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TIDES

The tidal motion perpetually present in the Arctic Ocean influences the ice distribution and generates periodic leads in the pack ice associated with periodic divergence and convergence of the tidal flow over the tidal cycles. These periodic openings and closings of the pack ice cover influence both heat exchange between the ocean and the atmosphere and the rate of the ice production. Tides are also responsible for maintaining the basic level of turbulence beneath the ice cover and in close proximity of the bottom. The mixing and stirring due to the tides is especially strong along the Eurasian Shelf, but it also play an important role in the deep Arctic Ocean because the general circulation there appears to be extremely weak. Tides in the Arctic Ocean generally propagate in the same fashion as in the ice-free water bodies. The long tide wave of several hundred kilometers in length has very small surface inclination. On such surfaces the pack ice cover behaves like a flexible membrane, which weakly damps the vertical mode of motion but strongly resists the horizontal motion. Due to the friction damping at the ice-water boundary the water particles near this boundary move slower than in the deeper layers. This leads to the occurrence of the boundary layer in the tidal flow and variability of the tidal motion along the vertical direction. Tides along the coastline of the Arctic Ocean are known from observations; however, in the Central Basin the tides are inferred from hydrodynamical models. Tidal heights are composed of a sum of simple waves, which are called constituents. Their periods are clustered around 12h and 24h bands. The first ones are known as semi-diurnal tides (or constituents); the second ones are called diurnal tides (or constituents). The major contribution to the tides in the Arctic Ocean is related to the four tidal waves: semidiurnal constituents M2 and S2, and diurnal constituents K1 and O1. The numbers associated with the letters i.e., 1 and 2, denote the diurnal and semidiurnal constituents respectively. The strongest component of all tidal waves is usually M2; it is forced by the moon attraction. The S2 constituent is of the solar origin. The strongest constituent in the diurnal band of oscillations is K1; it is of the mixed luni-solar origin. The O1 constituent is forced by the moon attraction.

Tidal wave in every location is associated with the vertical movement of the free surface. The time interval between two successive peaks (or troughs) is called period. The sea level due to tide repeats itself after one tidal cycle (period), and therefore it is well represented as a periodic function such, as cosine function. In the periodic function the time changes can be altered to the phase changes from 0° to 360° . Therefore, in the tidal analysis, instead of using the time difference as related to the tidal period, the phase difference as related to 360° is used. The sea level changes in time cause horizontal tidal currents. The water particle transported by tidal current follows a closed elliptical path during one tidal cycle, i.e., in one cycle it runs along an elliptical path, returning to its initial position. The magnitude of the tidal current is given along the major axis of such tidal ellipse.

The largest component of the tide in the Arctic Ocean is the semidiurnal M_2 (period 12.42h). Since the tide producing force for this constituent in the Arctic Ocean is very small, the origin of this wave is an incoming tide from the Atlantic Ocean. The M_2 tide entering the Arctic Ocean between Greenland and Scandinavia is divided by Spitsbergen into two branches. The main wave enters through the Greenland Sea and the secondary wave propagates around Scandinavia towards the White Sea. The latter has amplitude at Northern Norway of about 1m. In the White Sea at the entrance it grows to about 2-3m and in the shallow Mezen Bay the amplitude is greater than 4m.

The M_2 wave in the main basin of the Arctic Ocean propagates during one period, counterclockwise around an amphidromic point located off the Canadian Archipelago. The tidal amplitude is zero at an amphidromic point, and it increases towards the shoreline. While traveling in the Arctic Ocean the M_2 wave undergoes transformation. When it impinges on the North Siberian Shelf its amplitude diminishes through the bottom friction. Along the North Siberian Shelf the amplitude is about 20-30cm and further the amplitude decreases to 5-10cm at the Alaskan shore. The M_2 tidal currents in the deep basin are quite small of the order of 2cm/s. The strong currents were observed along the coasts in the shallow water of the Barents Sea, especially over Spitsbergenbanken and close to the Bear Island. The strongest currents often up to 2m/s occur at the entrance to the White Sea. Along the North Siberian Shelf,

especially in the region of the New Siberian Islands, the M₂ tide currents are often of the order of 50 cm/s. The variability of the tidal currents is much stronger compared to the tidal levels, because currents depend on the local conditions, e.g., the currents along Alaska Beaufort coast are of the order of 5-10cm/s, but in the narrow entrances to the coastal lagoons they can be enhanced several times. Amplitudes of the second semidiurnal constituent S₂ (period 12h) are much smaller but the general picture of the wave propagating counterclockwise in the main basin is very similar to the M₂ wave.

