2019. 12. 23

Prof. Ilker Fer
Handling Topic Editor
Ocean Science

Dear Topic Editor,

Please find the second revised version of our manuscript (ID: os-2019-80), "**Spatio-temporal variations in High-Salinity Shelf Water production in Terra Nova Bay polynya, Antarctica**" which has been corrected according to the provided comments. The following text provides our point-by-point responses (blue) to these comments (black).

We would like to thank you and the reviewers for your careful and helpful comments regarding our manuscript. We believe this feedback has allowed us to significantly improve our paper prior to resubmission. Some of our primary changes have included:

- Improving the English language usage throughout the text.
- Updating the arrangement and content of the figures and tables.
- Rearranging the text to improve flow and clarity, particularly in Sections 3 and 4.

We hope that our manuscript is now acceptable for publication in *Ocean Science*.

Sincerely,
Dr. Seung-Tae Yoon, on behalf of all authors.
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P.S. Note that Seung-Tae Yoon (corresponding author) and Won Sang Lee (second contact) will be onboard I.B.R.V. ARAON from 29 December 2019 to 25 February 2020. During this period, our email accesses will be limited. Please additionally contact Ms. Jiyeon Lee (jylee14@kopri.re.kr), one of our co-authors, who can directly contact people onboard on the I.B.R.V. ARAON.

Responses to comments by Referee #3

Comments on (the revised) ms "Spatio-temporal variations in High Salinity Shelf Water production in Terra Nova Bay polynya"

The quality of the revised paper is much improved – but there are still issues that needs to be addressed prior to publication; the work still appears somewhat immature, the new data are not sufficiently compared to historical data – e.g. to discuss the relevance of the salinity increase observed during the three year-long deployment period, results and discussion is still mixed, figures are not in order, the language level is not acceptable - and it admittedly annoys me as a reviewer that the native English speakers in the author list did not put more efforts into correcting the text before re-submitting. In my opinion, the ms can be published only after significant revision, including all authors.

We thank the referee for his/her valuable and careful comments. Following the comments, we have improved the language significantly via a professional English editing service as well as via proofreading by native English speakers.

Specific comments – language issues are not addressed here.

1. L 38 – TNBP is not shown in Fig 1

We have deleted "(Fig. 1)" based on your comment [Tracked-changes version on L45].

2. L 51-52 Not correct as it now reads.

We have corrected this sentence based on your comment [Tracked-changes version on L58-60].

3. Fig 2 – Not needed, information is in Table 1

Figure 2 indicates the recorded sensor depths during the three observation legs. The depth information in Table 1 is the averaged value for the recorded sensor depths. Thus, we retained Fig. 2.

4. L103-104 – Mean tidal velocity is not of interest, please give mean speed and or tidal range.
We have estimated the mean speed of tidal currents and additionally suggested mean tidal ranges during each survey based on your comment [Tracked-changes version on L133-135].

5. L 107. To facilitate comparison with studies using absolute salinities, give a rough number for how big the difference between S_A and S_P is in this location.
We have added a rough number for the magnitude of the difference between S_A and S_P in TNB [Tracked-changes version on L124-125].

6. L 109. You later use Temperature to identify TISW?
We have added a sentence about the properties of TISW based on your comment [Tracked-changes version on L126-128].

7. Section 2.2 use either westerly or eastward – don't mix.
We have changed "eastward" into "westerly" based on your comment [Tracked-changes version on L157; L159; L735].

8. Figures are not referred to in order
We have modified Section 3 and Section 4 so that figures are referred to in order.

9. L. 126 Figure caption says it shows temperature correlation.
We have deleted Fig. 3b based on the editor's comment and corrected this sentence based on your comment [Tracked-changes version on L157-159].

10. L. 127 Winds are synchronized with the wind?
We have corrected this sentence based on your comment [Tracked-changes version on L160].

11. L. 128 – Is temperature correlation relevant?
We agree that the temperature correlation is not relevant here. Thus, we have moved this sentence into Section 4.6.

12. L. 140 Very hard to see the seasonality in Fig 5a. I suggest to complement with a panel showing the records from all years superimposed, e.g. starting in September, where the data are low-pass filtered and potentially presented as anomalies compared to the September value (i.e. all years start out at s'=0 in September)

We have added a small panel for the one-day moving average near-bed salinity time series from August to December of each year in Fig. 4 based on your comment.

13. L150 MWDW is not marked in Fig3

We have added "MCDW" in Fig. 6 based on your comment.

14. L 154 How can a bottom layer represent HSSW formation?

This sentence indicated that the properties in a quasi-homogenous layer represent those of HSSW formed just before the austral winter. We have corrected this sentence based on your comment [Tracked-changes version on L197-199].

15. L 153 This year = what year?

We have changed "this year" to "this layer" based on your comment [Tracked-changes version L199].

16. L 160-163. I don't think this is a valid conclusion – is this supported by the mooring data?. What about inter-annual variability? More vigorous ice-shelf circulation due to more HSSW-production? Given the differences in the spatial coverage of CTD-stations, the absence of TISW in based solely on fig 7 is not convincing. Include an improved (and zoomed) in version of the figure that was used in the response to my earlier comments and include also the two years with ISW coverage (you can then remove the CTD-stations from Fig 1 and use it to show the extent of the polynya)

We deleted this paragraph from Section 3.1 [Tracked-changes version on L205-210], and added Section 4.3 and Fig. 13 [Tracked-changes version on L432-443] to better discuss the issue. The extent of TNBP shown in Fig. 3 was not redundantly shown in Fig. 1.

17. L 168 What flow was nearly southward when?

We have modified Fig. 4b and corrected this sentence based on your comment [Tracked-changes version on L178-179].

18. L 169 Fig 5b does not support the statement that the flow is southwestwards during "periods with increased salinity" (I guess you mean the periods during which the salinity increases)

We have modified Fig. 4b and corrected this sentence based on your comment [Tracked-changes version on L178-179].

19. L 170 and around – Lots of confusing velocity measurements here.

We have deleted lots of confusing velocity measurements and modified this section based on your comment [Tracked-changes version on L172-237].

20. L 173 How can a southward current give propagation in a northern direction?

We have deleted this sentence and modified this section based on your comment [Tracked-changes version on L172-237].

21. L 175 The conclusion might be valid, but it does not follow logically from the text above it. (and I'd recommend presenting results in the results section and saving conclusions/discussions to those sections)

We have moved our discussion about the horizontal currents from the DITN mooring into Section 4.2.

22. L 191 You previously argue that there is seasonality in the bottom record too – with a salinity increase in September.

We have corrected this sentence based on your comment [Tracked-changes version on L241-242].

23. L 195 What reduction in mixing?

We have corrected this sentence based on your comment [Tracked-changes version on L249].

24. L 197 "Longer over time" suggests a longer trend. You have three years of data.

We have changed "longer over time" into "longer over the three years" based on your comment [Tracked-changes version on L245-246].

25. L 200. Isopycnal - > homogenous

We have corrected this based on your comment [Tracked-changes version on L255; L445].

26. L 201. I'm not a statistician – but I find these correlations a bit questionable (especially the latter) – and I don't understand why you introduce them? Figure 8a confirms that convection reached 273 m during the freezing season.

We agree with your comment. We have deleted the sentences about correlations between the salinity values at 75 and 273 m based on your comment and have otherwise modified this section [Tracked-changes version on L252-260; L239-301].

27. L 203 In other words – what follows has not been presented before? and I don't understand what you mean by most rapid mixing

We have deleted these parts and modified this section based on your comment [Tracked-changes version on L258-260; L239-301].

28. L 209 Specify that it is local HSSW production and that it is not responsible for salinity increase at depth.

We have specified these based on your comment [Tracked-changes version on L263-267].

29. L. 216-243 Speculate in the discussion section and present results here.

We modified Sections 3 and 4 based on your comment.

30. L 234 No, salinity at the bottom is clearly higher (Figure 8a) and not locally produced. Again, You do not need to look at the correlations to infer that, Figure 8a does the job.

We agree with your comment. We have deleted the "Types of HSSW" section and combined Section 3.2 with some components of the "Types of HSSW" section [Tracked-changes version on L265-267].

31. L. 247 Do you take auto-correlation into account when calculating significance?

Yes, we took auto-correlation into account when calculating the significance. When we calculated the statistical significance of the correlation coefficients, the degree of freedom is estimated by dividing the effective decorrelation time scale into the data length. An effective decorrelation time scale is determined as the first zero crossing of the autocorrelation function. The detailed methods are explained in Emery and Thomson (1997).

[Emery, W. J. and Thomson, R. E.: Data Analysis Methods in Physical Oceanography, 2nd ed., Elsevier, Amsterdam, Netherlands, 638, 1997]

32. L. 249 when is the austral winter?

Austral winter is from April to October. We have modified this sentence based on your comment [Tracked-changes version on L305].

33. L 260 I the length of a polynya event also an indicator of HSSW formation rate?

Yes, we have added some sentences based on your comment [Tracked-changes version on L321-322; L382; L485-487].

34. L 265-270 Homogenous layer not necessarily caused by wind! Buoyancy flux from ice production. This section and the related figures needs to be improved/revised.

We agree with your comment. We have moved the part about mixed-layer development in the eastern TNB into Section 4.4 based on your comment and a similar one from the editor [Tracked-changes version on L444-455].

35. Section 3.3, 3.4, 4: Discussion and results are mixed – revise

We have modified Sections 3 and 4 based on your comment.

36. L 293 Your current analysis does not show this. Include e.g. a map showing the upper HSSW limit from CTD-stations.

We have added Fig. 10 for a map showing the upper HSSW limit (σ_θ= 28 kg/m^3 isopycnal line) from CTD stations and modified this paragraph [Tracked-changes version on L368-378].

37. L 294 – You cannot use “in other words” when introducing a new statement!

We have deleted “in other words” based on your comment [Tracked-changes version on L371].

38. L 303 – The arrows in Fig 11 are not convincing – they don't show what you write in the text.

We agree with your comment. We have modified Fig. 12 and Section 4.2 based on your comment.

39. L 307 – Not sure I'd use the word "stable" here.

We have deleted "stable" and modified this paragraph based on your comment [Tracked-changes version on L403; L392-415].

40. L 316 – not convincing.

We have corrected this sentence based on your comment [Tracked-changes version on L419-421].

41. Fig 11 No scale arrow

We have modified Fig. 12 based on your comment.

42. L 323 how can a basin be a path?

We have corrected this sentence based on your comment **[**Tracked-changes version on L428-429].

43. Section 4.3: This text in and the goal of this section is unclear – and the scale analysis is not convincing.

We have modified this section (4.5 TNBP Mechanical scales) and deleted the less convincing sentences based on your comment. In addition, we have estimated the convective velocity scale based on the editor's comment [Tracked-changes version on L456-483].

44. Section 4.4 Discussion in this section is not linked to this study. Why don't you present the ice production estimates and compare – at least qualitatively - to your salinity increases/wind/polynya statistics?

We have estimated a quantification of sea ice production in TNB based on your comment and the editor's comment [Tracked-changes version on L484-513].

45. L 365. I do not agree that you have answered the questions. 1 – not at all (you show that

HSSW is advected, not that the circulation influences the production), 2 partly (but you could do better given the data at hand 3) maybe. Adapt the questions to the answers you do have/can answer, improve the presentation and recapitulate your answers here.

We have modified questions and recapitulated our answers in the conclusion section [Tracked-changes version on L76-79; L516-526].

46. L 374. I miss a compilation of previous HSSW-observations, to put your observations in perspectives. Surely there are CTD-data available in archives/values in literature that you can use?

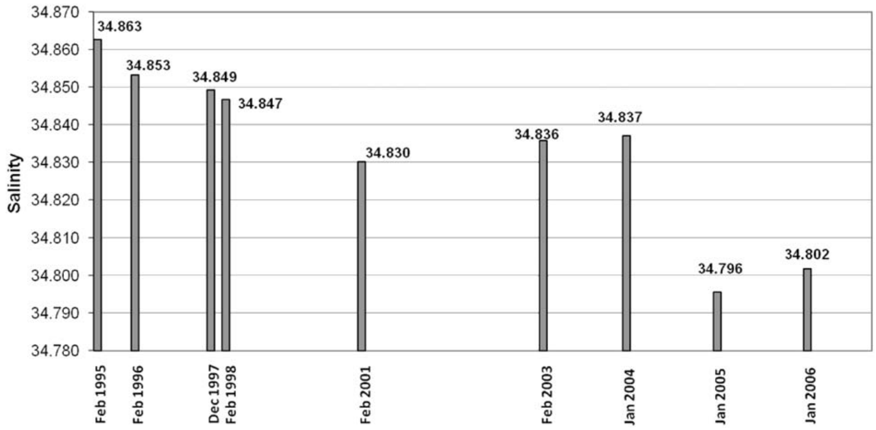

Fig. 5. Average salinity in a 10 m thick layer at 900 m depth (that is the maximum common depth for all the analysed cruises) from 1995 to 2006.

We referred to Fig. 5 from Fusco et al. (2009). We have added these salinity values in Fig. 7a.

47. Figures: Figures can generally be improved – labels and scales are sometimes missing, figures are not referred to in order, data ought to be filtered before its plotted etc. I will not go into details, but let the authors have a first go on their own.

Use figure 11 to introduce the water masses in the area to readers not familiar with the hydrography here.

We have modified/improved Fig. 3, 4, 6, 7, 11, and 12, and have added Fig. 10 for a map of the upper HSSW limit and Fig. 13 for the ISW based on your comment and a comment from the editor. We have used Fig. 11 to introduce the water masses based on your comment [Tracked-changes version on L375-378]. The convection feature and daily katabatic wind events shown in Figs. 8 and 9 with original (non-filtered, rather than filtered) time-series were not removed but were retained.

Thank you again for your detailed comments. We hope that you find these changes make this manuscript suitable for publication.

Variability~~Spatio-temporal variations~~ in High-Salinity Shelf Water production in Terra Nova Bay polynya, Antarctica

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Abstract.

Terra Nova Bay in Antarctica is a formation region ~~he formation of~~for High-Salinity Shelf Water (HSSW), which is ~~the~~a major source of Antarctic B~~b~~ottom W~~w~~ater~~ (AABW), has been observed in Terra Nova Bay (TNB) in Antarctica~~. Here, we present~~We believe that a description of the ~~spatio-temporal salinity variation ~~of salinity ~~in Terra Nova Bay~~NB~~ to advance understanding of the local ~~would help understand the production of ~~HSSW ~~in the region~~production. ~~Hence, the aim of this study is to investigate variations in salinity in the Drygalski Basin (DB) and eastern TNB near Crary Bank in the Ross Sea. For this, we~~The salinity~~ use the moored and profiled hydrographic data, as well as available wind and sea ice products~~ variations in the Drygalski Basin and eastern Terra Nova Bay near Crary Bank in the Ross Sea were investigated by analyzing hydrographic data from instrumented moorings, vessel-based profiles as well as available wind and sea-ice products. N~~We found that the deep salinity~~ear-bed salinity in the eastern Terra Nova Bay~~NB~~ (~ 660 m) and Drygalski Basin~~DB~~ (~ 1,200 m) increases each year beginning in September. Significant ~~increases in salinity~~salinity increases (> 0.04) were observed in 2016 and 2017, which is likely related to active HSSW formation. According to velocity data observed at identical depths, the salinity increase from September~~e increases~~ ~~in salinity from September ~~was~~ere~~ primarily due to ~~the ~~advection of the HSSW originating from the coastal region of the Nansen I~~i~~ce S~~s~~helf ~~(NIS)~~. In addition, ~~The significant increases in salinity are related to active HSSW formation. In addition, ~~we show that HSSW can also be formed locally~~ formed~~ in the upper water column~~layer~~ (< 300 m) of the eastern Terra Nova Bay~~TNB~~ ~~-~~through convection ~~led by a ~~supplied~~y~~ by~~of~~ brine from the surface, which is related to polynya development via winds. While the general consensus is that the salinity of the HSSW has been decreasing from 1995 to the late 2000s in the region,~~Moreover, as compared with historical observations,~~ the salinity~~ of the HSSW~~ has been increasing since 2016.~~ and,~~ I~~i~~n 2018, ~~the salinity~~it returned to values comparable to those in the ~~was similar to that in~~ early 2000s.~~ Observations of fluctuations such as this, which are in contrast to previous freshening, may contribute to the estimation of the properties of recently formed AABW and improve the accuracy of both regional and global climate models.~~

[YS1]: Topic Editor: This sounds like you observed it in this study. Perhaps reword along the lines of TNB is a region of HSSW formation, which is a major source of AABW.

[YS2R1]: We have modified this sentence based on your comment.

[YS3]: Topic Editor: move all this to the end of next sentence.

[YS4R3]: We have rearranged this part based on your comment.

[YS5]: Topic Editor: hyphen between sea and ice here is OK (as it is a 3-word description), but in ALL other "sea ice", remove the hyphen.

[YS6R5]: We have deleted a hyphen in all other "sea ice" (2 word description) based on your comment.

1 Introduction

The strength of the global meridional overturning circulation is closely associated with~~with~~ the production of Antarctic B~~b~~ottom ~~w~~Water (AABW) (Jacobs, 2004; Johnson, 2008; Orsi et al., 1999, 2001), and approximately 25% of the AABW is produced in the Ross Sea (Orsi et al., 2002). In the western Ross Sea, as a result of the strong tidal movement of the Antarctic Slope Front across the shelf break and eddy interaction with the slope's bathymetry, C~~c~~ircumpolar ~~d~~Deep ~~w~~Water (CDW) intrudes on to the continental shelf to balance the High-Salinity Shelf Water (HSSW) off-continental ~~the ice~~ shelf flow (Dinniman 2003; Budillon et al., 2011; St-Laurent et al., 2013; Stewart and Thompson, 2015; Jendersie et al., 2018). Model results suggest that the modified CDW (MCDW) is advected as far south as Crary Bank, east of Terra Nova Bay (TNB) (Dinniman 2003, Jendersie 2018), although this has ~~not been~~yet to be confirmed by observation. AABW is formed by the mixing of HSSW and CDW or MCDW (Budillon and Spezie, 2000; Budillon et al., 2011; Cincinelli et al., 2008; Gordon et al., 2009). Therefore, HSSW is the major and densest parent water mass of AABW (Budillon and Spezie, 2000; Gordon et al., 2009).

