Reply on RC1

The authors estimated the turbulent heat flux in the Amundsen Sea Polynya region during summer using in situ atmospheric data collected aboard the RV Nathaniel B. Palmer. They observed episodic heat loss events triggered by the outflow of cold, dry air from the Antarctic continent. A comparison with turbulent heat flux data from ERA5 revealed that ERA5, with its relatively coarse spatial resolution of 0.25 degrees, did not accurately reproduce the turbulent heat flux in the ocean along the ice shelf edge, leading to an underestimation. Heat flux estimates based on in situ observations in the Antarctic coastal areas, particularly in coastal polynya regions, are rare, making this study a valuable contribution to the polar science community. The data and analysis methods employed in this study appear to be reasonable. However, I have the following concerns and look forward to the authors' responses and revisions to the manuscript.

We thank referee #1 for careful reading and insightful comments. Throughout this document the initial comments from referee #1 are in black and our answers in blue.

This study emphasizes the importance of estimating turbulent flux due to its impact on heat loss and sea-ice production in coastal polynyas (*e.g.*, P. 1, L. 2–, P. 2, L. 37–). While this is undoubtedly true during the winter months, this study is based on summer observations. In winter, the dominant heat flux component is turbulent heat flux, whereas in summer, it is shortwave radiation, as shown in Fig. C2. This distinction should be clearly described in the manuscript. During summer, coastal polynyas act as "meltwater factories" due to solar heating of the upper ocean through open water with low albedo, contrasting with their role as "ice factories" in winter (Ohshima et al. ,1998 and Morales Maqueda et al., 2004). Therefore, I do not suggest removing the descriptions of coastal polynyas but rather believe they should be described with care. In recent years, the Antarctic sea-ice extent during summer has been unusually small (Purich and Doddridge, 2023). A prolonged open-ocean period in summer, resulting from anomalous sea-ice retreat, leads to increased solar heating and warming of the upper ocean, with this heat anomaly potentially influencing subsequent ice advance (Nihashi and Ohshima, 2001; Stammerjohn et al., 2012). The key factor here remains shortwave radiation, though heat loss to the atmosphere in autumn and winter is driven by turbulent heat flux. In the Amery Ice Shelf area, a reduction in summer sea-ice extent has been found to weaken the formation of Antarctic Bottom Water (Aoki et al., 2022). This is because anomalously small summer sea-ice extent leads to increased solar heating of the ocean, which accelerates the melting of the ice shelves and the supply of freshwater to the coastal polynya area, limiting the production of dense shelf water. Again, the primary heat flux component here is shortwave radiation, but turbulent flux also contributes to the total heat flux. Given the significant changes occurring in the Antarctic sea ice, I believe that incorporating these perspectives could be valuable.

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- Morales Maqueda, M. A., A. J. Willmott, and N. R. T. Biggs (2004), Polynya dynamics: A review of observations and modeling. Rev. Geophys., 42, RG1004, doi:10.1029/2002RG000116.
- Purich, A. and E. W. Doddridge (2023), Record low Antarctic sea ice coverage indicates a new sea ice state. Commun. Earth Environ. 4, 314, doi:10.1038/s43247-023-00961-9.
- Nihashi, S. and K. I. Ohshima (2001), Relationship between the sea ice cover in the retreat and advance seasons in the Antarctic Ocean, Geophys. Res. Lett., 28, 3677–3689, doi: 1029/2001GL012842.
- Stammerjohn, S, R. Massom, D. Rind, and D. Martinson (2012), Regions of rapid sea ice change: An inter-hemispheric seasonal comparison. Geophys. Res. Lett. 39, L06501, doi:10.1029/2012GL050874
- Aoki, S., T. Takahashi, K. Yamazaki, D. Hirano, K. Ono, K. Kusahara, T. Tamura, and G. D. Williams (2022), Warm surface waters increase Antarctic ice shelf melt and delay dense water formation. Commun. Earth Environ. 3, 142, doi:10.1038/s43247-022-00456-z

We thank referee #1 for providing perspectives and references to improve the contextualization of our study. We took into account their suggestion:

- In the abstract we state that sea–ice formation and melting occur in polynyas (and not only sea–ice formation):

  Initial sentence:

  In coastal polynyas, where sea–ice formation occurs, it is crucial to have accurate estimates of heat fluxes in order to predict future rates of sea–ice formation.

