

27 Abstract

28 Siberian river water is a first-order contribution to the Arctic freshwater budget, with the
29 Ob, Yenisey, and Lena supplying nearly half of the total surface freshwater flux. However,
30 few details are known regarding where, when and how the freshwater transverses the vast
31 Siberian shelf seas. This paper investigates the mechanism, variability and pathways of the
32 fresh Kara Sea outflow through Vilkitsky Strait towards the Laptev Sea. We utilize a high-
33 resolution ocean model and recent shipboard observations to characterize the freshwater-laden
34 Vilkitsky Strait Current (VSC), and shed new light on the little-studied region between the
35 Kara and Laptev Seas, characterized by harsh ice conditions, contrasting water masses, straits
36 and a large submarine canyon. The VSC is 10-20 km wide, surface-intensified, and varies
37 seasonally (maximum from August-March) and interannually. Average freshwater (volume)
38 transport is $500 \pm 120 \text{ km}^3 \text{ a}^{-1}$ ($0.53 \pm 0.08 \text{ Sv}$), with a baroclinic flow contribution of 50-
39 90%. Interannual transport variability is explained by a storage-release mechanism, where
40 blocking-favorable summer winds hamper the outflow and cause accumulation of freshwater
41 in the Kara Sea. The year following a blocking event is characterized by enhanced transports
42 driven by a baroclinic flow along the coast that is set up by increased freshwater volumes.
43 Eventually, the VSC merges with a slope current and provides a major pathway for Eurasian
44 river water towards the Western Arctic along the Eurasian continental slope. Kara (and
45 Laptev) Sea freshwater transport is not correlated with the Arctic Oscillation, but rather
46 driven by regional summer pressure patterns.

47 1) Introduction

48 The Arctic Ocean receives nearly 11% of the earth's river runoff but contains only 1%
49 of the global volume of seawater [Shiklomanov et al., 2000]. The Arctic Ocean surface
50 freshwater flux is a large net input to the ocean, dominated by runoff from North American
51 and Eurasian Rivers [Aagaard and Carmack, 1989, Serreze et al., 2006]. Rivers discharge on
52 the shallow Arctic shelf seas, where different mixing processes produce moderately saline and
53 cold shelf waters. These eventually feed into (and below) the Arctic halocline [Aagaard et al.,
54 1981], insulating the ice cover from the warmer Atlantic-derived waters below. A recent
55 idealized Arctic Ocean model study [Spall, 2013] highlighted the role of freshwater from the
56 Arctic shelves in setting up horizontal salinity gradients across the continental slopes, which,
57 through the dominant impact of salinity on density, are a major driver for the Atlantic water
58 circulation.

59 The largest freshwater content (FWC) is found in the Canada Basin [Aagaard and
60 Carmack, 1989], where FW accumulates due to Ekman convergence under a predominant
61 anticyclonic atmospheric circulation [Proshutinsky et al., 2009]. FWC varies on interannual
62 and interdecadal time scales [Rabe et al., 2014], which has been linked to large-scale Arctic
63 indices of sea level pressure [Morison et al., 2012; Proshutinsky and Johnson, 1997] and to
64 changes in wind forcing [Giles et al., 2012]. Freshwater budgets, supported by hydrochemical
65 data [Alkire et al., 2010], suggest that ~70% of the Canada Basin's meteoric freshwater must
66 result from Eurasian Rivers [Yamamoto-Kawai et al., 2008; Carmack et al., 2008]. However,
67 the exact pathways and links between the Eurasian shelves and the Canada Basin remain
68 poorly understood.

69 Nearly 50% of the Arctic river water enters from three of the largest rivers on earth
70 over the vast Kara and Laptev Sea shelves from the Lena ($531 \text{ km}^3 \text{ a}^{-1}$), Ob ($412 \text{ km}^3 \text{ a}^{-1}$), and
71 Yenisey ($599 \text{ km}^3 \text{ a}^{-1}$; Figure 1) [Dai and Trenberth, 2002]. The discharge is highly seasonal
72 (Figure 2) and controls the summer stratification [Janout et al. 2013] and biogeochemical

73 environment on the Siberian shelves [Holmes et al. 2012]. The distribution and fate of the
74 river plumes is primarily dominated by winds in summer [Dmitrenko et al., 2005]. During
75 years with weak or predominantly westerly winds over the Laptev Sea, Lena River water
76 propagates into the East Siberian Sea and further along the coast toward Bering Strait
77 [Weingartner et al., 1999]. During summers with easterly or southerly winds, the plume
78 remains on the central and northern Laptev shelf, and is available for export into the Arctic
79 Basin [Guay et al., 2001].

80 The Siberian shelves are important ice formation regions. While polynyas are frequent
81 along most of the Laptev and East Siberian coasts, the Kara Sea polynyas are mainly
82 concentrated along the Novaya Zemlya coast and north of Severnaya Zemlya [Winsor and
83 Björk, 2000]. Landfast ice (LFI) can form along the northeast Kara Sea coast as early as in
84 November, and more consistently covers a larger region from February-June [Divine et al.,
85 2004]. Atmospheric conditions considerably affect LFI variability, where the largest extent
86 coincides with high pressure over the Arctic leading to cold offshore winds over the Kara Sea,
87 while cyclones favor a lesser LFI extent and earlier breakup in spring [Divine et al., 2005].
88 The increasing cyclonicity in the Arctic [Zhang et al., 2004] may in part explain the LFI
89 decrease in the Kara Sea by $\sim 4\%$ decade⁻¹ between 1976 and 2007, reported by Yu et al.
90 [2014]. A 5-year model study estimated an average ice volume flux out of the Kara Sea of
91 $220 \text{ km}^3 \text{ a}^{-1}$ [Kern et al., 2005], which is the equivalent of $\sim 200 \text{ km}^3$ of freshwater or \sim half of
92 the Ob's annual runoff.

93 The Kara Sea received considerable attention in the 1980's and 1990's, when
94 circulation and freshwater dispersion studies were designed to predict the fate, residence time,
95 and dilution of nuclear waste deposited in the region, which resulted in a large pool of
96 literature [Pavlov and Pfirman, 1995; Schlosser et al., 1995; Pavlov et al., 1996; Johnson et
97 al., 1997; Harms et al., 2000]. Summer surveys from the 1960's [Hanzlick and Aagaard,
98 1980] and 1990's [Johnson et al., 1997] observed a northward river plume dispersion during

99 summer. Numerical tracer experiments [Harms et al., 2000] found a similar summer
100 distribution and then a shoreward return of the plume under changing wind directions in the
101 fall. Model results [Harms and Karcher; 1999; Harms and Karcher, 2005; Panteleev et al.,
102 2007], in agreement with previous circulation schemes [Pavlov and Pfirman, 1995; Pavlov et
103 al., 1996], suggest that Vilkitsky Strait (VS) is a prominent pathway for the fresh coastal
104 waters carried within the West Taymyr Current (WTC). The WTC is assumed to wrap around
105 the Taymyr peninsula to continue southward as the East Taymyr Current [Pavlov et al., 1996],
106 which implies that the fresh Kara Sea waters are advected onto the Laptev Sea shelf.
107 However, a detailed Laptev Sea survey from September 2013 suggests that only a small part
108 of the northwestern Laptev Sea shelf is influenced by fresher Kara Sea waters with salinities
109 of ~30 (Figure 3). The provenance of the waters can be determined by dissolved neodymium
110 isotope compositions and preliminary analyses indicate that at least the central Laptev Sea
111 was almost exclusively dominated by Lena River water at that time (G. Laukert, pers.
112 comm.). The comparatively small amount of Kara Sea freshwater on the Laptev Sea shelf
113 may be explained by the region's bathymetry, which is far more complex than previously
114 considered. Immediately eastward of the ~200 m deep VS, the bathymetry deepens into a
115 large submarine canyon (Vilkitsky Trough, VT, see Figure 1). VT is a maximum of 350 m
116 deep, 80 km wide and more than 200 km long [Jakobsson et al., 2008]. Unfortunately,
117 detailed observations and published information from the canyon are missing, which may be
118 primarily due to the harsh ice conditions that often prevail in the region. In a numerical
119 circulation study, Aksenov et al. [2011] mention a fresh current that exits the Kara Sea
120 through VS, and eventually forms the near-surface part of a "pan-arctically persistent current"
121 propagating along the Arctic continental slopes. This proposed pathway of Kara Sea
122 freshwater is contrasted by a propagation along the inner Laptev Sea shelf, and urgently
123 requires observational evidence considering the implications of Siberian freshwater for the
124 Arctic Ocean.

125 The goal of this study is to shed light on the region between VS and the continental
126 slope along the northern Laptev Sea in order to understand the regional conditions and derive
127 their larger-scale importance for the Arctic Ocean. In particular, we aim to characterize the
128 fresh Kara Sea outflow, investigate its structure, seasonal and interannual variability, and
129 forcing mechanisms based on a high-resolution circulation model combined with recent
130 observations.

131 The paper is structured as follows. “Data and methods” are provided in section 2. The
132 results section 3 provides a characterization of the Vilkitsky Strait Current (section 3a),
133 associated volume and freshwater transports (section 3b), their variability and forcing
134 mechanisms (section 3c), observations and further pathways (section 3d), and finally the fate
135 of the Kara Sea freshwater (section 3e). The paper finishes with a discussion in section 4 and
136 summary in section 5.

137

138 **2) Data and methods**

139 a) Model

140 In this study we analyzed results from an Ocean General Circulation Model (OGCM)
141 developed under the Nucleus for European Modelling of the Ocean (NEMO) framework for
142 ocean climate research and operational oceanography (<http://www.nemo-ocean.eu>). The
143 NEMO configuration used here is a z-level global coupled sea ice-ocean model, which
144 includes the ocean circulation model OPA9 [Madec et al., 2011] and the Louvain-la-Neuve
145 sea ice model LIM2 [Fichefet and Morales Maqueda, 1997] updated with elastic-viscous-
146 plastic rheology. The ocean model is configured at 1/12 degree on a tri-polar Arakawa C-grid
147 with the model poles at the geographical South Pole, in Siberia and in the Canadian Arctic
148 Archipelago. The nominal horizontal resolution is ~3 km in the area of interest (Kara and
149 Laptev Seas and the eastern Eurasian Basin; Figure 1), 2-4 km in the central Arctic Ocean and
150 Canadian Arctic, and ~9 km in the rest of the ocean. The model is eddy-resolving in the

151 Arctic Ocean and eddy-permitting on the shelves [Nurser and Bacon, 2014]. The model has
152 75 vertical levels with 19 levels in the upper 50 m and 25 levels in the upper 100 m. The
153 thickness of top model layer is ~1 m, increasing to ~204 m at 6000 m. Following Barnier et
154 al. [2006], partial steps in the model bottom topography are implemented to improve model
155 approximation of the steep continental slopes. The high vertical resolution and partial bottom
156 steps in topography allow for better simulations of the boundary currents and shelf
157 circulation. The model has a non-linear ocean free surface, improving simulations of the sea
158 surface height. An iso-neutral Laplacian operator is used for lateral tracer diffusion and a bi-
159 Laplacian horizontal operator is applied for momentum diffusion. A turbulent kinetic energy
160 closure scheme is used for vertical mixing [Madec et al., 2011]. The model has been
161 successfully used in several studies of the Arctic Ocean [Lique and Steele, 2012] and the
162 North Atlantic [Bacon et al., 2014]. Amongst the known biases are a ~10% higher than
163 observed sea ice concentration and a 7% higher inflow through Bering Strait [Woodgate et al.,
164 2012].

