Historical Changes in the Davis Strait Baffin Bay Surface Winds and Waves, 1979–2016

XIAOLAN L. WANG,^a MERCÈ CASAS-PRAT,^a YANG FENG,^a ALEXANDER CROSBY,^b AND VAL R. SWAIL^a

^a *Climate Research Division, Science and Technology Branch, Environment and Climate Change Canada, Toronto, Ontario, Canada*

^b *Oceanweather, Inc., Stamford, Connecticut*

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ABSTRACT: This study presents and analyzes Environment Canada's Davis Strait Baffin Bay (EC-DSBB) Wind and Wave Reanalysis for the period 1979–2016 to characterize the historical changes in the surface wind speed and ocean surface waves. The trend analysis is carried out only for the months of May–December, when there is a significant ice-free sea area. The results show that 10-m wind speed (W_s) has increased significantly in most areas of the domain in September–December, with some significant decreases over the open water area in June and July. The W_s increases are most extensive in September, with significant increases in both the mean and extremes. It is also shown that the mean wind direction (W_d) has a distinctive seasonal variation, being mainly northward and northwestward in June–August, and predominantly southward and southeastward in May and September–December. The most notable changes in W_d are seen in June. The results also show that significant wave height (H_s) and wave power (W_p) have significantly increased in September–December and decreased in June. For example, the September regional mean H_s has increased at a rate of $0.4\% \text{ yr}^{-1}$. In September–December, the local W_s increases seem to be the main driver for the H_s and W_p increases, but the southeastward direction is favored by increasing fetch as sea ice retreats. In September and December, the positive trend in both W_s and H_s has intensified in the 2001–16. In June, however, the mean W_d and the changes therein also play an important role in the H_s changes, which are more affected by remotely generated waves.

KEYWORDS: Arctic; Wind waves; Climatology; Ice loss/growth; Sea ice; Trends

1. Introduction

As global temperatures rise, the minimum Arctic sea ice extent has shrunk by an average of $13.4\% \text{ decade}^{-1}$ since 1979 (Witze 2020). This rate of decrease seems to accelerate as the Northern Hemisphere sea ice extent has been lower in each of the past 13 years than any other year in the previous 29 years (Landrum and Holland 2020). The lowest record occurred in 2012, with the second lowest taking place in 2020. In both years, the minimum sea ice cover dropped below 4 million square kilometers (Witze 2020). The multimodel ensemble mean of CMIP6 simulations under high-emission scenarios show that the Arctic will likely be ice-free in September by midcentury (Wei et al. 2020). However, using a climate model with improved model physics, Guarino et al. (2020) recently showed that an ice-free summer could occur as early as 2035.

Decreased sea ice extent not only opens the ocean surface up for wind-wave generation but also affects the existing waves

in nearby areas by changing the fetch conditions. A larger fetch will result in larger waves and favors the development and propagation of swell waves (Thomson and Rogers 2014). Recently, Casas-Prat and Wang (2020a) showed that the annual maximum significant wave height might increase up to 6 m in the Arctic region by the end of this century under a high greenhouse gas emission scenario. Sea ice retreat is found to play a significant role in explaining the projected changes in the regional maximum wave heights (Casas-Prat and Wang 2020b).

There is a broad range of potential wave-driven impacts on the Arctic environment and activities, posing new challenges and opportunities. As sea ice cover declines, coastal areas will be less protected by landfast sea ice and therefore become more exposed to ocean waves, leading to increased vulnerability to processes such as erosion, inundation, etc. (Overeem et al. 2011; Casas-Prat and Wang 2020a). In addition, the possibility of new shipping trans-Arctic routes is raising economical interest (Melia et al. 2016; Wei et al. 2020) and environmental awareness due to the potential risks posed to Arctic wildlife and habitat (Huntington 2009; Miller and Ruiz 2014; Pirota et al. 2018). Waves are an important element to take into account when assessing safety and sustainability aspects related to increased Arctic marine operations and resource development. In addition, they can also provide a feedback mechanism to accelerate ice retreat (Zhang et al. 2020).

For all the aforementioned reasons, it is important to characterize and understand the historical evolution of the ocean surface wave conditions in the emerging seas in the Arctic region, which is also exposed to changes in the surface winds driven by global warming (IPCC 2013). Arctic storms might become more intense and frequent as a result of sea ice retreat

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X. Wang and M. Casas-Prat are co-lead authors.

Corresponding author: Mercè Casas-Prat, merce.casasprat@ec.gc.ca

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FIG. 1. The wave grid of the EC-DSBB reanalysis (modeling and archive regions in light and dark blue, respectively). The MSC50 coarse grid providing boundary conditions shown in black. The MSC50 fine archive shown for reference in green.

and increasing temperatures (Mioduszewski et al. 2018; Rinke et al. 2017). Unfortunately, such studies are scarce and very limited to recent years; and more so if considering high spatial and temporal resolution coverage.

