Remote Sensing Letters
February 2023, Volume 14 Issue 2 Pages 135-147
https://doi.org/10.1080/2150704X.2022.2164231
https://archimer.ifremer.fr/doc/00815/92657/

Anomalously fresh Chukchi Sea surface salinity in summer-autumn 2021

Grodsky Semyon A. [1, *], Reul Nicolas [2], Bentamy Abderrahim [2], Vandemark Douglas [3]

[1] Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD, USA
[2] Laboratoire d'Océanographie Physique et Spatial (LOPS), Institut Francais pour la Recherche et l'Exploitation de la Mer, Plouzané, France
[3] Ocean Process Analysis Laboratory, University of New Hampshire, Durham, NH, USA

* Corresponding author : Semyon A. Grodsky, email address : senya@atmos.umd.edu

Abstract :

The Chukchi Sea is a marginal sea in the Arctic with a mixed layer that is a few psu units saltier than ambient open Arctic water. Such higher salinity is maintained by salty and warm Pacific water inflow through the Bering Strait, implying that changes in inflow characteristics should affect the thermohaline properties of the Chukchi Sea. Recently, two additional controlling factors have been highlighted – the strength of boundary currents along the Siberian coast, and meridional exchanges due to wind-driven transport. In this note, we illustrate that anomalous fresh Chukchi Sea surface salinity in summer-autumn 2021 may be related to the anomalous southward shift of the ice edge and its meltwater source. These anomalous ice conditions occur concurrently with anomalously low Beaufort High, anomalous westerly cyclonic winds over ice-covered and open water Chukchi Sea, and related southward Ekman transport of late season meltwater. The September 2021 ice expansion was the largest in 1981–2021 detrended ice records.

Keywords : Chukchi Sea, Bering Strait, Bering Sea, satellite, salinity, wind, sea level, currents

1 Introduction

The unique ocean circulation and highly productive ecosystem of the Chukchi Sea are largely determined by inflow from the Bering Sea. Pacific water inflow through the Bering Strait delivers heat, salt, and nutrients (Grebmeier et al. 2006). All of these affect the physical oceanography and ecosystem in the Chukchi Sea. Warmer and saltier water inflow from the Bering Sea maintains a relatively salty regime there, with surface salinities exceeding those of the ambient Arctic waters by a few psu (Fig. 1). Bering Strait salinity transport depends on upstream water salinity in the northern Bering Sea and on the dynamical drivers of its volume transport. Applying the geostrophic balance in meridionally oriented shallow channels with zero cross-channel velocity, Woodgate (2018) showed that Bering Strait volume transport is governed by the strength of local meridional winds as well as by the Pacific to Arctic sea level difference (a “pressure head”), as originally identified by Shtokman (1957). The pressure head is a persistent large-scale Pacific-Arctic sea level gradient that drives the time mean northward Bering Strait transport (Stigebrandt 1984). The transport maximizes in the summer and minimizes in the winter when northeasterly winds oppose the pressure head, e.g., (Shtokman 1957; Gong and Pickart 2015). Recent studies, e.g., (Peralta-Ferriz and Woodgate 2017; Serreze et al. 2019) suggest that the summer pressure head is also remotely controlled by the strength of the Arctic zonal winds that impact sea level in the Chukchi and East Siberian Sea through meridional Ekman advection. Also, wind-generated coastal Kelvin waves propagating northward from the Bering Sea to the eastern Chukchi Sea along the Alaska coast, and southward from the East Siberian and Chukchi Sea into the Gulf of Anadyr along the Chukotka coast, may convey non-local transient wind impacts on the Strait transport (Danielson et al. 2014).

Given the predominantly meridional wind direction over the Strait, the meridional velocity in the Bering Strait is geostrophically balanced on monthly and longer time scales by the zonal, cross-strait sea level gradient (Spaulding et al. 1987; Woodgate 2018), which can be estimated using satellite altimetry (Cherniawsky et al. 2005). Such geostrophic transport estimates, e.g., (Zhuk and Kubryakov 2021) show summer amplification in line with the seasonality of in-situ currents from Bering Strait moorings (Woodgate, Aagaard, and Weingartner 2005). Hence, satellite-observed surface salinity mapping, available in summer open-water periods, reflects the seasonal peak of the Strait exchanges while its spatial distribution in the Chukchi Sea is related to the horizontal advection downstream of the Bering Strait (Tian et al. 2021). Summer advection through the Bering Strait dominates the seasonal cycle of salinity in the southern and central Chukchi Sea. Because the water entering the Chukchi Sea from the Bering Strait has less than a year residence time, interannual variability in the Bering Strait salinity should reflect in the salinity across the Chukchi Sea (Spall 2007).

Surface circulation in the Bering-Chukchi area is discussed in multiple papers, e.g., (Brugler et al. 2014; Stabeno et al. 2018). The source waters for Bering Strait transport are advected by the Anadyr Current along the Russian coast, the Alaska Coastal Current along the US coast (Fig. 1a), as well as Bering shelf water transport (not shown). All these inputs cross the northern Bering Sea north of St. Lawrence Island (Chirikov Basin), an area that is considered here as a useful domain for gauging upstream Bering Strait salinity (Fig. 1b). The circulation of the Chukchi Sea is quite complex, and it is roughly depicted here as a combined northward flow that produces relatively salty Chukchi Sea water and advances as far north as the shelf break, where it turns to the right and continues as an eastward shelf break flow (Figure 1a). In some years, the cold and fresh Siberian Coastal Current reappears along the northern Chukotka peninsula (Weingartner et al. 1999).

