Ocean wave conditions in the Chukchi Sea from satellite and *in situ* observations

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[1] In situ observation of significant wave heights (SWHs) conducted from three fixed bottom-mounted Recording Doppler Current Profiler (RDCP) instruments in the south-eastern Chukchi Sea in 2007 and 2009 were compared with corresponding satellite observations from Envisat. A strong correlation (0.96) was indicated between satellite and *in situ* observations for the off-shore RDCP located approximately 82 km to the nearest coastline in the region with uniform topography. However, the corresponding cross-correlations are much lower (0.79 and 0.58) for the RDCPs located within 3.5 km and 10.8 km, respectively, of the nearest coastline probably due to a strong spatial topography gradient and an insufficient number of satellite data points for validation. Cross-validated satellite observations were used for the analysis of wave conditions in the Arctic during the years 1993–2011. We found approximately a 0.020 m/year increase of SWH for the SE Chukchi Sea and a 0.025 m/year increase for the Pacific-Arctic, which correlates well with gradual ice retreat observed in the Arctic during the last two decades. **Citation:** Francis, O. P., G. G. Panteleev, and D. E. Atkinson (2011), Ocean wave conditions in the Chukchi Sea from satellite and in situ observations, *Geophys. Res. Lett.*, *38*, L24610, doi:10.1029/2011GL049839.

1. Introduction

[2] Satellite altimeter radar observations offer clear advantages of studying the sea state. They allow homogeneous, global, and continuous coverage, at improved resolution while *in situ* observations only offer localized coverage. Past studies have been done which compare the two methods [e.g., *Young*, 1994; *Janssen et al.*, 2007; *Li and Holt*, 2007; *Zieger et al.*, 2009] including the systematic calibration and cross-validation of the SWH data from different sensors. Recently, *Young et al.* [2011] analyzed data from all seven available altimeter missions and showed that global wind speeds and wave heights were increasing during the last 23 years, and assumed that the increase of the wind speed is the major factor contributing to the increase of the waves. However, all these studies did not include the Arctic Ocean where wave data is lacking for both satellite and in situ measurements due to the unavailability of several satellites (e.g., Topex/Poseidon and Jason −1 where the maximum northern extent ends at +66°, compared to ERS-1/2 and Envisat where the maximum northern extent ends at +81.5°) and due to sea ice coverage and remoteness. Also, in the North Pacific region, nearest to the area this paper focuses on, *Young et al.* [2011] showed in some analyses they conducted that there was a slight decrease in the wind speed and wave height trend. So, further examination is warranted for regions near the North Pacific. Our study focuses on the Pacific Sector of the Arctic Ocean and thus partly closes the existing gap in the analysis of the inter-annual variability of the wave conditions of the World Ocean. The paper is organized as follows: In the next section we describe the utilized RDCP data sets and available satellite observation. In section 3 we provide a cross-validation between RDCP and satellite observation. In section 4 we analyze interannual variability of the wave conditions in the south-eastern part of the Chukchi Sea and in the Pacific Sector of the Arctic Ocean. Section 5 summarizes the results of the study.

2. Data

[3] In this paper we utilize the following significant wave height (SWH) datasets.

2.1. SWH From Recording Doppler Current Profilers (RDCPs) in the SE Chukchi Sea

[4] Recording Doppler Current Profiler (RDCP) [*Aanderaa Data Instruments*, 2006] measurements collected in the southeast Chukchi Sea for 2007 and 2009–2010 were used for this study. There were three RDCP deployments mounted at the bottom of the sea floor in a fixed upright position, one RDCP was deployed to an open-water location during the ice-free period, July–December 2007 ("2007" in Figure 1), and two RDCPs were later deployed to coastal locations during ice-free and ice-covered periods October 2009–September 2010 ("2009S" and "2009N" in Figure 1). Motivation for deployment was due to the lack of *in situ* measurements where instrument deployment and retrieval in this remote and ice-covered area is problematic. Freeze-up periods were estimated from RDCP recorded sea surface temperature (SST) as follows: 1) Station 2007 freeze up began December 8, 2007, 2) Station 2009S freeze up began November 12, 2009 and ended July 1, 2010, 3) Station 2009N freeze up began November 9, 2009 and ended July 2, 2010.

