



1 **Numerical Simulation of a Severe Blowing Snow Event over the Prydz Bay Region**

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16 **Abstract**

17 Blowing snow in Antarctica is a critical process regulating ice sheet mass balance.
18 Using the CRYOWRF real-time atmosphere-snow surface coupling model, this study
19 simulates a severe wind and blowing snow event that occurred near Zhongshan Station,
20 East Antarctica, from 15 to 17 July 2022. Triggered by a mid-latitude cyclone, the event
21 was characterized by distinct local atmospheric dynamics influenced by terrain forcing
22 and katabatic winds. Specifically, enhanced katabatic winds induced an atmospheric
23 hydraulic jump at the ice shelf edge before the cyclone's warm front arrival, resulting
24 in subsidence adiabatic warming that formed a local warm pool along the eastern coast
25 of Prydz Bay. The cyclone driven strong winds not only exacerbated blowing snow but
26 also triggered intense snowfall on windward slopes, where the snowfall mixed with
27 blowing snow to form snowstorms. As the cyclone entered its terminal phase, the
28 model-simulated wind speed decrease aligned with observations, which should have
29 led to a reduction in blowing snow. However, field observations revealed that blowing
30 snow persisted. Snowfall from the cyclone's shallow cold front made a significant
31 contribution to maintaining this persistent blowing snow. These results highlight the
32 complex interactions between synoptic-scale systems and local topography,
33 emphasizing the importance of more accurate simulations in elucidating the intricate
34 dynamics of Antarctic local weather processes.

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1. Introduction

Antarctica, as the coldest continent on Earth, is characterized by its unique ice-snow underlying surface, strong surface temperature inversion layer, and topography, which jointly shape the katabatic winds that prevail almost throughout the continent all year round (Parish and Bromwich, 1987). During their movement, winds can cause snow particles on the surface of the ice sheet to saltate and detach from the snowpack through stress, and then be entrained into the atmospheric boundary layer by turbulent eddies for further transport, forming blowing snow. Blowing snow is the most direct physical connection between the Antarctic atmosphere and the land surface, and also the main way for the redistribution of surface snow and the adjustment of surface mass balance (Gallée et al., 2001; Déry and Yau, 2002; Lenaerts et al., 2012; Filhol and Sturm, 2015). It profoundly affects almost every link in the Antarctic cryosphere.

The steep topography in the Antarctic marginal zone provides topographical conditions for the formation of strong katabatic winds (Parish and Cassano, 2003), thus providing triggering conditions for the formation of blowing snow. Based on the identification results of blowing snow layers by the Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), and using the response of the blowing snow layer to the backscatter signal intensity and depolarization ratio of spaceborne lidar, it was found that blowing snow increases significantly when wind speed exceeds 4 m s^{-1} , and the winter blowing snow frequency in the coastal area of East Antarctica is over 70% (Palm et al., 2011). On this basis, further analysis of CALIPSO data from 2006 to 2016 revealed a significant correlation between the occurrence frequency of blowing snow and topographic slope, strong wind duration, etc. (Palm et al., 2017). Statistical analysis based on multi-year observation data from Adélie Land in East Antarctica showed that the occurrence frequency of blowing snow at the two observation sites, D47 and D17, increased significantly with the increase in wind speed, but the average wind speed thresholds for the two were slightly different. Meanwhile, the topography of Adélie Land has a strong controlling effect on the surface wind field, making the wind direction almost unidirectional, indicating that topographic factors play an important role in guiding wind direction and forming blowing snow conditions (Amory, 2020). A study further comprehensively used ground observations (DDU, D17, etc.), satellite remote sensing, and high-resolution WRF numerical simulation to conduct research on strong katabatic wind cases in this region, and found that katabatic winds can trigger gravity waves under the combined action of topographic abrupt changes and supercritical dynamic conditions. The upper edge of the resulting blowing snow wall reaches 1000 m, extending 400 km along the coast, indicating that the impact of katabatic winds on blowing snow is not a simple linear enhancement, and the complex dynamic and thermal processes of the boundary layer should be fully considered (Vignon et al., 2020). Similar atmospheric gravity wave phenomena were also observed by the very high frequency doppler radar installed at Syowa Station, but it focused on the vertical disturbance of wind and its dynamic mechanism, without discussing the possible impact on blowing snow (Tomikawa, 2015). Satellite MODIS



78 images reveal frequent snow billows in Terra Nova Bay, driven by strong katabatic
79 winds. These billows reach 200 m vertically, extend tens to 200 km horizontally, and
80 exhibit 5-10 km wavelengths, likely linked to gravity wave activities over steep terrain.
81 They dissipate at ice fall topographic discontinuities, where abrupt topography
82 accelerates winds and enhances snow particle sublimation. This process reduces coastal
83 snow accumulation and transports solid freshwater to the ocean, potentially biasing
84 current local mass balance estimations (Scarchilli et al., 2010). The above studies show
85 that although strong winds are the core initiation mechanism of blowing snow, the steep
86 topography in the Antarctic marginal zone may have significant local differences and
87 nonlinear characteristics in the impact of katabatic winds and blowing snow.

88 The Antarctic margin zone, besides featuring steep topography, serves as a
89 transition zone connecting the Antarctic inland plateau and the Southern Ocean. Here,
90 cold katabatic winds converge with relatively warm onshore flows, leading to strong
91 atmospheric baroclinicity and frequent influences from local polar lows (Stoll, 2022)
92 or mid-latitude cyclone incursions (Priestley et al., 2020). These meso-microscale
93 weather systems not only induce strong winds and temperature advection but also
94 enhance or alter katabatic winds by strengthening the horizontal pressure gradient force
95 between the ice sheet and sea. For instance, a study analyzing 60 years of ground-based
96 meteorological station data revealed that most strong wind events along the coast are
97 associated with the enhancement of downslope winds by synoptic scale cyclone
98 systems (Turner et al., 2009). Another study, leveraging reanalysis data and momentum
99 budget analysis, quantified the contributions of synoptic-scale and local processes to
100 Antarctic coastal wind fluctuations. Results showed that ERA5 reanalysis
101 systematically underestimated extreme wind speeds, implying its inability to fully
102 resolve local dynamics like gravity wave drag or topographic friction (Harrison et al.,
103 2024). Cyclones not only induce strong winds but also bring about abundant snowfall,
104 and the snowfall amount and snow quality directly affect the erodibility and transport
105 volume of blowing snow. A study using micro-rain radar and automatic weather station
106 observations at Princess Elisabeth Station showed that approximately 70% of snowfall
107 events at this site were associated with cyclone activities, prolonged snowfall events
108 expand the snow cover, increasing the likelihood of snow being transported from
109 upstream areas to the observation site by wind. Additionally, the traditional conclusion
110 that katabatic winds dominate snow transport toward the coast may be incomplete, as
111 some snow might be transported inland by strong winds carried by cyclones
112 (Souvereinset al., 2018). In recent years, in-situ observations have confirmed that newly
113 fallen snow, due to its loose structure and low inter-particle bonding strength, is more
114 easily entrained into the air by wind. For example, a study combining lidar ceilometer
115 data from Princess Elisabeth Station and Neumayer III Station found that 92% of
116 blowing snow was related to snowfall introduced by synoptic scale cyclones. The
117 occurrence of blowing snow depends not only on wind speed thresholds but also on
118 recent snowfall amounts, challenging the mainstream view and model parameterization
119 schemes that blowing snow primarily relies on wind speed (Gossart et al., 2017).



Similar phenomena have recently been confirmed by lidar ceilometer observations at Zhongshan Station (St. ZS) in Antarctica (Ye et al. 2025). Additionally, a simulation study based on snowdrift events over the Antarctic Peninsula has revealed that the sublimation of snowdrift is pronounced in dry air, leading to atmospheric cooling and humidification, and may enhance snowfall through cloud microphysical processes (Luo et al., 2021). Synthesizing the above research conclusions, it is evident that multiple factors including cyclones, strong winds, snowfall, snowdrift, and topography are intricately interwoven, exerting significant impacts on the surface mass balance budgets across different regions of Antarctica. Considerable work remains to be conducted to finely characterize this process.

One of the main challenges in accurately characterizing blowing snow in Antarctic lies in the extensive snow-covered land surface, where snow has unique processes such as high albedo, low thermal conductivity, and phase changes, which significantly affect the heat exchange at the atmospheric surface (Mote, 2008; Betts et al., 2014). In recent years, with the development of numerical simulation techniques, most models participating in the World Climate Research Programme Coupled Model Intercomparison Project Phase 6 (CMIP6) have begun to adopt multi-layer snow models with more complex physical process descriptions, considering parameterization processes such as albedo, thermal conductivity, snow density, surface exchange, and snow-vegetation interactions (Eyring et al., 2016). However, from the simulation results of Northern Hemisphere snow cover by CMIP6 models, it is difficult to simply define their improvements over CMIP5 as significant (Mudryk et al., 2023), which to a certain extent indicates that some snow models may not have well solved the previous problems such as resolution simulation limitations under complex terrain (Verfaillie et al., 2018) and snow albedo simulation biases (Thackeray et al., 2019) when inheriting CMIP5. At the same time, CMIP6 models mainly focus on large-scale climate phenomena and long-term climate change trends. However, refined complex models such as SNOWPACK (Bartelt and Lehning, 2022) or Crocus (Vionnet et al., 2012) are more essential for short-term high-resolution simulations. Early models of this type did not achieve real-time coupling of atmospheric processes, and the snow surface model could only run independently. The recently released CRYOWRF coupling model realizes real-time coupling of the non-hydrostatic atmospheric model WRF (Weather Research and Forecasting Model, Skamarock et al. 2008) and SNOWPACK, and adds a blowing snow double-moment scheme, achieving atmospheric non-hydrostatic and refined blowing snow process simulation capabilities in Antarctica and Swiss alpine regions (Sharma et al., 2023), providing a powerful tool for blowing snow simulation under complex terrain and weather backgrounds in Antarctica.