Of the HSSW in the Ross Sea, 33% is produced in Terra Nova Bay polynya (TNBP) (Fusco et al., 2009; Rusciano et al., 2013; Jendersie et al., 2018). TNBP ~~(Fig. 1)~~ is a coastal latent-heat polynya~~, upon whose surface dense water is formed~~ (Fusco et al., 2002). The Drygalski I~~i~~ce T~~t~~ongue (DIT), which forms the southern boundary of TNBP, blocks ~~sea-ice~~sea ice moving in from the south (Stevens et al., 2017). Katabatic winds that blow from the Nansen I~~i~~ce S~~s~~helf (NIS) remove~~take~~ the heat from the polynya (Fusco et al., 2009; Tamura et al., 2016; Toggweiler and Samuels, 1995), producing ~~sea-ice in TNBP (Fusco et al., 2009; Tamura et al., 2016; Toggweiler and Samuels, 1995), which is responsible for the production of~~as much as 3–4% of the total ~~sea-ice~~sea ice in the Antarctic coastal polynyas (Tamura et al., 2016). The release of ~~salty~~ brine as a result of the sea-ice production~~growth~~ initiates the formation of HSSW and determines its properties (Fusco et al., 2009; Rusciano et al., 2013).

HSSW is mainly produced during the austral winter (April–October) when TNBP most efficiently produces ~~sea-ice~~sea ice in response to the persistent katabatic winds (van Woert, 1999; Rusciano et al., 2013; Sansiviero et al., 2017; Aulicino et al., 2018). TNBP can~~does~~ open in the austral summer, but HSSW is rarely formed during this period due to the cessation of sea-ice production in the upper layer, along with ice-melting processes (Rusciano et al., 2013). According to historical observations and ~~the results of~~ numerical modelling, the densest HSSW is formed from August to October~~, during~~ wh~~ich period~~en the maximum salinity of the HSSW increases to approximately 34.86 (Buffoni et al., 2002; Fusco et al., 2009; Mathiot et al., 2012; Rusciano et al., 2013). ~~Previous~~ S~~s~~tudies ~~have~~ suggest~~ed~~ that convection led by polynya activity~~, which is preceded by wind-driven mixing~~ is the primary mechanism for producing HSSW ~~formation mechanism (Buffoni et al., 2002; Mathiot et al., 2012)~~. ~~Besides~~ In addition to the polynya activity, both CDW transport in the Ross Sea continental shelf and water masses that flow from the southern part of the DIT have also been suggested ~~as the factors that influences changes in~~ to affect the HSSW properties (Fusco et al., 2009; Stevens et al., 2017).

[YS7]: Topic Editor: throughout: sea ice

[YS8R7]: We have deleted a hyphen based on your comment.

[YS9]: Topic Editor: brine is salty by definition!

[YS10R9]: We have deleted salty based on your comment.

The coastal region of the NIS is considered to be the primary location of HSSW formation in TNB, because this region is relatively shallow and katabatic winds blowing from across the NIS first encounter the ocean surface here. Thus, ~~For this reason,~~ salinity variations ~~were investigated~~ in the western part of the Drygalski Basin (DB) rather than the eastern TNB have received some attention (Fusco et al., 2009; Rusciano et al., 2013; Fig. 1). However, the shape of TNBP has varied over time ~~based on MODIS (Moderate-resolution Imaging Spectroradiometer) ice surface temperature imagery~~ (Ciappa et al., 2012; Aulicino et al., 2018), ~~indicating~~ suggesting that polynya activity ~~may~~ varies~~y~~ both spatially and temporally. Moreover, as suggested by model results, water masses in the deepest parts of the DB and eastern TNB may interact with water masses in the western Ross Sea via cyclonic circulation over Crary Bank (Jendersie et al., 2018; Fig. 1). This suggests that t~~In other words, t~~he HSSW accumulates in the deepest parts of the DB and eastern TNB before being predominantly transported north towards the shelf break. As a result, the formation of HSSW in the region may be spatially and temporally modulated by influences from bathymetry, sea-~~-~~ice formation, and winds.

This study ~~uses~~ combines ship-based in-~~-~~situ data collected in the austral summer (December–March) and ~~hydrographic~~ instrumented mooring data collected in the DB and eastern TNB during December 2014–March 2018 to explore sub-polynya scale (tens of ~~~10s~~ kilometers~~m~~) dynamics. In particular, we seek to answer the following research questions: (1) How ~~D~~does the nature of the circulation in TNB influence HSSW ~~production~~variation? (2) Is~~Are~~ there a significant difference~~s~~ between the salinity variation in~~of~~ the western (nearshore) and eastern (offshore) parts of TNB? and (3) Does katabatic wind variability play a significant role in salinity variation? We then ~~use the answers to these questions to pose~~propose a sequence of typical mechanistic scales for HSSW production ~~the polynya~~.

2 Data and Methods

2.1 Hydrographic measurements

We examined the spatio-temporal variations in HSSW production using ~~the~~ time-series data from mooring stations in the eastern TNB (DITN) and the deepest depth level of the DB (DITD) (~~blue diamond and magenta star, respectively, in~~ Fig. 1). T~~he DITN mooring, which supports measurements~~ime-series of water temperature, salinity, pressure, and ocean currents at three depths~~,~~ were measured using SBE37SM (Sea-Bird Scientific, Bellevue, WA, USA), RCM9 (Xylem, Inc., Rye Brook, NY, USA), and Aquadopp (Nortek, Norway) current meters attached to the DITN mooring (Fig. 2 and Table 1). The DITN mooring~~,~~ has been continuously maintained with annual turn-arounds since December 2014 (Table 1). ~~Data from these devices have been retrieved, downloaded, and maintained, with annual instruments redeployment thereafter. The redeployments are collocated, such that the depths at sensor locations in each observation period were nearly identical during the three year study period (Fig. 2 and Table 1).~~ During the second leg of the DITN, the pressure sensor of the~~an~~ deepest SBE37SM ~~installed in a deep layer incorrectly recorded the pressure value.~~failed~~ Therefore~~, necessitating that a nominal sensor depth of 660 m ~~was~~be used ~~to calculate the salinity~~. T~~In addition, t~~he DITD mooring was deployed at the 1,230 m isobath for a single year during

[YS11]: Topic Editor: avoid caption material throughout

[YS12R11]: Done.

[YS13]: Topic Editor: no information in these sentences. Annual turn over covers it.

[YS14R13]: We have added “with annual turn-arounds” based on your comment [Tracked-changes version on L88].

February 2017–March 2018, ~~which recorded the same variables as the DITN, but operated~~with instruments below 1,200 m (Fig. 2 and Table 1). The DITN (DITD) is located 32 km southeast (20 km south) of mooring D (Fig. 1). Mooring D was deployed near the NIS from 1995 to 2007, performing observations of various ocean variables at depths of up to 1,000 m for 13 years (Rusciano et al., 2013).

The temperature and salinity parameters obtained from two~~hese~~ moorings (DITN and DITD) were validated and corrected with conductivity-temperature-depth (CTD) casts ~~in the mooring positions~~ before recovery and after ~~the~~ deployment ~~of the DITN and DITD~~. The salinity time-series contains the short-term fluctuations induced by tidal motions and ocean currents, such that the magnitude of the salinity change suggested in Section 3.3 was calculated after applying a 160 hour (~ 7 days) low-pass filter to the time-series using a 6th order Butterworth filter. The horizontal~~The~~ current direction was corrected for the magnetic declination ~~was corrected to the current direction and the velocities were averaged monthly to investigate the mean advection speed and direction during each month rather than short-term variabilities in the ocean currents over the course of a month~~. Current data observed with the RCM9 at~~instrument during~~ the DITN ~~mooring~~ were used for consistency of the data analysis, except for the uppermost current data of the third leg of the DITN. Current data from the RCM9 ~~instrument~~ at ~~a depth of~~ 75 m were recorded until August 1, 2017;~~.~~ t~~T~~hereafter, an Aquadopp current meter was used. Mean differences in the current direction (speed) between observed data from the RCM9 and Aquadopp current meters at 75, 273, and 660 m~~each depth~~ were 2°, 3°, and 8° (1.8, 0.2, and –1.2 cm/s), respectively during the third leg of the DITN. The velocities were averaged monthly to investigate the mean advection speed and direction on monthly and seasonal time scales.~~The salinity time-series contains the short-term fluctuation (Fig. 8a) induced by tidal motions and ocean currents, such that the magnitude of the change in the salinity was calculated after applying a 160 hour (~ 7 days) low-pass filter to the time-series using the 6th order Butterworth filter.~~

Full-depth CTD profile ~~data~~ measurements were conducted in December 2014, December 2015, January–February 2017, and March 2018 (Table 1) aboard~~by~~ the icebreaking research vessel IBRV ARAON (Korea Polar Research Institute (KOPRI)) ~~during hydrographic surveys to analyze the water mass properties of TNB~~. The profiles were recorded using an SBE 911 (Sea-Bird Electronics) ~~along with the CTD~~ with dual temperature and conductivity sensors. The sensors' calibration dates were within seven months of the observation dates. They were processed using standard methods recommended by SBE (Sea-Bird Electronics, Inc., 2014). ~~Surveys on TNB were conducted during December 2014, December 2015, January–February 2017, and March 2018 (Table 1), although profile~~The locations of CTD casts varied annually depending on sea ice and cruise priorities (Fig. 1).

To directly compare this study with results from previous studies (Budillon and Spezie, 2000; Budillon et al., 2002; Budillon et al., 2011; Orsi and Wiederwohl, 2009), we used the practical salinity scale, rather than results based on the thermodynamic equation of seawater, i.e., ~~(~~TEOS~~)~~-10 (McDougall and Barker, 2017). The practical salinity is smaller than the absolute salinity by about 0.17 in TNB. Potential densities (σ_θ) over 28 kg/m^3 were used as criteria for the properties of the HSSW, to distinguish the HSSW from TNB Ice Shelf Water (TISW). TISW is characterized by its potential temperatures being lower than the freezing point at the surface (θ < –1.93 °C) and a salinity of approximately 34.73 (Budillon and Spezie, 2000). TISW is the product of mixing between meltwater from ice-shelf melting and HSSW (Rusciano et al., 2013).

Vertical p~~P~~rofiles of horizontal currents (5-m depth interval) were measured using a lowered acoustic Doppler current profiler (LADCP) ~~instrument~~ attached to the CTD frame. The LADCP data were processed (Thurnherr, 2004) and velocities lower than the error velocity were not used in this study. The error velocity indicates uncertainty in the velocity estimated using the LADCP profile (Thurnherr, 2004). In addition, the ~~velocities~~ horizontal currents were de-tided using all ten available tidal components from the CATS2008 (Circum-Antarctica Tidal Simulation) model~~)~~ (Padman et al., 2002). The mean speed ~~velocity~~ of tidal currents during each survey were~~as~~ 1~~0~~.9~~0~~, 1.8~~5~~, ~~1~~0.7~~0~~, and 0.7~~5~~ cm/s, which were ~~much~~ weaker than the velocities observed from the moorings and LADCP. The mean tidal ranges during each survey were 0.22, 0.45, 0.20, and 0.17 m.

~~To directly compare this study with results from previous studies (Budillon and Spezie, 2000; Budillon et al., 2002; Budillon et al., 2011; Orsi and Wiederwohl, 2009), we used the practical salinity scale, rather than results based on the thermodynamic equation of seawater, i.e., (TEOS)-10 (McDougall and Barker, 2017). Potential densities (σ_θ) over 28 kg/m^3 were used as a criterion for the properties of the HSSW, to distinguish the HSSW from TNB ice shelf water (TISW) (Fig. 3). TISW is the product of mixing between meltwater from ice-shelf melting and HSSW (Rusciano et al., 2013).~~

2.2 Wind and sea-ice data

Hourly time-series of wind and air temperature~~data~~ (2014–2018) record~~observ~~ed at the Automatic Weather System (AWS) Manuela station (Ciappa et al., 2012; Fig. 3~~4a~~) were used to investigate katabatic winds blowing over TNB and estimate the sensible heat flux. The AWS Manuela station is managed by the Automatic Weather Station Program of the ~~AMRC (~~Antarctic Meteorological Research Center~~)~~ at the University of Wisconsin-Madison. A katabatic wind event is defined as a period in which the~~having a westerly -~~ wind direction is between ~~of~~ 225° and~~–~~ 315° (westerly) and the~~a~~ wind speed ~~of over~~exceeds 25 m/s. The AWS Manuela station is located~~situated~~ ~~such that it is~~ within the main pathway of the katabatic winds along Reeves Glacier, making it the best option to detect the katabatic winds ~~that blow~~ over TNB (Ciappa et al., 2012; Sansiviero et al., 2017).

T~~he three-hourly~~ ime-series of the ~~10-m~~ wind and ~~2-m~~ air~~-~~ temperature at heights of 10 and 2 m ~~data~~, with an interval of 3 hours and a grid size of 0.75° × 0.75°, provided by the ERA-Interim reanalysis data set (Dee et al., 2011)~~,~~ were ~~also~~ used to identify atmospheric conditions in TNB from January 2014 to March 2018 (Fig. 3). ~~A grid size of 0.75° × 0.75° was attributed to the data set.~~ The a~~A~~veraged wind at the AWS Manuela station was approximately four times faster than that provided by the ERA-Interim reanalysis data, but its direction was nearly identical to ~~with~~ that at the grid located near Manuela (an approximately 6° ~~°~~ difference) (Fig. 3~~4a~~). ERA-Interim is a spatially smoothed product with a grid that is generally too coarse to resolve steep glacial slopes, which may be the reason for the large difference in wind speed compared to the observed data

(Fusco et al., 2002; Dee et al., 2011). However, variations in the westerly~~eastward~~ (225°~~°~~ ≤ θ ≤ 315°~~°~~) wind speed at Manuela had a significant correlation (99% confidence level) with ERA-Interim retrieved values from TNB~~, including the region near the DITN,~~ from July 2014 to March 2018 (correlation coefficient (*r*) > 0.70)~~ (Fig. 4b)~~. Westerly~~Eastward~~ winds detected at the Manuela station were ~~synchronized~~ similar to~~with~~ the wind in all regions of TNB in terms of the occurrence and speed variability~~ in all regions of TNB~~, despite slower offshore wind speeds (Fig. 3). In this paper, all significant *r* have a 99% confidence level.~~ In addition, the daily air temperature observed at Manuela also had a significant *r* value (> 0.90) with that from the ERA-Interim (Fig. 4b).~~

~~We also investigated~~For sea-ice concentrations, we use the daily ~~ARTIST (Arctic Radiation and Turbulence Interaction Study) sea-ice algorithm concentration~~ product~~s~~ from the Arctic Radiation and Turbulence Interaction Study with a grid spacing of 3.125 km resolved from the Advanced Microwave Scanning Radiometer 2 data set (Spreen et al., 2008). The selected data period was from July 2014 to March 2018, in~~with~~ a ~~data~~ domain within the McMurdo Sound (Fig. 3~~4a~~). We applied the same continental masking obtained from recent data and defined regions of sea-ice concentrations below 20% as open water (Parkinson et al., 1999; Zwally et al., 2002). Finally, the topographic data were derived from the International Bathymetric Chart of the Southern Ocean~~ (IBSCO)~~.

3 Results

3.1 ~~Deep salinity~~Near-bed salinity variations in TNB

S~~Deep s~~alinity observed at the deepest sensor (660 m) at~~in a~~ ~~mooring~~ the DITN mooring located in the eastern TNB (~~DITN, blue diamond in~~ Fig. 1) exhibited interannual variations during 2015–2017 (Fig. 4~~5~~a) and ~~. Moreover, at approximately 660 m, during a span of three years, the salinity significantly~~ increased from 34.80 to 34.85~~, despite certain periods where the salinity decreased by 0.01–0.02 (Fig. 5a)~~. The annual cycle of salinity begins to increase from September (Fig. 4~~5~~a), where the change in salt contents (Fusco et al., 2009) is estimated as 2.84, 7.64, and 5.23 μg salt/m^3/s (0.007, 0.019, and 0.013 psu/month) from September to October during 2015, 2016, and 2017, respectively. Southward currents were observed when the salinity increased at the corresponding depth (Fig. 4b). The mean current direction was southwestward (191°), with a mean speed of approximately 1.5 cm/s during the August–November period over the three year study period (Fig. 1).

Consistent salinity variation was observed at the other mooring (DITD) located in the DB (Figs. 1 and 4a). The salinity in the deepest part of TNB also begins to increase from September, and the salt change from September to October 2017 is estimated as 6.66 μg salt/m^3/s (0.017 psu/month) (Fig. 4a). The maximum salinity measured at the DITD is larger (~ 0.006) than that at the DITN (Fig. 4a). In contrast with those observed at the DITN, northwestward currents are observed at a similar depth of salinity as that from the DITD (1,222 m) during the observation periods (Fig. 4b). The mean direction of the current is northwestward (300°), and its mean speed is approximately 3.0 cm/s during August–November 2017 (Fig. 1).

Seawater properties (temperature and salinity) observed from the DITN and DITD during August–October~~during this period were included in~~correspond to the ~~range of the~~ HSSW properties (~~blue dots in~~ Fig. 5~~6~~), so~~.~~ ~~Therefore, t~~the relatively large changes in salt during 2016 and 2017 are an indication of active HSSW formation during the austral winter in TNBP.

