PHILOSOPHICAL
TRANSACTIONS A

royalsocietypublishing.org/journal/rsta

Opinion piece

Cite this article: Tamsitt V. 2023 New insights into air-sea fluxes and their role in Subantarctic Mode Water formation. *Phil. Trans. R. Soc. A* **381**: 20220066.
https://doi.org/10.1098/rsta.2022.0066

Received: 29 July 2022
Accepted: 6 October 2022

One contribution of 13 to a discussion meeting issue 'Heat and carbon uptake in the Southern Ocean: the state of the art and future priorities'.

Subject Areas:
oceanography

Keywords:
air-sea fluxes, Subantarctic Mode Water, ocean observing, mooring time series, water mass formation

Author for correspondence:
V. Tamsitt
e-mail: veronica.tamsitt@gmail.com

THE ROYAL SOCIETY
PUBLISHING

New insights into air-sea fluxes and their role in Subantarctic Mode Water formation

V. Tamsitt

College of Marine Science, University of South Florida,
St. Petersburg, FL, USA

VT, 0000-0001-8816-2239

The formation of Subantarctic Mode Water SAMW in the Southern Ocean plays a key role in the global oceanic uptake and storage of anthropogenic heat and carbon. Wintertime ocean surface heat loss is a dominant driver of Subantarctic Mode Water formation and variability, but wintertime air-sea flux observations in the Southern Ocean are extremely sparse. Recent advances in our understanding of the role of air-sea fluxes in Subantarctic Mode Water Formation from novel ocean observations are summarized here, particularly the role of synoptic atmospheric extreme events, and the drivers of interannual variations in SAMW. These advances in understanding have important implications for variability in Southern Ocean heat and carbon uptake, and can inform future Southern Ocean observing system design.

This article is part of a discussion meeting issue 'Heat and carbon uptake in the Southern Ocean: the state of the art and future priorities'.

1. Introduction

In the wintertime in the Southern Ocean, thick homogeneous layers of well-mixed waters up to 700 m deep form on the northern flank of the Antarctic Circumpolar Current (ACC) in the Indian and Pacific sectors. These thick layers of well-ventilated water subduct into the ocean interior and spread northward, ventilating the subtropical thermocline. This water mass has a relatively large volume compared with surrounding water masses, and thus is referred to as Subantarctic Mode Water (SAMW) [1]. SAMW, together with underlying Antarctic Intermediate Water (AAIW), which is denser than SAMW and generally characterized by a salinity

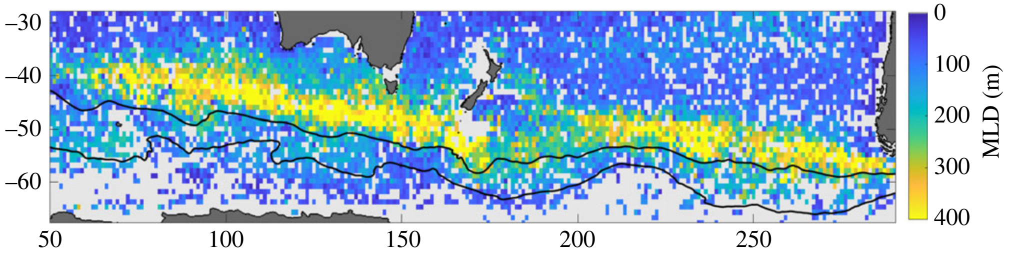

Figure 1. Climatological September mixed layer depth (m) using gridded Argo float data from [6]. Black lines show the approximate positions of the Subantarctic and Polar Fronts from [7]. Yellow regions north of the Subantarctic Front with mixed layers in excess of 300 m show the SAMW formation regions. (Online version in colour.)

minimum [2], form the northward moving component of the upper branch of the Southern Ocean overturning circulation.

SAMW and AAIW are important in the uptake and storage of anthropogenic heat and carbon, with approximately 70% of anthropogenic heat uptake and 40% of the anthropogenic carbon dioxide uptake occurring in the Southern Ocean [3,4]. Additionally, the nutrients supplied to the low latitude thermocline from the Southern Ocean are estimated to fuel three-quarters of the biological production north of 30°S [5].

