Reply to the comments of refree#2

Summary: The paper details a promising drilling facility tailored for polar conditions. However, to enhance the overall description of such equipment, clearer articulation of the research gap and system advantages, and stronger connections between design choices and operational outcomes for both Air system and DFCS, would be welcome.

Thanks for your fruitful comments. The manuscript has been carefully revised according to your suggestion.

Remarks and suggestions:

- Abstract:

1. Suggest starting with a scientific/operational challenge (e.g., xxx current problem in sampling of subglacial bedrock in polar regions… this is why this type of MPDS is needed).

   The following sentences has been added at the beginning of abstract '*Liquid drilling is commonly utilized in sampling of subglacial bedrock in Antarctica. However, this drilling method has relatively low penetration rate compared with air drilling. Additionally, the drilling method may lead to hydraulic fracturing of ice borehole. In this study, A multi-process drilling system (MPDS) incorporated with different drilling methods…*'

2. The abstract is focusing heavily on the list of components, suggest highlighting the unique integration or operational principle that makes this MPDS different.

   The two sentences '*The air system comprised a compressor, receiver, freezing dryer, desiccant dryer and cooler. The DFCS comprised a refrigerating machine, heat exchanger, circulation pump, drilling-fluid pump, vibration sieve, vertical centrifuge, circulation tank, stirring tank, and settling tank*' were rewritten as '*The air system uses a compressor to generate compressed air at a flow rate of 10 Nm3·min-1 and maximum pressure of 1.5 MPa. The compressed air was then dried by a freezing dryer and a desiccant dryer to a dew point of -40℃. Before injected into the borehole, the compressed air was cooled to ≤-5 ℃ by an air cooler. The DFCS can pump drilling fluid to the borehole at a flow rate of 100 L·min-2 and maximum pressure of 2 MPa. The drilling liquid can be cooled to ≤-5 ℃ by a refrigerating machine and a heat exchanger within DFCS. The ice or rock cuttings are separated by a vibration sieve and a vertical centrifuge*'.

3. The narrative could be more sharply focused on key innovations and results. Including at least 2 or 3 key quantified performance metrics (for e.g., air system pressure, DFCS fluid temperature, maximum drilling depth achieved, or...), will help evaluate the advance.

   Some key parameters of the two system have been presented in abstract as '*The air system uses a compressor to generate compressed air at a flow rate of 10 Nm3·min-1 and maximum pressure of 1.5 MPa. The compressed air was then dried by a freezing dryer and a desiccant dryer to a dew point of -40℃. Before injected into the borehole, the compressed air was cooled to ≤-5 ℃ by an air cooler. The DFCS can pump drilling fluid to the borehole at a flow rate of 100 L·min-2 and maximum pressure of 2 MPa. The drilling liquid can be cooled to ≤-5 ℃ by a refrigerating machine and a heat exchanger within DFCS. The ice or rock cuttings are separated by a vibration sieve and a vertical centrifuge*'.

- Introduction:

1. While the introduction reviews many past projects, it could more clearly state what existing systems lacked and how the MPDS, DFCS solve them. It would be better to add a clear, simple sentence or two just before introducing the MPDS that says exactly what was missing in previous work (e.g., insufficient fluid control in deep ice drilling or lack of integrated, transportable drilling systems, or … something else?). Currently, this research gap is implied but not explicitly stated.

   The following sentences were added.

   '*Compared with the cable-suspended electromechanical drill, a conventional drill rig can drill longer rock cores. However, the aforementioned conventional drill rigs often utilize liquid drilling, which has relatively low penetration rate compared with air drilling and may lead to hydraulic fracturing of ice borehole. Air drilling has higher penetration rate in ice, however, the drilling depth is limited due to unbalanced ice pressure on the borehole wall*'.

   '*In summary, the existing air-cooling techniques are insufficient to fully satisfy the requirements of drilling operations in Antarctic environments and new air-cooling method is required*'.

   '*Field test of the heated melter tank proved to be inefficient and power consumption*'.

   '*In conclusion, the current method for separating ice chips requires improvement, and the integration of a cooling system into the DFCS is preferred*'.

‘*To solve the above-mentioned problems of conventional drill rig, a conventional drill rig-based MPDS (Fig.1) incorporated with air drilling and liquid drilling, was developed in China for sampling at least 10 m bedrock beneath 1000 m ice sheet in Antarctica*’.

