



HAL
open science

Atlantic Water Inflow Through the Yermak Pass Branch: Evolution Since 2007

Camila Artana, Christine Provost, Zoé Koenig, Marylou Athanase, Ava Asgari

► **To cite this version:**

Camila Artana, Christine Provost, Zoé Koenig, Marylou Athanase, Ava Asgari. Atlantic Water Inflow Through the Yermak Pass Branch: Evolution Since 2007. *Journal of Geophysical Research. Oceans*, 2022, 127 (2), pp.e2021JC018006. 10.1029/2021jc018006 . hal-03562925

HAL Id: hal-03562925

<https://hal.science/hal-03562925>

Submitted on 21 Feb 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Atlantic Water inflow through the Yermak Pass Branch: Evolution since 2007

Camila Artana^{1,2}, Christine Provost¹, Zoé Koenig^{3,4}, Marylou Athanase⁵, and
Ava Asgari¹

¹Laboratoire LOCEAN-IPSL, Sorbonne Universités (UPMC, University Paris 6), CNRS, IRD, MNHN,
Paris, France

²Mercator Ocean, Toulouse, France

³Norwegian Polar Institute, Fram Centre, 9296 Tromsø, Norway

⁴Geophysical Institute and Bjerknæs Center for Climate Research, The University of Bergen, Bergen,
Norway

⁵Alfred Wegener Institute, Bremerhaven, Germany

Key Points:

- New mooring data in the Yermak Pass Branch documented larger velocity variations (40%) in 2017-2020 than in 2007.
- Year 2018 stood out with exceptionally ice-free conditions and enhanced eddy activity at the mooring location.
- Synoptic model-based estimate of Atlantic Water volume transport in the Yermak Pass Branch from 2007 to 2020 varies from -1 to 5 Sv.

Abstract

Thirty-four months (2017-2020) of mooring data were recently obtained at 80.6°N , 7.26 °E in the main branch of Atlantic Water inflow to the Arctic, the Yermak Pass Branch. The Yermak Pass Branch was sampled at that same location during 14 months a decade ago (2007-2008) when sea ice was abundant (mean sea ice concentration of 74% versus 39% during the recent deployment). We focus on time-scales larger than 50 hours. The new mooring data set shows an increase in the velocity variations of 40% compared to the 2007-2008 period. Year 2018 was exceptional with ice-free conditions over the entire year and an intensified mesoscale activity compared to other years. Temperature and salinity time series at 340 m showed significant trends over 3 years (freshening of -0.07 g/kg and cooling of about -0.9°C in 3 years). The performance of 1/12° Mercator ocean operational model at the mooring location was precisely assessed. The modelled Atlantic Water transport was on average larger during 2017-2020 (40% larger) than during 2007-2008. The synoptic transport time series ranged between -1 and 5 Sv over 2007-2020 and showed large seasonal and interannual variations. The transport was larger in winter than summer. However, occasionally negative transport (< -0.7 Sv) through the Yermak Pass Branch occurred during winters ('Blocking events'). These blocking events are associated with recirculations and eddy activity and were more common over the last years from 2016 onwards. The model suggested that a northern branch crossing the Yermak Plateau further north (81.6°N) intermittently developed.

Plain Language Summary

The Atlantic Water flowing through the Fram Strait via the West Spitsbergen Current is the main source of heat and salt for the Arctic Ocean. At the entrance to the Arctic the West Spitsbergen Current splits into several branches as it meets the Yermak Plateau. Thirty four months of observations were recently obtained in the main branch of Atlantic Water inflow to the Arctic, the Yermak Pass Branch. This location used to be ice covered year round. Our results show that the exceptional ice-free conditions in year 2018 were associated with a highly variable flow. An oceanic model, in good agreement with the observations, showed that the Atlantic Water transport through the Yermak Pass Branch was more irregular from 2016 onwards. Changes in the Atlantic Water inflow pathways have important implications for the heat, salt and nutrients reaching the Arctic.

51 **1 Introduction**

52 The Atlantic Water (AW) flows through the Fram Strait via the West Spitsbergen
53 Current (WSC). The AW inflow is the main source of heat and salt for the Arctic Ocean,
54 and plays an important role in the reduction of sea ice (Onarheim et al., 2014; Polyakov et
55 al., 2017) and in the supply of nutrients to the Arctic (Aagaard and Carmack, 1989; Henley
56 et al., 2020). The seasonal variability of the WSC is important, with a stronger flow in
57 winter than in summer (Beszczynska-Möller et al., 2012). The Yermak Plateau located to
58 the northwest of Svalbard is a main obstacle to the warm AW inflow into the Arctic and
59 the WSC splits into several branches as isobaths diverge (Figure 1).

60 A seasonally varying fraction of the WSC, called recirculation branch (rB in Figure
61 1), recirculates in northern Fram Strait, primarily as eddies, and returns southward (e.g.,
62 Teigen et al., 2011; Hattermann et al., 2016; Wekerle et al., 2017). North of Svalbard, the
63 shallow Svalbard Branch (SB in Figure 1b) crosses the Yermak Plateau inshore of the 500-
64 m isobath (Cokelet et al., 2008) and lacks seasonality (Koenig, Provost, Sennéchael et al.,
65 2017; Crews et al., 2019). Another branch, the deeper Yermak Branch (YB in Figure 1b)
66 flows along the western edge of the Yermak Plateau roughly following the 1000-m isobath
67 (Manley, 1995) and carries relatively little transport (Koenig, Provost, Sennéchael et al.,
68 2017; Crews et al., 2019).

69 Koenig, Provost, Sennéchael et al. (2017) highlighted the importance of an additional
70 pathway: the Yermak Pass Branch (YPB in Figure 1b) in which a significant portion of
71 the AW navigates the central plateau following the 700-m isobath, that is northward to
72 81.2°N before turning southeast and rejoining the onshore Svalbard Branch around 10°E.
73 The Yermak Pass Branch is winter-intensified and is the main route through which AW from
74 the WSC enters the Arctic Ocean. The YPB flow is characterized by strong intermittent
75 flow pulses parallel to isobath of 1-2 month duration in winter (Koenig, Provost, Sennéchael
76 et al., 2017). These intermittent coherent YPB pulses in winter are well reproduced in
77 numerical models (Koenig, Provost, Sennéchael et al., 2017; Crews et al., 2019; Athanase
78 et al., 2021). Crews et al. (2019) found that the winter increase in WSC volume transport
79 is divided between the YPB, dominant earlier in winter when AW is less dense, and Fram
80 Strait recirculations dominant later when AW is denser.

81 The circulation in this region has been evolving rapidly since 2007 (Athanase et al.,
82 2021). In particular, AW recirculations towards Fram Strait (rB) shifted further north

83 while the Yermak Branch (YB) strengthened over the northern Yermak Plateau, occasion-
 84 ally crossing the Plateau north of 81.6°N as a branch called Northern Branch (NB, dashed
 85 line in Figure 1) hereafter. The strengthening of the AW circulation over and around Yer-
 86 mak Plateau was widespread and coincided with an overall warming in the upper ocean
 87 layer (0-1000 m) (Athanasé et al., 2021). As winter sea-ice retreats, the northward progres-
 88 sion and shoaling of AW led to enhanced deep winter convection (Athanasé et al., 2020).
 89 In particular, since 2011, the previously ice-covered central Yermak Plateau occasionally
 90 exhibited ice-free conditions in winter, 50-m ocean temperatures always above 0°C, highly
 91 variable mixed layer depths and ocean-to-atmosphere heat fluxes, and became a "marginal
 92 convection zone" (Athanasé et al., 2020). Indeed, during extreme winters, particularly deep
 93 convection reached down to the 27.95 kg/m³ isopycnal (600 m depth), considerably cooling
 94 and freshening the AW layer (Athanasé et al., 2020).

95 A mooring was deployed in the Yermak Pass in 2017, ten years after another pioneering
 96 mooring, to document variations in the YPB Atlantic water inflow. We analyze the new 34
 97 month-long times series of temperature, salinity and velocities focusing on time scales larger
 98 than 50 hours to examine the recent YPB flow and address changes since 2007 compared
 99 to the former observations. The skills of the 1/12° Mercator Ocean operational model
 100 in reproducing the new observations are assessed and the 14-year long model time series
 101 are used to put the observations into a larger spatial and temporal context. We finally
 102 summarize and discuss several hypotheses that could explain the observed variations on
 103 both sub-seasonal and interannual scales.

104 **2 Material**

105 **2.1 Mooring data**

106 A mooring was deployed at 80.6°N and 7.26°E, in the Yermak Pass on the eastern flank
 107 of the Yermak Plateau, on 15 September 2017 from Norwegian Research Vessel Lance and
 108 retrieved on 19 July 2020 from Norwegian Icebreaker K.V. Svalbard. The mooring was only
 109 2.6 km away from the position of the former 2007 mooring line (Figure 1b and 1c).

110 The 2017 mooring comprised 3 instruments: at about 340 m an upward-looking RDI 75
 111 kHz Long Ranger Acoustic Doppler Current Profiler (ADCP) measuring velocity profiles (25
 112 bins of 16 m each), at 348 m a Seabird SBE37 measuring temperature salinity and pressure,
 113 and, at 645 m an Aquadopp currentmeter (Figure 1c). The current data were corrected from

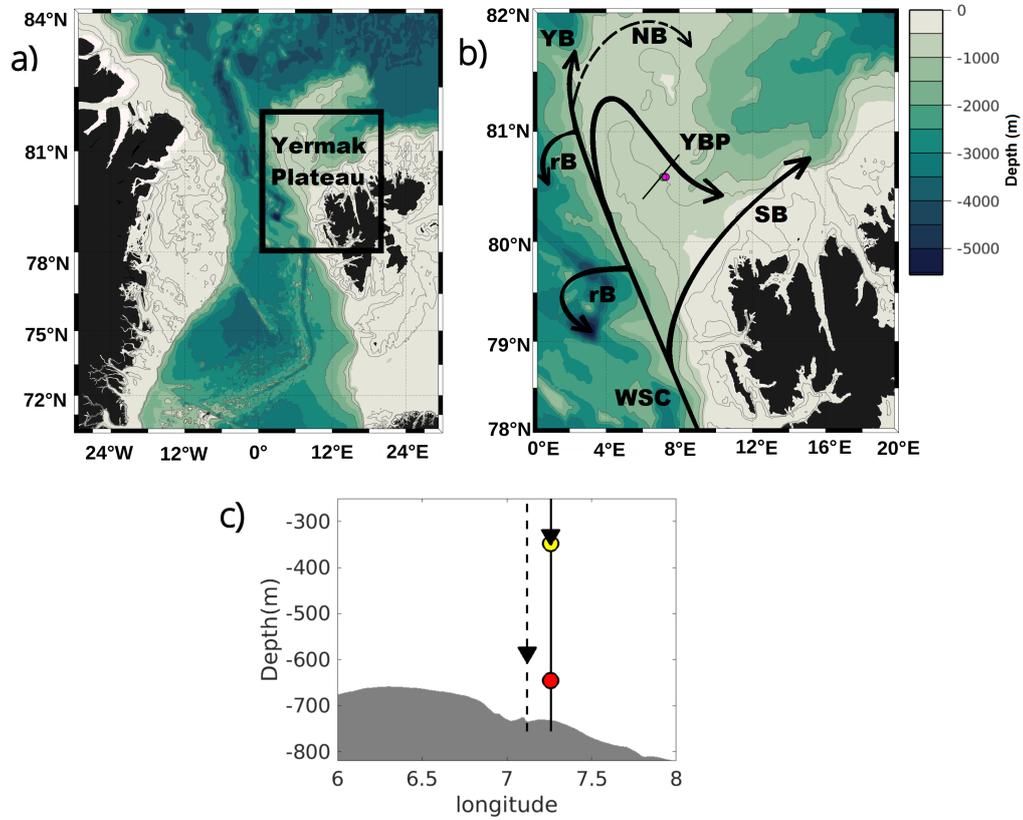


Figure 1. (a) Bathymetry around Fram Strait from IBCAO (Jakobsson et al., 2012). (b) Close-up on the Yermak Plateau. The West Spitsbergen Current (WSC) splits into branches schematized with black arrows: recirculation branches (rB) to the west and south, and four branches navigating over the Yermak Plateau: the Svalbard Branch (SB), the Yermak Pass Branch (YPB), the Yermak Branch (YB) and the Northern Branch (NB) (dashed line) (adapted from Athanase et al., 2021). (c) Schematic of the mooring lines and location along the section shown in (a): the dotted line represents the 2007-2008 mooring carrying an upward-looking ADCP (black triangle) at 585 m, the full line is the 2017-2020 mooring with an aquadopp (red dot) at 645 m, a Seabird microcat (yellow dot) and an upward-looking ADCP at about 340 m (black triangle). Bathymetry along the section in grey.

date	instrument	depth	U	V	T	S	P	δt	δz
2017-2020	ADCP	50 m to 300 m	x	x	x			2 hours	16 m
2017-2020	Sea Bird	348 m				x	x	10 minutes	-
2017-2020	Aquadopp	645 m	x	x			x	2 hours	-
2007- 2008	ADCP	250 m, 300 m, 570 m	x	x	x			2 hours	-

Table 1. Sampling specificity of the mooring instruments. U: eastward velocity; V: northward velocity; T: temperature, S: salinity, P: pressure. δt : time sampling. δz : vertical sampling.

