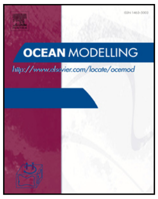
Ocean Modelling 105 (2016) 1–12

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod



Emerging trends in the sea state of the Beaufort and Chukchi seas

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ARTICLE INFO

Article history:
Received 29 September 2015
Revised 18 February 2016
Accepted 29 February 2016
Available online 6 July 2016

Keywords:
Sea ice
Arctic Ocean
Ocean surface waves

ABSTRACT

The sea state of the Beaufort and Chukchi seas is controlled by the wind forcing and the amount of ice-free water available to generate surface waves. Clear trends in the annual duration of the open water season and in the extent of the seasonal sea ice minimum suggest that the sea state should be increasing, independent of changes in the wind forcing. Wave model hindcasts from four selected years spanning recent conditions are consistent with this expectation. In particular, larger waves are more common in years with less summer sea ice and/or a longer open water season, and peak wave periods are generally longer. The increase in wave energy may affect both the coastal zones and the remaining summer ice pack, as well as delay the autumn ice-edge advance. However, trends in the amount of wave energy impinging on the ice-edge are inconclusive, and the associated processes, especially in the autumn period of new ice formation, have yet to be well-described by in situ observations. There is an implicit trend and evidence for increasing wave energy along the coast of northern Alaska, and this coastal signal is corroborated by satellite altimeter estimates of wave energy.

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http://dx.doi.org/10.1016/j.ocemod.2016.02.009

1. Introduction

The extent of seasonal sea ice in the Beaufort and Chukchi Sea of the Arctic Ocean is changing (Jeffries et al., 2013). This paper explores the timing and location of the annual ice minimum and transition to refreezing conditions, with application to the sea state over the open water portion of the domain. The sea state is set by the wind forcing, the open water fetch distance available for wave generation, and the duration of time over which the waves can accumulate energy from the wind. The wind forcing is episodic, and thus best interpreted as probabilities for events (i.e., storms). The open water distance, by contrast, has a much smoother signal that is dominated by the seasonal retreat and advance of the sea ice. It is the combination of these signals that determines the sea state of the Beaufort and Chukchi seas.

Trends in the Arctic sea ice have been examined by many previous studies (e.g., Wadhams, 1990; Wadhams and Davis, 2000; Stroeve et al., 2005, 2008; Simmonds and Keay, 2009; Kwok and Untersteiner, 2011). Meier et al. (2013) show that in recent decades the Arctic sea ice cover has thinned and become more seasonal, such that the total area covered is nearly 30% less at the annual minimum than the corresponding mean from 1979 to 2000. Stammerjohn et al. (2012) show that the duration of the summer open water season since 1979 has become much longer in the Beaufort and Chukchi seas due to an approximately 1.6 months earlier ice-edge retreat in spring, followed by an approximately 1.4 month later ice-edge advance in autumn. Stammerjohn et al. (2012) also find inter-annual links to the reduced ice extent which are attributed to heat fluxes, especially increased duration of summer solar heating, coupled with an overall thinner ice cover.

Coincident with the delay in the timing of the autumn ice advance, there is a trend towards stronger autumn storms in recent years (Serreze et al., 1993, 2001; Zhang et al., 2004). The combination of these winds and increased open water distances is expected to create high sea states (Francis et al., 2011; Francis and Vavrus, 2012; Vermaire et al., 2013; Thomson and Rogers, 2014) and increase air-sea fluxes of heat and momentum, particularly in the Beaufort and Chukchi seas (e.g., Simmonds and Keay, 2009). Some studies have connected reduced ice cover with specific storm activity, such as in August 2012 (Simmonds and Keay, 2012; Zhang et al., 2013; Parkinson and Comiso, 2013). Of these, Parkinson and Comiso (2013) conclude that the storm reduced the September ice extent minimum by an additional 5 percent. This relatively small effect suggests that high sea states may be the result of diminishing sea ice, but that high sea states are not yet the leading cause of diminishing sea ice.