The maximum mixed layer depth (MLD), which occurs at the end of Austral winter (figure 1), is a strong determinant of the volume of SAMW formed in a given year, and hence the relative amount of carbon and heat subducted into the ocean interior [8,9]. As a result, wintertime processes that drive mixed layer deepening control SAMW formation. Among these processes, wintertime ocean heat loss [10,11], and Ekman transport of relatively cold, fresh water northward across the Subantarctic Front [12], are the dominant processes controlling the mixed layer deepening. Several other processes have been found to contribute to SAMW formation, including freshwater fluxes [13,14], eddy heat diffusion [15], upwelling [16], diapycnal ocean mixing [17] and eddy-driven jet scale overturning circulation [18]. Yet, due to the wild wind and wave conditions of the open Southern Ocean, wintertime processes are the most difficult to measure, and as such very few wintertime observations of air-sea fluxes exist [19,20].

In situ observations of surface variables needed to estimate air-sea fluxes of heat, freshwater and momentum using bulk formulae require simultaneous measurements of the surface ocean and overlying atmosphere (air and sea surface temperature, specific humidity, air density, wind speed, surface current speed, shortwave and longwave radiation, evaporation and precipitation) [21]. Until recently, these observations have been largely limited to measurements collected aboard research vessels. As a result, open Southern Ocean air-sea flux measurements are sparse year round, and almost non-existent in winter [19,20]. In regions covered by sea-ice seasonally and where ship access is difficult, the data coverage is even poorer, but is of great importance and has been shown to influence the downstream production of SAMW to the north [22]. In the SAMW formation regions in the Southeast Indian and Southeast Pacific sectors, targeted ship-based process studies have allowed for more spatially and temporally dense sampling, particularly the Southeast Pacific SAMW, revealing the relative importance of different processes in SAMW formation [10]. Additionally, the multi-decadal time series of Argo float data has allowed a recent boom of research into interannual variability [23–25] and decadal trends [25,26] of SAMW. This has revealed a significant increase in the volume and change in properties of SAMW, with implications for the future uptake of carbon and nutrients in SAMW [25,26].

Over the past 12 years, a combined engineering effort and large scientific investment has resulted in two multi-year surface flux mooring deployments in the Southern Ocean. The Southern Ocean Flux Site (SOFS) mooring has been deployed annually southwest of Tasmania in the Indian SAMW formation region since 2010 and is ongoing [27]. The Ocean Observatories

Initiative (OOI) mooring, the southernmost surface flux mooring ever deployed, was deployed at 55°S southwest of South America from 2015 to 2020 [28].

These two overlapping mooring time series offer a unique opportunity to investigate high- and low-frequency temporal variability in air-sea fluxes and SAMW formation, validate satellite-based air-sea flux products and weather predictions, and give insight into future observational needs for better constraining air-sea fluxes in the Southern Ocean [23,27,28]. In particular, these moorings offer a window into the role of wintertime air-sea heat loss events associated with synoptic storms in driving variability in MLDs and subsequent SAMW formation.

In §2, the key role of synoptic extreme events on air-sea fluxes and consequent SAMW formation is described. The drivers of interannual variability in fluxes and SAMW formation and the implications for carbon and nutrient transport are discussed in §3. Finally, §4 discusses implications for future ocean observing system design.

2. The role of high-frequency events in air-sea heat flux and SAMW formation

Mooring time series of air-sea fluxes in the Southern Ocean show that the wintertime heat loss is characterized by extreme heat loss events occurring on timescales of a few days, driven by atmospheric storm systems [23,28]. These heat loss events are dominated by the turbulent heat flux, which is a combination of sensible heat flux (dependent on air-sea temperature difference) and latent heat flux (dependent on the air-sea humidity difference), both of which are modulated by wind speed [21]. Storms bring large temperature and humidity anomalies, which result in large air-sea gradients, which when combined with strong wind speeds drive strong turbulent ocean heat loss. As a result, the formation of SAMW in a given winter is inferred to be highly dependent on the frequency and intensity of extreme events.

