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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

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ABSTRACT

We develop a conceptual model of the closely co-dependent Bering shelf, Bering Strait, and Chukchi shelf circulation fields by evaluating the effects of wind stress over the North Pacific and western Arctic using atmospheric reanalyses, current meter observations, satellite-based sea surface height (SSH) measurements, hydrographic profiles, and numerical model integrations. This conceptual model suggests Bering Strait transport anomalies are primarily set by the longitudinal location of the Aleutian Low, which drives oppositely signed anomalies at synoptic and annual time scales. Synoptic time scale variations in shelf currents result from local wind forcing and remotely generated continental shelf waves, whereas annual variations are driven by basin scale adjustments to wind stress that alter the magnitude of the along-strait (meridional) pressure gradient. In particular, we show that storms centered over the Bering Sea excite continental shelf waves on the eastern Bering shelf that carry northward velocity anomalies northward through Bering Strait and along the Chukchi coast. The integrated effect of these storms tends to decrease the northward Bering Strait transport at annual to decadal time scales by imposing cyclonic wind stress curl over the Aleutian Basin and the Western Subarctic Gyre. Ekman suction then increases the water column density through isopycnal uplift, thereby decreasing the dynamic height, sea surface height, and along-strait pressure gradient. Storms displaced eastward over the Gulf of Alaska generate an opposite set of Bering shelf and Aleutian Basin responses. While Ekman pumping controls Canada Basin dynamic heights (Proshutinsky et al., 2002), we do not find evidence for a strong relation between Beaufort Gyre sea surface height variations and the annually averaged Bering Strait throughflow. Over the western Chukchi and East Siberian seas easterly winds promote coastal divergence, which also increases the along-strait pressure head, as well as generates shelf waves that impinge upon Bering Strait from the northwest.

1. Introduction

1.1. Background

This study is motivated by the need to reconcile the following observations of the Bering/Chukchi circulation field (Fig. 1). Current meter records show that the annual mean northward Bering Strait transport increased from 2001 to 2011 (Woodgate et al., 2012). From 2006–2011, the mean winter position of the Aleutian Low shifted eastward into the Gulf of Alaska (Danielson et al., 2011a; Overland et al., 2012) relative to a more westward position over the Bering Sea from 2000–2005. In contrast, Danielson et al. (2012a,b) show that an eastward-displaced Aleutian Low results in more northerly winds over the central Bering shelf that force anomalously southward advection there, suggesting that transport in Bering Strait should have decreased in the latter half of the decade, rather than increased. We here construct an integrated view of the Bering/Chukchi shelf circulation field that is consistent with these observations by determining (1) the effect of remote wind forcing over the Bering and Chukchi shelves and their adjacent basins on the flow through the Bering Strait; and (2) the time

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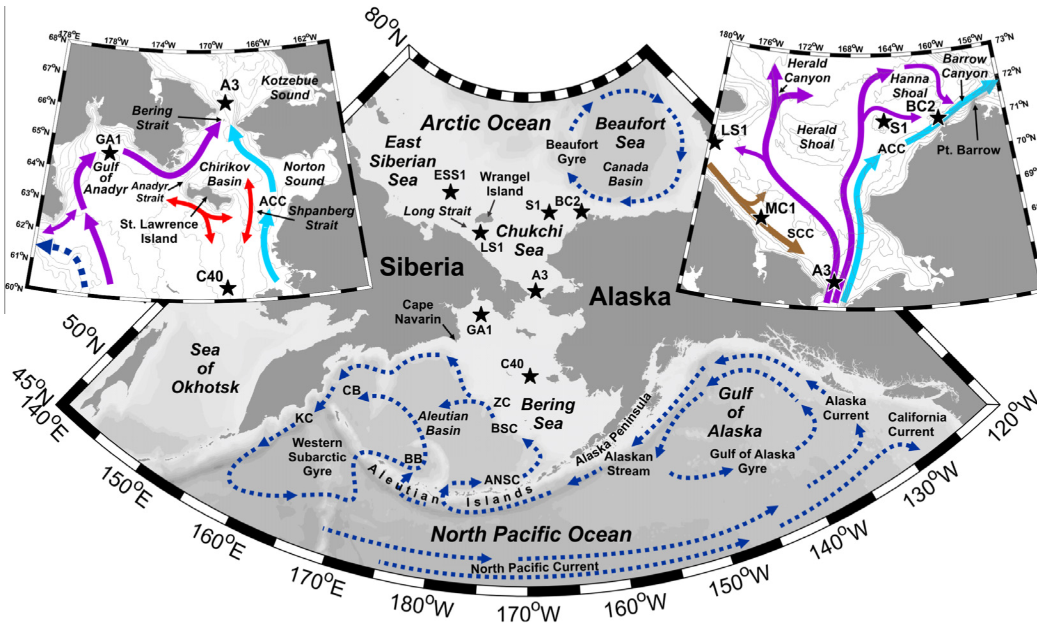