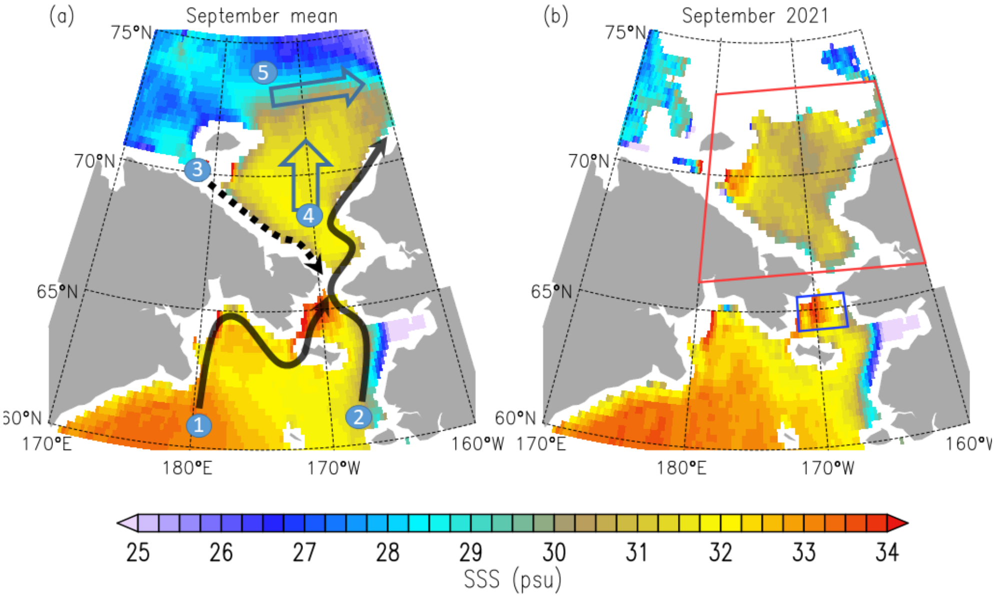

Figure 1. SMAP satellite September SSS (a) 2015-22 mean and (b) 2021. Numbers in (a) denote the (1) Anadyr Current, (2) Alaska Coastal Current, (3) intermittent Siberian Coastal Current, (4) combined northward Chukchi Sea flow, (5) eastward shelfbreak flow. In (b), (red) Chukchi Sea, (blue) north Bering Sea domains.

Until recently, most information about the sea surface salinity (SSS) came from in situ measurements. In the last decade, these have been augmented by SSS measurements from three microwave satellite L-band (1.4 GHz) instruments (Reul et al. 2020). Here we exploit Soil Moisture Active Passive (SMAP) V5.0 satellite SSS data (Meissner and Manaster 2021) to examine the variability of SSS anomalies in this northern region (https://www.remss.com/missions/smap/salinity/). Although regional satellite SSS retrievals are challenging due to cold water temperatures and land contaminations, the SSS variability in the Chukchi and Bering Seas is large enough to produce detectable satellite-derived SSS measurements (Supply et al. 2020), including fresh meltwater lenses (Supply et al. 2022), and allow evaluation/validation of satellite SSS accuracy against collocated in-situ data (Vazquez-Cuervo et al. 2021).

Using the anomaly (SSSA) instead of SSS directly when working with SMAP observations is important in cold SST due to low salinity sensitivity in the L-band and 'antenna land contamination', the factors causing non-negligible and seasonally-varying biases in satellite SSS measurements. Computing SSS anomalies relative to the observed seasonal cycle effectively removes static and seasonal bias components of satellite SSS along with the real seasonal cycle. Most critically, this expands SMAP salinity observational data utility beyond warm SST areas to higher latitudes and nearer to the coast (Boutin et al. 2016; Lee 2016). This approach permits a refined assessment of interannual SSSA as well as their spatial gradients, as verified by Grodsky, Vandemark, and Feng (2018) in the Gulf of Maine, where winter SST is similarly cold and adjoining land configuration is similarly complex.

Anomalous winds have a strong impact on the thermohaline characteristics of the Chukchi Sea. In particular, anomalously warm SST caused by a rapid ocean response to the southerly winds associated with episodic atmospheric blocking over the Bering Sea (Kodaira et al. 2020) was observed in autumn 2018, which delayed the seasonal southward sea ice advance. Opposite conditions observed in September 2009 were caused by anomalous northerly winds over the Strait due to an abnormally deep Aleutian Low and elevated Siberian High (Pisareva et al. 2015). In this paper, we focus on a summer-autumn 2021 period when surface salinity in the Chukchi Sea was the freshest among other years (2015-onward) of SMAP satellite observations. These fresh conditions are attributed to the anomalous southward shift of the sea ice edge and its related meltwater source. A depressed mean sea level pressure (MSLP) over the Beaufort High may have also contributed through anomalous cyclonic westerly winds, their impact on ice drift, and open water southward Ekman transport of late season meltwater into the central and southern Chukchi Sea. Likely, ice edge shift and open water Ekman transport anomalies are interrelated through atmospheric pressure fields.

2 Results

Firstly, anomalously fresh salinity conditions in the Chukchi Sea in the summer-autumn of 2021 are verified by in situ data. A qualitative comparison of salinity data from two thermosalinograph (TSG) surveys conducted by the Japanese research vessel (R/V) MIRAI in the Chukchi Sea area (Fig. 2) shows a substantial difference between near-surface salinity conditions there in the autumn of 2019 (Fig. 2a) and 2021 (Fig. 2b), with apparently fresher (by ~ 1 psu) salinity values in autumn 2021. Salinity distributions in Fig. 2 are augmented by ice cover maps, which display a larger (by about 400 km) 2021 southward ice extent even though the 2019 survey was conducted one calendar month later than the 2021 survey.