In this study, we present and analyze the Environment Canada's Davis Strait Baffin Bay (EC-DSBB) Wind and Wave Reanalysis for the period 1979–2016. The Davis Strait and Baffin Bay (DSBB) comprise a semi-enclosed basin located between Canada and Greenland, which connects the Arctic Ocean with the Atlantic (see Fig. 1). Wave conditions in DSBB

are poorly known as the area is poorly sampled and availability of visual observations experienced a drastic drop after the 1970s (Gulev et al. 2003). In 2016, the Government of Canada initiated the Strategic Environmental Assessment in Baffin Bay and Davis Strait (since 2017 coordinated by the Nunavut Impact Review Board) to assess the potential environmental, social, economic, and cultural impacts of possible future offshore oil and gas activities in the region. The final report identified waves as an important environmental factor impacting these activities and highlighted the current knowledge

gap derived from a low confidence in current and future wave estimates in this region (NIRB 2019). This study contributes to fill in this gap by improving understanding of the historical wave climate in DSBB and changes therein.

The remainder of the paper is arranged as follows. The data and methods used in this study are described in sections 2 and 3, respectively. Section 4 presents and discusses the results, which are summarized in section 5. Section 6 concludes the paper with an overall discussion.

2. Data

The EC-DSBB Wind and Wave Reanalysis is a 38-yr (1979–2016) corrected wind reanalysis and wave hindcast for the DSBB region. As shown in Fig. 1, the domain covers Baffin Bay, Davis Strait, and the Labrador Sea, with a resolution of $0.25^\circ \times 0.1^\circ$ in longitude and latitude, respectively. The boundary conditions along the Atlantic side of the Labrador Sea were obtained from the coarse-resolution (0.5°) archive of the MSC50 (Meteorological Service of Canada) Wave Reanalysis, which was previously produced using the OWI (Oceanweather, Inc.) wave model (Swail et al. 2006). The boundary conditions were applied with statistical corrections based on bulk wave parameter regressions of the spectral archives. As shown in Fig. 1, the MSC50 fine-resolution (6-min grid) archive, which was developed for the Gulf of Saint Lawrence region (Swail et al. 2006), was used to choose the southern boundary of the EC-DSBB domain in order to minimize differences due to changes in wind and bathymetry (Fig. 1). Note that the MSC50 coarse grid includes the DSBB area. However, it is at a lower resolution and therefore it cannot capture well the wave climate at regional scale. Higher resolution is needed to account for the complex orography of the study area.

For the EC-DSBB dataset, wind, bulk waves, and wave partition parameters were archived at 1-h steps at 14 473 points, and directional wave spectra archived at a subset of 107 points. As shown in Fig. 1, the archive region is slightly smaller than the modeling domain. In this study we focus on the wind speed (W_s), wind direction (W_d), significant wave height (H_s), and mean wave period (T_m), with the latter being calculated as the zero-crossing mean wave period obtained using the second integral moment of the frequency wave spectrum.

In contrast to the MSC50 (both coarse and fine grids), the surface wind fields for EC-DSBB are taken from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) data product (Saha et al. 2010). Statistical wind corrections were based on the Globwave satellite Geophysical Data Records (Queffelec and Croizé-Fillon 2017) for the period 2000–12, which have a reasonable spatial and temporal coverage for these high latitudes. The correction was applied as follows: CFSR winds were interpolated to the DSBB wave grid and matched with corresponding available altimeter data. A quantile matching bias approach was carried out using quantile–quantile (Q–Q) plots for each grid point, 45° directional bin, and month (allowing for overlapping to ensure consistency in correction factors). However, the corrections were small as the differences between CFSR and satellite are small: mean differences in W_s below 0.4 m s^{-1} and correlation coefficient of 0.90 in most of the domain (see Fig. S1 in the online supplemental material).

The sea ice concentration (SIC) data for the EC-DSBB reanalysis were based on ice concentration from two sources: the gridded concentration data sourced from CFSR and the high-resolution ice charts developed by the Canadian Ice Service (CIS) (Canadian Ice Service 2009). CFSR data were supplemented with postprocessed CIS data where and when available to produce a merged weekly sea ice coverage, ensuring continuity in space and time. CIS ice charts are obtained from the analysis and integration of several data sources including in situ observations (from land, ship, and aircraft), airborne radar, and satellite imagery. In this study, CIS data are assumed to be a higher-quality product than the CFSR data due to the scale and mission of CIS, which is to provide the most timely and accurate information about ice in Canada's waters. Recent studies have also used CIS data for data assimilation and climate assessment. For example, CIS data was used in the sea ice data assimilation at 10-km resolution in the latest pan-Canadian ocean analysis system RIOPS-v2 (Smith et al. 2021) and to assess shipping navigability in the Canadian Arctic between 1972 and 2016 (Copland et al. 2021).

The aforementioned W_s and SIC were combined to produce the EC-DSBB wave reanalysis, using the third-generation wave model OWI-3G (same as for the MSC50). Bathymetry was sourced from 30 arc-second interval grid of General Bathymetric Chart of the Oceans (GEBCO2014) (Weatherall et al. 2015) and the Canadian Hydrographic Service (CHS). The wind source term is similar to WAM's ST3, but with an additional linear excitation and with a different friction velocity formulation (Swail et al. 2006). OWI-3G considers sea ice concentration of above 50% as land, for which there is no wave generation and/or propagation, and no ice effect for SIC below 50%. Tables 1 and 2 provide condensed information about the EC-DSBB wave model settings.