Understanding the origin and transport of atmospheric storm events, and how this relates to the geography of the continental land masses surrounding the Southern Ocean, is useful for revealing the differences in wintertime ocean heat loss and SAMW formation in the Indian and Pacific SAMW regions. The frequency of winter extreme heat loss events was found to be higher at the SOFS mooring in the Southeast Indian than at the OOI mooring in the Southeast Pacific [23]. Two regimes of extreme heat loss events are present in the Southeast Indian as observed at the SOFS mooring: storms originating from the Australian continent carrying anomalously dry air to the region, and anomalously cold air carried in storms originating from Antarctica. In the Southeast Pacific, the absence of a landmass to the north and west restricts extreme turbulent heat loss events to a single regime of cold air from the south [23]. The extreme heat loss events that occur due to cold air advected from the south are typically associated with marine cold air outbreaks from the Antarctic continent, which are northward excursions of cold Antarctic air masses across the sea ice boundary [29]. Cold air outbreaks are linked to cyclone frequency, with a peak in winter, and explain a majority of extreme events in turbulent heat fluxes in the subpolar Southern Ocean, with their impact extending northward to the SAMW formation regions [29]. These regional differences emphasize the need for considering land masses and synoptic atmospheric processes in understanding wintertime ocean heat loss and SAMW formation variability.

Although the role of extreme events in heat loss variability is relatively well established, understanding on carbon fluxes is lacking. While analysis of SOFS mooring time series of mixed layer CO_2 partial pressure reveals variability due to synoptic extreme events [30], there have not been any further attempts to quantify the impact of storms on the total carbon flux variability at the SOFS mooring, and CO_2 fluxes at the OOI mooring have not been explored. Recent observations from Uncrewed Surface Vehicles emphasize the role of storms in mixed layer deepening and carbon fluxes in the subpolar Southern Ocean [31], but these results indicate that the impact of storm events on carbon fluxes is highly dependent on regional variations in the depth of the maximum winter mixed layer, and the vertical and horizontal gradients of dissolved inorganic carbon [31]. Further work is needed to understand the role of winter extreme events in the CO_2 uptake and storage within SAMW.

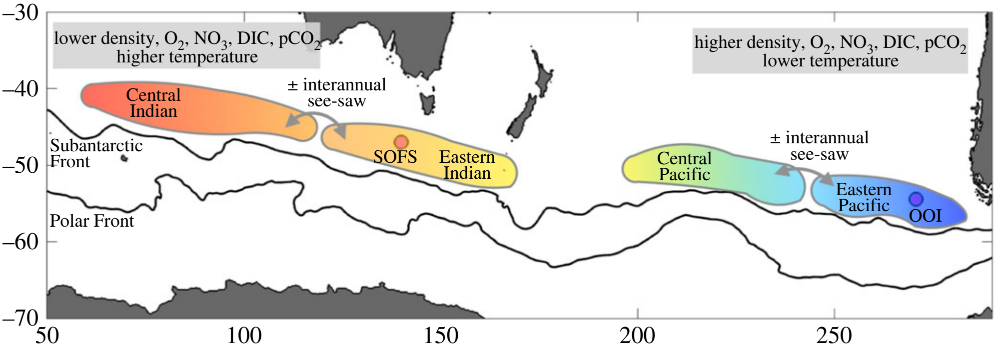

Figure 2. Schematic illustrating the location and relative physical and biogeochemical properties of each of the Central Indian, Eastern Indian, Central Pacific and Eastern Pacific SAMW formation pools. (Online version in colour.)

3. Interannual variability in SAMW formation

The maximum MLD and total formation of SAMW can vary greatly year to year, and on interannual timescales are modulated by climate modes including the El Niño Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) [11,16,22,32–34]. Interannual variability and trends in SAMW volume and formation is often analysed in an integrated view, summed either by basin or across both the Indian and Pacific SAMW regions. However, within each of the Indian and Pacific SAMW formation regions, strong regional differences are present in anomalies of air-sea heat fluxes, mixed layers, and water mass formation that are masked when integrating by basin. Therefore, regional analyses are essential for characterizing interannual variability in SAMW formation and properties.