During July 15 to 17, 2022, a severe blowing snow event struck St. ZS in Antarctica. The automatic surface observation station recorded a maximum minute-averaged wind speed exceeding 30 m s^{-1} , while the lidar ceilometer and manual observations indicated that blowing snow persisted for approximately 36 hours, making it one of the strongest blowing snow events affecting St. ZS in 2022. This study uses



the CRYOWRF model to conduct high-resolution simulations of this event, aiming to analyze its development process. The remainder of this paper is structured as follows. Section 2 introduces the data and model; section 3 presents an overview of the synoptic meteorological background and observations. Section 4 analyzes the detailed process of this event, and section 5 provides discussions and conclusions.

2. Data and methods

2.1 ERA5 Reanalysis Data

ERA5 is the fifth-generation global atmospheric reanalysis dataset produced by the Copernicus Climate Change Service (C3S) of the European Centre for Medium-Range Weather Forecasts (ECMWF). It covers climate data from January 1940 to the present (Hersbach et al. 2020). Due to its high precision, high-resolution, long-time span, and diverse parameter types, it has become an essential tool in multiple fields such as meteorological forecasting, climate simulation, environmental monitoring, and climate change research. The ERA5 dataset provides global meteorological variables on a 0.25° grid at hourly intervals across pressure levels ranging from 1000 to 1 hPa. In this study, three-hourly pressure-level data and land surface data were used as background fields and boundary conditions to jointly drive the numerical model.

2.2 Field Observation Data

This study primarily uses two automatic observations: an automatic weather station and a ceilometer, installed at St. ZS, which is located on the Rasman Hills of Princess Elizabeth Land, southeastern Antarctica, along the southeast coast of Prize Bay ($69^\circ 22' 24.7''\text{S}$, $76^\circ 22' 14.2''\text{E}$; see Fig. 1). The automatic weather station provides minute-by-minute measurements of surface wind speed, wind direction, pressure, temperature, etc. The C12 ceilometer, deployed since January 2022, serves as an all-weather cloud measurement sensor. It continuously monitors cloud base height, thickness, and cover, and outputs vertical visibility during obscured sky conditions. Employing 905 nm Mie-scattering LiDAR technology, the ceilometer emits vertical pulse signals every minute, receiving scattered signals from blowing snow, snowfall, clouds, and fog to generate 12000 m vertical analog digital signals with 5 m range gates. The raw signal strength correlates with airborne particulate concentration and size, enabling 5 m resolution for cloud height and vertical visibility (with a measurement uncertainty of ± 15 m). Featuring a sloped south-facing window to avoid direct sunlight, the ceilometer incorporates lens contamination detection and automatic heating for ice/snow removal, ensuring stable operation in Antarctica's extreme winds and temperatures (Ye et al., 2025).

Additionally, this study uses manual observation records from meteorological staff to assist in validating on-site weather conditions. These records mainly document the duration of daily weather phenomena—including blowing snow, snowfall, blizzard, and clear-sky conditions—with measurements taken every 6 hours from 0000 to 1200 UTC.

2.3 Satellite Remote Sensing Data



Thermal infrared channel data from Band 31 (central wavelength of $11.03 \mu\text{m}$) obtained by the Moderate Resolution Imaging Spectroradiometer (MODIS) payload aboard the Terra and Aqua Earth-observing satellites is also used to visually observe the movement of the cyclone. The data has a spatial resolution of $1 \text{ km} \times 1 \text{ km}$ and a swath width of 2330 km. Based on this data, infrared brightness temperature images of the area around Prydz Bay during the event were generated to visually reflect the brightness temperature of the surface or cloud tops.

2.4 Model Description and Case Simulation Configuration

The CRYOWRF model is a multi-scale atmospheric-snowpack coupling simulation framework specifically developed for the cryosphere (such as snow cover, glaciers, ice sheets and other regions). Its core integrates the mainstream mesoscale atmospheric model WRF with the high-complexity SNOWPACK model through online coupling technology, and introduces a new blowing snow parameterization scheme to achieve snow-atmosphere interaction simulation from synoptic scale to turbulent scale. The model aims to address the problems of simplified snow processes and missing blowing snow effects in traditional models, and provides more accurate tools for climate change, water resource management, natural disaster prediction and other fields. Among them, SNOWPACK can resolve the vertical stratification of snowpack and particle-scale processes, such as the physical processes of snow density, temperature, and grain morphology evolution. In addition, bidirectional real-time interaction between the atmosphere and snowpack is realized, that is, WRF provides driving data such as wind and radiation to SNOWPACK, and SNOWPACK feeds back surface albedo, sensible/latent heat flux and snowpack status (such as erosion/deposition amount) to achieve mass and energy conservation. In terms of blowing snow simulation, by introducing a double-moment blowing snow scheme in WRF cloud microphysical parameterization, the ability to simulate the mass mixing ratio and number concentration of blowing snow particles in WRF is realized.

The model domain features a triple-nested configuration with horizontal grid resolutions of 12, 4, and 1 km, comprising grid sizes of 123×124 , 187×190 , and 505×505 , respectively. Vertically, it employs 69 vertical layers with the model top set at 50 hPa. The horizontal domain configuration is illustrated in Fig. 1. For parameterization schemes, both long-wave and short-wave radiation are handled by the RRTMG (Rapid Radiative Transfer Model for General Circulation Models) scheme (Iacono et al., 2008). The planetary boundary layer is resolved by the MYNN 2.5-level TKE (Turbulent Kinetic Energy) scheme (Nakanishi, M., & Niino, H., 2004). The Morrison double-moment microphysics scheme is applied for microphysical parameterization (Morrison et al., 2005), and the Kain-Fritsch (new Eta) scheme is used for cumulus convection parameterization (Kain, 2004). The land surface component utilizes the SNOWPACK module. The simulation was initiated at 12:00 UTC on 14 July 2022, running for 60 hours. Notably, the first 12 hours of this simulation served as a spin-up phase, and results from this period were excluded from the analysis.

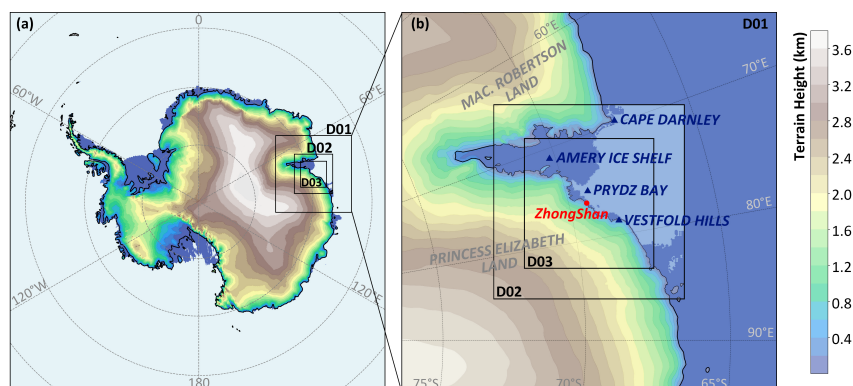


Figure 1. Model domain and corresponding topographic distribution for the three nested domains: D01, D02, and D03. The model utilizes a triple-nested setup with horizontal grid resolutions of 12 km for the outermost domain (D01), 4 km for the intermediate domain (D02), and 1 km for the innermost domain (D03).

3. Weather background, observations and model validation

Figure 2 depicts the circulation background fields at the 500 hPa and 850 hPa pressure levels during the period from 00:00 UTC on 15 July 2022 to 00:00 UTC on 17 July 2022, as derived from ERA5 data. At 00:00 UTC on 15 July 2022, an incipient extratropical cyclone was positioned in the vicinity of coordinates (58.8°S, 62.0°E). At this specific time point, a fully developed closed circulation center had already manifested at the 850 hPa, whereas the corresponding closed center structure at 500 hPa was in its nascent stage of development (Figs. 2a and 2d). Under the steering influence of an upper-level trough, the extratropical cyclone commenced its trajectory towards the Prydz Bay region of the Antarctic continent. Within the subsequent one-day period, the cyclone underwent explosive development. By 00:00 UTC on July 16 2022, a complete rotational structure of the cyclone was observed from the 850 hPa to the 500 hPa levels, and its center was approaching the Cape Darnley in the north, located on the western side of the Amery Ice Shelf (Figs. 2b and 2e). At 850 hPa, the cyclone carried a strong maritime warm advection, resulting in a significant temperature rise in Prydz Bay and along the continental margin to its east (Fig. 2e). At 500 hPa, the warm ridge had extended deep into the upper atmosphere of the continent, reaching approximately 75°S (Fig. 2b). Thereafter, during the process of the cyclone making landfall on the Antarctic continent, under the combined influence of unfavorable factors such as topographic friction and the entrainment of cold air masses, the intensity of the core part of the cyclone began to decrease rapidly. As can be seen from the situation at 00:00 UTC on July 17 2022, the air pressure at the cyclone center started to rise, the temperature dropped, and the wind force in the periphery decreased significantly (Figs. 2c and 2f). The cyclone dissipated within the following one day.

