Prof. Ilker Fer
Handling Topic Editor
Ocean Science

Dear Editor,

Please find a revised version of our manuscript (os-2019-80), "Spatio-temporal variations in High-Salinity Shelf Water production in Terra Nova Bay polynya," which has been corrected based on comments from the three referees (RC1, RC2, and RC3). We have also attached detailed replies to all comments documented with a tracked-changes version of the manuscript.

We would like to thank the reviewers for their valuable comments, which have allowed us to significantly improve the manuscript and clarify several points of confusion. We also acknowledge their appreciation of our research and their positive comments. We note that, after revisions, the main results of our study remain unchanged but now are more accessible to the reader.

The main changes made to this manuscript were:

– Based on comments from referees #1 and #3, we corrected several confusing presentational issues about salinity variations in the upper layers of eastern Terra Nova Bay and the processes involved with these changes.

– As suggested by referees #1 and #3, we deleted the figure showing the monthly rate of change in salinity and the entire second half of section 3.4, which did not convincingly demonstrate the correlations among salinity changes, wind speed, duration, and sea-ice coverage. Instead, we analyzed the total magnitude of the increase in the salinity during katabatic wind events in section 3.4 and changed Fig. 10 to the CTD-sections from the 2017/18 survey.

– As proposed by referee #3, we corrected areas in the manuscript were mixed between new findings and previous results, as well as modifications to the discussion section to make it more clear.

– Based on comments from referees #1 and #3, we modified Figs. 1, 2, 3, 7, and 11, and clarified the article via correcting the language.

We hope that these modifications and clarifications to our manuscript will make it suitable for publication in *Ocean Science*.

Sincerely,
Dr. Seung-Tae Yoon, on behalf of all authors.

Responses to comments by Referee #1

Spatio-temporal variations in High-Salinity Shelf Water production in Terra Nova Bay polynya, Antarctica, by Yoon et al.

1. The authors use CTD and mooring observations from the Terra Nova Bay Polynya to investigate the temporal and spatial variation in HSSW production over a three-year period. The most notable result, perhaps, is the marked increase in HSSW salinity seen over the time series. The authors also find a circulation of newly formed HSSW from near Nansen Ice Shelf, around the Drygalski Basin, to be observed a month or two later at one of their mooring sites in the eastern Terra Nova Bay, ie remote from the primary HSSW production area. There is also some discussion about local production of HSSW at the eastern Terra Nova Bay site. The data are very nice, and the underlying results deserve publication. There are, though, many presentational issues to be resolved before the manuscript is ready to be published. There are also one or two arguments that need more explanation, although my confusion is possibly language-related.

We thank the referee for their valuable comments and the time taken to carefully review our manuscript. We include below point-by-point replies to all your comments, written in blue.

2. One of those is connected with the discussion about the idea of “Open ocean convection, which is led by wind-driven mixing” (L53-54, for example). There are a couple of points here, and, again, it is probably purely a matter of language. The implication of the sentence is that wind-driven mixing is a prerequisite for HSSW production via brine rejection. I suspect that was not what the authors meant. Probably just the use of the word “led”. Perhaps “preceded” would be better? But see below.

My understanding of the authors' interpretation of the salinity evolution shown in figure 8(a) is that the summer stratification is eroded by wind-driven mixing, which gets the water column to 273 m depth to a salinity of between 34.5 and 34.6. The authors actually suggest that the increase in salinity at the mooring site might be a result purely of wind-driven mixing, presumably bringing up the more saline water from below the 273-m instrument, or an additional contribution might be from local brine rejection. The argument for local brine rejection, rather than advection of more saline waters from the east, is that those advected waters would actually have a lower, not higher salinity.

We have changed "led" to "preceded" based on your suggestion [Tracked-change version on L55]. Your understanding is correct. The increase (decrease) in salinity at 75 (273) m was observed from March to May, which indicates that wind-driven mixing erodes the summer stratification. The increase in salinity at both 75 and 273 m after wind-driven mixing indicates that a local brine supply via sea-ice production drives convection with the development of a mixed-layer from the surface. This appears to be the same process suggested by previous modelling studies in TNBP (Buffoni et al., 2002; Mathiot et al., 2012).

3. The confusion is in the use of the phrase "open ocean convection", and the idea that HSSW can be formed by wind-driven mixing. Open ocean convection is a bit like a reserved word, and for polynyas, tends to be used only for (what used to be called) sensible heat polynyas, which are found off the continental shelf. They are found there because of the ready supply of heat at depth, which can be mixed up to keep the surface ice-free. As for the wind-driven mixing, I don't believe that HSSW can be considered as being produced by mixing in this context. In this case, it seems that very high salinity water is being diluted to form a larger volume of a water mass that might still be classified as HSSW (depending on the definition adopted), but it strikes me as confusing to consider it "HSSW production by wind-driven mixing".

We thank the reviewer for identifying this point of potential confusion. We have changed "open ocean convection" to "convection" and deleted "HSSW formation by wind-driven mixing" [Tracked-changes version on L22–25 and L55]. In addition, we corrected several sentences related to variations in upper ocean salinity in eastern TNB [Tracked-changes version on L202–247]. As we have replied to comment #2, variations in the salinity of the upper ocean show not only stratification erosion due to wind-driven mixing (March–May) but also the convection of dense seawater (HSSW in 2016 and 2017) led by a supply of brine (June–September) as described in previous modelling studies in TNBP (Buffoni et al., 2002; Mathiot et al., 2012). Please also see the answer to comment #25.

4. Abstract: This needs some work. It seems a bit more detailed than necessary for an abstract.

We agree with your comment. We have deleted and/or modified several sentences to shorten the abstract [Tracked-changes version on L11–29].

5. L53-54 See comment above

We have corrected these lines based your comment [Tracked-changes version on L55]. Please also see the responses to comments #2 and #3.

6. L88 Low pass filtering by monthly averaging can lead to some spectral unpleasantness. It would be better to use a properly-constructed low-pass filter. I admit that it's likely that there will be no difference in the final conclusions.

We agree with your comment. However, as you have mentioned, we also think that there will be no difference in the final conclusions between monthly-averaged and low-pass filtered velocities. Thus, we re-phrased the reasons why we used the monthly averaged velocities, and deleted “low-pass filtered by monthly averaging” [Tracked-changes version on L93–95].

7. L135 and 136 “Deep-ocean”. This is a bit confusing. For most oceanographers “deep ocean” refers to abyssal areas off the continental shelf. As this is on the continental shelf (even if it is a deep continental shelf basin) it might be best to leave out the “ocean” and just call it “Deep salinity variations in TNB”.

We agree with your comment and have changed “deep-ocean salinity” to “deep salinity.”

8. L143-144 A minor point. Do the authors mean that there is also evidence for active HSSW formation taking place “3 and 5 months later”, or that 3 and 5 months later, we can still see the evidence from the active formation that took place earlier? The next sentence points out an increased salinity seen in January, which implies additional brine rejection between October and January. It does not, though, tell us that HSSW was being formed in January. A similar point: how, from Figure 3, do the authors distinguish between the presence of HSSW and its active formation? How do we know when it formed? Vertical profiles of salinity would give a clue: if well-mixed from top to bottom, that would suggest active formation even if it doesn’t prove it.

This sentence indicates that, three and five months later, we can still observe evidence for active HSSW formation, which occurred during the previous austral winter. We corrected the next sentence based on your comment [Tracked-changes version on L156–158]. As also suggested in Fusco et al. (2009), changes in the properties and volume of the HSSW can be observed in the deep layers of the water column in the austral summer. We can hypothesize that this reaction, i.e., HSSW formation through convection led by a supply of brine from the surface to deep layer with a deepening of the mixed-layer; stratification in austral summer due to surface freshening; the properties and volume of the HSSW still remain in the deep layer. In addition, brine rejection by sea-ice production at the surface hardly occurred during austral summer (November–February). At this time, dense water formation in the polynya is hindered by surface freshening via melting of sea-ice due to solar radiation. Thus, HSSW is formed in TNBP from April to late October. Finally, based on Fig. 3, we find that the salinity and density of the HSSW (σ_θ > 28 kg/m^3) in 2017/18 and 2016/17 was larger than that in 2015/16 and 2014/15. If the HSSW did not actively form in 2017/18 and 2016/17, the already existing HSSW in the deep layer should have become fresher and lighter than its own properties due to mixing with Ice Shelf Water or Modified Shelf Water in the upper parts.

9. L153-154 Change “fewer amounts of”, to “less”.

We have corrected these lines based on your comment [Tracked-changes version on L168].

10. L155, and 9 other locations. The use of the phrase “upper depth(s)” should be changed. An upper depth is either a depth that is larger (ie deeper) or a depth that is ‘up above’ (ie shallower). The authors mean the latter, but it is ambiguous and needs changing in each of the 10 cases.

We have changed “upper depth(s)” to “upper part(s)” based on your comment.

11. L156-157 ISW is usually defined as water with a temperature below the surface freezing point. So is the idea that TISW is characterised as having a temperature below the freezing point at 50 m depth a way of distinguishing it from ISW with a different source? As this is ‘Terra Nova Bay’ Ice Shelf Water, it refers to any ISW found in this area, so I would prefer the normal definition to be used. If the authors wish to continue with their definition, they need to explain why.

We have changed the freezing point at a depth of 50 m to the surface freezing point and we used the normal definition for Terra Nova Bay Ice Shelf Water.

12. L160 "mooring D" This is the first mention of mooring D, although it is marked in Figure 1. Please give a sentence to introduce it, rather than relying on the readers tracking down the reference. It would be worth at least mentioning the time period over which the mooring was active, as it ended in 2008 according to the referenced paper, well before the present datasets. If data from mooring D are available from the time period of the authors' measurements, then the data from the overlapping period should be included here.

We have added sentences to introduce mooring D [Tracked-changes version on L174–176]. Unfortunately, data from mooring D are not available during the period of our measurements.

13. L191 Should "shorter" not be "longer"?

We corrected this based on your comment [Tracked-changes version on L210].

14. L203 "compared to" should be "compared with"

We corrected this based on your comment [Tracked-changes version on L225].

15. L211-212 It would be more useful to quote the draft, not the thickness, of Drygalski Ice tongue.

We have quoted Fig. 1 and section 1, not the thickness of the Drygalski Ice tongue [Tracked-changes version on L234].

16. L223 "since" should be "in".

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

17. L229 “nearly as large as” should be “only a little higher than”

We corrected this based on your comment [Tracked-changes version on L256].

18. L233 Delete “current”

We have deleted this based on your comment [Tracked-changes version on L261].

19. L236 “easterly” should be “westerly”?

We corrected this based on your comment [Tracked-changes version on L264].

20. L237 Delete “a”

We deleted this based on your comment [Tracked-changes version on L266].

21. L238 Was it 0.46 for each year? Or is there a different r value for each year? Or is this an average across the three years?

A correlation coefficient (0.46) is an average across a seven-month period during the three year study period. We corrected this sentence to make it clearer [Tracked-changes version on L266–268].

22. L248 Would it be possible to quote the mean wind speed during these events as a check? If the mean wind speed also correlates with the length of time the polynya is open, it draws into question the assertion that the duration of the katabatic is key.

The mean wind speed for 7 months (April-October) in 2015, 2016, and 2017 was 17.6, 18.3, and 20.3 m/s, respectively. The mean wind speed for the katabatic wind events during a 7 month period (April–October) in 2015, 2016, and 2017 was 29.8, 30.3, and 30.8 m/s, respectively. As a result, the mean wind speed significantly increased to approximately 30 m/s during the katabatic events but there was a reduction in the differences among the mean wind speeds during the three years. Moreover, the mean wind speed during the katabatic wind events became faster by approximately 169% (2015), 166% (2016), and 152% (2017) as compared with that of the entire period. In other words, the mean katabatic wind speed became strongest in 2015 as compared with the mean wind speed. As a result, the length of time that the polynya was open appears to have a higher correlation with the mean duration of a single katabatic wind event rather than the mean wind speed during all katabatic wind events. Thus, we did not quote the mean wind speed during the katabatic wind events in this study.

23. L251-253 This is now a more positive assertion that wind-driving created a mixed layer, followed by brine release that forces convection. If this is the authors' interpretation of Figure 8(a), a statement to that effect at the end of section 3.2 would be helpful. At the end of section 3.2, this was left only as a possibility.

We added a statement on the interpretation of Fig. 8(a) based on your comment [Tracked-changes version on L245–247].

24. L255-258, and Fig 10. The monthly salinity differences shown in Figure 10 seem a very weak way of showing the correlation with wind and open water. Is there no way of improving on this?

We changed Fig. 10 to show the CTD-sections from the 2017/18 survey (based on comment #9 from referee #3) and modified the entire second half of section 3.4 based on your comment [Tracked-changes version on L286–304]. Please also see the answer to comment #25.

25. L264 This is not very convincing in Figure 10b. In fact, the entire second half of section 3.4 needs rethinking. Attempts to demonstrate correlations between salinity change, wind speed and duration and sea-ice coverage are very unconvincing, based on the time series of those quantities. It would be better to find a stronger way of finding the correlations, rather than simply picking out short sections. Figure 10 is particularly weak and unconvincing. I'm sure there must be a better way of demonstrating the relevant correlations.

We changed Fig. 10 to show the CTD-sections from the 2017/18 survey (based on comment #9 from referee #3) and modified the entire second half of section 3.4 based on your comments [Tracked-changes version on L286–304]. We estimated the total magnitude of the increase in salinity for the katabatic wind events from June to September using hourly time-series of winds from Manuela station and the salinity in the upper layers of the DITN. The salinity time-series contains the short-term fluctuation 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. The table below shows the calculated results of the increase in salinity during the katabatic wind events from June to September.

	Total magnitude of the increase in salinity for katabatic wind events from June to September	The percentage of salinity rise due to katabatic winds from an increase in the total salinity from June to September.
2015	75 m: 0.082; 273 m: 0.065	75 m: 31 %; 273 m: 23 %
2016	75 m: 0.118; 273 m: 0.050	75 m: 65 %; 273 m: 35 %
2017	**75 m: 0.120; 273 m: 0.142**	**75 m: 54 %; 273 m: 76 %**

26. L291-292 Same concern as above about HSSW being formed by mixing.

We deleted "wind-driven mixing" [Tracked-changes version on L341]. Please also see the responses to comments #2 and #3.

27. L297 Change “with” to “from”.

We corrected this based on your comment [Tracked-changes version on L347].

28. L300-305 I think this paragraph can be deleted, or possibly moved to the Conclusions?

We deleted this paragraph in section 4.1 and moved several sentences in this paragraph to the conclusions [Tracked-changes version on L446–449].

29. L319 “HSSW flowing under greater depths is circulated over the DB.” Should this be “HSSW flowing at greater depths circulates around the DB”? And, why “Despite this”? Despite what?

“Despite this” indicates that we still don’t understand how the HSSW that flows at significant depths circulates around the DB. LADCP data, however, may provide evidence for circulation in the DB region. We corrected this based on your comment [Tracked-changes version on L373–376].

30. L330 “slower” should be “lower”

We corrected this based on your comment [Tracked-changes version on L386].

31. L331 “deepest” should be “greatest”

We corrected this based on your comment [Tracked-changes version on L388].

32. L335 The ratio between vertical and horizontal velocities: is there a citation for this? I’m unaware of this rule of thumb.

We added a citation (van Haren, 2018) for the ratio between the vertical and horizontal velocities in the ocean (i.e., identical to the aspect ratio) [Tracked-changes version on L393].

Conservation of mass > $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$

Scale analysis > $\frac{U}{L} \sim \frac{W}{H} \rightarrow$ aspect ratio (δ) = H/L ~ W/U

ex) Aspect ratio in TNBP ~ 1,000 m/100,000 m ~ 10^{-2}

33. L336 "similar with" should be "similar to a"

We corrected this based on your comment [Tracked-changes version on L393].

34. L341 Change "due to" to "by"

We corrected this based on your comment [Tracked-changes version on L399].

35. L345 Should "June or July" be "March to May"?

This sentence indicates that salinity values at both 75 and 273 m have increased concurrently from June or July. We, therefore, we corrected this sentence [Tracked-changes version on L402–403].

36. L349 Delete "Therefore"

We deleted this based on your comment [Tracked-change sversion on L407].

37. L365 Change "depths" to "parts". Change "deepest" to "greatest". Change "since" to "from"

We corrected this based on your comment [Tracked-changes version on L424–425].

38. L366 Change "Due to this" to "As a result"

We corrected this based on your comment [Tracked-changes version on L425].

39. L378 Change "becomes increases" to "is increasing"

We corrected this based on your comment [Tracked-changes version on L439].

40. L379 Delete "although not an absolute salinity".

We deleted this based on your comment [Tracked-changes version on L439–440].

41. L383 to 385 Delete from "which is yet another: : :..changes in TNBP".

We deleted this based on your comment [Tracked-changes version on L443–445].

42. Figure 2. It would be helpful to add years (not just leg numbers).

We added years to Fig. 2.

43. Figure 3. Move the 50-m freezing point line to the surface freezing point, (unless there is a good case for defining TISW as water with temperatures below the 50-m freezing point).

We moved the 50 m freezing point line to the surface freezing point line in Figs. 3, 6, and 7.

44. Why is there a -1.85 degree C isotherm in the inset figure?

Orsi and Wiederwohl (2009) used a –1.85ºC isotherm to distinguish Modified Shelf Water (MSW) from Shelf Water (SW) in the Ross Sea (Fig. 2 in Orsi and Wiederwohl, 2009). The inset figure shows the full range of θ-S diagram, where the –1.85º isotherm is also used to define the MSW.

45. Figure 10. I don't like this figure. In particular, the monthly salinity changes.

We changed Fig. 10 to show the CTD-sections from the 2017/18 survey (based on comment

#9 from referee #3) and modified the entire second half of section 3.4 based on your comment [Tracked-changes version on L286–304]. Please also see our response to comment #25.

46. Figure 11. Is there a particular reason for interpolating the LADCP data onto a grid? Until we can see it we won't be sure, but I think I would much prefer to see the vectors at the locations they were measured. Data from stations that close together could be spatially averaged, perhaps? The reason that we interpolated the LADCP data onto a grid was to simplify the figure. We modified Fig. 11 based on your comment. We plotted the current vectors at the locations that they were measured and we spatially averaged the LADCP data from adjacent stations (< 3 km). We also modified the sentences describing Fig. 11 in section 4.2 [Tracked-changes version on L358–383]. Please also see our response to comment #25 from referee #3.