Multiple recent independent analyses of mixed layer depths and SAMW formation using over a decade of Argo float data have shown a consistent dipole pattern of positive and negative anomalies in MLD or SAMW thickness within the central and eastern Pacific SAMW pools in a given year (figure 2) [23–25,35,36]. This dipole pattern is also evident in the central and eastern Indian SAMW formation regions [23,25,36]. In years with a deeper MLD and stronger SAMW formation in the eastern Pacific and weaker formation in the central Pacific, the dipole pattern tends to reverse in the following year, leading to what has been referred to as a ‘see-saw’ [24], or quasi-biennial variation [25] in mixed layers, SAMW thickness and SAMW subduction.

Much of this recent research effort has focused on identifying the role of major Southern Hemisphere climate modes, which drive changes in SAMW via anomalous air-sea fluxes and wind stress-induced Ekman transport and wind stress curl-induced Ekman upwelling [23–25,35,36]. One analysis of Argo data found that both the SAM and ENSO indices are positively correlated to SAMW thickness in the eastern Pacific SAMW pool and negatively correlated to SAMW thickness in the central Pacific SAMW pool. As a result, when SAM and ENSO are in phase, the dipole pattern in SAMW layer thickness is reinforced; when SAM and ENSO are out of phase, the anomalies in SAMW thickness are less coherent [24]. A separate analysis of Argo data found that MLD variability is modulated by the SAM via changes in wind stress curl-driven Ekman upwelling and wind stress-driven northward Ekman transport across the Subantarctic Front [25]. The Quasi-biennial Oscillation [37] may also be important for modulating the SAMW variability given the quasi-biennial variation seen in SAMW anomalies [38]. Analysis of a high-resolution ocean model was able to link basin scale changes to Rossby wave teleconnections emanating out of the tropical Pacific and Indian Oceans to the dipole in MLD anomalies in the central and eastern SAMW formation regions [35]. These results indicate an influence of tropical teleconnections on SAMW variability from the Indian Ocean (Indian Ocean Dipole) as well as ENSO.

There are significant quasi-stationary zonal asymmetries in the Southern Ocean zonal atmospheric flow, and these are mostly associated with wave number 1 and wave number 3 [39,40]. The Zonal Wave 3 index is strongly correlated to the SAM [41], and is also spatially correlated with the anomalies in mixed-layer depth and subsequent SAMW formation [23]. However, a mechanistic relationship between Zonal Wave 3 and SAMW variability has not been demonstrated. A significant drawback of using atmospheric pressure in these analyses is that they are defined as stationary, while the peaks and troughs of the non-zonal patterns in these modes (such as Zonal Wave 3) can propagate over time. Given the year to year see-saw nature of alternating anomalies, it is reasonable to hypothesize that propagating modes may be important in forcing this variability. A newly developed Zonal Wave 3 index using both the magnitude and the phase [42] could facilitate novel investigation of the role of propagating Zonal Wave 3 anomalies in SAMW formation.

Physical and biogeochemical properties differ between central and eastern SAMW pools, and as a result the interannual see-saw impacts heat and carbon uptake. The lightest, warmest, and lowest carbon and nutrient concentrations occur in the central Indian SAMW pool, with increasingly dense, salty, cool, and carbon- and nutrient-rich SAMW moving progressively to the east (figure 2) [43]. This anti-correlation between temperature and nutrients/carbon implies that the see-saw variability may have opposite impacts on heat and carbon uptake by SAMW: we would expect more heat uptake and storage in years with anomalously strong formation in the central Indian/Pacific SAMW (and weak formation in the eastern Indian/Pacific SAMW), but more carbon uptake in alternating years with stronger formation in the eastern Indian/Pacific SAMW. This hypothesis has not yet been tested, however as the data available from BGC Argo floats in SAMW formation regions increases over time, there will be opportunity to investigate the role of the SAMW see-saw in carbon uptake.

A notable result of these analyses is the consistency of the see-saw in MLD and SAMW anomalies observed from year to year. This suggests there may be an important role for ocean advection in the SAMW pools from the central SAMW formation region in the Indian/Pacific to the eastern SAMW formation region, preconditioning the downstream region for mixed layer deepening in the following winter. Analysis of the SAMW subduction supports this hypothesis, showing eastward propagation of these anomalies [25]. Given the complex coupling between the lower atmosphere and upper ocean, untangling the impact of ocean advection from atmospheric forcing is challenging. Forced experiments in a coupled ocean-atmosphere model could yield insight into the role of advection in interannual variability in SAMW.