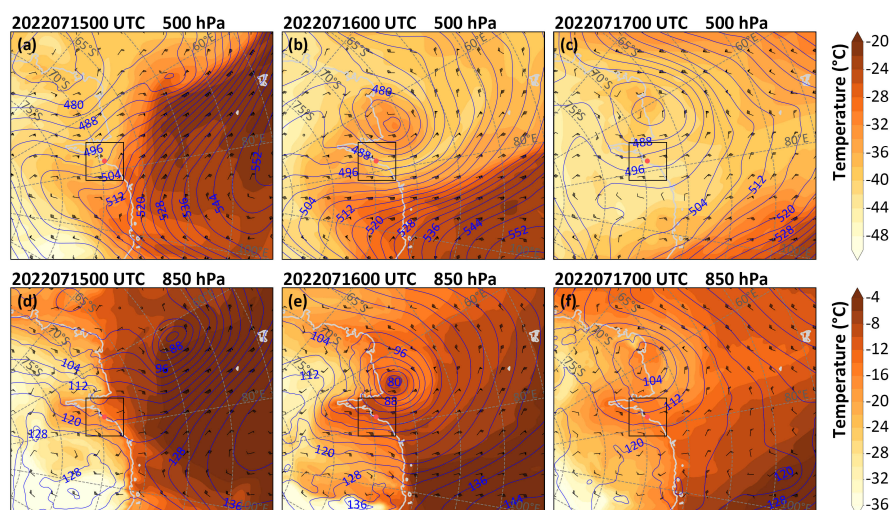


Figure 2. Distribution of geopotential metre (gpm, blue solid lines), temperature (color shading), and wind vectors (triangular pennants representing 20 m s^{-1} , long horizontal bars indicating 4 m s^{-1} , and short horizontal bars denoting 2 m s^{-1}) at 500 hPa ((a)-(c)) and 850 hPa ((d)-(f)) from 00:00 UTC on 15 July 2022 to 00:00 UTC on 17 July 2022, as derived from ERA5 data. The red dot in these subplots represents the location of St. ZS. The black rectangles denote the D03 domain of the model simulation.

During this event affected by the cyclone intrusion, St. ZS, marked with a red dot in Fig. 1) endured a remarkable onslaught of strong winds and snowstorms, where the snowstorm refers to the simultaneous occurrence of blowing snow and snowfall. This process was completely recorded by the ground-based automatic weather station, laser ceilometer, and through manual observations at St. ZS. Figure 3 shows the time-varying conditions of wind speed, wind direction, temperature, and sea level pressure obtained from the automatic weather station and the model simulation. According to the surface wind observations, it can be found that the process affected by the cyclone can be roughly divided into three characteristic stages. The first stage is prior to 11:00 UTC on July 15 2022. Throughout this period, even though there was a notable decrease in sea level pressure, the wind speed at St. ZS remained at a relatively low magnitude. There was even a gentle breeze (less than 5 m s^{-1}) that persisted for several hours. In the meantime, the wind direction exhibited the characteristic of unstable oscillation. To be specific, when the wind speed was relatively high, the wind predominantly blew from the northeast, whereas when the wind speed was relatively low, the east-southeast wind became the dominant. In addition, the increase in temperature preceded the increase in wind speed. The second stage was from 11:00 UTC on July 15 2022, to 00:00 UTC on July 16 2022. During this period, as the sea level pressure continued to drop, the wind speed surged, and the temperature kept rising, indicating that the core wind speed area of the cyclone had affected the station area. The surface wind speed reached its maximum of 30 m s^{-1} at 15:00 UTC on July 15 2022. Meanwhile, after the wind speed exceeded 15 m s^{-1} , the wind direction remained stable at around 65 degrees. The third



stage was from 00:00 UTC on July 16 2022, to 00:00 UTC on July 17 2022 (the end of the simulation). During this time, accompanied by the rising rate of sea level pressure, the wind speed decreased in tandem, and the wind direction remained stable at around 60 degrees, indicating that the influence of the cyclone was weakening.

The results of the model simulation are in good agreement with the observations both in terms of the trend and the magnitude of the elemental values. There are two obvious discrepancies. One is in the wind direction from 09:00 to 11:00 on July 15 2022. This may be because the wind speed value is very low at this time, and the simulation results are easily affected by local topographical or thermal disturbances, and the wind direction may experience disordered fluctuations. The other is after 08:00 on July 16 2022. Although the surface temperature decreases, the simulation result shows a greater decrease than that of the observation.

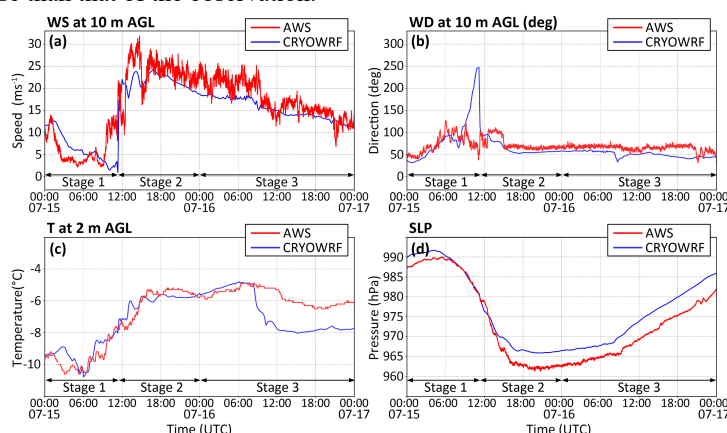


Figure 3. Time series of (a) wind speed and (b) wind direction at a height of 10 meters above the ground (AGL), (c) temperature at a height of 2 meters AGL, and (d) sea level pressure obtained from the automatic weather station and model simulations at St. ZS.

Based on the backward scattering signal profile of the lidar ceilometer installed at St. ZS shown in Fig. 4, around 11:00 UTC on July 15 2022, the lidar ceilometer first detected snowfall in the air, with the signal appearing at a height of approximately 300 meters above the ground (AGL). About an hour later, the backward scattering signal almost reached the ground, indicating the occurrence of blowing snow at the surface. At this time, manual observations simultaneously recorded snowfall, blowing snow, and snowstorms, which verifies the credibility of the observations from the lidar ceilometer. According to the model simulations, strong winds, snowfall, and blowing snow all started at 11:00 UTC on July 15 2022. Among them, the blowing snow reached its peak around 18:00 UTC on July 15 2022, when its development height also reached 500 meters AGL. Overall, the intensity of the blowing snow obtained from the simulation shows a good consistency with the wind speed. This is quite understandable because the blowing snow in the model originates from the saltation of snow particles on the surface, which mainly depends on the critical velocity.

Simulation results clearly demonstrate that the magnitude of the mass mixing ratio



for snowfall is significantly higher than that for blowing snow. Nevertheless, in the actual atmospheric environment, the scattering signal detected by the lidar ceilometer encompasses a combination of blowing snow and snowfall components. Consequently, it is logical and expected that the high values measured by the lidar ceilometer exhibit a closer correspondence with snowfall. In this case for instance, the snowfall event that took place from 11:00 UTC to 19:00 UTC on July 15 2022, precisely overlaps with the time interval during which the lidar ceilometer registered elevated backward scattering signals. It is important to emphasize that owing to the substantial attenuation effect exerted by snow particles, the lidar ceilometer's signal is unable to penetrate areas characterized by a high density of particles. As a result, the vertical thickness of the region with high intensity scattering signals is around 100 meters. Following 00:00 UTC on July 16 2022, a rapid decline in wind speed led to the disappearance of blowing snow in the model simulation outcomes. In contrast, both lidar ceilometer measurements and manual observations indicate the intermittent occurrence of blowing snow or snowstorms, suggesting that the model may encounter certain limitations in simulating this particular stage of the process.

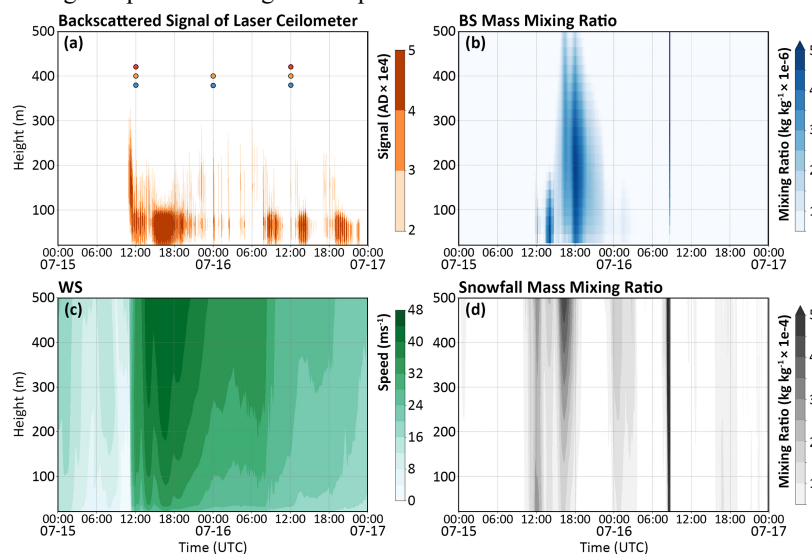


Figure 4. (a) Backscatter profile observed by the lidar ceilometer at St. ZS, as well as (b) the profiles of mass mixing ratio of blowing snow, (c) horizontal wind speed and (d) mass mixing ratio of snowfall calculated by the model. In (a), the manual observation results at 6-hour intervals are marked with dots in three colors, with blue, yellow, and red respectively representing snowfall, blowing snow, and snowstorm. The starting point of the vertical coordinate is 13 meters (the height of St. ZS at the corresponding position in the model).

4. The Main characteristics of the three stages of the event

4.1 Atmospheric hydraulic jump and local breeze

Both the wind speed observations from the automatic surface meteorological station and the simulation results (Fig. 3) indicate that St. ZS experienced approximately six hours of gentle breeze and a significant temperature increase before



the arrival of strong winds (11:00 UTC on 15 July 2022), and the temperature rise preceded the increase in wind speed. Figure 5 depicts the distribution of meteorological elements along the surface (ground/sea) at 10:00 UTC on 15 July 2022. From the vertical wind speed field at 10 m (Fig. 5b) and the surface temperature at 2 m (Fig. 5c), a prominent downward motion, characterized by cold katabatic winds, can be observed across the continental surface, with vertical velocities exceeding 1 m s^{-1} in the coastal areas. The winds in the St. ZS region flow from the plateau towards the ocean along the terrain gradient, approximately 30° counterclockwise from the maximum slope line (Fig. 5a). At this time, wind speeds exceeded 16 m s^{-1} both upstream on the continental plateau and downstream over the ocean. However, a localized low wind speed zone accompanied by a corresponding high temperature region emerged over the ocean near St. ZS. Additionally, due to the already strong surface winds on most parts of the plateau, extensive blowing snow was simulated (Fig. d), whereas no blowing snow was detected at St. ZS due to the weak winds (Fig. 4b).