Responses to comments by Referee #2

I enjoyed reading this well-written, well researched paper. Please keep up the good work

We would like to thank the referee for their positive evaluation. We will attempt to perform good research in other oceans, as well as the Antarctic region.

1. I suggest changing month to months on line 160

We corrected this based on your comment [Tracked-changes version on L177].

Responses to comments by Referee #3

1. The authors present three years of mooring data 2015-2017 and four years of hydrographic data from the Terra Nova Bay and use the data to discuss the temporal and spatial variability in HSSW-formation. They find that the salinity of the HSSW has increased during the investigation period and suggest that the increase is caused by stronger winds and increased polynya activity. I completely agree with the comments made by Anonymous Referee #1 – the data are interesting and deserves publication, but the presentation and the analysis needs to be (much) improved. The language is often unclear and mis-leading; I recognize that the first author is a non-native English speaker, but there appears to be native English speaker in the author list who ought to have read/corrected the article prior to submission. I will not repeat the critic/points made by reviewer #1, but add a few points.

We thank the referee for their valuable comments and time taken to carefully review our manuscript. A point-by-point reply to all your comments can be found below, written in blue. We especially corrected the unclear and mis-leading parts (i.e., mostly language-related confusion) based on your comments. Please also see our responses to comments from referee #1.

2. General comments - New findings and old results are often mixed, and it is often unclear what is what. - Discussions of what could or should be done, should be omitted - or at least kept to a minimum and placed in the end of the article.

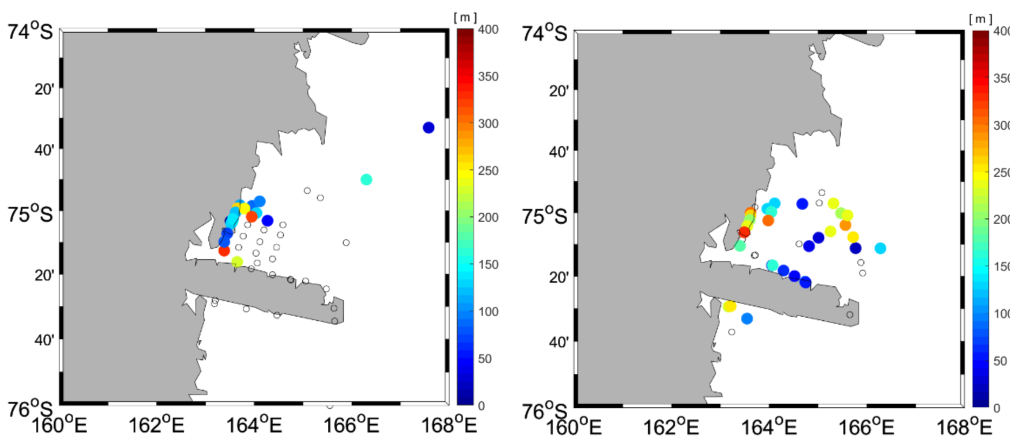
We agree with your general comments. We mainly corrected the results and discussion sections to make them clearer in the revised manuscript.

3. L. 140 Why not just give salinity increase in psu/month or the increase over the period? (a number that the reader can immediately relate to?)

In this part, we suggested a salinity increase in μg salt/m^3/s following the methods reported in Fusco et al. (2009). Based on Fig. 4 in Fusco et al. (2009), salinity increases over 3 μg salt/m^3/s are large in deep layers (> 500 m). In addition, we included psu/month in brackets [Tracked-changes version on L151 and L193].

4. L 154-159 Can the absence of TISW in the first two surveys be explained by differences in the spatial distribution of the CTD-stations? There appears to be no stations close to the ice shelves those years?

In the 2016/17 and 2017/18 surveys, the TISW (< –1.93ºC) was also found at stations not adjacent to the NIS, although it had slightly warmer temperature than the TISW observed near the NIS. Therefore, the absence of the TISW in the first two surveys was due to an absence of meltwater outflow in December rather than differences in the spatial distribution of the CTD-stations. The figures below show the distributions of the TISW thickness (= the thickness of a layer whose temperature is below –1.93ºC) in the 2016/17 and 2017/18 surveys. The left panel is the 2016/17 survey and the right panel is the 2017/18 survey.



5. L209 Ekman currents?

We deleted Ekman currents and re-phrased this sentence [Tracked-changes version on L231–233].

6. L 244 Cyclic argument Â´l

We corrected this part based on your comment [Tracked-changes version on L273–277].

7. L. 247 210 events? This is not supported by Fig 10.

We intended to show wind speeds over 25 m/s in Fig. 10. We deleted the citation based on your comment [Tracked-changes version on L280].

8. L 250 three years?

We corrected this part based on your comment [Tracked-changes version on L283].

9. L 317 For a reader not familiar with the region it would have helped to see some of these CTD-sections!

We agree with your comment. We changed Fig. 10 to the CTD-sections from the 2017/18 survey.

10. L 320 Do you expect the summer-time LADCP data to show seasonality?

We rephrased this sentence based on your comment and comment #29 by referee #1 [Tracked-changes version on L373–376].

11. L 324 Here and elsewhere – you need to somehow distinguish between HSSW formed locally and HSSW that's being advected

We corrected several sentences to distinguish between locally formed HSSW and HSSW affected by advection [Tracked-changes version on L276–277; L284; L302–304; L380]. Moreover, in section 3.4, we investigated the role that winds play in TNBP from two points of view: 1) The role of winds in HSSW formation near the NIS, 2) The role of winds in HSSW formation in the upper layers of eastern TNB.

12. L. 329 – 334 Unclear where these numbers come from and how appropriate they are

We quoted our figures in the draft and Rusciano et al. (2013). The horizontal distance from the NIS to eastern TNB (DB) was obtained from based on the distance from the NIS to the DITN (DITD) mooring. The greatest depth in the DB was regarded as the depth of the SBE37SM sensor in the DITD mooring. According to Fig. 11, cyclonic circulation in the 400–700 m layer appears to cover the TNB (163.5–165.5ºE). Therefore, we assumed that the radius of cyclonic circulation to be one longitudinal degree. We also added a citation (van Haren, 2018) for the ratio between the vertical and horizontal velocities in the ocean (identical to an aspect ratio) [Tracked-changes version on L384–404].

Conservation of mass > $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$

Scale analysis > $\frac{U}{L} \sim \frac{W}{H} \rightarrow$ aspect ratio (δ) = H/L ~ W/U

ex) Aspect ratio in TNBP ~ 1,000 m/100,000 m ~ 10^{-2}

13. L 348 What/ how did you correlate here?

We deleted the figure for the monthly change in the rate of salinity. We also removed this sentence based on your comment [Tracked-changes version on L406–407].

14. L. 367 as far as I understand, (A) you don’t investigate the area near NIS and (B) mixing is not what cause the increase in salinity

We agree with your comment. We corrected this sentence based your comment and comments #2 and #3 from referee #1 [Tracked-changes version on L426–429].

15. L 379 not an absolute salinity?

:We deleted this part based on your comment and comment #40 from referee #1 [Tracked-changes version on L439-440].

16. Fig 1: Include bathymetry under DIT, currents from D?

We included bathymetry under the DIT in Fig. 1 by removing the filled grey color for the DIT (only for Fig. 1). Unfortunately, we have no current data from mooring D and were unable to find the results for ocean currents from mooring D in Fusco et al. (2009) and Rusciano et al. (2013). Thus, we cannot include currents from mooring D in Fig. 1.

17. Fig2: indicate bottom depth - or put information in a table?

We added the depths of the mooring position to Table 1.

18. Fig 3: Include Freezing line at surface, more than one isopycnal

We added the freezing point line at surface and isopycnals to Fig. 3. In addition, we deleted the freezing point line at 50 m.

19. Fig 4: Air temperature is not discussed in the paper?

Air temperature was only discussed in section 2.2 [Tracked-changes version on L137–138] to show that atmospheric data at Manuela AWS station sufficiently represent atmospheric conditions in TNB.

20. Fig 5: The same data are shown in Fig 8

In Fig. 8, we wanted to show the deep changes in salinity together with salinity variations in the upper layers (only for the DITN). The range of the salinity variations is different among the different depths, such that it is hard to directly compare deep salinity variations in Fig. 5a with salinity variations in the upper parts in Fig. 8.

21. Fig 7: Show surface freezing point rather than -1.95C. How come data from 2016 is warmer??

We added the surface freezing point (–1.93°C) line and deleted –1.95°C. The 2017/18 survey was conducted in March 2018 and the 2016/17 survey was conducted in February 2017, such that melt water (cold and fresh water) flowing out from the NIS may have had more of an influence on the TISW found in 2017/18. Thus, the TISW was warmer in 2016/17 than in 2017/18.

22. Fig 8: Why don't you show density difference between 75 & 660 m to make your point that the HSSW at the bottom isn't formed locally?

In section 3.3, we had already discussed the poor correlations between salinity variations in the upper parts (75 and 273 m) and the salinity time-series at 660 m in the DITN. Moreover, the salinity at 660 m was slightly higher than that observed in the upper parts (Figs. 6 and 8a). These indicate that the mixed layer does not extend to 660 m in eastern TNB and that higher salinity in the deep layer derives from other regions in TNB, i.e., not the surface of the DITN. Thus, we suggest that these results are adequate to show that the HSSW at the bottom does not form locally.

23. Fig 9: Data shown again in Fig 10?

We changed Fig. 10 to show the CTD-sections from the 2017/18 survey based on your comment and modified the entire second half of section 3.4 based on comment #25 by referee #1 [Tracked-changes version on L286–304].

24. Fig 10: In the text you state that there are 210 events of catabatic winds - this is not supported by fig. 10c

We deleted the citation based on your comment. Please also refer to our response for comment #7 [Tracked-changes version on L280].

25. Fig 11: Include mean velocity from moorings for the summer period. Include some measure of uncertainty/variability. How strong are the tides and how good is the tidal model?

We modified Fig. 11 and corrected the sentences about the LADCP data in section 2.1 based on your comment [Tracked-changes version on L109–113]. When the LADCP data were processed, we removed velocity data lower than an error velocity. The tidal current velocities were significantly weaker than the velocity observed by the LADCP. In addition, CATS2008 (Circum-Antarctica Tidal Simulation model) (Padman et al., 2002) is a high-resolution regional inverse model of the entire circum-Antarctic ocean. This model was used in the northwestern Ross Sea (Padman et al., 2009). Please also refer to our response to comment #46 by referee #1.

Padman et al., 2009 > Padman, L., Howard, S. L., Orsi, A. H., and Muench, R. D.: Tides of the northwestern Ross Sea and their impact on dense outflows of Antarctic Bottom Water, Deep Sea Res. Part II: Topical Studies in Oceanogr., 56, 818–834, https://doi.org/10.1016/j.dsr2.2008.10.026, 2009.

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

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Abstract.

The formation of High-Salinity Shelf Water (HSSW), which is the major source of Antarctic bottom water (AABW), has been observed in Terra Nova Bay (TNB) in Antarctica. We believe that a description of the spatio-temporal variation of salinity in TNB would help understand the production of HSSW in the region. Hence, the aim of this study is to investigate ~~salinity~~ variations in salinity in the Drygalski Basin (DB) and eastern TNB near~~close to~~ Crary Bank in~~of~~ the Ross Sea. For this, we use the moored and profiled hydrographic data, as well as available wind and sea-ice products. We found that the deep~~ ocean~~ salinity in the eastern TNB (~660 m) and DB (~1,200 m) increases each year beginning~~starting~~ in September.~~,~~ Significant increases in~~and large amounts of~~ salinity ~~increase~~ (> 0.04) were observed in 2016 and 2017. According to ~~the~~ velocity data observed at identical~~the same~~ depths, the increases in salinity from September were due to the advection of the HSSW from the coastal region of the Nansen ice shelf (NIS). The significant increases in salinity are related to ~~the~~active HSSW formation ~~of active HSSW~~. ~~, evidence of which can be found from the HSSW properties obtained in February 2017 and March 2018.~~ In addition, we show that HSSW can be locally formed in the upper layer (< 300 m) of the eastern TNB through convection led by ~~by wind-driven mixing. HSSW in the upper layer was only detected in 2016 and 2017 when much saltier HSSW was observed below 800 m. This indicates that~~ a supply of brine~~ supply~~ from the surface, which is related to polynya development via winds~~related to the development of polynya by winds has contributed to the HSSW formation not only near the NIS, but also in the eastern TNB~~. Moreover, as compared with historical observations, the salinity of the HSSW has been increasing since 2016 and, in 2018, ~~it became~~the salinity was similar to~~with~~ that in~~ the~~ early 2000. O~~The o~~bservations of fluctuations such as this, which are in contrast~~s with~~to previous~~ast~~ freshening, may~~could~~ contribute to the estimation~~ing~~ of the properties of recently formed AABW and improv~~ing~~e the accuracy of both regional and global climate models.

1 Introduction

The strength of the global meridional overturning circulation is closely associated with the production of Antarctic bottom 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, ~~the~~ circumpolar deep water (CDW) intrudes the continental shelf to balance ~~the~~ High-Salinity Shelf Water (HSSW) off 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 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).~~;~~ T~~t~~herefore, 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~~the~~ surface ~~of which~~ dense water is formed (Fusco et al., 2002). The Drygalski ice tongue (DIT), which forms the southern boundary of TNBP, blocks ~~the~~ sea-ice moving from the south (Stevens et al., 2017). Katabatic winds that blow~~ing~~ from the Nansen ice shelf (NIS) take the heat from the polynya, producing sea-ice in TNBP (Fusco et al., 2009; Tamura et al., 2016; Toggweiler and Samuels, 1995), which is responsible for the production of 3–4% of the total sea-ice in ~~the~~ Antarctic coastal polynyas (Tamura et al., 2016). The release of salty brine as a result of sea-ice 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 ~~is~~ most efficiently produc~~ing~~es sea-ice in response to the persistent katabatic winds (v~~V~~an W~~w~~oert, 1999; Rusciano et al., 2013; Sansiviero et al., 2017; Aulicino et al., 2018). TNBP does open in the austral summer, but HSSW is rarely formed during~~in~~ this period due to~~because of~~ the cessation of sea-ice production in the upper layer, along with ice-melting processes (Rusciano et al., 2013). According to ~~the~~ historical observations and the results of numerical modelling, the densest HSSW is formed from August to October, during which period ~~and~~ 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 studies have suggested that ~~Open ocean~~ c~~c~~onvection, which is preceded~~led~~ by wind-driven mixing~~,~~ is ~~suggested as~~ the HSSW formation mechanism ~~of HSSW~~ (Buffoni et al., 2002; Mathiot et al., 2012). Besides ~~the~~ polynya activity, CDW transport in the Ross Sea continental shelf and water masses that flow~~ing~~ from the southern part of the DIT have been suggested as the factors that influenc~~ing~~es ~~the~~ changes in HSSW properties (Fusco et al., 2009; Stevens et al., 2017).

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

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

2 Data and Methods

2.1 Hydrographic measurements

We examined the spatio-temporal variations in ~~the~~HSSW production ~~of HSSW by ~~using the time-series data from mooring stations in the eastern TNB (DITN) and the deepest depth of the DB (DITD) (blue diamond and magenta star, respectively, in Fig. 1). The DITN mooring, which supports measurements of temperature, salinity, pressure, and ocean currents at three depths, using SBE37SM (Sea-Bird Scientific, Bellevue, WA, USA), RCM9 (Xylem, Inc., Rye Brook, NY, USA), and Aquadopp (Nortek, Norway) current meters (Fig. 2 and Table 1), has been continuously maintained since December 2014 (Table 1). Data from these devices have been retrieved, downloaded, and maintained, with annual instruments redeployment thereafter~~and the instruments redeployed annually since~~. The redeployments are ~~well ~~collocated, such~~o~~ that the depths at~~of the~~ sensors~~'~~ locations in each observation period ~~a~~were nearly identical~~almost the same~~ during the three year study period~~s~~ (Fig. 2 and Table 1). During the second leg of the DITN, an SBE37SM installed in a deep layer incorrectly recorded the pressure value~~ from an SBE37SM installed in a deep layer was recorded incorrectly;~~. T~~t~~herefore, a nominal sensor depth of 660 m was used to calculate the salinity. In addition, the DITD mooring was deployed for a single year during February 2017–March 2018, which record~~ing~~ed the same variables as the DITN, but operated~~ing~~ below 1,200 m (Fig. 2 and Table 1).

The temperature and salinity parameter~~value~~s obtained from these moorings were validated and corrected with conductivity~~–~~-temperature-~~–~~depth (CTD) casts in the mooring~~s'~~ positions before ~~the ~~recovery and after the deployment of the DITN and DITD. The magnetic declination ~~is~~was corrected to~~in~~ the current direction and the velocities were~~are~~ 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. ~~low-pass filtered by monthly averaging. ~~Current data observed with the RCM9 instrument during the DITN mooring were used for consistency of 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~~l~~ August 1, 2017.~~;~~ ~~t~~Thereafter, an Aquadopp current meter was used~~ instead~~. Mean differences in~~of~~ the current direction (speed) between observed data~~ observed~~

from the RCM9 and Aquadopp current meters at each depth were~~are~~ 2°, 3°, and 8° (1.8, 0.2, and –1.2 cm/s), respectively during the third leg of the DITN.

Full-depth CTD profile data measurements were conducted by the icebreaking research vessel IBRV ARAON (Korea Polar Research Institute (KOPRI)) during hydrographic surveys ~~conducted were used~~ to analyz~~s~~e 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.~~, and~~ ~~t~~The sensors' calibration dates ~~are~~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 the profiles~~ varied annually~~from year to year~~ depending on sea ice and cruise priorities ~~in cruise~~ (Fig. 1). Profiles of horizontal currents (5-m 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 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 were de-tided using all ten available tidal components from the CATS2008 (Circum-Antarctica Tidal Simulation model) (Padman et al., 2002). The mean velocity of tidal currents during each survey was 0.9, 1.5, 1.0, and 0.5 cm/s, which were much weaker than the velocities observed from the moorings and LADCP.

T~~In order t~~o directly compare th~~e present work~~is study with results from~~of~~ 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)~~ results~~. ~~We return to this point in Sect. 4.~~ 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

H~~The h~~ourly wind data (2014–2018) observed at the Automatic Weather System (AWS) Manuela station (Ciappa et al., 2012; Fig. 4a) were used to investigate ~~the~~ katabatic winds blowing over TNB. 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 having a westerly wind direction of 225–315° and a wind speed of over 25 m/s. The AWS Manuela station is situated such that it is within the pathway of ~~the~~ katabatic winds along ~~the~~ Reeves Glacier, making it the best option to detect the katabatic winds that blow~~ing~~ over TNB (Ciappa et al., 2012; Sansiviero et al., 2017).