The SIC methodology employed in EC-DSBB is undoubtedly a simplification of the complex interactions between waves and ice, such as ice-induced wave attenuation and scattering and wave-induced sea ice breaking. The modeling of these feedback processes is an area of active research under continuous development, and depends on several sea ice and wave properties such as wave frequency and ice floe distribution (Squire 2020). When extensive ice information is available and for short periods of simulation, more complex approaches have been recently employed (e.g., Boutin et al. 2020; Liu et al. 2020). However, our 50% threshold approach is reasonable within the context of the present study due to the length of the climate product and the limited knowledge about the sea ice conditions for the entire duration of the period of analysis. Similar approaches have been used in recent studies of long wave datasets. For example, a SIC cutoff of 30% is used in ERA5 wave reanalysis (Hersbach et al. 2020); two SIC thresholds (25%, 75%) are used in the North Atlantic Atmospheric Downscaling (NAAD) wave hindcast (Gavrikov et al. 2020). The latter approach was also adopted by Casas-Prat and Wang (2020a) and Sharmar and Markina (2021).

A preliminary statistical analysis of the time and spatially matched H_s showed an overall difference in the mean H_s of -2 cm (Fig. S2), and correlation coefficient of 0.94 compared to the Globwave satellite measurements for this region.

TABLE 1. Drivers, boundary conditions (b.c.), and model settings for wind and sea ice used in EC-DSBB, NAAD, ERA5, and ASRv2.

Dataset	W_s	Domain	Atmospheric b.c.	Original resolution	SIC
EC-DSBB	Corrected CFSR reanalysis	Global	—	38 km	CFSR reanalysis + CIS
NAAD	WRF-ARW 3.8.1. model	Atlantic	ERA-I	14 km	ERA-I reanalysis
ERA5	ERA5 reanalysis	Global	—	31 km	ERA5 reanalysis
ASRv2	High-resolution PWRf	Arctic	ERA-I	15 km	ASRv2 reanalysis

Additionally, the EC-DSBB data product is validated against the ERA5 reanalysis, NAAD high-resolution hindcast, and the Arctic System Reanalysis version 2 (ASRv2) wind reanalysis (Bromwich et al. 2018) (see section 4). ERA5 and NAAD provide wind and wave data for the same period of EC-DSBB (1979–2016) while ASRv2 does not provide wave information and is only available for the period 2000–16. The basic characteristics of these products are provided in Tables 1 and 2.

3. Methodology

The analysis is carried out for eight months from May to December, for which the wave area exists in a significant area of the domain during the period 1979–2016 (see Fig. 2). The wave area is significantly larger in the period from August to October; it reduces approximately by half in May–July and November–December, with the northern part (Baffin Bay) being mostly covered by ice. Note that in this study “wave area” means an area for which waves are computed (i.e., SIC < 50% for EC-DSBB; see section 2). The monthly mean wave areas in Fig. 2 are obtained as follows. First, monthly maps of wave areas are derived accounting for all grid points for which waves are computed (SIC drops below 50%) at any time of the corresponding month (even if there are days with SIC > 50%). Second, the climatological monthly mean wave areas are shown for grid points with wave data for all monthly maps for the calendar month during the period analyzed.

The mean wave areas derived from EC-DSBB (Fig. 2) are in good agreement with the corresponding SIC < 50% areas simulated by ERA5 (Fig. S3) with the exception of July, for which EC-DSBB simulates a smaller area. A similar behavior is seen when comparing EC-DSBB and ASRv2 mean SIC < 50% areas for the period 2000–16 (Fig. S4): they are also in reasonably good agreement except for July, for which the EC-DSBB wave area is also smaller. EC-DSBB also has a slightly smaller wave area in June and November. If we compare the EC-DSBB and ERA5 mean wave areas, we find a very good agreement for all months (Fig. 2 vs Fig. S5) although ERA5 used the threshold of SIC < 30% to model waves while EC-DSBB used a threshold of SIC < 50%. Little difference exists

between ERA5 mean areas with SIC < 50% (Fig. S3) and SIC < 30% (Fig. S5), respectively, for all months except July. However, the mean wave area does not provide information about the intramonthly variability. For example, if the mean area only considered grid points for which SIC is below a given threshold for all time steps of the period and month analyzed, then the corresponding SIC < 50% and SIC < 30% areas would be more different from each other in July–October for the Baffin Bay in the earlier periods (not shown). In conclusion, although EC-DSBB and ERA5 mean wave areas are very similar, the use of a lower SIC threshold in ERA5 reduces the number of days of wave generation and propagation during the summer months for certain areas. This arguably contributes to the obtained discrepancies between EC-DSBB and ERA5 waves, in particular for the T_m climatological fields and trends, as discussed in section 4.

Despite the interannual fluctuations, time series of the wave area show a steady increase over the period of analysis, but with an exceptionally low value in 1996 for the warm months from August to October (Fig. 2b). The singularity in 1996 is consistent with the late ice breakup observed that year (Stirling and Parkinson 2005).