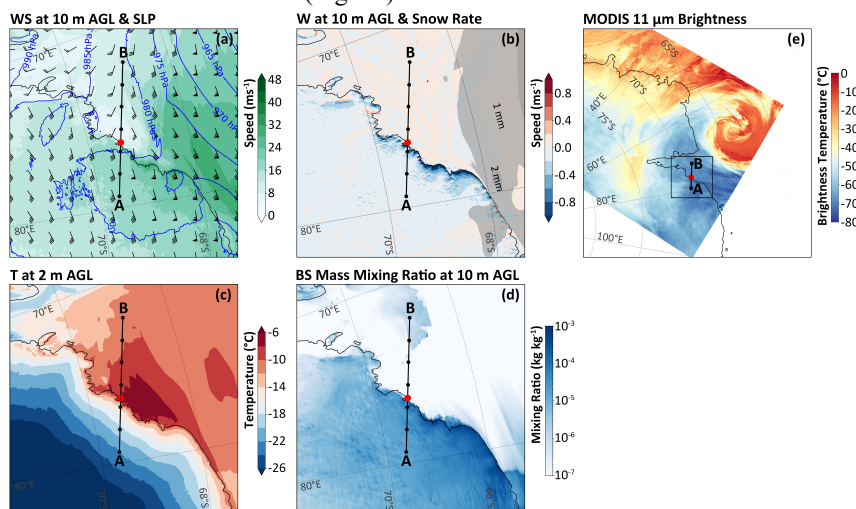


Figure 5. Simulation results of meteorological elements at the ground (sea surface) at 10:00 UTC on July 15 2022. (a) Horizontal wind at 10 meters AGL (color filling representing speed value; triangular pennant, long horizontal bar and short horizontal bar on the wind barb indicating a wind speed of 20 m s^{-1} , 4 m s^{-1} and 2 m s^{-1} , respectively) and sea level pressure (blue solid lines). (b) Vertical wind speed at 10 meters AGL (color filling) and snowfall rate at the surface (snowfall amount per hour, grayscale filling). (c) Air temperature at 2 meters AGL, (d) Mass mixing ratio of blowing snow at 10 meters AGL. (e) MODIS $11 \mu\text{m}$ brightness product at 11:30 UTC on July 15 2022. The black straight lines represent the position of the cross-section shown in Fig. 7, and the black rectangle on (e) denotes the D03 domain of the model simulation, i.e., the area of Figs. (a)-(d).

Figure 6 presents the distributions of wind speed, pressure, and temperature at three altitude levels of 20 m, 1.5 km, and 3 km at 10:00 UTC on 15 July 2022. The warm advection transported by the warm front of the cyclone intruded over the continent at higher altitudes earlier. For instance, at 3 km, a significant high-temperature region has emerged across the eastern part of Prydz Bay. In contrast, the warming areas at 1.5 km and 20 m are notably smaller. At 20 m, a localized warming zone between the



outer edge of the Amery Ice Shelf and the West Ice Shelf is particularly prominent. However, this warming is not attributed to horizontal advection, as indicated by the combination of wind direction and temperature distribution (Figs. 6a and 6d), which shows that this area remains unaffected by the warm advection. At 1.5 km, the airflow moves across the terrain promontory (around Vestfold Hills), accelerates along the steep terrain, and forms a horizontal jet stream (barrier wind) with speeds approaching 40 m s^{-1} , extending westward to 75°E . This jet stream transports warmer air masses toward the continent, creating a warming belt along the eastern coast of Prydz Bay at 1.5 km. Additionally, a distinct low wind speed belt exists along the north of the jet stream, and St. ZS is precisely located on this low wind speed belt.

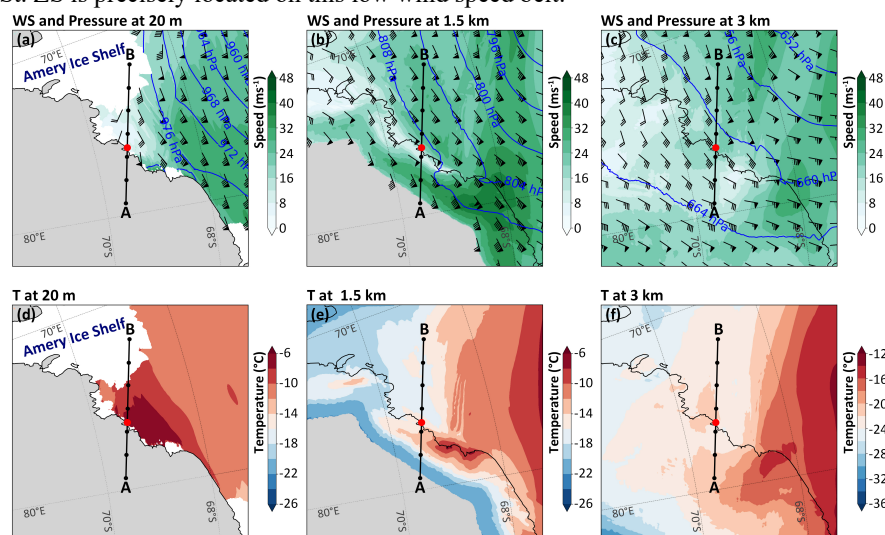


Figure 6. Simulation results of meteorological elements at an altitude of 20 m ((a) and (d)), 1.5 km ((b) and (e)) and 3 km ((c) and (f)) at 10:00 UTC on July 15 2022. The first row shows the horizontal wind (color filling representing speed value; triangular pennant, long horizontal bar and short horizontal bar on the wind barb indicating a wind speed of 20 m s^{-1} , 4 m s^{-1} and 2 m s^{-1} , respectively) and air pressure (blue solid lines), and the second row shows the temperature. The black straight lines represent the position of the cross-section shown in Fig. 7, and the white masked areas in (a) and (d) represent the regions of the ice shelf.

In order to further analyze the airflow movement at the upper and lower levels, a cross-sectional analysis was conducted along the direction of the surface wind speed at St. ZS at this moment, as shown in Fig. 7. From the cross-sectional wind field (Figs. 7a and 7c), it can be seen that there is a high wind speed layer with a thickness of approximately 1 km near the surface of the plateau ice sheet. The horizontal wind speed in the section exceeds 24 m s^{-1} , and it moves downward along the terrain from the plateau, which is a cold katabatic wind (Fig. 7b). There is a folded area of potential temperature isopleths above the katabatic wind layer, the horizontal wind speed in the sectional projection is very low in this area while the vertical movement is significant, indicating that the kinetic energy is dissipated by the hydraulic jump. The low wind speed zone observed at an altitude of 1.5 km mentioned earlier (Fig. 6b) is precisely the



location of the hydraulic jump area. At the same time, as the terrain gradient becomes rapidly steeper when approaching the continental margin, the thickness of the katabatic wind is further compressed. The most intense warming and vertical leap occur at the location with the largest gradient in the marginal area of the ice sheet (at the 115 km position of the section). The potential temperature isopleths here are almost perpendicular to the ground, indicating that after the downslope air mass reaches the ground, it piles up and moves vertically due to obstruction, resulting in a sharp decrease in the wind speed and an increase in temperature downstream. The low wind speed zone below an altitude of 0.5 km extends downstream to the edge of the Amery Ice Shelf.

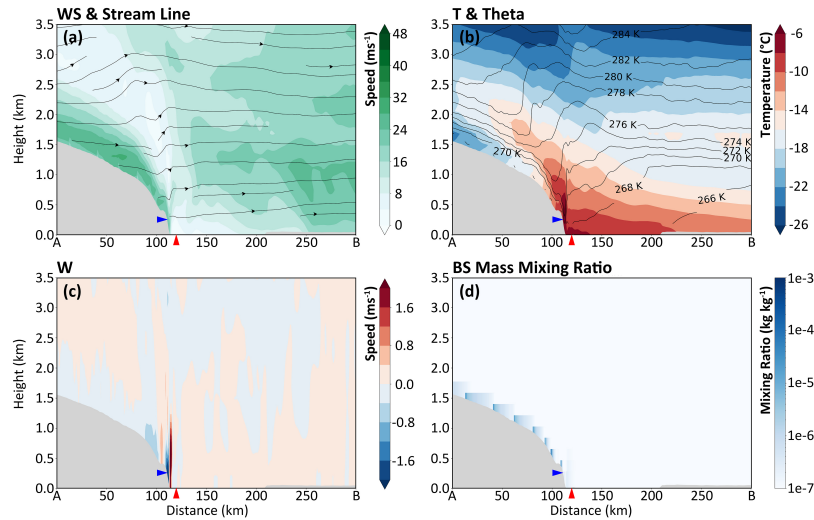


Figure 7. Simulation results of meteorological elements at the cross-section passing through St. ZS (marked by the black straight line in Figs. 5 and 6) at 10:00 UTC on July 15 2022. (a) Horizontal wind speed and streamlines of the sectional projection (the vertical wind speed is magnified by 400 times when drawing the streamlines). (b) Temperature field (color shading) and potential temperature field (black solid lines). (c) Vertical wind speed. (d) Blowing snow mass mixing ratio. The position marked by the red triangle is the location of St. ZS, and the blue triangle is the selected point for the advection analysis (see the main text for details).