The three-hourly 10-m wind and 2-m air-temperature data, provided by the ERA-Interim reanalysis data set (Dee et al., 2011), we~~a~~re also used to identify ~~the~~ atmospheric conditions in~~at~~ TNB from January 2014 to March 2018. A grid size of 0.75° × 0.75° was~~is~~ attributed to the data set. A~~The a~~veraged wind at the AWS Manuela station wa~~i~~s approximately four times faster than that provided by the ERA-Interim reanalysis data, but its direction was~~is~~ nearly identical~~the same~~ with that at the grid located near Manuela (an approximately~~bout~~ 6° difference) (Fig. 4a). ERA-Interim is a spatially smooth~~en~~ed product with a grid that is generally too coarse to resolve steep glacialer 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 inof eastward (225° $\leq \theta \leq$ 315°) wind speed at Manuela had aare significantly correlationed (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). EThe eastward winds detected byat the Manuela station wereare synchronizsed with the wind in terms of occurrence and speed variability in all regions of TNB, despite the slower offshore wind speeds being slower offshore. In addition, the daily air temperature observed atin Manuela also hads a significant r value (> 0.90) with that from the ERA-Interim (Fig. 4b).

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

3 Results

3.1 Deep-ocean salinity variations in TNB

Deep-ocean salinity observed in a mooring located in the eastern TNB (DITN, a blue diamond in Fig. 1) clearly exhibiteds interannual variations during 2015–2017 (Fig. 5a). Moreover, at approximately 660 m, during a span of three years, ithe salinity significantly increaseds from 34.80 to 34.85, despite certainalthough there were some periods where the salinity decreased by 0.01–0.02 (Fig. 5a). The annual cycle of salinity begins to increaseincreasing from September (Fig. 5a), and 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 duringof 2015, 2016, and 2017, respectively. Seawater properties during this period weare included in the range of the HSSW (blue dots in Fig. 6).; Ttherefore, the relatively large changes in salt change duringin 2016 and 2017 areis an indication of active HSSW formation during the austral winter in TNBP.

EThe evidence of the pastfor active HSSW formation fromduring April to October of 2016 and 2017 wasis still observed three3 and five5 months later, in January 2017 and March 2018, respectively (Fig. 3). The maximum salinity in theof HSSW found during January–February 2017 (2016/17) and in March 2018 (2017/18) was similar tohigher than that ofin the preceding observationsurveys infrom April to October of 2016 and 2017, respectively (Fig. 3 and Fig. 5a). The mean salinity in theof HSSW (σ_θ>28 kg/m^3) wais 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 weare rare in the θ-–S diagram (small panel in Fig. 3), such thato its effect on the changes inof deep-ocean salinity throughoutin TNB weare limited.

Vertical CTD profiles of CTD also haved features consistent with the θ-–S diagram (Fig. 7). A quasi-homogeneous bottom layer below 800 m represents the HSSW formedation just before the austral winter (Fig. 7). TheIts salinity of this year wais relatively high in the 2016/17 and 2017/18 surveys (Fig. 7a; peak salinities ofy, 34.83 and 34.85, respectively). Such a high-salinity water mass can be only formed only in TNBP (Orsi and Wiederwohl, 2009). Thus, active HSSW formation in TNBP during the austral winters of 2016 and 2017 increasedds the salinity of the water at 660 m at theof DITN mooring.

The latter two surveys were conducted in the late austral summer (January–February 2017 and March 2018).; Ttherefore, lessfewer amounts of saline (dense) seawater in the upper partdepths and a strong salinity (density) gradient between the upper and lower layers were observed (Figs. 7a and 7c). The TISW, characterizsed by its potential temperatures lower than the freezing point at the surface50 m (approximatelyθ ≤ –1.9335°C) and a salinity of approximately 34.73 (Budillon and Spezie, 2000), was observed from at depths between 300 toand 600 m in 2016/17 and 2017/18, but was not observed during in the surveys in December surveys (2014/15 and 2015/16) (Figs. 3 and Fig. 7b). Therefore, It seems that the meltwater outflow from nearby ice shelves may occurs 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 occurreds approximately 1–2 months later than that observed at mooring D (a triangle filled with black in Fig. 1) 33 km northwest of DITN. (Rusciano et al., 2013). Saline seawater over 34.80 is only formed in TNBP, which is the reason behind the increase in salinity increase measured in September. According to the current measurements obtained at the same depth (~660 m) as the salinity, flows weare nearlyalmost southward and slower than 4 cm/s (blue arrows in Fig. 5b). Southwestward flows weare mainly observed during the periods of increased salinity, with episodic detection of and southeastward flows are episodically detected (Fig. 5b). The mean current direction of the current wais southwestward (191°), with a and its mean speed ofis approximately 1.5 cm/s during the August–November period over theof three year studys period (a blue arrow in Fig. 1). WeIt is assumed that the propagation of the HSSW propagating into the eastern TNB for a month along the mean current, HSSW would result in HSSW movement come from 40 km of the DITN in a northern direction. Moreover, the HSSW is known to be formed near the NIS during the austral winter and propagates towards the centerre of TNB along 800–1,000-m isobaths (Fig. 1) (Rusciano et al., 2013). Thus, we can conclude that the deep-ocean salinity in the eastern TNB has increased since September due to the southward advection of HSSW from the centrer 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/m^3/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 ~~of HSSW~~ 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, salinity in the upper part~~depth~~s show a distinct seasonal variation. Salinity at both 75 m and 273 m decreased, while salinity at 75 m~~the upper depth~~ decreased to below 34.0 in February of each year (Fig. 8a). Thereafter, the salinity of the two layers start mixing, as the salinity increases (decreases) at 75 (273) m. The salinity of the two layers then increases in tandem from May to October (Fig. 8a). In December, mixing of the two layers ceases and their salinity difference becomes larger again (Fig. 8a). The reduction in mixing 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~~re~~ these layers are well mixed has become long~~short~~er over time (Fig. 8a). If we~~it is~~ assume~~d~~ that the two layers are mixed when the difference in σ_θ ~~difference~~ between the two layers is less than 0.1 kg/m^3 (~0.0005 kg/m^2) (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~~become more highly~~ correlations~~ed~~ than during the entire period. The salinity at 75 m had~~s~~ correlation coefficients of~~a~~ 0.64, 0.58, and 0.62 ~~correlation coefficient~~ with the salinity ~~at~~ at 273 m during the 1st, 2nd, and 3rd legs (Table 1), respectively. However, for ~~the~~ periods in which the salinity at the~~of~~ two depths simultaneously increased ~~together~~, the r values increase~~s~~d to 0.94, 0.88, and 0.93 (Fig. 8a), respectively. ~~That is~~In other words, the salinity at the two depths was characterized by ~~showed~~ the most rapid~~ly~~ mixing during March-April 2017 among the three year~~s~~ study period, with the longest ~~and they are~~ co-variation time~~ed for the longest time~~ until October, 2017.

T~~Moreover, t~~he maximum salinity observed at depths of 75~~ m~~ 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~~ values~~ observed at~~in~~ ~~the~~ deeper depths (Figs. 5a, 7 and 8a). The HSSW ~~i~~was detected even in the upper part~~depth~~s during the months of August to October ~~months~~ in 2016 and 2017 (red and black dots in Figs. 6d–6i). ~~On~~In ~~the~~ contra~~ry~~st, ~~the~~ HSSW formation wa~~i~~s rarely observed from August to October 2015, when the increase in salinity~~ increase~~ ~~i~~was relatively small compared with~~to~~ that during the same period in 2016 and 2017 (Fig. 5a;~~,~~ red and black dots in 6a–6c).

The reasons for the ~~greater~~ higher increase in salinity in the upper part~~depth~~s may~~could~~ be due to~~considered as~~ the formation of increasing amounts of dense water via~~by~~ brine rejection at~~in~~ 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 part~~depth~~s, westward currents ~~a~~were dominant at the two depths during December 2014–March 2018 (Fig. 8c), with an~~and~~ ~~the~~ average~~d~~ current speed (direction)~~ of the currents~~ from June to November of~~is~~ 7.4 cm/s (279°, westward) at 75 m~~,~~ and 4.0 cm/s (270°, westward) at

273 m (Fig. 1). These currents ~~could be~~are possibly led by density gradients between under the DIT and in TNB~~the Ekman currents driven by the northeastward winds blowing across the DIT (Fig. 4a)~~ or ~~the geostrophic currents induced by~~ a latitudinal gradient of sea-surface height near the DIT. These ~~would be the~~ phenomena are confined to~~in~~ coastal regions due to the existence of the DIT (Fig. 1 and Section 1~~~300 m thickness~~). However, ~~from~~based on ~~these~~our observations, only the upper water columns of the DITN appear~~seem~~ to be affected by seawater from the eastern part of TNB during periods of increased upper level salinity. As identified in previous studies, water masses farther away TNB~~, water masses~~ are less saline due to mixing with the CDW or the intrusion of~~due to~~ MCDW into~~ruding~~ the western Ross Sea (Orsi and Wiederwohl, 2009; Fusco et al., 2009; Budillon et al., 2011).

Thus, ~~the~~ salinity increases in the upper layers are~~is~~ related to ~~the~~ local brine supplied by sea-ice formation near the DITN region, rather than the~~an~~ advection of saline water from the western Ross Sea. As a result, ~~the~~ salinity (density) variations in the upper layers exhibit dense water formation ~~of dense water~~ in the polynya via convection led by a supply of brine from the surface~~wind-driven mixing~~ as suggested by modelling studies on TNBP (Fig. 8a; Buffoni et al., 2002; Mathiot et al., 2012). ~~In addition,~~ We observed t~~t~~he HSSW ~~found~~ in the upper layers during the months from~~of~~ August to October of 2016 and 2017 (Fig. 6d–6i, and 8a), which indicates~~implies~~ that ~~it could be~~the HSSW can be formed ~~by the open-ocean convection~~ through convective processes in the eastern TNB~~, as suggested by model studies on TNBP (Buffoni et al., 2002; Mathiot et al., 2012)~~. 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~~-ocean~~ salinity began to increase in~~since~~ September, and the HSSW was detected in the upper part~~depth~~s of the DITN during August–October (Fig. 5a and 6). Based on~~From~~ 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~~That is~~, the increase in~~of~~ the deep~~-ocean~~ salinity (i.e., at 660 ~~m~~ and 1,208 m) observed in 2016 and 2017 may have been partly induced by ~~the~~ local HSSW formation ~~of HSSW~~ combined with HSSW advection ~~the advected HSSW~~ from the cent~~r~~er of TNB. However, the salinity time-series at 660 m had a~~is~~ poor~~ly~~ correlat~~ed~~ion with ~~the~~ salinity variations in the upper part~~depth~~s of the DITN during September–October in 2016 and 2017 ($r < 0.30$). The salinity at 660 m~~, and its value~~ wa~~i~~s a little higher than~~nearly as large as~~ that observed in the upper water column (Figs. 6 and 8a). This indicate~~mean~~s that the mixed layer does not extend to 660 m in the eastern TNB. ~~and~~ T~~t~~he higher salinity in the deep layer derive~~come~~s 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~~needs to~~ 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~~would be also~~ interesting research topics~~;~~ but~~however,~~ these types of HSSW are difficult to investigate with the ~~current~~ observational data used in this study.

3.4 Role of wind~~s~~ in TNBP

The wind in TNB is primarily westerly, whichand on an average, creates an L-shaped polynya along the NIS and DIT, as shown by thea contour line that represents a sea-ice concentration of 50% sea-ice concentration in Fig. 4a. The Weasterly winds measured at Manuela effectively open TNBP during the austral winters of the three year study periods (Fig. 9). The *r* value between the daily wind speed (a blue line in Fig. 9) and the percentage of open water (sky blue bars in Fig. 9) wais 0.46 acrossduring a seven-month period (April – to October, red dashed boxes in Fig. 9) duringof 2015, 2016, and 2017the three year period (2015–2017), which is significant at a 99% confidence level. In the austral winter duringof each year, the *r* value wasis 0.49, 0.50, and 0.37, and where all values awere significant at a 99% confidence level (Fig. 10). The period from the end of June to July 2017, when the open water did not significantly expand greatly despite the strong winds, affecteds the estimation of the lowest *r* value duringin the austral winter of 2017 austral winter (Fig. 10c). The weak response of the polynya to these winds appearseems to be associated with a blocking effect of sea-ice in the offshore region (Tamura et al., 2016).
Previous studies have suggestedIt was suggested that the HSSW formation near the mooring D is more dependent on the duration of a single katabatic wind events, than on itstheir frequency during April–October (Rusciano et al., 2013). As inferred fromBased on the hydrographic surveys of TNB, there was more active formation of the HSSW had more actively formed in 2016 and 2017 than in 2014 and 2015.; tTherefore, the deep ocean salinity was increased due to HSSW advection from mooring D during late 2016 and 2017. It was suggested that the HSSW formation near the mooring D is more dependent on the duration of single katabatic wind events, than on their frequency during April–October (Rusciano et al., 2013). This is consistent In line with the wind observations atby the Manuela station., aAmong the three years, katabatic wind events most frequently occurred most frequently from April to October 2017 (210 events) (see wind speeds over 25 m/s in Fig. 10). The mean duration of a single katabatic wind event during these seven7 months in the years 2015, 2016, and 2017 wasis estimated as 6.5, 7.0, and 7.7 hours, respectively. Moreover, the average length of time for which the polynya iwas open (i.e., > 20 % open water) during the same periods is calculated was 5.8 (2015), 6.7 (2016), and 7.7 days (2017), respectively. These resultsdata suggest that, during the fourthree years of the study period, HSSW formation was the most active near the NIS during the 2017 austral winter of 2017 is when the HSSW formation is the most active.
In addition, fromduring September to October of 2016 and 2017, the upper layers of the eastern TNB also experienced theHSSW production of HSSW via convective processes after the development of a mixed layer. This indicatemeans that the katabatic winds — considered as pivotal to the development of a polynya (Fig. 9) and HSSW formation of HSSW near the NIS (Rusciano et al., 2013) — generate wind-driven mixing and induce the convection by a supply of brine related to polynya development in the eastern TNB and even produce HSSW. 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), the total magnitude of the increase in salinity during the katabatic wind events 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. 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 katabatic wind events also accounted for over 50% (54% at 75 m and 76% at 273 m) of the total salinity increase from June to September in 2017. In other 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. ~~This could be partly explained by the relationship between the opening of TNBP by eastward winds and monthly change of salinity in the upper layers of DITN (positive values at 75 (273) m only shown as triangle (circle) black lines in Fig. 10). For example, the rate of salinity variation in April indicates a difference between mean salinities of water in April and March.~~

~~The rate of increase in salinity itself had increased during the April months of 2015 to 2017, due to stronger winds and a higher percentage of open water in TNB (Fig. 10). The faster rate of change of salinity is led by faster mixing; therefore, in May 2017, the rate of change of salinity at both 75 and 273 m became positive (Fig. 8a and 10c). In May 2015 and 2016, the rate of change of salinity is positive only at 75 m, while it was slightly larger in 2015 due to stronger winds (> 20 m/s) in early May (Figs. 10a and 10b).~~

~~Second, the high-speed winds (> 20 m/s) persistently blowing from late May to early July of 2016 create 50% more open sea in TNBP, and the rate of change at the two depths becomes positive and larger in June 2016 (Fig. 10b). In June 2015, a positive rate is observed at the two depths, but only a slight increase at 273 m (~0.025/month) is observed due to relatively weak winds and polynya development compared to those in 2016 (Figs. 10a and 10b). In addition, salinity in the upper depths increased by over 40% in June 2017 in relation to the developments of TNBP, due to the winds blowing from early June to mid-June 2017 (Fig. 10c).~~

~~Third, both wind speed and open water area have decreased since June 2016. Consequently, the rate of change of salinity in the upper layers has remained below 0.05/month after June 2016 (Fig. 10b). On the contrary, the rate of increase in July 2015 and July 2017 became larger than in the previous month, because of higher wind speeds in July 2015 and July 2017 relative to June 2015 and June 2017 (Figs. 10a, 10c). However, after July 2015, the rate of increase has been constantly decreasing with the decrease of wind speed (Fig. 10a). During August–September 2017, the winds were still strong but could not effectively open TNBP; therefore, the rate of change of salinity continued to decrease until October (Fig. 10c).~~

~~In summary, the mixing process during early 2017 is the fastest among the three years due to relatively strong winds from March to April, and the brine supply related to the polynya development with persistently strong winds during May–September 2017 would produce HSSW in the upper layers of the eastern TNB. The HSSW observed from September to October 2016 in the upper layers was fresher than that in 2017, which may be related to relatively weak winds and less brine supply in the late~~

~~2016. In 2015, HSSW is rarely found in the upper layers of DITN due to the absence of strong winds (> 25 m/s) during April–June 2015.~~

4 Discussion~~s~~

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 ~~processes at~~ small scale~~s~~ processes from a regional perspective. Here, we investigate HSSW behaviours ~~of HSSW~~ in TNB are investigated with the spatio-temporal variations in salinity observed in the eastern TNB and DB.

4.1 P~~The p~~resent data in the context of previous analyses

Data from ~~The~~ mooring D (Fig. 1) ~~data of~~in TNBP ~~have~~ show~~n~~ seasonal variation ~~of~~in the stratification of~~in~~ the water column and interannual variation in the~~of~~ HSSW properties, which are closely associated with ~~the~~ polynya activity (Rusciano et al., 2013). This proves that HSSW production occurs~~is produced~~ during the austral winter, and a series of katabatic wind events in a certain period of time during the austral winter controls the properties of the HSSW~~ properties~~. Data gathered for this study ha**ve**~~s~~ revealed that the HSSW c~~ould~~an also form at the surface of the eastern TNB via~~by~~ ~~wind-driven mixing and~~ an identical~~the same~~ polynya process as that involved in ~~the~~ vigorous HSSW formation ~~of HSSW~~ near the NIS. In addition, we~~it was~~ found that ~~the~~ large increases in salinity (> 0.04) observed in the deepest part of the DB and eastern TNB were~~are~~ due to HSSW~~the~~ advection~~ of HSSW~~ and not a~~the~~ sinking HSSW directly from the surface at the mooring locations. The HSSW formed near the NIS arrives at these depths within a few months.~~;~~ T~~t~~hus, the HSSW is evenly distributed over TNB during the austral summer. In other words, the average salinity of the HSSW~~ averaged~~ in the eastern part ~~of~~at 164.5°E (34.802) shows no difference from~~with~~ that in the western part ~~of~~at 164.5°E (34.802) during the CTD observation periods. According to vertical sections of salinity from the 2017/18 survey, salinity in the deep layer (> 600 m) was nearly identical between the western and eastern part of TNB (Fig. 10a), with a sufficiently distributed salinity over 34.80 at greater depths (> 800 m) of the DB (Fig. 10b). As a result, the DITN, DITD, and four hydrographic surveys, along with ~~the~~ previous data from ~~the~~ mooring D, reveal spatio-temporal variations in ~~the~~ HSSW production~~ of HSSW~~ and ~~the~~ movement ~~of HSSW~~ in TNBP.