114 pitch, roll and magnetic declination. All the data (velocities, temperature, and density) have
 115 been quality controlled against the ship CTD (Conductivity Temperature Depth) done at
 116 the mooring’s deployment location and time. Measured variables and sampling interval are
 117 summarized in table 1. For the ADCP, the 2 hour sampling resulted from averaging 24 pings
 118 obtained every 5 minutes. For the Aquadopp it was a burst sampling every two hours. The
 119 seafloor is 730 m below sea level at the mooring location and rises to 650 m at the Yermak
 120 Plateau crest 10 km to the west of the mooring (Figure 1c).

121 The upper 50 m of the water column were not sampled (Figure 2). The vertical extent
 122 of the ADCP data was limited by the paucity of backscattering particles. The data return
 123 for all instruments (below 50 m) was close to 100%. Indeed, the only data gaps corresponded
 124 to 2% missing data between 100 and 50 m. A linear vertical interpolation was applied to
 125 fill the few gaps. Over the 34 months (2017-2020) of measurements, the mooring stayed in
 126 a straight position: the Seabird pressure had a mean of 355 db and a standard deviation
 127 of 5 db (largest drawdown of 35 db on January 15 2020). We applied a 50-h third-order
 128 low-pass Butterworth filter to all time series to remove high frequencies including tide and
 129 inertial signals.

130 The data return of the 2007-2008 mooring was reduced as a malfunctioning ocean
 131 profiler stuck on the mooring line above the ADCP reflected part of the acoustic bins
 132 (ADCP represented with a black triangle on the dashed line in Figure 1c) (cf. Koenig,
 133 Provost, Sennéchaël et al., 2017). As a result, the mooring provided complete 14-month
 134 long velocity time series at three depths (250, 300 and 570 m) from 25 July 2007 to 23
 135 September 2008, and there were no measurements of temperature nor salinity time series

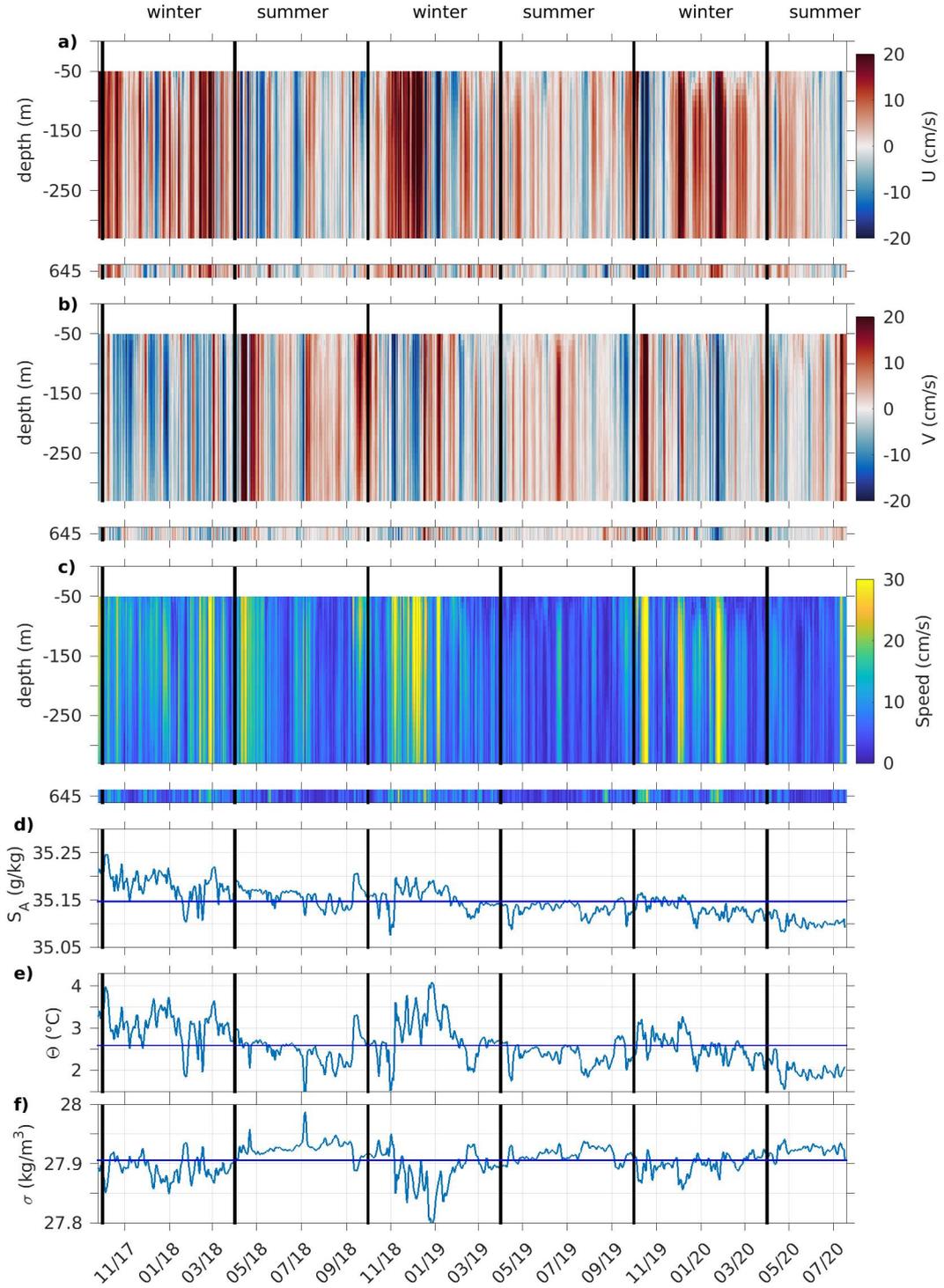


Figure 2. (a) Zonal component of velocity from ADCP (50-330 m profiles) and Aquadopp at 645 m, (b) meridional velocity component (ADCP and Aquadopp) and (c) horizontal speed (ADCP and Aquadopp). (d) Absolute Salinity S_A , (e) Conservative Temperature Θ and (f) Potential Density σ at 348 m. Blue horizontal lines indicate the mean over the 34 months and black vertical lines delimit the seasons (summer: April to September, winter: October to March).

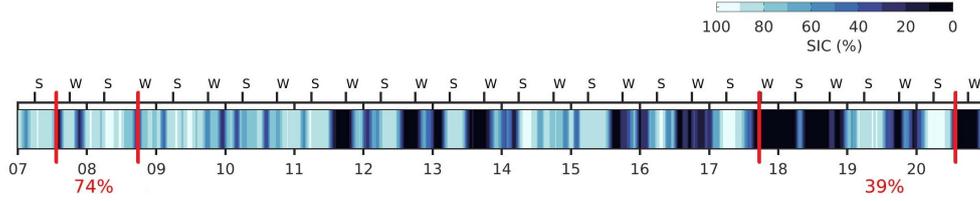


Figure 3. Sea-ice concentration (SIC, %) at a daily resolution at the mooring location from January 2007 to December 2020. Ticks below the ice concentration indicate years, ticks above mark beginning of seasons (W: winter from October to March, S: summer from April to September). The mooring periods are indicated with vertical red lines. Mean sea ice concentrations over each period are reported in red below.

136 (Koenig, Provost, Sennéchaël et al., 2017) (Table 1). The 50-h low-pass filtered velocities
 137 at those three depths are used to address time changes.

138 In the following, we use the Conservative Temperature (Θ) and Absolute Salinity (S_A)
 139 calculated using the International Thermodynamic Equations of Seawater (TEOS-10) (Mc-
 140 Dougall et al., 2011).

141 2.2 Environmental conditions

142 Wind data are from ERA5 reanalysis at 10 m. The wind stress τ is estimated as follows:
 143 $\tau = \rho C_d \mathbf{u} |\mathbf{u}|$, where ρ is the air density, C_d is the drag coefficient and \mathbf{u} is the wind vector.
 144 C_d is computed taking into account the sea ice concentration for estimates of C_d as given
 145 by Lupkes et al., (2005).

146 Sea-ice concentration are from satellite data (EUMETSAT OSI SAF product at daily
 147 temporal resolution, <https://osi-saf.eumetsat.int/products/sea-ice-products>).

148 Sea ice concentration at the mooring location exhibits a seasonal cycle with more ice in
 149 early summer (average of 85% from April to June over the 14 years and 54% over the full 14
 150 years). Year 2012 marks a diminution in winter sea ice cover (a mean ice cover of 70% before
 151 January 2012 and 54% afterwards) (Figure 3). Note that summer 2018 is the only ice-free
 152 summer of the time series. The mean sea-ice concentration at the mooring location is 74%
 153 during the first deployment (2007-2008) and 39% during the most recent one (2017-2020).

2.3 Mercator-Ocean model (PSY4)

Within the frame of Copernicus Marine Environment Monitoring Service (CMEMS; <http://marine.copernicus.eu/>) Mercator Ocean delivers the high resolution $1/12^\circ$ global operational PSY4 system since January 2007 (Lellouche et al., 2018). The modeling component is based on the NEMO (Nucleus for European Modeling of the Ocean) platform with a $1/12^\circ$ ORCA grid type (i.e. horizontal resolution of 4 km in the region) and a water column comprising 50 levels with typically 1 m resolution at the surface decreasing to 450 m at the bottom. The forcing atmospheric fields are from the European Centre for Medium Range Weather Forecasts - Integrated Forecast System (ECMWF-IFS) at 3-h resolution. When oceans are ice-covered, only sea ice concentration (EUMETSAT OSI SAF product) is assimilated. This is in stark contrast with the open ocean regions where PSY4 assimilates along-track satellite sea level anomalies, sea surface temperature and in situ vertical profiles of temperature and salinity (Lellouche et al., 2018). The system begins in October 2006 from a "cold" start (initial currents are null and temperature and salinity initial conditions are from EN4.2.1 climatology; Good et al., 2013).

Thorough comparisons of the modelled variables with non-assimilated in situ and satellite data in the western Nansen Basin region demonstrated the model's remarkable performances (e.g. Koenig, Provost, Villacieros-Robineau et al., 2017; Athanase et al., 2019; 2020; 2021) in spite of inherent limitations. Indeed, the model lacks tides which are important on the Yermak Plateau (Koenig, Provost, Sennéchaël et al., 2017, Padman et al., 1992). Moreover the model resolution is not fully eddy resolving (grid size of 4 km and Rossby deformation radius of about 10 km) in the region (Richez, 1998; Nurser and Bacon, 2014). Modelled variables will be further compared to the mooring data and PSY4 daily outputs from January 2007 to December 2020 will be used to put the data in a larger spatial and temporal context.

3 Mooring data analysis

3.1 Velocity statistics

3.1.1 Velocity means

Mean velocities averaged over 34 months (2017-2020) ranged between 1.5 and 3.2 cm/s in amplitude, the largest value being reached at a depth of 140 m (Figure 4a).

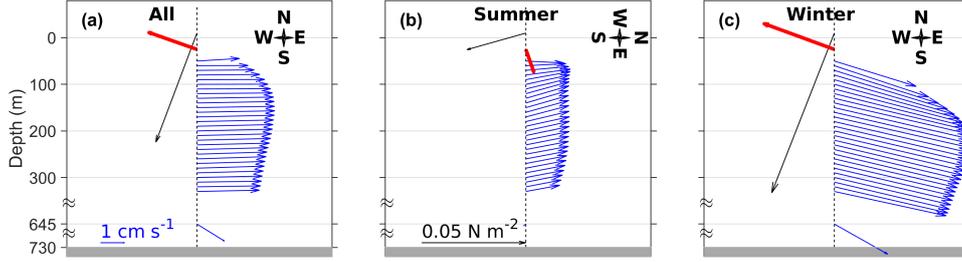


Figure 4. Mean horizontal ocean velocities (blue arrows) as a function of depth over (a) the 34-month (2017-2020) long record, (b) summer (April-September), and (c) winter (October-March). The black arrow shows the corresponding mean wind stress at the ocean surface (N m^{-2}). The red arrows at the surface indicate the velocities corresponding to the Ekman transports with the hypothesis of a 20-m deep Ekman layer. Respective vector scales (ocean in blue, air in black) are indicated in panel (a) and (b). For sake of clarity, the compass is rotated to the right by 90° in (b). The tildes in the y-axis marks the depth gap between Aquadopp and ADCP and the Aquadopp and the seafloor. Seafloor is at 730 m.

184 Mean velocities have the same general direction (eastward), the upper levels (40 to 120
 185 m) being slightly more to the northeast and the lower level more to the southeast (Figure
 186 4a).

187 The mean velocities vary seasonally, with smaller velocities in summer (maximum of 1.7
 188 cm/s from 80 to 230 m) (Figure 4b). Summer mean velocities exhibit a northward direction
 189 except at the upper levels (48-120 m) (northwestward), and are close to zero at the lower
 190 645 m level (Figure 4b). In winter, mean velocities are larger (reaching 5.7 cm/s at 160 m)
 191 and roughly in the southeastward direction, that is parallel to isobaths (Figure 4c).

192 Mean winds are northeasterlies (black arrows in Figure 4), larger in winter than in
 193 summer. They induce a mean Ekman transport (red arrows in Figure 4) to the northwest
 194 opposite to the mean ocean flow, likely contributing to the smaller mean ocean velocities in
 195 the upper layer.