165

166 b) Observations

167 Conductivity-Temperature-Depth (CTD) measurements from the Laptev Sea originate
168 from several different expeditions. In 2004 and 2005, CTD transects were taken during the
169 NABOS (Nansen and Amundsen Basins Observational System) program aboard the research
170 icebreaker *Kapitan Dranitsyn* using a Seabird 19plus profiler. Accuracies for temperature and
171 conductivity are 0.005°C and 0.0005 Sm⁻¹, respectively. VT sampling in 2011 was carried out
172 during “TRANSARC” aboard *RV Polarstern*, using a Seabird SBE911 CTD with accuracies
173 of 0.001 °C and 0.0003 Sm⁻¹ for temperature and salinity, respectively (data published in
174 Schauer et al., [2012]). *Polarstern* operates a 75 kHz vessel-mounted Acoustic Doppler
175 Current Profiler (ADCP), which provides along-track velocity profiles in 8 m bins with an
176 accuracy of 3 cm s⁻¹. In September 2013, the Transdrift-21-expedition to the Laptev Sea was

177 carried out aboard *RV Viktor Buinitskiy* within the framework of the Russian-German “Laptev
178 Sea System”-program. Temperature and salinity transects were carried out using an Ocean
179 Science underway (U-)CTD system, which allows profiling while the ship is in transit. The U-
180 CTD sensors are manufactured by Seabird and provide accuracies of 0.0004 °C and 0.002-
181 0.005 S m⁻¹ at a sampling frequency of 16 Hz. The sensors operate in free-fall mode with a
182 non-constant sinking velocity, and subsequent salinity computations require careful alignment
183 of conductivity and temperature samples. The U-CTD post-processing followed the
184 recommendations of Ullmann and Hebert [2014].

185

186 3) **Results**

187 a) *Structure, seasonality and pathway of the Vilkitsky Strait Current*

188 A state-of-the-art numerical model (NEMO) with a proven track-record in simulating
189 Arctic Ocean circulation features was investigated for the circulation in the Kara Sea outflow
190 region around VS and the western Laptev Sea (Figure 4). Based on long-term (1990-2010)
191 mean October velocities, the model shows the variable Western Taymyr Current (WTC) in
192 the eastern Kara Sea, which carries western Kara Sea waters mixed with river water along-
193 shore in agreement with Pavlov and Pfirman [1995]. Upon reaching the narrowing strait, the
194 WTC intensifies and continues eastward, first along the southern edge of VT, and then along
195 the continental shelf break of the northern Laptev Sea. In VS, the diffuse WTC develops into
196 a strong and well-defined current, which we henceforth refer to as the Vilkitsky Strait Current
197 (VSC). The VSC is swift and narrow (10-20 km) and propagates eastward along the slopes
198 surrounding the Laptev Sea (Figure 4). During the first 200 km of its propagation along VT
199 the velocities decrease with depth, but increase again once the VSC reached the Laptev
200 continental slope, presumably due to the interaction with other slope currents such as
201 described by Aksenov et al. [2011].

202 Climatological sections of currents (Figure 5) and salinity (Figure 6) across VS reveal
203 the vertical and horizontal structure and seasonal development of the VSC. Cross-strait
204 velocities show a pronounced surface-intensified jet on the strait's south side, with maximum
205 velocities of $>0.5 \text{ m s}^{-1}$ during October-December. The jet is ~ 20 km wide, most intense in the
206 upper 20 m and clearly defined to a depth of 80-100 m from July through March, while it is
207 nearly absent from April – June. The structure of the geostrophic velocities (referenced to the
208 bottom;not shown) computed from the model's density cross-section is identical to that of the
209 current magnitude (Figure 5). Average monthly (0-60m) geostrophic velocities are 10-30%
210 (summer and fall) to 50% (spring) smaller than the total velocities (Figure 7). The baroclinic
211 flow constitutes $70\% \pm 13\%$ of the currents in VS and implies that the flow is largely
212 buoyancy-driven, which explains the strong coupling of the jets' magnitude and structure to
213 the seasonal freshwater cycle of the Ob and Yenisey (Figure 2) and the cross-strait salinity
214 (Figure 6). Discharge of both rivers peaks in June and subsequently decreases to the minimum
215 runoff rates from November-April (Figure 2). The ~ 3 -month-lag between peak runoff in June
216 and maximum VS velocities in fall may be explained by the time it takes the freshwater to
217 cover the distance of 700-900 km from the rivers' estuaries to VS.

218 Salinities are markedly lower on the south-side of VS (Figure 6), with minimum
219 values of ~ 29 from October-January. During this time, across-strait isohalines have the
220 steepest slopes corresponding to maximum velocities. Isohalines level out during spring,
221 when surface salinities are maximum (~ 31 - 32), and velocities are minimum. Upper-ocean
222 temperatures in VS (not shown) are near-freezing year-round except from July–September,
223 when the climatological mean reaches ~ 2 °C on the strait's south side in the core of the VSC.
224 Deeper waters in VS are warmer (> -1 °C) and more saline (34.5-34.8), and influenced by
225 Barents Sea Branch water [Rudels, 2012], which is found in the canyon east of VS as will be
226 shown later.

227

228 *b) Freshwater and volume transport through Vilkitsky Strait*

229 Transports across VS were quantified based on NEMO results. Volume transport F_{Vol}
230 is computed according to:

$$231 \quad (1) F_{Vol} = \int u dA,$$

232 where u is the cross-strait velocity and A the area of the strait's cross section. Liquid
233 freshwater transport F_{FW} is estimated using:

$$234 \quad (2) F_{FW} = \int u \times \frac{S_{ref} - S}{S_{ref}} dA,$$

235 where S is the salinity and a reference salinity $S_{ref}=34.80$, following Aagaard and Carmack
236 [1989].

237 Applying (1) and (2) to monthly velocity and salinity from the 21-year simulation
238 results in volume and freshwater transports that strongly resemble each other, as well as a
239 seasonal cycle that is clearly governed by the seasonality in the VSC (Figure 7). Monthly-
240 mean transports are small during spring and early summer, with a minimum in May in volume
241 and freshwater transport of 0.2 ± 0.15 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) and 4.8 ± 3.6 mSv, respectively.
242 Transports increase in late summer/early fall to become maximum in December/January, with
243 monthly-mean transports of 0.85 ± 0.30 Sv (26.4 ± 11.8 mSv). The average volume and liquid
244 freshwater transports through VS over 21 years of NEMO simulation are 0.53 ± 0.08 Sv and
245 $497 \pm 118 \text{ km}^3 \text{ a}^{-1}$, respectively.

246 The mean annual freshwater transport through VS accounts for nearly half of the Kara
247 Sea's annual river runoff, and hence the VSC provides a significant amount of freshwater to
248 the western Laptev Sea shelf and slope region. As shown above, transports vary seasonally
249 with maxima in late fall, but in addition feature considerable interannual variability (Figure
250 8). The 2-decade-long transport record suggests a volume transport that peaks at 1.5 Sv down-
251 strait, such as in late 2001 and in early 2005 (Figure 8), with occasional reversals (i.e. up-

252 strait transports). In high-flow years, maximum flow in peak transport months can be more
253 than twice the average transport. In low-flow years, maximum flow may only be half as much
254 as the average.

255 The dominant baroclinic nature of the VSC explains the close resemblance of the
256 volume and freshwater transports (Figure 8) and hence a considerable range in the baroclinic
257 flow fraction. While only ~30% of the flow appears to be baroclinic during low transports in
258 2004, a baroclinicity of >95% occurs in 2008 and 2009. Overall, the interannual variability in
259 volume and freshwater transport is large enough to play a significant role for the regional and
260 larger-scale freshwater distribution.

261

262 *c) Interannual transport variability and atmospheric forcing*

263 The transports (Figure 9a) have negative anomalies during several years such as in
264 1990, 1993, 1998, 2004, and 2010, with values that are up to 0.2 Sv below average for several
265 months. Our modeled salinity/freshwater content anomaly fields during these years shows
266 considerably more freshwater in the western Kara Sea along Novaya Zemlya's east coast, as
267 well as less freshwater in the northeastern Kara Sea along the Taymyr peninsula toward VS in
268 summer and fall (Figure 10). The corresponding Arctic-wide NCEP [Kalnay et al., 1996] sea
269 level pressure patterns and the resulting wind fields over the Kara Sea show anomalously
270 northerly winds during each of these minimum transport periods, often accompanied by
271 enhanced easterly winds (Figure 9b). These conditions favor the advection of river water
272 towards the west, and at the same time a reduction of the VS outflow. These results confirm
273 and expand on a previous study [Harms and Karcher, 2005], which described wind-forced
274 blocking of the VS outflow in 1998 based on a 5-year-long Kara Sea simulation.

275 Blocking-favorable winds develop under the influence of either a summer high
276 pressure system over the Barents and western Kara Seas and/or a low over the northern
277 Laptev Sea (Figure 9). In the summer after a year with blocking conditions, the runoff gets

278 added to accumulated freshwater and sets up an enhanced northeastward baroclinic flow
279 along the coast in late summer, which may explain why years with negative transport
280 anomalies are followed by years with enhanced volume and freshwater transports (Figures 8
281 and 9). The residence time for Kara Sea river water is between 2.5 years [Hanzlick and
282 Aagaard, 1980] and 3.5 years [Schlosser et al., 1994], and considering that the annual mean
283 modeled freshwater transport through VS is only ~half of the annual discharge from Ob and
284 Yenisey, the fate of a significant portion of river water remains uncertain. The Kara Sea's
285 only wide opening is to the north between Novaya Zemlya and Severnaya Zemlya, which,
286 based on our results and previous simulations [Panteleev et al., 2007] is bounded by the strong
287 influence of the Barents Sea throughflow (Figure 1b) at least on climatological time scales.
288 For further insights into the Kara Sea-internal conditions during blocking-years, we computed
289 summer volume and freshwater transports across all major Kara Sea openings (Figure 11).
290 Volume transports in particular indicate a larger-scale effect of these blocking situations such
291 as in 1993, 1998 or 2004, when the largest transport reductions of nearly 0.5 Sv occurred in the
292 Barents Sea opening and the northern Kara Sea. This is plausible considering that the
293 corresponding pressure systems (Figure 9) favor an Ekman transport against the east- and then
294 northward flow of the Barents Sea outflow. At the same time, the inflow through Kara Gate is
295 reduced. In contrast, both volume and freshwater transports across the opening between
296 Novaya Zemlya and Severnaya Zemlya (Figure 11) are slightly elevated during blocking
297 years, which indicates that ~one-third (e.g. 1993 and 1998) of the negative freshwater
298 transport anomaly exits through the northern Kara Sea instead of VS, while the larger share
299 remains in the Kara Sea. Overall, our simulations largely agree with previous studies
300 [Panteleev et al., 2007] and highlight the importance of the narrow VS as the major Kara Sea
301 freshwater gateway.