Generally, diurnal tides K₁ (period 23.93h) and O₁ (period 25.82h) have smaller amplitudes than M₂ tide and their currents over shallow regions are also small compared to M₂. Although in some regions around Alaska and the Canadian Archipelago the amplitude of diurnal tides are close to semidiurnal tides. In these regions the semidiurnal tides were damped by friction. The diurnal tides propagate differently from the semidiurnal tides. This difference occurs in the currents. The diurnal tides generate regions of enhanced tidal currents along the shelf break at the depth of several hundred meters. These are so-called topographic trapped shelf waves. The discovery of the enhanced diurnal tidal currents in the entire water column above the Yermak Plateau (depth about 700m), by measuring currents below the drifting pack ice, showed importance of this mechanism for the deep processes in the Arctic Ocean. Along the shelf break in the Arctic Ocean and in the Nordic Seas, the tidal models predicted about 26 locations where diurnal trapped shelf waves occur. These are locations where the bathymetry (contours of the seafloor) at the shelf break (where the continental shelf falls away sharply to the deep ocean floor) shows irregular features such as seamounts and canyons. The tidal energy due to diurnal tides, dissipated over these 26 locations, is larger than the energy dissipated over the entire Arctic Ocean. Because large tidal currents occur either along the shelf (for the semidiurnal constituents) or at some locations along the shelf break (for the diurnal constituents) the nonlinear effects are important factors in the tidal dynamics of the Arctic Ocean. These effects are determined by averaging tidal current over a tidal period. If the average current is not equal to zero, a residual (or steady) current has been generated over the tidal cycle. This residual current constitutes a measure of the nonlinear effects. Therefore the water particle in such tidal currents during one tidal

cycle will depict an open ellipse with the initial and the final positions after one tidal period at the different locations. The well-known example of the steady motion due to oscillating tide is a circular ice motion around Bear Island in the Barents Sea. The individual ice floes circle around the island in a few days. The role of the strong tidal currents over shallow coastal regions is connected to the generation of the tidal fronts. Strong currents induce vigorous mixing (homogenizing) of the water salinity and temperature along the vertical direction in the shallow water. These tidally-mixed coastal regions are separated from the open ocean by tidal fronts. The well-known tidal front is located around Bear Island and Spitsbergenbanken. Tidal fronts occur along the entire Eurasian shelf, the fronts in the White Sea and around the New Siberian Islands are especially well described. Their position is often defined by the tidal velocity of about 50cm/s.

The periodic tide motion through divergence/convergence processes generates the periodic change in the ice compactness distribution. Russians and Scandinavians discovered these periodic openings and closings in the pack ice in calm weather during northern voyages. Grounded icebergs on the Spitsbergenbanken, and in other shallow domains, are the best image-makers of the elliptically shaped traces caused by the tidal motion. In a field of drifting ice floes, grounded icebergs induce trailing wakes (similar to an icebreaking ship) which, on satellite imagery, reveal the size of the tidal ellipses. The major feature of the Arctic tides is seasonal change of the tidal constituents. In most regions of the Arctic Ocean the seasonal changes from the summer to the winter in the pack ice compactness result in the diminishing of the tide amplitude about 3% and in the phase lag of about 5% (time lag is equal 5% of a tide period). Locally, especially in proximity to the shore fast ice (ice attached to the shore), these differences occur in a wider range. Canadian observations from Tuktoyaktuk revealed strong dependence of the tide on the ice cover. The M₂ amplitude changes from 16cm during summer to 11cm during winter. The seasonal phase difference is about 60° (or time difference is 1/6 of a tide period).

Tidally-induced motion of the pack ice interacts with other motions of the ice cover caused by the wind and permanent currents. The most interesting phenomenon

generated through these interactions is polynya, i.e., permanently or semi-permanently open water surrounded by the ice. The largest polynya occurs along the continental slope of the East Siberian and Laptev Seas. Tidally-induced motion is also one of the main factors in generating and sustaining polynyas in the region of the Lincoln Sea, Chukchi Cap, Yermak Plateau and Northeast Water Polynya.

The tidal research and the history of the Arctic tide research till 1960 is well described by Defant (1961). New developments have been summarized by Gjevik and Straume(1989) and Kowalik and Proshutinsky (1994). A basic understanding of the principles of tidal theories can be gleaned from Macmillan (1966). Tidal phenomena in the oceans and research methods to study tides are described by Pugh (1987).

Further Reading

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Macmillan, Donald, H., *Tides*, American Elsevier Publishing Company, New York, 1966.

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