  Updated sentence (change in black):

  P. 1, L. 2–3 in the revised manuscript: *In coastal polynyas, where sea–ice formation* *and melting occur,* *it is crucial to have accurate estimates of heat fluxes in order to predict future sea–ice* *dynamics.*

- In the introduction we add background on the Amundsen Sea Polynya (opening mechanism, contribution to sea–ice formation in winter and melting in summer, size):

P. 2, L. 36–38: *Polynyas are defined based on their opening mechanism. The ASP is a wind-driven latent heat polynya that forms along the coastline. It has a mean open water area in the austral summer of 27,333 km^2 +/- 8749 km^2 and an average open duration of 131.9 +/- 17.5 days over 1997–2010 (Arrigo et al., 2012).*

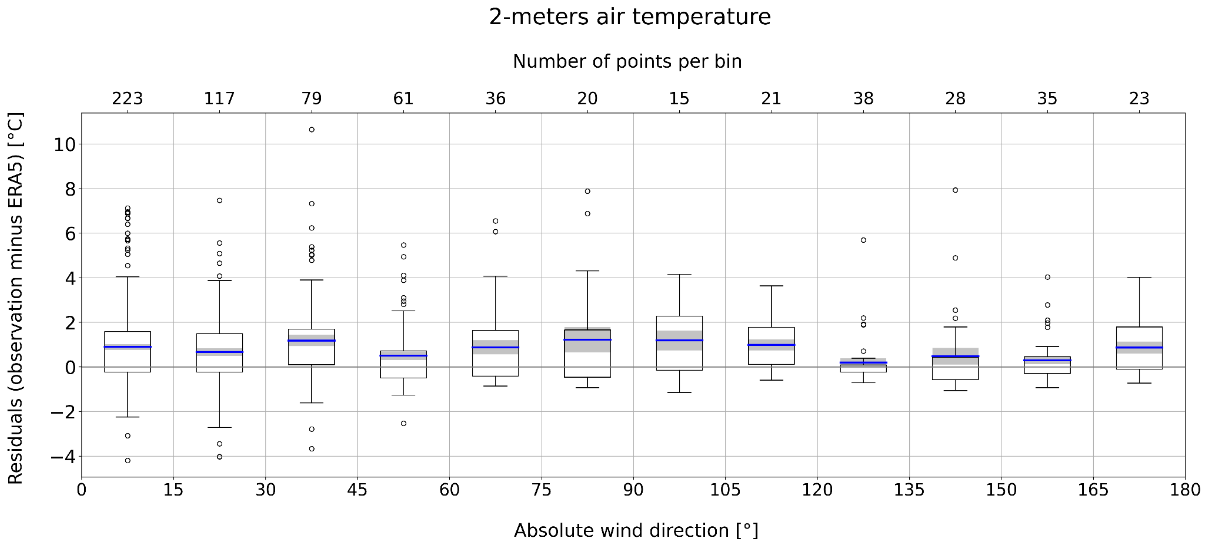
P. 2, L. 39–43: *During winter, shelf water latent heat polynyas like the ASP usually inherit the "sea–ice factory" nickname (Morales Maqueda et al., 2004, Ohshima et al., 1998) because sea–ice is continually created and conveyed away by winds or currents. On the other hand, in summer the latent heat polynyas are "ice–melting factories" as the low albedo of open–water compared to surrounding sea–ice favours solar heating, resulting in melting sea–ice.*

P. 2–3, L. 59–62: *The turbulent heat flux is the main air–sea heat flux component during winter, whereas the radiative component dominates during summer (Morales Maqueda et al., 2004). Despite the importance of the radiative component in summer, key atmospheric conditions could set the scene for important episodic heat loss events.*

- In the discussion we add a paragraph on the implications of our work for sea–ice using the literature suggested by referee #1 (P. 26-27, L. 391–409).

Temperature and wind speed are crucial parameters for determining turbulent heat flux. A comparison of in situ observed wind speed with ERA5 data is shown in Fig. A1. How about including a similar comparison for temperature? As a reader, I believe such a comparison would provide valuable insights.

Fig. A1 main objective is to investigate the wind distortion imposed by the superstructure of the research vessel on wind speed values using ERA5 as a reference (evaluate if the residuals are decreasing/increasing with wind direction). In the initial manuscript, we didn't expect a temperature bias related to the wind direction and therefore didn't perform a similar comparison. When we perform the same analysis, comparing the ERA5 2-meter air temperature with the 2-m height adjusted air temperature from the research vessel show that there is indeed no bias in the 2-meters air temperature dependent on the wind direction (see Figure below).