Evidence of ~~the past~~ HSSW formation from April to October of 2016 and 2017 was still observed three to~~and~~ five months later, in January 2017 and March 2018, respectively (Fig. 6~~3~~). The maximum salinity in the HSSW during January–February 2017 (2016/17) and in March 2018 (2017/18) was close~~similar~~ to those~~at~~ ~~of~~observed in the preceding~~observations in~~ October in~~of~~ 2016 and 2017, respectively (Figs. 4a~~3~~ and ~~Fig.~~ 6~~5a~~). The mean salinity in the HSSW (σ_θ>28 kg/m^3) was also calculated as 34.788 (σ= 0.002), 34.785 (0.005), 34.801 (0.009), and 34.815 (0.016) for each survey. ~~Possible traces of MCDW were rare in the θ-S diagram (small panel in Fig. 3), such that its effect on the changes in deep salinity throughout TNB were limited.~~

Vertical ~~CTD~~ profiles of salinity and potential density also had features consistent with the θ–S diagram (Fig. 7). ~~A~~The properties in a quasi-homogeneous bottom layer below 800 m (Fig. 7) represent~~s~~ ~~HSSW formation~~the properties of HSSW formed just before the austral winter ~~(Fig. 7)~~. The salinity of this layer~~year~~ was relatively high in the 2016/17 and 2017/18 surveys (Fig. 7a; peak salinities of 34.83 and 34.85, respectively) and was similar with that observed in the early 2000s in which HSSW transport was relatively large (> 1.2 Sv) in TNB during 1995–2006 (Fig. 7a; Fusco et al., 2009). ~~Such a high-salinity water mass can be only formed in TNBP (Orsi and Wiederwohl, 2009). Thus, active HSSW formation in TNBP during the austral winters of 2016 and 2017 increased the salinity of the water at 660 m at the DITN mooring.~~

~~However, the timing of the salinity increase at the DITN occurred approximately 1–2 months later than that observed at mooring D.~~ ~~The latter two surveys were conducted in the late austral summer (January–February 2017 and March 2018). Therefore, less saline (dense) seawater in the upper parts and a strong salinity (density) gradient between the upper and lower layers were observed (Figs. 7a and 7c). The TISW, characterized by its potential temperatures lower than the freezing point at the surface (θ < −1.93°C) and a salinity of approximately 34.73 (Budillon and Spezie, 2000), was observed at depths between 300 and 600 m in 2016/17 and 2017/18, but was not observed during December surveys (2014/15 and 2015/16) (Figs. 3 and 7b). Therefore, meltwater outflow from nearby ice shelves may occur in late summer.~~

~~Mooring D (a black-filled triangle in Fig. 1) 33km northwest of the DITN, was deployed near the NIS from 1995 to 2007, performing observations of various ocean variables at depths of up to 1,000 m for 13 years. Data from mooring D showed that periods of deep salinity (~ 550 m) increase beginning in July due to HSSW production (Rusciano et al., 2013).~~ ~~However, the timing of the salinity increase at the DITN occurred approximately 1–2 months later than that observed at mooring D.~~ ~~Saline seawater over 34.80 is only formed in TNBP, which is the reason behind the increase in salinity measured in September. According to the current measurements obtained at the same depth (~660 m) as the salinity, flows were nearly southward and~~

~~slower than 4 cm/s (blue arrows in Fig. 5b). Southwestward flows were mainly observed during periods of increased salinity, with episodic detection of southeastward flows (Fig. 5b). The mean current direction was southwestward (191°), with a mean speed of approximately 1.5 cm/s during the August–November period over the three year study period (a blue arrow in Fig. 1). the HSSW is formed near the NIS during the austral winter and propagates towards the center of TNB along 800–1,000-m isobaths (Fig. 1) (Rusciano et al., 2013). We assumed that the propagation of the HSSW into the eastern TNB for a month along the mean current would result in HSSW movement from 40 km of the DITN in a northern direction. Moreover, the HSSW is formed near the NIS during the austral winter and propagates towards the center of TNB along 800–1,000-m isobaths (Fig. 1) (Rusciano et al., 2013). Thus, we can conclude that the deep salinity in the eastern TNB has increased since September due to the southward advection of HSSW from the center of TNB (75°S, 165°E) near mooring D.~~

~~The one-year of moored hydrographic data from the deepest depth of DB (DITD, a magenta star in Fig. 1) also captures the salinity variation feature demonstrated during the third leg of DITN mooring (a magenta line in Fig. 5a). The salinity in the deepest part of TNB also begins to increase from September, and the salt change from September to October 2017 is estimated as 6.66 μg salt/m³/s (0.017 psu/month) (Fig. 5a). Seawater properties observed from the DITD are also included in the range of HSSW (magenta dots in Figs. 6g–6i). However, northwestward currents are observed at a similar depth of salinity as that from the DITD (1,222 m) during the observation periods (Fig. 5b). The mean direction of the current is northwestward (300°), and its mean speed is approximately 3.0 cm/s during August–November 2017 (a magenta arrow in Fig. 1). The maximum salinity measured at the DITD is larger than that at the DITN (Fig. 5a), so the salinity increase in the DITD is not related to the northwestward HSSW advection from the eastern TNB. Consequently, the current observed from the DITD is considered as a part of the circulation in the deepest parts of DB along the 1,000 m isobath. In other words, HSSW flowing into the DB from the NIS would circulate over the DB, which is being detected at the DITD since September 2017. The circulation in the DB is discussed further in Section 4.2.~~

3.2 Upper ocean salinity variations in the eastern TNB

~~Salinity was observed at around 75 and 273 m to investigate the variations in the upper water column of the eastern TNB (Fig. 8a). In contrast to the salinity at 660 m,~~ S~~s~~alinity in the upper water column of the eastern TNB~~parts~~ shows a more distinct seasonal variation compared to the salinity at 660 m (Fig. 8a). The s~~S~~alinity at both 75 m and 273 m decreased, while the salinity at 75 m decreased to below 34.0 in February of each year (Fig. 8a). Thereafter, the salinity of the two layers started mixing, as the salinity increased~~s~~ ~~(decreases)~~ at 75 ~~(273)~~ m and decreased at 273 m. The salinity ~~of the two layers~~ at both depths then increased~~s~~ in tandem ~~from May to~~until ~~October~~ September (Fig. 8a). Note that the vertically well-mixed period gets longer over the three years. The well-mixed period, defined as a period in which the difference in σ_θ between the two layers is less than 0.1 kg/m^3 (Dong et al., 2008), was initiated in early May 2015, at the end of April 2016, and in early April

[YS15]: Topic Editor: rewrite as separate sentences.

[YS16R15]: Done.

2017 (Fig. 8b). In December, the mixing of the two layers ceases, and their salinity difference becomes larger again (Fig. 8a). The ~~reduction in mixing~~restratification is due to changes in buoyancy as a result of ice melting at the surface during the austral summer.

~~We have noted that the period when these layers are well mixed has become longer over time (Fig. 8a). If we assume that the two layers are mixed when the difference in σ_θ between the two layers is less than 0.1 kg/m^3 (~0.0005 kg/m^3) (Dong et al., 2008), then early May in 2015, the end of April in 2016, and early April in 2017 are when the upper (at least to 273 m) water column becomes isopycnal (Fig. 8b). From these times until October, salinities at the two depths are characterized by higher correlations than during the entire period. The salinity at 75 m had correlation coefficients of 0.64, 0.58, and 0.62 with the salinity at 273 m during the 1st, 2nd, and 3rd legs (Table 1), respectively. However, for periods in which the salinity at the two depths simultaneously increased, the r values increased to 0.94, 0.88, and 0.93 (Fig. 8a), respectively. In other words, the salinity at the two depths was characterized by the most rapid mixing during March–April 2017 among the three year study period, with the longest co-variation time until October, 2017.~~

The maximum salinity observed at depths of 75 and 273 m, during September–October also increased from 2015 to 2017 (34.774, 34.804, and 34.849, respectively), which is consistent with the trend of maximum salinity observed at deeper depths as presented in the previous subsection (Figs. 4~~5~~a, 6, 7, and 8a). Water properties corresponding to t~~T~~he HSSW w~~as~~ere detected even in the upper parts during the months of August to October in 2016 and 2017 (~~red and black dots in~~ Figs. 5~~6~~d–6~~5~~i), suggesting that the HSSW can be locally formed through convective processes in the eastern TNB. The averaged salinity in the upper water column during September–October in 2016 and 2017 was lower (~ 0.05) than that observed at 660 m (Figs. 5 and 8a), so it is not responsible for the salinity increase at the near-bed level of the eastern TNB (Fig. 4a). In contrast, HSSW formation was rarely observed from August to October 2015, when the increase in salinity was relatively small compared with th~~at~~e increases during the same period in 2016 and 2017 (Figs. 4~~5~~a and~~;~~ ~~red and black dots in~~ 5~~6~~a–5~~6~~c).

~~The reasons for the higher increase in salinity in the upper parts may be due to the formation of increasing amounts of dense water via brine rejection at the surface of the eastern TNB or by the advection of more saline water from other regions of TNB. According to current data obtained from the upper parts,~~ During December 2014–March 2018, westward currents were dominant at the two depths ~~during December 2014–March 2018~~ (Fig. 8c), with an average current speed (direction) from June to November of 7.4 cm/s (279°~~°~~, westward) at 75 m and 4.0 cm/s (270°~~°~~, westward) at 273 m (Fig. 1). ~~These currents are possibly led by density gradients between under the DIT and in TNB or a latitudinal gradient of sea-surface height near the DIT. These phenomena are confined to coastal regions due to the existence of the DIT (Fig. 1 and Section 1). However, based on our observations,~~ The westward currents suggest that the ~~only the~~ upper water column~~s~~ of the DITN~~–~~ ~~appear to be~~was affected by seawater advected from the eastern part of TNB ~~during periods of increased upper level salinity~~. ~~As identified in~~

[YS17]: Topic Editor: throughout replace "the r values" with "r"

[YS18R17]: We have replaced "the r values" with "r" in other parts.

[YS19]: Topic Editor: please quantify

[YS20R19]: Done.

~~previous studies, water masses farther away TNB are less saline due to mixing with the CDW or the intrusion of MCDW into the western Ross Sea (Orsi and Wiederwohl, 2009; Fusco et al., 2009; Budillon et al., 2011).~~

~~Thus, salinity increases in the upper layers are related to local brine supplied by sea-ice formation near the DITN region, rather than the advection of saline water from the western Ross Sea. As a result, salinity (density) variations in the upper layers exhibit dense water formation in the polynya via convection led by a supply of brine from the surface as suggested by modelling studies on TNBP (Fig. 8a; Buffoni et al., 2002; Mathiot et al., 2012). We observed the HSSW in the upper layers during the months from August to October of 2016 and 2017 (Fig. 6d–6i, and 8a), which indicates that the HSSW can be formed through convective processes in the eastern TNB. In addition, mixing of the upper layers in the eastern TNB was observed before convection, which implies that winds drive mixing as well as polynya development. We discuss to this point further in Section 3.4.~~

~~**3.3 Types of HSSW**~~

~~We found that the deep salinity began to increase in September, and the HSSW was detected in the upper parts of the DITN during August–October (Fig. 5a and 6). Based on numerical modelling, a water column in TNB can be mixed to a depth of 750 m, forming an HSSW layer from the surface to this depth (Buffoni et al., 2002; Mathiot et al., 2012). In other words, the increase in the deep salinity (i.e., at 660 and 1,208 m) observed in 2016 and 2017 may have been partly induced by local HSSW formation combined with HSSW advection from the center of TNB. However, the salinity time-series at 660 m had a poor correlation with salinity variations in the upper parts of the DITN during September–October in 2016 and 2017 (*r* < 0.30). The salinity at 660 m was a little higher than that observed in the upper water column (Figs. 6 and 8a). This indicates that the mixed layer does not extend to 660 m in the eastern TNB. The higher salinity in the deep layer derives from the other regions in TNB and, not the surface of the DITN. Thus, in this case, the HSSW formed in the eastern TNB must be distinguished from that produced in the coastal region of the NIS. Its movement in the upper layers of TNB or its influence on the eastern TNB are equally interesting research topics but these types of HSSW are difficult to investigate with the observational data used in this study.~~

[YS21]: Topic Editor: please clarify what "Its" and "these" refer to

[YS22R21]: We have deleted this sentence.

3.34 The r~~R~~ole of wind in TNBP

The wind in TNB is primarily westerly, which on average, creates an L-shaped polynya along the NIS and DIT, as shown by the contour line that represents a sea-ice concentration of 50% in Fig. 3~~4a~~. Westerly winds ~~measured~~ at Manuela effectively opened TNBP during the austral winters (April–October) of the three year study period (Fig. 9). The ~~*r* value between the~~ daily wind speed ~~(blue line in Fig. 9)~~ and the percentage of open water ~~(sky blue bars in Fig. 9)~~ during the austral winter are significantly correlated (*r* = 0. 46)~~was 0.46 across a seven-month period (April–October , red dashed boxes in Fig. 9)~~ during ~~the three year period (~~2015–2017~~)~~ (Fig. 9)~~, which is significant at a 99% confidence level~~. In the austral winter during each year, ~~the~~ *r* ~~value~~ was 0.49, 0.50, and 0.37, respectively where all values were significant ~~at a 99% confidence level~~. ~~The period~~

~~from the end of June to July 2017, when open water did not significantly expand despite strong winds, affected the estimation of the lowest *r* value during the austral winter of 2017. The weak response of the polynya to these winds appears to be associated with a blocking effect of sea-ice in the offshore region (Tamura et al., 2016).~~

~~Previous studies have suggested that HSSW formation near mooring D is more dependent on the duration of a single katabatic wind event, than on its frequency during April–October (Rusciano et al., 2013). Based on the hydrographic surveys of TNB, there was more active formation of the HSSW in 2016 and 2017 than in 2014 and 2015. Therefore, deep salinity was increased due to HSSW advection from mooring D during late 2016 and 2017. This is consistent with wind observations at Manuela station. Among the three years,~~ K~~k~~atabatic wind events most frequently occurred from April to October 2017 (210 events) at Manuela station. The mean duration of a single katabatic wind event during these seven months in 2015, 2016, and 2017 was 6.5, 7.0, and 7.7 hours, respectively. ~~.~~ Moreover, the average length of time for which the polynya was open (i.e., > 20% open water in Fig. 9) during the same periods was 5.8 (2015), 6.7 (2016), and 7.7 days (2017)~~, respectively~~. ~~These results suggest that,~~In short, ~~during the three year study period,~~ the polynya opens for a longer time period with more persistent katabatic winds~~HSSW formation was the most active near the NIS~~ during the 2017 austral winter than during the other two years.

F~~In addition, f~~rom June to September ~~to October~~ of 2016 and 2017, a footprint of ~~the upper layers of the eastern TNB also experienced~~ HSSW production via convective processes was found in the upper water column in the eastern TNB (Fig. 8a) ~~after the development of a mixed layer~~. This indicates that katabatic winds — considered as vi~~pivo~~tal to the development of a polynya (Fig. 9) ~~and HSSW formation near the NIS (Rusciano et al., 2013) — generate wind-driven mixing and~~ induce ~~the~~ convection by a supply of brine related to new ice production in the eastern polynya ~~development in the eastern TNB~~. ~~Wind-driven mixing mainly occurs from March to May in the upper layers of the eastern TNB (Figs. 8a, and 8b), such that the mean wind speed (number of katabatic wind events) from March to May during 2015, 2016, and 2017 was calculated as 18.6, 20.2, and 21.0 m/s (74, 85, and 96), respectively. These wind statistics represent that wind-driven mixing was the strongest between March and May 2017 among the three years, which is consistent with the fastest mixing at two depths observed during the same period in the upper layers of the eastern TNB (Fig. 8a, and 8b).~~

~~When the salinity in the upper layers of the eastern TNB were predominantly increased through the convection led by a brine supply from the surface (June–September) (Fig. 8a),~~ T~~t~~he total magnitude of the salinity increase ~~in salinity~~ during the katabatic wind events from June to September was the largest in 2017 at both 75 ~~(0.082, 0.118, and 0.120 in each year),~~ and 273 m ~~(0.065, 0.050, and 0.142 in each year)~~ among the three years. At 75 (273) m, salinity increases of 0.082, 0118, and 0.120 (0.065, 0.050, and 0.142) were observed in 2015, 2016, and 2017, respectively. ~~The salinity time-series contains the short-term fluctuation (Fig. 8a) induced by tidal motions and ocean currents, such that the magnitude of the change in the salinity was calculated after applying a 160-hour (~ 7 days) low-pass filter to the time-series using the 6th order Butterworth filter.~~ ~~Increases in the salinity related with~~Salinity increases due to katabatic wind events ~~also~~ accounted for ~~over 50% (~~54% ~~at 75 m~~ and 76% ~~at 273 m)~~ of the total salinity increase observed at 75 and 273 m ~~from~~ during June~~–~~ ~~to~~ September in 2017. ~~In other~~

[YS23]: Topic Editor: In general, deep salinity does not read well. Improve throughout.

[YS24R23]: We have changed "deep salinity" into "near-bed salinity" based on your comment.

[YS25]: Topic Editor: in the detail is not important, better with "comparable, approximately 7 hours"

[YS26R25]: According to Rusciano et al. (2013), HSSW formation is more dependent on the duration of a single katabatic wind event. Thus, a difference in the mean duration of a single katabatic wind event between 2015 and 2017 (~1.2 hours) is meaningful and important. The meaning of these results are also discussed in Section 4.1.

[YS27]: Topic Editor: write out in separate sentences if necessary.

[YS28R27]: Done.

~~words, the convection promoted by the most brine supply during the katabatic wind events in 2017 contributed to a larger increase in salinity in the upper layers of the eastern TNB and local HSSW formation.~~

4 Discussion

Despite being a small, confined polynya, TNBP generates a substantial proportion of the global AABW. Understanding the supply of HSSW, and ultimately AABW, requires a focus on small~~-~~scale processes from a regional perspective. Here, we investigate the evolution of HSSW ~~behaviours~~ in TNB, through~~are investigated with~~ the spatio-temporal variations in salinity observed in the eastern TNB and DB.

4.1 Present data in the context of previous analyses

Data from mooring D (Fig. 1) in TNBP show seasonal variation in the stratification of the water column and interannual variation in the HSSW properties, which are closely associated with polynya activity (Rusciano et al., 2013). This impli~~prov~~es that HSSW production occurs during the austral winter, and ~~a series of~~favorable katabatic wind events ~~in a certain period of time during the austral winter~~ control~~s~~ the properties of the HSSW.

Data gathered for this study have revealed that the HSSW can also form at the surface of the eastern TNB. The salinity (density) variations in the upper layers at the DITN exhibit HSSW formation in the polynya via convection led by a supply of brine from the surface, as suggested by modelling studies on TNBP (Fig. 8a; Buffoni et al., 2002; Mathiot et al., 2012). Water masses farther away from TNB are less saline due to mixing with the CDW or the intrusion of MCDW into the western Ross Sea (Fusco et al., 2009; Orsi and Wiederwohl, 2009; Budillon et al., 2011), so the advection of seawater from the eastern part of TNB (Fig. 8c) would hardly contribute to the salinity increase in the upper water column of the DITN.