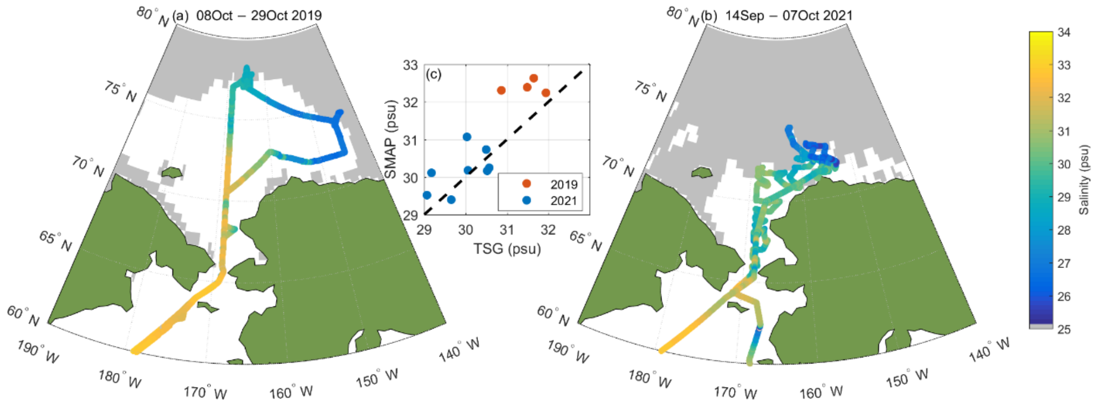

Figure 2. Salinity along TSG transects conducted by the R/V MIRAI in the autumn of (a) 2019 and (b) 2021. Gray shading is (a) Oct. 2019 and (b) Sept. 2021 ice cover from NOAA OI SST v2.1. Early October salinity data are plotted last (they may obscure other data taken at the same location). (c) Daily averaged collocated SMAP SSS versus TSG salinity in the Chukchi Sea between 65 and 70°N. Panel titles show periods when the ship was north of the Bering Strait.

A comparison of TSG and collocated satellite salinity data from the Chukchi Sea segment of TSG transects shows that regional satellite SSS data have up to a few psu biases (Fig. 2c), also discussed by Supply et al. (2020). To evaluate the interannual variability, we rely on anomalous rather than absolute SSS, which eliminates most of the seasonally-dependent SSS bias. The remaining anomalies of satellite and TSG salinity data are consistent, with SSS in 2021 being about 1 psu fresher than in 2019 (Fig. 2c).

The observed difference in SSS reflects different ranges of near-surface density (density is not shown in Fig. 2). On the Chukchi Sea segment of TSG transects along 168.75°W (from Bering Strait to about 72°N, see Fig. 2), approximately 90% of measurements correspond to water density, $\rho > 1024$ kg m^{-3}, in 2019, while approximately 60% of measurements correspond to $\rho < 1024$ kg m^{-3} (~90% correspond to $\rho < 1024.5$ kg m^{-3}) in 2021. The observed density difference suggests that in 2019, Pacific Summer Water classes were present in the near-surface central and southern Chukchi Sea, while in 2021, they were replaced by less dense late season (old) sea ice meltwater (usually defined based on 1024 kg m^{-3} isopycnal), see, for example, (Yang and Bai 2020) for summer Chukchi Sea water mass overview. Note that in 2021, more dense near-surface water, with $1024 < \rho <$ 1024.5 kg m^{-3} and cold temperatures, $T < 1$ °C, was observed in the northern part of the TSG transect approaching the ice edge and associated with newly melted water.

Corresponding Chukchi Sea CTD transects taken from the R/V Mirai along 168.75°W (Fig. 3) show the presence of diluted meltwater in the shallow (~20-m depth) mixed layer. It is conditionally identified by fresh salinities ($S \leq 31$ psu) and, as any surface water mass exposed to air-sea interactions, has a wide range of temperatures (not shown in Fig.3). Meltwater's spatial distribution follows its source area at the ice edge. It is not typically present in the central and southern Chukchi Sea in mid-summer, e.g., (Danielson et al. 2020). Such typical meridional distribution is illustrated by the 2019 transect (Fig. 3a) in which meltwater is present only north of 73°N (with some occasional fresh lenses at ~ 69°N). In contrast, it was present in the central and southern Chukchi Sea in 2021 due to this year's anomalously southward ice edge shift (Fig. 3b).

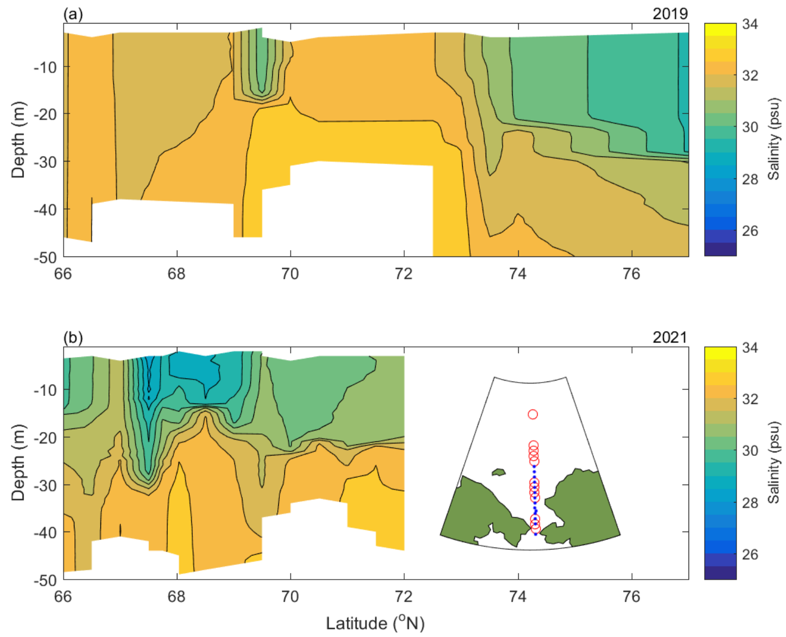

Figure 3. Depth-longitude diagrams of water salinity from CTD transects along 168.75°W taken in the autumn of (a) 2019 and (b) 2021. The northern edge of the transects roughly corresponds to the ice edge. Open red and closed blue circles in (b) show CTD station locations for 2019 and 2021 transects, respectively.

