



The pole tide/14-month oscillations in the Baltic Sea during the 19th and 20th centuries: Spatial and temporal variations

Igor P. Medvedev^{a,b,*}, Alexander B. Rabinovich^{a,c}, Evgueni A. Kulikov^a

^a P.P. Shirshov Institute of Oceanology, Moscow, Russia

^b Fedorov Institute of Applied Geophysics, Moscow, Russia

^c Institute of Ocean Sciences, Sidney, B.C., Canada

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ABSTRACT

Sea level changes with a period of 14 months (P_{14}) are usually associated with the pole tide, which is the oceanic response to the Chandler wobble in the Earth's axis of rotation. The amplitudes of these changes in the Baltic Sea are anomalously large, much larger than follows from the equilibrium pole tide theory. It appears that the oscillations are related to meteorological forcing rather than to pole motions. To examine the P_{14} properties, we used long-term (48–213 years) tide gauge records from 77 stations located in the Baltic Sea and adjacent area of the North Sea. High-resolution sea level spectra revealed a cluster of peaks with periods from 410 to 450 days. The temporal variations in the P_{14} sea level amplitudes and peak frequencies are found to be considerable and poorly correlated with the modulation of the Earth's pole motions. In contrast, our findings for 1871–2011 demonstrate strong resemblance between temporal (year-to-year) variations of the P_{14} peak and zonal wind, confirming earlier results of Ekman (1996) and O'Connor et al. (2000), who indicated the major role of the zonal wind in formation of the 14-month oscillations in the Baltic and North seas. The integral amplitudes of the P_{14} oscillations in the Baltic Sea gradually increase eastward from the entrance (the Danish straits) to the farthest ends of the sea with the largest amplitudes (up to 6.5 cm) observed at the very head of the Gulf of Finland. Similar P_{14} amplification toward the west coast of Denmark is also observed along the south coast of the North Sea. The geographical distribution of the P_{14} in these two regions are almost the same as of the seasonal sea level oscillations, indicating presumably similar formation mechanisms. Extensive shallow-water areas in the Baltic Sea and southeastern part of the North Sea, combined with intense meteorological forcing, appear to be two key factors responsible for the formation of anomalously strong 14-month oscillations in these regions.

1. Introduction

Traditionally, the “pole tide” is defined as an oceanic response to the 14-month free motions of the Earth's axis of rotation, known as the Chandler wobble. According to the equilibrium theory (Schweydar, 1916), the amplitude of the pole tide can be presented as

$$A_{pt} = \frac{\Delta U}{g}(1 + k - h), \quad (1)$$

where g is the gravitational acceleration, $k \approx 0.30$ and $h \approx 0.61$ are Love numbers, ΔU is the variation of the Earth's centrifugal potential,

$$\Delta U = -1/2\Omega^2 a^2 \Delta\theta \sin 2\theta, \quad (2)$$

where Ω and a are the mean rotation rate and the mean radius of the Earth, θ is the co-latitude and $\Delta\theta$ is the magnitude of the radius-vector of the Earth pole motion relative to the mean pole position. The

observed counterclockwise (CCW) motions of the Earth's pole associated with the Chandler wobble have rather complicated character, with the magnitude of $\Delta\theta$ varying between 0.05 and 0.40” (arc seconds) (Munk and MacDonald, 1960; Smith and Dahlen, 1981). According to (1), for a typical value $\Delta\theta \approx 0.22''$ (which corresponds to the radius-vector magnitude of approximately 6.8 m), the equilibrium pole tide has maximum amplitude of about 0.8 cm at 45° latitude and sinusoidally diminishes toward the poles and equator (Munk and MacDonald, 1960; Pugh and Woodworth, 2014).