The thermodynamic energy equation is employed to determine the cause of temperature change on an isobaric surface (Clark, et al., 2021), which is mathematically expressed as:

$$\frac{\partial T}{\partial t} = -\left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}\right) - w \frac{\partial T}{\partial z} - w\Gamma_d + Q$$

Where $-\left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}\right)$ denotes the horizontal temperature advection term, $-w \frac{\partial T}{\partial z}$ represents the vertical temperature advection term, and $-w\Gamma_d$ is the adiabatic term. The temperature changes and their contributing terms at an altitude of 20 m AGL at St. ZS and its adjacent upstream point (coordinates (69.39 °S, 76.60 °E), located on the cross-section in Fig. 7 and marked by a blue triangle) were diagnosed, and the results are shown in Fig. 8. Although the horizontal distance between the two points is less than 10 km, and their warming paces are consistent, that is, rapid warming begins



at 06:00 UTC on 15 July 2022, the main contributing terms are quite different. Since the upstream diagnostic point is located at the core of adiabatic warming, the adiabatic warming effect is the key reason for its temperature increase, while the horizontal advection acts to transport the heat generated by adiabatic warming downstream (Fig. 8b). Notably, around 08:40 UTC on 15 July, significant subsidence occurred at the upstream point. At this time, the dynamic pressure ($\frac{1}{2}\rho v^2$) gradient exhibited a significant negative growth, indicating a sudden decrease in dynamic pressure at this point (Fig. 8d), with kinetic energy converted into potential energy and turbulent kinetic energy. The abrupt increase in subsidence velocity coincided with a rapid decline in the dynamic pressure gradient, reflecting the subsidence velocity's response to the continuity of the flow field. Concurrently, the adiabatic warming effect and vertical advection intensified significantly with the subsidence motion. At approximately 09:30 UTC on 15 July, both vertical advection transport and adiabatic subsidence warming peaked simultaneously. This phenomenon can be attributed to both the enhanced subsidence motion and the arrival of higher-altitude temperature advection above the observation point, which initiated the warming of the upper air earlier than the ground surface (see Fig. 6e). Driven by the intense katabatic wind, this heat was rapidly advected downward and concurrently transported downstream via horizontal advection.

For St. ZS, situated downstream of the steep terrain, the warming it experiences primarily stems from horizontal and vertical advection. When compared to its upstream location, the contributions of advection and adiabatic effects to the temperature are one order of magnitude smaller. This is because St. ZS is influenced by strong turbulent mixing within the hydraulic jump, consequently leading to a significantly low wind speed at its location. Moreover, since these two points are situated in the transition zone from laminar to turbulent flow of the hydraulic jump, the contribution of the adiabatic effect to warming exhibits an opposite trend, which denotes opposing vertical movements. Meanwhile, the contribution of the advection effect also shows an inverse pattern, indicating the transfer of energy from the upstream region.

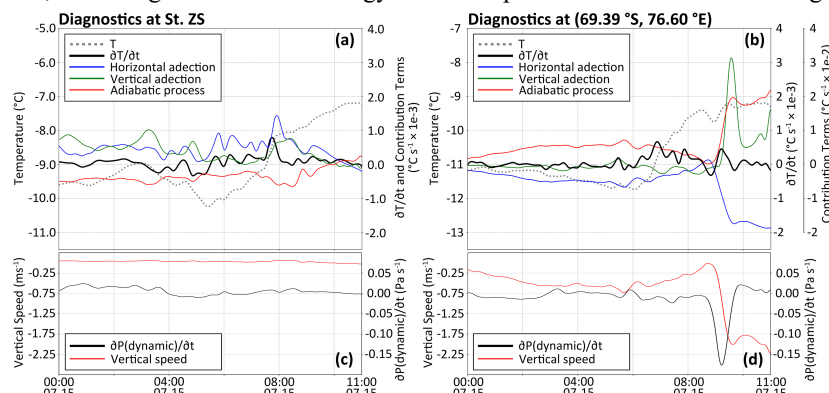


Figure 8. Thermodynamic diagnostics at St. ZS and its adjacent upstream point (69.39 °S, 76.60 °E). (a) Temperature, temperature changes, and their contributing terms at St. ZS. (c) Vertical velocity and horizontal gradients of dynamic pressure. (b) and (d) are consistent with (a) and (c), except that



the diagnostic point is (69.39 °S, 76.60 °E).

4.2 Strong winds, blowing snow and snowfall

After 11:00 UTC on July 15 2022, as the cyclone approached the western side of the Prydz Bay (Figs. 2b and 2e), the strong wind zone swept across the eastern side of the Prydz Bay. By 18:00 UTC on July 15 2022, the strong shear line of the surface frontal zone was located over the Amery Ice Shelf, fierce northeasterly winds prevailed from the sea surface to the plateau land surface (Fig. 9a). The intense surface winds triggered severe blowing snow over the land. Concurrently, northeasterly winds transported the blowing snow at the terrain promontory around Vestfold Hills and the West Ice Sheet downstream, forming a distinct transport belt over the sea surface. In addition, influenced by the cyclone's water vapor transport and orographic lifting, heavy snowfall centers with a rate exceeding 3 mm per hour emerged on the frontal surface of the Amery Ice Shelf and at the terrain promontories on both the east and west sides of St. ZS, which is mainly attributed to dynamic orographic lifting.

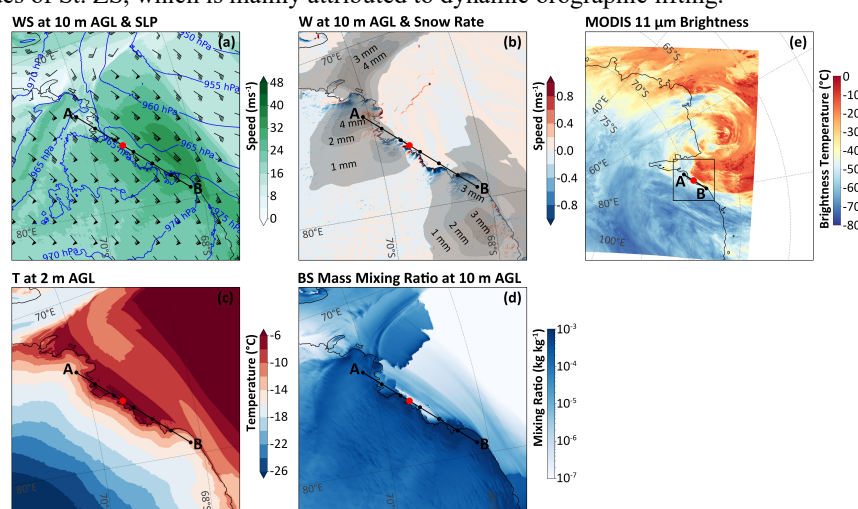


Figure 9. Similar to Fig. 5, but the simulation results ((a)-(d)) are taken at 18:00 UTC on July 15 2022; while the MODIS product is taken at 19:35 UTC on July 15 2022. The black straight lines represent the position of the cross-section shown in Fig. 11, and the black rectangle on (e) denotes the D03 domain of the model simulation, i.e., the area of Figs. (a)-(d).

Figure 10 presents the distributions of wind speed, pressure, and temperature at three altitude levels of 20 m, 1.5 km, and 3 km at 18:00 UTC on 15 July 2022. At this moment, the warming brought about by the cyclone has basically covered the entire region at the three altitude levels. At the altitudes of 20 m and 1.5 km, the strong winds flow along the terrain, this topographically guided movement leads to a significant departure from the conditions during the previous hydraulic jump stage; specifically, the low altitude region of St. ZS now features consistent northeasterly winds.

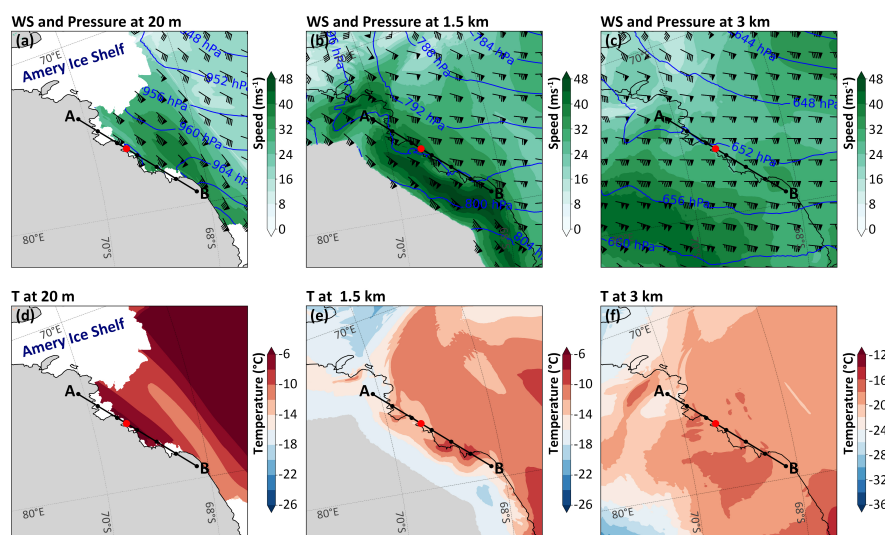


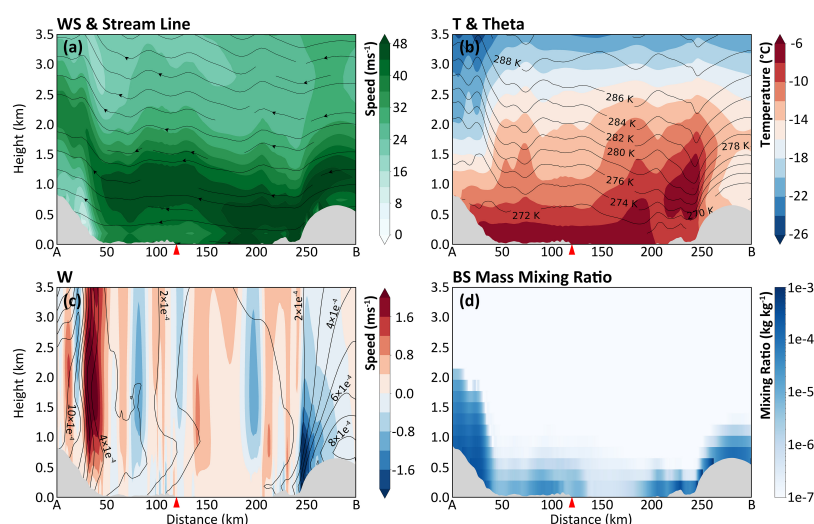
Figure 10. Similar to Fig. 6, but taken at 18:00 UTC on July 15. The black straight lines represent the position of the cross-section shown in Fig. 11, and the white masked areas in (a) and (d) represent the regions of the ice shelf.