196 Seasonal mean velocities show large interannual variations in amplitude and direction
 197 as illustrated by the velocity means and variance ellipses during the summer (April to
 198 September) and winter (October to March) seasons produced for each year of available data
 199 (Figure 5).

200 Only three levels were fully sampled in the 2007-2008 data set: 250, 300 and 570 m
 201 (Table 1). As the 570 m is not sampled in the recent data set, it was compared to the closest
 202 available level that is 645 m (Figure 1c). The data ensemble covers three complete summers
 203 and four complete winters. Upper level velocities (shown at 100 m in Figures 5a and 5b)
 are only available in the recent data set.

	Summer			Winter			
	2008	2018	2019	2007-08	2017-18	2018-19	2019-20
Mean ice concentration (%)	76	10	61	72	0.7	49	49
\bar{V} / a (in cm/s) at 100 m	-	4.3/8.0	1.6/5.1	-	7.4/8.9	4.8/13.2	4.3/12.3
\bar{V} / a (in cm/s) at 250 m	4.7/4.3	3.8/7.4	1.7/4.6	3.4/7.9	7.1/8.1	4.5/10.6	4.6/11.7
\bar{V} / a (in cm/s) at 570-645 m	2.7/2.1	0.4/4.7	1.2/4.6	1.1/5.2	2.5/6.9	3.3/7.1	1.8/8.4

Table 2. Seasonal statistics: mean ice concentration at the mooring location, mean velocity \bar{V} and half-length a of the major axis of velocity variance ellipses at selected depths.

204

205 Summer velocities means tend to be directed toward the north when above 1 cm/s
 206 in amplitude, and are overall smaller than winter means, except for summer 2008 (red in
 207 Figure 5) which exhibits the largest summer mean (Table 2). Winter velocity means during
 208 the second deployment have a southeastward direction parallel to isobaths as the AW flow
 209 pulses identified in Koenig, Provost, Senéchael et al., (2017) (means in excess of 4 cm/s at
 210 100 and 250 m Table 2 and Figures 5b and 5d) while winter means in 2008 are smaller and
 211 perpendicular to isobaths (red in Figure 5d; Table 2).

212 *3.1.2 Horizontal velocity variations*

213 Velocity variance ellipses reveal the magnitude, principal direction and anisotropic na-
 214 ture of the flow variability. In general velocity variance ellipses are significantly smaller in
 215 summer than in winter (Figure 5, Table 2) and the major axes are parallel to isobaths in all
 216 seasons (Figure 5). Striking exceptions are ellipses from the ice-free summer 2018 which are
 217 large and round (yellow in Figure 5a and 5c) and from winter 2017-18 which have a main
 218 axis in zonal direction (yellow in Figure 5b and 5d). Year 2008 (red in Figure 5) features
 219 the smallest velocity variance ellipses in all seasons (Table 2).

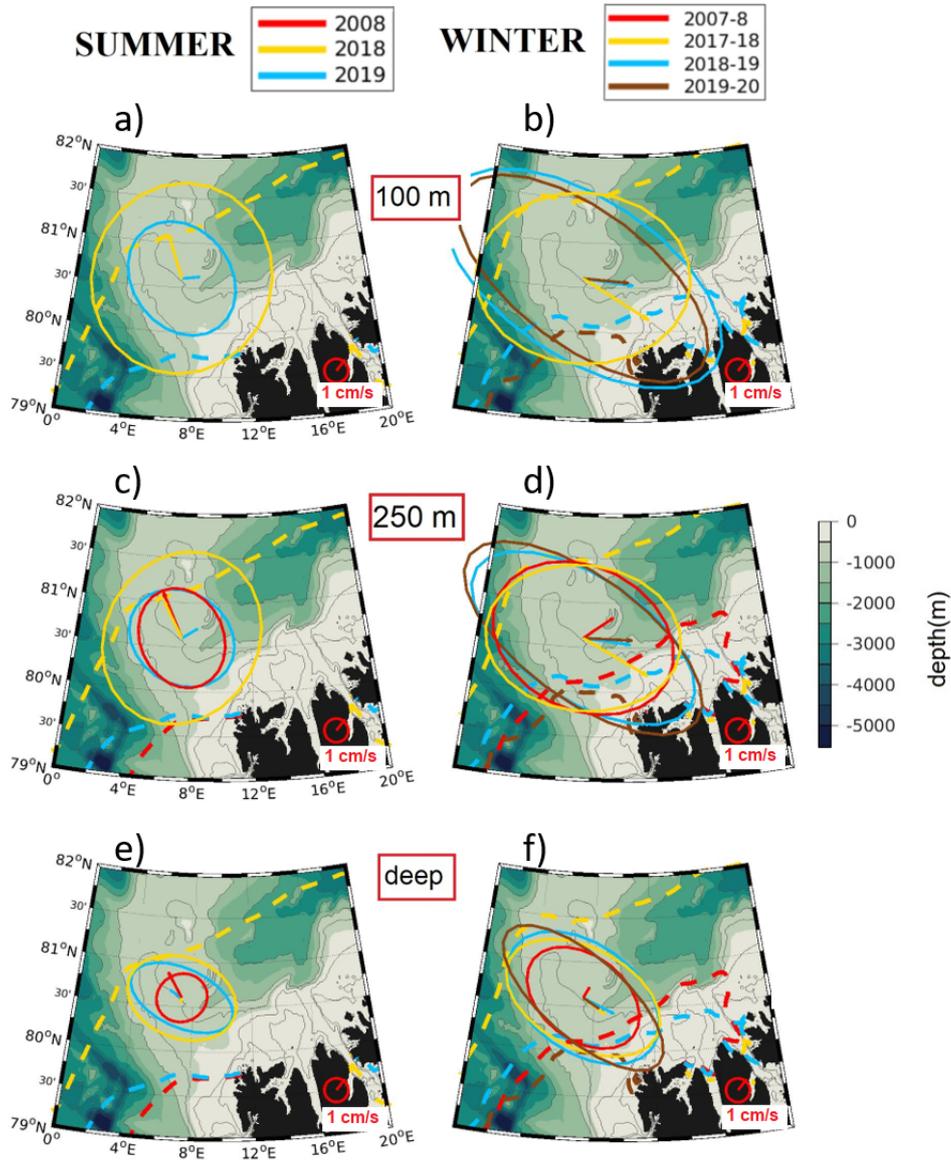


Figure 5. Means and variance ellipses of 50-h filtered horizontal velocities for summer (April to September, left panels) and winter (October to March, right panels) at (a), (b) 100 m; (c), (d) 250 m; and (e), (f) the deepest levels (570 and 645 m). Colors correspond to years: red is first mooring deployment (2007-08), yellow is year 2017-18, blue is 2018-19, and brown is 2019-20. Thick dashed lines are the mean sea-ice edge (defined as the 20% sea-ice concentration) over the corresponding seasons and years (same color code).

220 Velocities from the exceptional ice-free summer 2018 result in a larger variance ellipse
221 at all depths (yellow in Figures 5a, 5c, 5e) compared to ice covered summer 2008 and 2019
222 (red and blue respectively). Winters 2018-19 and 2019-20, with a mean ice cover of 49%
223 at the mooring location, exhibit elongated velocity variance ellipses with the largest major
224 axes in excess of 20 cm/s (brown and blue in Figures 5b, 5d, 5f; Table 2).

225 The mooring was located close to the marginal ice zone, with the ice-pack to the north.
226 The wind direction in summer 2018 was predominantly from the East (direction from 45-
227 90° with respect to north) (Figure 6b), thus favorable to pushing the ice away to the north
228 and providing ice-free conditions at the mooring location. Indeed the mean sea-ice edge in
229 summer 2018 (yellow dashed line in Figures 5a, 5c, and 5e) is located to the North of 81°N
230 at the mooring longitude. In contrast, northwesterlies like in summer 2008 and 2019 (Figure
231 6a and 6c) bring ice to the area and the sea-ice edge is south of 80°N (red and blue dashed
232 lines in Figures 5a, 5c, and 5e). This is consistent with the ice conditions reported in Figure
233 3.

234 Generally the strong winter winds are favorable to pushing the ice away (Figures 6d
235 to 6g) and the region just to the north of Svalbard known as Whalers Bay is ice free. The
236 particularly ice-free winter 2017-18 at the mooring location (cf. Figure 3) corresponds to a
237 mean sea-ice edge north of 81°N at the mooring longitude (yellow dashed line Figures 5b,
238 5c, and 5f). Winter 2017-18 features even more easterlies and southerlies (Figure 6e) both
239 favorable to pushing the ice away.

240 In contrast, the mean sea-ice edge in winters 2007-08 and 2018-19 (red and blue dashed
241 lines in Figures 5b, 5d, and 5f) remained south of the mooring although north of their
242 summer location (Figures 5a, 5c, and 5e). Winter 2019-20 stands out as the winter with
243 the southernmost mean ice edge location (brown dashed line in Figures 5b, 5d, and 5f)
244 associated with a prevalence of northerlies and northwesterlies (Figure 6g).

245 The size of the winter ellipses do not bear any obvious relation with the sea-ice edge as
246 the winter 2019-20 features the largest winter ellipses and the southernmost ice edge (Figures
247 5b, 5d, 5c). These results are consistent with Lundesgaard et al. (2021) who showed that
248 anomalous sea-ice years (over 2012-2019) in the Atlantic water inflow region west and north
249 of Svalbard are associated with anomalies in atmospheric circulation and ice advection.
250 They argued that although ocean heat maintains ice-free conditions in the Atlantic inflow

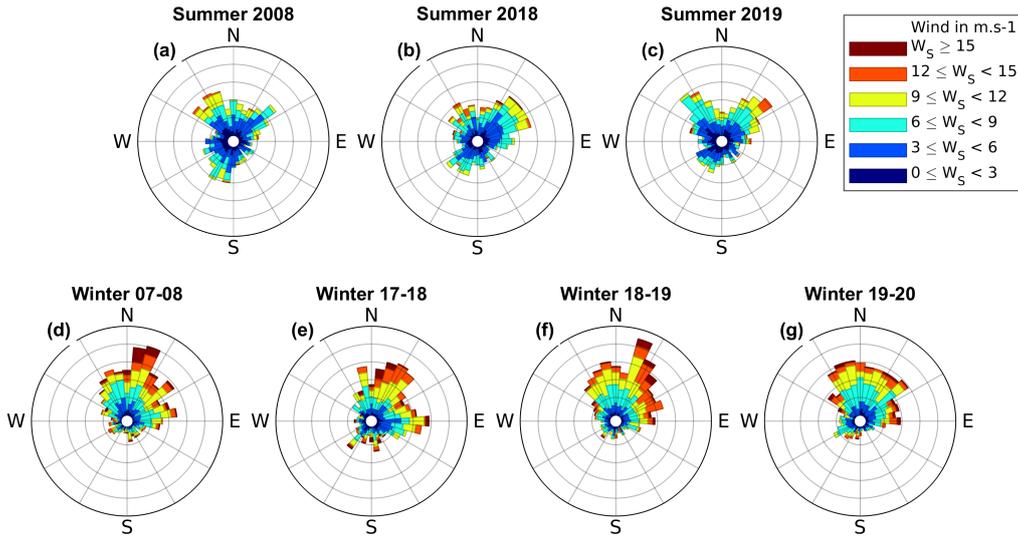


Figure 6. Wind roses for: (a) summer 2008, (b) summer 2018, (c) summer 2019, and (d) winter 2007-08, (e) winter 2017-18, (f) winter 2018-19, (g) winter 2019-20. The outside circle is 10% occurrence and inner circles mark every 2%.

251 region during winter, interannual sea ice variability was not driven by changes in ocean heat
 252 during 2012-2019.

253 The 50-h filtered velocity time series feature variations at smaller than seasonal time
 254 scales (Figure 2) that are examined next.

255 3.2 Eddy Activity in the Yermak Pass

256 Rotary spectra of the 50-h filtered velocities (ADCP and aquadopp) showed rather
 257 similar energy levels for cyclonic and anticyclonic motions, although cyclonic motions were
 258 in general slightly more energetic than anticyclonic motions at all periods in the 330-50 m
 259 depth range (Table 3 and Supplementary S1).

260 In contrast, near the seafloor two period bands (3-7 days and 25-50 days) showed more
 261 energy in anticyclonic motions (Table 3).

262 Seasonal rotary spectra are presented at two levels available for both the former (2007-
 263 2008, 300 and 570 m) and recent (2017-2020, 300 m and 645 m) moorings (full and dashed
 264 lines in Figure 7).

Period	3 to 5 days	5 to 10 days	10 to 25 days	25 to 50 days	50 to 100 days	>100 days
300 m	1.2	1.6	1.1	1.7	1.2	1.1
645 m	0.7	1.1	1.4	0.9	1.2	1.1

Table 3. Ratio of cyclonic (CCW) to anticyclonic (CW) energy as a function of periods at 300 and 645 m for the second deployment (2017-2020)

265 The ice-free summer 2018 stands out with more energy (both CW and CCW) at all
 266 periods than other summers at 300 m depth (full yellow curve in Figures 7a and 7b) resulting
 267 in the largest ellipse (shown in yellow in Figure 5c). Rather heavily ice-covered summer 2007-
 268 08 shows low levels of energy (5 times smaller) at periods larger than 8 days (both CCW
 269 and CW) at depth (dashed red lines in Figures 7a and 7b, small red ellipse in Figure 5e).
 270 There is more energy in anticyclonic motions between 20 and 40 days at 300 m in recent
 271 summers compared to summer 2008, while no difference is observed for cyclonic motions
 272 (Figures 7a and 7b).