[5] The RDCP sampled at a frequency of 2 Hz. Each N observation was comprised of 15 minutes of individual wave observations i. The RDCP recorded individual wave heights H_i for 15 minutes where the significant wave height (SWH) H_{m0} (i.e., $\sim H_s$) was estimated from the highest 33% of waves in its 15-minute wave record. H_{m0} is expressed as $4\sqrt{E}$ where E is the total variance of the wave field and expressed as $E = (1/16)\rho_w g H_{m0}^2$, and the terms ρ and g are

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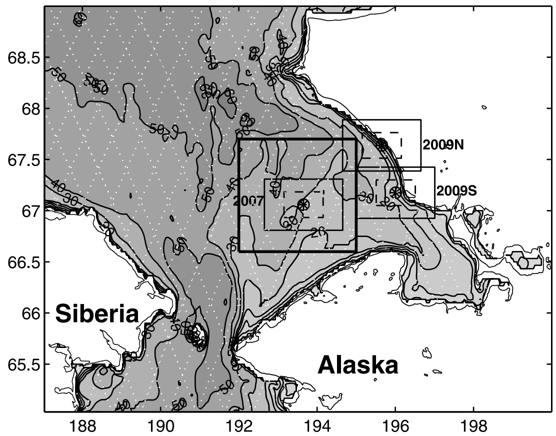

Figure 1. Region, satellite tracks (ERS-12, Envisat), locations, squares.

dropped when expressing variance. Station 2007 recorded every 2.0 hours (i.e., the instrument was 2.0 hours at rest) for 3816 hours and 6 minutes, so the number of wave observations was N = 1704. Station 2009N recorded every 1.5 hours for 8041 hrs and 15 minutes, for N = 4596. Station 2009S recorded every 1.5 hours for 8204 hours, for N = 4689. Estimates of the RDCP SWH comes from a quartz pressure sensor with accuracy ranging between 0.001 m and 0.005 m for the installations in 2007 and 2009–2010, respectively. High accuracy of the pressure center and set-up of the RDCP observation ensure the high accuracy (no more than 1%) of the SWH estimates.

2.2. Satellite Along-Track Observations From Aviso

[6] Satellite along track altimeter radar observations from ERS-1/2 and Envisat satellites (http://www.aviso.oceanobs.com/) from 1993-present were used in our study. The ERS-1, ERS-2, and Envisat radar altimeter have a foot print of 7 km. The significant wave height is defined as $H_s = 4\sqrt{\sigma^2}$, where σ^2 is the variance of the sea surface elevation defined by the returned wave form detected by the satellite sensor [*Chelton et al.*, 2001]. Typically, altimeter measurements of H_s have an accuracy (rms error) within σ_{track} = 0.5 m [*Zieger et al.*, 2009] which was assumed for this study. ERS-1/2 and Envisat satellites have a period of 35 days. During this period, these satellites provide wave observations along the tracks separated by approximately 40 km in the Chukchi Sea (Figure 1).

3. Cross-Validation RDCP and Satellite Observations

[7] The location of the satellite tracks (Figure 1) and relatively high period (35 days) of the available satellites does not allow one to conduct point-by-point cross validation between satellite and RDCP SWH estimates. Because of this, we compared RDCP data with satellite observations within spatial-temporal domain defined by temporal and spatial scales. For satellite comparison to the RDCP, only ENVISAT is shown because it was the only satellite flown during the years 2007, 2009–2010, the years of the RDCP measurements. ENVISAT replaced the decommissioned ERS-2 satellite. The temporal scale was defined as equal to the temporal resolution of the wave observations in 2007 (1.5 hour) and 2009 (2 hours). The spatial scale was estimated by the distance that the wave travels for a corresponding time scale.

[8] Taking into account that larger waves have a higher travelling speed we provide comparison for two different spatial scales (~30 and 50 km) defined by the traveling distance for small (<1.5 m) waves and large (>1.5 m) waves, respectively, based on RDCP SWH. The corresponding spatial scales are shown in Figure 1. We also excluded from consideration all satellite observations located closer than 10 km to the coast and located in the shallow (<10 m) regions.

[9] As seen from Figure 1, each satellite track intersects the spatial domains in several locations. The satellite SWH observations for each spatial domain were estimated as a mean over all k satellite observations within the chosen temporal-spatial domain. Treating individual satellite observation as independent observation of the SWH with standard deviation (STD) σ_{track}, we estimated the corresponding standard deviation of the SWH for the binned areas as $\sigma_{sat} = 1/\sqrt{k/\sigma^2_{track}}$. We found that this approach to estimating satellite STD is robust and gives similar results for large and small domains (Figure 2). The mean RDCP SWH was estimated as a mean over the chosen temporal window (usually 1–2 available values). We used a double temporal window to get estimates of the corresponding STD.