~~via an identical polynya process as that involved in vigorous HSSW formation near the NIS.~~ In addition, we found that large ~~increases in~~ salinity increases (> 0.04), related to active HSSW formation, were observed in the deepest part of the DB and eastern TNB from September to October (Fig. 4a); however, the salinity increase was observed at the DITN and DITD approximately 1–2 months later than that at mooring D. The Salinity observed at 550 m of mooring D increased since the beginning of July due to HSSW production (Rusciano et al., 2013). They also suggested that HSSW formed near the NIS advected towards the center of TNB along the 800–1,000 m isobaths. Therefore, the salinity increase from September at the DITN and DITD (Fig. 4a) would be ~~were~~ due to HSSW advection from the NIS but~~and~~ not from~~a~~ the sinking of HSSW directly from the surface at the mooring locations.

The HSSW formed ~~near the NIS~~ in the austral winter arrives at the deepest part of the DB and eastern TNB~~these depths~~ within a few months. Thus, the HSSW ~~is~~ evenly distribute~~ed~~s over TNB during the austral summer (Fig. 10). The depths for the upper HSSW limit (σ_θ= 28 kg/m^3) exist within a range from 400 to 700 m over TNB (Fig. 10), so the HSSW occupies a 500–800 m

[YS29]: Topic Editor: Overall, you use too many "In other words"….

[YS30R29]: We have deleted many "In other words" based on your comment.

water column from the sea bed in the austral summer. In addition, ~~In other words,~~ the average salinity of the HSSW in the eastern part at 164.5°E (34.802) shows no difference from that in the western part at 164.5°E (34.802) during the CTD observation periods. According to vertical sections of salinity from the 2017/18 survey, the salinity in the deep layer (> 600 m) was nearly identical between the western and eastern part of TNB (Fig. 11~~0~~a), with a ~~sufficiently~~ distributed salinity over 34.80 at greater depths (> 800 m) of the DB (Fig. 11~~0~~b). In the upper parts of the HSSW ($\sigma_\theta < 28$ kg/m^3), modified Shelf Water and Antarctic Surface Water were dominantly distributed over TNB during the austral summer (Fig. 11). Water properties corresponding to the MCDW were rarely shown for the austral summer (Figs. 6 and 11), such that its effect on salinity changes throughout TNB seems to be limited.

Furthermore, the role of wind in TNBP was investigated by statistics of katabatic winds during 2015–2017. We showed that the number of katabatic wind events was the largest in the 2017 austral winter (April–October) among the three years. The mean duration of katabatic wind events and the mean time for which the polynya was open were also the longest during the austral winter of 2017. The longer the polynya is exposed to wind, the more heat would be removed in the surface. Thus, these results support more active formation of the HSSW in 2017 than in 2015 and 2016 (Figs. 6 and 7). The upper ocean salinity increases estimated during the katabatic wind events of each year also suggest that more brine was released from ice formation during more persistent katabatic winds in 2017 and contributed to a larger salinity increase in the upper water column in the eastern TNB and to local HSSW formation. Rusciano et al. (2013) have suggested that HSSW formation is more dependent on the duration of a single katabatic wind event, than on its frequency during the austral winter. However, for the three year study period, both duration and frequency of katabatic wind events are important factors for active HSSW formation in TNBP. ~~As a result, the DITN, DITD, and four hydrographic surveys, along with previous data from mooring D, reveal spatio-temporal variations in HSSW production and movement in TNBP.~~

4.2 Circulations in TNBP

For the austral summer (December–March), westward currents flowing along the DIT and northward currents flowing along the NIS were observed based on the de-tided LADCP current data averaged over a depth range of 400–700 m (Fig. ~~11a~~12a). The currents resemble a cyclonic pattern together with the southeastward currents in the northeastern TNB, despite southward currents that flow toward the DIT ~~along 800–1000 m isobaths, as well as at the center of the DB~~ (Fig. 12~~1~~a). The c~~However,~~urrent speed is relatively weaker at the center of the DB than that in other TNB regions, and southeastward currents that cross over from the NIS to the DIT were not~~rarely~~ observed~~ in TNBP~~.

–The wind-driven cyclonic gyre in the upper layer of TNBP (van Woert et al., 2001) may induce an upwelling in the center of TNB, so it would hinder the development of horizontal flows in the central region of the gyre. The upwelling feature is visible in the vertical sections of the 2017/18 survey as upward-bending isopycnals in the upper layers (> 400 m) of the mid-point of

TNB (Fig. 11b). Similarly, depths for the upper HSSW limit seems to be shallower in the center of TNB than other regions of TNB (Fig. 10).

~~The direction of the ocean current at 660 m in the DITN was stable during December 2014–March 2018 (Figs. 5b and 8c).~~ I~~Therefore, i~~f we assume that the circulation pattern was maintained throughout the year, then the HSSW formed near the NIS ~~may~~ would circulate clockwise~~, arriving in the DITN around September and induced an increase in the salinity,~~ rather than directly ~~propagating~~ flowing southeastward toward the DITN.~~ Furthermore,~~ The southward currents observed at 660 m at the DITN mooring during periods of the salinity increase (Fig. 4b) would also be thought of the southern rim of the cyclonic circulation in TNB. ~~the wind-forcing-driven cyclonic gyre in the upper layer of TNBP (van Woert et al., 2001) may induce an upwelling in the center of TNB, which hinders the development of horizontal flows in the central region of the gyre. For example, the upwelling feature is visible in the vertical sections of the 2017/18 survey as upward-bending isopycnals in the upper layers (> 400 m) of the mid-point of TNB (Fig. 10b).~~Thus, we can conclude that the deep salinity in the eastern TNB has increased since September due to the advection of HSSW originating from the NIS. In addition, the reason why the salinity increase at the DITN occurs later (1–2 months) that at mooring D is that the HSSW flows along the cyclonic circulation. The distance from the DITN to mooring D is so close (~32 km) that the seawater at mooring D can arrive at the DITN within 13 days if there exist 3 cm/s southeastward currents between the two moorings.

As HSSW salinity observed at the DITD is larger than that at the DITN (Figs. 5g–5i), the salinity increase at the DITD (Fig. 4a) is not related to the northwestward HSSW advection from the eastern TNB along the cyclonic circulation (Fig. 12a). The near-bed~~bottom~~ ocean currents in the DB flow under the influence of gravity (Jendersie et al., 2018);~~.~~ h~~H~~owever, it is still unclear how the HSSW ~~flowing~~ at greater depths ~~is~~ circulates~~d~~ around the DB. The LADCP data for December–March might~~can~~ provide~~be~~ an indication of the circulation in the deeper parts of the DB ~~region~~ (> 1,000 m) because the current direction at the DITD remains approximately northwestward for about one year ~~exhibits little seasonal variation~~ (Fig. 4~~5~~b).

The southwestward currents appear in the northeastern part of the DB, while the northwestward and northeastward currents appear in the southern and western region of the DB, according to the currents averaged from 900 m to the seafloor during the austral summer (Fig. 12~~1~~b). The currents resemble a cyclonic circulation confined in the DB, which is different from the upper ocean cyclonic gyre in TNB (van Woert et al., 2001). The northwestward current observed at 1,222 m at the DITD mooring during the salinity increase period (Fig. 4b) is considered to be a part of this circulation, ~~In~~thus suggesting~~ other words,~~ that the HSSW flow~~propagat~~ing into the DB from the NIS circulated cyclonically in this region and can be detected at the sensors of the DITD mooring~~-~~ from September to October. The DB is an export pathway for HSSW formed in the Ross Sea polynya and TNBP~~Together with the Ross Ice Shelf polynya, the DB region is regarded as an outflow path of the HSSW towards the Ross Sea~~, so~~. Therefore,~~ the circulation pattern in this region further ~~also~~ requires investigation by acquiring more in-~~-~~situ ocean current data and ocean circulation model developments.

4.3 Characteristics of the TISW

The TISW, which is colder than –1.93 °C, was observed at depths between 300 and 600 m in January–February 2017 (2016/17) and March 2018 (2017/18) but was not observed during December surveys (2014/15 and 2015/16) (Figs. 6 and 13a). It seems that the TISW was formed when the HSSW was actively produced in TNB (Fig. 6); however, the discovery of the TISW is dependent on the observation period. For example, characteristics of the TISW becomes colder (~ 0.05 °C) and less saline (~ 0.02) from late January (2016/17) to March (2017/18) (Figs. 6 and 13a). The TISW with over 200 m thickness was only found near the NIS in late January (Fig. 13b), but, in March, it was distributed from the NIS to the northeastern TNB (Fig. 13c). It seems that the TISW near the NIS advects along the cyclonic circulation in TNB (Figs. 12a and 13c). Therefore, meltwater outflow from nearby ice shelves may occur from the late January to March. As compared with the previous observations, the TISW becomes much colder (> 0.1 °C) than the potential temperature of the TISW observed in the late 1990s (Budillon and Spezie, 2000). The colder TISW could contribute more sea-ice production at the surface of TNB, so characteristics of the TISW and their variations should be studied in the near future.

4.4 Mixed-layer development in the eastern TNB

As shown in Section 3.2, the time in which the upper (at least to 273 m) water column becomes homogenous is the earliest in 2017 across the three year study period (Figs. 8a and 8b). This suggests that the salinity at the two depths was characterized by rapid mixing during March–April 2017, with a long-lasting co-variation time until October 2017 (Fig. 8a). The mean wind speed (number of katabatic wind events) from March to May during 2015, 2016, and 2017 was calculated as 18.6, 20.2, and 21.0 m/s (74, 85, and 96), respectively. These wind statistics indicate that wind-driven mixing (mechanical mixing between two layers) was the strongest between March and May 2017. Thus, katabatic winds would also play a role in mixed-layer development before inducing HSSW production through the convective process in the eastern TNB. However, the magnitude of the salinity increase at 75 m was much larger than that of the salinity decrease at 273 m during March–May of each year, so the surface buoyancy flux from heat loss and/or sea-ice production have contributed more to the mixing in this period. For example, the salinity at 75 m increased over 0.5 from March to May 2017, but the salinity at 273 m decreased about 0.15 in the same period.

4.5~~3~~ TNBP mechanical scales

~~Considering the range and scale of the physical processes active in TNBP is useful.~~ HSSW produced near the NIS spreads horizontally into the eastern TNB~~ (~35 km)~~ and DB~~ (~25 km)~~, at current speeds lower than 5 cm/s in less than two~~2~~ months (from July to September) (Figs. 1, 4~~5~~, 8, and 12~~8~~; Rusciano et al., 2013). ~~Simultaneously, the HSSW sinks vertically to the greatest depths of the DB (~1,200 m) (Fig. 5).~~ If we assume that the circulation in TNBP has a radius of 25 km (approximately one longitudinal degree) (Fig. 12a~~1~~), the circumference of the circulation is about 160 km. T~~t~~hen we can deduce that the HSSW

[YS31]: Topic Editor: does this refer to HSSW formed locally or is the advecting HSSW sinks... not clear

[YS32R31]: We have deleted this sentence because it is related with the w argument.

circulates cyclonically about 80 km (~ 160/2 km) from the NIS to the eastern parts of TNB, which takes about one month at a current speed of 3 cm/s.

A velocity scale for the convective mixed-layer can be represented as $(B_0D)^{1/3}$ (B_0: Buoyancy flux per unit area, D: mixed-layer depth) (Kantha and Clayson, 2000). During the vertically well-mixed period (Fig. 8a), the mean buoyancy flux per unit area from the surface to 273 m is estimated as 0.0015 m^2/s^3 using the potential density time-series at 273 m at the DITN mooring. If the depth of the mixed-layer is deepened at least to 273 m, the convective velocity in TNBP is estimated to be on a scale of approximately 0.75 m/s. ~~In this case, the sinking process should take less than one month at an average velocity of 0.05–0.07 cm/s. The vertical velocity may be at a scale of about 10^{-2} that of the horizontal velocities in TNBP, which is regarded as a reasonable result for the ocean (van Haren, 2018).~~

TNBP usually forms as an L-shape, similar to a model-derived polynya (Sansiviero et al., 2017; Fig. 3~~4a~~). This indicates that the open water is predominantly formed along the coasts near NIS (DIT) for approximately~~–~~ forty latitudinal minutes over 75 km (two longitudinal degrees being equivalent to ~~(~~5~~8~~5~~)~~ km). The average area for polynya activity is approximately 1,3~~6~~00 km^2 (75 km × 10 km + 55 km × 10 km), based on the assumption ~~assuming~~ that the width of the open water is 10 km from the coast using the 40% sea-ice concentration contour line (Fig. 3~~4a~~). This accounts for about 4~~5~~% of the sea~~-~~-ice production area in the Ross Ice Shelf polynya (Cheng et al., 2017). ~~In the eastern TNB, wind-driven mixing from the surface to a depth of 273 m occurs within 3 months (from March to May). The homogenous mixed layer is maintained above 273 m during the austral winter by persistent, strong winds, and the water column is stratified again from December.~~ The opening of TNBP by westerly winds that blow from across the NIS occurs over the span of a day (Fig. 9). During this time, the percentage of ~~the~~ open water can vary by up to ±40% (Fig. 9). The mean duration of the polynya opening is about ~~6.~~seven~~7~~ days during the austral winter in the analysis period. ~~Salinity at both 75 and 273 m increased together from June or July (i.e., after the development of a mixed layer from the surface to a depth of 273 m), which indicates that brine rejection by sea-ice formation begins during this period.~~

4.~~6~~4 Quantification of sea-ice production

The link between katabatic winds and HSSW formation can be described as follows: (i) katabatic winds move sea ice into the offshore region, (ii) polynya opening, (iii) katabatic winds remove the heat from the polynya, (iv) sea-ice production in the surface, (v) brine rejection, (vi) breakdown of stratification, and (vii) HSSW formation through convective processes. Thus, ~~The~~ precise quantification of sea-ice production and brine formation in the polynya region is required for an in-depth understanding of ~~dense-water~~HSSW formation processes. However, current data for the brine supply from sea-ice formation in the polynya provided insufficient constraints. ~~According to previous results obtained using the ERA-Interim data set (Tamura et al., 2016), the estimated amounts of sea-ice production in TNBP had a high correlation (r = 0.96) with a thin ice area (< 0.2 m), but exhibited a poor correlation (r < 0.3) with offshore winds from the NIS and air temperature in TNB (see~~

[YS33]: Topic Editor: how you get to these numbers is not clear

[YS34R33]: We have corrected this sentence based on your comment.

[YS35]: Topic Editor: w argument here is not good. Remove the next sentence. I suggest you estimate a buoyancy flux, B, to convection from brine release, and estimate the convection velocity scale as (BD)^1/3 where D is the convection or mixed layer depth. Please search and find relevant citation. Revise the numbers if necessary.

[YS36R35]: We have deleted w argument and added the convection velocity scale based on your comment,

[YS37]: Topic Editor: why only "wind driven"? In winter, through heat loss etc., attemptionsyou probably have mixing by convection too (more general convection than polynya-related brine release etc.). Why are you ignoring this?

[YS38R37]: This part is considered to be not related to scale analysis, so we have deleted this sentence. Instead, we have added the convective velocity scale and Section 4.4 based on your comment.

[YS39]: Topic Editor: do you want so accurate numbers? Probably 7 days better for this discussion.

[YS40R39]: Done.

[YS41]: Topic Editor: My colleagues (in early 2000s, R. Skogseth and Peter M Haugan) have done a lot of work in estimating sea-ice production and related salinity increase in Storfjorden polynya (in Svalbard). This involves polynya area measurements (from satellite) and sea ice thermodynamics formulations. I find this discussion particularly poor. No attempts were made toward quantification.

[YS42R41]: We have added a quantification of sea-ice production based on your comment and referee #3's comment.

~~Table 1 in Tamura et al., 2016). This implies that the reanalysis data set did not reflect the air-sea heat exchange induced by winds that blow over TNBP or the differences in temperature between the ocean and atmosphere in TNBP.~~ In this part, we have an attempt to estimate the net heat flux from only the sensible heat flux by assuming that it is the main component for determining the net heat flux in TNB (Fusco et al., 2009). The sensible heat flux was calculated by using the AWS Manuela station's daily wind and air temperature data (Budillon et al., 2000), and the sea surface temperature was assumed to be near the freezing point (–1.9 °C). The daily air temperature observed at Manuela was also significantly correlated (r > 0.90) with ERA-Interim retrieved values from TNB from July 2014 to March 2018.

According to the calculations, the mean sensible heat flux was –178, –182, and –232 W/m^2 during katabatic wind events from April to October in 2015, 2016, and 2017, respectively. The sea-ice production and HSSW transport can be parameterized by the heat flux (Fusco et al., 2009), and, correspondingly, sea-ice production and HSSW transport were obtained as 32, 33, and 42 km^3 and 1.6, 1.6, and 1.9 Sv for 2015, 2016, and 2017, respectively. The estimated sensible heat flux, sea-ice production, and HSSW transport during April–October 2017 were very similar to values in 2003 when the largest sea-ice production occurred during 1990–2006 (Fusco et al., 2009). Moreover, in January of 2004, the averaged salinity in a 10 m layer at a depth of 900 m was observed to be 34.837 (Fusco et al., 2009), which is almost the same as the value (34. 838) observed in March 2018 (2017/18 survey) (Table 1). Since it is the rough estimation for sea-ice production, ~~HSSW production was estimated using the changes in the heat flux averaged over TNB (Fusco et al., 2009). In near future, however, spatio-temporal variabilities in surface heat flux should also be investigated to determine the spatial variations in polynya functions throughout TNB over time. Therefore,~~ in~~-~~-situ data should be continuously collected to ~~-validate reanalysis data sets and~~ clarify~~suggest~~ spatial and temporal relationships among wind speed, heat flux, sea-ice production, and the brine ~~effect~~ release in TNBP. ~~In addition, algorithms should be developed to accurately process satellite data or new satellite observations to extract data on small-scale ice formations such as frazil ice.~~

5 Conclusions

This study investigated~~d~~ the spatial patterns and temporal changes in HSSW formation in TNBP during a~~the~~ period from December 2014 to –March 2018 using a comprehensive in-situ observational~~large, collaboratively produced~~ data set. We tried to answer the three research questions listed in Section 1 as follows: (1) ~~We found that~~ HSSW formed near the NIS flows ~~along~~ cyclonically ~~pattern currents~~ in the deeper parts of TNBP ~~and influences~~ultimately reaching to the eastern TNB from September to October (Fig. 14).~~.~~ The HSSW formed near the NIS~~with~~ also reaches the greatest depth in the DB from~~from~~ September to October and is horizontally distributed by the cyclonic circulation in the DB (Fig. 1~~4~~2). (2)~~.~~ ~~As a result,~~ ~~T~~the salinity ~~timing of the~~ increase ~~in salinity is about two months later~~occurs in the western (nearshore) parts of TNB first from July to September, and then in the eastern (offshore) parts ~~of TNB than in the western (nearshore) parts~~about two months later from September to October, however, there are no significant salinity differences between the eastern and western parts during

[YS43]: Topic Editor: not clear if this is "reaching depths in September" or starting in Sept. Please clarify

[YS44R43]: We have clarified this sentence based on your comment.

the austral summer (Figs. 10 and 11). ~~.~~ (3)~~Moreover, w~~The~~e found that~~ katabatic winds that blow from across the NIS drive general salinity increases and even HSSW formation through ice production and brine release ~~by promoting convection with more brine supply~~ in the upper parts of the eastern TNB (Fig. 14~~2~~)~~. These findings answer the three research questions proposed in Section 1,~~ These answers complement~~ing~~ the ~~results of~~ previous ~~studies~~results on HSSW formation in TNBP well.