However, as highlighted in the comment, Fig. A1 also shows a comparison of in situ observed wind speed with ERA5 (even if it wasn't the main point of this figure). Such comparison was not included in our study for air temperature. We do agree that a comparison between ERA5 and in situ observations would provide valuable insights. Such comparison has already been carried out in the Amundsen Sea by Jones et al., 2016 between in situ observations and ERA-Interim. We find biases with the same order of magnitude. We add the Figure below in the Appendix (Fig. D1) and discuss it in the subsection *4.2 Assessing ECMWF turbulent heat flux in the Amundsen Sea* (P. 26, L. 373–374): (the black sentence below is added, text in blue is copied for context)

Jones et al. (2016) evaluated the performance of four reanalyses products in the Amundsen Sea, and showed that ERA-Interim has a cold bias in the air temperature and a dry bias in the specific humidity, which is greater near the ice shelves and weaker far from the coast. As a consequence, they hypothesize that the heat loss would be overestimated. This hypothesis has been verified in our work with the bias found (Table 4) in ERA5 hybrid fluxes (computed from the atmospheric and sea surface ERA5 variables). This bias indeed arises from a cold and dry bias in ERA5 air and humidity (Figure D1b, c).

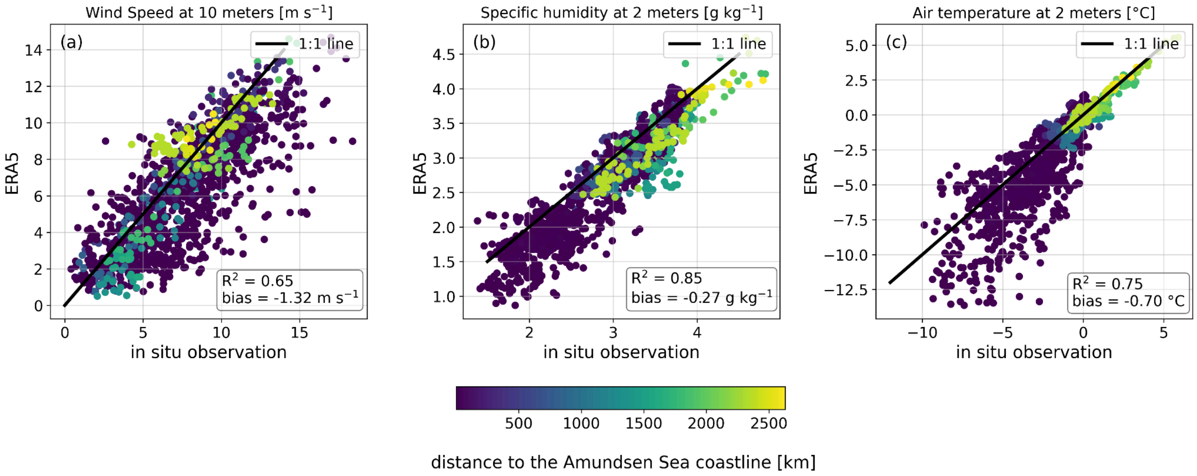


Figure D1: Comparison of (y-axis) ERA5 and (x-axis) in situ observations for (a) wind speed at 10 meters, (b) specific humidity at 2 meters and (c) air temperature at 2 meters. The in situ observations were adjusted down to 10 and 2 meters thanks to AirSeaFluxCode which applies a logarithmic adjustment and stability functions to account for atmospheric stability. To determine specific humidity from ERA5, we convert the dewpoint temperature to specific humidity using the saturation vapour pressure function of Buck (2012). The scatters are coloured by the distance to the Amundsen Sea coastline in kilometers, that is defined as the closest coast point in the region lat = [73.66 ; 75.27]°S, lon = [108.10 ; 122.64]°W to the ship position.