Similarly, an analysis was conducted along the cross-section passing through St. ZS, as illustrated in Fig. 11. The figure reveals that once the strong winds reached the Vestfold Hills, they were disrupted by the topography, leading to the generation of powerful downslope winds on the leeward side. The strong wind zone, situated below 1.5 km, recorded wind speeds surpassing 40 m s^{-1} . In contrast, the strong surface winds, upon being uplifted by the terrain to the west, formed a region with comparatively reduced wind intensity below 500 meters, as illustrated in Fig. 11a. The downslope wind was accompanied by significant adiabatic warming. Consequently, regions with increased temperatures amassed along the eastern coast of Prydz Bay, as shown in Fig. 10d. A detailed examination of the conditions at the 1.5 km and 3 km constant elevation surfaces (Figs. 10e and 10f) reveals that the air temperature predominantly originates from the warm advection transported by the cyclonic circulation. Based on the vertical velocity distribution, the downslope winds induced lee waves, leading to an alternating sequence of positive and negative vertical velocity values along the cross section (Fig. 11c).

The terrain promontory on the western side of St. ZS exerts a blocking effect on the airflow, thereby forcing the air to rise. This forced updraft effectively transports blowing snow to higher altitudes, with regions characterized by a high mass mixing ratio of blowing snow extending up to 1 km above the ground. Additionally, as indicated by the snowfall mass mixing ratio in Figs. 9b and 11c, the areas with peak snowfall amounts are located above the windward slopes of the terrain (e.g., at the positions corresponding to 10 km and 290 km on the horizontal axis of Fig. 11c), which is strongly associated with the dynamic orographic lifting effect. The strong winds generated on the leeward slopes of the terrain can entrain more snow particles into



538 saltation, and simultaneously, heavier snowfall above the terrain makes the newly fallen
539 snow on the surface more prone to saltation, thus resulting in the leeward slopes
540 witnessing a mixture of blowing snow and snowfall, which significantly increases the
541 likelihood of snowstorm occurrences.



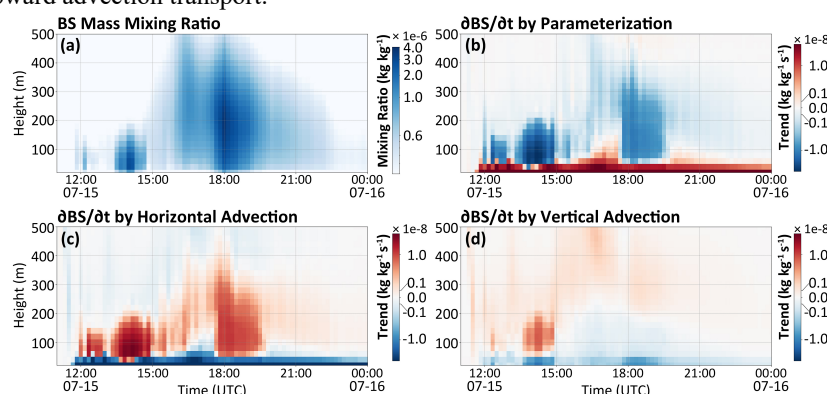
542 Figure 11. Similar to Fig. 7, but taken at 18:00 UTC on July 15. Additionally, the solid line in (c)
543 represents the mass mixing ratio of snowfall obtained from model simulations. The cross-section is
544 indicated by the black straight line shown in Figs. 9 and 10.
545

546 Precisely positioned between two elevated terrain promontories, St. ZS lies in the
547 region of less intense wind (Fig. 11a), resulting in relatively weak blowing snow (Fig.
548 11d). By diagnosing the variations in the blowing snow mass mixing ratio at St. ZS
549 obtained from model simulations, Figure 12 illustrates the primary sources of blowing
550 snow at this site during this stage. Since the blowing snow mass mixing ratio in the
551 model is determined by the SNOWPACK surface model's output of saltation flux to the
552 lower atmospheric boundary, which mainly depends on the critical threshold of
553 frictional velocity. As illustrated in Fig. 12b, positive parameterization contributions
554 predominantly manifest at an altitude of 50 - 60 meters above the ground within the
555 surface layer, primarily due to the enhanced external forcing (saltation) at the lower
556 boundary, which, driven by strong winds, infiltrates the surface layer via surface
557 turbulent mixing. Meanwhile, although the blowing snow mass mixing ratio is strongest
558 in the surface layer, the horizontal advection due to strong winds is also intense (Fig.
559 12c), significantly diverting the blowing snow mass mixing ratio from the surface.
560 Additionally, the parameterization process mainly shows negative contributions from
561 the surface layer upwards, as the other three physical processes included in the
562 parameterization scheme, i.e., deposition, diffusion, and turbulent mixing, act jointly to
563 reduce the blowing snow in the air.

564 Besides diverting the blowing snow mass mixing ratio in the surface layer,
565 horizontal advection also contributes to the relatively higher blowing snow mass



566 mixing ratio above the surface layer, which mainly stems from the transport of upstream
567 winds. Furthermore, throughout the entire stage, strong winds, disrupted by the terrain,
568 predominantly induced upward vertical motion in the lower atmosphere of St. ZS (refer
569 to Fig. 11c). This vertical motion facilitated the upward transport of blowing snow
570 particles, resulting in positive vertical advection above the high value region of the
571 blowing snow layer and negative advection below (Fig. 12d). Overall, the impact of
572 vertical advection was approximately an order of magnitude smaller than that of
573 horizontal advection and parameterization, with only during the wind onset phase, such
574 as around 14:00 UTC on July 15, the sudden surge in upward motion led to significant
575 upward advection transport.



576
577 Figure 12. Profiles of (a) the mass mixing ratio of blowing snow, and (b) - (d) the variation tendency
578 of blowing snow, encompassing the contributions from the parameterization scheme, horizontal
579 advection, and vertical advection.

580

581 4.3 Weakened wind and continuous blowing snow

582 After 00:00 UTC on July 16 2022, as the cyclone center made landfall near Fram
583 Bank, the cyclone began to weaken. Both surface observations and simulation results
584 have shown that the air pressure started to gradually rise, and the wind speed also
585 gradually decreased (Fig. 3). As previously mentioned, although with the rapid decay
586 of the wind speed, the blowing snow simulated by the model ceased quickly, and the
587 observations from the lidar ceilometer also showed that the blowing snow weakened
588 rapidly and was intermittent. However, after 08:00 UTC on July 16 2022, both the lidar
589 ceilometer and manual observations indicated the occurrence of snowfall and blowing
590 snow, and manual observations also recorded the occurrence of a snowstorm, which
591 ended at 00:00 UTC on July 17 2022. Coincidentally, at 08:30 UTC on July 16 2022,
592 the model simulation showed a short-term heavy snowfall, which precisely coincided
593 with the time when the lidar ceilometer again detected continuous blowing snow around
594 08:00 UTC on July 16 2022 (Fig. 4).

595 Figure 13 and Figure 14 respectively show the distribution of meteorological
596 elements along the surface and at various altitude levels at 08:30 UTC on July 16 2022.
597 From the simulation results, it can be seen that as the cyclone makes landfall, although



598 the intensity of its center weakens, due to the center approaching the continent, the
599 annular flow field around the center drives the air to move along the eastern coastline
600 of the Prydz Bay, while the strong wind speed area has moved to the middle-eastern
601 region of the Amery Ice Shelf. At this time, a narrow rain belt just sweeps across the
602 eastern coast of the Prydz Bay, and the snowfall rate at St. ZS reaches 2 mm per hour
603 (Fig. 13b). From the temperature field configuration at multiple altitude levels (Figs.
604 14d and 14e), it can be found that the rain belt is located on the temperature gradient
605 zone (i.e., the cold front) in the lower atmosphere. The cold front is relatively shallow,
606 being more evident below an altitude of 1.5 km and less so above 3 km. On the section
607 along the dominant wind direction at St. ZS and crossing the frontal surface, the
608 potential temperature isopleths bend upward from the ground to an altitude of 1.5 km
609 in the northeast area of St. ZS, while within this altitude range the temperature exhibits
610 a southwest-northeast gradient with higher values in the southwest and lower values in
611 the northeast (Fig. 15b). Judging from the vertical velocity and the mass mixing ratio
612 of snowfall (Fig. 15c), the strongest vertical upward motion occurs exactly on the
613 frontal surface, which is significantly related to the superposition of the dynamic
614 characteristics of the cold front and the topographic lifting effect. Consequently, this
615 position also features the highest mass mixing ratio of snowfall, serving as the primary
616 cause of the snowfall on the surface of St. ZS at this moment.

617 In addition, from the time series of the mass mixing ratio of blowing snow obtained
618 from the model simulation (Fig. 4b), at this moment, accompanied by snowfall, blowing
619 snow occurs for a very short period, but the blowing snow does not reach the ground.
620 This is mainly because the strong wind in the frontal convergence zone causes the
621 blowing snow to form a slender blowing snow conveyor belt along the frontal surface,
622 which precisely coincides with the rain belt (Fig. 13d). However, the reality is that both
623 the observations by the laser ceilometer and manual observations show that after the
624 cold-front snowfall simulated by the model, the blowing snow phenomenon continues
625 to occur (Fig. 4a), indicating that new snow, due to its fluffy structure, low adhesion,
626 and uncompacted snow layer, is more prone to saltation.