302 The concept of a simple (atmospherically-forced) storage-release mechanism is
303 supported by two hydrographic cross-slope transects across the presumed pathway of the VSC

304 in the northern Laptev Sea along 126°E occupied during the 2004-blocking and 2005-release
305 years (Figures 1 for location; Figure 12). In 2004, salinities above the slope were
306 comparatively high (>30), concurrent with an atmospheric “blocking” pattern and reduced VS
307 model outflow. In the following year, the waters were significantly fresher (~28),
308 representative of enhanced volume and freshwater transports in the simulation.

309 Meridional summer winds over the eastern Kara Sea appear to influence the variability
310 of volume and freshwater transport through VS. Therefore, we decompose monthly mean
311 reanalyzed SLP from 60-90°N into their principal components by use of empirical orthogonal
312 function (EOF) analysis to identify the dominant modes of variability in Arctic atmospheric
313 patterns and their relation with Siberian shelf processes. The decomposition results in three
314 leading EOF modes, which explain 54.6 %, 12.5 % and 9.1 % of the variance in mean July-
315 September SLP, similar to findings by Overland and Wang [2010]. The first mode is identical
316 to the Arctic Oscillation [Thompson and Wallace, 1998], and describes the strength of the
317 polar vortex. The second highlights the Arctic Dipole Anomaly [Wu et al., 2006], which
318 favors a transpolar circulation from Siberia towards Fram Strait. Both patterns have the
319 largest signals during winter and show no apparent correlation with VS transports.
320 Considering that river discharge and wind-driven currents are maximum in the open water
321 season and when sea ice is thin and mobile, we find that the VS transports best correspond to
322 the third mode (EOF3). This mode is slightly more pronounced during summer (9.1 %) than
323 winter (6.9 %) and describes a pressure pattern centered approximately half-way between the
324 New Siberian Islands and the North Pole (Figure 13), and was previously linked with the
325 freshwater distribution on the Laptev Sea shelf [Dmitrenko et al., 2005; Bauch et al., 2011].

326 Positive EOF3 patterns within the 1990-2010 simulation period coincide (although not
327 statistically significant) with minimum modeled VS transports (Figures 8 and 9), such as in
328 1993, 1998, 2004, and 2010. Larger-scale pressure systems are not necessarily stationary and
329 minor shifts may cause different winds in the topographically complex eastern Kara Sea,

330 which may in part explain the weak correlations. Further, average summer winds are weaker
331 and may not prevent the establishment of a predominantly buoyancy-driven outflow with the
332 VSC. The mean summer SLP during anomalously positive patterns highlights a cyclone,
333 which leads to predominantly shoreward winds in the eastern Kara Sea and along-shore winds
334 in the Laptev Sea (Figure 13). Overall, the implications of cyclonic vs. anticyclonic patterns
335 are considerable for the distribution of Lena, Ob and Yenisey waters. Cyclonic conditions
336 block the Kara Sea outflow and favor an eastward removal of Lena water, which enhances the
337 positive salinity anomaly in the northern Laptev Sea (Figure 13), possibly supported by wind-
338 driven onshelf transport of more saline basin water. The opposite occurs during anticyclonic
339 conditions, which enhance the accumulation of freshwater in the northern Laptev Sea due to
340 both a northward diversion of the Lena River plume and an unhampered outflow of fresh Kara
341 Sea waters through VS, likely favoring an export of Siberian river water into the Eurasian
342 Basin.

343

344 *d) The further pathways and observations in Vilkitsky Trough*

345 Upon exiting VS, the VSC encounters the complex topography of VT with its steep
346 slopes and strong gradients in water mass properties between canyon and Laptev Sea shelf.
347 Along the Laptev shelf-canyon edge, the model features a topographically-guided VSC while
348 the subsurface waters inside the canyon are influenced by recirculating Barents Sea water (not
349 shown). A high-resolution shelf-to-canyon transect was occupied in September 2013 using an
350 underway CTD system (Figure 14). The entire transect is characterized by a sharp halocline,
351 separating the fresh (<31) surface waters from the more saline (>33) waters below 30 m.
352 Surface temperatures are highest (>3°C) on the shelf and low over the slope and canyon,
353 which is likely due to the presence of sea ice in and west of VS at the time of sampling.

354 The interior canyon waters between 100-250 m feature maximum salinities of 34.8
355 and temperatures around 0°C, characteristic for the water mass properties that exit the Barents

356 Sea through the eastern side of St. Anna Trough [Schauer et al., 1997, Schauer et al., 2002,
357 Dmitrenko et al. 2014]. Considering that the Barents Sea waters are transported along the
358 Eurasian slope in the Barents Sea branch [Rudels et al., 1999; Rudels et al., 2000, Aksenov et
359 al. 2011], it is plausible to find that these waters followed the topography into the
360 dynamically-wide VT, where the canyon width of 50-80 km is much larger than the first
361 baroclinic Rossby Radius (~ 4 km, Nurser and Bacon [2014]).

362 Near the base of the canyon's slope, isotherms and isohalines become vertical, which
363 translates into a distinct boundary layer at the slope favorable for baroclinic flow. The upper
364 50-100 m above the slope feature clearly depressed isohalines, which implies the presence of
365 enhanced amounts of freshwater directly above the slope. Geostrophic velocities based on the
366 hydrographic structure imply surface-intensified currents above the shelf edge as well as in a
367 thin boundary layer on the slope. A similar velocity structure was measured with a vessel-
368 mounted ADCP from a cross-canyon transect in September 2011 (Figure 15). Maximum
369 along-canyon velocities of 25 cm s^{-1} were measured over the south-side of VT, suggesting
370 that the southern edge of VT is indeed a region carrying waters that exited the Kara Sea in a
371 surface-enhanced current.

372 The volume transport through VT at this location amounts to 0.53 Sv, based on a
373 canyon width of 75 km, an average depth of 250 m, and average down-canyon velocities of
374 0.03 m s^{-1} . This estimate may be low, since the vmADCP misses the strongest flow generally
375 found in the upper 20 m, but provides a first observation-based transport estimate from VT,
376 which is close to NEMO's average VS volume transport. The hydrographic cross-canyon
377 structure from 2011 (Figure 15) is similar to the one measured in 2013, with strong shelf-to-
378 canyon gradients and canyon temperature-salinity-properties that imply Barents Sea origin
379 ($34.8, \sim 0^\circ\text{C}$). Overall, these observations confirm the existence of a current coming out of the
380 Kara Sea and hence lend support to NEMO's physically plausible suggestions and underline
381 the importance of the VT region for the Eurasian Slope and Basin.

382

383 *e) On the fate of the Kara Sea freshwater*

384 The fate of $\sim 500 \text{ km}^3$ of freshwater exiting VS per year is clearly of regional
385 importance, but may also impact the larger-scale Arctic freshwater distribution. To investigate
386 the impact of the VSC on the Arctic continental slope currents near the mouth of VT, we
387 extracted three transects from the model domain: 1) upstream; 2) mouth; 3) downstream of
388 VT (Figure 16). The current speed in the “upstream” transect shows a narrow and swift slope-
389 current, with maximum velocities below 100 m and only a weak surface signature. The slope
390 current originates from St. Anna Trough and carries Barents Sea water around the Arctic, and
391 was previously described in detail as the ASBB (Arctic Shelf Break Branch) by Aksenov et
392 al. [2011]. Transect 2 still shows the ASBB as a subsurface feature, and additionally
393 highlights the surface-intensified VSC in the southwestern part of the transect, as it crosses
394 the slope and the outer edge of the northwest Laptev Sea and canyon. Downstream, i.e. east of
395 the canyon mouth (transect 3), the model shows a unified current, which continues along the
396 continental slope as a combination of the near-surface VSC and the sub-surface ASBB. The
397 current now carries Barents Sea branch water at depth and Kara Sea freshwater in the upper
398 layer, reflected by a (0-50 m) freshwater content that is on average $\sim 75\%$ larger in transect 3
399 compared with transect 1.

400 Aksenov et al. [2011] previously suggested that nearly 80% of this current propagates
401 along the continental slope into the western Arctic, which (if these results hold in reality)
402 would make it a primary pathway for Siberian river water into the Canada Basin and toward
403 the freshwater storage system of the Beaufort Gyre [Proshutinsky et al., 2009]. The
404 contribution from Eurasian Rivers to the Canada Basin’s meteoric freshwater is estimated to
405 be as large as 70% [Yamamoto-Kawai et al., 2008; Carmack et al., 2008], although a clearly
406 defined pathway along the Eurasian slope has not been observed despite numerous
407 expeditions into the Arctic Ocean in the recent decades. One explanation may be that usual

408 sampling strategy in large-scale surveys could easily miss a narrow current such as the one
409 described here. A similar current along the Beaufort Sea slope with horizontal scales of 10-15
410 km was observed with hydrographic observations [Pickart et al., 2004] and a high-resolution
411 mooring array [Spall et al., 2008; Nikolopoulos et al., 2009], which provides an excellent
412 example for the benefits of finer-scale sampling. The 2013 cross-slope U-CTD transects
413 resolved the shelf break region with a maximum horizontal resolution of 3-6 km near 113°E
414 and 116°E (Figure 14). Both transects resolve a front located in a narrow band between the
415 slopeward edge of the warmer (Barents Sea branch) water and the slope, most pronounced
416 below 100 m depth. Isotherms are vertical in the front, with horizontal temperature gradients
417 of up to 2°C over less than 10 km. These transects highlight a density structure that is
418 favorable for maintaining a geostrophic baroclinic flow along the continental slope as
419 suggested by the model, and underline the need for more modern sampling strategies that
420 allow better resolution of these narrow fronts.

421

422 **4) Discussion**

423 The aim of this paper is to characterize the VSC including its transports and variability
424 on seasonal and interannual time-scales, and we therefore provide only limited insights into
425 processes that occur on shorter (tides to storms) time scales. On seasonal scales, the VSC is a
426 stable current that (in the model) steadily flows from the origin in VS all the way into the
427 Canada Basin. However, along its path the VSC experiences sudden topographic changes near
428 the mouth of VT (see Figure 1) where it is also exposed to fast-propagating Arctic storms,
429 both conditions which are favorable for generating barotropic and baroclinic instabilities.
430 Instabilities in a buoyant current can generate eddies which may transport some of the Kara
431 Sea freshwater into the Eurasian Basin and potentially modify our conclusions gained in this
432 paper, and should therefore be subject to future investigations.