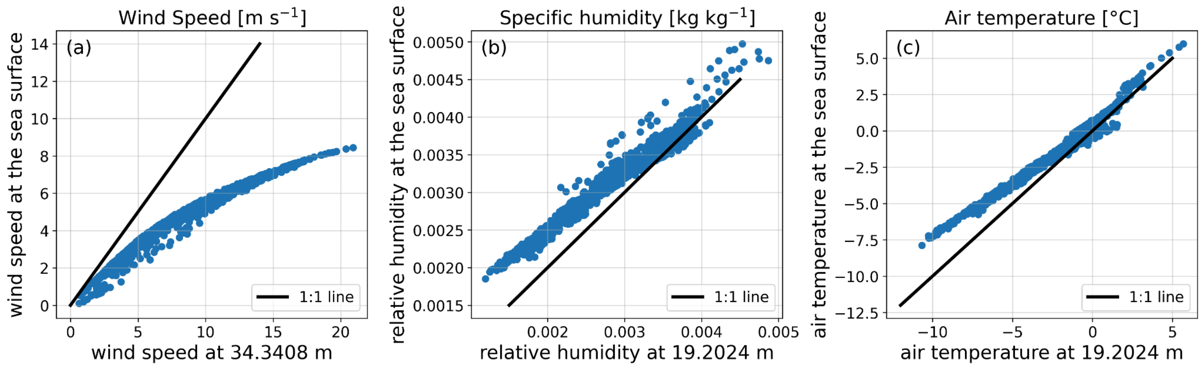
In Fig. A1, the wind speed from in situ observations is higher than that from ERA5. Could this discrepancy be due to the difference in observation heights, with the ship's measurements taken at 34.4 m (Table 1) and ERA5's at 10 m? A similar consideration applies to temperature: the ship's observations are taken at 19.2 m, while ERA5's are at 2 m. I suspect there may also be a bias in the temperature data. I believe the impact of these biases in wind speed and temperature on the turbulent heat flux estimates should be quantitatively discussed.

The sensor's heights (for in situ observations) or variable heights (for ERA5 data) of humidity, temperature and wind speed are input parameters of AirSeaFluxCode that need to be provided by the user. AirSeaFluxCode then computes the transfer coefficient $C_t(z_u,z_m)$ and $C_q(z_u,z_m)$ corresponding to the height z_u of wind speed measurement and the height z_m of humidity and temperature measurement using logarithmic corrections (we refer to Equations 1 and 3 of Biri et al., 2023). Any bias resulting from difference in observation heights is thus prevented.

The logarithm correction was very briefly explained on page 6, L. 95 of the initial manuscript, but only for the wind. We thank the reviewer for pointing out this lack of precision regarding the method used. We update Eq. (1) and (2) to make it clear that the transfer coefficients depend on the measured height of temperature, humidity and wind speed. The following sentence is also added to the manuscript (P. 7, L. 121–122):

> *The AirSeaFluxCode applies a logarithmic correction in the transfer coefficient definitions ($C_t(z_m, z_u)$and $C_q(z_m, z_u)$) to account for the height z_u of wind speed and z_m of air temperature and humidity measurements (Biri et al., 2023)*

AirSeaFluxCode allows the output of humidity, air temperature and wind speed at a reference height chosen by the user. For the example, we show below scatter plots of before (x-axis) and after (y-axis) the height correction from the sensors height (indicated in Table 1 of the manuscript) to 0.1 meters for (a) wind speed (b) specific humidity and (c) air temperature of the in situ data.



Regarding the estimation of turbulent flux (Eqs. 1 and 2), the influence of atmospheric stability on the heat transfer coefficient should be mentioned in this manuscript, even though it is discussed in the cited paper.

The following sentence is added to the manuscript (P. 7, L. 122–123): *“Atmospheric stability is accounted for in the definition of the transfer coefficients C_t and C_q through stability functions“.*

Furthermore, since this study primarily focuses on the open ocean area of the summer coastal polynya region, I believe the influence is minimal. However, turbulent flux is also estimated in the sea-ice area (Fig. 3). In regions where sea ice and open water coexist, the estimation of turbulent flux is complicated by the significant thermal contrast between the sea ice, which acts as an insulator, and the open water. Additionally, considering atmospheric stability in such areas is challenging. How was the insulating effect of sea ice accounted for in the estimation of turbulent flux in this study?

We thank the reviewer for raising this oversight. We didn’t account for the insulating effect of sea ice in the initial manuscript due to the low importance of flux variability in sea ice for our study. To account for the reduced flux imposed by sea ice cover, we modify the initial flux computation by scaling the turbulent fluxes by the fraction of sea–ice concentration A when A > 15 % (Eqs. (3), (4) and (5)). For instance, the sensible heat flux would be modified in the presence of sea ice using (1-A)*SHF, where A is the fraction of sea ice coverage and SHF is the sensible heat flux. We add the following sentences (P. 7, L. 131–134) to clarify this in the manuscript.