~~Hydrographic data have been collected from TNB for more than 20 years, and the longer-period variation of HSSW (~5 year) could be re-visited. However, each data set would contain an artificial uncertainty induced by the sensors' calibration date, sensor types, data processing tool, and other factors. Here, the potential temperature and practical salinity were used to ensure consistency of results with the previous studies; however, in future studies, HSSW in TNB need to be re-defined with a conservative temperature and absolute salinity (TEOS-10), to reduce uncertainties in the long-term trend of HSSW properties, and find a quantitative relation with properties of water masses in the other regions.~~

4.2 Circulations in TNBP

For the austral summer (December–March), westward currents flowing along the DIT and northward currents along the NIS were~~are~~ ~~found~~observed based on~~from~~ the de-tided LADCP current data averaged over a depth range of 400–700 m (Fig. 11a). The currents resemble a cyclonic pattern together with the southeastward currents in the northeastern TNB, despite southward currents that flow toward~~heading for~~ the DIT along ~~the~~ 800–1000 m isobaths, as well as at the center of the DB (Fig. 11a). However, southeastward currents that cross~~ing~~ over from the NIS to the DIT were rarely observed in TNBP. The direction of the ocean current at 660 m in~~of~~ the DITN was stable during December 2014–March 2018 (Figs. 5b and 8c). Therefore, if we assume that the circulation pattern ~~i~~was ~~assumed to be~~ maintained throughout the year, then the HSSW formed near the NIS may circulate clockwise, arriving in the DITN around September and induced~~ing~~ an increase in the salinity, rather than directly propagating southeastward to the DITN. Furthermore, the wind-forcing-driven cyclonic gyre in the upper layer of TNBP (v~~V~~an W~~w~~oert et al., 2001) may induce an upwelling in the cent~~r~~er of TNB, which ~~would~~ hinders the development of horizontal flows in the central region of the gyre. For example, t~~T~~he upwelling feature is visible in the vertical sections of the 2017/18~~four hydrographic~~ survey~~s~~ as upward-bending isopycnals in the upper layers (> ~~~~400 m) of the mid-point of TNB (~~not shown~~Fig. 10b).

The bottom currents in the DB flow under the influence of gravity (Jendersie et al., 2018).~~,~~ H~~h~~owever, it is still un~~not~~ clear how the HSSW flowing at~~under~~ greater depths is circulated around~~over~~ the DB. T~~Despite this, t~~he LADCP data for~~of~~ December–March can be an indication of circulation in the DB region (> 1,000 m) because the current direction at the DITD exhibit~~show~~s little seasonal variation (Fig. 5b) ~~of the current direction at DITD, which can be an indication for the circulations in the DB region (> 1,000 m)~~. The southwestward currents a~~re shown~~ppear in the northeastern part of the DB, while the northwestward and northeastward currents appear~~re identified~~ in the southern and western region of the DB, according to the currents averaged from 900 m to the seafloor during~~in~~ the austral summer (Fig. 11b). 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). In other words, the HSSW propagating into the DB from the NIS circulated~~s~~ cyclonically in this region and can be detected at the DITD from September. Together with the Ross Ice Shelf polynya, the DB region is regarded as an outflow path of the HSSW towards the Ross Sea. Therefore, the circulation pattern in this region also requires~~needs to be~~ investigation~~ed~~ by acquiring more *in situ* ocean current data and ocean circulation model developments.