As in Wang et al. (2015), we characterize changes/trends for each of the eight months (May–December) in three ways in this study. First, we calculate the 1979–88 and 2007–16 climatological mean fields of each variable analyzed and the changes between these two periods, to show the changes in the climatological mean field, namely, changes in the climatological mean condition over the study area between the two periods. Second, we derive the regional mean time series of each variable and estimate linear trends in these time series to show the linear trends in the regional mean series, which does not provide information on spatial patterns of trend. Note that in each calendar month the sampling region for the regional mean time series varies. Third, we estimate the linear trends at each wave grid point for the periods 1979–2016 and 2001–16 to show the spatial patterns of trend and any changes therein.

We analyzed monthly mean and maximum values of W_s and H_s , as well as monthly means of W_a , mean T_m , and wave power (W_p). For all grid points, the wave-related monthly means are

TABLE 2. Drivers, boundary conditions (b.c.), and model settings for waves used in EC-DSBB, NAAD, and ERA5. (Note that ASRv2 does not have waves.)

Dataset	Model	Wave/ice b.c.	Resolution	SIC	Direction $\times$ frequency	W_s
EC-DSBB	OWI-3G	Corrected MSC50	$0.25^\circ \times 0.1^\circ$	50%	24×23	~ST3
NAAD	WW3	ERA-I	$0.2^\circ \times 0.2^\circ$	25%, 75%	36×25	ST6
ERA5	WAM	—	$0.5^\circ \times 0.5^\circ$	30%	24×30	ST3

FIG. 2. (a) The mean area of wave data (open water) in the indicated months over the indicated periods. (b) The standardized time series of the area of wave data in the Davis Strait Baffin Bay (DSBB) domain for each month from May to December. The eight time series were standardized using the same mean and standard deviation, which were derived from pooling the eight time series together. Thus, the differences between these time series are proportional to the differences in the area of open water between the eight months.

computed for the time periods with wave data for the corresponding month. Since the energy wave period T_e was not calculated in the wave simulations, T_e is estimated as a function of T_m as in Cahill and Lewis (2014), Cornett (2008), and Reguero and Losada (2019). Specifically, we use $T_e = 1.14T_m$ and therefore $W_p = 0.491 \times H_s^2 \times 1.14T_m$ as in Lavidas and Kamranzad (2021). Note that since this study focuses on trends rather than climatological values, the choice of the constant ratio between T_e and T_m is of little relevance. The mean W_d is computed as the direction associated to the averaged zonal and averaged meridional components of W_s .

Considering that W_s , H_s , T_m , and W_p are nonnegative non-normal data, we used the trend analysis method of Wang and Swail (2001), which is a Mann–Kendall method (Kendall 1970; Mann 1945) that accounts for the effect of lag-1 autocorrelation on trend estimates and has been found to perform best in comparison with other trend calculation methods (Zhang and Zwiers 2004). The Mann–Kendall estimator is based on ranks (nonparametric) and is thus less vulnerable to outliers. The results of trend analysis are discussed in section 4 and summarized in section 5.

4. Results

a. Changes in surface winds

For each calendar month from May to December, Figs. 3 and 4 show the changes in W_d and W_s between 1979–88 and 2007–16.

As shown in Fig. 3, there is a distinctive seasonal variation in the mean W_d , with June, July, and August being very different from the other months. In the colder months (May and September–December), the mean W_d is predominantly southward and southeastward, which can be related to a positive phase of the North Atlantic Oscillation (NAO) that is typically more predominant in winter (Martinez-Asensio et al. 2016). However, the mean W_d in June, July, and August is mainly north- and northwestward, which can be related to weaker westerlies and a mean sea level pressure gradient that favors a prevailing northward wind in this area (Bilello 1973). Such seasonality is similar between the two 10-yr periods, 1979–88 and 2007–16, with very small changes in the mean W_d in May and September–December and some notable changes in June–August (especially in June). For June–August, some of the differences between the two 10-yr periods exceed 120° , though they are not statistically significant. The largest changes are seen in June in the area from northern Labrador Sea to Davis Strait, with the mean W_d having changed from southward or southwestward to northwestward (Fig. 3). The 1979–88 mean W_d in June is a mixture of the mean W_d of the preceding (May) and successive (July) months. The changes in June mean W_d indicate that the summer-type directional pattern starts earlier in the year in 2007–16, as compared to 1979–88. Large changes, from an east- or northeastward to a northwestward direction, are also seen in July–August in the area between 57° and 66°N latitudes. The changes in August mean W_d are also indicative of a more summer-type directional pattern. Thus, changes in mean W_d suggest not only an earlier but also longer summer season.

Consistent with this, Griffies and Yin (2014) also observed a general tendency of the mean wind stress to rotate toward that direction in this area for the period 1993–2007 using CORE-II simulations. Furthermore, this agrees with the general tendency toward more anticyclonic summertime circulation with the reduction of sea ice (Wernli and Papritz 2018), which is also observed in the ERA5 reanalysis (Fig. S6).