433 Sea ice-ocean models including the one used in this study generally do not correctly
434 implement landfast ice (LFI) [Proshutinsky et al., 2007], which might affect certain aspects of
435 the coastal ocean circulation. For instance Itkin et al. [2015] discussed consequences of LFI
436 on brine formation and river water pathways in the Laptev Sea based on a simple LFI
437 parameterization in a regional circulation model. Kasper and Weingartner [2015] investigated
438 the effect of LFI on a river plume along a straight shelf such as the Alaskan Beaufort Sea with
439 an idealized model. They found that introducing LFI enhanced vertical mixing due
440 to frictional coupling between ice and river plume and resulted in a subsurface velocity
441 maximum and a seaward displacement of the plume. Johnson et al. [2012, hereafter J12]
442 implemented LFI in a model by not allowing sea ice to move from November-May in regions
443 shallower than 28 m, and found an ice thickness decrease in parts of the Siberian shelves
444 (most noticeable between the eastern Laptev and the western Chukchi Sea) relative to a
445 control run without LFI. J12 explained their findings by slower (thermodynamic) ice growth
446 because LFI inhibits ice ridging and deformation.

447 Since significant parts of the northeastern Kara Sea are covered by LFI in winter and
448 spring [Divine et al. 2004], we investigated the previous model results from J12 in more detail
449 in order to obtain qualitative insights regarding the role of LFI on VS transports. We
450 compared the volume and freshwater transports in VS from both experiments (LFI and the
451 control run) described in J12, and found only marginal differences in the volume transports
452 (2% in summer June-October, <1% from December-March). Freshwater transports were $11 \pm$
453 7% larger in summer-fall (June-October), and $15 \pm 4\%$ smaller in the winter-spring
454 (December-March) with an implementation of LFI, thus the seasonal cycle of the transports is
455 reduced in the LFI simulations. The LFI parameterization in the model inhibited ice export in
456 the Eastern Kara Sea (predominantly north-eastward towards the Nansen Basin in the control
457 run), increasing ice divergence and open water at the outer LFI edge. The effect of the LFI
458 parameterization was such that ice production and salt fluxes in winter and spring were
18

459 moderately reduced near the LFI-covered coast, but greatly enhanced at the outer LFI edge,
460 thus overall reducing VS freshwater transport in the LFI run. While we cannot necessarily
461 expect a realistic representation of LFI with a simple parameterization, this comparison
462 indicates that the absence of LFI on the southern Kara and Laptev Sea shelves moderately
463 increases the uncertainty in our results, although it is not detrimental for the presented
464 conclusions. A more physical representation of LFI should be considered in future model
465 studies.

466 Tides are not implemented in our study, and although tides are generally small in the
467 Arctic [Padman and Erofeeva, 2004], some shelf regions such as the Laptev Sea feature
468 substantial tidal currents with the potential to increase vertical mixing [Janout and Lenn,
469 2014]. A similar conclusion is reached by model studies regarding the role of tides on Arctic
470 hydrographic properties [Luneva et al., 2015], which found indications for enhanced tide-
471 induced mixing manifested by colder and fresher bottom waters in parts of the Kara Sea.
472 However, tidal currents are weak along the northeastern Kara Sea coast and the VSC pathway
473 in VT [Padman and Erofeeva, 2004] and north of the Laptev Sea [Pnyushkov and Polyakov,
474 2011] and likely would not noticeably affect the properties of the VSC. Therefore, we expect
475 that our conclusions regarding the pathway of the VSC and the Siberian freshwater are not
476 substantially biased by neglecting the tides.

477 Our results suggest that a considerable portion of the Kara Sea freshwater enters the
478 Laptev Sea and Eurasian continental slope region in a pronounced surface-intensified current,
479 which strongly varies on seasonal and interannual time scales. The estimated $\sim 500 \text{ km}^3 \text{ a}^{-1}$
480 only account for the liquid freshwater portion, while an additional part of the Kara Sea
481 freshwater may leave the shelf as sea ice. However, the Siberian shelves are vast and often
482 ice-free during recent summers. Satellite-based studies showed that sea ice formed in the river
483 plume near the Lena Delta region is not exported into the Basin but rather melts on the shelf
484 [Krumpfen et al., 2013], which supports the assumption that the majority of freshwater is

485 exported in its liquid phase, at least in the Laptev Sea. Mean model-based Kara Sea ice export
486 estimates are $220 \text{ km}^3 \text{ a}^{-1}$ [Kern et al., 2005], although the recent advances to remotely sense
487 sea ice thickness may allow more robust ice volume fluxes in the future.

488 The VS freshwater transport alone, computed as the freshwater anomaly relative to a
489 salinity of 34.8 [Aagaard and Carmack, 1989], comprises ~30% of the Pacific freshwater
490 inflow through Bering Strait [Woodgate et al., 2012]. However, our estimate is low since
491 additional smaller export pathways through the Severnaya Zemlya islands as well as sea ice
492 export were not considered. Further, the model uses climatological mean river discharge [Dai
493 and Trenberth, 2002] and does not consider observed trends or interannual variability in
494 runoff [Peterson et al., 2002]. These, however, are small ($O(10\%)$) compared with the
495 atmospherically-controlled VS freshwater transport variability ($O(50\%)$). The Kara Sea
496 outflow is regulated by pressure patterns that may simultaneously affect the distribution of the
497 Laptev Sea freshwater. Figures 9 and 13 indicate that onshore winds in the Kara Sea block the
498 VS outflow, while along-shore winds near the Lena Delta export freshwater into the East
499 Siberian Sea. This implies that larger-scale pressure systems during summer may primarily
500 control the distribution and fate of three of the earth's largest rivers. Morison et al. [2012]
501 observed an increase in Canadian Basin freshwater along with a decrease in Eurasian Basin
502 freshwater, which they attributed to alterations in the pathways of Siberian river runoff under
503 varying AO conditions. Similarly, Steele and Ermold [2004] linked decadal salinity trends on
504 the Siberian shelves to the AO. Panteleev et al. [2007] related moderately elevated VS
505 transports in their assimilation model to anomalous westerly winds over the Kara Sea
506 prevalent during positive summer AO conditions. In contrast, the interannual variability in
507 Arctic Ocean freshwater storage in recent decades does not noticeably relate to the AO, but
508 rather corresponds to changes in regional wind and ocean circulation [Rabe et al., 2014].
509 Similarly, our VS transports show no obvious relationship with summer or winter AO, which

510 indicates that, as earlier studies suggest [Bauch et al., 2011], regional conditions dominate the
511 Siberian freshwater pathways.

512 The open water season is crucial in shaping the hydrographic conditions, as this is the
513 time of the year of maximum river discharge, baroclinic flows develop, and wind stress
514 imparts advection and vertical mixing. The recent years were characterized by freeze-ups that
515 were delayed well into October, which leaves the ocean under a prolonged and stronger
516 influence of fall storms. A continuation of this trend might potentially alter the predominantly
517 baroclinic structure of the VSC and enhance synoptic-scale horizontal and vertical freshwater
518 dispersion, which makes the pathways and distribution of Siberian freshwater depending more
519 on the local variability of the wind patterns and less on the continental freshwater discharge.

520

521 **5) Summary and conclusion**

522 This paper characterizes the Vilkitsky Strait Current (VSC) including its volume and
523 freshwater transports and their seasonal and interannual variability based on a well-resolved
524 (~3 km) numerical model (NEMO) complemented by recent shipboard observations. The
525 surface-intensified 10-20 km-wide VSC is the continuation of the variable West Taymyr
526 Current in the eastern Kara Sea and the primary pathway to carry river runoff from the Kara
527 Sea through Vilkitsky Strait (VS) and subsequently along Vilkitsky Trough (VT) and the
528 continental slope along the Laptev Sea (Figure 4). Some recent shipboard surveys from VT
529 across the presumed VSC pathway qualitatively confirm the existence of enhanced flow and
530 lower salinity waters over the southern canyon slope (Figures 14 and 15), although a direct
531 comparison with model results is not possible due to non-overlapping time periods. The VSC
532 is strongest during October-March and nearly recedes from April-July (Figures 5-7), with
533 annual mean volume and freshwater transports of 0.53 ± 0.08 Sv and 497 ± 118 km a⁻¹,
534 respectively, based on a 21 year simulation. The VSC is predominantly buoyancy-driven, with
535 a fraction of baroclinic to total flow that varies from ~50% in spring to ~90% in fall.

536 Strong interannual VSC transport variability is explained by a storage-release
537 mechanism, which is dominated by atmospheric pressure patterns during summer (Figures 9
538 and 13), when winds have the maximum impact on the river plume distribution. Minimum
539 transports occur, when northerly or northeasterly winds due to a low pressure system north of
540 the Laptev Sea prevent the along-coast spreading of freshwater and block the outflow through
541 VS. The blocking accumulates freshwater on the shelf, which is then released in the following
542 year when the next pulse of runoff gets added and sets up an along-shore baroclinic flow
543 toward VS. The same pattern causes westerly winds over the Laptev Sea, which then favors
544 the removal of Lena water towards the East Siberian Sea, and overall strengthens a positive
545 salinity anomaly in the northern Laptev Sea (Figure 13).

546 The model suggests that upon arrival at the canyon mouth, the VSC merges with the
547 Barents Sea Branch of the Arctic Boundary Current (Figure 16), and subsequently follows the
548 Eurasian continental slope into the Canadian Basin. The interaction between these two
549 baroclinic currents is not understood and requires a closer investigation. If these results hold,
550 the VSC would be a primary pathway for Siberian river water towards the Beaufort Gyre
551 freshwater storage system, and would hence impact Arctic freshwater distribution. Our
552 conclusions here are mainly based on long-term mean model results. These are qualitatively
553 supported by the few observations that exist from this region that is characterized by complex
554 bathymetry (straits, submarine canyon, steep slopes), multiple contrasting water masses,
555 difficult sea ice conditions, and the largest river discharge to be found in the Arctic. The
556 measurements presented in this paper underline the need for modern sampling strategies to
557 better resolve fronts and baroclinic currents, regional features that occur on small enough
558 scales to be missed by classic large-scale surveys, but which may explain missing links in the
559 Arctic Ocean system.