4.3 TNBP mechanical scales

~~It is useful to c~~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 ~~the~~ DB (~25 km), at current speeds low~~slow~~er than 5 cm/s~~,~~ in less than 2 months (from July to September) (Figs. 1, 5, and 8; Rusciano et al., 2013). Simultaneously, ~~It also~~ the HSSW sinks vertically to the great~~deep~~est depths of the DB (~1,200 m) ~~at the same time~~(Fig. 5). If ~~it is~~we assume~~d~~ that the circulation in TNBP has a radius of 25 km (approximately~~bout~~ one longitudinal degree) (Fig. 11), then we~~it~~ can ~~be~~ deduce~~d~~ that the HSSW circulates cyclonically about 80 km from the NIS to the eastern parts of TNB, which takes about one month at a current speed of 3 cm/s. In this case, the ~~process of~~ sinking process should ~~would~~ take less than one month at an average velocity of 0.05–

~~~~0.07 cm/s. The vertical velocity may~~ight~~ be at~~on~~ a scale of about 10^{-2} that of the horizontal velocities in TNBP, which is regarded as a reasonable result for~~in~~ the ocean (van Haren, 2018). TNBP usually forms as an L-shape, similar to a~~with~~ model-derived polynya (Sansiviero et al., 2017; Fig. 4a).~~;~~ T~~t~~his indicate~~mean~~s that the open water is ~~mostly~~predominantly formed along the coasts near NIS (DIT) for approximately 75 (85) km. The average area for ~~the~~ polynya activity is approximately 1,600 km^2, based on~~y~~ assuming that the width of the open water i~~a~~s 10 km from the coast using~~through~~ the 40% sea-ice concentration contour line (Fig. 4a). This~~It~~ accounts for about 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~~due to the~~ persistent, strong winds, and the water column is stratified again from December. The opening of TNBP by westerly winds that blow~~ing~~ from across the NIS occur~~s~~ over the span of a day.~~, and in~~During this time, the percentage of the open water can vary by up to ±40%. The mean duration of the polynya opening is about 6.7 days during the austral winter in the analysis period. Salinity ~~values~~ at both 75~~ m~~ and 273 m ~~have~~ 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 thi~~s~~at period.

4.4 Quantification of sea-ice production

~~The wind-driven polynya opening of TNBP is highly correlated with the monthly rate of change of salinity in the upper layers of the eastern TNB (Fig. 10).~~ T~~herefore, t~~he precise quantification of sea-ice production and brine formation in the polynya region is requir~~need~~ed for an in-depth understanding of dense-water formation processes. However, current data for the~~of~~ brine supply from~~by~~ sea-ice formation in the polynya provided insufficient constraints. According to ~~the~~ previous results obtained using the ERA-Interim data set (Tamura et al., 2016), the estimated amounts of sea-ice production in TNBP had~~s~~ a high correlation (r = 0.96) with a thin ice area (< 0.2 m), but exhibited a poor correlation (r < 0.3) with ~~the~~ offshore winds from the NIS and air temperature in TNB (see 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~~ing~~ over TNBP or the differences in temperature between the ocean and ~~the~~ atmosphere in TNBP. HSSW production was estimated using the changes in the heat flux averaged over TNB (Fusco et al., 2009).~~;~~ In near future, however, ~~in near future,~~ spatio-temporal variabilities in surface heat flux should also be~~ also~~ investigated to determine the spatial variations in polynya~~the~~ functions~~ing~~ ~~of the polynya~~throughout ~~in~~ TNB over time. Therefore, *in situ* data should be continuously collected~~ continuously~~ to validate reanalysis data sets and suggest spatial and temporal relationships among wind speed, heat flux, sea-ice production, and the brine effect 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