> *To account for the insulating effect of sea–ice we scale the turbulent fluxes by the sea–ice concentration (SIC) when SIC ≥ 15 % (Eq. (3), (4) and (5)). We acknowledge that this is a simplified method to account for sea–ice effect on turbulent fluxes, but accept this considering the little time spent by the RV in sea–ice covered area (3 days out of 57) and low importance of the flux variability in sea-ice for the results of this study.*

Minor comment:

1. 1, L. 3–: "The Amundsen Sea Polynya is the fourth largest coastal polynya ..." Is this referring to the size of the polynya or the sea-ice production?

This is referring to the size of the polynya and was obtained from Mu et al. (2014). However upon closer inspection we find their paper reference Arrigo et al., 2012 to provide the Amundsen Sea Polynya area but did not reference any sources that ranked Antarctic polynyas by size. For that reason, we remove this from our manuscript.

1. 1, L. 5: "NBP22/02" This expression makes sense to readers familiar with the observations by RV Nathaniel B. Palmer but is confusing to those who are not. It would be better to be more specific. Additionally, the description of the ship observation data begins on P. 2, L. 54, but the specific ship name does not appear until P. 3, L. 63. The ship name should be described earlier.

The acronym NBP22/02 was removed from the abstract and the specific ship name now appears at the beginning of the observations data section.

1. 6, L. 98: "... a heat loss (gain) for the ocean surface." would be appropriate.

It has been modified.

1. 7, L. 118: "... fresh water flux ..." During summer, the freshwater supply from melting sea ice is significant. Does this study consider that, or only precipitation?

The freshwater flux takes into account the evaporation and precipitation (P-E). The precipitation is an input of the PWP model whereas the evaporation is computed by the PWP model using the latent heat flux. We consider that sea–ice (which was already anomalously low in 2022) had already melted by the time the observations began and their impacts on sub-daily freshwater change is negligible over the time span of the research vessel stay in the Amundsen Sea. We add the following sentences on P. 8-9, L. 160–163:

The input freshwater flux only contains precipitation and evaporation, freshwater input from melting sea–ice was not considered in this study. We consider this reasonable as 2022 was a record-low sea–ice year (Turner et al., 2022; Yadav et al., 2022), and most of the sea–ice melt had already occurred in the polynya region (https://data.seaice.uni-bremen.de/databrowser/).

1. 8, Fig. 2c: It would be helpful if you could show the freezing point. Furthermore, since temperatures below 0°C are important, I would appreciate it if you could display them in a taller figure.

Fig. 2 has been updated.

References:

Arrigo, K.R., Lowry, K.E. and van Dijken, G.L., 2012. Annual changes in sea ice and phytoplankton in polynyas of the Amundsen Sea, Antarctica. *Deep Sea Research Part II: Topical Studies in Oceanography, 71,* pp.5-15.

Biri, S., Cornes, R.C., Berry, D.I., Kent, E.C. and Yelland, M.J., 2023. AirSeaFluxCode: Open-source software for calculating turbulent air-sea fluxes from meteorological parameters. *Frontiers in Marine Science, 9,* p.1049168.

Buck, A.L., 1996. Model Cr-1a hygrometer with autofill operating manual. *Buck Research Instruments LLC: Aurora, CO, USA*.

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Mu, L., Stammerjohn, S.E., Lowry, K.E. and Yager, P.L., 2014. Spatial variability of surface p CO2 and air-sea CO2 flux in the Amundsen Sea Polynya, Antarctica. *Elementa*, *3*, p.000036.

Turner, J., Holmes, C., Caton Harrison, T., Phillips, T., Jena, B., Reeves‐Francois, T., Fogt, R., Thomas, E.R. and Bajish, C.C., 2022. Record low Antarctic sea ice cover in February 2022. *Geophysical Research Letters*, *49*(12), p.e2022GL098904.

Yadav, J., Kumar, A., Srivastava, A. and Mohan, R., 2022. Sea ice variability and trends in the Indian Ocean sector of Antarctica: Interaction with ENSO and SAM. *Environmental Research*, *212*, p.113481.