Large-scale freshening of AABW sources (including HSSW) has been reported in the Ross Sea and TNB in recent decades (Jacobs et al., 2002; Fusco et al., 2009; Jacobs and Giulivi, 2010), which may be relevant to the findings presented herein. We showed~~The intensification of Southern Hemisphere westerlies (in associated with a more positive phase of the Southern Annular Mode) was proposed as a possible driver of ice-sheet melting and corresponding seawater freshening upstream of the Ross Sea, because these processes induce an upwelling of warm water in the Amundsen and Bellingshausen Seas (Jacobs and Giulivi, 2010). In addition, variability in sea-ice production is expected to play a large role in HSSW formation (Jacobs and Giulivi, 2010).~~

~~The averaged salinity in a 10-m layer at a depth of~~higher (> 0.025) salinity values near 900 -m depth ~~shows larger values (> 0.025)~~ in ~~the~~ January–February 2017~~2016/17~~ and March 2018~~2017/18~~ ~~surveys~~ than those in December 2014~~the~~ ~~2014/15~~ and ~~2015/16~~December 2015 ~~surveys~~ (Table 1), implying more active HSSW formation in TNBP that was comparable to that in the ~~. In other words, the salinity of the HSSW formed in TNBP is increasing again, and its value corresponds to those observed in the~~ early 2000s (Fig. 7a; Fusco et al., 2009). The HSSW formed in TNB can flow off the shelf break along Victoria Land (Cincinelli et al., 2008; Jendersie et al., 2018)~~, which also contributes~~and potentially affect ~~to~~ the volume~~s~~ or property~~ies~~ of AABW in the western Ross Sea. Most recently, the rebound of HSSW salinity was reported from the observations in the western Ross Sea (Castagno et al., 2019). These recent findings have roughly suggested that active sea-ice formation in TNBP and Ross Ice Shelf polynya and a decrease in freshwater input from the Amundsen Sea would contribute to this salinity rebound.~~However~~ Also, our findings have implications on the ~~the~~ response of the overturning circulations in the Southern Ocean to regional anomalies in buoyancy forcing ~~have not been investigated~~ (Rintoul, 2018) as local HSSW may significantly contribute to the response and requires~~.~~ additional studies.

~~Lastly, here, the potential temperature and practical salinity were used to ensure consistency between our results and previous studies. In future studies, however, the HSSW in TNB needs to be re-defined with a conservative temperature and absolute salinity (TEOS-10) to reduce uncertainties in the long-term trend of HSSW properties, as well as to find a quantitative relationship with water mass properties in other regions.~~

[YS45]: Topic Editor: You have a chance to do it right here, in this study, but chose not to do so. Please do it, or delete this statement.

[YS46R45]: We have deleted this statement based on your comment. Instead, we have added a rough number for the magnitude of the difference between the practical salinity and absolute salinity. Please also see the response to comment #5 from referee #3.

Data Availability

The observational data used in this study are held at the Korea Polar Data Center (https://kpdc.kopri.re.kr) and metadata DOIs are as follows: https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00001062.1, https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00000601.1, https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00001063.1, and https://dx.doi.org/doi:10.22663/KOPRI-

KPDC-00000895.1 for CTD data; https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00000895.1, https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00001061.1, https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00001065.1, and https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00000896.1 for LADCP data; https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00001060.1, https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00000749.1, and https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00000898.1 for DITN data; and https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00000906.1 for DITD data. The wind data at the AWS Manuela station and sea-~~–~~ice concentration data used in this manuscript were~~are~~ obtained from http://amrc.ssec.wisc.edu/aws/api/form.html, and https://seaice.uni-bremen.de/data/amsr2/asi_daygrid_swath/s3125/, respectively. The daily ERA-Interim reanalysis dataset can be~~is~~ downloaded from https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/.

Author contribution

WSL and CS conceived and designed the experiments. STY, WSL, CS, SY, CYH, GIJ, and JL collected the observational data in TNBP, and STY and CS processed them. STY led the analysis with contributions from WSL, CS, SJ, SN, and CYH. STY wrote the paper.

Competing Interests

The authors declare no conflicts of interest.

Acknowledgements

This study was sponsored by a research grant from the Korean Ministry of Oceans and Fisheries (KIMST20190361; PM19020), the New Zealand Antarctic Research Institute, NZ Ministry of Business, Innovation and Employment, and the New Zealand National Institute of Water and Atmospheric Research (NIWA) (NZARI1401). We thank Gary Wilson, Christopher J. Zappa, Pierre Dutrieux, Brett Grant, Fiona Elliott and Alex Forrest for their support of this study through data collection and analysis as well as contributions to earlier versions of the paper.

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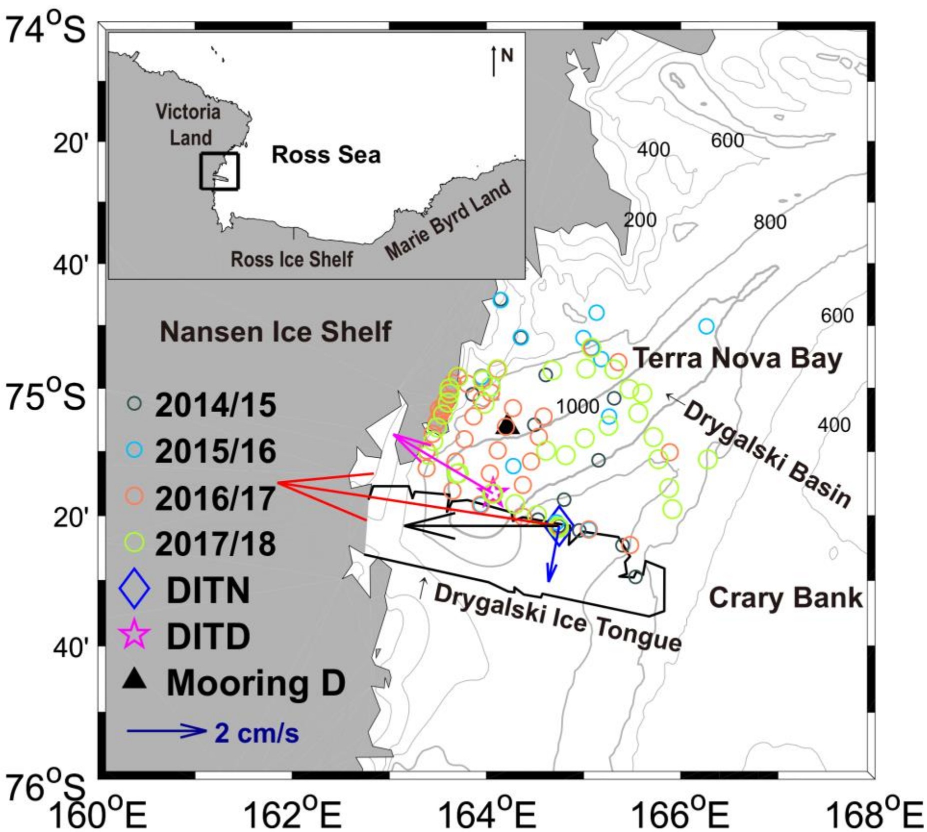


Figure 1: A topographic map of Terra Nova Bay (TNB). The location of TNB in the Ross Sea is shown in the upper-left inset. The bold graey line indicates the 1,000 -m isobaths, and the interval between the thinner graey lines is 200 m. Conductivity-temperature-depth (CTD) stations in the austral summers (i.e., 2014, 2015, 2017, and 2018) are denoted by open circles. The averaged current vector from August to November at 660 m in the eastern TNB (DITN) (1,222 m in the Drygalski Basin (DITD)) is denoted by a blue (magenta) arrow. The red (black) arrow indicates the mean current vector from June to November at 75 (273 m) in the DITN. The blue arrow in the bottom left indicates the reference velocity (2 cm s^{-1}).

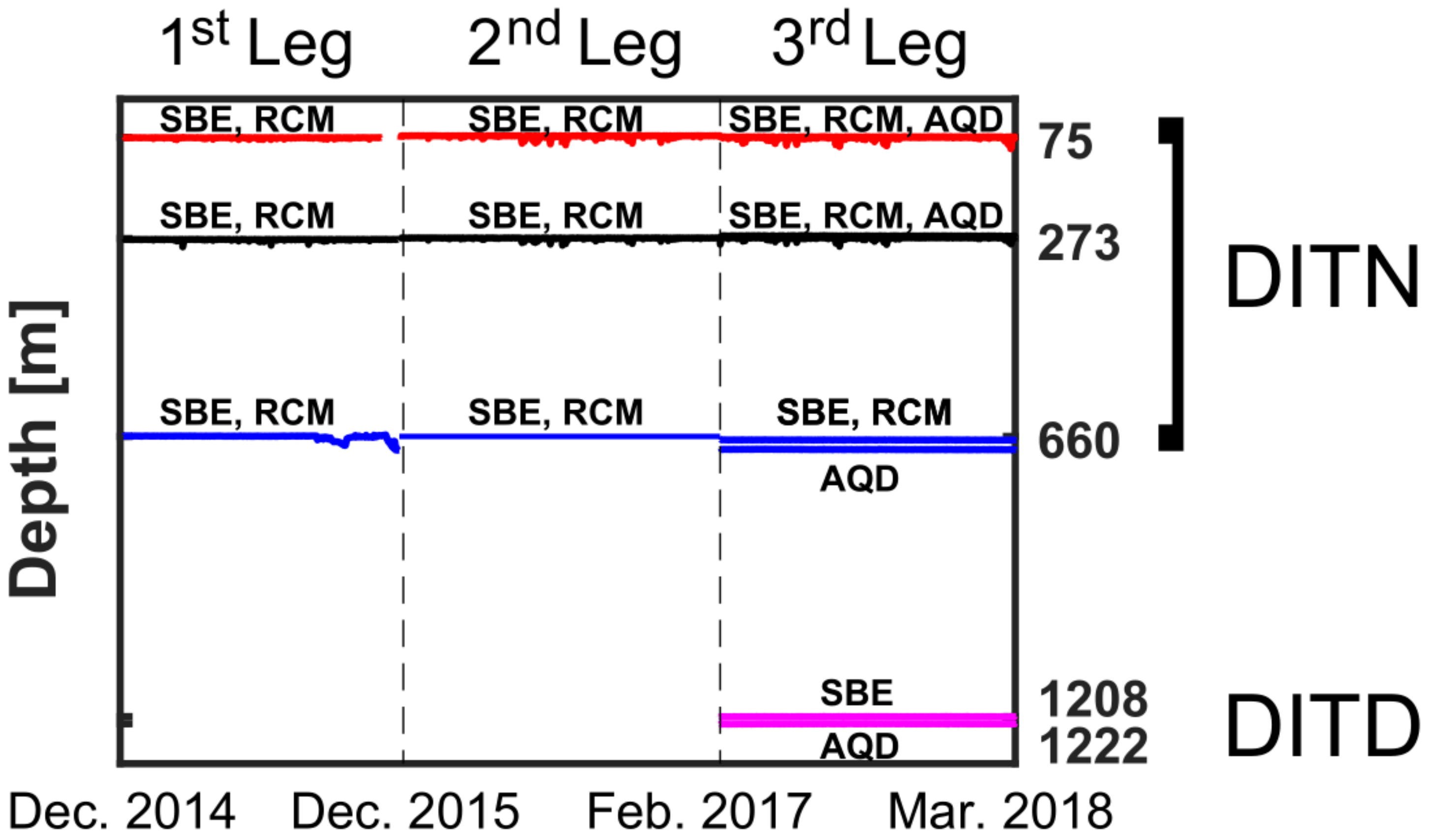
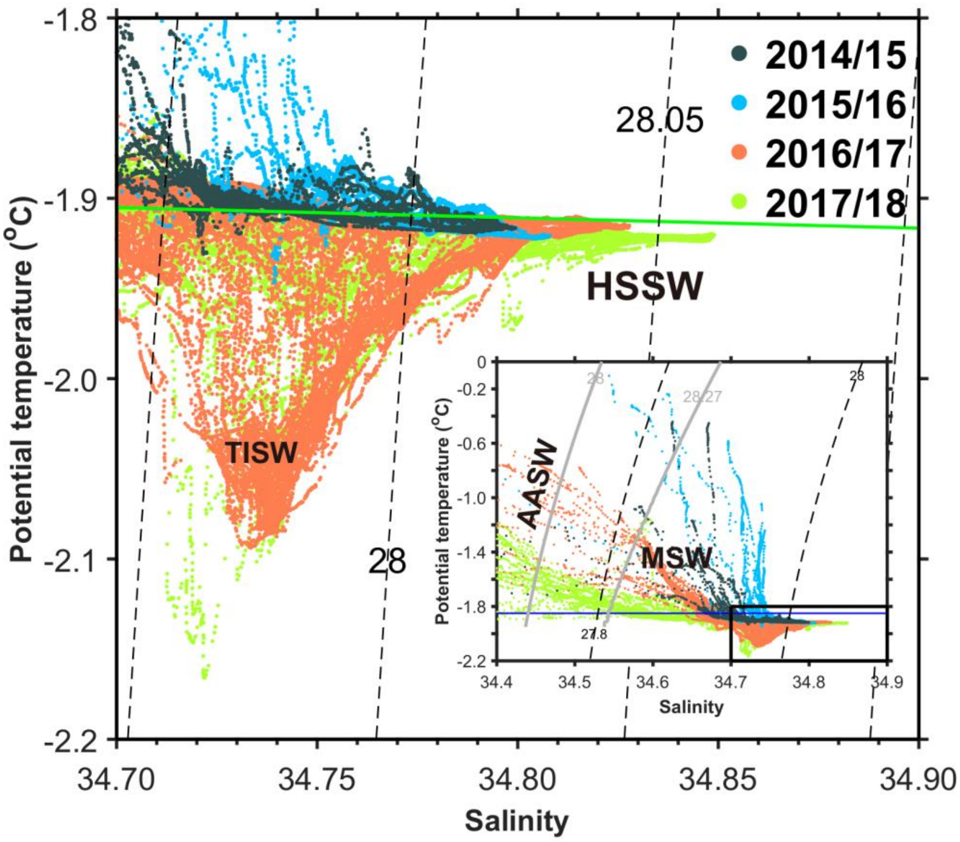
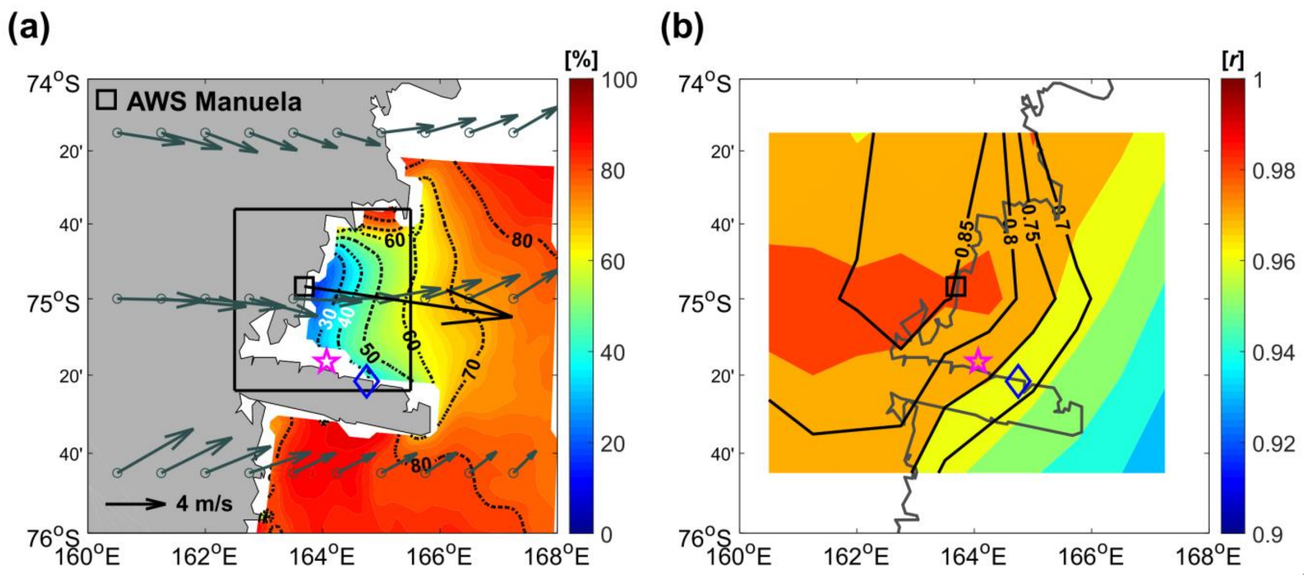


Figure 2: The recorded sensor depths during the three observation legs. The red, black, and blue lines show the depth time-series for sensors at the upper-, mid-, and deep-layer of the DITN. A magenta line also shows the recorded sensor depths of the DITD. The SBE, RCM, and AQD represent the SBE37SM, RCM9, and Aquadopp current meters, respectively (see details in Table 1).



