Continental Shelf Research 30 (2010) 656–667

Contents lists available at ScienceDirect

Continental Shelf Research

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

Variability of baroclinic tidal currents on the Mackenzie Shelf, the Southeastern Beaufort Sea

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A R T I C L E I N F O

Article history:
Received 6 May 2009
Received in revised form
29 September 2009
Accepted 16 November 2009
Available online 24 November 2009

Topical issue on "Tides in Marginal Seas" (in memory of Professor Alexei V. Nekrasov). The issue is published with support of the North Pacific Marine Science Organization (PICES).

Keywords:
Internal tides
Beaufort Sea
Semidiurnal currents
Inertial motions
Shelf-break
Complex demodulation

A B S T R A C T

Semidiurnal tidal currents on the outer shelf of the Mackenzie Shelf in the Beaufort Sea were found to be strongly influenced by the locally generated baroclinic tide. Two primary factors are involved in this process: (1) the sharp shelf break along the northeastern Mackenzie Shelf, promoting the generation of vigorous internal tidal waves; and (2) the proximity to critical latitudes for M_2 and N_2 motions locking these waves and preventing them from leaving the source region. As a result, internal tides are resonantly trapped between the shelf and critical latitudes. The physical properties and temporal variations of tidal motions were examined using current meter measurements obtained from 1987–1988 at four sites (SS1, SS2, SS3, and SS4) offshore of the shelf break at depths of ~200 m. Each mooring had Aanderaa RCM4s positioned at ~35 m below the surface and ~50 m above the bottom. Complex demodulation was used to compute the envelopes (amplitude modulation) of these components. A striking difference in the variability of clockwise (CW) and counterclockwise (CCW) tidal currents was found. The CW tides are highly variable, have greater amplitude, exhibit a burst-like character associated with wind events and contain about 80% of the total energy of the semidiurnal tidal currents. In contrast, the CCW components have a more regular temporal regime with distinct monthly, fortnightly and 10-day modulation at astronomical periodicities associated with frequency differences M_2–N_2 (0.03629 cpd), S_2–M_2 (0.06773 cpd), and S_2–N_2 (0.10402 cpd). Significant horizontal correlation of the CW current envelopes was found only between stations near the northeast Mackenzie Shelf, indicating this to be the main area of baroclinic internal wave generation.

1. Introduction

A substantive fraction of the energy of semidiurnal currents is associated with a baroclinic (internal) component. Baroclinic tidal motions are found to be highly intermittent, being dependent on variations of stratification and mean flow, so that their estimation and prediction remains a serious challenge (cf. Wunsch, 1975; Munk, 1997). Since, the direct baroclinic response of the ocean to astronomical forcing is negligible; generation of internal tidal waves is commonly thought to be caused by an interaction of barotropic tidal flow with topography, especially over shelf breaks and underwater ridges (cf. Morozov, 1995; Cummins et al., 2001). Variations in density and velocity fields near the source area initiate variations in the response of the internal tide (Hendershott, 1981). The generation mechanism of internal tidal waves is very sensitive to vertical and horizontal density distributions, but the details of the conversion of barotropic to baroclinic tidal energy depends on specific topographic features and is not yet fully understood (Müller and Briscoe, 1999).

Semidiurnal tidal currents in Arctic marginal seas have specific features, associated with the influence of ice cover and relatively weak stratification. However, the most important factor is the proximity of critical latitudes (ψ_{crit}) and the near-matching of semidiurnal and inertial frequencies. This proximity creates a serious challenge in the separation of two physically distinct processes: internal tides and inertial motions (cf. Pease et al., 1995). Also, as was shown by Munk and Phillips (1968), the internal tidal currents are significantly amplified at near-critical latitudes. This amplification mechanism enhances the clockwise (CW) component of tidal currents (in the northern hemisphere), but not the counterclockwise (CCW) (cf. Foldvik et al., 1990; Furevik and Foldvik, 1996). This follows from the properties of internal waves (Gonella, 1972): the CCW spectrum, $S^+(\omega)$, relates to the CW spectrum, $S^-(\omega)$, as

$$\frac{S^+(\omega)}{S^-(\omega)} = \frac{(\omega - f)^2}{(\omega + f)^2}, \quad (1)$$

where ω is the circular frequency and $f = 2\Omega \sin\varphi$ is the Coriolis (inertial) frequency, Ω is the Earth rotation frequency, and φ is the

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doi:10.1016/j.csr.2009.11.006

latitude. So, if $\omega \approx f$ (i.e. in the vicinity of a critical latitude, $\varphi \sim \psi_{\text{crit}}$) then this ratio tends to zero, thus explaining the strong dominance of the CW component in semidiurnal currents in the Arctic region. Internal waves in the ocean may exist only at superinertial frequencies (cf. Garrett, 2001); i.e. internal tides can only be present in "subcritical" latitudes. Thus, in Arctic Ocean, internal tidal waves may be generated by semidiurnal tides, but not by diurnal tides.

Another important effect is enhanced energy concentration of internal tidal waves at critical latitudes due to near-zero group velocity (cf. Garrett, 2001), and the vigorous generation of such waves at shelf break (Dushaw and Worcester, 1998), especially when this break is located equatorward of ψ_{crit}. Thus, local generation of internal tides near-critical latitudes is an essential contribution to baroclinic currents, while these latitudes do not noticeably affect the barotropic tide (Huthnance, 1978). Robertson (2001), particularly, made several numerical experiments to demonstrate that critical latitude resonance produces negligible effect on barotropic tidal currents but significantly affects baroclinic tidal motions. Kowalik and Proshutinsky (1994) numerically simulated barotropic M_2 tidal currents in the Arctic Ocean (including the Beaufort Sea) and did not obtain any specific peculiarities at the M_2 critical latitude.