The difference in mixed layer salinity between 2019 and 2021 observations (Figs. 2 and 3) is most pronounced in the southern and central Chukchi Sea. It is expected to be a likely consequence of the preceding deceleration of Bering Strait salt transport. But, CTD observations indicate that, in contrast, this difference is related to the southward shift in meridional meltwater distribution, which could be attributed to at least two factors. First, in 2021, the ice edge and its related meltwater source were unusually shifted to the south (Fig. 2). Possible causes of this unusual shift are not detailed in this paper. Second, westerly winds were unusually strong over the Chukchi Sea in the summer of 2021 (as we will see later). Anomalous southward Ekman advection due to these westerly winds also contributed to meltwater shift southward into the southern Chukchi Sea.

Before analyzing those changes, the Bering Strait transport seasonality and its connection to the seasonality of winds and pressure head are briefly reviewed. All satellite-derived surface parameters, including sea surface temperature (SST), sea surface height (SSH), SSS, and scatterometer winds are remotely detectable only in ice-free conditions during the local summer. In line with Zhuk and Kubryakov (2021), the seasonal cycle of altimeter-derived northward geostrophic velocity (v), averaged across the Strait, exhibits a marked strengthening in May to August (reaching about 20 cm s^{-1} in July), in phase with the seasonal cessation of northerly winds (V_{10}, Fig. 4a). The yearly peak of v-variability increases from Aug. to Nov., partly due to the increased variability of meridional winds. Similarly strong v-variability is expected to persist through winter and spring (Coachman and Aagaard 1988), but altimetry-derived v is unavailable during this period due to ice cover in the Strait.

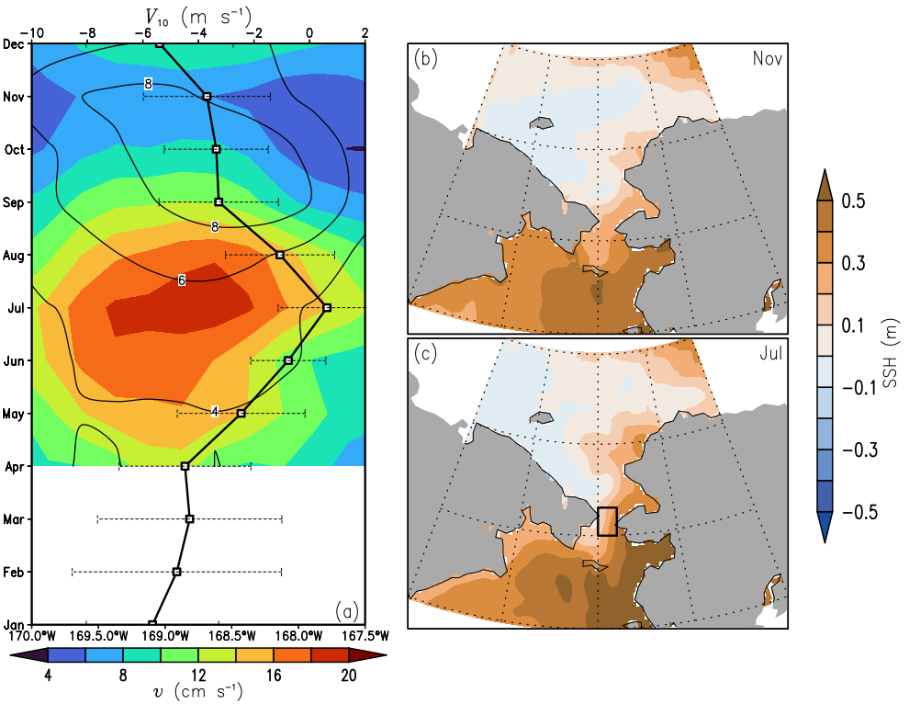

Figure 4. (a, left) Seasonal cycle of Bering Strait altimeter-derived meridional geostrophic current averaged 65°N to 66.5°N (v, shaded) and standard deviation (STD) of its monthly

anomalies (contours). Bering Strait meridional wind velocity at 10 m height (V_{10}, bold black line) area-averaged over the black rectangle shown in (c) and STD of its anomalies (dashed bars). (right) Climatological sea surface height (SSH) in the Bering-Chukchi Sea during (b) November minimum and (c) July maximum of Bering Strait transport.

In contrast to strong wind seasonality, the pressure head (SSH difference between the Bering and Chukchi Seas) is roughly comparable during the maximum and minimum transport phases in July and November (Figs. 4b, c). Despite opposing winter northerly winds, this persistent large-scale Pacific-Arctic sea level gradient accounts for the mean northward Bering Strait transport (Stigebrandt 1984). This demonstrates the critical role that winds play in regional ocean dynamics, such as summer Strait transport acceleration (Coachman and Aagaard 1988).