[10] Figures 2a and 2b show results of cross–validation in the large and small domain for Station 2007. We found that the linear fit between Envisat and the RDCP (Figure 2a) is almost ideal. Our results also show a very high mean correlation of approximately 0.96 between the RDCP and satellite data both for the large (Figure 2a) and small (Figure 2b) domains. This indicates the robustness of the cross-validation between RDCP and Envisat data in the 2007. We also would like to note that according to Figure 2a, the correlation should be higher for the larger waves (>1.5 m), which is closer to the central diagonal than the waves with a smaller height. This indicates a higher accuracy for satellite observations of larger waves.

[11] Figures 2c and 2e show results of the cross-validation between the RDCP and satellite data for the large domains for Stations 2009N and 2009S. The linear fit and the cross-correlation (0.79) is not as high for Station 2009N as for Station 2007, but these results are still significant. The correlation (0.58) for Station 2009S is even smaller. We speculate that we obtained relatively low cross-correlations for Stations 2009N and 2009S due to two basic reasons. First, is that because of the near-shore location, much of the domain is covered by land (Figure 1). Second, is the sharper topography gradient from the shoreline to Stations 2009N and 2009S therefore only Envisat depths greater than 10 m were considered which eliminated much of the coastal region in the domain.

[12] A similar cross-validation for the small domains (Figures 2d and 2f) gives a higher correlation. Unfortunately, the number of available data pairs of RDCP and Envisat are too low to state whether this cross-validation is statistically significant. However, it gives us ground to believe that if we had more data pairs for the small domain, we could obtain similar results we achieved for Station 2007. Overall, despite