Eqs. (1) and (2) are, in fact, simplistic representations of the pole tide and the Earth's centrifugal potential that do not take into account the effects of loading, self-gravitation and conservation of mass. As shown by Dahlen (1976) and Desai et al. (2015), the combined effects of these factors amplify the modelled geocentric pole tide by about 15%, or up to 2 mm of sea surface displacement. In any case, even with these corrections, the theoretical amplitudes of the pole tide are below

* Corresponding author at: P.P. Shirshov Institute of Oceanology, Moscow, Russia.

E-mail address: patamates@gmail.com (I.P. Medvedev).

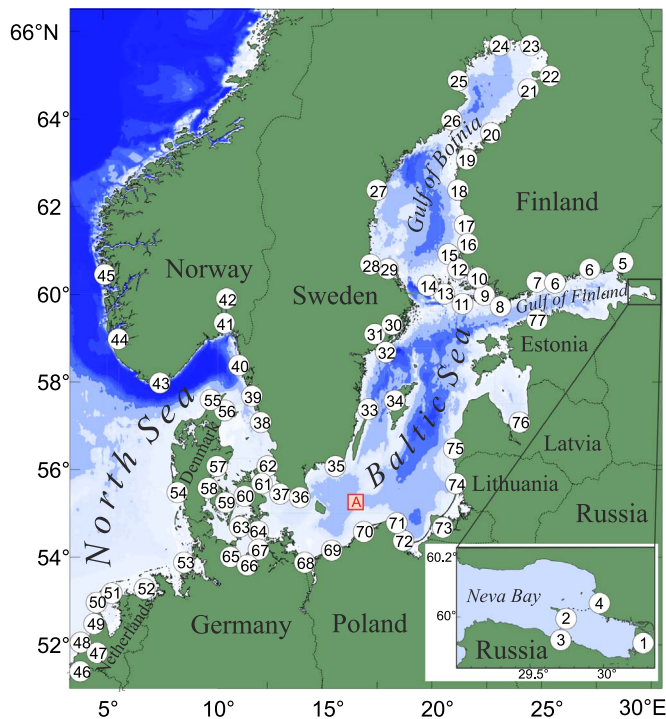


Fig. 1. Locations of tide gauge stations (white circles) on the coasts of the Baltic Sea and the southeastern North Sea; the names of the stations are given in Table 1. The red box labelled “A” indicates the reanalysis grid point (“Site A”) that was used to analyse the atmospheric data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1 cm. Moreover, the 15% amplification is related to an open ocean response, whereas for a small nearly enclosed basin, such as the Baltic Sea, the actual increase is likely to be smaller. However, observed amplitudes estimated from long tide gauge records, demonstrate that in some regions of the world oceans the 14-month oscillations are substantially stronger than predicted by equilibrium theory of the pole tide. Miller and Wunsch (1973) and Wunsch (1986) indicated fast growth of the pole tide amplitudes eastward along the Dutch, German and Danish coasts of the North Sea and into the Baltic Sea. According to Maksimov (1970) and Lisitzin (1974), the maximum amplitudes of the pole tide oscillations in the Gulf of Bothnia in the northeastern Baltic Sea (Fig. 1), are 4.5–5 cm, which are about 8–10 times larger than theoretical amplitudes of the pole tide for the corresponding latitudes.

The theories explaining this large difference in the pole tide amplitude are controversial: Wunsch (1986) suggested basin resonance at the pole tide frequency, while Tsimplis et al. (1994), Ekman (1996) and Xie and Dickman (1995) concluded that the ‘anomalous pole tide’ in the North and Baltic seas is entirely due to meteorological forcing. A remarkably high coherence between sea level and zonal wind stress along the southern coast of the North Sea was found by O’Connor et al. (2000) at the 14-month period. But this leads to ‘an even more difficult problem’: To explain the existence of the 14-month periodicity in the wind field (Wunsch, 2001; Pugh and Woodworth, 2014). It is evident that the problem is far from trivial and needs further research.