273 At periods less than 8 days, the winter rotary spectra at 300 m and at the deepest levels
 274 show similar energy levels for all years in CW (clockwise) and CCW (counterclockwise)
 275 (Figures 7c and 7d). There is more energy at 300 m than at the deepest level (both CW
 276 and CCW) at periods larger than 8 days.

277 Differences between years in winter are subtle although variance ellipses are rather
 278 dissimilar (Figures 5b, 5d, 5f). Winter ellipses in 2018-19 and 2019-20 are elongated along
 279 isobaths and reflect large pulses to the south-east (Figure 5d) while winter ellipses for 2017-
 280 18 are more round and reflect more isotropic variations. The ice-free winter 2017-18, with
 281 round-shaped ellipses, exhibits more cyclonic energy in the 10 to 20-day and 2 to 5-day
 282 period bands (yellow in Figure 7d). On the other hand, compared to winter 2017-18 the
 283 winters 2018-19 and 2019-20 show more energy (both CW and CCW) at periods larger than
 284 30 days, probably associated with AW pulses along topography.

285 At the deepest level, there is more energy at periods larger than 8 days during the
 286 recent years (dashed lines in Figure 7). This is consistent with the smaller ellipses of year
 287 2007-2008 (red ellipses in Figures 5e and 5f). This may be related with a thicker AW layer
 288 in recent years as described in Athanase et al. (2021).

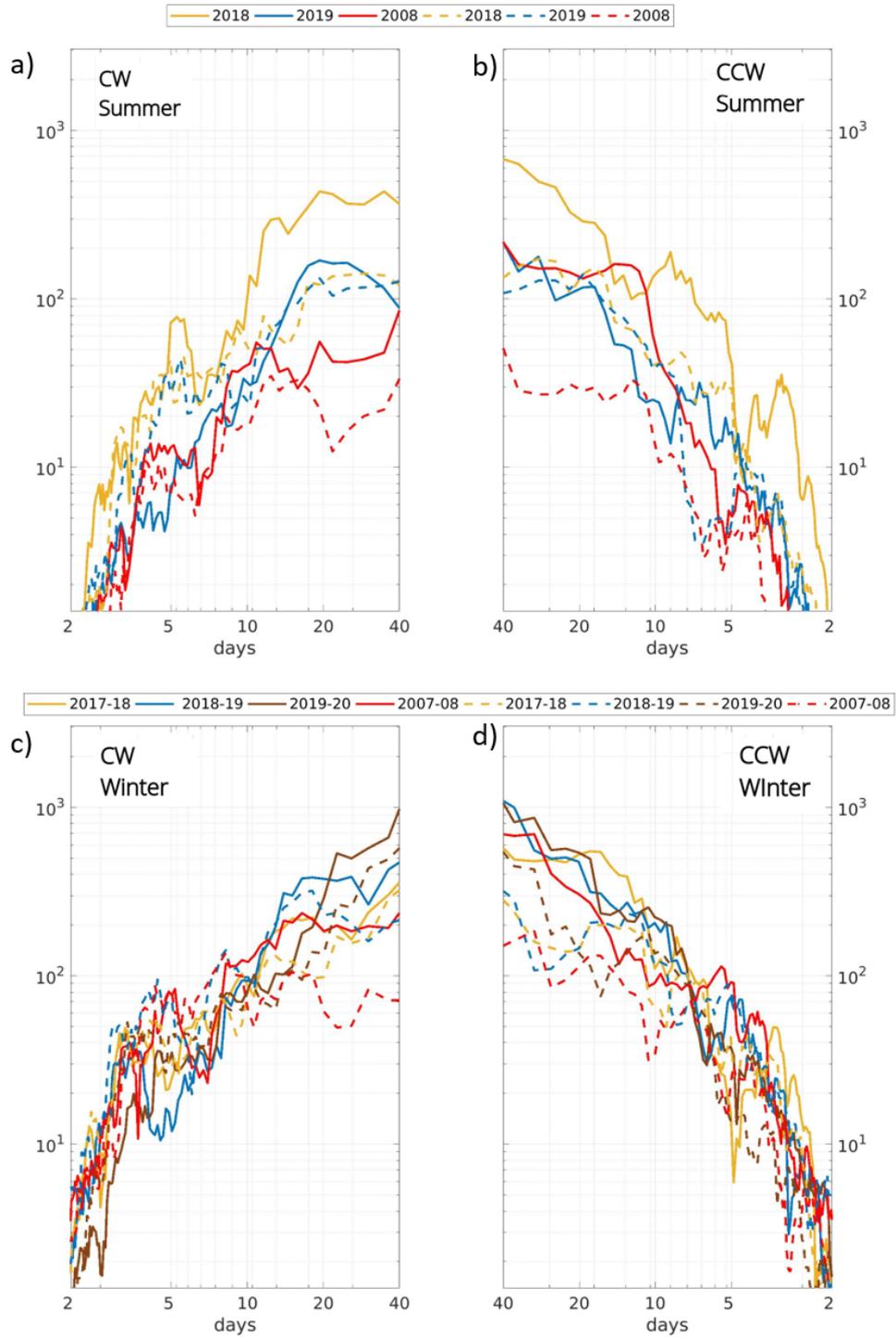


Figure 7. Rotary spectra of horizontal velocities at 300 m (full line) and at the deepest level (645 m for 2017-2020 and 570 m for 2007-2008 in dashed line) averaging over groups of 4 adjacent frequencies (50-h filtered velocities with 2 h resolution). Color indicate years, as in Figure 5. (a), (b) Summer spectra; (c), (d) Winter spectra. X-axis is the period in days and y-axis is the energy in cm^2/s^2 .

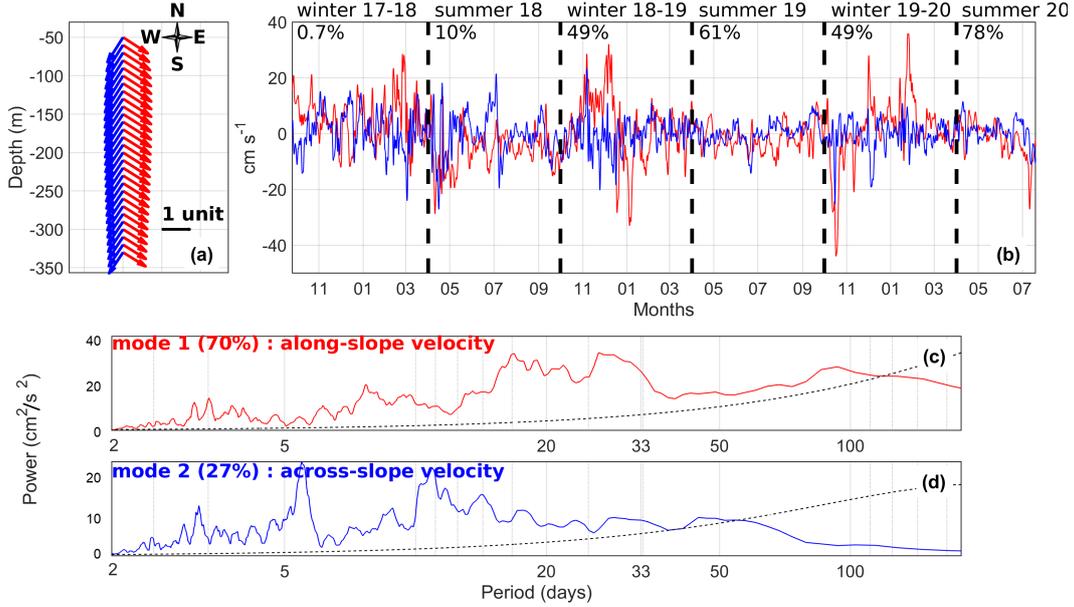


Figure 8. Empirical orthogonal function (EOF) decomposition of the 50-h filtered horizontal velocities with a 2 h resolution: first mode, parallel to isobaths, (explaining 70% of the variance) in red, second mode, perpendicular to isobaths, (27%) in blue: (a) vertical structure and (b) associated time series. (c), (d) Variance-preserving spectra of the EOFs time series (averaging over groups of 10 adjacent frequencies). The dotted lines show the 95% confidence level. Y-axis units are cm^2/s^2 . Percentages in black in (b) indicate mean seasonal ice-concentration.

289

3.3 Modes of horizontal velocity variations

290

An empirical orthogonal function (EOF) analysis was performed on the 50-h filtered horizontal velocity data from the ADCP. The first two modes accounted for 97 % of the velocity variance (Figure 8).

292

293

The first and second modes (respectively 70% and 27% of the total variance, in red and blue in Figure 8) are close to a barotropic structure with the same direction in the vertical (slightly subsurface intensified) (Figure 8a). Mode 1 is parallel to isobaths while mode 2 is perpendicular to isobaths.

296

297

The EOF time series featured distinct spectral contents with significant broad band energy until 140 days for the first mode (hereafter EOF1) and 60 days for the second mode (EOF2) (Figures 8c, 8d). EOF1 showed salient peaks at 16, 30 and 90 days and EOF2 at 3.5, 6 and 11 days (Figures 8c, 8d).

300

301 The first mode EOF1 can be interpreted as pulses of AW through the Yermak Pass in
 302 the direction parallel to isobaths. Those pulses have large energy peaks at periods between
 303 15-day and a month (Figure 8c). The higher frequency peaks of the second mode EOF2
 304 (peaks at 6 and 11 days, blue in Figure 8d) could be the signature of mesoscale activity.
 305 Indeed, drifting floats at 300 m depth documented vortices with rotating time scales of 5
 306 to 15 days, curvature radius of about 4 km and tangential speed of 10 cm/s in the Yermak
 307 Pass area (Gascard et al., 1995 and Richez, 1998). EOF1 also bears the signal of mesoscale
 308 activity at time scales smaller than 20 days (Figure 8c).

309 The time series associated with the EOFs are not stationary: they show little fluctu-
 310 ations from February to October 2019 and from February to July 2020 (Figure 8b) which
 311 correspond to large sea ice concentration at the mooring site (Figure 3). In contrast, the
 312 EOFs time series, especially EOF2, exhibit important variations during the ice-free summer
 313 2018 (Figure 8b) in accordance with the corresponding large variance ellipses and large eddy
 314 kinetic energy (yellow in Figure 5a, 5c and 7c, 7d).

315 The extreme event on the 7 October 2019 (EOF1 reaching -50 cm/s and EOF2 +25 cm/s
 316 Figure 8b) corresponds to a northwestward flow (Figure 2). Koenig, Provost, Villaceros-
 317 Robineau et al. (2017) showed that northwestward velocities in the YPB were frequent in
 318 summer, however to our knowledge it is the first time that such a large (about 30 cm/s)
 319 and prolonged (about 3 weeks) northwestward YPB flow is recorded in winter.

320 **3.4 Temperature and salinity variations**

321 At 348 m depth, conservative temperature ranges between 4 and 1°C, absolute salinity
 322 between 35.07 and 35.25 g/kg (Figures 2d and 2e). These values fall within the Atlantic
 323 Water property range with $\Theta > 1^\circ\text{C}$ and $S_A > 35.05$ g/kg (e.g. Perez-Hernandez et al.
 324 (2019)). The two time series feature significant (above the 99% confidence level threshold)
 325 negative trends of about 0.9°C and 0.08 g/kg in 3 years (Figures 2d and 2e). Mercator model
 326 PSY4 also features this freshening trend and cooling trends over 2017-2020 (Athanasé et
 327 al., 2021).

328 Salinity, temperature and density time series show larger and more variable values in
 329 winter than in summer (Figures 2d, 2e and 2f, Table 4). Water is denser in summer (colder
 330 and fresher) than in winter (warmer and saltier) (Figure 2f, Table 4).