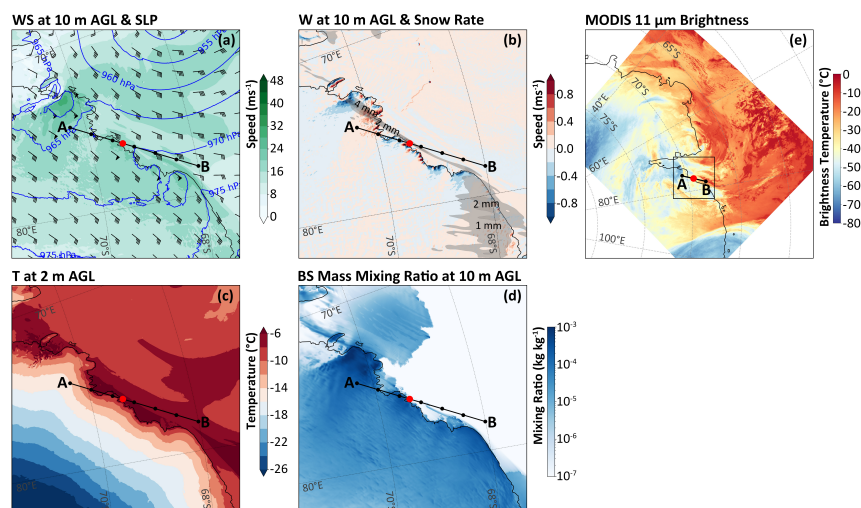


Figure 13. Similar to Fig. 5, but the model simulations ((a)-(d)) are taken at 08:20 UTC on July 16 2022; while the MODIS product is taken at 10:35 UTC on July 16 2022. The black straight lines represent the position of the cross-section shown in Fig. 15, and the black rectangle on (e) denotes the D03 domain of the model simulation, i.e., the area of Figs. (a)-(d).

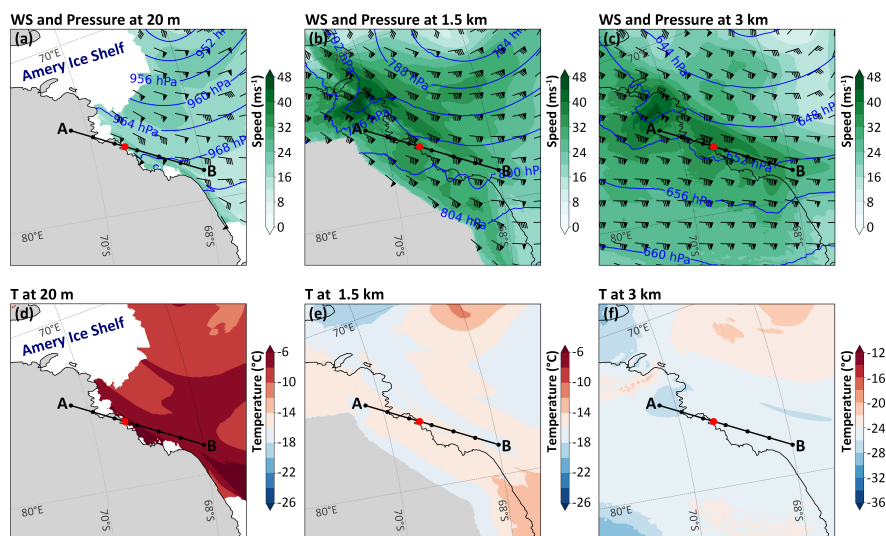


Figure 14. Similar to Fig. 6, but taken at 08:20 UTC on July 16. The black straight lines represent the position of the cross-section shown in Fig. 15, and the white masked areas in (a) and (d) represent the regions of the ice shelf.

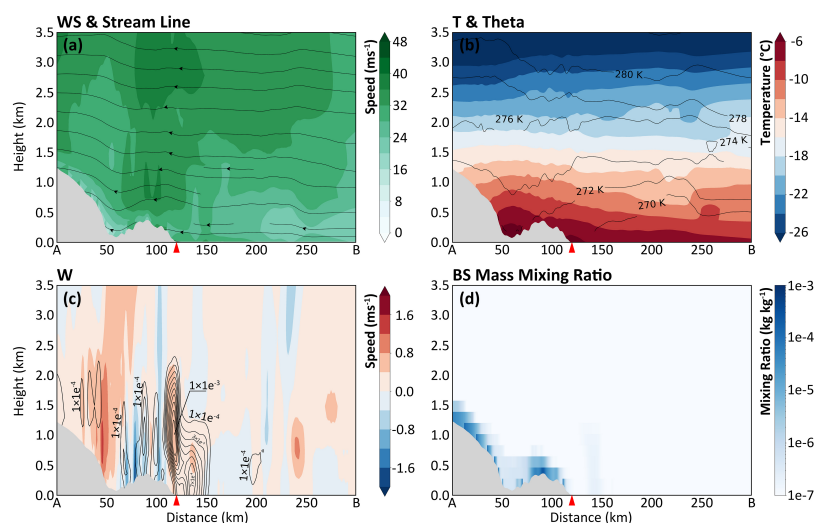


Figure 15. Similar to Fig. 7, but taken at 08:20 UTC on July 16. Additionally, the solid line in (c) represents the mass mixing ratio of snowfall obtained from model simulations. The cross-section is indicated by the black straight line shown in Figs. 13 and 14.

In the design of the CRYOWRF model, atmospheric and snowpack processes are coupled in real-time. Through sensitivity experiments, the impacts of atmospheric precipitation on land surface processes (e.g., snow depth, temperature, and erosion) are further analyzed. Figure 16 presents the change of snow depth during the event from 00:00 UTC on July 15, 2022 to 00:00 UTC on July 17, 2022. A comparison of the results from the control experiment (which considers both blowing snow and snowfall) and the sensitivity experiment (which only considers snowfall without blowing snow) shows that during the entire event, snowfall was the main source of snow accumulation on the ice sheet surface. The areas with the most significant increase in snow depth correspond to the high-value regions of cyclonic frontal precipitation (as shown in Fig. 9b). In the control experiment, due to the presence of blowing snow erosion, the accumulated snow depth was generally smaller than that in the sensitivity experiment. Meanwhile, the most significant blowing snow erosion occurred along the coast of Prydz Bay (including St. ZS) and the leading edge of the Amery Ice Shelf. Based on the analysis of previous simulation results, these areas had relatively little snowfall overall and were located in the core strong wind zones (Fig. 10a and Fig. 11a), thus experiencing significant loss of snow accumulation during the entire event.

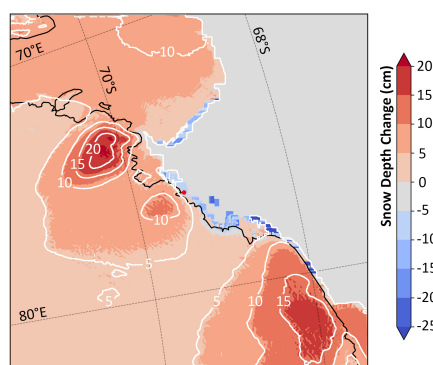


Figure 16. Change of snow depth during the event (from 00:00 UTC on July 15, 2022 to 00:00 UTC on July 17, 2022). The filled colors show the results of the control experiment, while the contour lines represent the results of the sensitivity experiment considering only snowfall.

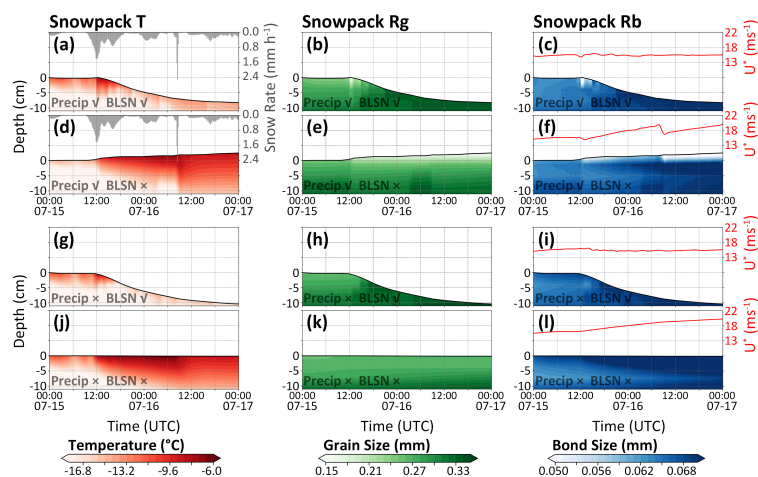
Furthermore, based on sensitivity experiments with pairwise combinations of turning on or off blowing snow and snowfall respectively, an analysis was conducted on snow layer erosion and snow layer properties at the St. ZS site, with the results shown in Figure 17. Specifically, when neither the erosion of the snow surface by blowing snow nor the replenishment of snowpack by atmospheric snowfall is considered, the snow depth remains stable (Fig. 17j); when only snowfall is considered without erosion, the snow depth gradually increases (Fig. 17d), and in contrast, when only erosion is considered, the snow depth significantly decreases after the strong surface winds start at 11:00 UTC on July 15, 2022, and the erosion loss of snow is notably more than the precipitation replenishment (comparing Fig. 17a and Fig. 17g).

Notably, during the first intense snowfall at St. ZS (accompanied by strong winds around 11:00 UTC on July 15, 2022, corresponding to the passage of a cyclone warm front), the SNOWPACK land surface model exhibited rapid responses to both the warm advection and snowfall induced by the cyclone. In particular, in the control experiment, the temperature of the surface snow cover increased rapidly (Fig. 17a). However, as strong winds eroded surface snow particles via blowing snow, the surface temperature began to decline. The snowfall process partially compensated for snow erosion, resulting in a slightly greater increase in surface temperature than that in snowfall-free sensitivity tests (comparing Fig. 17a with Fig. 17g). In the two sensitivity tests without blowing snow erosion, the temperature increase in the snow layer was most pronounced (Fig. 17d and Fig. 17j), primarily attributed to the sufficient time for the surface snow layer to conduct heat with the atmospheric underlying surface throughout the process. With continuous erosion of the snow surface by strong winds, the surface snow layer was rapidly removed, exposing the underlying snow layers with lower temperatures and larger particle sizes. Meanwhile, compaction by strong winds increased the bond size of the snow layer, a phenomenon more evident in sensitivity tests without both blowing snow and snowfall (Fig. 17l).