560 Clearly, further steps have to be taken to investigate the stability of the VSC and
561 associated freshwater fluxes to obtain more reliable budgets and, perhaps more importantly, to

562 identify “hotspots”, where eddy fluxes export the shelves’ freshwater to the Arctic interior.
563 Eddy fluxes are assumed to supply the Arctic halocline waters as well as to provide the
564 potential energy needed to drive the cyclonic boundary current [Spall, 2013], and the only
565 way to investigate these further is by use of high-resolution numerical models, ideally
566 supported by high-resolution year-round measurements.
567

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590

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592 7) **References**

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783 **8) Figure captions**

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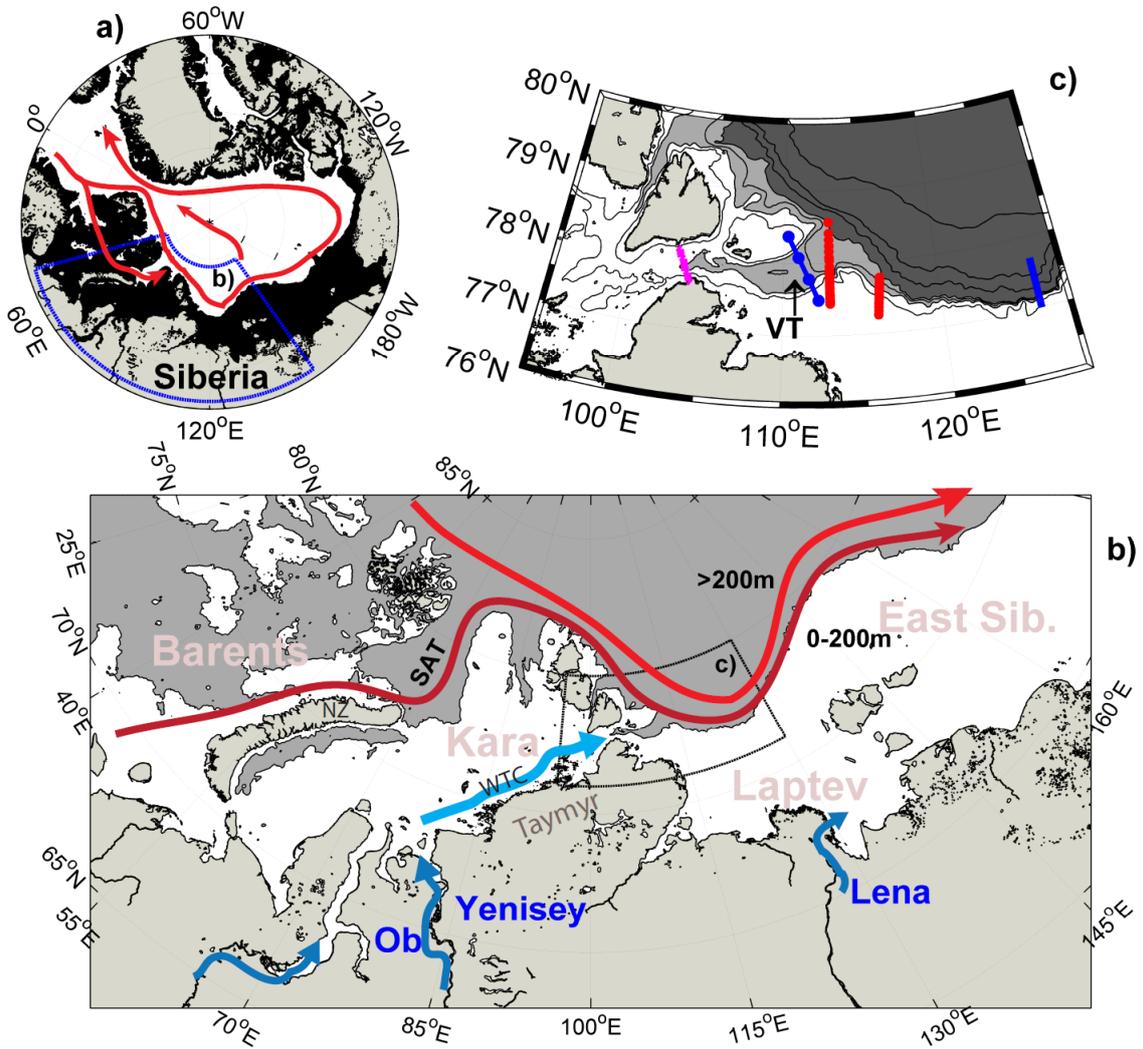
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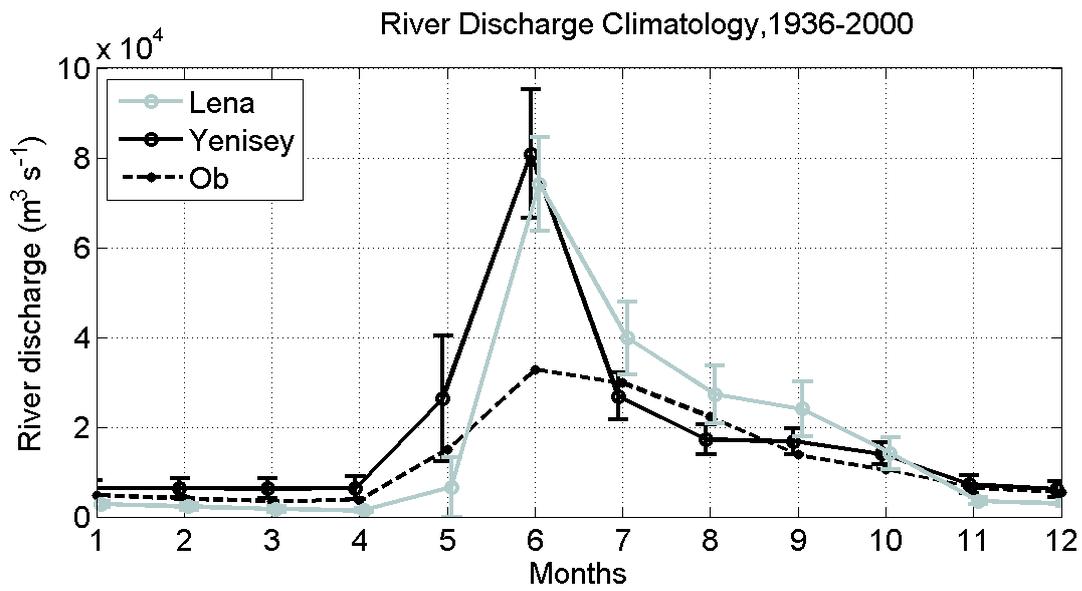
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9) Figures



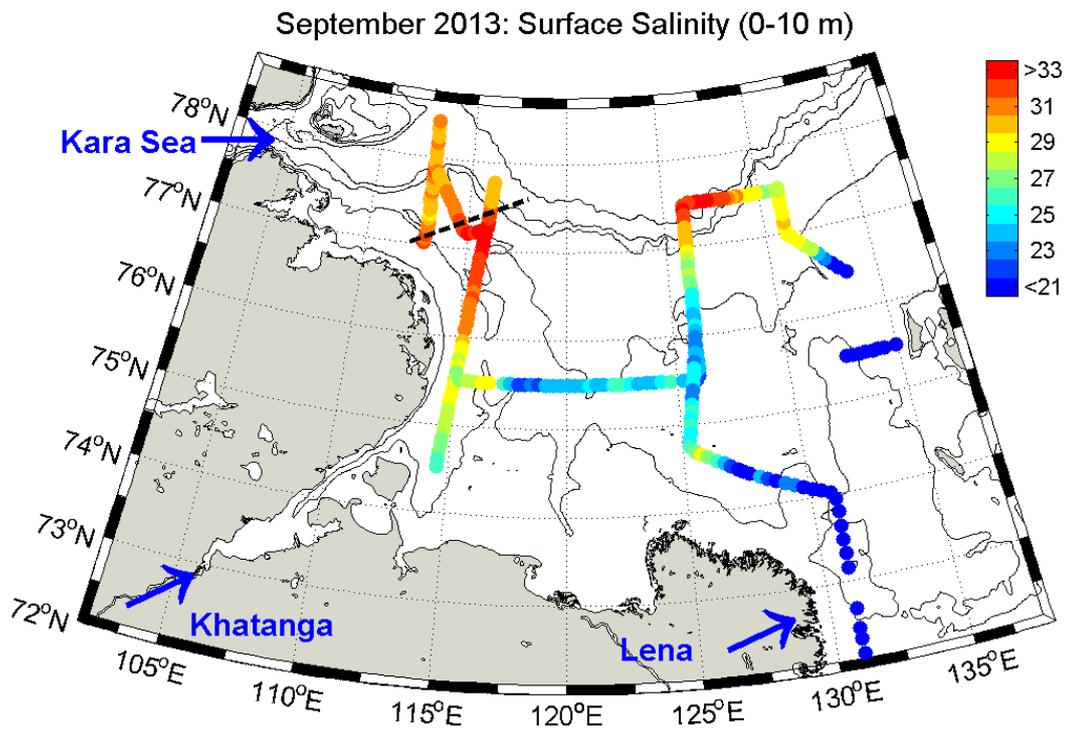
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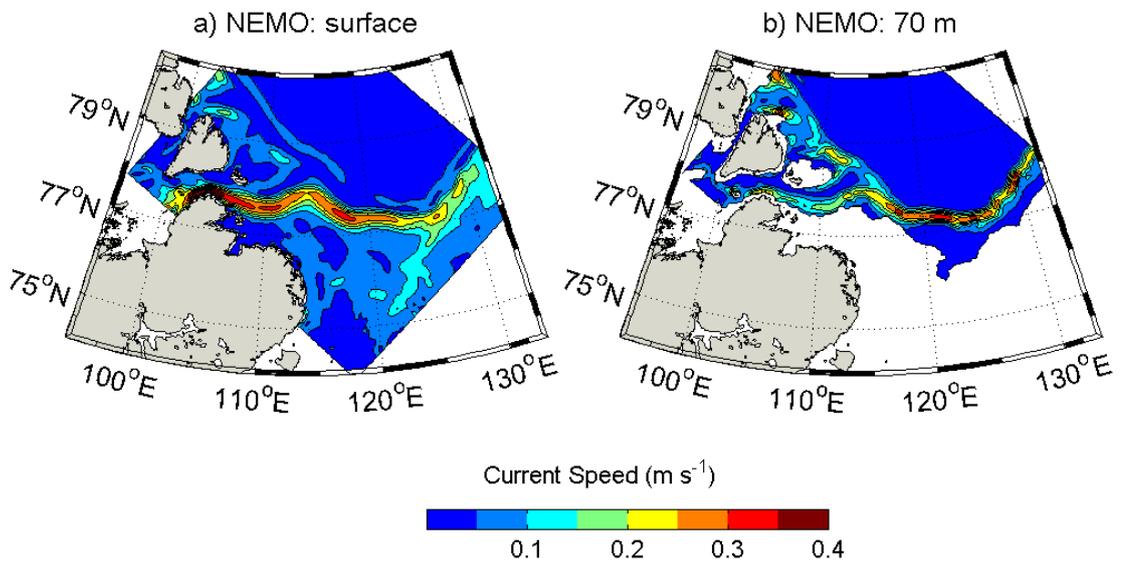