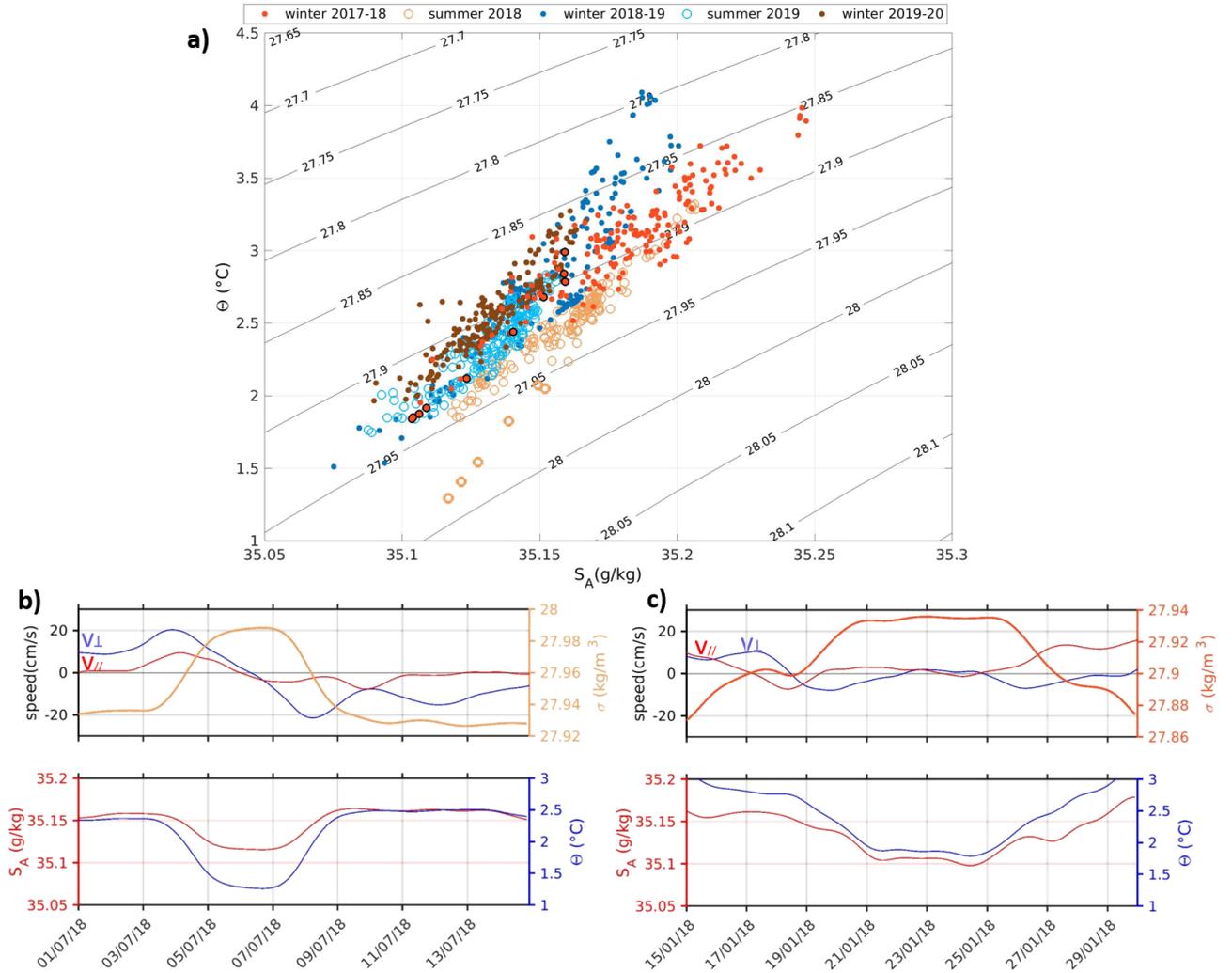


Figure 9. (a) Θ/S_A diagram at 348 m (50-h low-pass filtered data and daily resampled): full dots are winter data (October-March) and circles summer data (April-September). Colors indicate years: 2017-2018 in orange, 2018-2019 in blue and 2019-2020 in brown. (b) Time series of along and across slope velocities (rotation of +40°), density (σ), absolute salinity (S_A) and conservative temperature (θ) for early July 2018 corresponding to the light orange circles with densities larger than 27.95 kg/m³. (c) Same as (b) for mid-January 2018. The corresponding dark orange dots in the Θ/S_A diagram are highlighted with a black edge.

	SIC (%)	$\bar{\Theta}$ (STD)	$\Theta_{min/max}$	\bar{S}_A (STD)	S_A min/max	$\bar{\sigma}$ (STD)	$\sigma_{min/max}$
summer 2018	10	2.47(0.32)	1.29/3.31	35.15(0.02)	35.11/35.20	27.92(0.01)	27.88/27.98
summer 2019	61	2.36(0.23)	1.74/2.83	35.13(0.01)	35.08/35.15	27.91(0.01)	27.89/27.93
winter 2017-18	0.7	3.05(0.39)	1.84/3.98	35.18(0.03)	35.10/35.24	27.89(0.01)	27.84/27.93
winter 2018-19	49	2.83(0.53)	1.51/4.08	35.15(0.02)	35.07/35.20	27.88(0.03)	27.79/27.95
winter 2019-20	49	2.55(0.29)	1.96/3.27	35.13(0.01)	35.08/35.16	27.89(0.01)	27.85/27.92

Table 4. Statistics of conservative temperature ($^{\circ}\text{C}$), absolute salinity (g/kg) and density (kg/m^3) at 348 m as a function of seasons: means, standard deviation (STD) and extrema (minima and maxima). The first column recalls sea ice concentration (SIC).

331 The Θ/S_A diagram illustrates further the cooling and freshening trend over the three
332 years (orange dots are from 2017-2018, blue dots from 2018-2019 and brown dots from 2019-
333 2020) (Figure 9a). The diagram also reflects that on average at 348 m, water is denser in
334 summer than in winter (Figure 9a).

335 The densest points in the diagram ($\sigma > 27.95 \text{ kg/m}^3$) likely correspond to a cold core
336 structure (eddy or meander) ($T < 1.5^{\circ}\text{C}$) crossing the mooring in summer 2018 between July 3
337 and 10 (Figure 9b). During this event, velocity components changed sign while temperature
338 was minimum (Figure 9b). Salinity in the structure core was smaller (35.12 g/kg) than in
339 surrounding waters ($> 35.15 \text{ g/kg}$) and velocities exceeded 20 cm/s at the structure core
340 boundary (Figure 9b). This event is revisited in section 5.

341 During the second half of January 2018 (Figure 9c), the temperature dropped from
342 3.2°C to 1.6°C and salinity from 35.15 to 35.1 g/kg while density increased from 27.88 to
343 27.94 kg/m^3 (Figure 9c). This corresponds to a deep convective event further described in
344 section 5.

345 The EOF1 of velocity variations and temperature (or density) time series (detrended
346 or not) are correlated ($r = +0.2$ for temperature, 0.25 for density, both significant at the 90%
347 confidence level): intense southeastward pulses tend to carry rather warm and light waters.
348 This is congruent with Crews et al. (2019). The correlations although significant are modest

349 as deep winter convective events cool the Atlantic Water (e.g. Athanase et al., 2020; section
350 5).

351 4 Yermak Pass Branch in Mercator-Ocean operational model

352 4.1 Further model assessment: comparison with the 2017-2020 data

353 Comparisons between co-localized PSY4 variables and 10-day smoothed mooring obser-
354 vations are shown in Supplementary S2. We recall the main results. PSY4 temperature and
355 salinity reproduce well the mean and variations of the 10-day smoothed *in situ* time series at
356 348 m. PSY4 is on average 0.3°C warmer (2.9°C versus 2.6°C) and 0.03 g/kg saltier (35.18
357 versus 35.15 g/kg). Model standard deviations (STD) are on the same order (0.4°C and 0.03
358 g/kg) as observations and variations are correlated at the 99% significance level ($r=0.68$)
359 (Supplementary S2). The model reproduces the observed decreasing trends in salinity and
360 temperature. This comparison is performed with a longer time series than in Athanase et
361 al. (2021) and leads to the same conclusions.

362 Comparisons between model velocities and observations (Supplementary S2) suggest
363 that differences in mean velocities can probably be attributed to the lack of tide representa-
364 tion in the model. Tides are large over the Yermak Plateau and induce a residual current of
365 about 4 cm/s to the north (Koenig, Provost, Sennéchaël et al., 2017). The residual current
366 is present in the in-situ mean velocity and absent the model mean.

367 Model velocity variance ellipses are smaller than those resulting from the 20-day filtered
368 observed velocities: in summer the great axes are about 50% smaller and in winter only
369 10% smaller (Supplementary). Indeed, the $1/12^\circ$ grid resolution of the model does not fully
370 resolve the eddy scale in the region (Rossby radius of about 10 km; Crews et al., 2018).

371 An EOF decomposition of the model velocity over the ADCP range was performed
372 (model velocities were interpolated to the ADCP vertical resolution). The first two modes
373 of the EOF are similar in structure to those from the ADCP and explain 85 and 13% of the
374 variance respectively (Figure 10). The first mode (EOF1, parallel to the isobaths) represents
375 the pulses while the second mode (EOF2, perpendicular to the isobaths) is associated with
376 the weak model eddy field.

377 Correlation between EOF1 of model horizontal velocities and (50-h filtered) ADCP
378 velocity is 0.43 (above the 99.9% confidence level) showing that the model does represent

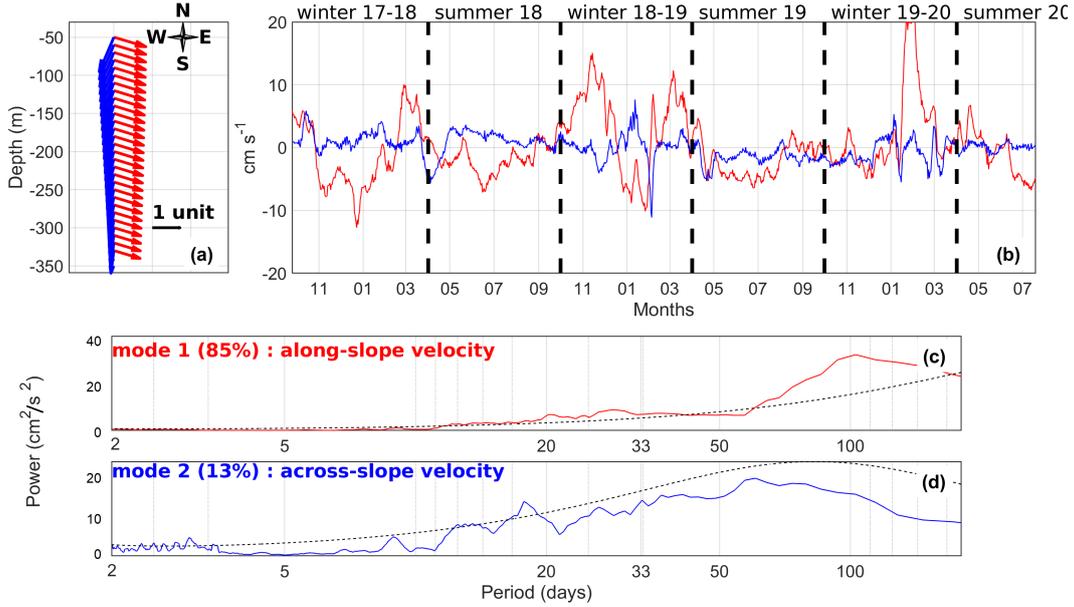


Figure 10. (a) Vertical structure of EOF1 and EOF2 of model daily velocities over the ADCP range. (b) EOF1 and EOF2 time series. (c) and (d) Variance-preserving spectra of the EOFs time series (averaging over groups of 10 adjacent frequencies). The dotted lines show the 95% confidence level. Y-axis units in cm^2/s^2 .

379 the major current pulses with some skill. Although levels of energy are smaller and energized
 380 periods slightly longer, the spectral contents of the time series have a distribution rather
 381 similar to those of the data EOFs with energy at 23, 30 and 128 days (EOF1) and 17 days
 382 (EOF2) (Figure 10).

383 The model EOF1 does represent some of the negative events present in the ADCP
 384 EOF1 such as the one in late December 2017 or late January 2019 (Figure 10b). The model
 385 velocity field at 266 m on 22 December 2017 features an anticyclonic eddy tangential to
 386 the mooring location and suggests that some of these negative events correspond to an
 387 intensified mesoscale eddy field (Figure 11). The Yermak Branch, flowing northward along
 388 the western edge of the Plateau, was particularly intensified at that time and feeding a
 389 Northern Branch (NB in Figure 1b) crossing the Yermak Plateau north of 81.8°N (Athanas
 390 et al, 2021) (Figure 11).

391 These stringent comparisons illustrate the model capabilities in representing water mass
 392 properties and velocity (in spite of a smaller velocity variance).

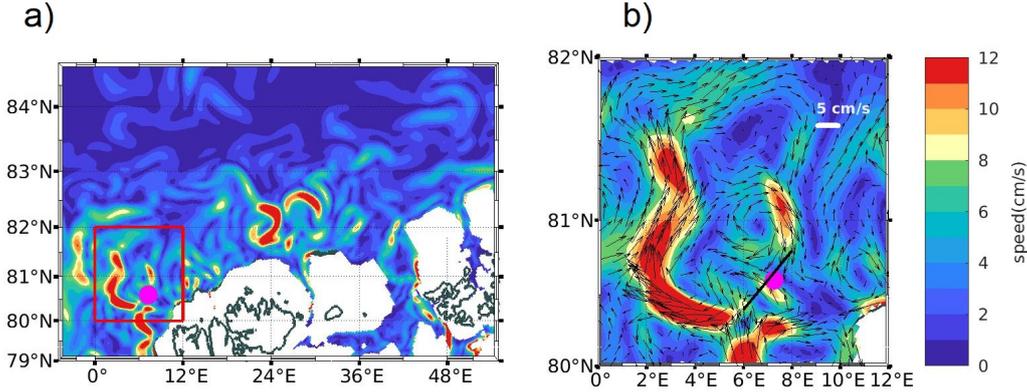


Figure 11. (a) PSY4 horizontal velocities at 266 m on the 22 December 2017 in the Western Nansen Basin, with (b) a close up on the Yermak Plateau (red box in a). Color scale in cm/s. For sake of clarity velocity vectors are only plotted in (b) and every other grid point. Magenta dot indicates the mooring location and black line is the section used to compute the AW transport. Green contours are isobaths.