We should also point out that, in general, it is expected to obtain more noticeable changes in W_d in summer than in winter because winds are weaker in warmer months and therefore their mean direction is more variable and sensitive to any change. This is consistent with the report that wind direction is more variable in summer than in winter (Bilello 1973).

As shown in Fig. 4, changes in W_s are characterized by significant increases in September–December and significant decreases in June and July, with small insignificant changes in May and August. The increases are most extensively significant in September and least extensive in October; the decreases are more extensively significant in June than in July. In June, the area of decreased W_s coincides with the wave area in that month. Over the Labrador Sea, W_s has significantly increased in September but decreased in June. The Baffin Bay area has experienced significant increases in W_s in September to December, with the changes being most extensively significant in September (Fig. 4). This is in agreement with the report that diminishing Arctic sea ice promotes stronger W_s in the fall–winter seasons for this area (Mioduszewski et al. 2018). ERA5 reanalysis shows very similar patterns of change for W_s but with a smaller area of statistically significant increase in September (Fig. S7).

The changes in W_s agree with the corresponding trend maps (Fig. 5; see also Fig. S8). The increase of W_s in the fall translates to a statistically significant increase of up to $8 \text{ cm s}^{-1} \text{ yr}^{-1}$ for the period 1980–2016. This trend intensifies in the 2001–16 period, exceeding $12 \text{ cm s}^{-1} \text{ yr}^{-1}$ (Fig. 5; see also Fig. S9). For 1980–2016, ERA5 and NAAD simulate similar trend patterns but with slightly smaller areas of statistically significant increases in September, November, and December (Fig. S8). For 2001–16, the differences in intensity exacerbate in September and October (Fig. S9). Such discrepancies in trends seem to be related to the differences in the mean fall climatology of W_s (Figs. S10 and S11), where W_s obtained from EC-DSBB is larger than that of NAAD, ERA5, and ASRv2 in the cold months: May and September–December (exceeding 1 m s^{-1} in some areas). This differences in climatology agree with the global study of Sharmar et al. (2020), which showed that zonally averaged W_s simulated by CFSR in the North Hemisphere is larger than that simulated by ERA5 and ERA-I (which is the underlying global atmospheric reanalysis used in NAAD and ASRv2; see Table 1).

The regional mean time series of monthly statistics (mean, maximum, and 90th and 99th percentiles) of W_s are shown in Fig. 6 and Fig. S12. In the regional mean series, statistically significant trends are seen only in June (negative), July (negative), and September (positive). The wind speed increases are statistically significant for all the four statistics in September, while the decreases are significant only for the mean and 90th

FIG. 3. The climatological (1979–88 and 2007–16) means of wind direction (W_d) in the indicated month over the DSBB, and the changes between the two 10-yr periods (2007–16 minus 1979–88). The green and black arrows represent the 1979–88 and 2007–16 mean wind directions, respectively. Stippling indicates areas where the changes are significant (at 5% level).

percentiles of W_s in June and for the July mean W_s . As shown in Fig. 5a, the positive trend in September mean W_s is notably accentuated in the last decade (2007–16), exceeding $12 \text{ cm s}^{-1} \text{ yr}^{-1}$.

In terms of the regional trends, EC-DSBB simulates slightly higher regional trends of W_s than ERA5, NAAD, and ASRv2 for the month of September, and lower trends for June (see Fig. 7a). However, these differences are not statistically

FIG. 4. The changes in the climatological mean of wind speed (W_s) in the indicated month over the DSBB between the two 10-yr periods (2007–16 minus 1979–88). Stippling indicates areas where the changes are significant (at 5% level).

significant. For 2001–16, the discrepancies in September, October, and December are exacerbated (see Fig. 7b). However, confidence intervals associated to EC-DSBB are also larger (showing larger variability) and mostly include the confidence intervals

corresponding to ERA5, NAAD, and ASRv2. Therefore, the period 2001–16 is probably too short to derive robust conclusions about trend performance at regional scale. As discussed in section 6, the fact that ERA5, NAAD, and ASRv2 have the

FIG. 5. Maps of linear trends over the periods 1980–2016 and 2001–16 in the indicated monthly mean wind speed (W_s) and significant wave heights (H_s) over the DSBB. Stippling indicates areas where the trends are significant (at 5% level).

same, or similar, parent global atmospheric reanalysis (ERA5 and ERA-I; see Tables 1 and 2) contributes to better agreement.

b. Changes in ocean surface waves

Figure 8 shows the changes in the climatological mean fields of H_s from 1979–88 to 2007–16. Note that, for the new wave

areas (i.e., areas in 2007–16 for which SIC drops below the 50% threshold imposed for wave blocking), we show the climatological mean field for 2007–16, which is illustrated using a different color bar to highlight the areas of ice retreat by 2007–16. Due to the parameterization used to account for SIC in the wave model (see section 2), the extension of such wave areas

FIG. 6. The regional mean time series of wind speed (W_s) and significant wave height (H_s). Here, avg, p90, p99, and max denote the monthly mean, 90th percentile, 99th percentile, and maximum of the variable in question, respectively. The trend estimates are also expressed in percentage of the 1980–99 climatological mean (the numbers in parentheses). Trends of 5% significance or higher are shown in bold.