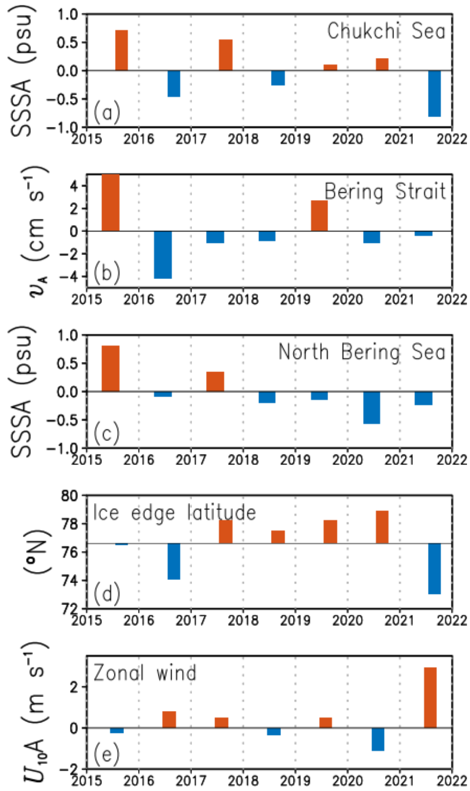

Figure 5. (a) Aug.-Oct. SMAP Chukchi Sea sea surface salinity anomaly (SSSA), May-Aug. (b) Bering Strait geostrophic meridional velocity anomaly (v_A), (c) North Bering Sea SSSA, (d) September Chukchi Sea ice extent (from SMAP ice mask) averaged between 185 and 195°E, and (e) ERA5 preceding August zonal wind anomaly ($U_{10}A$) averaged 70-75°N over the Chukchi Sea. See Fig.1b for area domains. X-axis ticks correspond to Jan. For each longitude, the ice edge is defined as the maximum ice-free latitude.

During the SMAP observation period (2015-onward), the Chukchi Sea salinity anomaly data are averaged from Aug. to Oct. in each year (Fig. 5a), and over the Chukchi Sea domain (shown in Fig. 1b). This Chukchi Sea SSSA reflects 3-month averaged regional salinity conditions centered on September, the month of maximum annual sea ice retreat. It includes only grid points with SSS>29 psu to eliminate occasional fresher Arctic water occurrences in the domain. The Chukchi Sea SSSA experiences detectable interannual changes, with the saltiest and freshest periods observed in 2015 and 2021, respectively (Fig. 5a). The Chukchi Sea SSSA is shown along with the preceding May-Aug. characteristics of Bering Strait salinity transport variability, including Bering Strait geostrophic meridional velocity anomaly (v_A) and northern Bering Sea SSSA (Figs. 5b, c). The above Bering Strait 'forcing' terms are averaged from May to August. This annual period roughly reflects the cumulative Bering Strait salt transport anomaly beginning with Chukchi Sea restratification in May, e.g., (Spall 2007) and preceding the September-centered Chukchi Sea SSSA shown in Fig. 5a.

Chukchi Sea SSSA values in 2015, 2016, 2018, and 2021 are consistent in their sign with the sign of corresponding changes in the transport and upstream SSSA. But, other years of SMAP observations show less consistency among these parameters suggesting other controls. Although Chukchi Sea SSSA and Bering Strait anomaly signs are consistent during the freshest Chukchi Sea SSSA in 2021, this fresh SSSA doesn't correspond to extrema in either v_A or upstream SSSA in the northern Bering Sea (Fig. 5). Our next focus is on the plausible causes of the satellite-record freshest SSSA in summer-autumn 2021. This freshening is accompanied by only slightly weakened northward Bering Strait transport (Fig. 5b), suggesting that it is primarily caused by influences from the north. First, this fresh SSS anomaly was concurrent with the anomalous southward extension of sea ice coverage and reflects the southward shift of the ice edge and its meltwater source (Figs. 2 and 3). The presence of a depressed MSLP over the Beaufort High in summer-autumn 2021 is also relevant (Fig. 6). Over the Chukchi Sea, this atmospheric pressure anomaly caused anomalous westerly winds and southward Ekman transport of near-surface meltwater, which can amplify due to reduced turbulent friction across the stable halocline. These processes also contributed to the advective freshening of the central and southern Chukchi Sea.

While the Aleutian Low dominates regional MSLP variability in the winter, the Beaufort High dominates it in the summer (May-Sept.) (Danielson et al. 2014, see Fig. 14d there). Normally, regional monthly mean winds calm down in the summer which is reflected in a nearly homogeneous climatological MSLP distribution (Fig. 6b). But in August 2021, anomalously strong westerly winds developed in response to unusually low atmospheric pressure over the Beaufort Gyre (Fig. 6a). During this period, near-surface winds from ERA5 atmospheric reanalysis and satellite Advanced Scatterometer, ASCAT, (Bentamy and Fillon

2012) display anomalous westerlies over the Chukchi Sea (Fig. 6). Besides exporting ice southward, these westerly winds caused southward Ekman transport that advected relatively fresh meltwater from the north into the otherwise salty central and southern Chukchi Sea. Interestingly, scatterometer winds (Fig. 6b) indicate the presence of even stronger westerlies (and thus stronger southward Ekman transport) than the ERA5 atmospheric reanalysis (Fig. 6a).

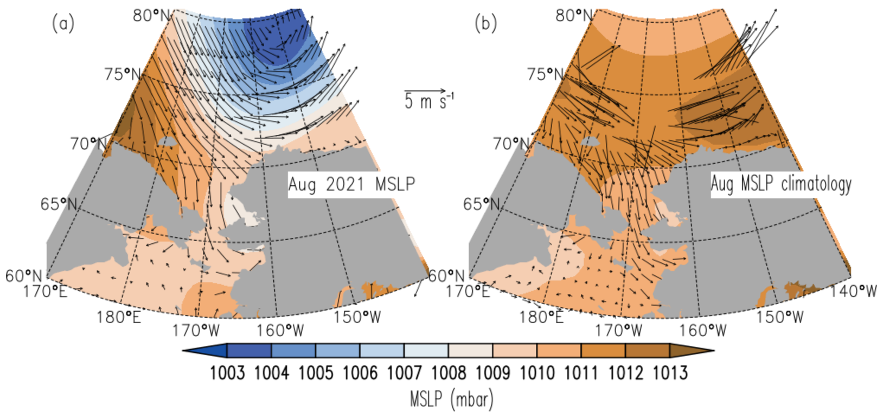

Figure 6. Aug. 2021 near-surface winds from (a) ERA5 and (b) ASCAT scatterometer (arrows). ERA5 mean sea level pressure (MSLP, shaded) in (a) Aug. 2021 and (b) climatological Aug. (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5)