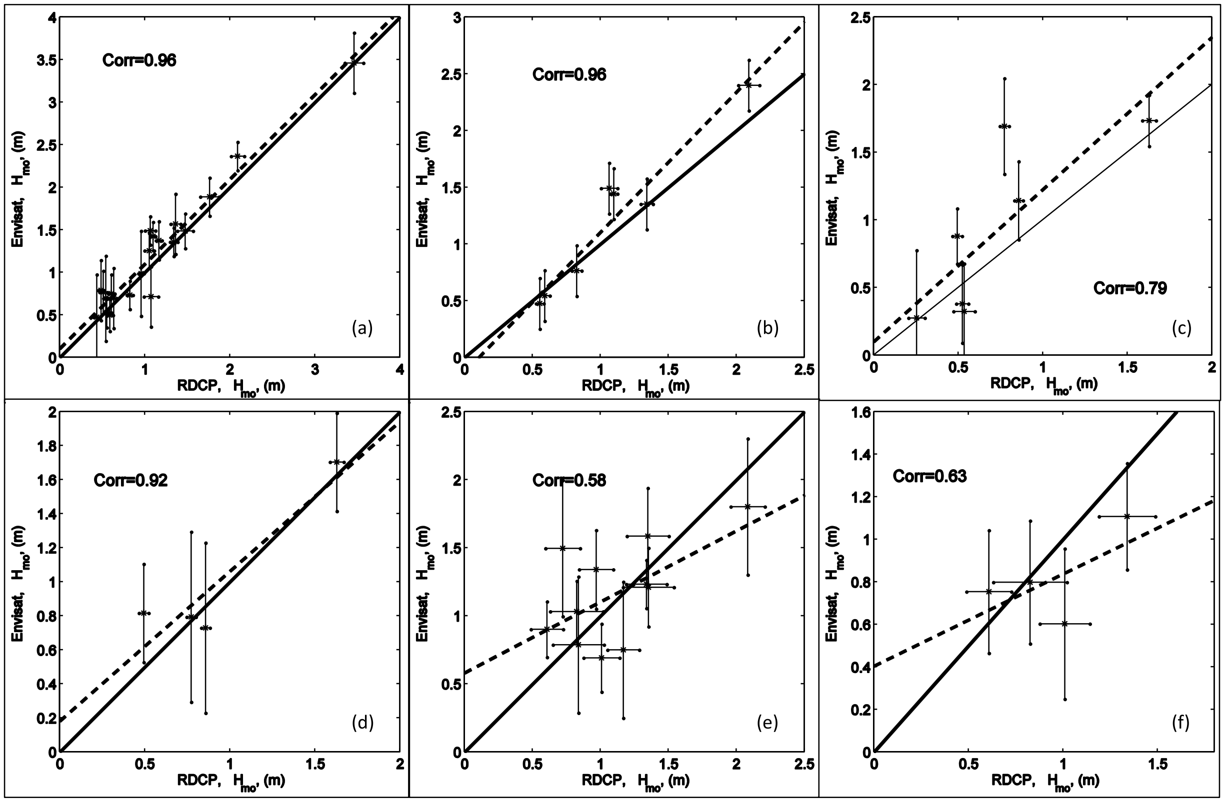

Figure 2. Significant wave height H_{m0} linear comparison from Recording Doppler Current Profiler (RDCP) dataset (x-axis) versus Envisat satellite altimeter dataset (y-axis) for (a) Station 2007 large domain (solid line, Figure 1), (b) Station 2007 small domain (dashed line, Figure 1), (c) Station 2009N large domain (solid line, Figure 1), (d) Station 2009N small domain (dashed line, Figure 1), (e) Station 2009S large domain (solid line, Figure 1), (f) Station 2009S small domain (dashed line, Figure 1).

the fact that the results of the cross-validation for Stations 2009N and 2009S were not robust, we would like to note that all cross-correlations were rather high. Therefore, we propose that satellite SWH observations can be successfully used for the analysis of wave conditions in the Chukchi Sea, and probably in the Arctic Ocean.

4. SHW for a Period 1993–2010

[13] Satellite SWH observation from ERS-1/2 and Envisat allows analyses of wave conditions in the Chukchi Sea from 1993-present. Figure 3 (top) shows all available satellite SWH observation within the square domain that occupies a major part of the south-eastern Chukchi Sea (Figure 1) while simultaneously excluding the shallow regions. The analysis of Figure 3 (top) shows that over the 17-year satellite SWH record (1993–2010) for the southeast Chukchi Sea, there was a 0.02 m/year increase which equates to a 0.34 m increase over 17 years (Figure 3, top). There is also an increase of the maximum SWH. In particular, according to Figure 3 (top) there were at least 5 events when SWH exceeded 4 m during the last decade (2002, 2004, 2005, 2006, 2010) compared to only two events in the 1990's.

[14] As we mentioned above, *Young et al.* [2011] reported that wind conditions over the North Pacific and Bering Sea were relatively stable and there was no increase in the wind speed over the Northern Pacific and Bering Sea. The mean wind speed in the eastern Chukchi Sea derived from NCEP/NCAR reanalysis (Figure 3, bottom) [*Kistler et al.*, 2001]

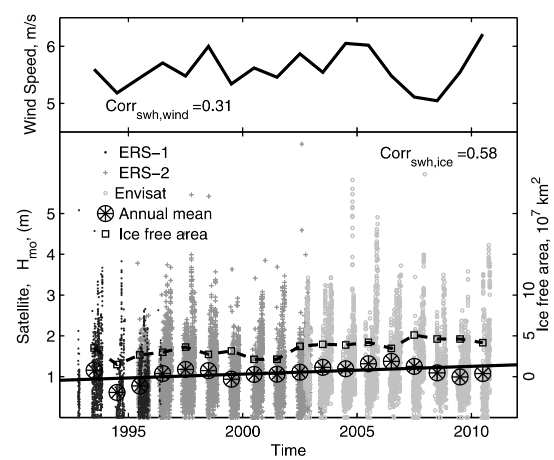

Figure 3. Significant wave height (SWH) for the period 1993–2010 for the southeast Chukchi Sea around Station 2007 (i.e., largest domain around Station 2007 in Figure 1) showing (top) NCEP NCAR Reanalysis I wind [*Kistler et al.*, 2001] trend and correlation to SWH. (bottom) Satellite data and its mean value (stars) with solid line showing SWH mean trend. Dashed line is the ice-free area over the Chukchi Sea (Lat 65–74°N, Lon 170–210°E) for the period May 1 – Nov 1 for each year [*Comiso and Nishio*, 2008], and the correlation of sea ice concentration to SWH. The linear fit to the satellite data has a positive increment of 0.02 m/year with 80% and 90% confident intervals 0.008–0.03 m/year and 0.005–0.033 m/year, respectively.