~~**Figure 3:** A zoomed-in plot of the θ-S (potential temperature-salinity) diagram for CTD data observed in TNB during each observation period. The green solid line denotes the freezing point at the surface depending on salinity, and the black dashed lines indicate isopycnals. The full range θ-S diagram is shown in the small lower-right inset. The black box and blue line indicate the ranges of the magnified plot, and the −1.85 °C isotherm, respectively. The grey solid lines denote 28 and 28.27 kg m^{-3} neutral density (γ^n) surfaces. AASW, MSW, TISW, and HSSW represent the Antarctic Surface Water, Modified Shelf Water, Terra Nova Bay Ice Shelf Water, and High-Salinity Shelf Water, respectively.~~


(a)
[%]
AWS Manuela
4 m/s
74°S
20'
40'
75°S
20'
40'
76°S
160°E
162°E
164°E
166°E
168°E
100
80
60
40
20
0
(b)
[r]
1
0.98
0.96
0.94
0.92
0.9
0.85
0.8
0.75
0.7

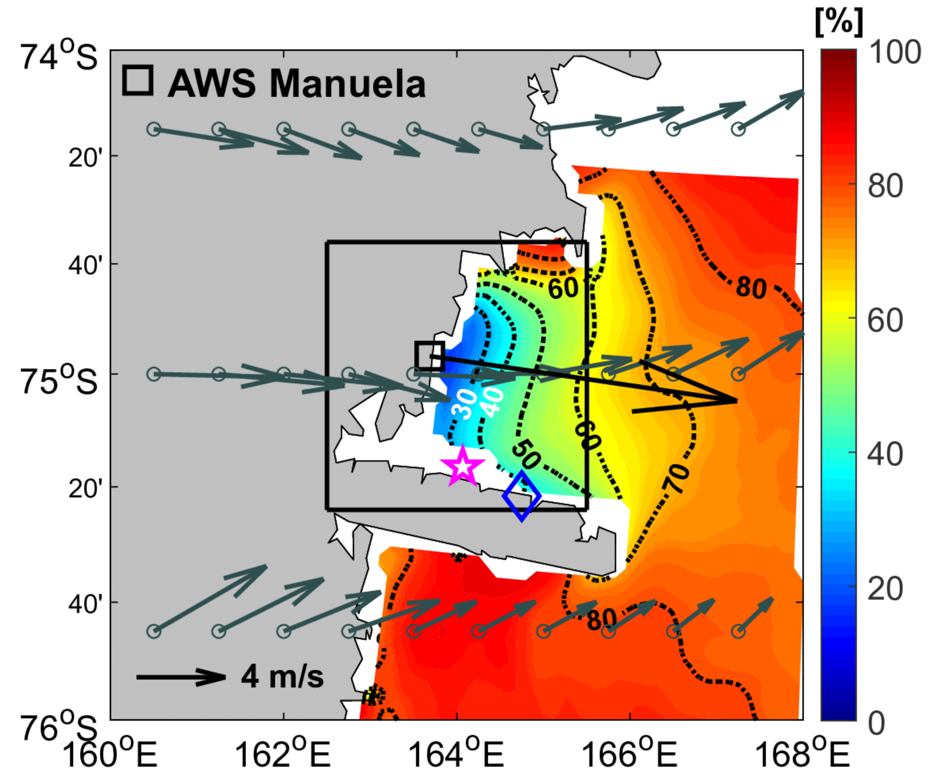
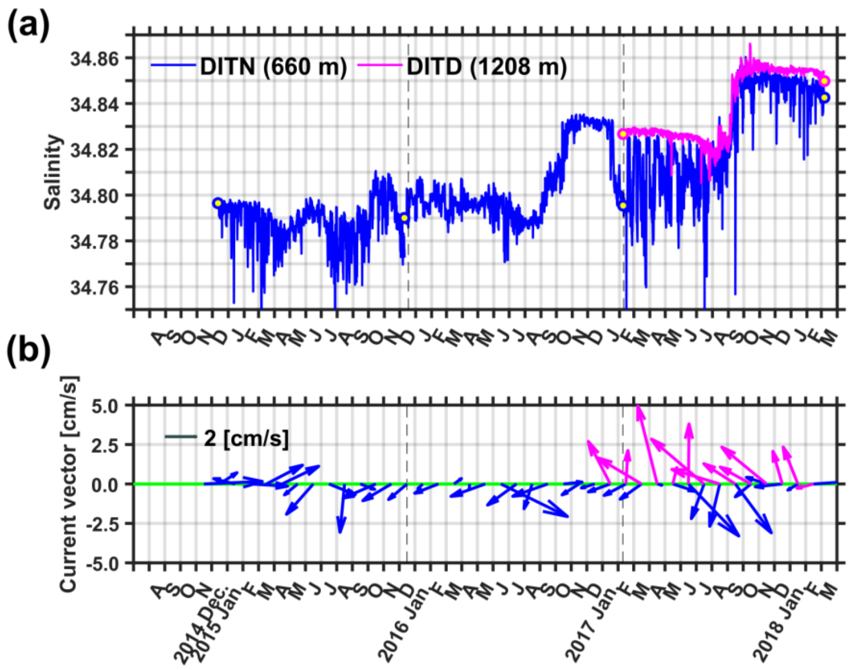


Figure ~~4~~3: ~~(a)~~ Spatial distributions of averaged sea-ice concentrations from July 2014 to March 2018. The interval of the dotted contour lines is a concentration of 10%. The black square (blue diamond and magenta star) indicates the Automatic Weather System (AWS) Manuela station (DITN and DITD). The dark-gra~~e~~y (black) arrows are ~~is a~~ mean wind vectors for July 2014–March 2018 using ERA-Interim data (data from AWS Manuela station). The black box denotes an averaged region for sea-ice concentrations. ~~(b) Spatial distributions of the correlation coefficients (*r*) between daily air temperature for ERA-Interim and Manuela during July 2014–March 2018. The black solid contour lines indicate the horizontal distributions of *r* between daily eastward wind speed from ERA-Interim and Manuela during the same period.~~

[YS47]: Topic Editor: Why do you show this figure (panel b)? Do we learn anything from it?

[YS48R47]: : We have deleted a panel b based on your comment.


(a)
DITN (660 m)
DITD (1208 m)
Salinity
(b)
Current vector [cm/s]
2 [cm/s]
2014 Dec.
2015 Jan
2016 Jan
2017 Jan
2018 Jan

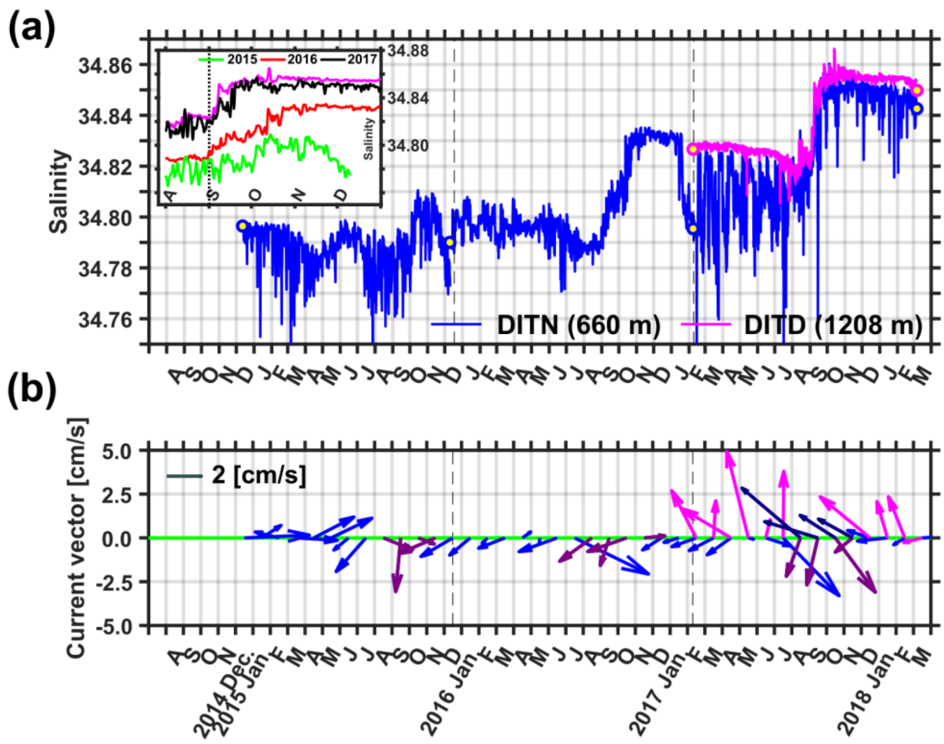


Figure ~~5~~4: (a) Time~~-~~-series of the ~~deep salinity~~near-bed salinity observed in the DITN (blue) and DITD (magenta) from December 2014 to March 2018. The blue (magenta) circles filled with yellow indicate the averaged salinity in a 5-m layer at the bottom obtained using CTD data observed near the DITN (DITD). The black dashed line divides periods of each leg in the moorings (see details in Table. 1). A zoomed-in plot for the one-day moving average near-bed salinity time-series from August to December of each year is shown in the small upper-left inset. (b) Monthly mean current vectors at 660 m in the DITN and 1222 m in the DITD are indicated by blue and magenta arrows. Mean current vectors from August to November in the DITN (DITD) are denoted by purple (navy) arrows.

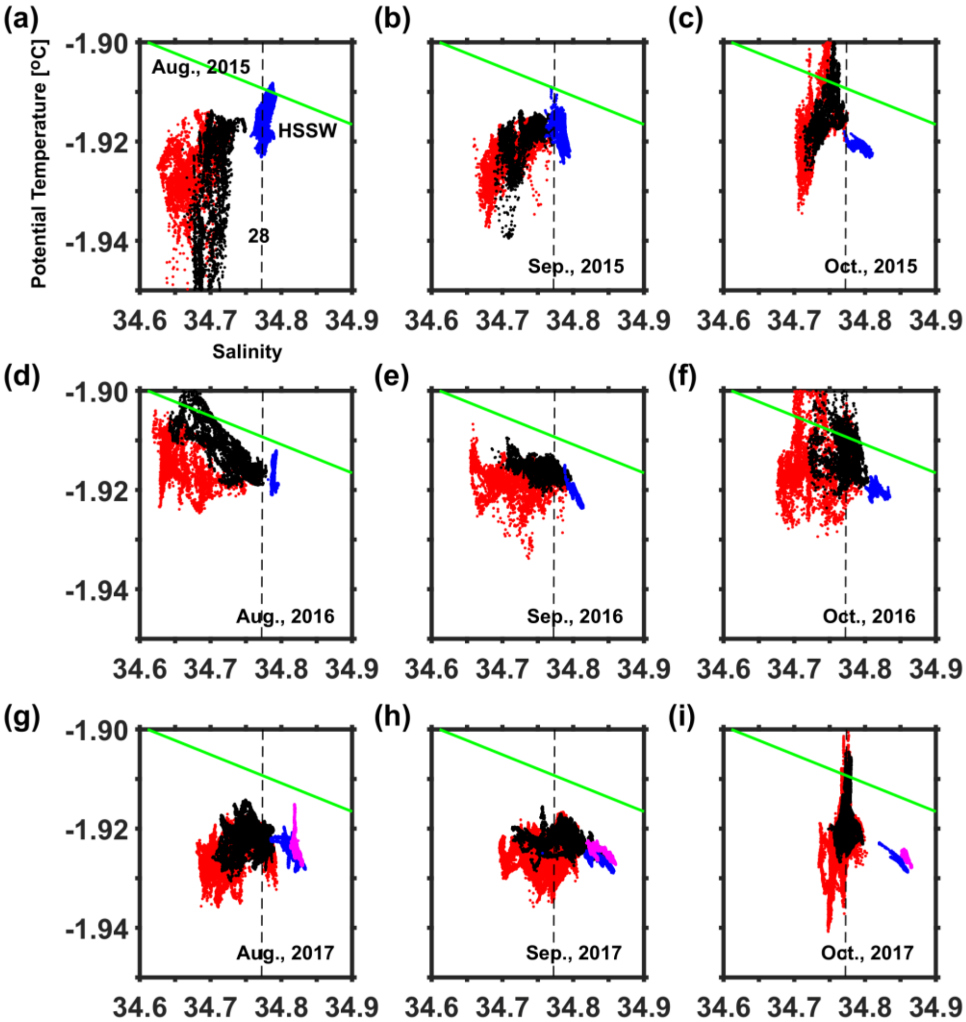


Figure ~~6~~5: (a) A magnified version of the θ–S (potential temperature-salinity) diagram for data from the DITN and DITD in August 2015. Red, black, and blue dots are θ–S at 75, 273, and 660 m, respectively. The thin green ~~thin~~ line denotes the freezing point at the surface depending on the salinity while the black dashed line indicates $\sigma_\theta = 28.00$ kg m^{-3}. (b) The same as Fig. 5~~6~~a, but for September 2015. (c) The same as Fig. ~~6~~5a, but for October 2015. (d–f) The same as Fig. 5~~6~~a–~~6~~5c, but for August–October 2016. (g–i) The same as Fig. ~~6a~~5a–5~~6~~c, but for August–October 2017. Magenta dots are θ–S at 1208 m.

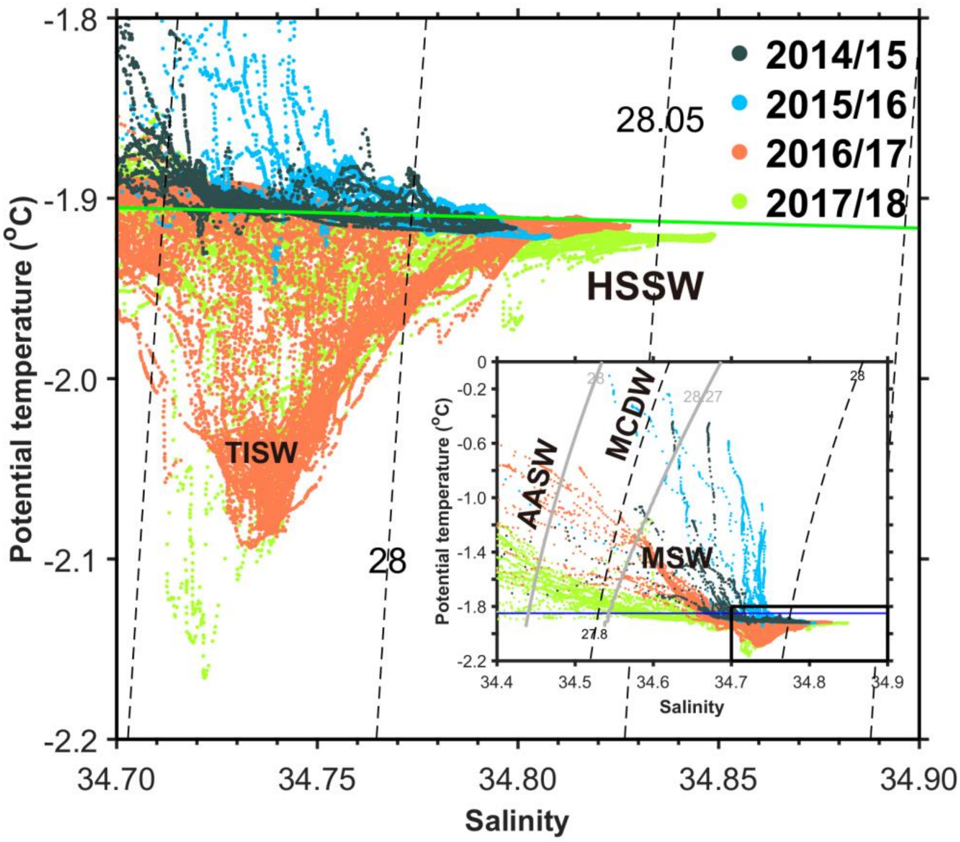
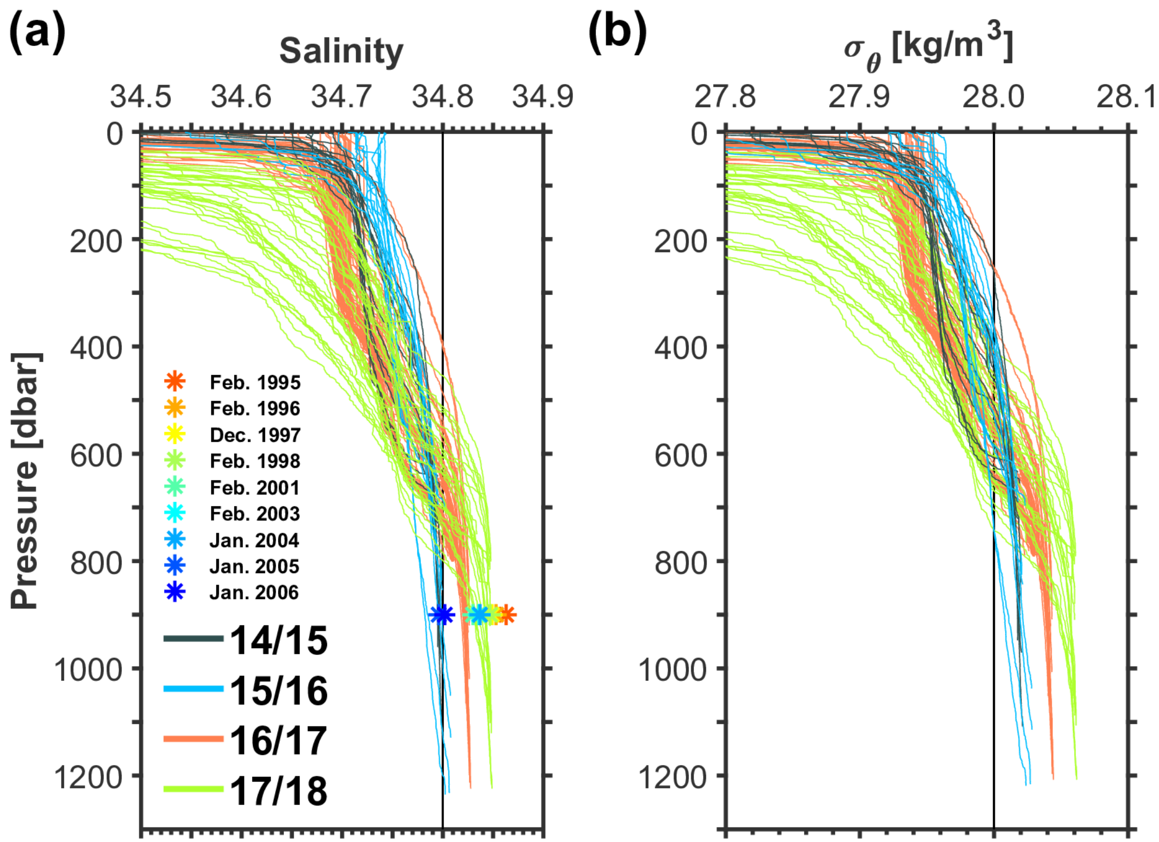


Figure 6: A zoomed-in plot of the θ–S diagram for CTD data observed in TNB during each observation period. The solid green line denotes the freezing point at the surface depending on the salinity, and the black dashed lines indicate isopycnals. The full range θ–S diagram is shown in the small lower-right inset. The black box and blue line indicate the ranges of the magnified plot, and the –1.85 °C isotherm, respectively. The gray solid lines denote 28 and 28.27 kg m^{-3} neutral density (γ^n) surfaces. AASW, MCDW, MSW, TISW, and HSSW represent the Antarctic Surface Water, modified Circumpolar Deep Water, modified Shelf Water, Terra Nova Bay Ice Shelf Water, and High-Salinity Shelf Water, respectively.