3 Summary and Discussions

Remote sensing observations (salinity, winds, altimetry), ERA5 mean sea level pressure (MSLP), and in-situ salinity from thermosalinograph and CTD casts are used to analyze the anomalously fresh sea surface salinity (SSS) in the Chukchi Sea in the summer of 2021. During this period, the SSS anomaly was the freshest among other years (2015-onward) of Soil Moisture Active Passive (SMAP) satellite observations. These fresh conditions developed even though northward Bering Strait transport was close to normal in the preceding period of 2021. This paper shows that, instead, low salinity in the Chukchi Sea in Sept. 2021 was caused by impacts from the north. It was concurrent with the anomalous southward shift in sea ice coverage and reflects the presence of ice meltwater. It is also suggested that a depressed mean sea level pressure over the Beaufort High in summer-autumn 2021 caused anomalous westerly winds and southward Ekman transport of meltwater that also contributed to advective freshening of the central and southern Chukchi Sea.

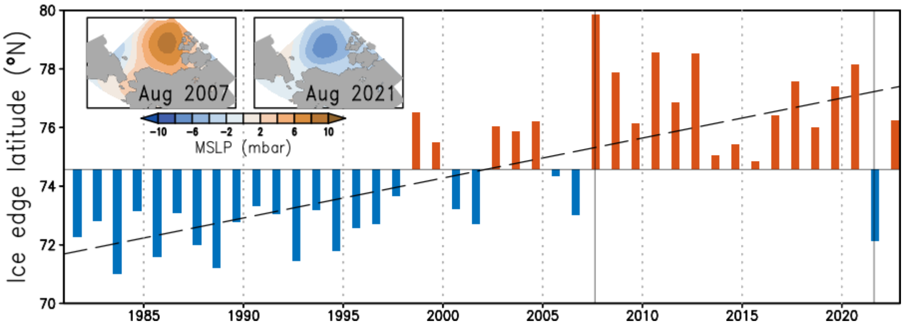

Figure 7. September ice edge latitude averaged 185 -195°E based on NOAA OISST v2.1 data, with its linear temporal trend (dashed). The inlay shows ERA5 Aug. 2007 and 2021 MSLP anomaly, preceding the largest September detrended northward and southward ice edge shifts, respectively. Grid lines correspond to the calendar January.

The southern latitude of the Chukchi Sea ice edge in September (during the maximum annual sea ice retreat) is displayed over the entire duration of NOAA OISST v2.1 ice data to compare the Sept. 2021 ice expansion event with other years (Fig. 7). Between 1981 and 2021, the September ice edge gradually shifted north, reflecting Arctic warming processes, but with significant interannual variations caused, in part, by changes in winds (Mallett et al. 2021). There are two largest deviations from this temporal trend. The largest northward deviation observed in Sept. 2007 corresponds to an amplified Beaufort High in Aug. 2007. The largest southward deviation in Sep. 2021, on the other hand, corresponds to a weakened Beaufort High in Aug. 2021 (Fig. 7). The latter event is truly unusual, with ice extent approaching pre-2000 Chukchi Sea levels. This suggests that variations in atmospheric pressure fields over the Beaufort High from year to year have an impact on regional summer ice edge anomalies. However, ice edge anomalies also depend on other processes, like surface heat budget and/or heat transport through the Bering Strait, and are not solely controlled by atmospheric pressure fields. In particular, the 2007 sea ice retreat event has been attributed to a combination of record-length high Pacific Water inflow through the Bering Strait (Woodgate, Weingartner, and Lindsay 2010) and high atmospheric heating (Steele, Zhang, and Ermold 2010). Due to the low-level atmospheric reaction to ocean heating (Kawai 2021), depressed low MSLP atmospheric conditions similar to those in 2021 may become more common as the Arctic loses ice cover and more areas with warmer open sea SST are exposed to the atmosphere.

Potential causes of the anomalous southward shift of the ice edge in early autumn 2021 are not investigated in this paper. It could have been caused by a lack of net surface heating in preceding months, which delays sea ice melt and shifts its edge and meltwater source southward. Also, ERA5 reanalysis (Figs. 6a and 7) shows unusually low MSLP over the Beaufort High and related cyclonic westerly winds over the Chukchi Sea in Aug. 2021, an atmospheric pattern that produces sea ice drift divergence in a mechanism discussed by Fukumori, Wang, and Fenty (2021). This drift pattern is confirmed by the GFDL Sea Ice Simulator (see data link in Acknowledgments) constrained by observed ice thickness data. These simulations show >10 cm s^{-1} (~300 km $month^{-1}$) southward ice drift in Aug. 2021 in the Chukchi Sea sector, which may have also contributed to the regional southward ice coverage shift observed in Sept. 2021.

Further investigation of the 2021 Chukchi Sea event is warranted given the observed magnitude of ice coverage and fresh SSS anomalies in summer-autumn 2021.

Acknowledgments. This research was supported by the NASA Ocean Surface Salinity (OSST) and Physical Oceanography Teams. SMAP salinity data are produced by Remote Sensing Systems and sponsored by NASA/OSST. Data are available at www.remss.com. R/V Mirai data are obtained from NOAA/NCEI https://www.ncei.noaa.gov/archive/accession/0251653 and https://www.ncei.noaa.gov/archive/accession/0246410 . Ice drift simulations are available at https://dsrs.atmos.umd.edu/DATA/rare1.15.2/REGRIDED/ice/rare1.15.2_mn_ice_reg_2021.nc . Anonymous reviewer comments and insights were useful and encouraging.

References:

Bentamy, Abderrahim, and Denis Croize Fillon. 2012. "Gridded Surface Wind Fields from Metop/ASCAT Measurements." *International Journal of Remote Sensing* 33 (6): 1729–1754. doi:10.1080/01431161.2011.600348.