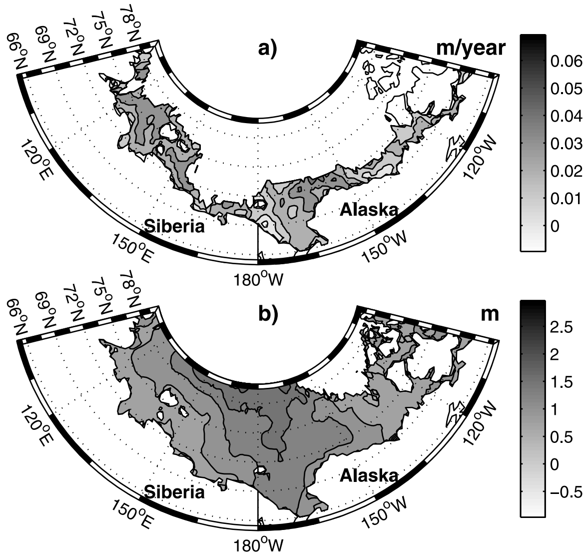

Figure 4. Significant wave height (SWH) for the period 1993–2010 for Pacific-Arctic region showing (a) SWH incremental change (m/year) and, (b) SWH mean value.

agrees well with *Young et al.* [2011]. It does not reveal significant trend and has insignificant (0.31) correlation with SWH.

[15] In order to identify physical mechanisms that control the SWH increase in the south-eastern Chukchi Sea, we analyzed the ice concentration [*Comiso and Nishio*, 2008] in the region limited to 66.6°–67.7°N and 192°–195°E. When ice concentration was <0.15, the ocean was considered ice free. The ice free area was calculated in (km^2). The annual mean ice-free area for this region is shown in Figure 3 (top) and reveals a relatively high mean correlation of 0.58 with observed SWH. Interestingly, for the period of 1993–2005, the correlation was even higher at 0.77. We speculate that is due to the relatively stable wind conditions during 1993–2005 and significant decrease of the wind speed after 2005 (Figure 3, bottom). In the absence of other physical mechanisms we assume that diminishing ice in the Arctic [*Comiso et al.*, 2008; *Screen and Simmonds*, 2010; *Perovich and Richter-Menge*, 2009; *Zhang*, 2010] is the primary cause responsible for the identified SWH changes.

[16] We suggest two possible mechanisms affecting ice decrease. First, is the increase of the fetch that allows the growth of higher waves under the same winds. Second, is the increase duration of the ice-free season in the Arctic Ocean. This may allow generation of high waves due to strong storms in the late fall and early winter, and favorable ice free conditions. The identified increase of SWH in the Chukchi Sea is not a local phenomenon. The analysis of the satellite SWH data for the Pacific Sector of the Arctic Ocean shows that this effect is global and also that the mean annual SWH significantly increases in almost every part of the Arctic Ocean (Figure 4). The regions with maximum SWH that reaches up to 0.03–0.04 m/year are usually located 100–200 km offshore. Figure 4a, shows that the highest growth of the SWH is near the northern Alaskan Coast. Taking into account, that 1993–2010 mean SWH for this region is about 1.5 m (Figure 4b), we find that SWH in this region has doubled (i.e., increased up to 2 times) during the last two decades. Our analysis of the ERS-1/2 and Envisat data shows similar SWH growth rates for the all regions north from 66°N.

5. Conclusions

[17] The analysis of the Envisat satellite data shows high correlations with the wave data from the RDCP obtained in 2007 and 2009. The correlation is very high for the offshore observation (2007) and lower for the coastal observations (2009N and 2009S) probably due to inhomogeneity of wave conditions and an insufficient amount of data for cross-validation.

[18] Using the ERS-1/2 and Envisat SWH data we found the mean SWH significantly increases during the last two decades with an averaged rate of 0.02 m/year for the south-eastern Chukchi Sea. The result shows that satellite data has excellent coverage for global oceans, but not for nearshore locations. Until better methods can be developed for obtaining satellite nearshore data, in situ measurements for coastal applications is recommended.

[19] Given the mean SWH for the SE Chukchi Sea and Pacific-Arctic regions, the 17-year trends were shown both shown to increase, with a larger increase over the Pacific-Arctic. However, the SWH is not increasing everywhere proportionately over the Pacific-Arctic region as seen in the comparison between the averaged rate and the mean of the SWH. This higher increase in SWH in some areas over others is likely due to longer open water season and therefore shorter periods of first-year sea ice. Also the higher increase results from some areas of the Pan-Arctic region may be due to more synoptic-scale meteorological activity than other regions, causing larger wind-waves to form.

[20] The 17-year trend in the mean SWH was explained by ice decline. However, internannual variability would be more related to the wind conditions. Taking that into account, it is important to analyze waves and atmospheric conditions in a potentially ice-free ocean in the future.

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