(and the intensity of the waves therein) largely depends on the SIC threshold to limit wave generation and therefore it cannot be considered an accurate estimate. However, it helps to qualitatively illustrate where water areas open up, and to what extent, in relation to the monthly changes in the wave climate in the overall study area.

In general, the spatial patterns of change in wave height (Fig. 8) resemble those of W_s (Fig. 4), featuring significant increases in September–December and significant decreases in June. The patterns of H_s increase in September–December indicate that the increases in W_s in the region are the primary driver of H_s changes (Figs. 4 and 8). The mean W_d arguably determines the gradient orientation of the spatial patterns of H_s increases as follows: in comparison to W_s , the areas of statistically significant H_s increases are shifted toward the windward side of the basin (Figs. 3 and 8). Like W_s , H_s increases are also most extensive in September. In December, the increases of 0.2 m or greater are still seen in most of the wave area, although these are not statistically significant. In June, the significant H_s decreases are seen only in the east side of the basin where swell waves might accumulate. This pattern of change indicates that the June mean W_d and the changes therein (Fig. 3) play an important role on the H_s changes in the wave

area in June, although the decreases in the upstream W_s (Fig. 4) also contributed to the June wave decreases. ERA5 exhibits a similar pattern and magnitude of changes for H_s (Fig. S13). However, in August, EC-DSBB shows a statistically significant increase in the Baffin Bay while ERA5 exhibits a statistically significant increase in the Labrador Sea. This is arguably related to the slight differences in SIC as simulated by the two reanalysis products. While areas with SIC < 50% simulated by EC-DSBB slightly increase in extent in August between 1979–88 and 2007–16 (Fig. 2), ERA5 does not present much change for the area with the same SIC range, time period, and month (Fig. S3).

As shown in Fig. 5, for H_s in the Labrador Sea in September and December, the trends are more extensively significant and the rates of increase have become higher in 2001–16 (in agreement with W_s), exceeding 3.2 cm yr^{-1} . Such trend strengthening is also seen in August H_s in the Labrador Sea. However, the decreasing trend in June has not become more extensively significant (not shown). The spatial patterns of these linear trends show similar areas of increase/decrease among EC-DSBB, ERA5, and NAAD. However, the latter show a much reduced area of statistically significant increases in September in comparison to EC-DSBB and ERA5. As we

FIG. 7. The regional mean time series of the monthly mean wind speed (W_s) and significant wave height (H_s) for EC-DSBB, ERA5, NAAD, and ASRv2 data, for the periods 1980–2016 and 2001–16, and their 95% confidence intervals.

observed with W_s , the climatological 1979–2016 mean H_s simulated by EC-DSBB is overall larger than of NAAD and ERA5 (Fig. S15). This is particularly seen for the fall season and northwest part of the wave area, where EC-DSBB mean H_s is up to 20 cm larger than the corresponding values of NAAD and ERA5. However, such discrepancies are not statistically significant.

The analysis of the changes in H_s is complemented by showing the monthly mean spectra for two representative locations (79.28°N, 65.0°W and 59.6°N, 57.5°W, hereafter denoted as PN and PS, respectively) for the periods 1979–2016, 1979–88, and 2007–16 (Fig. 9; see also Figs. S16–S18). For these two locations, we note two main wave systems, one associated with waves traveling northwest and another associated with waves traveling southeast. The former has larger wave periods and is likely associated with swells coming from the Atlantic. There is a strengthening of this system in PN in August (Fig. S16), which is arguably related to this location becoming more reachable by swell waves as sea ice retreats. In PS, however, swell energy seems to decrease in September,

October, and December (Fig. S16), which agrees with the negative trend in W_s and H_s simulated by CFSR in the North Atlantic (Sharmar et al. 2020). The second main wave system is linked to local wind conditions, and tends to increase in September–December for PS. This agrees with the positive changes discussed above for the mean H_s and W_s in the fall season, and the corresponding predominant mean W_d (which remains unchanged during the 1979–2016 period). This suggests that the W_s intensification previously seen in September–December leads to an increase in the energy of waves traveling southeastward, which is favored by an increasing fetch as sea ice retreats.

In terms of the regional mean series of H_s , the trend is significant only in the June mean and 90th and 99th percentiles and in the September mean H_s (Fig. 6; see also Fig. S12). The regional mean series of H_s and W_s share the same sign of trend in June and September, when the trends are the largest and most significant. For the other months, the H_s could have a trend that is of the opposite sign to the trend in the corresponding W_s , but these trends are small and statistically insignificant

FIG. 8. The climatological (1979–88 and 2007–16) means of significant wave height (H_s) in the indicated month over the DSBB, and the changes between the two 10-yr periods (2007–16 minus 1979–88). Stippling indicates areas where the changes are significant (at 5% level).