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This study investigated the spatial patterns and temporal changes in HSSW formation in TNBP during the period December 2014–March 2018 using a large, collaboratively produced data set. We found that HSSW ~~that~~ formed near the NIS flows along cyclonic pattern currents in the deeper part~~depth~~s of TNBP and influences the eastern TNB, with ~~and~~ the great~~deep~~est depth in~~of~~ the DB from~~since~~ September (Fig. 12). ~~Due to this~~As a result, the timing of the increase in salinity ~~increase~~ is about two months later in the eastern (offshore) parts of TNB than in the western (nearshore) parts. Moreover, we found that katabatic winds that blow~~ing~~ from across the NIS drive ~~both the formation of HSSW near the NIS, and~~ general salinity increases ~~in salinity~~ and even HSSW formation by promoting convection with more brine supply ~~mixing layers of water and the polynya activity~~ in the upper part~~depth~~s of ~~the~~ eastern TNB (Fig. 12). These findings answer the three research questions proposed in Section~~.~~ 1, ~~and~~ complementing ~~to~~ the results of previous studies~~research~~ on HSSW formation in TNBP.

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

The averaged salinity in a 10-m layer at a depth of 900-m depth shows larger values (> 0.025) in the 2016/17 and 2017/18 surveys than those in the 2014/15 and 2015/16 surveys (Table 1). In other words, the salinity of the HSSW formed in TNBP is~~becomes~~ increasing~~es~~ again, and its value corresponds to those observed in the early 2000 (Fusco et al., 2009)~~, although not an absolute salinity~~. The HSSW formed in TNB can~~ould~~ flow off the shelf break along Victoria Land (Cincinelli et al., 2008; Jendersie et al., 2018), which also contributes to the volumes or properties of AABW in the western Ross Sea. However, the response of overturning circulations in the Southern Ocean to regional anomalies in buoyancy forcing have not been investigated (Rintoul, 2018)~~, which is yet another limitation. Nevertheless, we will have to focus on the recent changes in salinity in the western Ross Sea, including TNB, with atmospheric and sea-ice conditions, and other observational results during the 2010s. Additionally, we will also have to keep monitoring ocean changes in TNBP~~.

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.

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 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 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 ~~analysed the results and provided crucial insights into data interpretations~~. STY wrote the paper~~prepared the manuscript with contributions from all co-authors~~.

Competing Interests

The authors declare no conflicts of interest.

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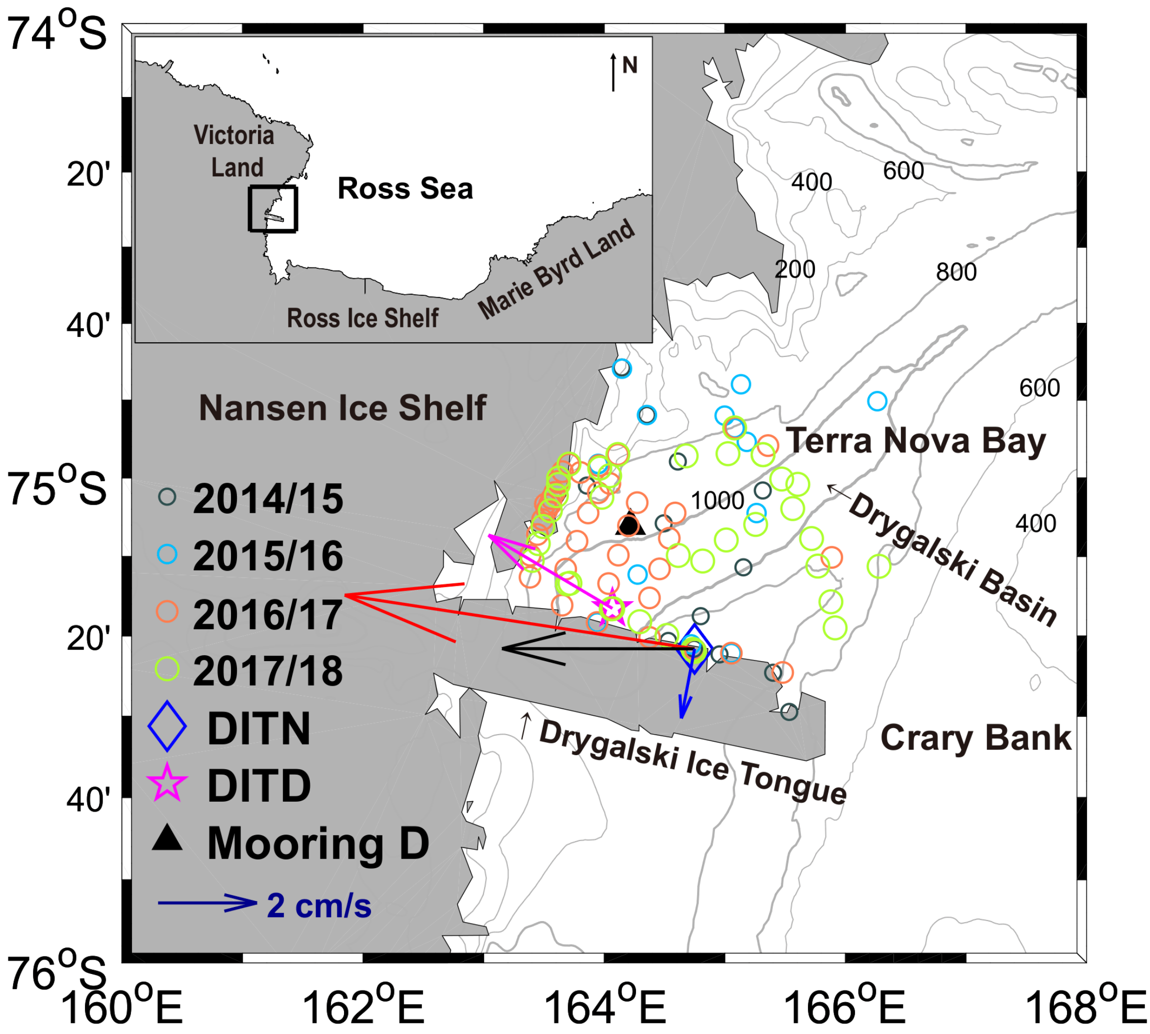

74°S
20'
40'
75°S
20'
40'
76°S
160°E
162°E
164°E
166°E
168°E
Victoria Land
Ross Sea
Marie Byrd Land
Ross Ice Shelf
N
Nansen Ice Shelf
Terra Nova Bay
Drygalski Basin
Crary Bank
Drygalski Ice Tongue
400
600
200
800
600
1000
400
2014/15
2015/16
2016/17
2017/18
DITN
DITD
Mooring D
2 cm/s

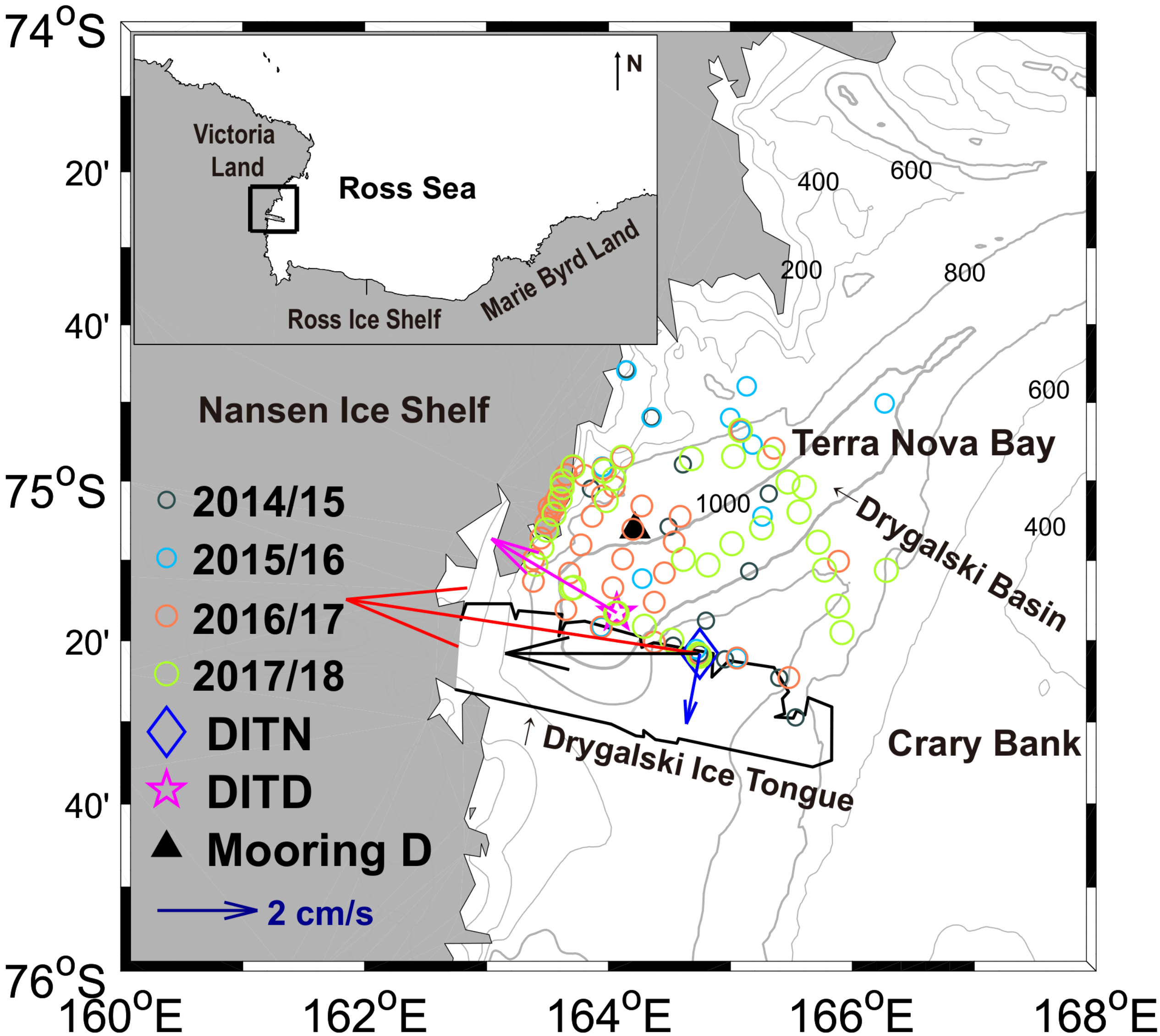
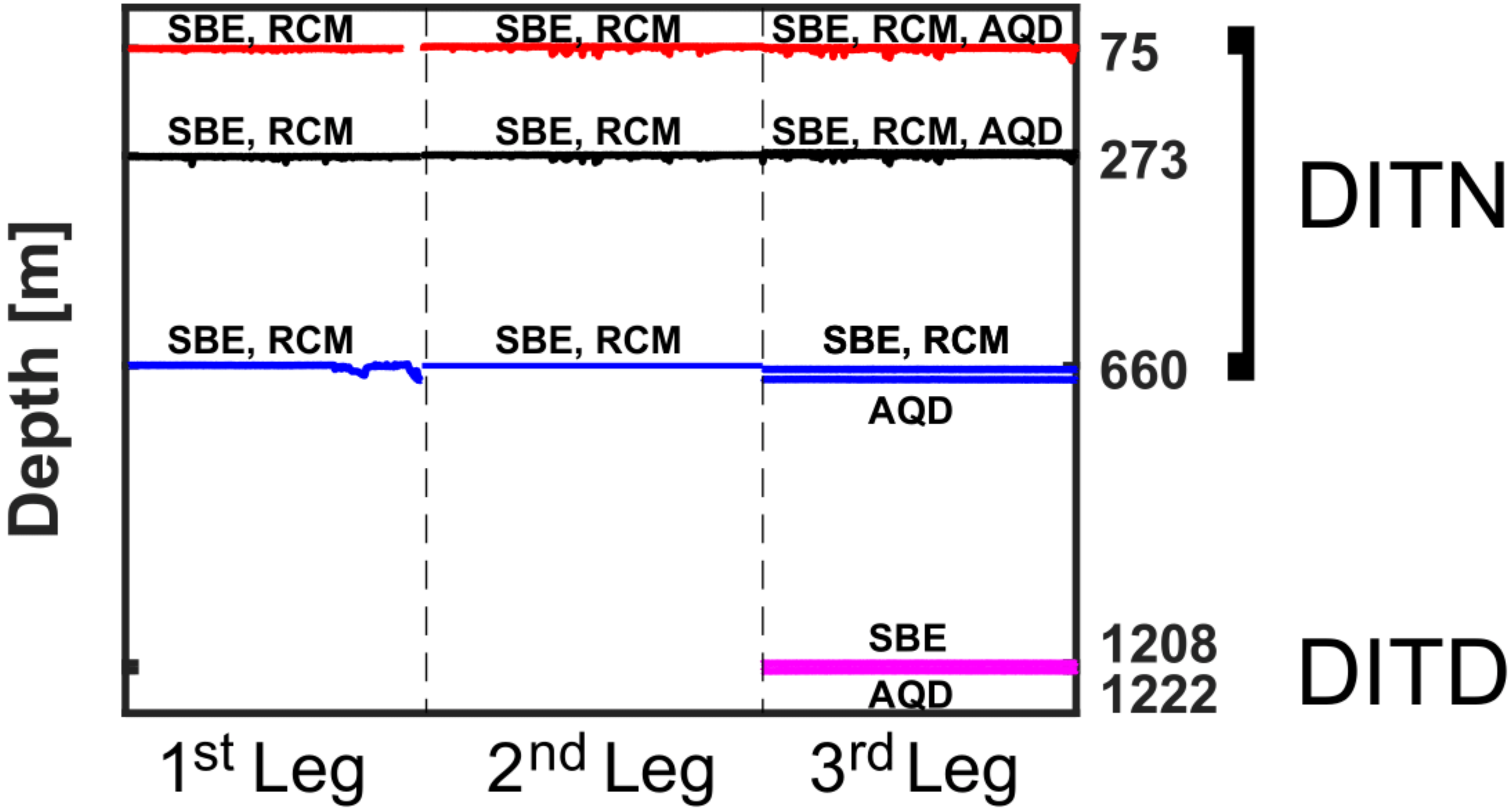


Figure 1: A t~~T~~opographic map of Terra Nova Bay (TNB). The location of TNB in the Ross Sea is shown in ~~an~~the upper-left inset~~panel~~. The bold grey line indicates the 1000-m isobaths and the interval between the thinner grey lines is 200 m. Conductivity-temperature-depth (CTD) stations in the 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~~of~~ DITN (1222 m in the~~of~~ 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~~of~~ DITN. The blue arrow in the bottom left indicates the reference velocity (2 cm s^{-1})~~ is shown by the blue arrow in the left-bottom~~.


SBE, RCM
SBE, RCM
SBE, RCM, AQD
75
SBE, RCM
SBE, RCM
SBE, RCM, AQD
273
DITN
Depth [m]
SBE, RCM
SBE, RCM
SBE, RCM
660
AQD
SBE
1208
AQD
1222
DITD
1st Leg
2nd Leg
3rd Leg

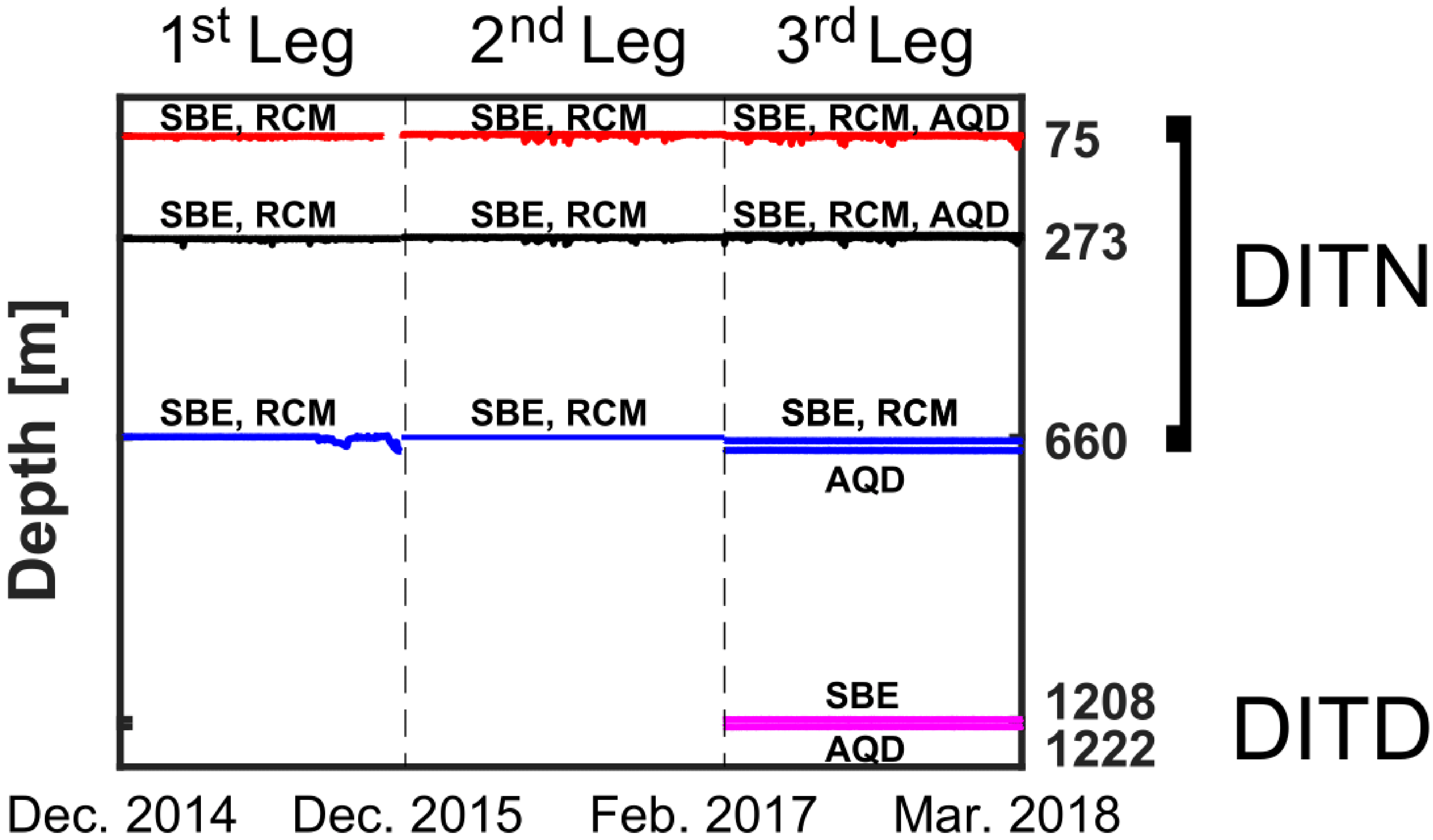
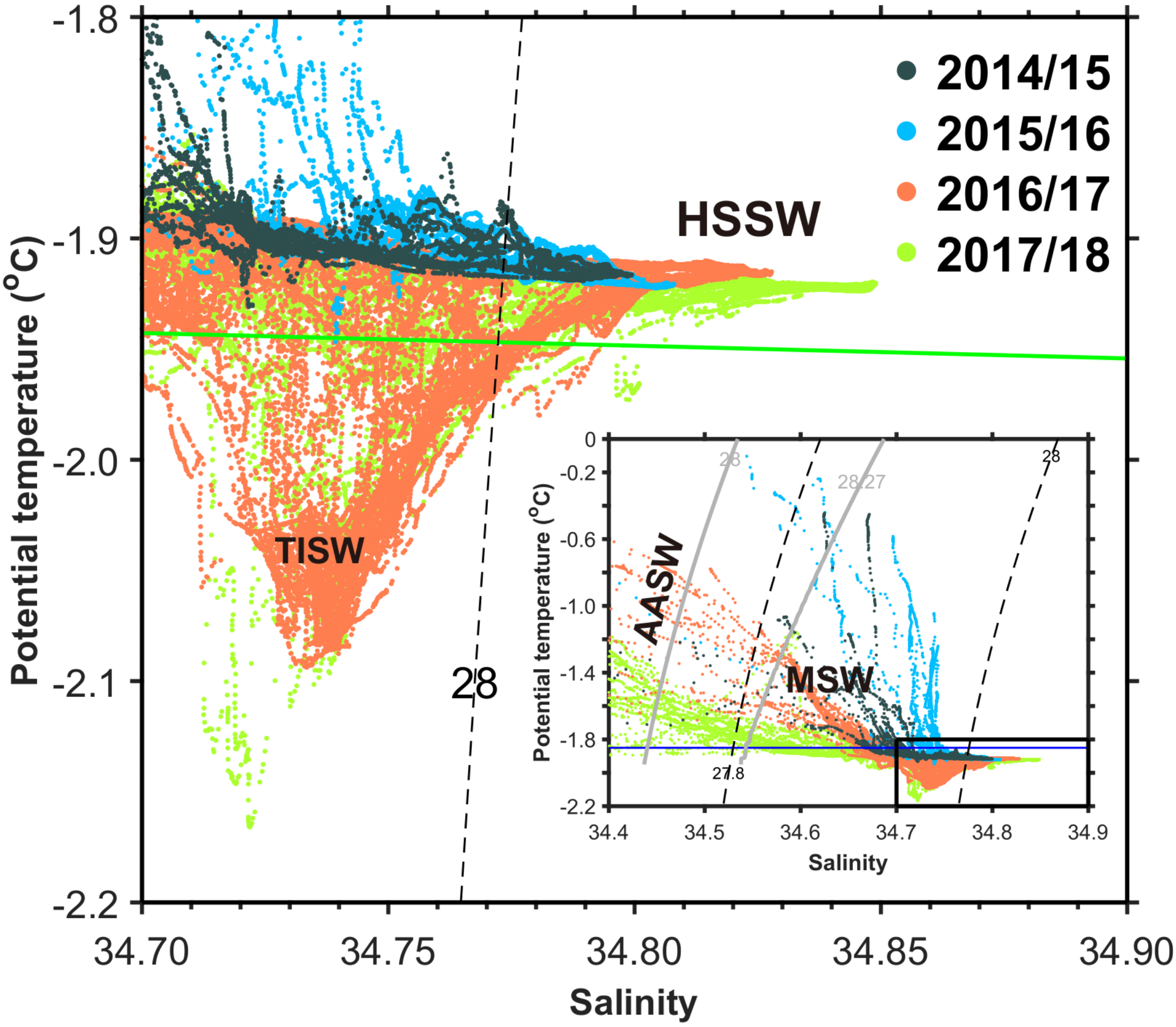


Figure 2: The recorded sensor depth~~ of sensors~~s during the three observation legs. The red, black, and blue lines show the depth time series for sensors at the upper-, mid-, and deep-layer of the DITN. A magenta line also shows ~~T~~the recorded sensor depths of ~~sensors from~~the DITD~~ are also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