Kulikov et al. (2004) used year-long (1987–1988) series of current meter observations at four sites (SS1, SS2, SS3, and SS4) offshore of the Mackenzie shelf in the Beaufort Sea (Fig. 1) to examine barotropic and baroclinic tides in this region and to identify possible generation sources of internal tides. Semidiurnal tidal currents were found to be strongly influenced by locally induced baroclinic tides. Two factors play the key role in this process: (1) the sharp shelf break of the northeastern Mackenzie Shelf (Fig. 1b), which promotes the intensive generation of the internal tidal waves; and (2) the vicinity of the M_2 and N_2 critical latitudes, which prevent these waves from leaving the source region. As the result, the internal semidiurnal tides are resonantly trapped between the shelf and their respective critical latitudes (a similar situation for diurnal waves is observed in the tropical Atlantic wherein these waves are resonantly trapped between the critical latitudes for diurnal tides and the shelf just north of Puerto Rico (Dushaw and Worcester, 1998)). At the same time, passing storms, which are especially vigorous in fall, generate energetic inertial waves with almost the same frequencies as those of semidiurnal tides, so that separation of tidal and inertial currents is far from trivial. Semidiurnal currents were found to be significantly variable in time and periodically experience short-term, "burst-like" abrupt amplifications, however, the reason of these bursts remained unclear.

In this study, the complex demodulation technique was used to examine these processes in detail and to gain insight into the reasons for their temporal changes. By treating the signal as a narrow-band stochastic process, we may apply the standard technique to extract the envelope (amplitude modulation) and phase for the entire semidiurnal band. A further modification of this approach was used to separate the vector signal into CW and CCW components, in order to estimate amplitude modulations and phase changes of each component and to compare these modulations with simultaneous modulations of semidiurnal sea level oscillations and variations of atmospheric pressure. The measurements used in this analysis, while collected over two decades ago using now-dated technologies, still constitute an important data set in that they give near-complete coverage of the annual cycle, and in that the moorings were well-placed around the perimeter of the Mackenzie Shelf to show spatial variations according to differing shelf-break geometries. Indeed, there remain very few long series of inter-comparable currents recorded in this region (owing to the severe conditions) and very few papers on the analysis of tidal currents in this region (despite their importance to vertical mixing). Use of the data set also allows direct comparison to other aspects of flow variability covered in Kulikov et al. (1998) and Carmack and Kulikov (1998). And while the general focus of this paper is similar to that of Kulikov et al. (2004), the application of new analytical methods here add new insight of the physical forcing and properties of baroclinic tidal currents.

2. Observations

Four current meter stations (SS1, SS2, SS3, and SS4) were deployed from the sea-ice during spring 1987 offshore of the Mackenzie Shelf Break at the depth of approximately 200 m (Fig. 1). They were redeployed from a survey vessel in August 1988. Each mooring consisted of two Aanderaa Recording Current Meters (RCM4s) with a near-surface instrument positioned at depth of about 40 m (to avoid collisions with drifting ice keels) and the second at about 50 m above the bottom. All four moorings were single-point, taut-line designs with subsurface floatation and acoustic releases (see Carmack et al., 1989; Kulikov et al., 1998 for details). The sampling interval was 1 h over the full year. The instruments were calibrated at the Institute of Ocean Sciences (IOS) prior to and after deployment. There were certain breaks between 1st and 2nd time series that have limited the analysis (at station SS3 upper the break between the records was about one month). Also, because of some technical problems, the actual current meter records suitable for the further tidal analysis were shorter than the duration of the mooring deployments (Kulikov et al., 2004).

3. Complex demodulation of semidiurnal currents

The objective of the present study is to analyze the structure and time variability of semidiurnal currents. Standard harmonic analysis, however, can extract only stationary currents associated with the barotropic tidal component forced directly by the harmonic tidal potential or with the "coherent" baroclinic component, which has a fixed phase relationship with the barotropic component and constant amplitude. Changes of mean flow or density field (seasonal or short-period) modify the internal tides and may cause amplitude modulation and phase variations of the harmonic tidal signal. The "incoherent" (variable) component of baroclinic tidal currents, and the inertial currents (which in this region have nearly the same frequencies as semidiurnal tidal currents), typically exhibit the character of individual wave-trains and may be treated as a random signal with a continuous narrow-band spectrum.

The complex demodulation technique (cf. Levine and Richman, 1989) is an efficient way to examine time variations of internal tides. This technique is based on multiplying the real time series $V(t)$ by a complex exponential $e^{i\omega t}$. The complex amplitude $\overline{u}$ of the resulting series near zero frequency is the same as the complex amplitude $V(t)$ near frequency ω_0. Applying a narrow-band low-pass filter to $V(t)e^{i\omega t}$ thus yields the complex amplitude at frequency ω_0. In our case we found it more reasonable to detect the integral variability of tides for the whole semidiurnal cluster. Treating the signal as a narrow-band stochastic process we may apply the standard technique to extract the envelope (amplitude modulation) and phase for all semidiurnal constituents together (cf. Whalen, 1971). A further modification of this approach was used to separate the vector signal into CW and CCW components and to estimate amplitude modulations and phase changes of both components (see Appendix A for details). Due to significant low-frequency fluctuations and the diurnal component we had to filter the original current meter data by a band-pass filter with frequency cutoffs of 1.5 and 2.5 cpd, thus creating a narrow-band series of semidiurnal currents. For comparison, we also examined