4.2 Evolution of the Yermak Pass Branch over the last 14 years in PSY4

Model velocity means over the two mooring periods at 266 m (Figures 12a and 12b) illustrate an intensified circulation (more northward reaching) during the second period (2017-2020) consistent with the schematics of circulation changes from Athanase et al. (2021). A close-up around the Yermak Plateau during the recent mooring period features a recirculation branch shifted to the north by 1 degree latitude, a stronger Yermak Branch (along the western side of Yermak Plateau) reaching further north, an intensified Yermak Pass Branch and a new branch (Northern Branch) crossing the Yermak Plateau at 81.8°N around a seamount located north of the YPB (Figure 12b).

Atlantic water transport associated with the modelled Yermak Pass branch (YPB) was computed across the section shown in Figure 12 in two ways: net transport as in Koenig, Provost, Sennéchaël et al. (2017) and "positive velocity only" transport only taking into account positive cross-section velocities as in Perez-Hernandez et al. (2019). The mean net transport (1 Sv) is only 0.1 Sv smaller than the "positive velocity only" transport and the two time series are highly correlated ($r=0.98$, Figure 13a with the net transport in red, and "positive velocity only" transport in blue). In addition the two transport time series are highly correlated with EOF1 time series (Figure 10b, $r=0.97$) suggesting that

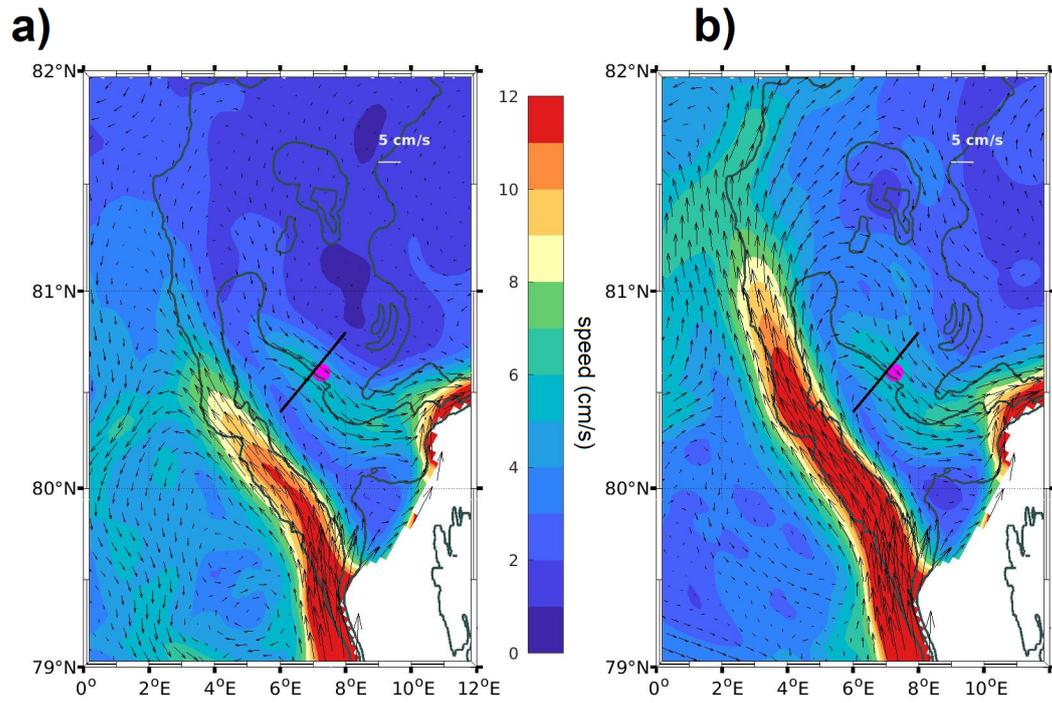


Figure 12. PSY4 horizontal velocities at 266 m averaged over (a) 2007-2008 and (b) 2017-2020 (full years). Background color is current speed in cm/s. The magenta dot indicates the mooring location and the black line is the section used to compute the AW transport. The green contours are isobaths.

410 the mooring location is well spotted at least in the model. The spectral content of the
411 volume transport features a strong seasonal cycle (maximum transport in winter) and large
412 interannual variations as shown in the wavelet transform amplitude (Figure 13b). Year
413 2016 marks a change in the spectral content: before 2016 energy is concentrated around the
414 annual period whereas after 2016 significant energy is found over a large range of periods
415 from bi-annual to 50 days (Figure 13b).

416 The mean AW volume transport through Yermak Pass (positive velocities only) is 0.7
417 Sv during the first mooring deployment and 1.04 Sv during the second one (close to the
418 14-year mean value of 1.13 Sv) (Figure 13). Transport STD increased from 0.6 Sv during
419 first deployment to 0.9 Sv during second deployment.

420 However, the AW transport means do not reflect a linear trend as they are both below
421 the 14 year average, and interannual and seasonal variations are large (Figure 13 and Sup-
422 plementary S3). In particular, the maximum annual mean transport (1.7 Sv) is reached in
423 2013/2014 and minima (about 0.7 Sv) in recent years are observed in 2015/16 and 2017/18
424 (Supplementary S3). Changes in AW transport through the YPB are modulated by changes
425 in the West Spitsbergen Current (WSC) transport itself and the distribution of WSC trans-
426 port among the different branches (Figure 1): Svalbard Branch, Yermak Pass Branch, Yer-
427 mak Branch, Northern Branch and recirculation branches (Athanasé et al., 2021). The
428 modeled YPB constitutes the main path for AW over the Yermak Plateau with an AW vol-
429 ume transport largely correlated with the West Spitsbergen Current AW transport ($r=0.75$)
430 (Athanasé et al., 2021). Model suggests that the maximum in 2013/14 can be attributed to
431 a smaller recirculation back to Fram Strait (thus more flow through the YPB) and minima
432 in 2015/16 and 2017/18 to a larger recirculation (thus less flow through the YPB) (Athanasé
433 et al., 2021; their Figure 5). PSY4 was consistent with recent moorings on the prime merid-
434 ian which also indicated that AW recirculations showed a maximum at 80°N in winter 2017
435 (Hofmann et al., 2021).

436 5 Discussion

437 The Mercator Ocean model proved its reliable performance and provided consistence
438 with measurements insights on the large variations of the Yermak Pass Branch. We used
439 the model to put observations in a larger spatio-temporal context.

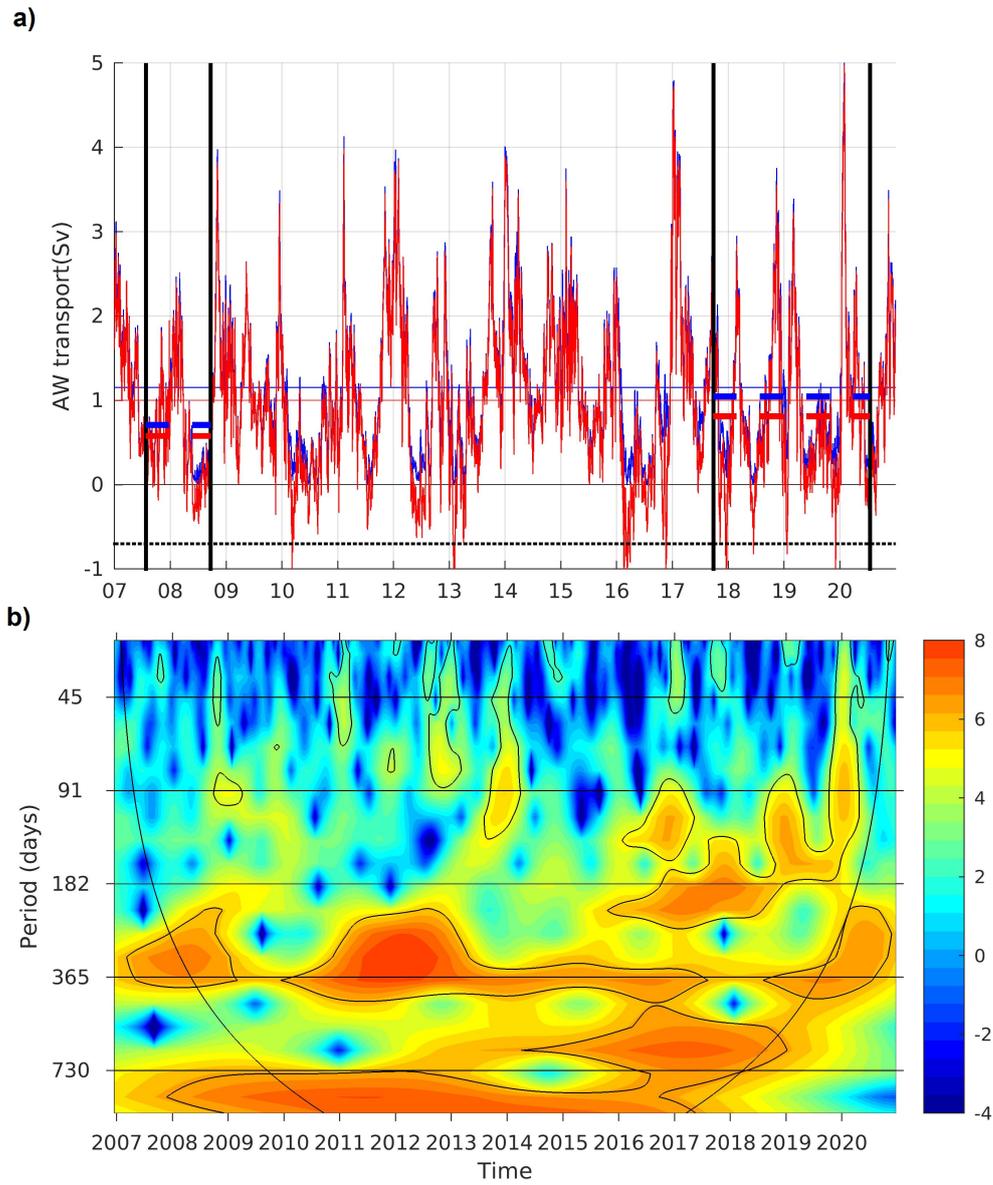


Figure 13. (a) 14-year time series of AW ($\Theta > 1^{\circ}\text{C}$, $S_A > 35.05$ g/kg) volume transport (Sv) across the Yermak Pass branch section shown in Figure 1b: net transport in red and "positive cross-section velocity only" in blue (see text). The two periods with mooring data are delimited and their respective mean transport indicated with dashed horizontal lines. The black dotted horizontal line marks the -0.7 Sv value. (b) Wavelet of net transport time series shown in base 2 logarithm; The black contours is the 95% confidence level; y axis is the period in days and x axis is the time in years.

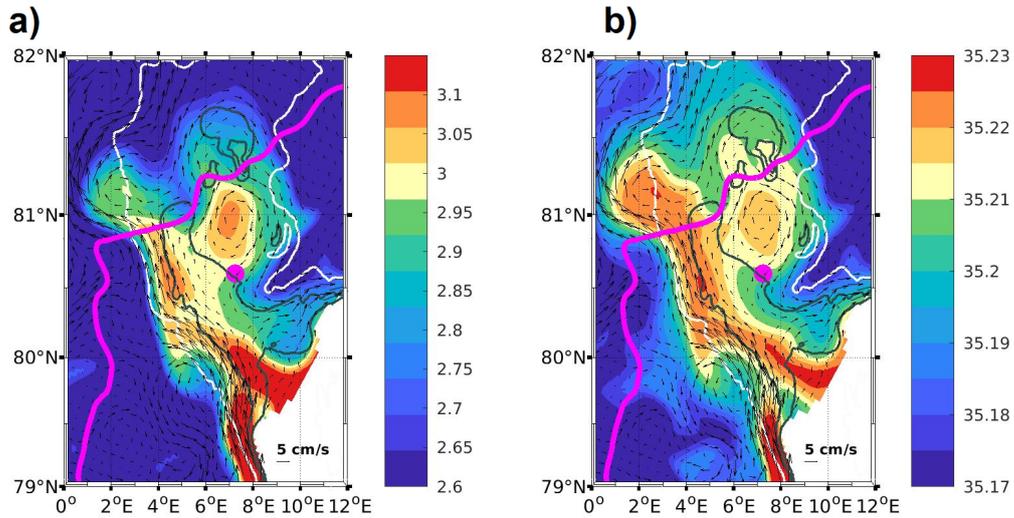


Figure 14. (a) Model Θ ($^{\circ}\text{C}$) and (b) S_A (g/kg) at 318 m on the first July 2018. Arrows indicate velocities at that depth. The magenta contour marks the synoptic ice edge and the white contour the 1000-m isobath. Magenta dot indicates the mooring location. Dark green contours are 700-m and 500-m isobaths

5.1 Water mass properties at 348 m

There was no temperature nor salinity times series recorded in 2007-2008. The 2017-2020 mooring data documented the seasonality and recent evolution of AW properties at 348 m depth in the YPB. Density changes were temperature-driven, and the AW water in the YPB was denser in summer (colder and fresher) than in winter (warmer and saltier), confirming model-based results from Crews et al. (2019). The densest waters at 348 m were recorded early July 2018 and corresponded to a cold and rather fresh cyclonic structure during ice-free summer 2018 (Figures 9a and 9b). Interestingly, PSY4 fields from that date suggest that the cyclonic structure was a sharp meander bringing colder and fresher waters from the Sofia Deep towards the mooring site (Figure 14). In the model, the sharp meander, located to the south of a large anticyclone near the ice edge, followed the slope of a canyon-like structure (see isobath 1000 m in Figure 14).