2014/15
2015/16
2016/17
2017/18
HSSW
TISW
28
Potential temperature (°C)
Salinity
AASW
MSW
27.8
28.27

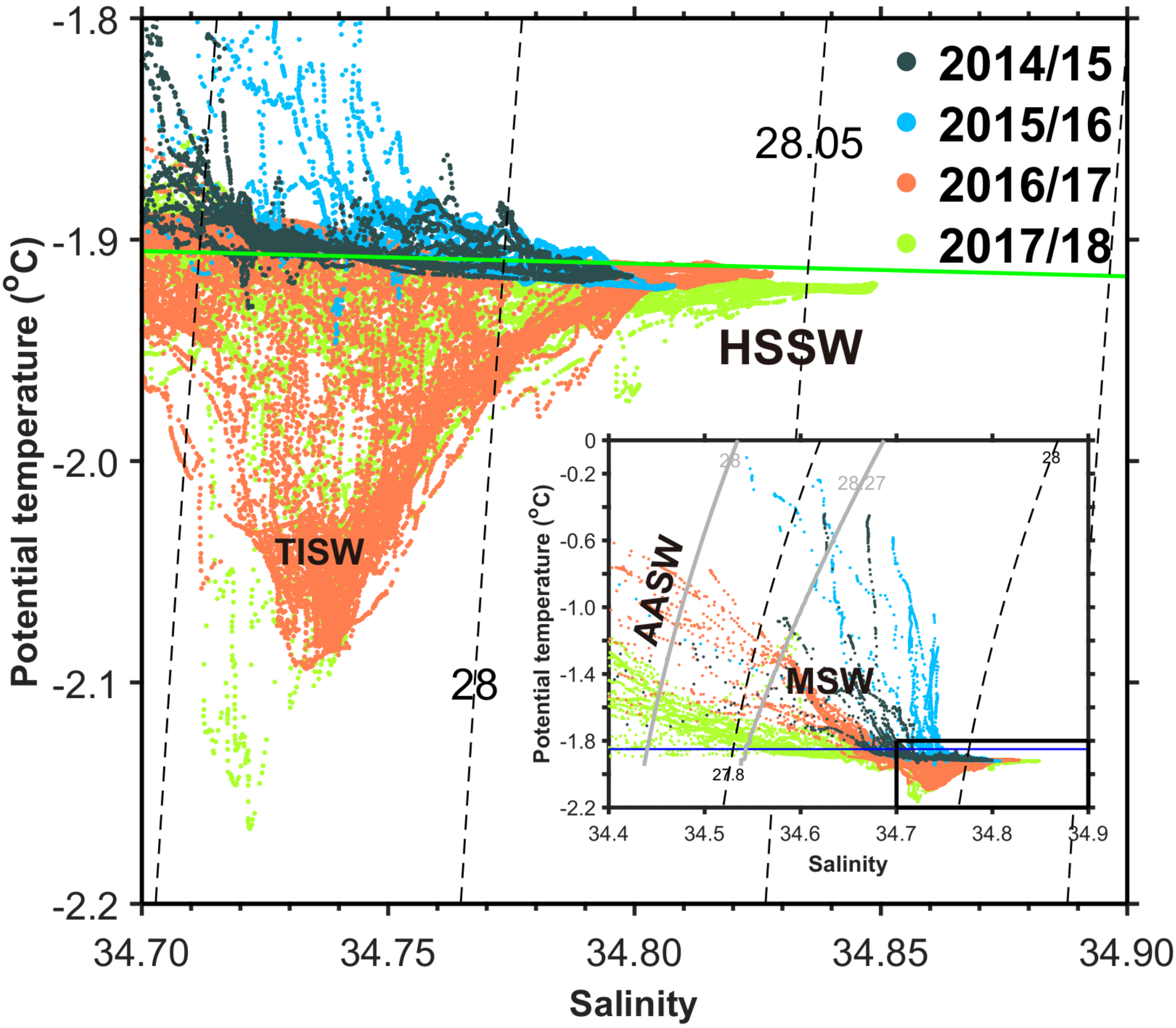


Figure 3: A zoomed-in plot of the θ-S (potential temperature-–salinity) diagram for CTD data observed in TNB during each observation period. The green solid line denotes the freezing point at the surface50 m depending on salinity, and the black dashed lines indicates an isopycnals. The full range θ-S diagram is shown in the small lower-right insetpanel. 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.

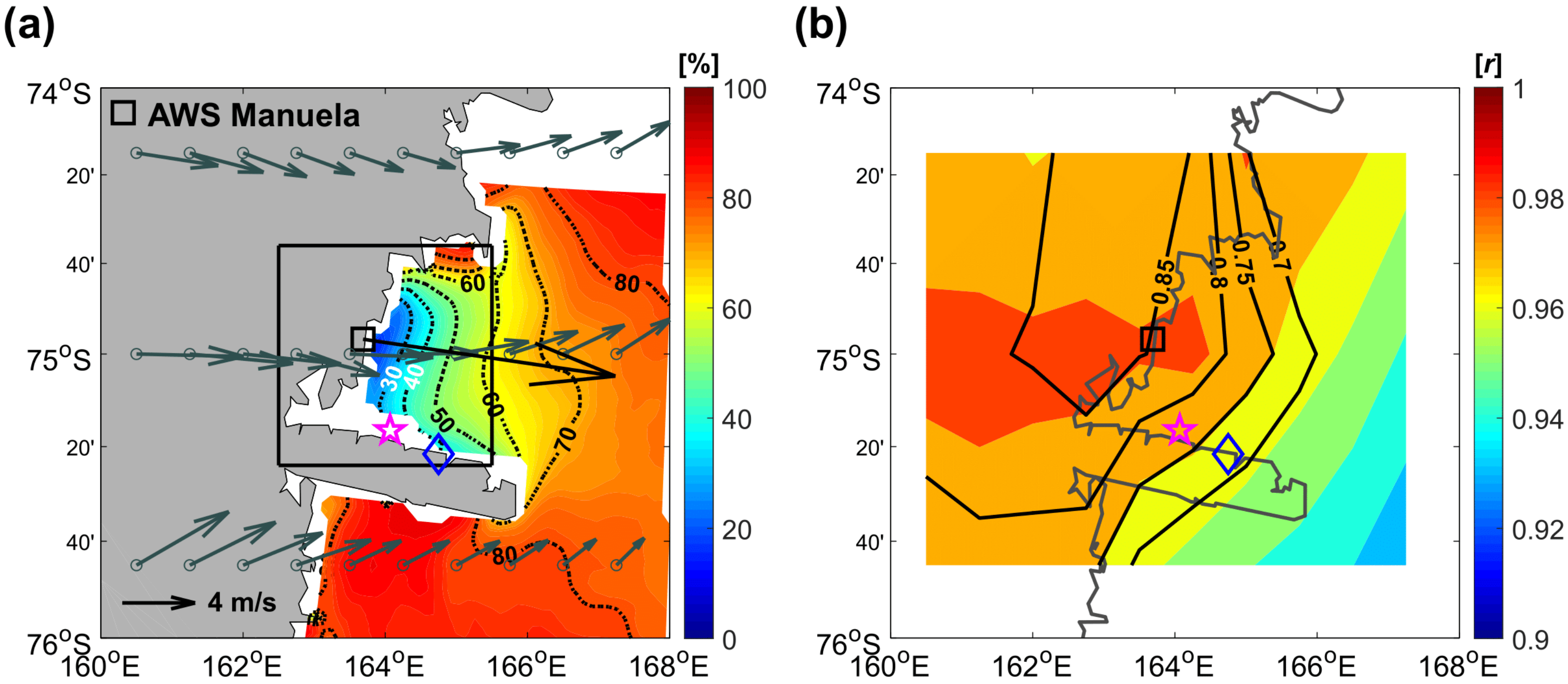


Figure 4: (a) Spatial distributions of averaged sea-ice concentrations from July 2014 to March 2018. The interval of the dotted contour lines is a concentration of~~the~~ 10%~~ concentration~~. The black square (blue diamond and magenta star) indicates the Automatic Weather System (AWS) Manuela station (DITN and DITD). The dark-grey (black) arrow is a mean wind vector for~~during~~ July 2014–March 2018 ~~by ~~using ERA-Interim data (data from AWS Manuela station). The~~A~~ black box denotes an averaged region for sea ice concentrations. (b) Spatial distributions of the correlation coefficients (*r*) between daily air temperature for~~rom~~ 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.

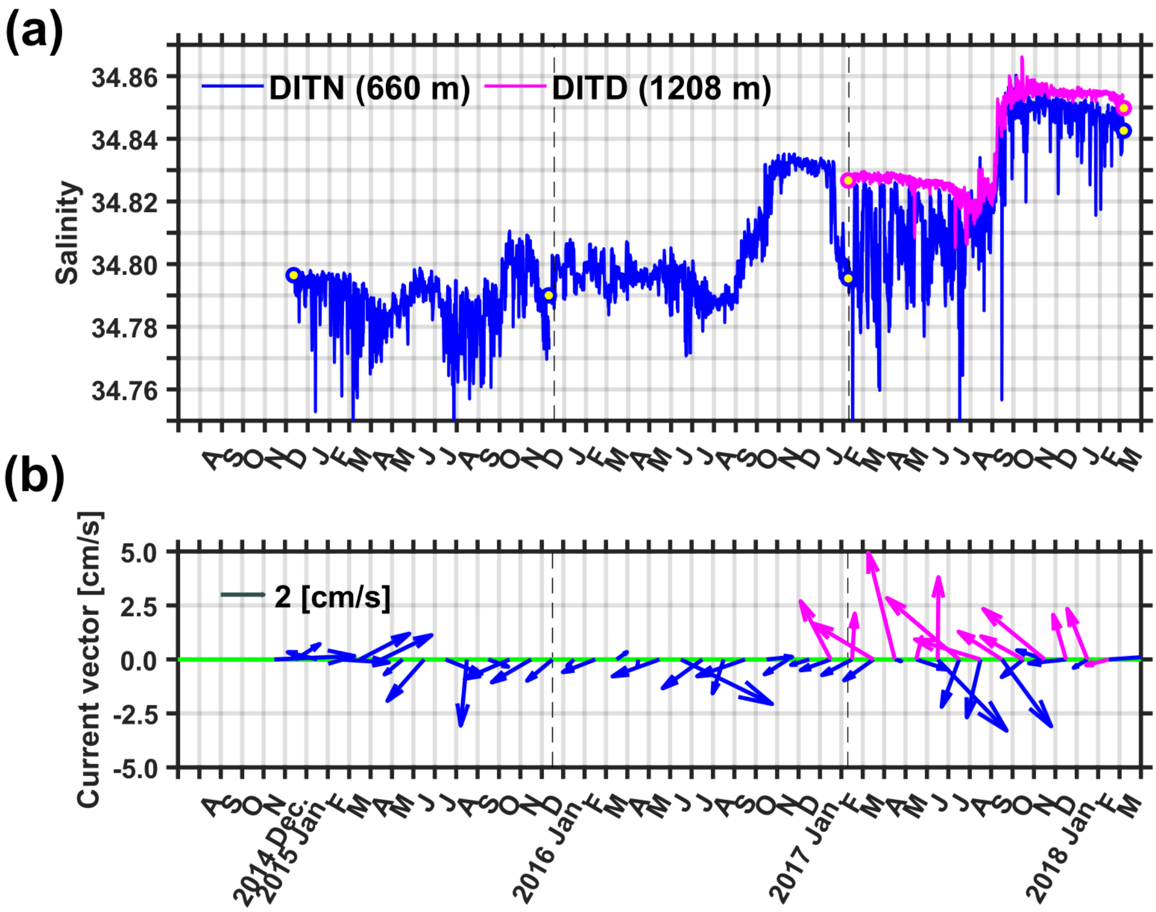
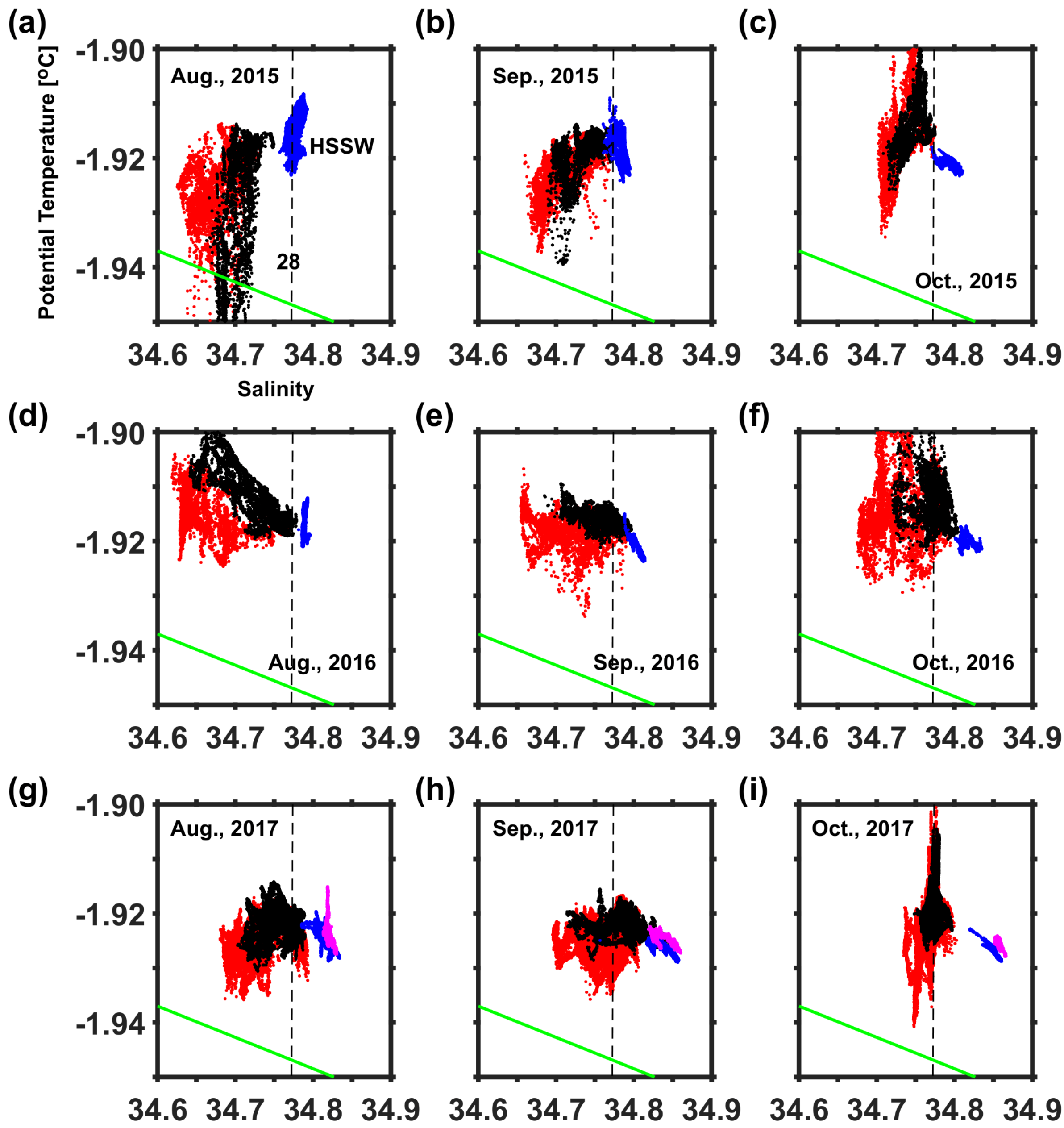


Figure 5: (a) Time series of deep~~-ocean~~ salinity observed in the DITN (blue) and DITD (magenta) from December 2014 to March 2018. The blue (magenta) circles filled with yellow indicate the averaged salinity in a 5-m layer at the bottom obtained using CTD data observed near the DITN (DITD). The black dashed line divides periods of each leag in~~of~~ the moorings (see details in Table. 1). (b) Monthly mean current vectors at 660 m in the ~~of~~ DITN and 1222 m in the~~of~~ DITD are indicated by blue and magenta arrows.


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
Potential Temperature [°C]
Salinity
-1.90
-1.92
-1.94
34.6
34.7
34.8
34.9
Aug., 2015
HSSW
28
Sep., 2015
Oct., 2015
Aug., 2016
Sep., 2016
Oct., 2016
Aug., 2017
Sep., 2017
Oct., 2017

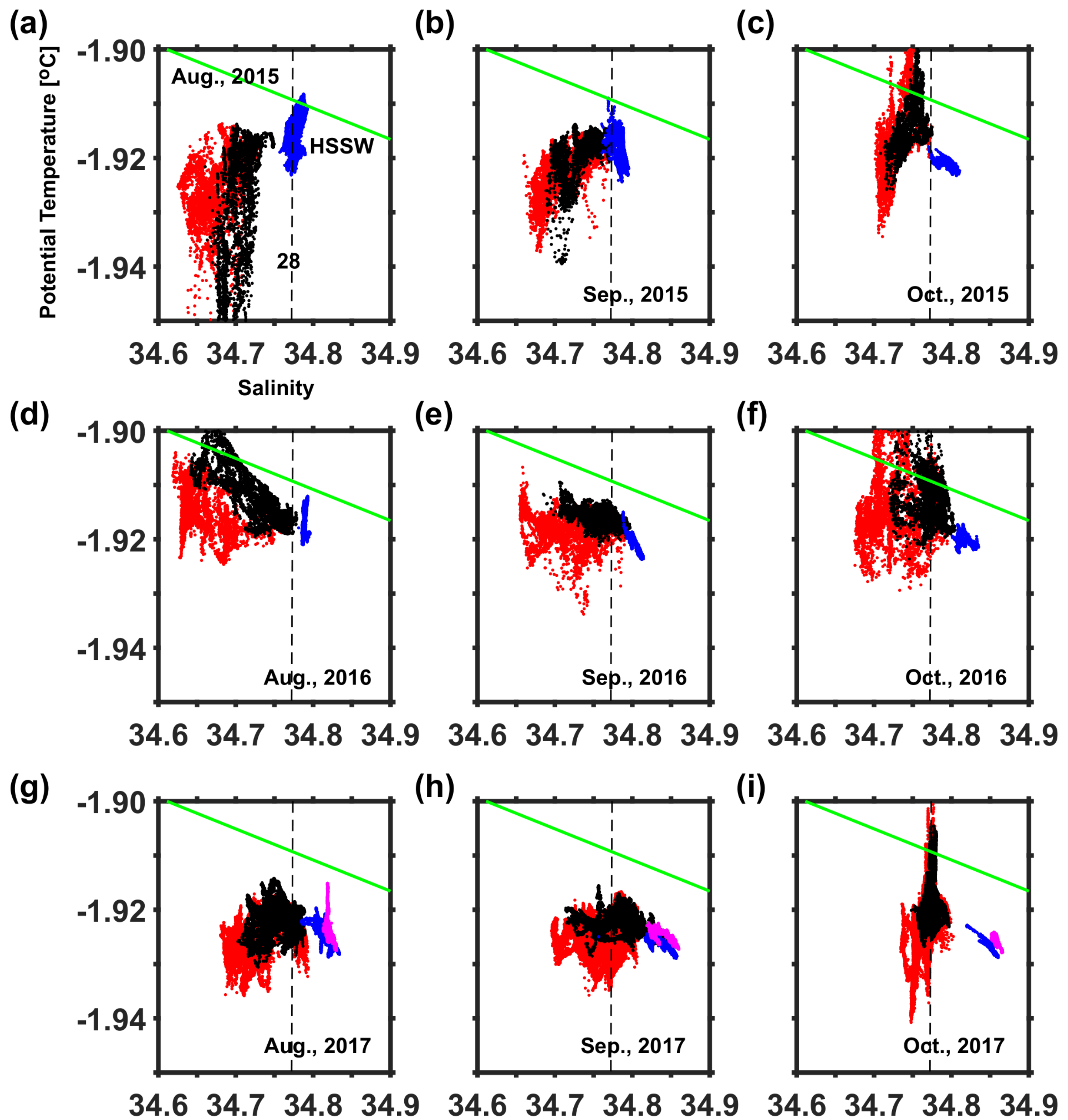
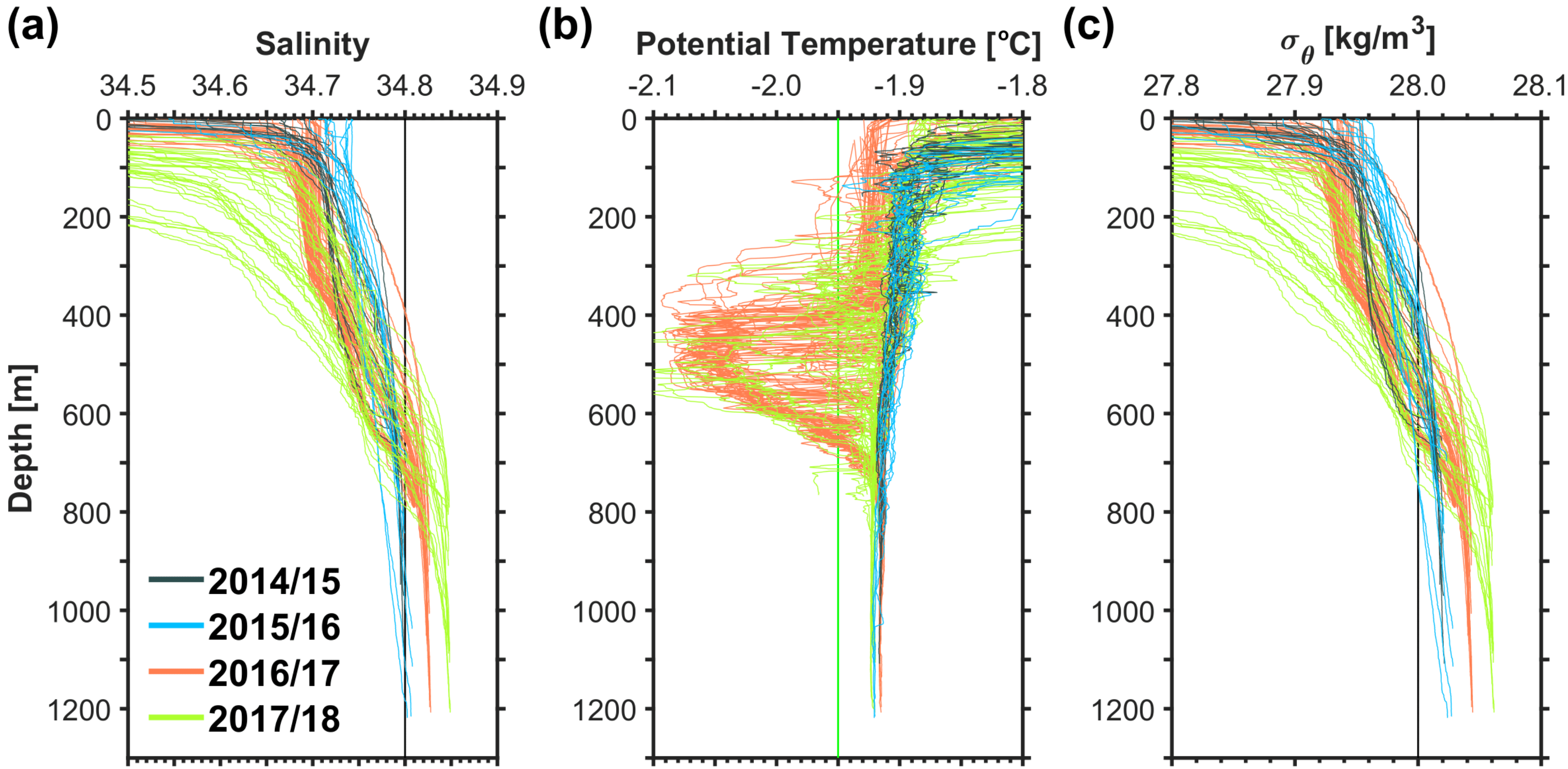


Figure 6: (a) A magnified version of the θ-S (potential temperature-~~–~~salinity) diagram for data from the DITN and DITD in August 2015. Red, black, and blue dots are θ-S at 75, 273, and 660 m, respectively. The green thin line denotes the freezing point at the surface~~50 m~~ depending on the salinity while~~, and~~ the black dashed line indicates $\sigma_\theta = 28.00$ kg m^{-3}. (b) The same as Fig. 6a, but for September 2015. (c) The same as Fig. 6a, but for October 2015. (d-~~–~~f) The same as Fig. 6a-~~–~~6c, but for August-~~–~~October 2016. (g-~~–~~i) The same as Fig. 6a-~~–~~6c, but for August-~~–~~October 2017. Magenta dots are θ-S at 1208 m.


(a)
Salinity
34.5
34.6
34.7
34.8
34.9
0
200
400
600
800
1000
1200
Depth [m]
2014/15
2015/16
2016/17
2017/18
(b)
Potential Temperature [°C]
-2.1
-2.0
-1.9
-1.8
(c)
σθ [kg/m3]
27.8
27.9
28.0
28.1

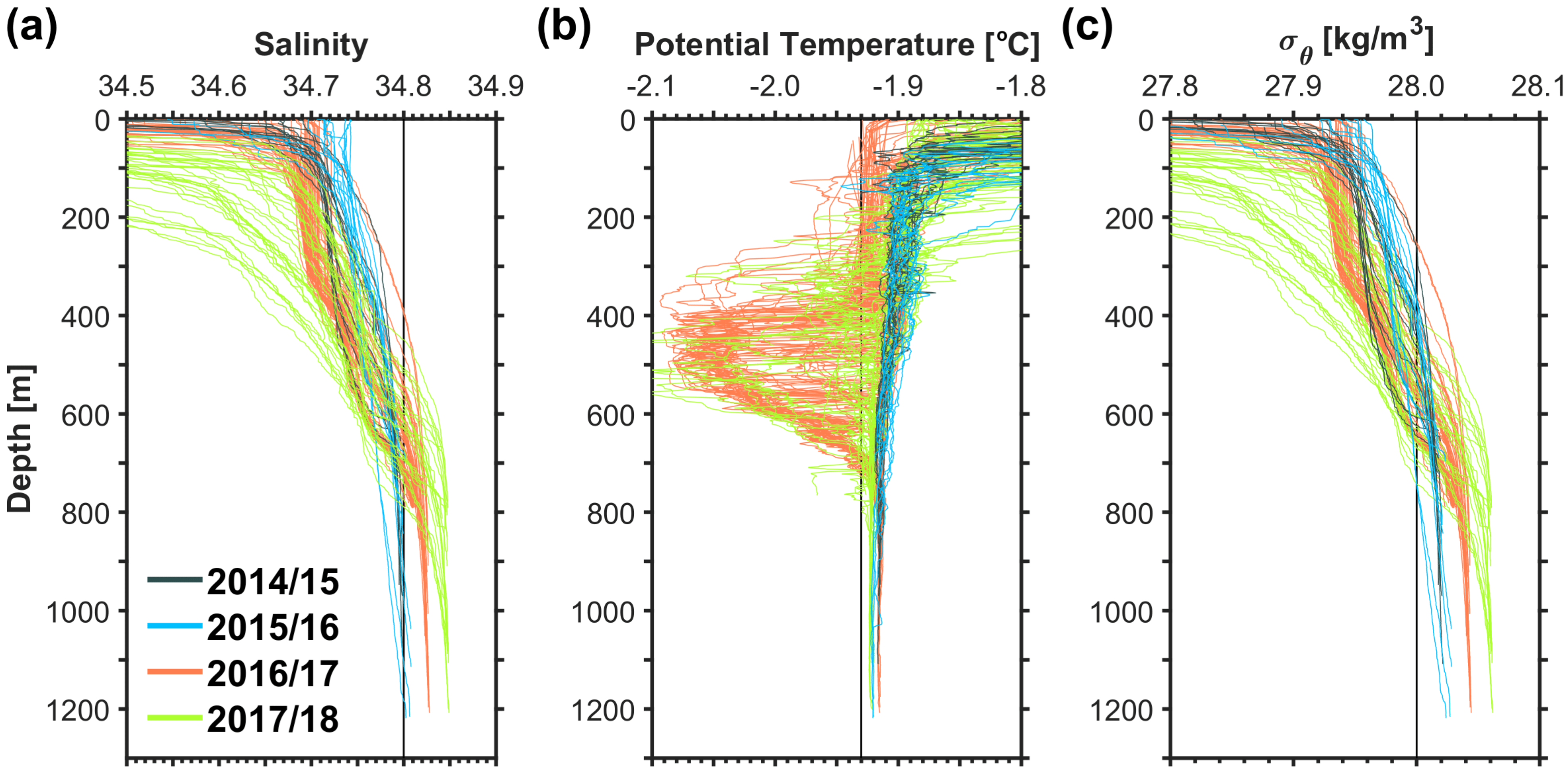


Figure 7: (a) Vertical salinity profiles at each observation period. The black solid line indicates 34.8 (b) The same as Fig. 7a, but for potential temperature, whereand the blackgreen solid line denotes –1.935°C. (c) The same as Fig. 7a, but for potential density (σ_θ), whereand the black solid line indicatemeans 28.0 kg m^{-3}

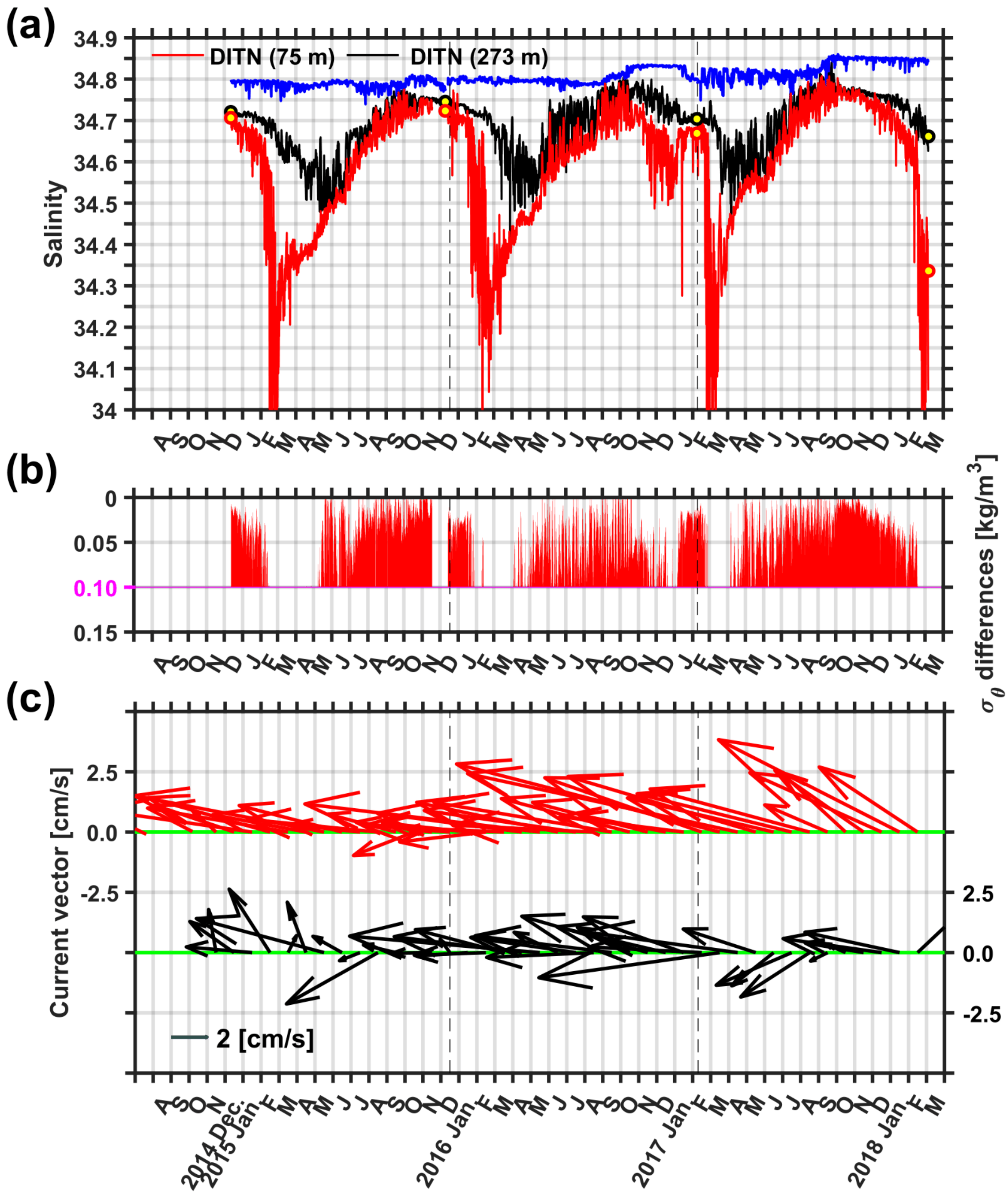
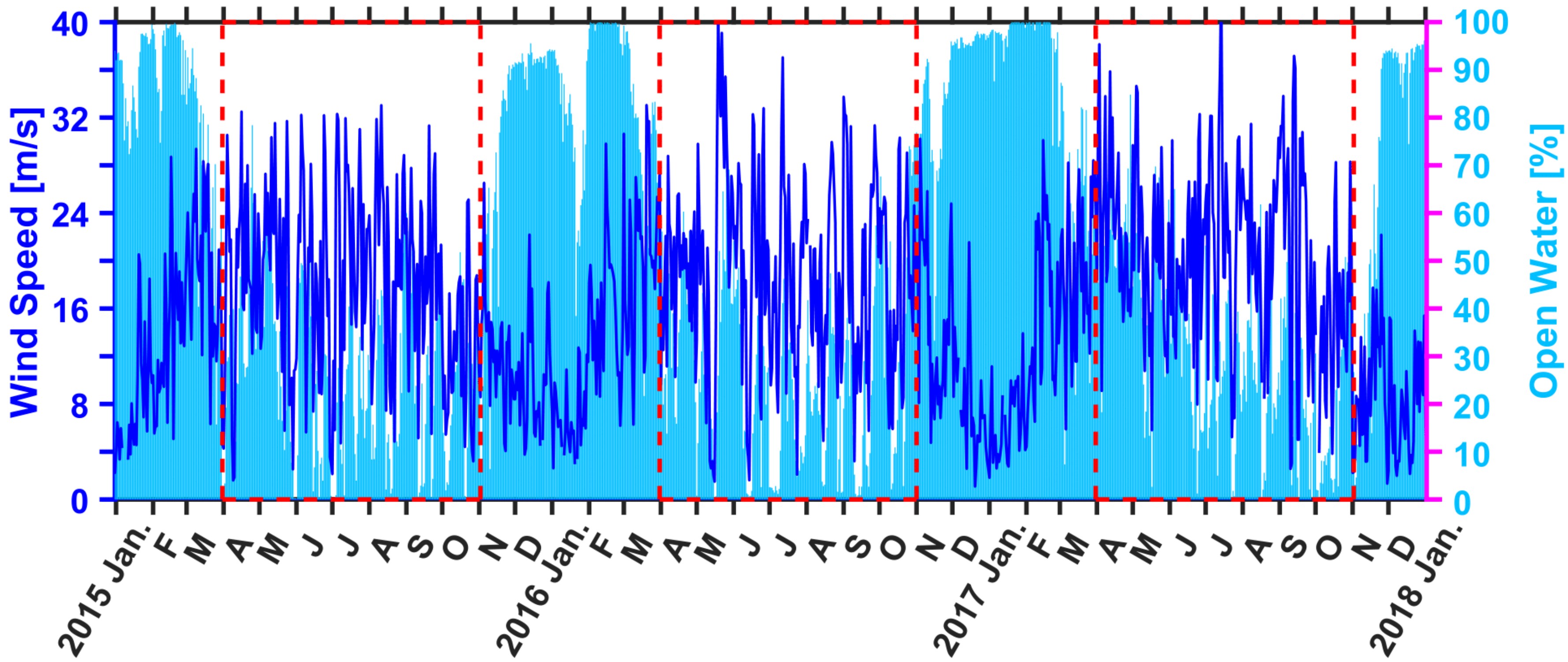


Figure 8: (a) Salinity time-series at three depths from the DITN. The red (black) circles filled with yellow are the averaged salinity in a 5-m layer at 75 (273) m obtained using CTD data observed near the DITN. The black dashed line divides periods of each leag at theof moorings (see details in Table. 1). (b) Potential density (σ_θ) differences lower than 0.10 kg m^{-3} forbetween σ_θ at 75 and 273 m. TheA 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.