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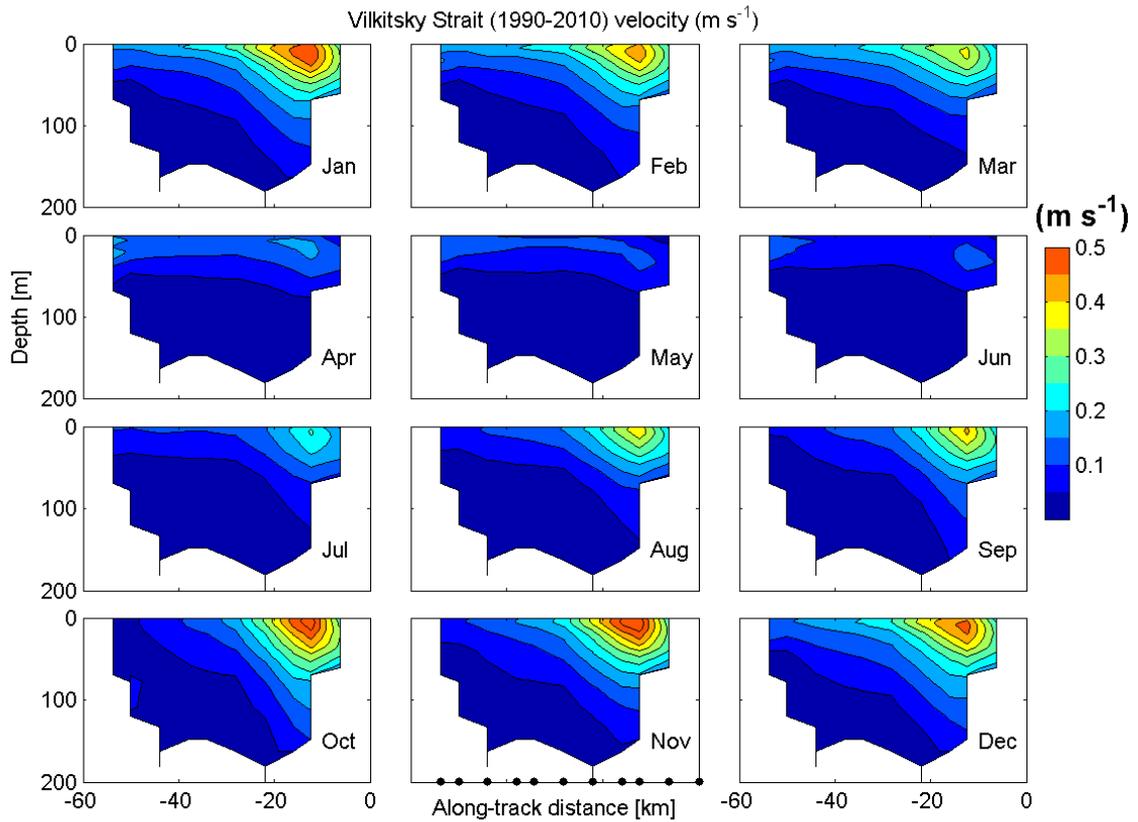


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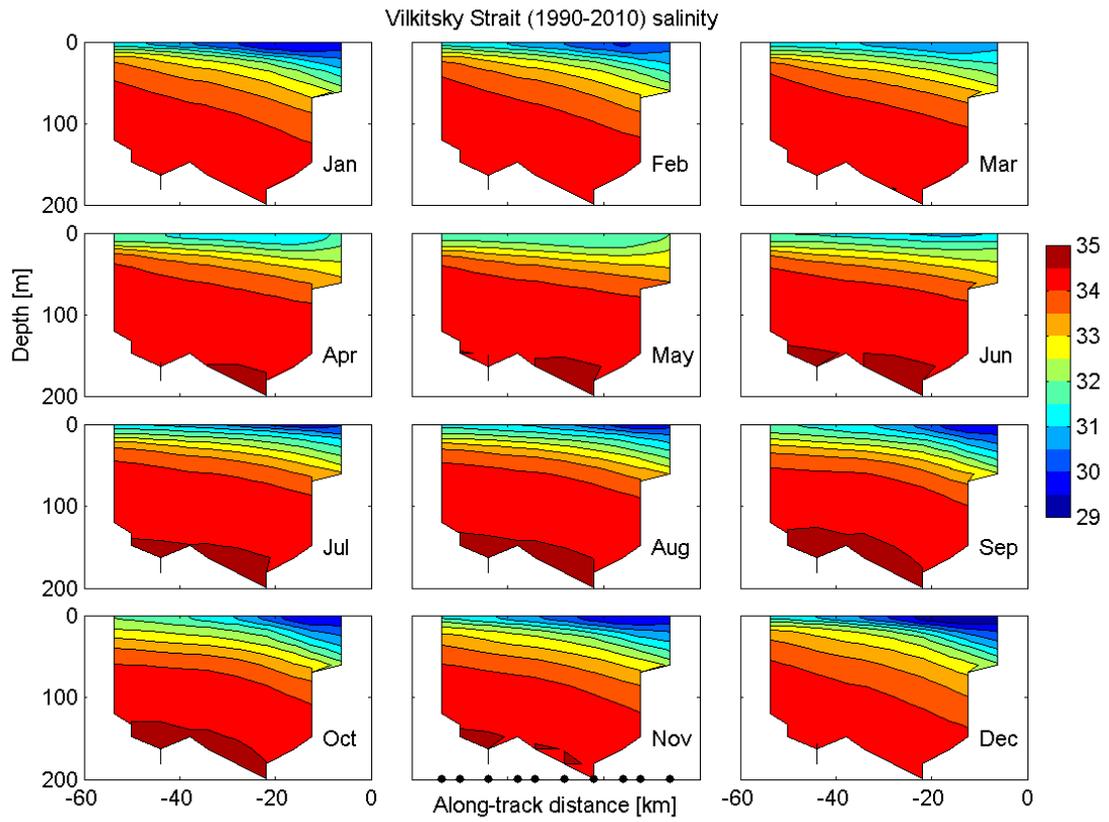


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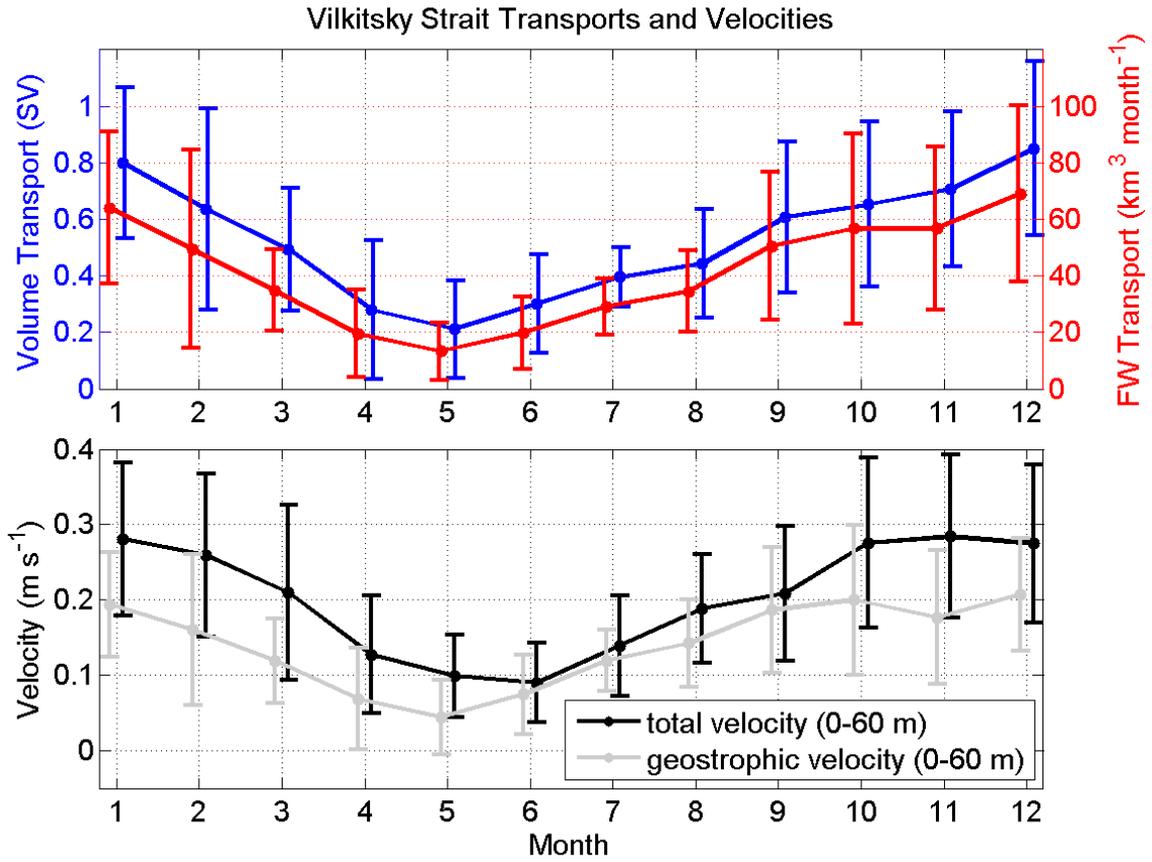
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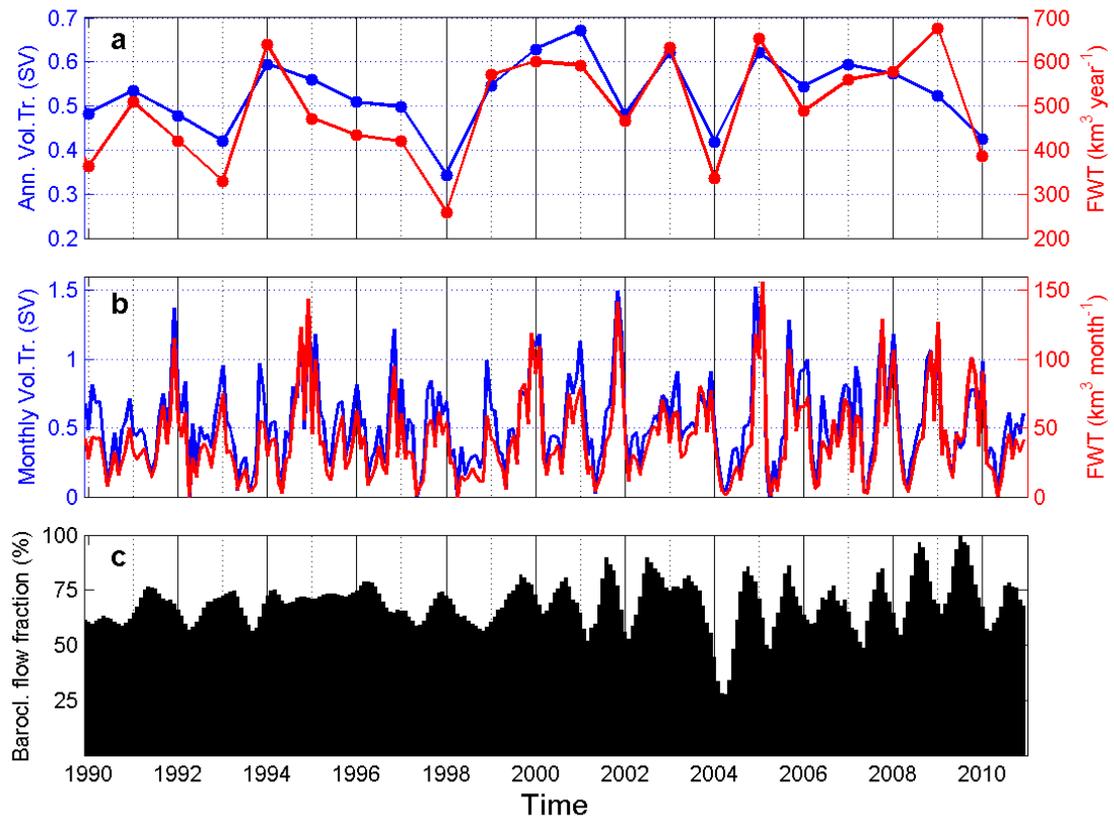


