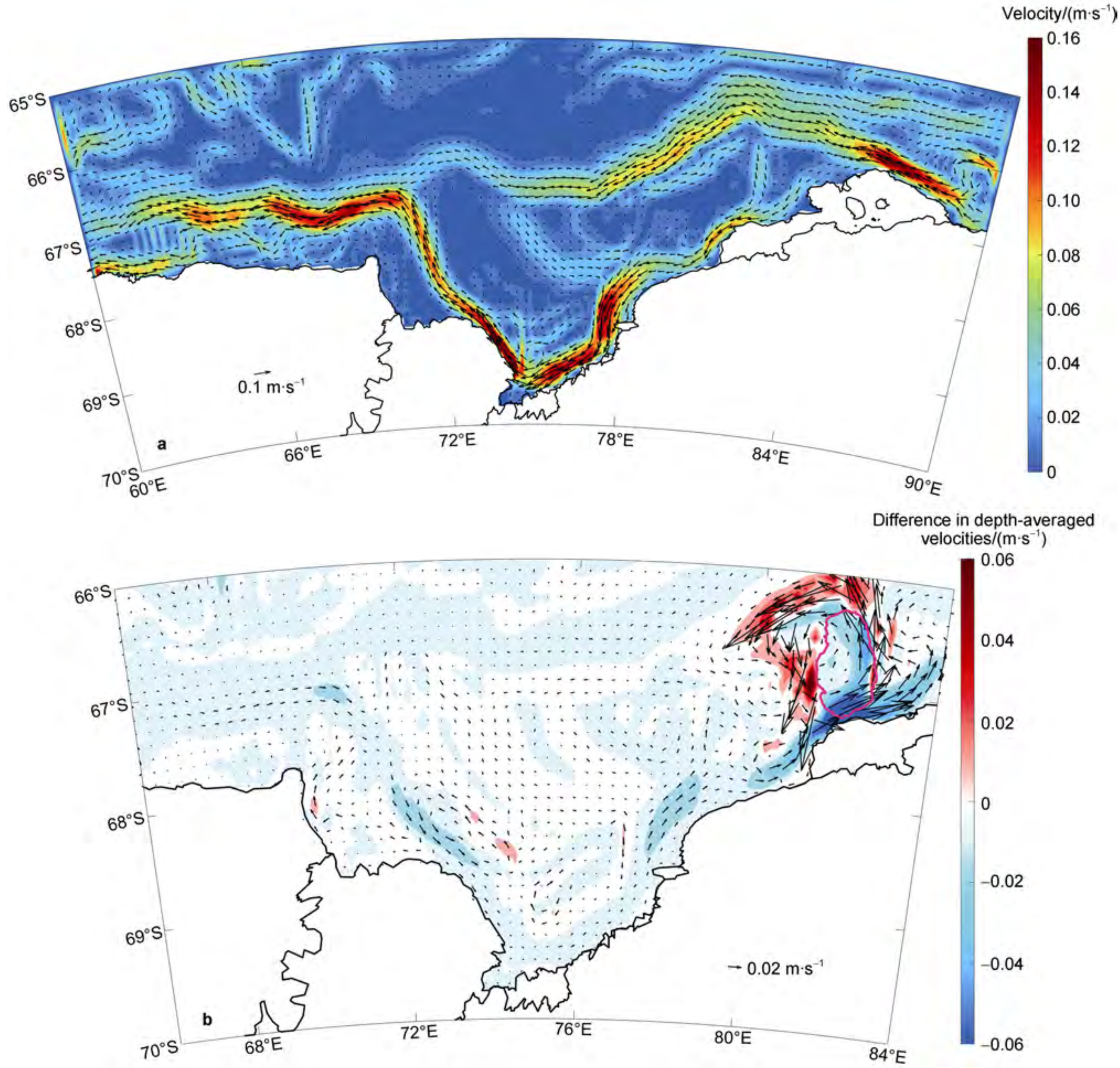


Figure 5 **a**, Depth-averaged velocity of E1; **b**, Difference in depth-averaged velocities in SR and E1. Positive (negative) values represent increased (decreased) velocity after adding iceberg D15 to the simulation. The solid magenta line is the outline of iceberg D15.

the velocity equivalent to the that of the inflow near Prydz Channel and the latter's width became narrower. These two inflows converged to the south of iceberg B15, resulting in an increase in the flow speed (Figure 6b), and then, they merged into the PBECC (Figure 6a).