Boutin, J., N. Martin, N. Kolodziejczyk, and G. Reverdin. 2016. "Interannual Anomalies of SMOS Sea Surface Salinity." *Remote Sensing of Environment* 180 (July): 128–136. doi:10.1016/j.rse.2016.02.053.

Brugler, Eric T, Robert S Pickart, G.W.K. Moore, Steven Roberts, Thomas J Weingartner, and Hank Statscewich. 2014. "Seasonal to Interannual Variability of the Pacific Water Boundary Current in the Beaufort Sea." *Progress in Oceanography* 127 (September): 1–20. doi:10.1016/j.pocean.2014.05.002.

Cherniawsky, J Y, W R Crawford, O P Nikitin, and E C Carmack. 2005. "Bering Strait Transports from Satellite Altimetry." *Journal of Marine Research* 63 (5): 887–900. doi:10.1357/002224005774464201.

Coachman, L K, and K Aagaard. 1988. "Transports through Bering Strait: Annual and Interannual Variability." *Journal of Geophysical Research* 93 (C12): 15535.

doi:10.1029/JC093iC12p15535.

Danielson, S.L., O Ahkinga, C Ashjian, E Basyuk, L.W. Cooper, L Eisner, E Farley, et al. 2020. “Manifestation and Consequences of Warming and Altered Heat Fluxes over the Bering and Chukchi Sea Continental Shelves.” *Deep Sea Research Part II: Topical Studies in Oceanography* 177 (July): 104781. doi:10.1016/j.dsr2.2020.104781.

Danielson, Seth L, Thomas J Weingartner, Katherine S Hedstrom, Knut Aagaard, Rebecca Woodgate, Enrique Curchitser, and Phyllis J Stabeno. 2014. “Coupled Wind-Forced Controls of the Bering–Chukchi Shelf Circulation and the Bering Strait Throughflow: Ekman Transport, Continental Shelf Waves, and Variations of the Pacific–Arctic Sea Surface Height Gradient.” *Progress in Oceanography* 125 (June): 40–61. doi:10.1016/j.pocean.2014.04.006.

Fukumori, Ichiro, Ou Wang, and Ian Fenty. 2021. “Causal Mechanisms of Sea-Level and Freshwater Content Change in the Beaufort Sea.” *Journal of Physical Oceanography* 51 (10): 3217–3234. doi:10.1175/JPO-D-21-0069.1.

Gong, Donglai, and Robert S Pickart. 2015. “Summertime Circulation in the Eastern Chukchi Sea.” *Deep Sea Research Part II: Topical Studies in Oceanography* 118 (August): 18–31. doi:10.1016/j.dsr2.2015.02.006.

Grebmeier, Jacqueline M, Lee W Cooper, Howard M Feder, and Boris I Sirenko. 2006. “Ecosystem Dynamics of the Pacific-Influenced Northern Bering and Chukchi Seas in the Amerasian Arctic.” *Progress in Oceanography* 71 (2–4): 331–361. doi:10.1016/j.pocean.2006.10.001.

Grodsky, Semyon, Douglas Vandemark, and Hui Feng. 2018. “Assessing Coastal SMAP Surface Salinity Accuracy and Its Application to Monitoring Gulf of Maine Circulation Dynamics.” *Remote Sensing* 10 (8). Multidisciplinary Digital Publishing Institute: 1232. doi:10.3390/rs10081232.

Kawai, Yoshimi. 2021. “Low-Level Atmospheric Responses to the Sea Surface Temperature Fronts in the Chukchi and Bering Seas.” *Frontiers in Marine Science* 8. doi:10.3389/fmars.2021.598981.

Kodaira, Tsubasa, Takuji Waseda, Takehiko Nose, and Jun Inoue. 2020. “Record High Pacific Arctic Seawater Temperatures and Delayed Sea Ice Advance in Response to Episodic Atmospheric Blocking.” *Scientific Reports* 10 (1): 20830. doi:10.1038/s41598-

020-77488-y.

Lee, Tong. 2016. "Consistency of Aquarius Sea Surface Salinity with Argo Products on Various Spatial and Temporal Scales." *Geophysical Research Letters* 43 (8): 3857–3864. doi:10.1002/2016GL068822.

Mallett, R D C, J C Stroeve, S B Cornish, A D Crawford, J V Lukovich, M C Serreze, A P Barrett, W N Meier, H D B S Heorton, and M Tsamados. 2021. "Record Winter Winds in 2020/21 Drove Exceptional Arctic Sea Ice Transport." *Communications Earth & Environment* 2 (1): 149. doi:10.1038/s43247-021-00221-8.

Meissner, Thomas, and Andrew Manaster. 2021. "SMAP Salinity Retrievals near the Sea-Ice Edge Using Multi-Channel AMSR2 Brightness Temperatures." *Remote Sensing* 13 (24): 5120. doi:10.3390/rs13245120.

Peralta-Ferriz, Cecilia, and Rebecca A Woodgate. 2017. "The Dominant Role of the East Siberian Sea in Driving the Oceanic Flow Through the Bering Strait—Conclusions From GRACE Ocean Mass Satellite Data and In Situ Mooring Observations Between 2002 and 2016." *Geophysical Research Letters* 44 (22): 11,411-472,481. doi:10.1002/2017GL075179.

Pisareva, Maria N, Robert S Pickart, M.A. Spall, C Nobre, D.J. Torres, G.W.K. Moore, and Terry E Whitledge. 2015. "Flow of Pacific Water in the Western Chukchi Sea: Results from the 2009 RUSALCA Expedition." *Deep Sea Research Part I: Oceanographic Research Papers* 105 (November): 53–73. doi:10.1016/j.dsr.2015.08.011.

Reul, N., S.A. Grodsky, M. Arias, J. Boutin, R. Catany, B. Chapron, F. D'Amico, et al. 2020. "Sea Surface Salinity Estimates from Spaceborne L-Band Radiometers: An Overview of the First Decade of Observation (2010–2019)." *Remote Sensing of Environment* 242 (June). Elsevier: 111769. doi:10.1016/j.rse.2020.111769.