Another open research question is how the frequency and intensity of synoptic storm events imprint on the major atmospheric modes, like the SAM. Typically SAM indices are diagnosed on monthly and seasonal timescales, but these mean wind conditions are the product of the frequency and intensity of synoptic atmospheric events. A recent analysis of Southern Ocean surface winds linked the SAM to cyclone intensity and extreme westerly winds [44]. The strengthened westerlies during positive SAM conditions lead to stronger northerly winds along the cold front of a low pressure system, while in negative SAM conditions the southeasterly winds on the western side of a low pressure system are enhanced [44]. These meridional wind anomalies drive large turbulent heat fluxes [23], and imply that atmospheric cyclones would lead to anomalously weak ocean heat loss (or ocean heat gain) in positive SAM conditions, and vice versa. This connection between the synoptic atmosphere, and the large-scale climate modes that are correlated to SAMW variability, is useful to move toward greater process-based understanding of what ultimately drives heat and carbon uptake in SAMW.

4. Implications for observing system design

Observations that capture synoptic temporal scales and sub-basin spatial scales are needed to improve process-based understanding of SAMW formation and the associated heat and carbon uptake. Importantly, the processes driving mixed layer deepening and SAMW formation occur predominantly in winter, highlighting the need for wintertime observations. Observing such high temporal frequencies simultaneously with regional spatial variations in winter in the Southern Ocean is a very challenging undertaking. However, the recent results reviewed here can provide some guidance on the needs of the future observing system.

Given the importance of high-frequency extreme heat loss events in SAMW formation, there is a need to maintain air-sea flux moorings over an extended time period. These data additionally provide a fixed reference point for comparison to floats observations, which can alias high-frequency synoptic events with the typical 10-day profiling rate. The availability of high-frequency *in situ* winds can also help validate flux calculations based on ocean measurements and satellite-derived winds. Mooring time series additionally offer an opportunity to evaluate the performance of reanalysis wind and flux products, and these data have been shown to improve regional weather prediction [28]. The SOFS mooring has now been redeployed continuously since 2010, and the continuation of this time series is crucial as decadal variability and trends begin to emerge from the extended time series.

Deploying a larger array of moorings would help constrain the variance in air-sea fluxes, and the placement could be optimized to capture separate central and eastern SAMW formation pools in the Indian and Pacific. As shown here the single SOFS mooring is not representative of the broader SAMW formation regions, and the flux variability in the SAMW formation regions is uniquely different from that further south in the Antarctic Circumpolar Current and Marginal Ice Zone, where no flux moorings have been deployed. Observing System Simulation Experiments are useful to inform the amount of variance captured in given mooring deployment locations [45]. However, maintaining a mooring array may be cost prohibitive, and Uncrewed Surface Vehicles [46] can offer a more affordable, dynamic platform to collect observations on broader spatial scales and close the wintertime gap in ship observations, and could piggyback on the existing mooring deployments.

Coupled atmosphere-ocean models must be used in tandem with expanded observations to maximize the value of the observations and better understand the processes governing air-sea fluxes and SAMW variability. The ongoing development of mesoscale and sub-mesoscale resolving (5 km or less horizontal resolution) coupled models [47] offer new opportunities to study air-sea fluxes at smaller spatial and time scales. For example, models could be used to untangle complex air-sea interaction processes occurring during high-frequency heat loss events that have been observed and understand the relative role of atmospheric forcing and ocean advection and mixing processes on mixed layer and SAMW formation variability on different timescales. Expanding observations of fluxes and water mass formation in the Southern Ocean are necessary to further improve model representation of these upper ocean processes, and in turn high-resolution models must be used to inform optimal observing system design.

Finally, more observations of biogeochemical properties and carbon fluxes in the SAMW formation regions are needed to understand the differences in uptake and transport of carbon and heat by SAMW. Biogeochemical float data are now allowing for an initial look at the carbon and nutrient characteristics of the different SAMW pools [43], but limited data coverage is an ongoing challenge. The continued growth of the global biogeochemical Argo program, ongoing mooring deployments, and increasing development and deployments of Uncrewed Surface Vehicles in the Southern Ocean in the wintertime will create an opportunity to greatly increase our ability to characterize the variability and controls on carbon uptake by SAMW.