2. Between lines 29 and 47, the two paragraphs jump between examples of drills and then types of drills, which makes it a bit repetitive and hard to follow. It would read much better if the drills were grouped into clear categories, e.g., conventional rotary rigs versus cable-suspended electromechanical drills with examples included inside each group. It would be better to also mention if and how different types have been used together.

These sentences were reorganized ‘*Many holes have been drilled in the ice-sheet beds in Greenland and Antarctica, but subglacial rocks have been rarely retrieved (Bentley and Koci, 2007; Talalay, 2013). There are two types of drills that have been used for subglacial bedrock drilling: conventional rotary drill rig and cable-suspended electromechanical drill.*

Conventional rotary drill rigs with drill pipes have often served as the basis for subglacial bedrock coring systems. Examples include purpose-built adaptations like the Longyear Super 38 drill rig, the Winkie drill, the Agile Sub-Ice Geological (ASIG) drill, and the Rapid Access Ice Drill (RAID) (Truffer et al., 1999; Boeckmann et al., 2021; Kuhl et al., 2021; Goodge et al., 2021). The first subglacial bedrock core was drilled in 1956 with a conventional rotary drill rig near Mirny station, Antarctica. The hole was only 66.7 m in depth, and the rock core was 2.2 m in length (Treshnikov, 1960). After that, the conventional rotary drill rig was abandoned for subglacial bedrock coring. Since 2010s, US researchers started to modify three conventional rotary drill rigs for subglacial bedrock drilling, and several subglacial bedrock cores have been sampled in West Antarctica and Transantarctic Mountains (Boeckmann et al., 2021; Kuhl et al., 2021; Goodge et al., 2021). Notably, RAID drilled the deepest subglacial bedrock borehole in Antarctica, reaching a depth of 681 meters, while the longest subglacial core with length of 8 m were drilled by ASIG (Kuhl et al., 2021; Goodge et al., 2021).

The cable-suspended electromechanical drill can also be used in subglacial-bedrock drilling. For example, the Polar Ice Coring Office-5.2” (PICO-5.2”), Percussive Rapid Access Isotope Drill (P-RAID), and Ice and Bedrock Electromechanical Drill (IBED) were also designed to obtain the bedrock core beneath ice (Kelley et al., 1994; Timoney, et al., 2020; Talalay et al., 2021a; Talalay *et al., 2021b). In last century, three subglacial bedrock cores had been drilled in Camp Century, Summit, and Taylor Dome by US scientists with cable-suspended electromechanical drill (Ueda and Garfield, 1968; Gow and Meese, 1996; Steig et al., 2000). In 2018/2019 season, Chinese drillers retrieved a short subglacial rock core at the margin of Princess Elizabeth Land, East Antarctica (Talalay et al., 2021a). Five years later, Chinese-Russian subglacial drilling project recovered a subglacial bedrock core of 0.48 m beneath 541 m ice sheet (Talalay et al., 2025).*

Compared with the cable-suspended electromechanical drill, a conventional drill rig can drill longer rock cores. However, the aforementioned conventional drill rigs often utilize liquid drilling, which has relatively low penetration rate compared with air drilling and may lead to hydraulic fracturing of ice borehole. Air drilling has higher penetration rate in ice, however, the drilling depth is limited due to unbalanced ice pressure on the borehole wall. At present, the deepest hole drilled by air in ice is only 309 m (Patenaude et al., 1959; Lange, 1973)'.

3. The introduction concludes nicely. However, the justification for choosing a reverse circulation design could be expanded. Is this the first application of reverse circulation in subglacial or polar drilling? If so, why is this approach necessary? If not, what specific advantages does it offer over prior implementations?

Reverse circulation has been used in ice drilling in Antarctica. In past Antarctic drilling projects, reverse circulation is usually established in normal drill rod. In this case, drilling fluid is pumped through the clearance of drill rod and borehole wall, and then flows back to surface through the central passage of the drill rod. The drilling fluid continuously erodes the borehole wall. The MPDS uses double-wall drill rod as flow channel of compressed air or drilling liquid. Compressed air or drilling liquid is injected through the inner and outer tube of the double-wall drill rod and returned to surface through the central passage of the inner tube.

The following presents several advantages of reverse circulation with double-wall drill rod.