(a)
Salinity
34.5
34.6
34.7
34.8
34.9
0
200
400
600
800
1000
1200
Pressure [dbar]
Feb. 1995
Feb. 1996
Dec. 1997
Feb. 1998
Feb. 2001
Feb. 2003
Jan. 2004
Jan. 2005
Jan. 2006
14/15
15/16
16/17
17/18
(b)
σ_θ [kg/m^3]
27.8
27.9
28.0
28.1

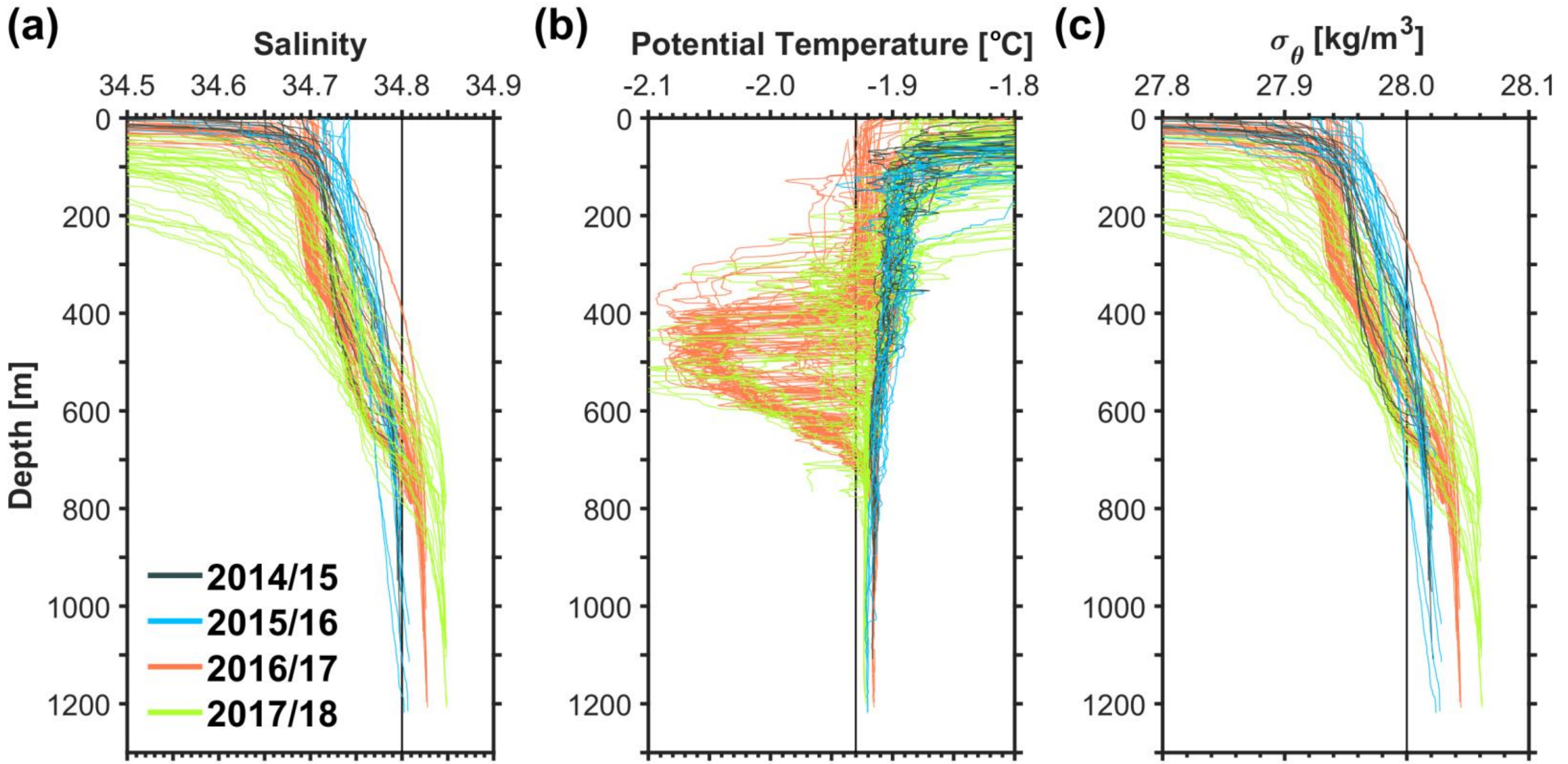


Figure 7: (a) Vertical salinity profiles at each observation period. The black solid line indicates 34.8. The asterisks indicate salinity at ~ 900 m depth in TNB observed during 1995–2006 from Fusco et al. (2009) (b) ~~The same as Fig. 7a, but for potential temperature, where the black solid line denotes −1.93°C. (c)~~ The same as Fig. 7a, but for potential density (σ_θ), where the black solid line indicates 28.0 kg m^{-3}

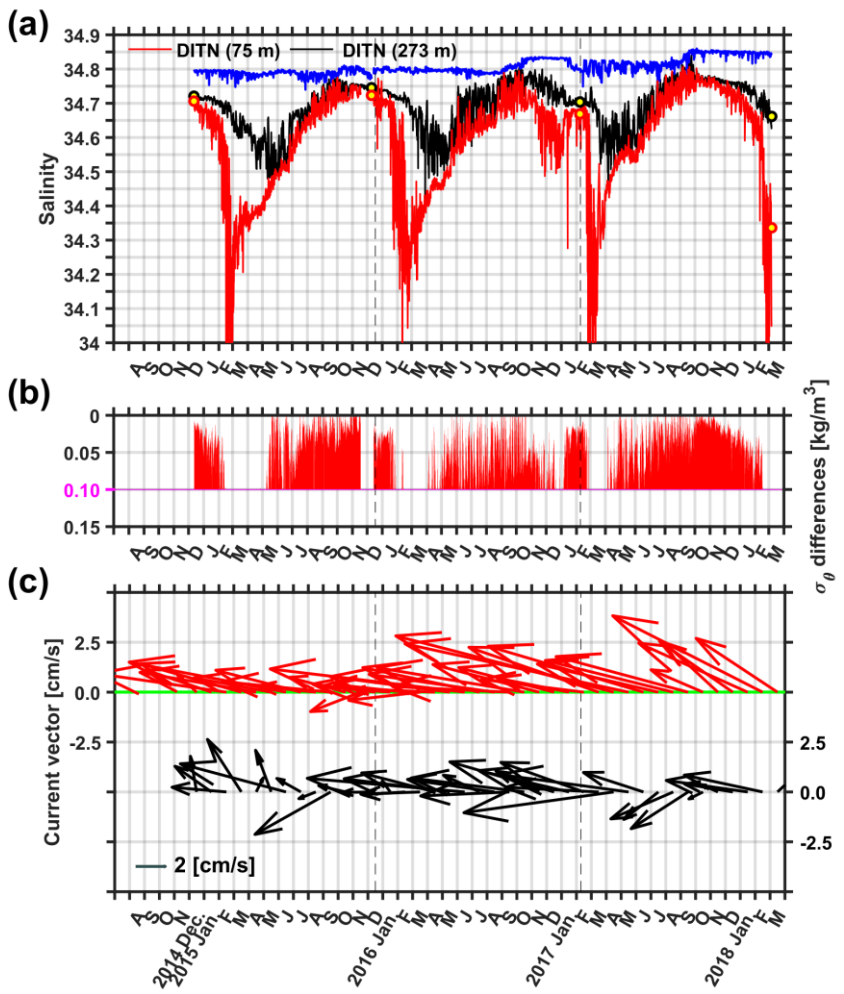


Figure 8: (a) Salinity time-series at three depths from the DITN. The red (black) circles filled with yellow are the averaged salinity in a 5-m layer at 75 (273) m obtained using CTD data observed near the DITN. The black dashed line divides periods of each leg at the moorings (see details in Table. 1). (b) Potential density (σ_θ) differences lower than 0.10 kg m^{-3} for σ_θ at 75 and 273 m are shown. The magenta line indicates a 0.10 kg m^{-3} difference. (c) Monthly mean current vectors at 75 and 273 m of the DITN are indicated by red and black arrows.

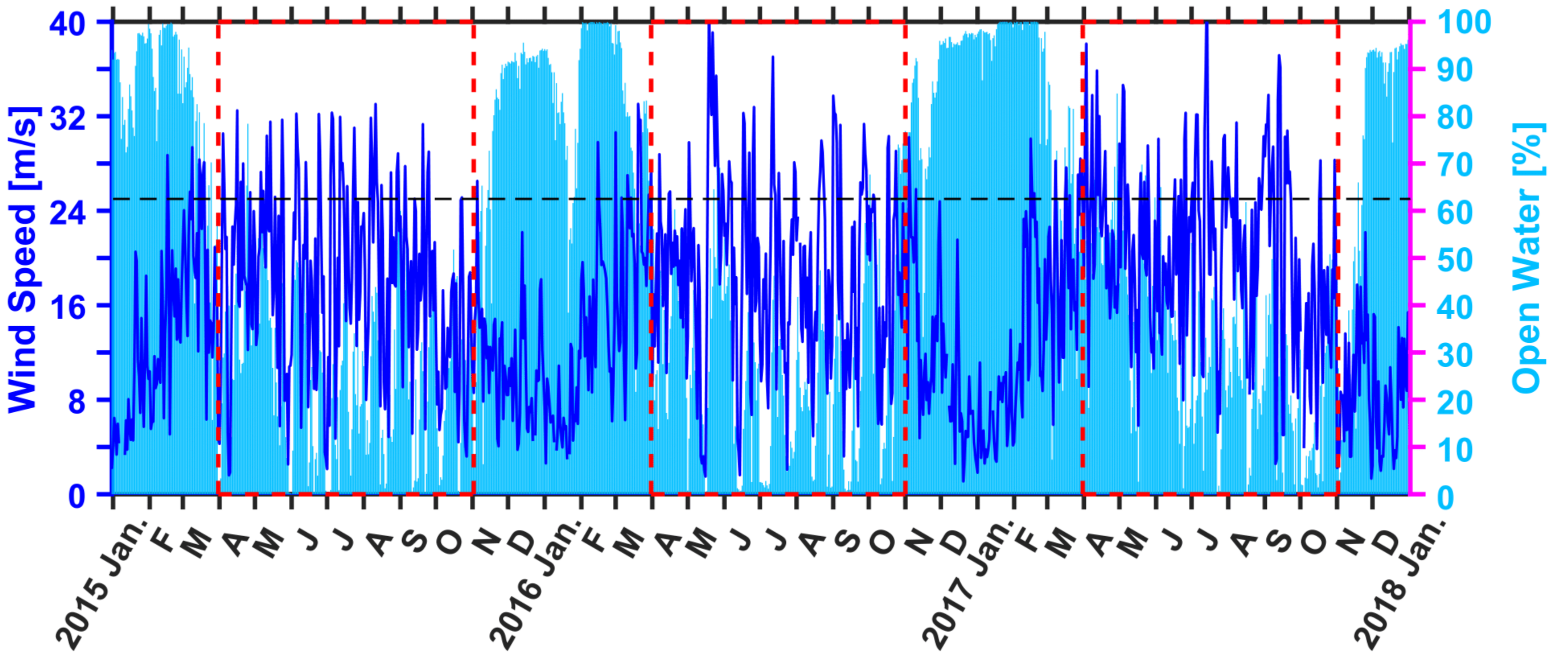


Figure 9: Time-series from 2015 to 2017 for daily ~~eastward~~ westerly (225°~~°~~ $< \theta <$ 315°~~°~~) wind speeds from Manuela (blue line), as well as the daily percentage of open water averaged from the black box shown in Fig. 3~~4a~~ (sky blue bar). Red dashed boxes indicate a time domain from April to October. The black dashed line indicates a wind speed of 25 m s^{-1}.

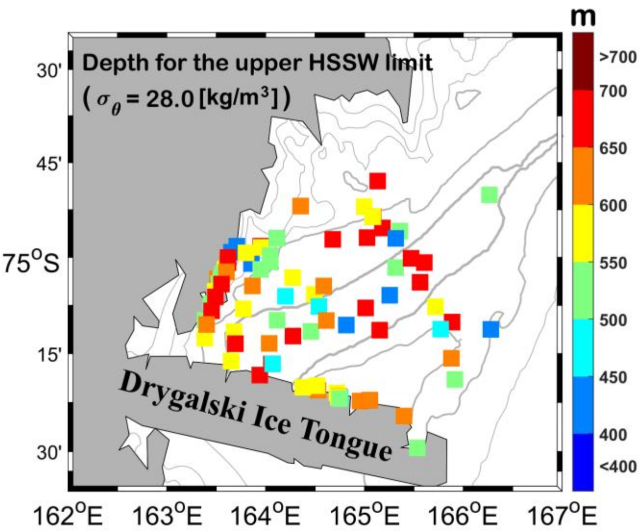
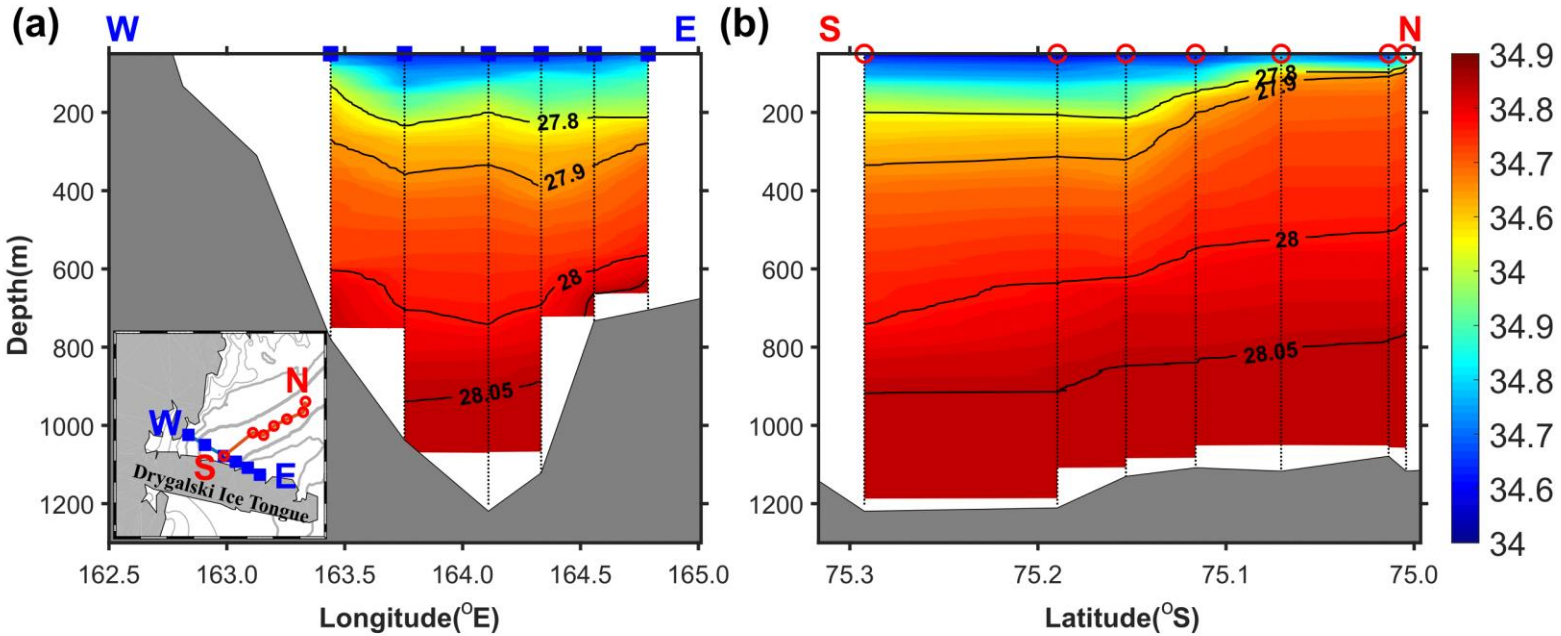


Figure 10: Distributions of depth (m) for the upper HSSW limit (σ_θ= 28 kg/m^3) in vertical CTD profiles during the four hydrographic surveys (see details in Table 1). The bold gray line indicates the 1,000 m isobaths and the interval between the thinner gray lines is 200 m.