Similar to iceberg D15, the north end of grounding iceberg B15 was close to the ASC, but the enhancement of the ASC by B15 was relatively small. The area occupied by iceberg B15 was only about 1/3 that occupied by D15, and B15 was not connected to the coast or ice shelf. As it was surrounded by water and grounded in a location with weak wind forcing (Figure 1c) and a weak current, iceberg B15 had a relatively small impact on the circulation. The effect of iceberg B15 on the circulation in Prydz Bay exhibited obvious spatial heterogeneity, and the regions with enhanced and weakened currents coexisted in the bay (Figure 6b). The distribution of the two regions to the west of Fram Bank indicates that the strong current became more concentrated and shifted towards the shallow water area. This remote effect may have been due to the change in the terrain vorticity caused by the grounding of iceberg B15.

4 Conclusion

In this study, the ROMS was used to create a three-dimensional numerical model of the summer

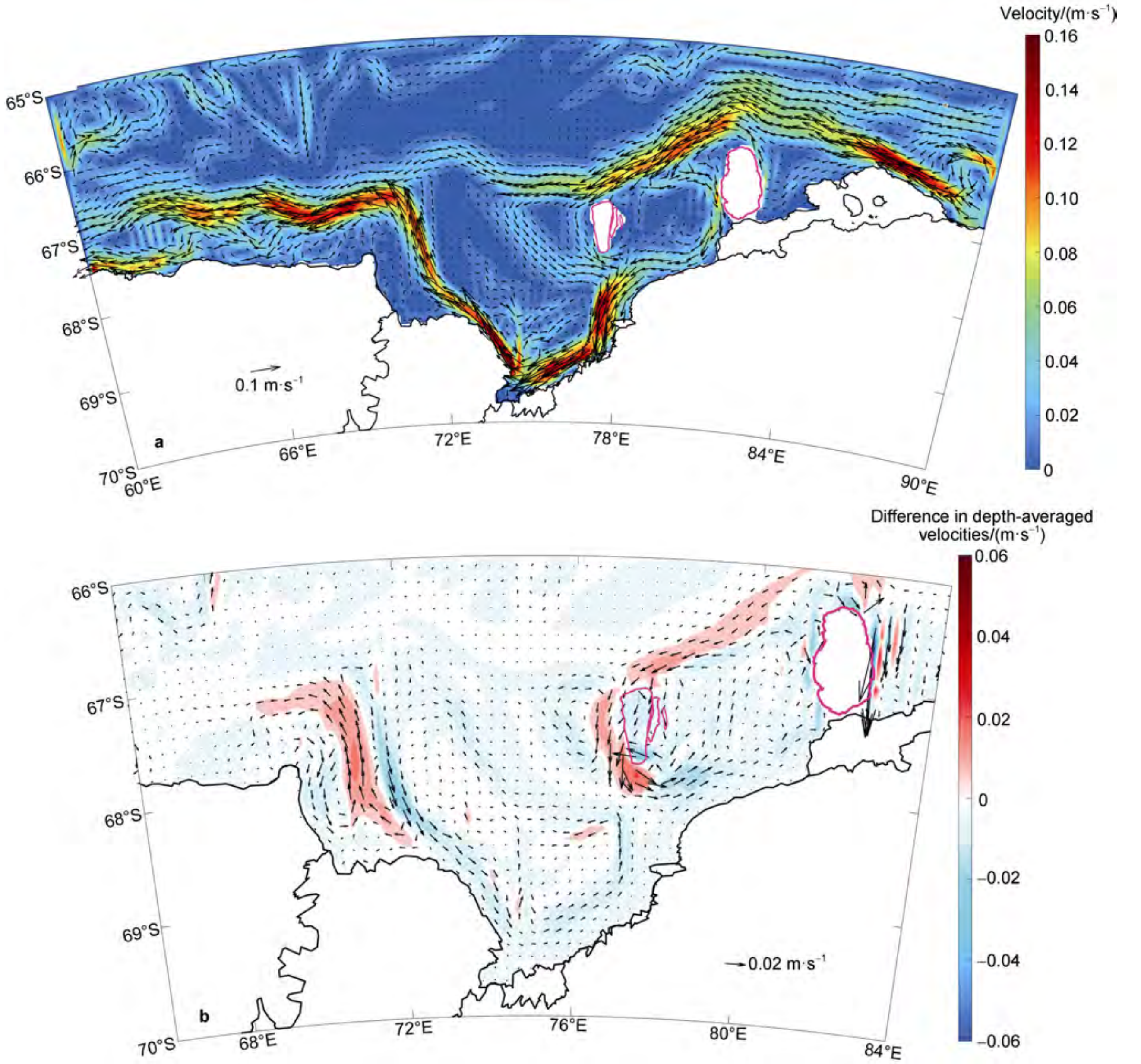


Figure 6 **a**, Depth-averaged velocity of E2; **b**, Difference in depth-averaged velocities in E2 and SR. Positive (negative) values represent increased (decreased) velocity after adding iceberg B15 to the simulation. The magenta lines are the outlines of icebergs D15 and B15.

circulation in the Prydz Bay region, Antarctica. By adding iceberg D15, which has grounded near the WIS for 30 years, to the model domain and using the climatological mean wind field in February as the forcing in the model, the ocean circulation in the Prydz Bay region was simulated in a Standard Run. Through comparison with the underway ADCP data collected during the 31st CHINARE, the reliability of the simulation was verified. Based on this, two numerical experiments were setup to study the effects of the grounding of giant icebergs on the circulation in Prydz Bay.

The Standard Run simulated the major features of the circulation in Prydz Bay region, and the simulation results were found to be in good agreement with the observations. The ASC flows westward along the continental shelf break at about 67°S in Prydz Bay, with a strong-weak-strong structure from east to west, i.e., it is weakest at the entrance of Prydz Channel and stronger on the west and east sides of the Prydz Channel, with a maximum depth-averaged velocity of about 0.16 $m·s^{-1}$. Several branches of the ASC cross the shelf break near Prydz Channel and flow into the bay. When the southeast-ward inflow reaches the east coast of Prydz Bay, it merges with the PBECC, which mainly originates from the ASC's branches between 78.5°E and 80.5°E. These branches flow southward along the west side of iceberg D15, arriving at the coastline near the southern part of the WIS and becoming the PBECC. The above two inflows dominate at different depths, with the latter mainly in the upper layer (shallower than 210 m) and the former mainly in the deep layer.