Mooring time-series of temperature, salinity and density at 348 m exhibited larger variations in winter than in summer (Figures 2d, 2e, 2f, and Table 3). This is congruent with a larger mesoscale activity in winter and occurrence of deep winter convection.

455 The dense event observed in January 2018 (Figure 9c) was also documented in PSY4
456 (Figures S2, 15) and occurred at a time of deep convection. Indeed, times series of PSY4
457 fields at the mooring location outline the exceptional conditions early 2018 with a net heat
458 flux of -400 W/m^2 during 3 months and mixed layers exceeding 400 m in depth (Figure 15).
459 Those convective conditions resulted in homogeneous waters (same water properties at 40
460 and 380 m) and cooler, fresher and denser AW (Figure 15). According to PSY4, the deep
461 mixed layer lasted until April when northerly winds pushed the ice back over the mooring
462 (not shown). These were the deepest (and most long-lasting) mixed layers in the 14-year
463 time series at the mooring location (Figure 15). Athanase et al. (2020) showed how winters
464 in early 2013 and early 2018 were outstanding with the deepest mixed layers and exceptional
465 sea-ice retreat on the slope and Yermak Plateau, respectively. Winter ventilation of the AW
466 layer through winter convection is a rather localized phenomenon in time and space as it
467 requires near-surface AW inflow, and appropriate forcing (wind pushing the ice away and
468 large negative heat fluxes; e.g., Ivanov et al., 2018, Koenig, Provost, Villaceros-Robineau
469 et al., 2017).

470 A notable freshening of the YPB Atlantic Water was recorded over the 2017-2020
471 period (-0.080 g/kg in 3 years) and was also reproduced by PSY4 (-0.087 g/kg in 3 years;
472 Supplementary S2). The 14-year long salinity time series from PSY4 suggests that the trend
473 started late 2016 in the YPB (Figure 15). The freshening trend likely resulted from the
474 poleward advection of fresh anomalies from the North Atlantic (Mork et al., 2010; Holliday
475 et al., 2020). The data at 348 m also displayed a significant negative temperature trend
476 (-0.90°C in 3 years) which PSY4 also reproduced (-0.63°C in 3 years; Supplementary S2).
477 PSY4 shows that over 14 years the temperature trend in YPB is not significant (Athanase
478 et al., 2021; Figure 15). PSY4 time series after the mooring recovery (April 2020) shows an
479 increase in temperature and salinity which suggest that the 3-year trends could be temporary
480 (Figure 15). However, caution is required with such a short time series.

481 **5.2 Velocities and volume transports**

482 A major result was the intensification of the increased variability of summer velocities in
483 2017-2020 compared to 2007-2008 (Figure 5). Overall the main axes of the velocity variance
484 ellipses increased by about 40% (Table 2).

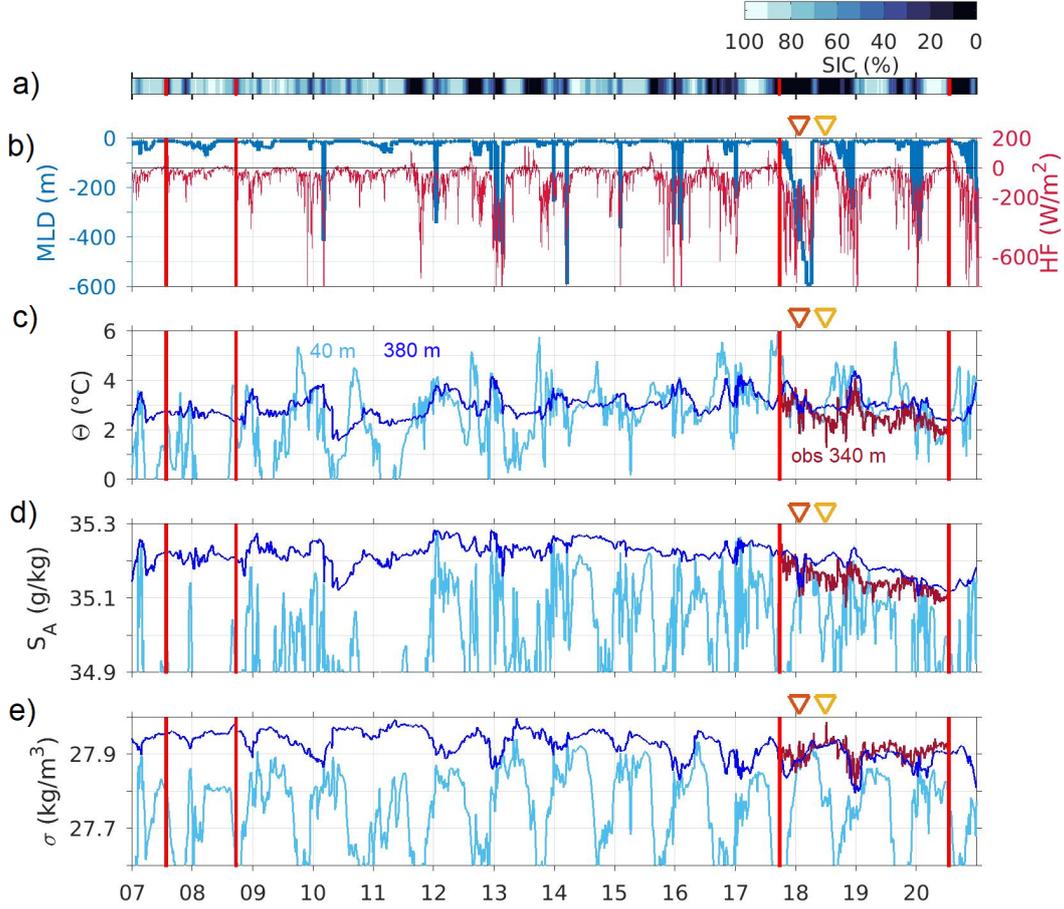


Figure 15. Time series of modelled (a) ice cover (SIC, %). (b) Net total heat flux (HF, W/m^2) and mixed layer depth (MLD, m). (c) conservative temperature Θ ($^{\circ}\text{C}$), (d) absolute salinity S_A (g/kg) and (e) potential density (σ , kg/m^3) from the model at 40 m (light blue) and 380 m (dark blue), and from observations at 340 m (red). The MLD was defined as the shallowest depth at which potential density exceeded the surface value by $0.01 \text{ kg}/\text{m}^3$. The vertical red lines indicate the moorings period. The orange and yellow triangles on the top indicate the dates of the deep convection event in January 2018 and the densest waters recorded in July 2018.

485 The ice-free year 2018 stood out with a more energetic ocean state (Figure 3a, Table 2).
486 Winter 2017-18 exhibited the largest mean velocities ever recorded in the YPB (Figure 5).
487 Summer 2018 was characterized by an enhanced eddy-activity (Figures 5a, 5c, 7c, 7d). That
488 summer, the ice edge was always located north of the mooring location (Figure 5). Several
489 studies proposed that eddies may be generated and enhanced at the vicinity of the ice edge
490 (e.g. Johannessen et al., 1987; Gascard et al., 1988) through interactions between AW and
491 cold, fresh surface water below the ice, or via wind-induced Ekman pumping along the ice
492 edge. Such processes could have been instrumental for the energetic eddy field recorded in
493 summer 2018.

494 The PSY4 model suggested changes in Atlantic Water routes over the Yermak Plateau
495 from 2013 onwards (section 4.2., Athanase et al., 2021). Recirculation branches shifted to
496 the north, while the Yermak Pass Branch and the Yermak Branch (circulating respectively
497 over and around the western edge of the Plateau) intensified. Intermittently, a northern
498 branch of AW (NB) crossed the Yermak Plateau north of 81.8°N (Figure 1b).

499 PSY4 featured a larger AW YPB transport during the recent 2017-2020 period than in
500 2007-2008 (+ 40%), yet both values were below the 14-year mean. Interannual variations
501 were important (Figure 13) likely due to the variable partitioning of the AW inflow between
502 recirculations towards Fram Strait and branches over the Plateau (Figure 1b). For instance,
503 the striking AW transport minimum in the YPB in 2017-18 (Figure 13 and S3) corresponded
504 to larger recirculations recorded in Fram Strait at 80.2°N, 0°E (Hofmann et al., 2021).

505 Periods with negative net transports intermittently occurred each year except in 2014
506 and 2015 (red in Figure 13a). We investigated the circulation during the salient negative
507 transports (net transport < -0.7 Sv). Those occurred in winter. We selected events with
508 transport < -0.7 Sv (corresponding to 49 days in winter) and built a composite of velocity
509 fields (Figure 16). The composite showed a mesoscale structure leading to northward ve-
510 locities (> 6 cm/s) in the proximity of the mooring. Synoptic ocean conditions resembled
511 those depicted in Figure 11, with a very active mesoscale field associated with an intensified
512 Yermak Branch (YB) feeding the Northern Branch (NB) (Figure 1b) north of 81.8°N on the
513 Yermak Plateau. Coincidentally, an anticyclonic eddy impinged the Yermak Pass blocking
514 the flow impeding the Yermak Pass Branch. Those periods of "blocking of the YPB", with
515 net transport < -0.7 Sv, occurred more often after year 2016 likely in relation with the
516 increase of the eddy activity (Figure 13 a).

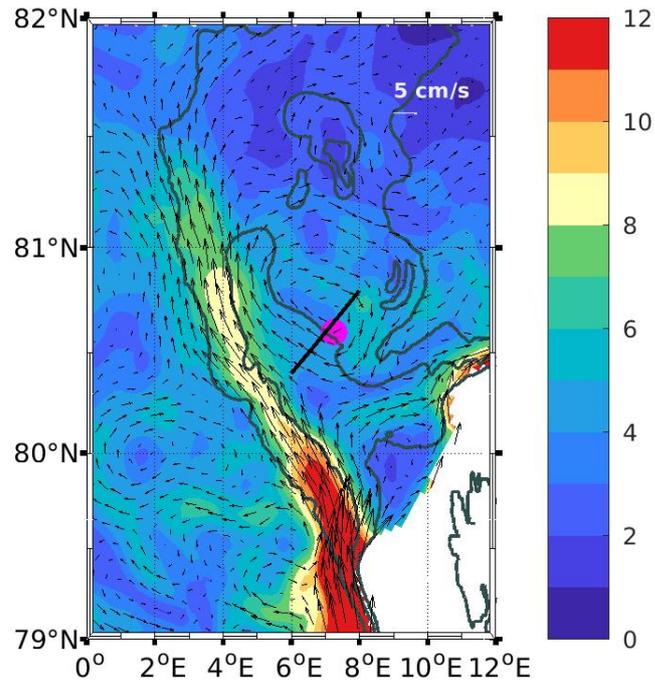


Figure 16. Velocity composite at 266 m associated with blocking events. The composite is built from velocities at dates with net transport < -0.7 Sv. 49 winter days are considered. Magenta dot indicates the mooring location and black line is the section used to compute the AW transport. Dark green contours are 1000-m, 700-m and 500-m isobaths.

6 Summary and conclusion

Ten years after a pioneering mooring deployment at the same location in 2007, the 2017-2020 mooring data documented the evolution of the Yermak Pass Branch under “new Arctic” conditions (e.g. Carmack et al., 2015). Indeed, while sea-ice was abundant in the area during the first 2007 deployment (mean ice concentration of 74% at the mooring location), the sea ice concentration was reduced over Yermak Pass during the second deployment (39%) (Figure 3). Time-scales larger than 50 hours were considered: high frequencies in the mooring observations will be examined in a subsequent study focusing on the large tidal and inertial activity over the Yermak Plateau (e.g. Fer et al., 2015).

The new mooring data in the Yermak Pass Branch documented larger velocity variations (40%) in 2017-2020 than in 2007. Within the recent period (2017-2020), year 2018 stood out with the exceptionally ice-free conditions and an enhanced eddy activity, possibly favored by the vicinity of the sea-ice edge.

Stringent comparisons of the Mercator Ocean operational system (PSY4) with the 2017-2020 mooring data confirmed the skills of the model in reproducing variations of water mass properties and velocities (for timescale larger than 20 days within the YPB). While PSY4 was less energetic than observations, the EOFs of modelled velocities were similar to those of the mooring data.

Daily outputs from PSY4 were used to put the observations in a broader spatio-temporal context within a 14-year period (January 2007 to December 2020). The model AW transport time series through Yermak Pass had synoptic values comprised between -1 and 5 Sv and showed large interannual and seasonal variations. The transport was larger in winter than in summer. PSY4 provided insights on anomalous winter northward velocity events recorded by the moored ADCP leading to transport lower than -0.7 Sv. We called those episodes “blocking events”. They were likely associated with eddy recirculations over the southern part of the Yermak Plateau, at a time of well-developed Yermak Branch and northern Branch at 81.8°N. These “blocking” episodes were more common after 2016 as the eddy activity intensified.