(a)
W
E
(b)
S
N
Depth(m)
Longitude(°E)
Latitude(°S)
27.8
27.9
28
28.05
Drygalski Ice Tongue

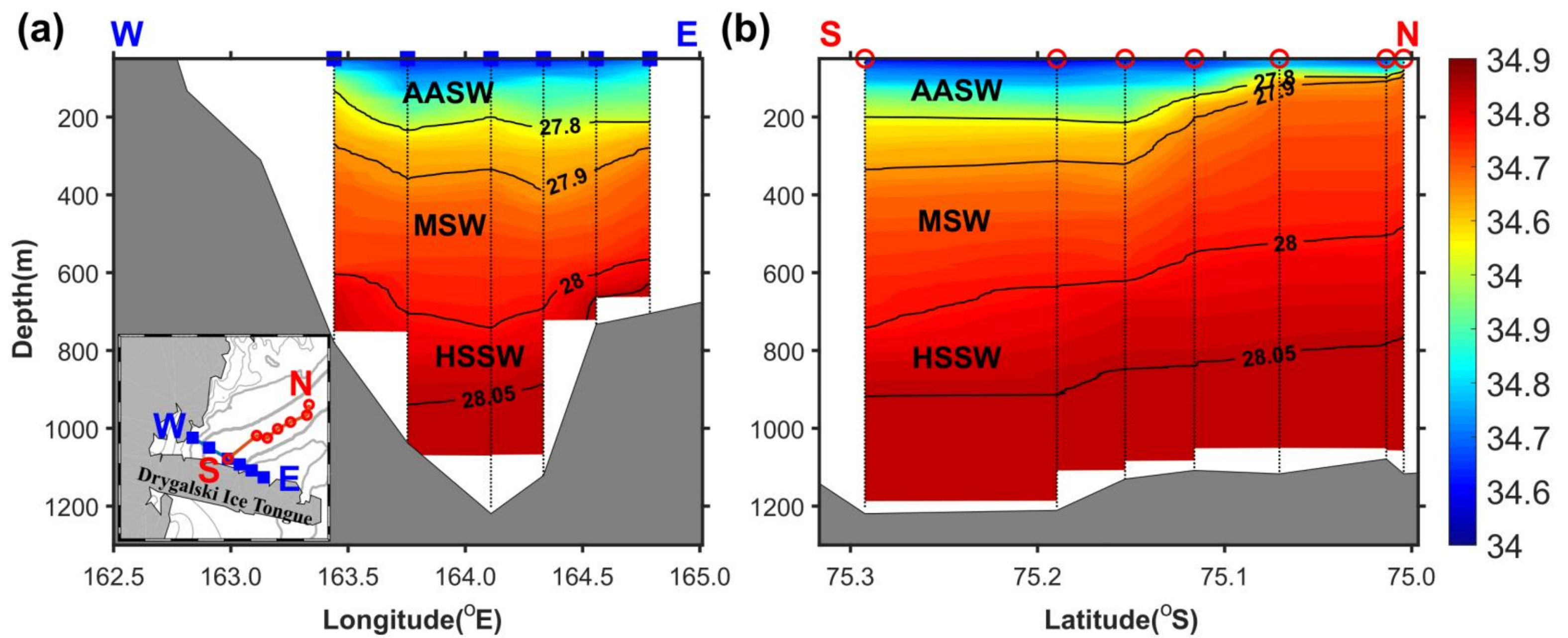
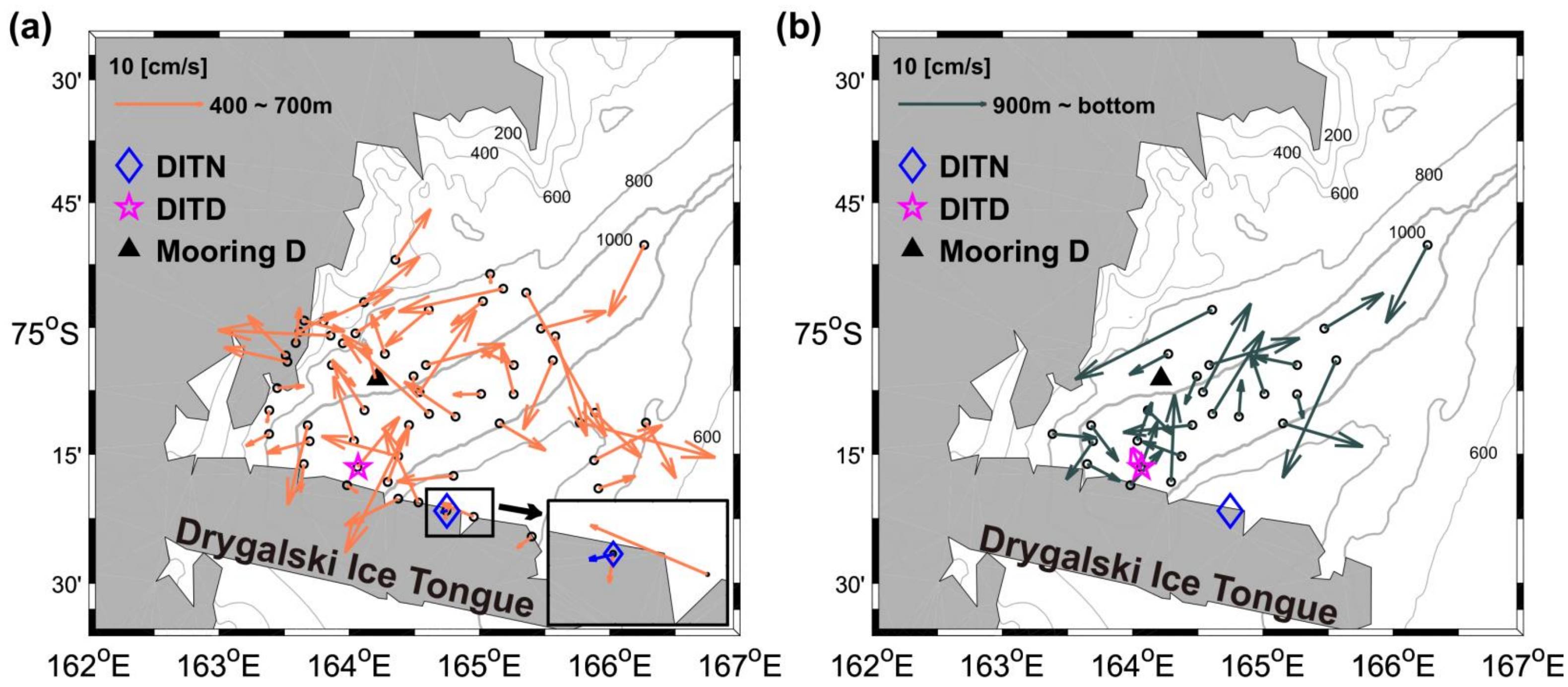


Figure 11~~0~~: (a) Vertical section of salinity along the Drygalski Ice Tongue (blue-filled squares in the inset) observed during the 2017/18 survey. The colorbar for salinity is denoted in Fig. 11~~0~~b and its interval is 0.01. The black contour lines indicate isopycnals (kg m^{-3}). AASW, MSW, and HSSW represent the Antarctic Surface Water, modified Shelf Water, and High-Salinity Shelf Water, respectively (b) The same as Fig. 11~~0~~a, but for the section along the Drygalski Basin (red circles in the inset of Fig. 11~~0~~a).


(a)
10 [cm/s]
400 ~ 700m
DITN
DITD
Mooring D
Drygalski Ice Tongue
200
400
600
800
1000
600
30'
45'
75°S
15'
30'
162°E
163°E
164°E
165°E
166°E
167°E
(b)
10 [cm/s]
900m ~ bottom
DITN
DITD
Mooring D
Drygalski Ice Tongue
200
400
600
800
1000
600

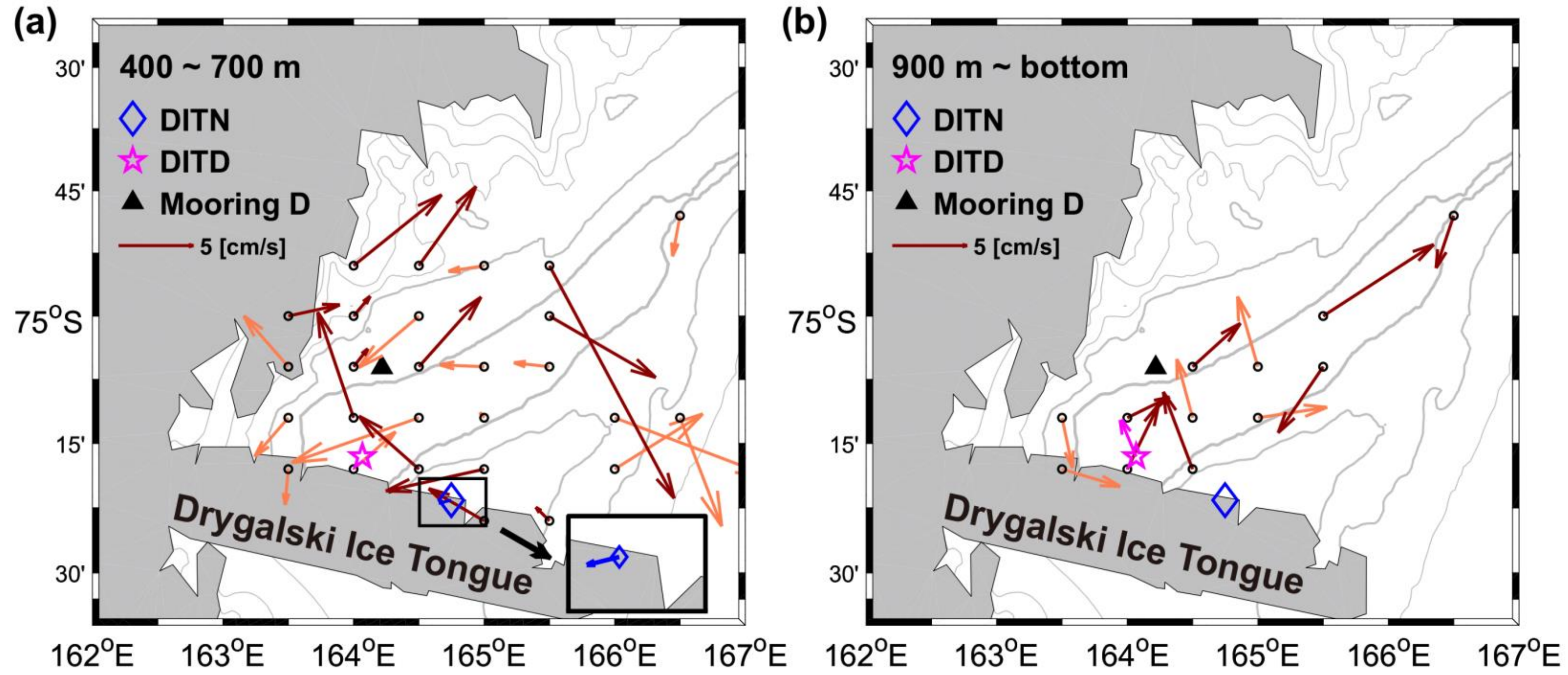


Figure 12~~1~~: (a) Mean currents in a range of 400–700 m during four hydrographic surveys (see details in Table 1). The LADCP data ~~from adjacent stations (< 3 km)~~ are ~~spatially~~ arranged by averaging the data on a 0.5° × 0.1° grid~~ed~~. ~~The black circles denote the LADCP stations.~~ The averaged current vector from January to February at 660 m in the DITN is denoted by a blue arrow. The inset shows the current vectors ~~near~~ of the DITN. The current vectors mainly discussed in Section 4.2 are highlighted by a dark red. The bold grey line indicates the 1,000 m isobaths and the interval between the thinner gray lines is 200 m. A scale arrow is denoted in the left part of the figure. (b) The same as Fig. 12~~1~~a, but for the range of 900 m–bottom. A magenta arrow shows the averaged current vector from January to February at 1,222 m in the DITD.

[YS49]: Topic Editor: These arrows point in all directions! I even doubt the data processing and data quality. Do we learn anything from this?

[YS50R49]: We agree with your comment. We have modified this figure (actually, similar with the original one) to show more clearly what we write in Section 4.2.

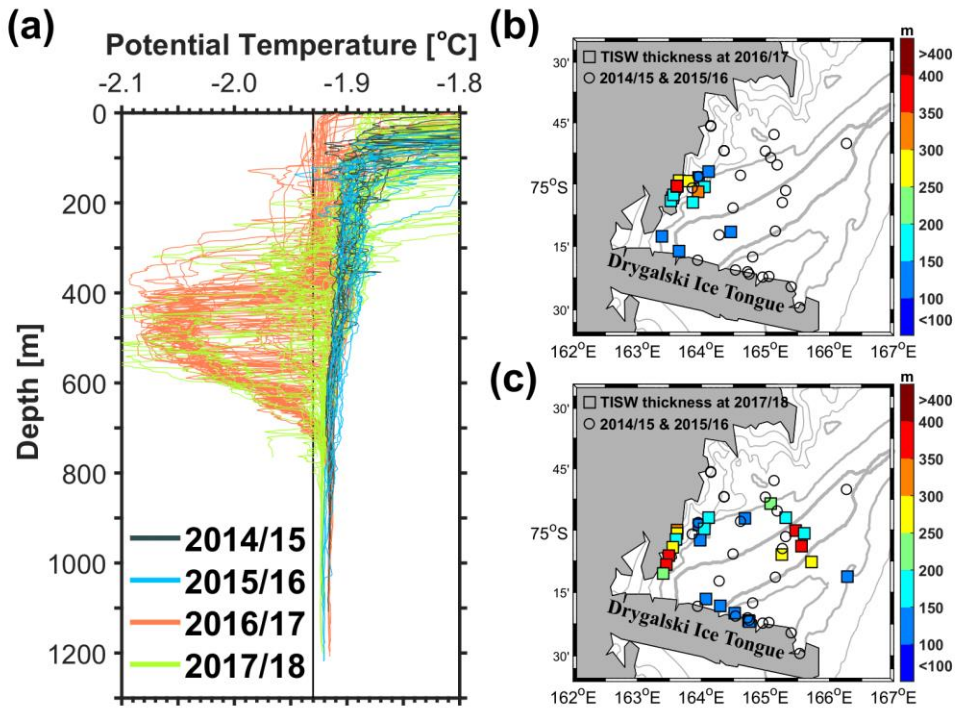


Figure 13: (a) The same as Fig. 7a, but for potential temperature, where the black solid line denotes –1.93℃. (b) Distributions of Terra Nova Bay Ice Shelf Water (potential temperature < –1.93℃) thickness (m) in vertical CTD profiles during the 2016/17 survey (see details in Table 1). The bold gray line indicates the 1,000 m isobaths and the interval between the thinner gray lines is 200 m. (c) The same as Fig. 13b, but for the 2017/18 survey.

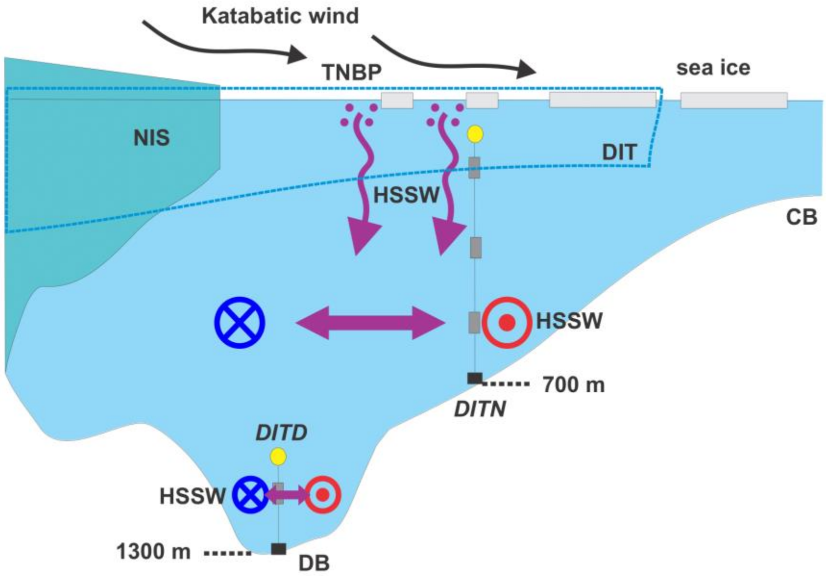


Figure 14~~2~~: A schematic of the spatio-temporal variations in the production of HSSW in TNBP. The downward arrows show HSSW formation through convection led by a supply of brine from the surface, which is related to polynya development via winds. The brine rejecting process associated with sea-ice formation, which is driven by katabatic winds, is denoted with dots near the surface. The horizontal bi-directional arrows indicate that the HSSW that formed near the Nansen Ice Shelf (NIS) advects at the deepest depths of both the eastern Terra Nova Bay (DITN) and Drygalski Basin (DITD) via cyclonic pattern flows in TNBP. The blue (red) circle represents outgoing (incoming) flow. DB, CB and DIT denote the Drygalski Basin, Crary Bank and Drygalski Ice Tongue, respectively.

Table 1. Information from the four oceanographic surveys and data observed from the DITN and DITD. U, V, T, C, and P represent the east-west current speed, north-south current speed, temperature, conductivity, and pressure, respectively. S, R, and A are the instrument abbreviations for the SBE37SM, RCM9, and Aquadopp current meters, respectively.

Survey	**Period**	**Observation**	**Number of stations in TNB**	**Ave. Salinity (± std) in a 10 m layer at 900 m depth**
2014/15	Dec. 11–16, 2014	Full-depth CTD/LADCP cast	11	34.796 (± 0.001)
2015/16	Dec. 8–15, 2015	Full-depth CTD/LADCP cast	10	34.791 (± 0.007)
2016/17	Jan. 26–Feb. 15, 2017	Full-depth CTD/LADCP cast	37	34.822 (± 0.002)
2017/18	Mar. 4–13, 2018	Full-depth CTD/LADCP cast	38	34.838 (± 0.005)

DITN	**Period**	**Position**	**Depth [m]**	**Variables**
1st leg	Dec. 12, 2014– Dec. 10, 2015	75° 21' 37" S, 164° 44' 58" E (Depth: 675 m)	75 (S, R) 275 (S, R) 660 (S, R)	S: 10 min T, C, P R: 30 min U, V
2nd leg	Dec. 12, 2015– Feb. 08, 2017	75° 21' 36" S, 164° 44' 55" E (Depth: 675 m)	72 (S, R) 272 (S, R) 660 (S, R)	S: 10 min T, C, P R: 60 min U, V
3rd leg	Feb. 09, 2017– Mar. 06, 2018	75° 21' 39" S, 164° 44' 47" E (Depth: 680 m)	74 (S, R, A) 272 (S, R, A) 665 (S, R, A)	S: 2 min T, C, P R: 60 min U, V A: 15 min T, P, U, V

DITD	**Period**	**Position**	**Depth [m]**	**Variables**
3rd leg	Feb. 08, 2017– Mar. 06, 2018	75° 16' 33" S, 164° 04' 02" E (Depth: 1230 m)	1208 (S) 1222 (A)	S: 2 min T, C, P A: 15 min T, P, U, V