In general, the energy balance of the 14-month oscillations (P_{14}) may be represented as

$$P_{14} = P_{pt} + P_{ap} + \varepsilon, \quad (3)$$

where P_{pt} is the sea level oscillation directly generated by the Chandler wobble (i.e. the equilibrium pole tide), P_{ap} are the 14-month oscillations induced by atmospheric processes (meteorological forcing), and ε is the natural background noise with a 14-month period. The principal goal

of the present study is to estimate relative importance of each term of Eq. (3).

The anomalous character of the P_{14} oscillations along the southern coast of the North Sea, and especially in the Baltic Sea, is a question of considerable geophysical interest. Until now, it is unclear whether the extreme amplitudes of P_{14} are a specific feature of the Gulf of Bothnia, or an inherent property of some other areas in the Baltic Sea, in particular, the Gulf of Finland (e.g. Wunsch, 1986, 2001; Ekman, 1996; Medvedev et al., 2014). As described in Eqs. (1 and 2), the pole tide amplitude varies in the meridional direction but should be uniform in the zonal direction. In fact, all observations of P_{14} sea level oscillations reveal evident eastward amplification of the P_{14} amplitude in the North and Baltic seas (e.g. Wunsch, 1986; Xie and Dickman, 1995; Ekman, 1996; Medvedev et al., 2014). This means that, at least for these two basins, there is an obvious contradiction between the theoretical representation of the pole tide, directly associated with the Chandler wobble, and the recorded 14-month sea level oscillations.

Long-term high-quality series of sea level observations at numerous stations, which have become available in recent years (Medvedev et al., 2013, 2014), enable us to extensively investigate the spatial variability of the P_{14} oscillations in the entire Baltic Sea and adjacent regions of the North Sea, and to explore the nature of anomalous features of these oscillations in the two basins.

A particular property of the P_{14} sea level changes is that they are not a deterministic process, like the astronomical tide, but have significant temporal variations in amplitudes and periods (between approximately 410 and 450 days). In other words, the P_{14} oscillations may be considered as an amplitude-modulated signal with slightly variable period; the typical time scale of these modulations is 10–15 years (Munk and MacDonald, 1960). The significant temporal modulation of the P_{14} amplitudes is one of the reasons for inconsistency in results obtained by various authors for the Baltic Sea and some other basins. Continuous long-term series of sea level observations can provide a more reliable and objective picture of the phenomenon.

In our previous study (Medvedev et al., 2014), we presented results of a preliminary analysis of 71 tide gauge stations located in the Baltic Sea and Danish straits. The main focus was on estimation of the amplitudes and spatial variations of the 14-month oscillations in these regions. In particular, it was shown that the amplitude (A) of these oscillations increase with the distance (X) from the entrance into the Baltic Sea to the heads of the gulfs of Finland and Bothnia as $A(X) \approx 0.002X + 1.4$ (cm), where X is in km. The largest amplitudes — up to 4.5–6.5 cm — were found in the heads of these gulfs. The authors (Medvedev et al., 2014) emphasized that “...The existing theories of pole tide formation... do not allow us to explain the anomalous character of this tide in the Baltic Sea and significant increase in its amplitude from the entrances to the <gulf> heads... The next step in the investigation of the 14-month sea level oscillations in the Baltic Sea may be a joint analysis of these oscillations and the fluctuations of the atmospheric pressure and wind...”. Specifically these questions are the main purpose of the present study.

Significant temporal fluctuations of amplitudes and periods of the 14-month oscillations, indicated in the Baltic Sea by several authors, including Maksimov (1970) and Plag (1997), is another important point of our interest. Long (> 140 years) high-quality time series of sea levels in the Baltic and North seas enable us to provide a comprehensive examination of year-to-year P_{14} variations and to correlate them with variations of polar motions and atmospheric processes. This intercomparison was found to be crucial for understanding the nature of the anomalously large P_{14} sea level oscillations in these two regions. High spatial resolution of available tide gauge sites enabled us to construct a detailed map of the 14-month oscillations in the Baltic Sea and to demonstrate its close similarity with maps of seasonal and other long-period processes in this sea.

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