(1) During snow/firn drilling with compressed air, reverse circulation with double-wall drill rod can effectively prevent the leakage of compressed air into the surrounding snow;

(2) During ice drilling with drilling liquid, reverse circulation with double-wall drill rod can avoid the erosion of drilling liquid to the borehole wall. Further, it can prevent possible hydraulic fracturing of ice borehole wall.

The following sentence has been added in revised manuscript '*During drilling with reverse circulation, the compressed air or drilling liquid is injected through the inner and outer tube of the double-wall drill rod and returned to surface through the central passage of the inner tube*'.

'*During snow and firn drilling, compressed air with reverse circulation was used, which can effectively prevent the leakage of compressed air into the surrounding snow*'.

'*In this way, the erosion of drilling liquid to the borehole wall can be avoided. Further, it may help in preventing possible hydraulic fracturing of ice borehole wall*'.

- Air system:

1. Authors note that the freezing dryer and desiccant dryer failed in the field. This is important, but the cause analysis is too brief. Authors have mentioned the reason as 'groundwater presence', but the section could better emphasise the implications of these failures for long-term operation in Antarctic conditions. Also, how severe was the downtime caused by repeated ice plug formation in terms of drilling efficiency?

The reason of the two dryer's failure in field is reanalyzed as following '*It was found that a lot of the condensate was not discharged from the air receiver through the drain valve (Fig. 9a). We suspect it is one of the reasons why the freezing dryer and the desiccant dryer could not dry the compressed air to desired dew-point. Additionally, lot of the condensate was also found in the freezing dryer and the air filters, which share the drainage channel. It is suspected that the drainage channel was blocked somewhere or the drain valve on the freezing dryer and the air filters stopped to work. Manufacturing defects of the freezing dryer and the desiccant dryer were also suspected. Due to limited working time in Antarctic field, the air system was not carefully checked and the specific reasons for the failure of the freezing dryer and the desiccant dryer remains unclea.*'.

The 'groundwater presence' is not the reason for the failure of the freezing dryer and the desiccant dryer in Antarctica field. In domestic test, the MPDS was used for drilling underground soil and rock and the groundwater was found in the borehole. Consequently, the freezing dryer, desiccant dryer, and cooler were determined not to be used in the testing.

The implications of these failures for long-term operation in Antarctic conditions were emphasized with following sentences '*Overall, long-term drilling with compressed air in Antarctic without freezing dryer and the desiccant dryer is unrealistic*'.

The downtime caused by repeated ice plug formation has been evaluated using the following sentences '*In this case, the condensate froze into an ice plug in the air-cooler conduit leading to a rapid rise in the outlet pressure of the air cooler. In common case, after 15–20 minutes, the pressure increased from 0.7 MPa to 1.3 MPa, which was close to the limited maximum pressure of air cooler. In the field, the ice plug was melted by hot compressed air after shutting off the air cooler. In this situation, the drilling work had to be stopped until the pressure dropped to normal values. This process took approximately 5–8 minutes. In addition, another 3–5 minutes were required to restart the cooler*'.

To make it more clear, other sentences has been added in revised manuscript '*Frequent ice plug formation in the air-cooler conduit significantly hinders continuous ice drilling operations, drastically reducing drilling efficiency. In some cases, drilling must be interrupted up to three times within a single run while waiting for the air system to be restored to operational readiness*'.

2. How the MPDS air system's cooling/drying capacity exceeds or differs from RAM, Winkie drill setups, etc.? Is it due to component selection, integration, or operational setup?

Winkie drill can only drill with liquid, so it has no air system.

Air treatment subassembly of RAM was modified to provide two stages of cooling and water separation. In addition, a coalescing filter was included as a means to remove any remaining water vapor. According to Gibson et.al (2021), compressed air can be cooled to temperature of 0°C to −10°C by adjusting fan speed and baffles on the aftercoolers. The cooling capacity of RAM is comparable to that of MPDS. The drying capacity of the RAM is not shown in public literature and still unknown.

The following sentences have been added in the revised manuscript '*In general, the air cooler can cool the compressed air effectively and its cooling capacity is comparable to that of RAM-2 drill (Gibson et. al, 2021)*'.