(Fig. S12). For example, the trends for W_s and H_s statistics have the opposite signs in November and December (Figs. S12k,l,o,p), which could be explained by the reduced water extent and the southward W_d in these months that

result in fetch-limited conditions for wave generation. Indeed, the highest positive trends in H_s , especially the extreme H_s , tend to occur in September when the water area achieves its greatest extent. Figure 7 illustrates that, in terms

FIG. 9. The December monthly mean wave spectra for the periods 1979–2016, 1979–88, and 2007–16 corresponding to the PS location in the Labrador Sea (59.6°N, 57.5°W).

of regional trend of the mean H_s , there is better agreement for H_s than for W_s , especially between EC-DSBB and NAAD.

Figure 10 shows the changes in the climatological mean fields of T_m from 1979–88 to 2007–16. In general, the T_m trend patterns are similar to their H_s counterpart, except that the T_m trends are more extensively significant in July in the southwestern part and in August in the northern part of the domain, and are less extensively significant in September–November (cf. Figs. 8 and 10). This agrees with summer-type wind seasonal pattern favoring longer fetches and incoming swell from the Atlantic, and sea ice retreat enabling waves to reach higher latitudes in the summer season. However, in terms of the regional trend, only the September mean is statistically significant, with an increase of $0.5 \text{ s century}^{-1}$ (Fig. S19).

The climatological mean fields of T_m simulated by ERA5 show larger increases in June–October between the 1979–88 and 2007–16 periods. Discrepancies are most notable in July–September (Fig. S20). For example, ERA5 predicts a statistically significant increase of September mean T_m in the Baffin Bay of $>0.3 \text{ s}$ while the EC-DSBB increase is not statistically significant and below 0.2 s . A similar, but milder, discrepancy is observed for the August mean T_m in the south part of the domain. Such discrepancies cannot be explained by the previously observed slight differences in the W_s patterns of change, and they were not observed for H_s .

Figure S21 shows the 1979–2016 climatology of T_m for both EC-DSBB and ERA5. The T_m simulated by ERA5 is notably lower. One possible explanation could be a discrepancy between the ERA5 and MSC50 W_s (which were based on the NCAR–NCEP winds) in the North Atlantic, as the latter were used to generate the wave boundary conditions used to develop the EC-DSBB wave reanalysis. Differences in W_s between reanalyses might decrease over time due to improvement resulting from the better quantity and quality of data included in the assimilation (Stopa and Cheung 2014), which might affect resulting trends. Also, discrepancies in remote winds might affect more the mean T_m climatology than H_s as the former is more affected by distant swells. However, although ERA5 presents less intense cyclones than CFSR (Gramscianinov et al. 2020), trends of ERA5 North Atlantic W_s are not notably

different from in their NCAR–NCEP counterpart (used to obtain MSC50 winds) (Ramon et al. 2019). Therefore, a more plausible reason might be the lower SIC threshold used to model ERA5 waves, which leads to smaller and more variable wave areas, especially in the earlier period of the reanalysis and in the northern part of the domain. As sea ice retreats, and areas become ice-free, the differences between EC-DSBB and ERA5 climatological mean T_m diminish, which leads to differences in trends for the whole period. This agrees with previous studies that observed that T_m is more affected by SIC variability than H_s (Casas-Prat and Wang 2020a).

As shown in Fig. 11, the patterns of changes in W_p are quite similar to the patterns of changes in the corresponding H_s (see Fig. 8); they are less similar to their T_m counterparts (Fig. 10). This is reasonable as W_p is proportional to H_s^2 (while W_p and T_m are linearly proportional). The regional mean W_p increased significantly in September; changes in the other months, including the decrease of $1\% \text{ yr}^{-1}$ in June, are not statistically significant (Fig. S19). These increases in W_p can pose a challenge for possible future energy resource development such as potential damage of oil and gas facilities and equipment, increasing the risk of spills, etc.

5. Summary

In this study, we have presented and analyzed the EC-DSBB wind and wave reanalysis data for the period 1979–2016. We have assessed the historical trends/changes in surface wind speed and ocean surface waves in this domain. Considering the changing open wave area, we characterized changes/trends in terms of changes in the climatological mean fields between two subperiods 1979–88 and 2007–16, as well as trends in the regional mean time series of each variable for the months where there is significant extension of open water area (May–December). The 1979–2016 and 2001–16 trends at each grid point were also estimated to show the spatial patterns of trends and changes therein.

The results show that 10-m wind speed (W_s) has increased significantly in most area of this domain in September–December.

FIG. 10. Changes in the climatological mean fields of mean wave period (T_m) in the indicated month over the DSBB between the two 10-yr periods (2007–16 minus 1979–88). Stippling indicates areas where the changes are significant (at 5% level).

In contrast, we obtain significant decreases over the wave area in June and July (Fig. 4). In September, the month of most extensively significant W_s increases, both the mean and extremes (90th and 99th percentiles and maximum) of W_s have

increased significantly (Fig. 6). It is also shown that the mean W_d has a distinctive seasonal variation, being mainly north- and northwestward in June, July, and August, and predominantly south- and southeastward in the colder months (May and

FIG. 11. Changes in the climatological mean fields of wave power (W_p) in the indicated month over the DSBB between the two 10-yr periods (2007–16 minus 1979–88). Stippling indicates areas where the changes are significant (at 5% level).