Data accessibility. Mixed layer depth data from [6] are available for download from http://mixedlayer.ucsd.edu. Surface flux mooring data discussed in this review are available for download from https://portal.aodn.org.au (SOFS) and https://ooiui.oceanobservatories.org/data_access/#GS (OOI).

Authors' contributions. V.T.: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing—original draft, writing—review and editing.

Conflict of interest declaration. I declare I have no competing interests.

Funding. V.T. acknowledges support from NSF OPP 2048840, NSF OPP 2149500, and NOAA NA21OAR4310259.

Acknowledgements. V.T. would like to thank S. Bushinsky and I. Cerovečki for sharing work in progress, and L. Talley, I. Cerovečki, M. Mazloff, S. Gille, and S. Josey for many discussions and ideas on this topic.

References

1. Hanawa K, Talley LD. 2001 Mode waters. In *In ocean circulation and climate*. International Geophysics Series (eds G Siedler, J Church), pp. 373–386. Academic Press.
2. Talley L. 1996 Antarctic intermediate water in the South Atlantic. In *The South Atlantic* (eds G Wefer, WH Berger, G Siedler, DJ Webb), pp. 219–238. Berlin, Germany: Springer.
3. Ito T, Woloszyn M, Mazloff M. 2010 Anthropogenic carbon dioxide transport in the Southern Ocean driven by Ekman flow. *Nature* **463**, 80–83. (doi:10.1038/nature08687)
4. Frölicher TL, Sarmiento JL, Paynter DJ, Dunne JP, Krasting JP, Winton M. 2015 Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. *J. Clim.* **28**, 862–886.
5. Sarmiento JL, Gruber N, Brzezinski M, Dunne J. 2004 High-latitude controls of thermocline nutrients and low latitude biological productivity. *Nature* **427**, 56–60. (doi:10.1038/nature02127)
6. Holte J, Talley LD, Gilson J, Roemmich D. 2017 An Argo mixed layer climatology and database. *Geophys. Res. Lett.* **44**, 5618–5626. (doi:10.1002/2017GL073426)
7. Orsi AH, Whitworth T, Nowlin WD. 1995 On the meridional extent and fronts of the Antarctic Circumpolar Current. *Deep Sea Res. I* **42**, 641–673. (doi:10.1016/0967-0637(95)00021-W)
8. McCartney MS. 1982 The subtropical recirculation of mode waters. *J. Mar. Res.* **40**, 427–464.
9. Talley LD. 1999 Some aspects of ocean heat transport by the shallow, intermediate and deep overturning circulations. *Geophys. Monogr.-Am. Geophys. Union* **112**, 1–22.
10. Holte JW, Talley LD, Chereskin TK, Sloyan BM. 2012 The role of air-sea fluxes in subantarctic mode water formation. *J. Geophys. Res.: Oceans* **117**, C03040. (doi:10.1029/2011JC007798)
11. Naveira Garabato AC, Jullion L, Stevens DP, Heywood KJ, King BA. 2009 Variability of subantarctic mode water and Antarctic intermediate water in the Drake passage during the late-twentieth and early-twenty-first centuries. *J. Clim.* **22**, 3661–3688. (doi:10.1175/2009JCLI2621.1)
12. Rintoul SR, England MH. 2002 Ekman transport dominates local air–sea fluxes in driving variability of subantarctic mode water. *J. Phys. Oceanogr.* **32**, 1308–1321. (doi:10.1175/1520-0485(2002)032<1308:ETDLAS>2.0.CO;2)
13. Iudicone D, Speich S, Madec G, Blanke B. 2008 The global conveyor belt from a Southern Ocean perspective. *J. Phys. Oceanogr.* **38**, 1401–1425. (doi:10.1175/2007JPO3525.1)
14. Cerovečki I, Mazloff MR. 2016 The spatiotemporal structure of diabatic processes governing the evolution of subantarctic mode water in the Southern Ocean. *J. Phys. Oceanogr.* **46**, 683–710.
15. Sallée JB, Morrow R, Speer K. 2008 Eddy heat diffusion and subantarctic mode water formation. *Geophys. Res. Lett.* **35**, L05607. (doi:10.1029/2007GL032827)
16. Sallée J, Speer K, Rintoul S. 2010 Zonally asymmetric response of the Southern Ocean mixed-layer depth to the Southern Annular Mode. *Nat. Geosci.* **3**, 273–279.
17. Sloyan BM, Talley LD, Chereskin TK, Fine R, Holte J. 2010 Antarctic intermediate water and subantarctic mode water formation in the southeast pacific: the role of turbulent mixing. *J. Phys. Oceanogr.* **40**, 1558–1574. (doi:10.1175/2010JPO4114.1)
18. Li Q, Lee S. 2017 A mechanism of mixed layer formation in the Indo–Western Pacific Southern Ocean: preconditioning by an eddy-driven jet-scale overturning circulation. *J. Phys. Oceanogr.* **47**, 2755–2772. (doi:10.1175/JPO-D-17-0006.1)
19. Gille S, Josey S, Swart S. 2016 New approaches for air-sea fluxes in the Southern Ocean. *EOS* **97**. (doi:10.1029/2016EO052243)
20. Swart S *et al.* 2019 Constraining Southern Ocean air-sea-ice fluxes through enhanced observations. *Front. Mar. Sci.* **6**, 421. (doi:10.3389/fmars.2019.00421)
21. Large WG, Yeager SG. 2009 The global climatology of an interannually varying air–sea flux data set. *Clim. Dyn.* **33**, 341–364. (doi:10.1007/s00382-008-0441-3)
22. Cerovečki I, Meijers AJ, Mazloff MR, Gille ST, Tamsitt VM, Holland PR. 2019 The effects of enhanced sea ice export from the Ross Sea on recent cooling and freshening of the southeast Pacific. *J. Clim.* **32**, 2013–2035.
23. Tamsitt V, Cerovečki I, Josey SA, Gille ST, Schulz E. 2020 Mooring observations of air–sea heat fluxes in two subantarctic mode water formation regions. *J. Clim.* **33**, 2757–2777. (doi:10.1175/JCLI-D-19-0653.1)