Wind Speed [m/s]
Open Water [%]
40
32
24
16
8
0
100
90
80
70
60
50
40
30
20
10
0
2015 Jan.
F
M
A
M
J
J
A
S
O
N
D
2016 Jan.
F
M
A
M
J
J
A
S
O
N
D
2017 Jan.
F
M
A
M
J
J
A
S
O
N
D
2018 Jan.

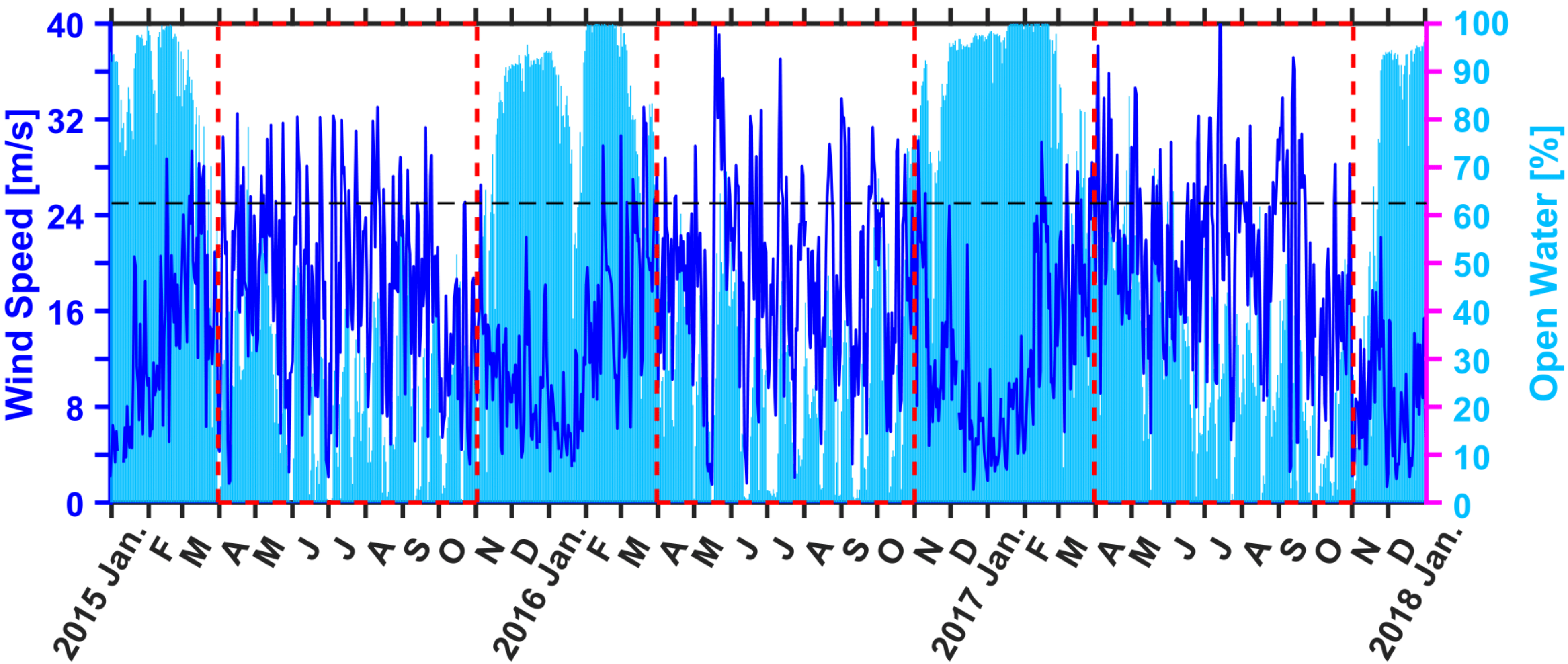
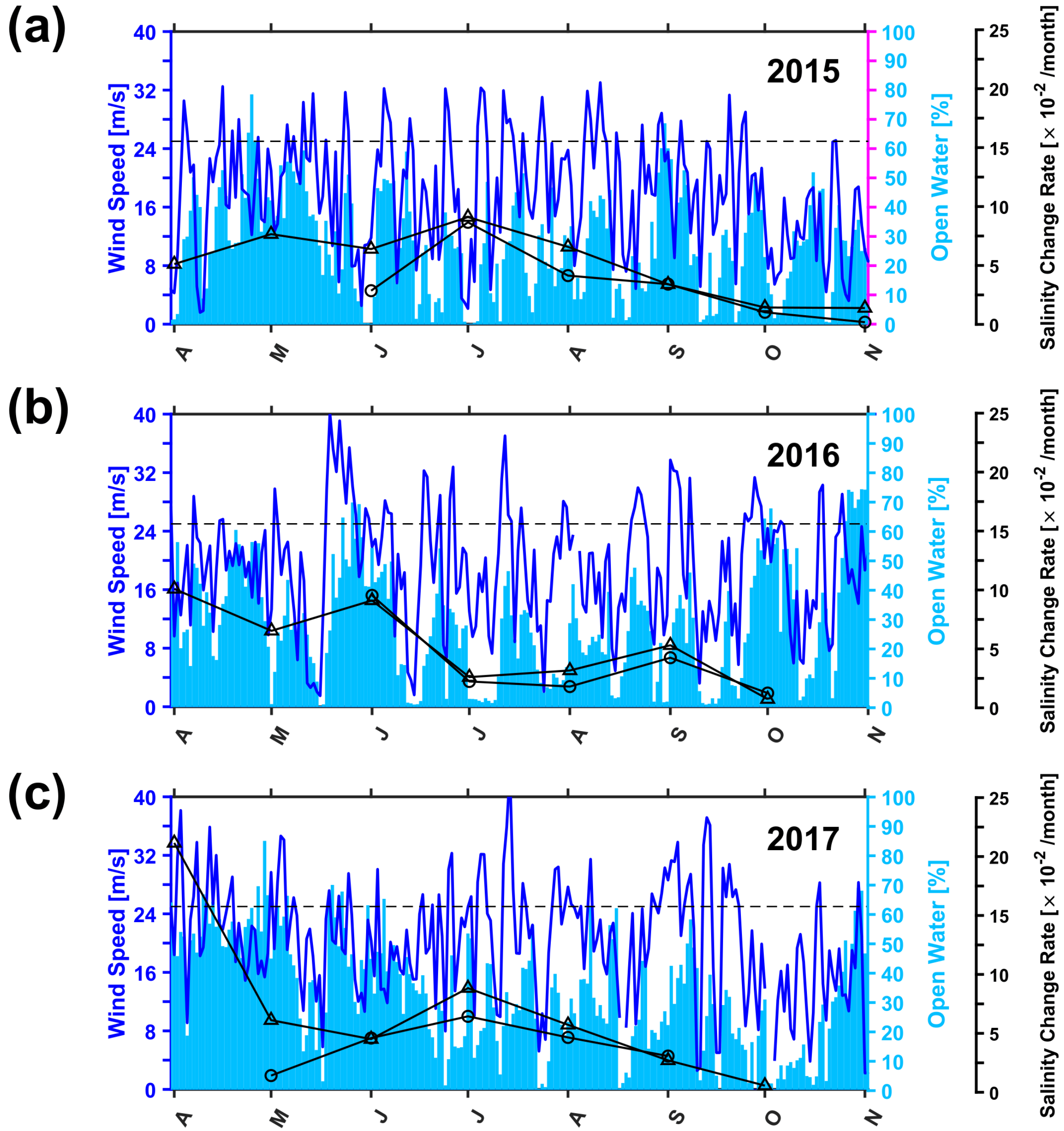


Figure 9: Time-series from 2015 to 2017 for daily eastward (225° < θ < 315°) wind speed from Manuela (blue line), as well as~~nd~~ the daily percentage of open water averaged from~~in~~ the~~a~~ black box shown in Fig. 4a (sky blue bar). Red dashed boxes indicate a time domain from April to October~~of Fig. 10a, 10b, and 10c~~. The black dashed line indicates a wind speed of 25 m s^{-1}~~ wind speed.~~



(a)
2015
Wind Speed [m/s]
Open Water [%]
Salinity Change Rate [× 10^-2 /month]
A M J J A S O N
(b)
2016
Wind Speed [m/s]
Open Water [%]
Salinity Change Rate [× 10^-2 /month]
A M J J A S O N
(c)
2017
Wind Speed [m/s]
Open Water [%]
Salinity Change Rate [× 10^-2 /month]
A M J J A S O N

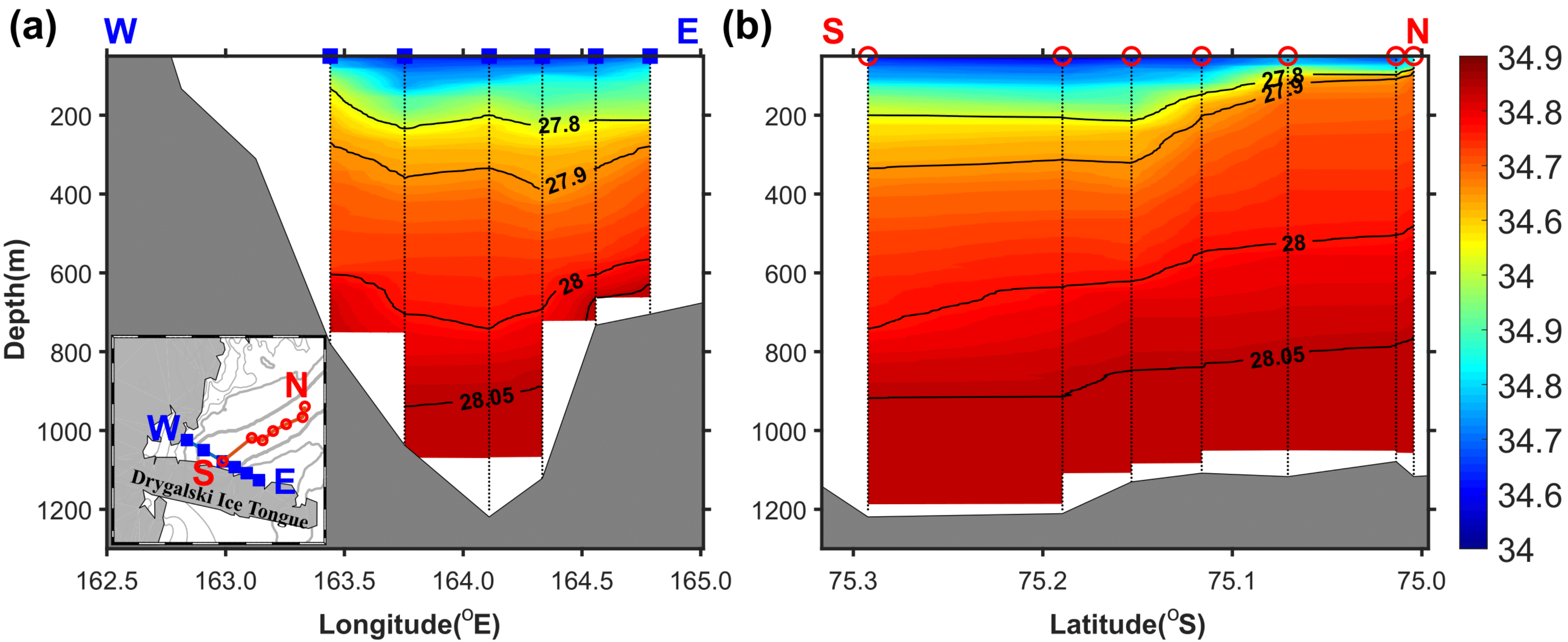
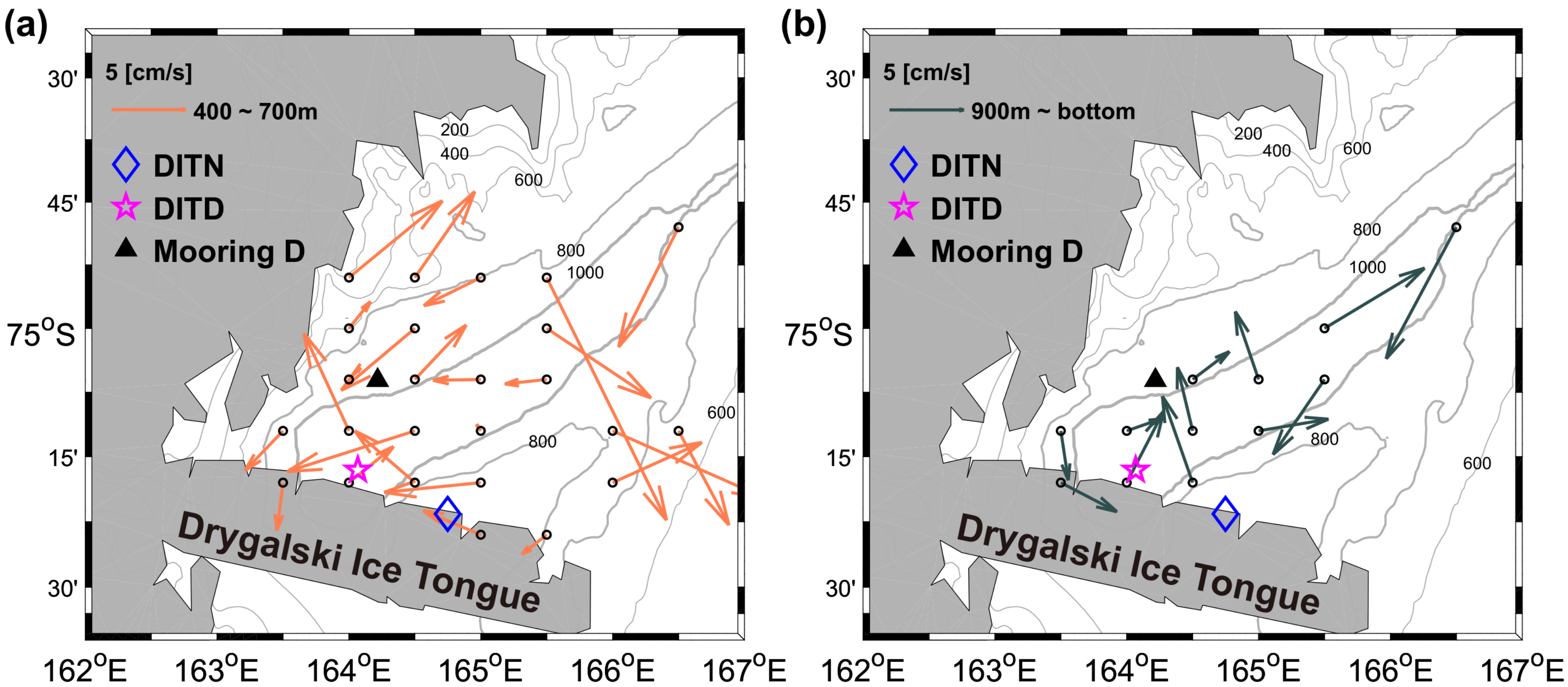


Figure 10: (a) The same as Fig. 9, but for the 2015 austral winter. The black triangle (circle) line indicates positive monthly salinity changes at 75 (273) m obtained by the salinity difference between two months Vertical section of salinity along the Drygalski Ice Tongue (blue-filled squares in the inset) observed during the 2017/18 survey. The colorbar for salinity is denoted in Fig. 10b and its interval is 0.01. The black contour lines indicate isopycnals (kg m^{-3}). (b) The same as Fig. 10a, but for the section along the Drygalski Basin (red circles in the inset of Fig. 10a).

. The black dashed line indicates 25 m s^{-1} wind speed. (b) The same as Fig. 10a, but for 2016. (c) The same as Fig. 10a, but for 2017.


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

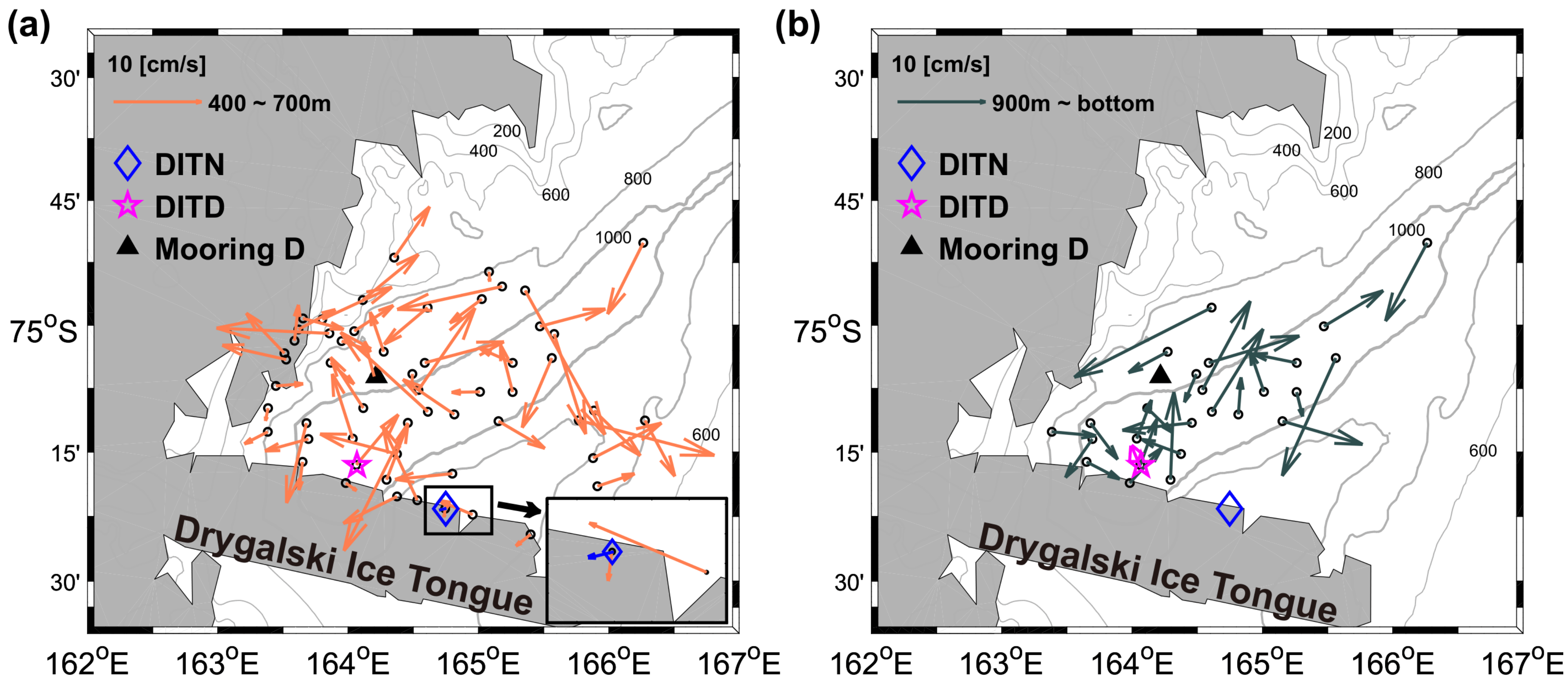


Figure 11: (a) Mean currents in a range of 400–700 m during four hydrographic surveys (see details in Table 1). The LADCP data from adjacent stations (< 3 km) are spatially ~~arranged by~~ averaged~~ing on a 0.5° × 0.1° grid~~. The black circles denote the LADCP stations. The averaged current vector from January to February at 660 m in the DITN is denoted by a blue arrow. The inset shows the current vectors near the DITN. (b) The same as Fig. 11a, but for the~~in a~~ range of 900 m–bottom. A magenta arrow shows the averaged current vector from January to February at 1,222 m in the DITD.

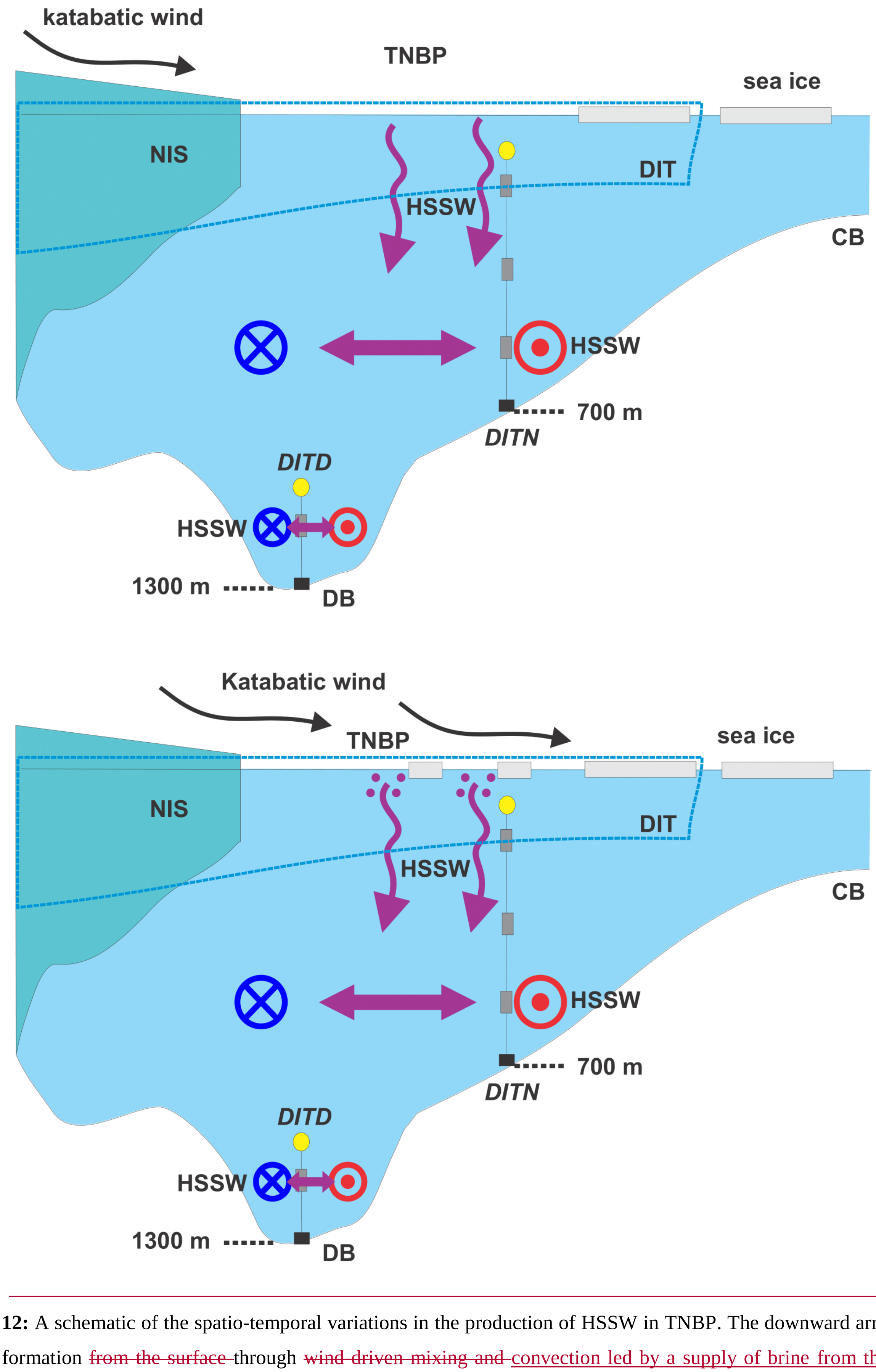


Figure 12: A schematic of the spatio-temporal variations in the production of HSSW in TNBP. The downward arrows show HSSW formation ~~from the surface~~ through ~~wind-driven mixing and~~ convection led by a supply of brine from the surface, which is related to polynya development via winds ~~operation~~. 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 ~~the deepest depth of the~~ Drygalski Basin (DITD) via cyclonic pattern flows in TNBP. The blue (red) circle represents outgoing~~incoming~~ (incoming~~outgoing~~) flow. DB, CB and DIT denote~~indicate~~ the Drygalski Basin, Crary Bank and Drygalski Ice Tongue, respectively.

Table 1. Information from~~or~~ 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~~'s~~ 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~~, Dec.~~ 2014	Full-depth CTD/LADCP cast	11	34.796 (± 0.001)
2015/16	Dec. 8–15~~, Dec.~~ 2015	Full-depth CTD/LADCP cast	10	34.791 (± 0.007)
2016/17	Jan. 26~~Jan.~~–Feb. 15~~, Feb.~~ 2017	Full-depth CTD/LADCP cast	37	34.822 (± 0.002)
2017/18	Mar. 4–13~~Mar.,~~ 2018	Full-depth CTD/LADCP cast	38	34.838 (± 0.005)

DITN	Period	Position	Depth [m]	Variables
1st leg	Dec. 12~~Dec.,~~ 2014–	75° 21' 37" S,	75 (S, R)	S: 10 min T, C, P

	Dec. 10,~~10 Dec.~~ 2015	164° 44' 58" E (Depth: 675 m)	275 (S, R) 660 (S, R)	R: 30 min U, V
2nd leg	Dec. 12~~Dec.~~, 2015– Feb. 08,~~ Feb.~~ 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~~Feb.~~, 2017– Mar. 06~~Mar.~~, 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~~Feb.~~, 2017– Mar. 06~~Mar.~~, 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