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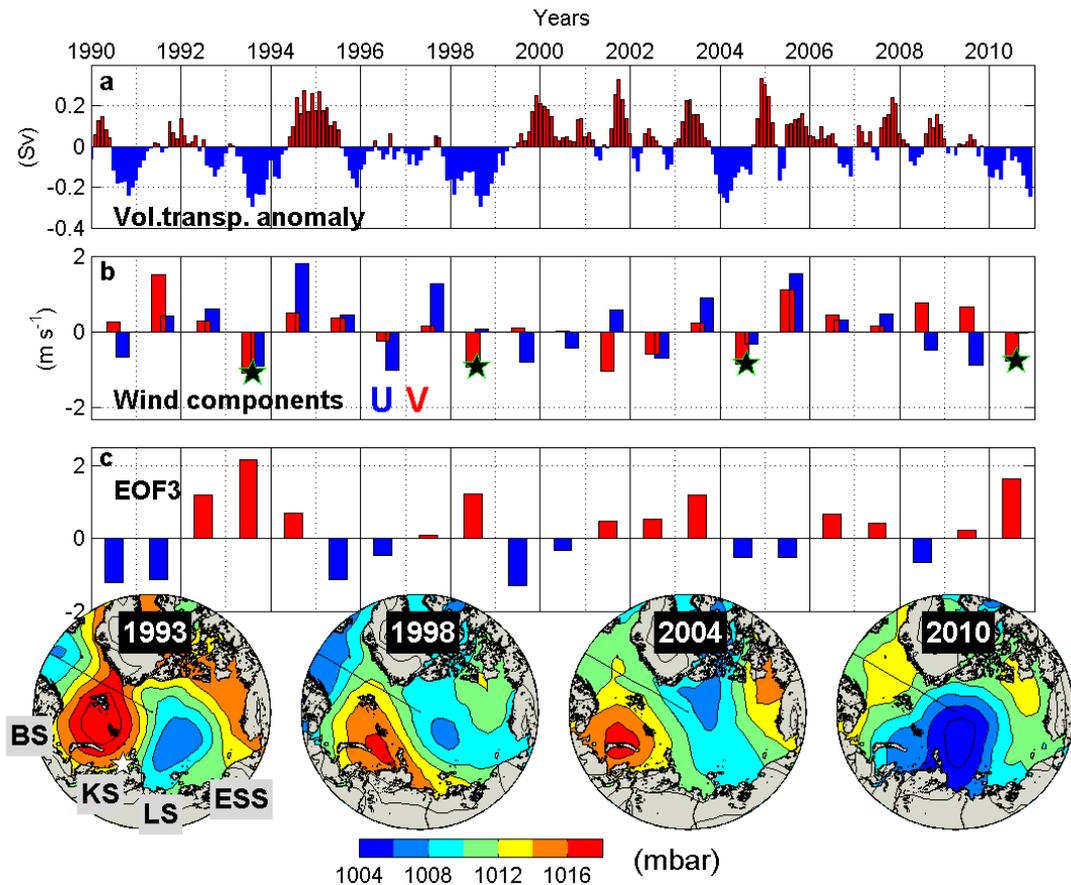


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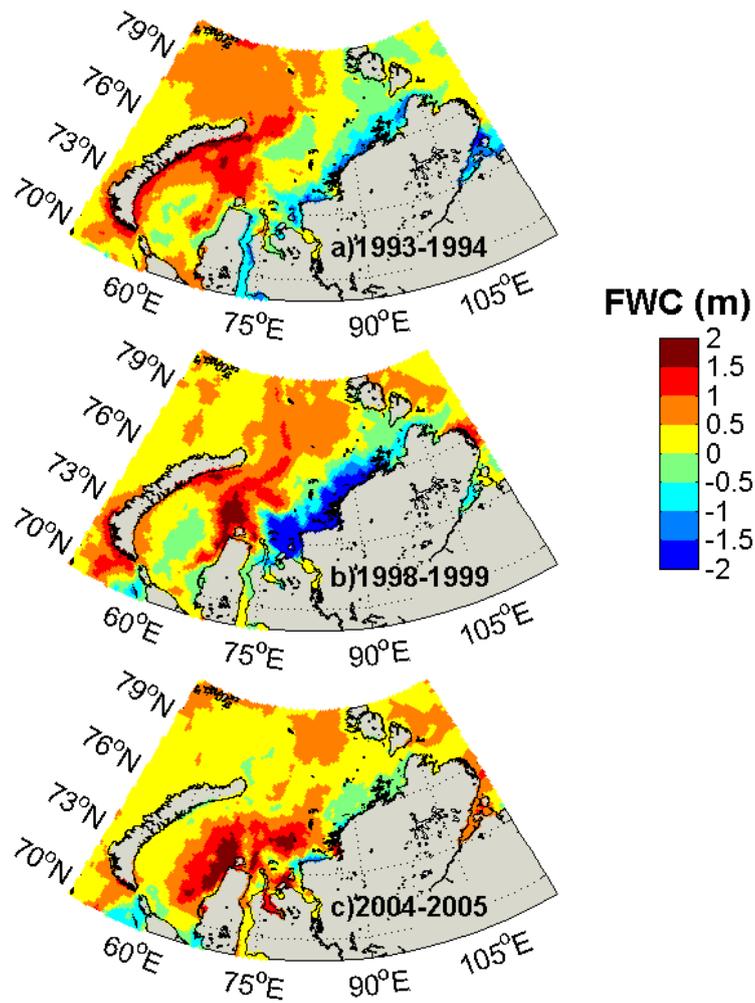


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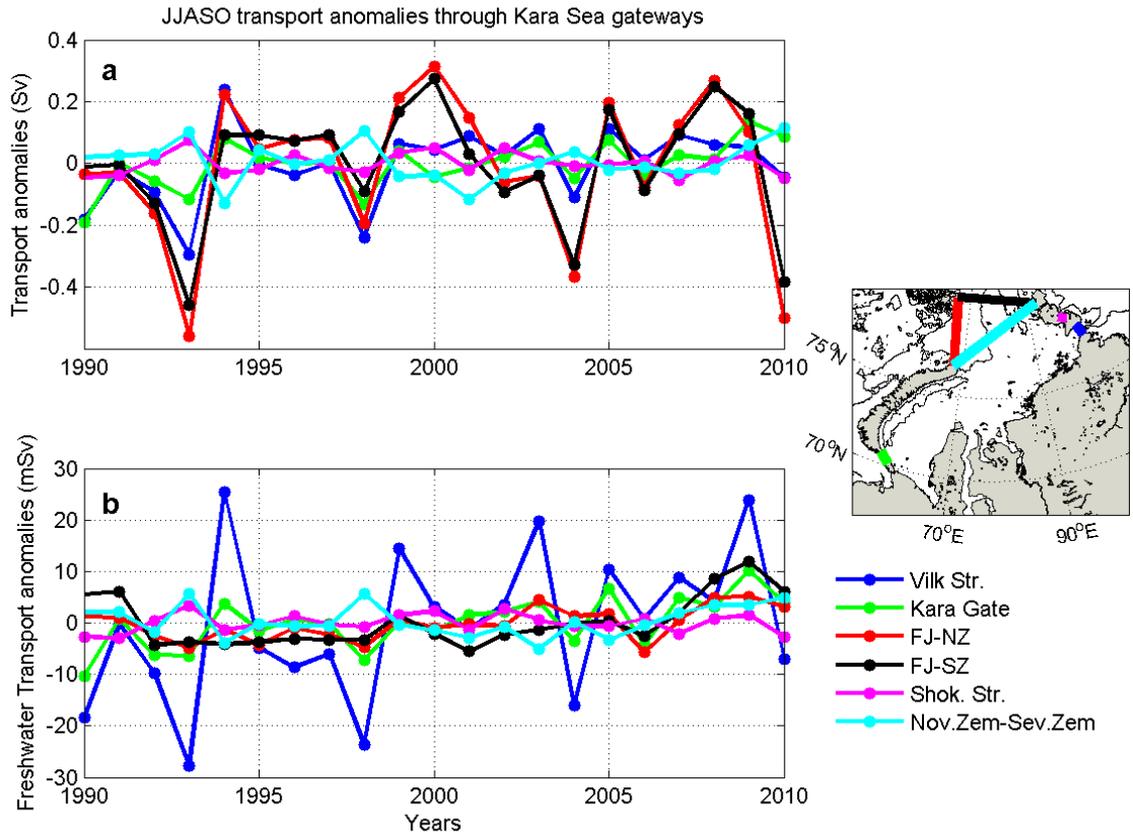
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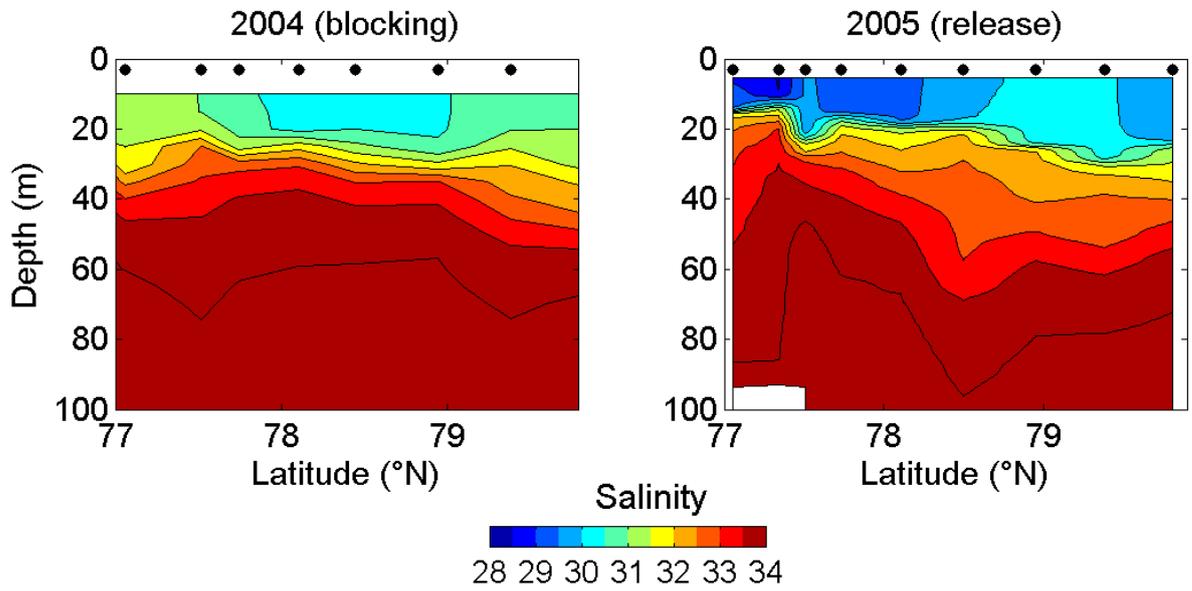
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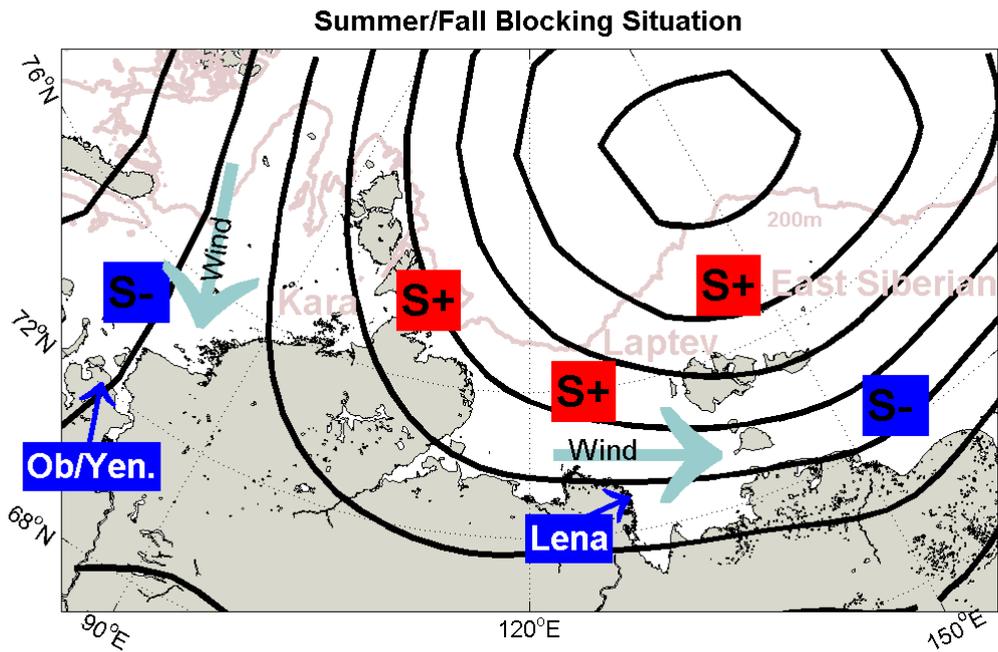