24. Meijers A, Cerovečki I, King BA, Tamsitt V. 2019 A see-saw in Pacific subantarctic mode water formation driven by atmospheric modes. *Geophys. Res. Lett.* **46**, 13 152–13 160. (doi:10.1029/2019GL085280)
25. Qu T, Gao S, Fin RA. 2020 Variability of the sub-Antarctic mode water subduction rate during the Argo period. *Geophys. Res. Lett.* **47**, e2020GL088248.
26. Gao L, Rintoul SR, Yu W. 2018 Recent wind-driven change in subantarctic mode water and its impact on ocean heat storage. *Nat. Clim. Change* **8**, 58–63. (doi:10.1038/s41558-017-0022-8)
27. Schulz EW, Josey SA, Verein R. 2012 First air-sea flux mooring measurements in the Southern Ocean. *Geophys. Res. Lett.* **39**, 16606. (doi:10.1029/2012GL052290)
28. Ogle SE, Tamsitt V, Josey SA, Gille ST, Cerovečki I, Talley LD, Weller RA. 2018 Episodic Southern Ocean heat loss and its mixed layer impacts revealed by the farthest south multiyear surface flux mooring. *Geophys. Res. Lett.* **45**, 5002–5010. (doi:10.1029/2017GL076909)
29. Papritz L, Pfahl S, Sodemann H, Wernli H. 2015 A climatology of cold air outbreaks and their impact on air–sea heat fluxes in the high-latitude South Pacific. *J. Clim.* **28**, 342–364. (doi:10.1175/JCLI-D-14-00482.1)
30. Shadwick E, Trull T, Tilbrook B, Sutton A, Schulz E, Sabine C. 2015 Seasonality of biological and physical controls on surface ocean CO2 from hourly observations at the Southern Ocean time series site south of Australia. *Global Biogeochem. Cycles* **29**, 223–238. (doi:10.1002/2014GB004906)
31. Nicholson SA, Whitt DB, Fer I, du Plessis MD, Lebéhot AD, Swart S, Sutton AJ, Monteiro PM. 2022 Storms drive outgassing of CO_2 in the subpolar Southern Ocean. *Nat. Commun.* **13**, 1–12.
32. Close SE, Naveira Garabato AC, McDonagh EL, King BA, Biuw M, Boehme L. 2013 Control of mode and intermediate water mass properties in Drake passage by the Amundsen Sea Low. *J. Clim.* **26**, 5102–5123. (doi:10.1175/JCLI-D-12-00346.1)
33. Buongiorno Nardelli B, Guinehut S, Verbrugge N, Cotroneo Y, Zambianchi E, Iudicone D. 2017 Southern Ocean mixed-layer seasonal and interannual variations from combined satellite and *in situ* data. *J. Geophys. Res.: Oceans* **122**, 10 042–10 060. (doi:10.1002/2017JC013314)
34. Kwon EY. 2013 Temporal variability of transformation, formation, and subduction rates of upper Southern Ocean waters. *J. Geophys. Res.: Oceans* **118**, 6285–6302. (doi:10.1002/2013JC008823)