PSY4 provided further insights on the water properties recorded by the in situ instrument. PSY4 suggested that the recorded negative temperature and salinity trend observed in the YPB were temporary. The dense waters observed in January 2018 were coincident

548 with a long convective episode in PSY4 with deep mixed layers in excess of 400 m and heat
549 fluxes from the atmosphere to the ocean on the order of -600 W/m^2 . PSY4 also suggested
550 that the densest waters recorded on 7 July 2018 were associated with a mesoscale structure
551 coming from the Sofia Deep.

552 Temperature and salinity measurements were only available at one level in the water
553 column (348 m). Although additional instrumentation on the mooring line would have
554 helped understanding the dynamics of the Yermak Pass Branch, the model proved to be a
555 most useful tool to complement the in situ data. Such a synergy provided valuable insights
556 on the recent changes in the YPB, major route for the warm AW to the Arctic.

557 **Acknowledgments**

558 We are deeply grateful to the officers, crews and scientists onboard the Norwegian Research
559 Vessel Lance (deployment) and Norwegian ice breaker KV Svalbard (recovery). We thank
560 A. Sundfjord and J.C. Gascard for their constant support and help. Matthieu Labaste
561 (LOCEAN) was instrumental in mooring preparation and logistics. We thank the two
562 anonymous reviewers and the editor for their careful and constructive comments.

563 The field work was funded through the ANR EQUIPEX IAOS project through ANR-
564 10-EQX-32-01 grant and the ICE-ARC programme from the European Union 7th Frame-
565 work Programme, grant 603887. Camila Artana acknowledges support from a CNES postdoc
566 scholarship, Marylou Athanase from a postdoc funded by the BMBF research group Seam-
567 less Sea Ice Prediction and Zoe Koenig a postdoc from the Nansen Legacy Project (number
568 276730). Ava Asgari's master internship was supported through the Pan Arctic Options
569 Belmont Forum project (ANR-14-AORS-003-01).

570 The Mercator ocean global operational system is part of the Copernicus Marine En-
571 vironment Monitoring Service (CMEMS; <http://marine.copernicus.eu>). The mooring data
572 from 2007-2008 and 2017-2020 are available in the SEANOE data base: <https://doi.org/10.17882/83214>
573 and <https://doi.org/10.17882/51023>.

574 **References**

575 Aagaard, K. E. C. Carmack (1989), The role of sea ice and other fresh water in the arctic
576 circulation. *Journal of Geophysical Research, Oceans*. DOI:10.1029/JC094iC10p14485

577 Athanase, M., Sennéchael N., Garric G., Koenig Z., Boles E. & Provost C. (2019). New
578 hydrographic Measurements of the Upper Arctic Western Eurasian Basin in 2017 Reveal
579 Fresher Mixed Layer and Shallower Warm Layer Than 2005–2012 Climatology. *Journal of*
580 *Geophysical Research, Oceans*, DOI:10.1029/2018JC014701581

581 Athanase, M., Provost C., Pérez-Hernández M.D., Sennéchael N., Bertosio C., Artana
582 C., Garric G., Lellouche J.-M. (2020). Atlantic Water modification north of Svalbard in
583 the Mercator physical system from 2007 to 2020. *Journal of Geophysical Research, Oceans*,
584 DOI:10.1029/2020JC016463

585 Athanase, M., Provost C., Artana C., Pérez-Hernández M.D., Sennéchael N., Bertosio
586 C., Garric G., Lellouche J.-M., & Prandi P. (2021). Changes in Atlantic Water Circulation
587 Patterns and Volume Transports North of Svalbard Over the last 12 years (2008-2020).
588 *Journal of Geophysical Research, Oceans*, DOI:10.1029/2020JC016825.

589 Beszczynska-Möller, A., Fahrbach, E., Schauer, U., & Hansen, E. (2012). Variability in
590 Atlantic water temperature and transport at the entrance to the Arctic Ocean, 1997-2010.
591 *ICES Journal of Marine Science*. DOI:10.1093/icesjms/fss056

592 Cokelet, E. D., Tervalon, N., & Bellingham, J. G. (2008). Hydrography of the west
593 Spitsbergen Current, Svalbard Branch: autumn 2001. *Journal of Geophysical, Research:*
594 *Oceans*. DOI:10.1029/2007JC004150606

595 Crews, L., Sundfjord, A., Albretsen, J., & Hattermann, T. (2018). Mesoscale eddy
596 activity and transport in the Atlantic Water inflow region north of Svalbard. *Journal of*
597 *Geophysical Research, Oceans*. DOI:10.1002/2017JC013198

598 Crews, L., Sundfjord, A., & Hattermann, T. (2019). How the Yermak Pass Branch
599 regulates Atlantic Water inflow to the Arctic Ocean. *Journal of Geophysical Research:*
600 *Oceans*. DOI:10.1029/2018JC014476

601 Fer, I., M., Müller, & A. K. Peterson (2015). Tidal forcing, energetics, and mixing near
602 the Yermak Plateau. *Ocean Science*. DOI:10.5194/os-11-287-2015615

603 Gascard, J.-C., Kergomard, C., Jeannin, P.-F., & Fily, M. (1988). Diagnostic study of
604 the Fram Strait marginal ice zone during summer from 1983 and 1984 Marginal ice zone ex-
605 periment Lagrangian observations. *Journal of Geophysical Research, Oceans*. DOI:10.1029/jc093ic04p03613.

606 Gascard, J.-C., Richez, C., & Rouault, C. (1995). New insights on large-scale oceanog-
607 raphy in Fram Strait: The West Spitsbergen Current. In W.O. Smith, Jr., J. M. Greib-
608 meier (Eds.), *Arctic oceanography, marginal ice zones and continental shelves* (Vol. 49, pp.
609 131–182). Washington, DC: American Geophysical Union

610 Good, S.A., Martin M.J., & Rayner N.A. (2013). EN4 Quality controlled ocean tem-
611 perature and salinity profiles and monthly objective analyses with uncertainty estimates.
612 *Journal of Geophysical Research, Oceans*, DOI:10.1002/2013JC009067.

613 Hattermann, T., Isachsen, P. E., von Appen, W.-J., Albretsen, J., & Sundfjord, A.
614 (2016). Eddy-driven recirculation of Atlantic Water in Fram Strait. *Geophysical Research*
615 *Letters*. DOI:10.1002/2016GL068323623

616 Henley S.F., Porter M., Hobbs L., Braun J., Guillaume-Castel R., Venables E.J., Du-
617 mont E., & Cottier F. (2020). Nitrate supply and uptake in the Atlantic Arctic sea ice zone:
618 seasonal cycle, mechanisms and drivers. *Phil. Trans. R. Soc. A*, DOI:10.1098/rsta.2019.0361

619 Hofmann, Z., von Appen, W.-J., & Wekerle, C. (2021). Seasonal and mesoscale variabil-
620 ity of the two Atlantic Water recirculation pathways in Fram Strait. *Journal of Geophysical*
621 *Research, Oceans*. DOI:10.1029/2020JC017057

622 Holliday, N. P., Bersch, M., Berx, B., Chafik, L., Cunningham, S., et al. (2020). Ocean
623 circulation causes the largest freshening event for 120 years in Eastern Subpolar North
624 Atlantic. *Nature communications*. DOI:0.1038/s41467-020-14474-y

625 Ivanov, V., Smirnov A., Alexeev, V., Koldunov, N.V., Repina, I., & Semenov, V. (2018).
626 Contribution of convection-induced heat flux to winter ice decay in the western Nansen
627 Basin. *Journal of Geophysical Research, Oceans*, DOI:10.1029/2018JC013995.

628 Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J. A., Forbes, S., Fridman, B., &
629 Weatherall, P.(2012). The International Bathymetric Chart of the Arctic Ocean (IBCAO)
630 Version 3.0. *Geophysical Research Letters*,39. DOI:48010.1029/2012gl05221

631 Johannessen, J. A., Johannessen, O. M., Svendsen, E., Shuchman, R., Manley, T. O.,
632 Campbell, W. J., et al. (1987). Mesoscale Eddies in the Fram Strait Marginal Ice Zone
633 during the 1983 and 1984 marginal ice zone experiments. *Journal of Geophysical Research*,
634 DOI:10.1029/JC092iC07p06754

635 Koenig, Z., Provost, C., Sennéchaël, N., Garric, G., & Gascard, J.-C. (2017). The
636 Yermak Pass Branch: A major pathway for the Atlantic Water North of Svalbard? *Journal*
637 *of Geophysical Research, Oceans*. DOI:10.1002/2017JC013271631

638 Koenig, Z., Provost, C., Villaceros-Robineau, N., Sennéchaël, N., Meyer, A., Lellouche,
639 J.-M., & Garric, G. (2017). Atlantic Waters inflow north of Svalbard: Insights from IAOOS
640 observations and Mercator ocean global operational system during N-ICE 2015. *Journal of*
641 *Geophysical Research, Oceans*, DOI:10.1002/2016JC012424

642 Lellouche, J.M., Greiner, E., Le Galloudec, O., Garric, G., Regnier, C., Drevillon, M.,
643 Le Traon, P.-Y., et al. (2018). Recent updates to the Copernicus marine service global
644 ocean monitoring and forecasting real-time 1/12 high-resolution system. *Ocean Science*,
645 DOI:10.5194/os-14-1093-2018

646 Lundesgaard, Ø., Sundfjord, A., & Renner, A. H. H. (2021). Drivers of interannual sea
647 ice concentration variability in the Atlantic Water inflow region north of Svalbard. *Journal*
648 *of Geophysical Research, Oceans*, DOI:10.1029/2020JC016522

649 Lupkes, C., & Birnbaum, G. (2005). Surface drag in the arctic marginal sea-ice
650 zone:507a comparison of different parameterisation concepts.*Boundary-layer meteorol-508ogy*,117(2),
651 179–211. DOI: 10.1007/s10546-005-1445-8

652 Manley, T. (1995). Branching of Atlantic Water within the Greenland-Spitsbergen pas-
653 sage: an estimate of recirculation. *Journal of Geophysical Research, Oceans*,DOI:10.1029/95JC01251651

654 McDougall, T. J., P. M., Barker, (2011). Getting started with teos-10 and the Gibbs
655 seawater (gsw) oceanographic toolbox. SCOR/IAPSO WG, 127, 1–28

656 Mork, K.A., Skagseth Ø. & Søiland H. (2019). Recent Warming and Freshening of
657 the Norwegian Sea Observed by Argo Data. *Journal of Climate*. DOI:10.1175/JCLI-D-18-
658 0591.1

659 Nurser, A. J. G. & Bacon, S. (2014). The Rossby radius in the Arctic Ocean, *Ocean*
660 *Science*, 10, 967–975, DOI:10.5194/os-10-967-2014.

661 Onarheim, I. H., Smedsrud, L. H., Ingvaldsen, R. B., Nilsen, F. (2014). Loss of sea
662 ice during winter North of Svalbard. *Tellus A: Dynamic Meteorology and Oceanography*.
663 DOI:10.3402/tellusa.v66.23933

664 Padman, L., Plueddemann, A. J., Muench, R. D., & Pinkel, R. (1992). Diurnal tides
665 near the Yermak Plateau. *Journal Geophysical Research, Oceans*. DOI:10.1029/92JC01097

666 Pérez-Hernández, M. D., R. S., Pickart, D. J., Torres, F., Bahr, A., Sundfjord, R.,
667 Ingvaldsen, V., Pavlov, (2019). Structure, transport, and seasonality of the Atlantic Water
668 Boundary Current North of Svalbard: Results from a yearlong mooring array. *Journal of*
669 *Geophysical Research: Oceans*. DOI:10.1029/2018JC014759

670 Polyakov, I. V., Pnyushkov, A. V., Alkire, M. B., Ashik, I. M., Baumann, T. M.,
671 Carmack, E. C., et al. (2017). Greater role for Atlantic inflows on sea-ice loss in the
672 Eurasian Basin of the Arctic Ocean. *Science*. DOI:10.1126/science.aai8204681

673 Polyakov, I. V., Rippeth, T. P., Fer, I., Alkire, M. B., Baumann, T. M., Carmack, E.
674 C., et al. (2020). Weakening of cold halocline layer exposes sea ice to oceanic heat in the
675 Eastern Arctic Ocean. *Journal of Climate*. DOI:10.1175/JCLI-D-19-0976.1685

676 Richez C. (1998). The West Spitzbergen Current as seen by SOFAR floats during
677 ARCTEMIZ 88 Experiment: Statistics, differential kinematic properties, and potential vor-
678 ticity balance. *Journal of Geophysical Research, Oceans*. DOI:10.1029/97JC02412.

679 Teigen, S. H., Nilsen, F., Skogseth, R., Gjevik, B., & Beszczynska-Möller, A. (2011)
680 Baroclinic instability in the West Spitsbergen Current. *Journal of Geophysical Research,*
681 *Oceans*. DOI:10.1029/2011JC006974

682 Wekerle, C., Wang, Q., von Appen, W.-J., Danilov, S., Schourup-Kristensen, V.,
683 & Jung, T. (2017). Eddy-resolving simulation of the Atlantic Water circulation in the
684 Fram Strait with focus on the seasonal cycle. *Journal of Geophysical Research, Oceans*.
685 DOI:10.1002/2017JC012974