However, there is some evidence for feedbacks between ocean surface waves and the loss of sea ice (e.g., Asplin et al., 2012). There are also feedbacks between waves and ice formation, such as the rapid freezing that occurs when waves cause pancake ice to develop (Wadhams et al., 1987; Lange et al., 1989). Waves are both associated with the formation of pancakes and attenuated by the pancakes, such that large areas of the ocean can freeze quickly. Although this process is typically associated with the Antarctic ice-edge or the Eastern Arctic, it is possible that this process will become important in the Beaufort and Chukchi seas of the Western Arctic. For example, this process is already common in the Sea of Okhotsk, which is relatively sheltered.

Here, we set aside the many interesting questions of wave-ice interactions (e.g., Squire et al., 1995; Squire, 2007) and focus instead on the large-scale patterns of the sea state in the Beaufort and Chukchi seas. In particular, we examine emerging trends in the probability of high sea states in the Beaufort and Chukchi seas. The recent work of Wang et al. (2015) indicate the wave heights are increasing slightly and wave periods are increasing strongly as a result of reductions in ice cover (as opposed to changes in the winds). We examine these trends and the autumn ice advance stage in particular. Section 2 describes the data products and model hindcasts used for the analysis. Section 3 presents the results, using a full climatology of ice products and a sub-set of wave hindcasts. Section 4 discusses the findings and corroborates the coastal signal with satellite altimeter estimates of wave trends. Section 5 concludes.

2. Methods

Analysis of ice and sea state trends uses satellite products and model hindcasts from an area-preserving domain shown in Fig. 1. The domain is a rectangle which is constant in area with latitude, such that the range of longitudes included must expand northwards. The domain is selected to cover the full extent of the seasonal variation in sea ice cover from the middle of the summer (1 August) to the late autumn (31 October). The analysis that follows uses this rectangle and is restricted to the months of August, September, and October.

2.1. *Sea ice satellite products*

The analysis of sea ice area coverage used the NASA Goddard Space Flight Center (GSFC) Bootstrap SMMR-SSM/I Version 2 quasi-daily time series (1979 to 2014) of sea ice concentration from the EOS Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center (NSIDC, University of Colorado at Boulder, http://nsidc.org). The day of autumn ice advance and spring retreat is identified for each gridded (25 by 25 km pixel) location and for each sea ice year that begins/ends during the mean summer sea ice minimum (from mid-September to mid-September). When identifying day of ice-edge advance and retreat, an annual search window is defined such that it begins and ends during the mean summer sea ice extent minimum in mid-September. Within this interval, the year day of ice-edge advance is identified as when sea ice concentration first exceeds 15% (i.e., the approximate ice-edge) for at least five days. See Stammerjohn et al. (2012) and Comiso (2000, updated 2015, 2010) for further details.

Sea ice type was estimated by scatterometer, following Gohin and Cavanie (1994) and Girard-Ardhuin and Ezraty (2012), with the goal of examining trends in the relative amounts of first-year ice versus multi-year ice. The sea ice type results are similar using the Envisat altimeter, following Tran et al. (2009).

2.2. *Wind reanalysis product*

The wind and ice product used for wave hindcasting is ERA-Interim, which is a global reanalysis of recorded climate observations over the past 3.5 decades (Dee, 2011). The spatial resolution of the data set is approximately 80 km (T255 spectral) with 60 vertical levels from the surface up to 0.1 hPa, and the grid employed is 0.75 deg resolution. ERA-Interim is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The temporal coverage is four time steps per day. The 10-m wind product is used to estimate the wind input to the wave model, following the latest source term formulation given in Ardhuin et al. (2010).

2.3. *Wave model hindcast*

Wave evolution, and thus the development of a sea state, is modeled by the Radiative Transfer Equation, as follows:

$$\frac{\partial E}{\partial t} + \nabla \cdot (\vec{c_g} E) = S_{\text{wind}} - S_{\text{brk}} + S_{\text{nl}} - S_{\text{ice}}, \tag{1}$$

where $E(\omega, \theta)$ is the directional wave energy spectrum and c_g is the group velocity (Masson and LeBlond, 1989; Young, 1999). The