35. Li Q, England MH. 2020 Tropical Indo-Pacific teleconnections to Southern Ocean mixed layer variability. *Geophys. Res. Lett.* **47**, e2020GL088466.
36. Cerovečki I, Meijers AJ. 2021 Strong quasi-stationary wintertime atmospheric surface pressure anomalies drive a dipole pattern in the subantarctic mode water formation. *J. Clim.* **34**, 6989–7004.
37. Baldwin M *et al.* 2001 The quasi-biennial oscillation. *Rev. Geophys.* **39**, 179–229. (doi:10.1029/1999RG000073)
38. Lu Y, Talley L, Cerovecki I, Xie SP, Mazloff MR, Gille ST. 2019 Interannual variation of Southern Ocean deep mixed layers and subantarctic mode water: patterns and mechanisms. Submitted.
39. Raphael MN. 2004 A zonal wave 3 index for the Southern Hemisphere. *Geophys. Res. Lett.* **31**, L23212. (doi:10.1029/2004GL020365)
40. Schlosser E, Haumann FA, Raphael MN. 2018 Atmospheric influences on the anomalous 2016 Antarctic sea ice decay. *Cryosphere* **12**, 1103–1119. (doi:10.5194/tc-12-1103-2018)
41. Turner J, Orr A, Gudmundsson GH, Jenkins A, Bingham RG, Hillenbrand CD, Bracegirdle TJ. 2017 Atmosphere-ocean-ice interactions in the Amundsen Sea embayment, West Antarctica. *Rev. Geophys.* **55**, 235–276. (doi:10.1002/2016RG000532)
42. Goyal R, Jucker M, Gupta AS, England MH. 2022 A new zonal wave 3 index for the Southern Hemisphere. *J. Clim.* **35**, 5137–5149. (doi:10.1175/JCLI-D-21-0927.1)
43. Bushinsky S, Cerovečki I. 2023 Subantarctic Mode Water biogeochemical formation properties and interannual variability. *AGU Advances* **4**, e2022AV000722.
44. Hell MC, Cornuelle BD, Gille ST, Lutsko NJ. 2021 Time-varying empirical probability densities of southern ocean surface winds: linking the leading mode to SAM and quantifying wind product differences. *J. Clim.* **34**, 5497–5522.
45. Wei Y, Gille ST, Mazloff MR, Tamsitt V, Swart S, Chen D, Newman L. 2020 Optimizing mooring placement to constrain southern ocean air–sea fluxes. *J. Atmos. Oceanic Technol.* **37**, 1365–1385. (doi:10.1175/JTECH-D-19-0203.1)

46. Sutton AJ, Williams NL, Tilbrook B. 2021 Constraining Southern Ocean CO_2 flux uncertainty using uncrewed surface vehicle observations. *Geophys. Res. Lett.* **48**, e2020GL091748. (doi:10.1029/2020GL091748)

47. Strobach E, Klein P, Molod A, Fahad AA, Trayanov A, Menemenlis D, Torres H. 2022 Local air-sea interactions at ocean mesoscale and submesoscale in a western boundary current. *Geophys. Res. Lett.* **49**, e2021GL097003. (doi:10.1029/2021GL097003)