The comparison of the results of the Standard Run and the numerical experiment without iceberg D15 indicate that the grounding of iceberg D15 changed the source of the PBECC. Without iceberg D15, the coastal current originates from two branches of the ASC at 82°E and 85°E. The latter flows along the outer edge of the WIS, converges with the former on the southwest side of the WIS, and then flows southwestward along the coastline as the PBECC. In the simulation with grounding iceberg D15, it cuts off the coastal current along the outer edge of WIS, enhancing the branch of the ASC that flows into Prydz Bay along its west side. The presence of grounding iceberg D15 also slightly reduces the velocity of the overall circulation in Prydz Bay.

Iceberg B15, which entered Prydz Bay and grounded on the southwestern part of the FLB during 2007–2009, also changed the branches of the ASC. The numerical experiment containing iceberg B15 revealed that inflow occurred along to its west flank, narrowing the ASC branch that entered the bay along the Prydz Channel. The velocities of these two inflows were equivalent. Iceberg B15 mainly contributed to the regional adjustment of the circulation. An obvious change was the further concentration and westward shift of the outflow along the east side of Fram Bank.

The above numerical experiments on the circulation in Prydz Bay show that the grounding of giant icebergs along the FLB and in its vicinity changed the location at which the ASC entered Prydz Bay and the intensity of the circulation in Prydz Bay. Considering that the FLB and its vicinity are also the main entrances through which the mCDW flows into Prydz Bay (Herraiz Borreguero et al., 2015; Liu et al., 2017, 2018), and the mCDW plays an important role in the basal melting of the AIS and the variations in the polynyas in east Prydz Bay (Herraiz Borreguero et al., 2015; Liu et al., 2017; Guo et al., 2019), it can be inferred that grounding icebergs will have important impacts on the ice-sea interactions in Prydz Bay. For simplicity, neither sea ice nor the cavity under the ice shelf was considered in this model. Only wind stress was applied for the atmospheric forcing, and the variables that affect the thermodynamic processes, such as rainfall and solar radiation, were not considered in the model. These deficiencies of the model will be remedied in the future in order to investigate the effects of grounding icebergs on the coupled ocean–sea ice–ice shelf system in Prydz Bay.

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