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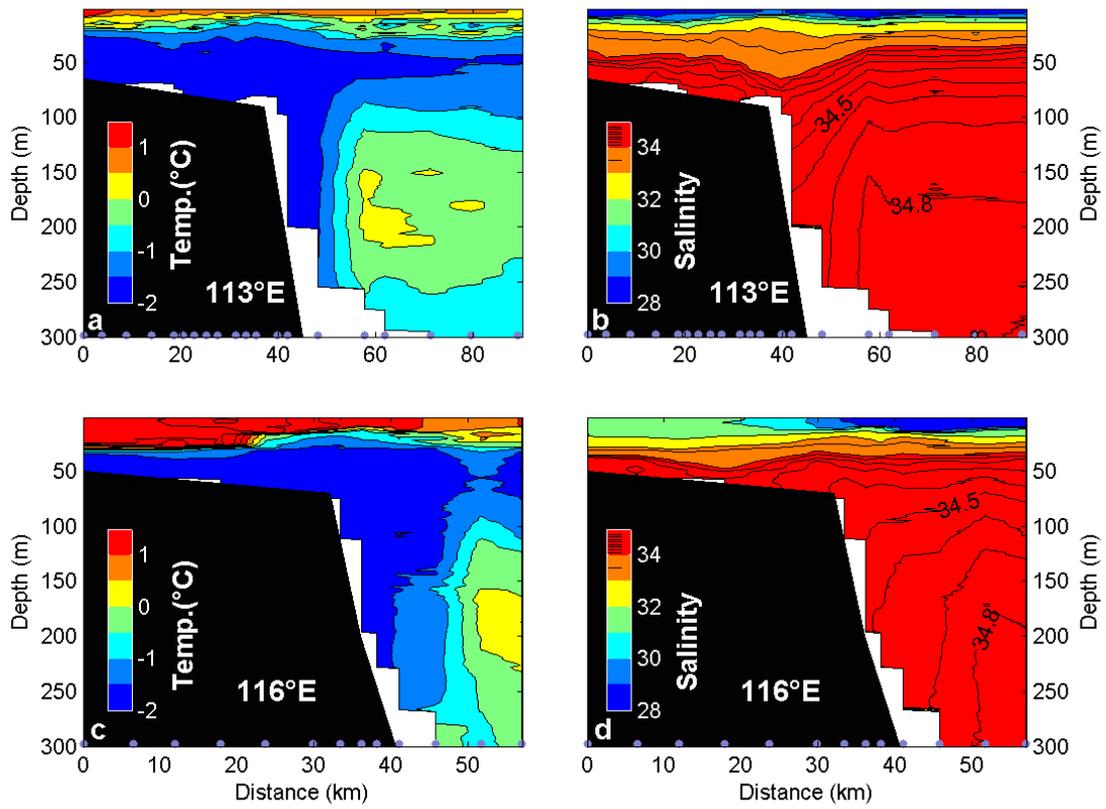


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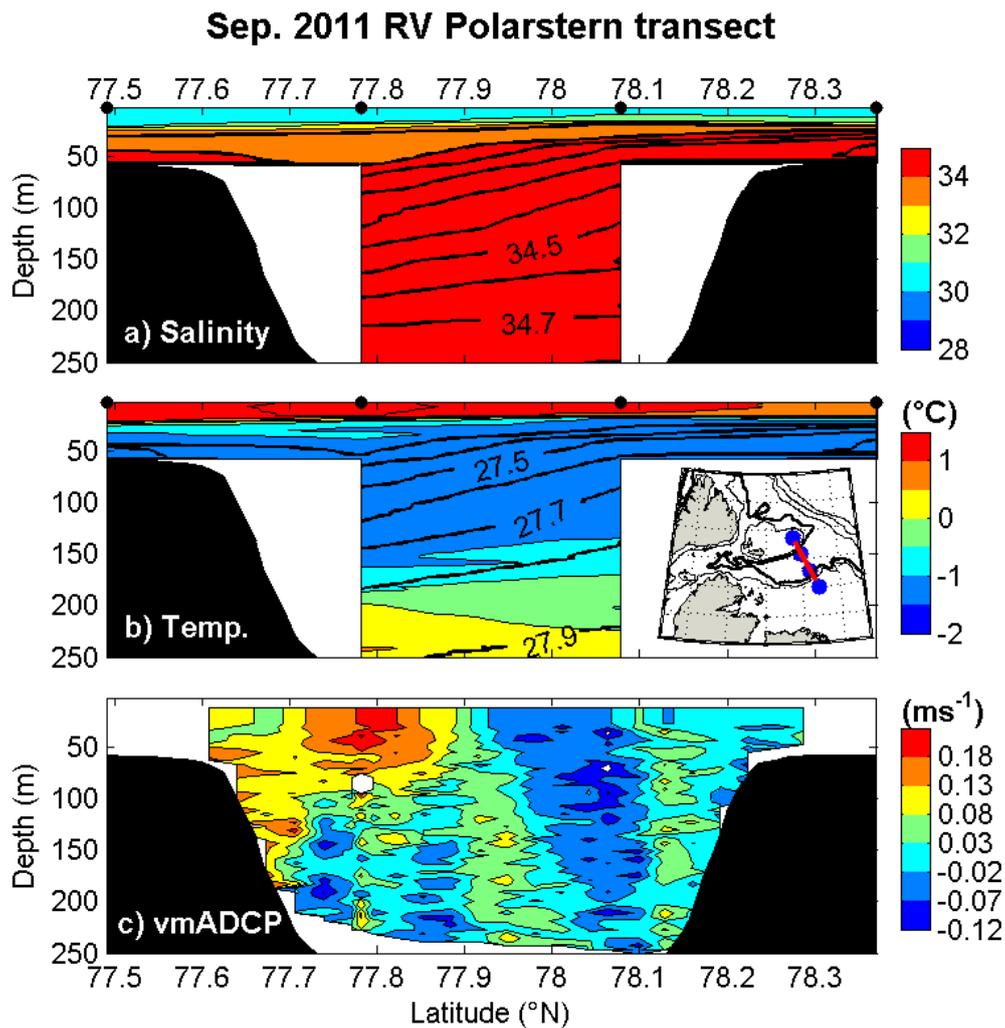
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Sep. 2013 Vilkitsky Trough U-CTD transects



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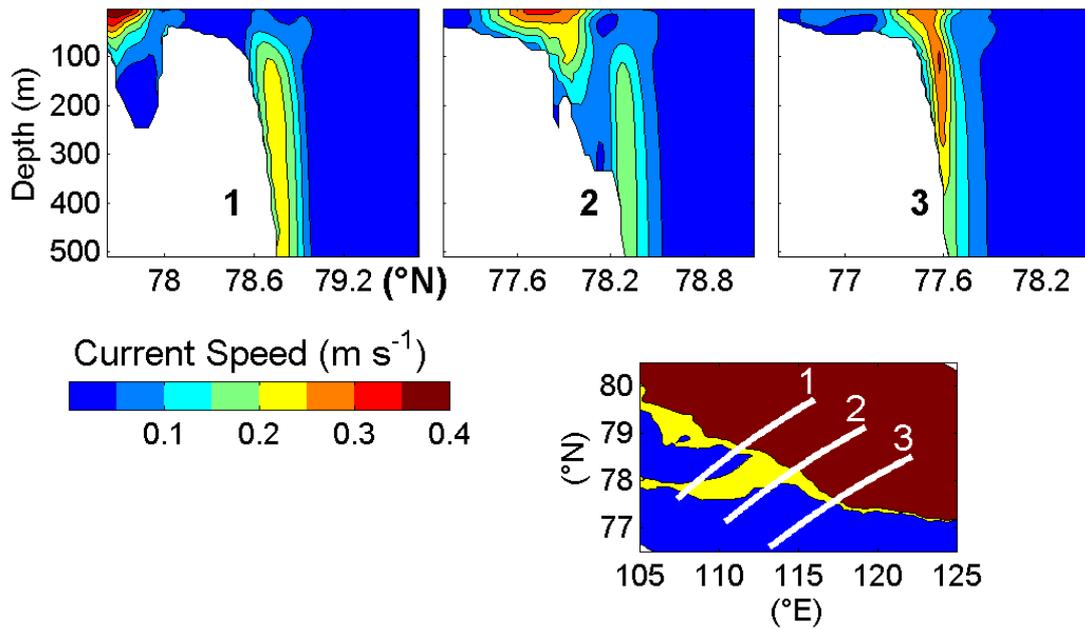
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