September–December). Such seasonality has not significantly changed between the periods 1979–88 and 2007–16 but there is a tendency for earlier and longer summer-type conditions. The most notable changes in the mean W_d are

seen in June, with very small changes in May and September–December (Fig. 3).

The results also show that significant wave height (H_s) and wave power (W_p) have significantly increased in most areas of

the domain in September–December and decreased in June. In terms of the regional mean, the September W_p and mean H_s have increased at a rate of 0.7% and 0.1% yr^{-1} , respectively; the corresponding decreases in June are statistically insignificant despite having higher rates (1.0% and 0.5% yr^{-1}). In September–December, the local W_s increases are the main driver for the H_s and W_p increases, thanks to the predominantly south- and southeastward mean W_d in these months that minimizes the accumulation and effects of swell waves in the domain. In the Labrador Sea in September, the positive trend in both W_s and wave height has intensified in 2001–16 (see Fig. 5). In June, the mean W_d and the changes therein play an important role in the H_s changes. A complementary analysis of the monthly mean wave spectra in two representative locations reveals two main wave systems of waves traveling northwest- or southeastward, which is coherent with the elongated shape of the DSBB basins. The previously mentioned increases in H_s are linked to an increase of the second wave system of waves traveling southeast, which is favored by fetch increase as sea ice retreats.

In general, the mean wave period (T_m) trend patterns are similar to their H_s counterpart, except that the T_m trends are more extensively significant in July and August and less extensively significant in September–November. A comparison with ERA5, NAAD, and ASRv2 products presents reasonably good agreement in terms of patterns of change and trends in W_s and H_s . However, EC-DSBB showcases milder T_m changes between 1979–88 and 2007–16 than ERA5. This can be arguably related to discrepancies in corresponding sea ice concentration (SIC) thresholds used to model waves, as this wave variable is more affected by SIC variability than H_s .

6. Discussion

The discrepancies observed between the presented EC-DSBB and analyzed modern climate products raises the question about the reliability of the driving forcings and wave modeling approach. There is no straightforward answer to that. Our study shows that CFSR-derived winds are in general stronger than ERA5/ERA-I (derived) winds, which is in agreement with recent studies (Feser et al. 2021; Sharmar et al. 2020). However, CFSR is not the only reanalysis with relatively stronger winds; JRA-55 [which was not assessed by Sharmar et al. (2020)] presents similar levels of storminess as CFSR (Feser et al. 2021). Due to the spatial heterogeneity of observations and the temporal inhomogeneities caused by increased number and types of observations over time, it is challenging to identify a single dataset as a universal reference. Also, Dodet et al. (2020) recently showed how sensitive the trends in the mean H_s are to data assimilation, and, in turn, how different postprocessing methods of satellite data can lead to different trends in observed H_s as well. This challenge is particularly present in the DSBB area, as it is a poorly sampled area. In the Fram Strait, Graham et al. (2019) showed that ERA5 outperformed other products using observations from 2017, but Belmonte Rivas and Stoffelen (2019) and Feser et al. (2021) showed that ERA5 and ERA-I might underestimate extreme winds in middle and high latitudes of the North Atlantic. As the satellite era expands and there is more knowledge and

consensus in postprocessing methods, likely increasing homogeneity in records, we will be able to better assess the historical wave climate and trends therein.

It is important to note that, despite the aforementioned discrepancies in the climatological mean between CFSR and other climate products in this study, and the discrepancies in trends at global scale reported by other studies, our results show a reasonable agreement in terms of the changes and trends in W_s and H_s , as simulated by EC-DSBB, NAAD, ERA5, and ASRv2. A similar agreement in trends was also obtained by Sharmar and Markina (2021) in their comparative assessment of the Arctic region, in which they assessed the seasonal trends of the mean W_s and H_s , as simulated by wave hindcasts driven by different modern wind products. CFSR has also been previously used to study the relationships between sea ice concentration and wind speed over that Arctic (Jakobson et al. 2019) and Stopa et al. (2016) identified CFSR as a good climate product to characterize Arctic wind extremes. This illustrates the potential suitability of this product for polar regions.

Although similar formulations are used by state-of-the-art wave climate products, one limiting aspect of the presented EC-DSBB dataset and corresponding analysis is the simplified sea ice methodology used to model waves in sea ice partially covered areas, which simulates an unrealistic discontinuity in wave climate estimates between areas with SIC just below and above 50%. Thomson et al. (2018) showed, for example, how the SIC parameterizations in ocean wave modeling can lead to 80% disparity in the estimation of the H_s peak of a storm. However, in the context of long-term datasets, it seems unreasonable to use a complex, and computationally expensive, sea ice parameterization if more detailed description of the sea ice state (such as ice floe distribution) is not available for the whole period of analysis.

Increased resolution of the wind fields is also probably a factor that can improve the climatology estimates in a future study. For example, Gavrikov et al. (2020) compared the H_s climatological mean and 95th percentile as obtained from forcing the wave model with NAAD winds and a corresponding lower-resolution version, and found discrepancies up to 20% near the DSBB. However, the increase in resolution did not seem to significantly affect the number of cyclones in the North Atlantic, which is a key variable affecting H_s trends in the region.

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