Serreze, Mark C, Andrew P Barrett, Alex D Crawford, and Rebecca A Woodgate. 2019. "Monthly Variability in Bering Strait Oceanic Volume and Heat Transports, Links to Atmospheric Circulation and Ocean Temperature, and Implications for Sea Ice Conditions." *Journal of Geophysical Research: Oceans* 124 (12): 9317–9337. doi:10.1029/2019JC015422.

Shtokman, Vladimir B. 1957. "Influence of Wind on Currents in Bering Strait, the Causes of Their High Speeds and Predominantly Northerly Direction." *Transactions Institute*

Oceanology, Acad. Sci. USSR 25: 171–197.

Spall, Michael A. 2007. “Circulation and Water Mass Transformation in a Model of the Chukchi Sea.” *Journal of Geophysical Research* 112 (C5): C05025. doi:10.1029/2005JC003364.

Spaulding, M, T Isaji, D Mendelsohn, and A C Turner. 1987. “Numerical Simulation of Wind-Driven Flow through the Bering Strait.” *Journal of Physical Oceanography* 17 (10). Boston MA, USA: American Meteorological Society: 1799–1816. doi:10.1175/1520-0485(1987)017<1799:NSOWDF>2.0.CO;2.

Stabeno, Phyllis, Nancy Kachel, Carol Ladd, and Rebecca Woodgate. 2018. “Flow Patterns in the Eastern Chukchi Sea: 2010–2015.” *Journal of Geophysical Research: Oceans* 123 (2): 1177–1195. doi:10.1002/2017JC013135.

Steele, Michael, Jinlun Zhang, and Wendy Ermold. 2010. “Mechanisms of Summertime Upper Arctic Ocean Warming and the Effect on Sea Ice Melt.” *Journal of Geophysical Research* 115 (C11): C11004. doi:10.1029/2009JC005849.

Stigebrandt, Anders. 1984. “The North Pacific: A Global-Scale Estuary.” *Journal of Physical Oceanography* 14 (2). Boston MA, USA: American Meteorological Society: 464–470. doi:10.1175/1520-0485(1984)014<0464:TNPAGS>2.0.CO;2.

Supply, Alexandre, Jacqueline Boutin, Nicolas Kolodziejczyk, Gilles Reverdin, Camille Lique, Jean-Luc Vergely, and Xavier Perrot. 2022. “Meltwater Lenses Over the Chukchi and the Beaufort Seas During Summer 2019: From In Situ to Synoptic View.” *Journal of Geophysical Research: Oceans* 127 (12): e2021JC018388. doi:10.1029/2021JC018388.

Supply, Alexandre, Jacqueline Boutin, Jean-Luc Vergely, Nicolas Kolodziejczyk, Gilles Reverdin, Nicolas Reul, and Anastasiia Tarasenko. 2020. “New Insights into SMOS Sea Surface Salinity Retrievals in the Arctic Ocean.” *Remote Sensing of Environment* 249 (November): 112027. doi:10.1016/j.rse.2020.112027.

Tian, Fei, Robert S Pickart, Peigen Lin, Astrid Pacini, G W K Moore, Phyllis Stabeno, Thomas Weingartner, et al. 2021. “Mean and Seasonal Circulation of the Eastern Chukchi Sea From Moored Timeseries in 2013–2014.” *Journal of Geophysical Research: Oceans* 126 (5): e2020JC016863. doi:10.1029/2020JC016863.

Vazquez-Cuervo, Jorge, Chelle Gentemann, Wenqing Tang, Dustin Carroll, Hong Zhang, Dimitris Menemenlis, Jose Gomez-Valdes, Marouan Bouali, and Michael Steele. 2021. “Using Saildrones to Validate Arctic Sea-Surface Salinity from the SMAP Satellite and from Ocean Models.” *Remote Sensing* 13 (5): 831. doi:10.3390/rs13050831.

Weingartner, Thomas J, Seth Danielson, Yasunori Sasaki, Vladimir Pavlov, and Mikhail Kulakov. 1999. “The Siberian Coastal Current: A Wind- and Buoyancy-Forced Arctic Coastal Current.” *Journal of Geophysical Research: Oceans* 104 (C12): 29697–29713. doi:10.1029/1999JC900161.

Woodgate, Rebecca A. 2018. “Increases in the Pacific Inflow to the Arctic from 1990 to 2015, and Insights into Seasonal Trends and Driving Mechanisms from Year-Round Bering Strait Mooring Data.” *Progress in Oceanography* 160 (January). PERGAMON-ELSEVIER SCIENCE LTD: 124–154. doi:10.1016/j.pocean.2017.12.007.

Woodgate, Rebecca A, Knut Aagaard, and Thomas J Weingartner. 2005. “Monthly Temperature, Salinity, and Transport Variability of the Bering Strait through Flow.” *Geophysical Research Letters* 32 (4): n/a-n/a. doi:10.1029/2004GL021880.

Woodgate, Rebecca A, Tom Weingartner, and Ron Lindsay. 2010. “The 2007 Bering Strait Oceanic Heat Flux and Anomalous Arctic Sea-Ice Retreat.” *Geophysical Research Letters* 37 (1): n/a-n/a. doi:10.1029/2009GL041621.

Yang, Yayu, and Xuezhi Bai. 2020. “Summer Changes in Water Mass Characteristics and Vertical Thermohaline Structure in the Eastern Chukchi Sea, 1974–2017.” *Water* 12 (5): 1434. doi:10.3390/w12051434.

Zhuk, V R, and A A Kubryakov. 2021. “Effect of the East Siberian Current on Water Exchange in the Bering Strait Based on Satellite Altimetry Measurements.” *OCEANOLOGY* 61 (6): 791–802. doi:10.1134/S0001437021060175.