References

Gibson, C. J., Boeckmann, G., Meulemans, Z., Kuhl, T. W., Koehler, J., Johnson, J. A. and Slawny, K. R.: RAM-2 Drill system development: an upgrade of the Rapid Air Movement Drill, Ann. Glaciol., 62, 99–108, https://doi.org/10.1017/aog.2020.72, 2021.

3. The section would benefit from a table comparing domestic test vs. Antarctic field performances side- by side.

The table comparing domestic test and Antarctic field test is shown in the following table. However, we think it is not necessary to present the table in the manuscript, because all the testing data has been shown in figure 8 and in text. Additionally, the data can also be found in supplement material Table S1.

Testing results of the air system

Property of compressed air	Domestic test	Field test in Antarctica
Flow rate/$Nm^3 \cdot min^{-1}$	10.9	9.3 – 12.4
Pressure/MPa	1.5	0.7 – 1
Temperature after compressing/°C	95 – 97	76 – 89
Temperature at the inlet of freezing dryer/°C	/	24 – 44
Temperature at the outlet of freezing dryer/°C	/	~35
Temperature after first cooler (first cooler worked)/°C	-4.5	-17.4 – -7.9
Temperature after second cooler (first cooler worked)/°C	/	-12.4 – -4.9
Temperature after first cooler (second cooler worked)/°C	/	17.6 – 41.7
Temperature after second cooler (second cooler worked)/°C	/	-15.9 – -5.1
Temperature after second cooler (both coolers worked)/°C	-10.8	/
Dew point at the inlet of the cooler/°C	/	-11.3 – 19.9
Dew point at the outlet of the cooler/°C	-48–-52	-21.2 – 4.6

- DFCS:

1. The section lists components but does not explicitly connect each one to the drilling challenges described in the introduction (e.g., how each device addresses heat, humidity, or borehole icing).

In section 2.1.1 of the revised manuscript, the following sentences were added.

'*Compared with air-cooling methods used in the past, using refrigerant to cool compressed air ensures a consistently sub-zero temperature (<0°C) regardless of external atmospheric variations*.'

'*Overall, the air system employs a two-stage dehumidification process, offering greater reliability than conventional air-drying methods used in polar regions*'.

In section 2.2.2 of the revised manuscript, the following sentences were added.

'*In this way, the drilling fluid can be actively cooled to a low temperature, preventing the melting of the ice-borehole wall—a phenomenon observed in other subglacial bedrock drilling projects*'.

'*Comparing with the heated melter tank used by RAID and ASIG, the vertical centrifuge is more efficient and energy-saving (Kuhl et al., 2021; Goodge et al., 2021)*'.

2. Similar to Air System, this section also would benefit from a table comparing domestic test vs. Antarctic field performances.

The table comparing domestic test and Antarctic field test is shown in the following table. However, we think it is not necessary to present the table in the manuscript, because all the testing data has been shown in figure 10 and in text. Additionally, the data can also be found in supplement material Table S2.

Testing results of the DFCS

Property of drilling liquid	Domestic test	Field test in Antarctica
Flow rate/L·min^{-1}	110	62–96
Pressure/MPa	/	0.15–0.29
Temperature/°C	2 m^3 water could be cooled from 24.8 to 7 °C in 50 minutes	-15.5–-4.5

3. The list in 3.4.2 is useful, but each suggestion could be strengthened by linking why it is needed to the actual observed field problem (e.g., "flow rate should be adjustable… because … Connect this back to the results"). Where possible, quantify desired capacities (e.g., "small stirrer" how small? Specify dimensions).

Some sentences have been added to strength the link between the suggestion and the observed field problem. The revised sentences are shown as following '*First, the flow rate of the drilling-fluid pump should be adjustable by variable-frequency drive for easy operation. Otherwise, the drilling-fluid pump has to be manually operated and can easily lead to mismatch of flow rate with drilling requirement. Second, the pump with suction capacity should be used as circulation pump, such as self-priming pumps and submersible pumps. Third, a high-capacity vibration sieve with double layer of screens is suggested to improve its processing capacity of drilling fluid. Fourth, a type of vertical centrifuge with built-in brake should be used and the vertical centrifuge should have the ability to* *remove the hard ice chips by itself, instead of operator, to reduce the intensity of manual labour. Additionally, small stirrer with size less should be added on the circulation tank, and a filter screen made by steel wire are strongly suggested to add between the circulation pump and the heat exchanger to prevent the settled clays block the flow channel*'.