Fig. 1. Western Arctic and North Pacific place names, shaded bathymetry, circulation features, and locations (stars) of moorings A3, BC2, C40, MC1, and S1 along with reference sites LS1, GA1 and ESS1. Insets provide details of the northern Bering continental shelf/Bering Strait region (left) and the Chukchi Sea (right). Bathymetric contours on the insets are drawn at 10 m, 20 m, 30 m, 40 m, 50 m, 70 m, 100 m, 150 m, 200 m, 500 m, 1000 m, 2000 m, and 3000 m depth levels. Abbreviations include: ACC = Alaskan Coastal Current; SCC = Siberian Coastal Current; KC = Kamchatka Current; BSC = Bering Slope Current; ANSC = Aleutian North Slope Current; BB = Bowers Basin; CB = Commander Basin; ZC = Zhemchug Canyon.

scales over which these winds are important. Our approach considers how the effects of both long-term (inter-annual) and short-term (synoptic; hours to days) atmospheric variations reinforce or oppose each other to determine the net Bering/Chukchi shelf circulation field.

1.2. Importance of Bering Strait

The Bering and Chukchi seas are linked by the narrow (85 km) and shallow (50 m) Bering Strait, through which the North Pacific communicates with the Arctic (Fig. 1). The net northward transport of Pacific waters through Bering Strait extensively affects Arctic sea ice (Aagaard et al., 1981; Paquette and Bourque, 1981; Shimada et al., 2006; Woodgate et al., 2010), the global hydrologic cycle (Aagaard and Carmack, 1989; Wijffels et al., 1992; Serreze et al., 2006; Stigebrandt, 1984), and the global thermohaline circulation (Shaffer and Bendtsen, 1994; Goose et al., 1997; Wadley and Bigg, 2002; De Boer and Nof, 2004a,b; Hu et al., 2010). These waters also carry carbon, nutrients, and plankton that sustain the enormously productive northern Bering–Chukchi ecosystem (Grebmeier et al., 1988; Walsh et al., 1989; Springer and McRoy, 1993). Hence, an understanding of the dynamics, properties, and fate of the transport through Bering Strait is essential to studies of these ecosystems.

1.3. Wind and the regional subtidal circulation

The winds over the Bering and Chukchi seas depend upon the time-varying strength and position of the Siberian and Beaufort highs and Aleutian Low atmospheric pressure systems. Moreover, in the North Pacific the cyclonic wind stress curl of the Aleutian Low forces both the Western Subarctic (Isoguchi et al., 1997; Pickart et al., 2009) and Gulf of Alaska gyres (Wilson and Overland, 1986; Lagerloef, 1995). In the Arctic, the anticyclonic curl of the Beaufort High drives the Beaufort Gyre (Proshutinsky and Johnson, 1997; Proshutinsky et al., 2002).

Despite the annual mean winds being northerly (blowing from the north) in the Bering Strait (Woodgate et al., 2005a), the long-term (mutli-decadal) mean transport through the Bering Strait is ∼0.8 Sv northward (Ratmanov, 1937; Shtokman, 1957; Coachman et al., 1975; Coachman and Aagaard, 1981, 1988; Roach et al., 1995; Woodgate et al., 2005b). It has long been argued that this flow is maintained by an along-strait sea surface slope of $\sim 10^{-6}$ (Shtokman, 1957; Coachman and Aagaard, 1966; Coachman et al., 1975), and Stigebrandt (1984) and Aagaard et al. (2006) have proposed a corresponding steric height difference between the Arctic and North Pacific oceans of ∼0.7 m relative to 800 db.

Transport variations are substantial, however, and occur on timescales from hourly to interannual, and likely longer (Bloom, 1964; Fedorova and Yankina, 1963; Coachman and Aagaard, 1966, 1981; Coachman et al., 1975; Coachman and Aagaard, 1981; Aagaard et al., 1985; Coachman and Aagaard, 1988; Roach et al., 1995; Woodgate et al., 2005a,b, 2006, 2010, 2012). The maximum monthly mean northward transport is typically in summer, when winds are weak (Aagaard et al., 1985; Woodgate et al., 2005b), and minimum monthly mean northward transport in winter, when there are more storms. Indeed, particularly strong northerly winds can reverse the transport for periods of days to weeks (Coachman and Aagaard, 1981; Woodgate et al., 2005a,b).

Linear regressions using local winds (generally taken within 150 km of the strait), atmospheric pressure, or atmospheric pressure gradients account for about half of the observed subtidal Bering Strait transport variance in winter and one-fourth in summer. These regressions include a constant term that is often assumed to represent the Pacific–Arctic pressure head (Coachman and Aagaard, 1981, 1988; Aagaard et al., 1985; Cherniawsky et al., 2005; Woodgate et al., 2005a, 2012), but the causes and magnitude of fluctuations in this term are not well known. In addition, the distinction between "local" and "regional" wind forcing is not always clear, in part because the wind records are often taken from relatively coarse atmospheric models. As we will show, a significant fraction of the strait transport variability is forced by continental shelf waves generated by winds well outside the strait region (defined herein as the Chirikov Basin and the southern Chukchi Sea).