Using the saltation threshold calculation formula adopted by the model (Lehning et al., 2000), the minimum wind speed threshold at a 10-meter height required to initiate



690 snow particle saltation was derived (this threshold was calculated using the average
691 values of parameters within a snow depth of 0.05 meters), as shown by the red solid
692 line in Fig. 17. The results show that in the two blowing-snow-free experiments, the
693 minimum wind speed threshold trended upward, primarily due to the surface snow
694 particle size remaining small throughout the event (especially when there was snowfall
695 replenishment, Fig. 17e) and wind-induced compaction (increasing bond size). In the
696 two experiments considering blowing snow, the particle size and bond size tended to
697 increase consistently, keeping the minimum wind speed threshold basically between 15
698 m s^{-1} and 16 m s^{-1} . It is worth noting that after 06:00 UTC on July 16, 2022, the 10-
699 meter wind speed in the model (Fig. 3a) was generally lower than the minimum wind
700 speed threshold, making it difficult for snow particles to saltate and form blowing snow,
701 and the blowing snow mass mixing ratio in the model was almost undetectable (Fig.
702 4b). However, at this time, both the laser ceilometer and manual observations still
703 showed strong blowing snow or blizzard. Combined with previous research conclusions
704 (when blowing snow occurs after snowfall at St. ZS, a wind speed of about 5 m s^{-1}
705 is only required to blow up a thickness of 300 meters, Ye et al., 2025), it can be inferred
706 that to simulate blowing snow more accurately, it is necessary to model the timing and
707 intensity of snowfall more precisely so that the snow surface model can more accurately
708 respond to atmospheric snowfall processes. In addition, since the minimum wind speed
709 threshold is closely related to the particle properties of the snow layer, more accurate
710 micro-scale measurements of Antarctic snow particles are needed to optimize existing
711 empirical formulas.



712
713 Figure 17. Profiles of (a) snow layer temperature, (b) snow layer particle size, and (c) snow layer
714 particle bond size over time in the control experiment. The black solid line represents the snow
715 surface (with the initial time marked as 0 m). The gray histogram in (a) indicates the surface snowfall
716 rate, and the red solid lines in (c) show the theoretical minimum wind speed threshold (at 10-meter
717 height) for snow particle saltation. The second to fourth rows are identical to the first row, except
718 for the results of the sensitivity experiments. The sensitivity experiments test the impacts of turning
719 on or off the snowdrift scheme and whether the land surface receives snowfall. The sensitivity
720 configurations are marked by check or cross symbols at the lower-left corner of the first column of
721 figures.



5. Discussion

This study employs the numerical model CRYOWRF to simulate and reproduce a representative case in which a cyclone system intruded into the Antarctic marginal zone, ultimately inducing severe gale and blowing snow phenomena. The high-resolution simulations distinctly reveals that several key physical processes, including atmospheric dynamic processes, topographic-induced perturbations, the occurrence and accumulation of snowfall, and snowpack erosion, interacted in a synergistic manner during this meteorological event. The schematic diagram of this event is shown in Figure 18.

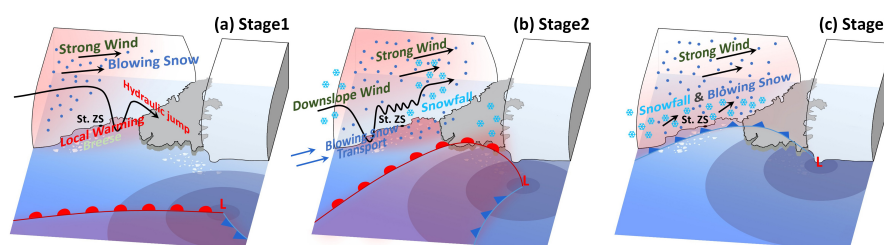


Figure 18. Schematic diagram of a typical strong wind and blowing snow event caused by cyclone invasion. The three stages in the figure correspond to those in the main text.

During the initial stage of the incursion of the cyclone's outer wind field (Fig. 18a), the katabatic wind on the surface of the ice sheet superimposed with the outer wind field of the cyclone, forming a significant angle with the topographic slope. When the katabatic wind reached the location with the steepest topographic slope in the marginal zone, a typical hydraulic jump flow field structure was generated, triggering intense subsidence warming. On one hand, due to turbulent dissipation of the kinetic energy of the upstream strong wind, a calm wind zone that could persist for a certain period was formed near the surface in the intense hydraulic jump area (such as the location of St. ZS in this study). This calm wind zone may, to some extent, hinder the downstream propagation of the cyclone's energy, a phenomenon that may be more pronounced in steep marginal areas where it enhances the topographic blocking effect. (Lin, 2007). As a result, as the cyclone approached the Antarctic continent, the pressure gradient between it and the cold high-pressure system over the continental surface was further amplified, enhancing the subsequent wind speeds. In this event, it was evident that the increase in wind speed was sudden, in stark contrast to the gradual change in air pressure (Fig. 3). Additionally, the intense warming generated by the hydraulic jump could extend further downstream through near-surface advection, reaching the Amery Ice Shelf region (Fig. 7). This warming arrived at the region earlier than the warm advection introduced by the cyclone, and its impact on the ice shelf requires further quantification and evaluation.

Upon the influence of the cyclone's core warm front on the marginal zone (Fig. 18b), strong winds demonstrated a pronounced tendency to move along the topographic contour lines of the continent, thereby forming barrier winds. However, due to the



757 significant undulations of the coastal terrain (such as the topography of Vestfold Hills
758 in this study), the airflows generated strong upward motions on the windward slopes of
759 the uneven terrain, rapidly condensing the abundant moisture they carried into snowfall.
760 As the airflow traversed the terrain, it triggered more vigorous downslope winds and
761 lee waves (Fig. 11). Given that wind speeds in the strong wind zones far exceeded the
762 threshold velocity required for snow particle saltation, the intensity of blowing snow
763 during this stage was notably elevated. Notably, the cyclone's strong winds and warm
764 advection occurred concurrently, leading to the synchronicity of snowfall and intense
765 blowing snow in undulating terrain areas. Meanwhile, snowfall-generated new snow
766 layers, featuring low density and weak cohesion, were more prone to being entrained
767 into the air, giving rise to snowstorm events incorporating both snowfall and blowing
768 snow. Another issue worthy of attention is that simulation results show strong upward
769 air currents in undulating terrain regions can transport blowing snow particles to an
770 altitude of 2 km. It is necessary to conduct in-depth research on whether these snow
771 particles can further form cloud condensation nuclei through collision and
772 fragmentation, or provide additional water vapor sources for snowfall via the
773 sublimation effect. These microphysical processes require thorough exploration.

774 During the gradual weakening stage of the cyclone (Fig. 18c), when the shallow
775 cold front reaches the marginal land area, the ice sheet topography induces strong
776 upward motion again, triggering snowfall. However, due to the weak intensity and thin
777 thickness of the cold front, the snowfall amount is significantly less than that of the
778 warm front (Fig. 15). At this stage, observations from lidar ceilometers and manual
779 measurements show that relatively weak wind speeds can still entrain snowfall into the
780 air to form blowing snow. However, in numerical models, the snow cover surface, after
781 prior wind erosion and compaction, exhibits surface snow particles that are no longer
782 capable of saltation, making it difficult to simulate blowing snow during this stage. This
783 highlights the need for continuous long-term synchronous observations of Antarctic
784 snowfall characteristics, snow physical properties, and atmospheric wind speed profiles,
785 which would provide critical parameters and field-measured evidence for model
786 optimization.

787 Cyclonic systems also exert a substantial influence on the formation and evolution
788 of coastal polynyas, including the Davis and Barrier polynyas over the Prydz Bay
789 region (Wenta and Cassano, 2020; Wang et al., 2021), through both dynamic and
790 thermodynamic mechanisms. In the vicinity of St. ZS, the prevailing wind field under
791 cyclonic conditions is typically alongshore or onshore winds rather than offshore winds
792 over this study period (July 15 to 17, 2022). Such wind patterns are generally
793 unfavorable for the coastal polynya expansion, as offshore winds are typically essential
794 for advecting sea ice away from the coast and maintaining open water areas.
795 Consequently, under this cyclonic condition, the limited polynya extent suppresses the
796 potential for enhanced sea ice production. In addition, such cyclones could transport
797 warm and moist air masses into the coastal region as discussed before, and their early-
798 stage development is often associated with the formation of nearshore hydraulic jumps.



These factors collectively contribute to elevated near-surface air temperatures along the coast. The resultant reduction in the air-sea temperature gradient weakens the air-sea heat flux over the Prydz Bay polynya, thereby diminishing the ice production rate. Under such meteorological conditions, the coastal polynya activities are significantly constrained, which in turn affects subsequent ice production and water mass formation over the Prydz Bay region. Therefore, a comprehensive understanding of polynya responses to specific cyclonic forcings is essential for elucidating broader sea ice and oceanographic processes.

Admittedly, case studies based on numerical models still have uncertainties, especially under the complex terrain and ice-snow underlying surface conditions in Antarctica. The simulation of microphysical processes of clouds, snowfall, and blowing snow, as well as their interactions, still contains significant gaps for improvement. Additionally, this study only analyzes a typical cyclone event, but the intensity, track, structure, and other characteristics of different cyclones may vary significantly. Therefore, the above conclusions may only have certain regional and seasonal representativeness. Future research should focus on improving the parameterization schemes of model physical processes, establishing a more refined and comprehensive observation system, and conducting statistical and comparative analyses of multiple cases. These efforts will provide important scientific support for Antarctic scientific expedition safety and climate change research.

Data availability.

The model data supporting the findings of this study can be accessed at <https://doi.org/10.5072/zenodo.273851>. Additional details regarding the observed and reanalysis data are provided in Section 2.

Author contributions.

JD and XW conceptualized the original ideas presented in this manuscript. JD performed the analysis of the model results and wrote the initial draft of the manuscript. XW, YS, YLS, JM, JY, XL, and LL contributed to the interpretation of results, manuscript preparation, and revisions. JD and YS carried out the model simulations. All authors contributed to the article and approved the final version.

Competing interests. The authors declare that there is no conflict of interest.

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