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Estimation of tidal constituents from sea level registrations in BAB "St. Kliment Ohridski", Livingston Island

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ABSTRACT

The report presents the first results of the tidal analysis from sea level records obtained from TG installed in the aquatory of the Bulgarian Antarctic base "St. Kliment Ohridski" (BAB) on Livingston Island, Antarctica. Sea level data are available from two Antarctic Expeditions, 26-st during 2017/2018 with more than 83-daily 15-minutes records and 28-th in the period January-December 2019. The tides in the aquatory of the BAB vary in the range of 2.4 m, and about 30 tidal constituents are determined to be significant using UTide software. The obtained results show that tides are mixed with semi-diurnal behaviour and a daily inequality between high and low waters. Comparisons have been made with the results of tidal regime analyzes from other studies for the Livingston Island area. The planned geodetic research activities in the area of BAB are briefly described.

1. Introduction

Making long-term recordings of sea-level variations to accurately determine the height of tides and their forecasting in the Antarctic region has essential scientific and practical value. Tidal oscillations at the ice-ocean interface of the Antarctic coast influence the location and extent of grounding zones control heat transfer and ocean mixing in cavities beneath the marine cryosphere and the calving and drift of icebergs (Padman et al. 2018). Tides range under most ice shelves fringing Antarctica are typically between 1-2 m, but spring tides can reach 2-4 m and occasionally exceed 6 m under the Filchner-Ronne Ice Shelf and in the southern Weddell Sea (Padman et al. 2002).

The Bulgarian Antarctic base "St. Kliment Ohridski" (http://www.bai-bg.net/bulgarian-base.html, Fig. 1) is located on the island of Livingston near the Spanish base "Juan Carlos I" (Vidal et al. 2012). The access to the BAB is by sea only, so it is essential to determine the tidal regime for unimpeded navigation, acoustics on the shore, and studying variations in sea level at different temporal and spatial scales under climate change conditions.

Tidal observations at BAB have been started in the last few years. Given that the permanent installation of sea level sensors must be per the extreme seasonal dynamic and harsh coastal conditions, the hydrostatic pressure sensor type "TideMaster" of Valeport Ltd, the UK, has been selected to be installed in a selected and protected location during the 26th Bulgarian expedition in 2017/2018 (Alexandrov 2019). This sensor measures the hydrostatic pressure of the water column at a fixed point and converts this to sea level. The goal was to overcome the damage to installed devices and cables that connect them to their onshore data logger and power supplies. The sensor is anchored at 3 m below sea level in the Emona Bay and records with sampling intervals of

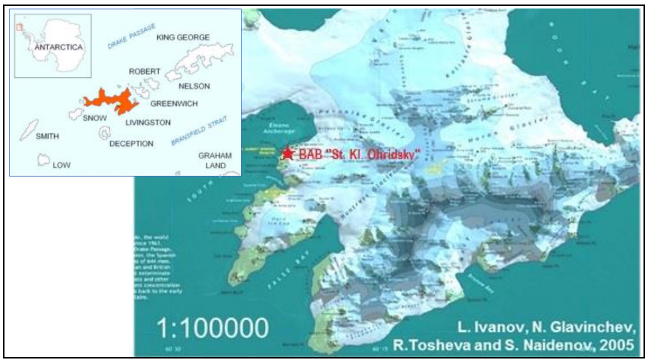

Figure 1. Location of the BAB "St. Kl. Ohridsky" on Livingston Island (shown in red on the inset map)

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15 minutes. The relative sea level was measured from Jan 3 to Feb 15 and from Apr 16 to May 22, 2018. A strong storm tears off the sensor and throws it ashore. The sensor was reinstalled again in another place during the 28th expedition after repairing the cables. The sea-level records are collected from Jan 9 until Oct 16, 2019, with two minor interruptions of several hours. Unfortunately, due to a sharp deterioration of the weather and heavy ice drift in the bay on Livingston Island, the power cable is was cut off, and the sensor stopped recording. The test location of the TG sensor installation in 2017 is with coordinates 62°38'39.9" S, 60°22'29.1" W (WGS'84), and the second in the Emona Bay has coordinates 62°38'32" S, 60°22'17" W, closer to the permanent GNSS site KOH2 established in 2019 (Alexandrov 2020).

This report provides the first analyses of the TG data collected from two sea-level campaign observations using UTide software (Codiga 2011). This study continues the previous one, as the time series of the sea level data have been supplemented with new ones, and other processing software has been used (Alexandrov and Pashova 2021). The obtained main tidal components through harmonic analysis (HA) are compared with the previous results and similar studies performed in this region. We estimated about 30 statistically significant tidal components and the tidal form factor F. We showing that the tidal regime in the Emona bay is mixed mainly semi-diurnal (0.25 < F < 1.5), similar to our previous result and confirming results of other studies (Vidal et al. 2012; Jigena et al. 2015). Studies of sea-level changes and tidal forecasting in the BAB region are needed for many other studies and applications. For example, tides are a vital component in the assimilation of sea level data into refined global and regional tidal models setup, investigation of the effect of future SLR on the tidal regime in this area of the Antarctic and the response of the primary tidal constituents to various SLR scenarios (see, e.g. Llanillo et al. 2019; Zhou et al. 2020).

2. Dataset and methodology

2.1. TG sea-level records

The selected sea-level datasets were subjected to data management procedures. All data undergo the QA/QC and convert into appropriate formats to use UTide software (Codiga 2011). In this study, two sea-level campaigns in 2018 and 2019 shown in Table 1 are used to evaluate the tidal regime at the BAB. Two more short observation periods are available, Apr 16 - May 22, 2018 and Jan 9 - Feb 19, 2019, but they are excluded from further analysis due to outliers in the data. For example, tidal records from the first observation period of 2018, obtained from the TG sensor, are presented in Fig. 2. The time series shows a maximum range of 2.28 m at TG BGLIV, defined as the largest difference between the maximum and the next minimum. Therefore, it can be classified as meso-tidal (spring tidal range of 1-2m).

A form number, F, has been defined as the sum of amplitudes of diurnal tidal species over semi-diurnal species (Defant 1958). A simplified definition of the F-ratio number is F = (K1+O1)/(M2+S2), and it can be used to characterize tidal types. If F is less than 0.25, the tide is semi-diurnal; if F is between 0.25 and 3.0 the tides are considered mixed, and if it is greater than 3.0, the tide is diurnal. The total 15-minute values used in this study are 24,294, and their histogram distribution is shown in Fig.3.

Table 1. 15-minute sea-level data used in this study

Year	Observed period		Days	Number of records
	start	end		
2018	3 Jan 12:15 LT	10 Feb 07:30 LT	38	3630
2019	14 Mar 21:15 LT	16 Oct 03:00 LT	215	20664

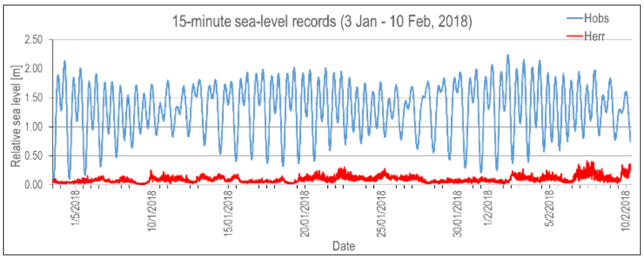

Figure 2. Tidal records H_{obs} (blue line) and residual series H_{err} (red line) at TG BGLIV on Livingston Island

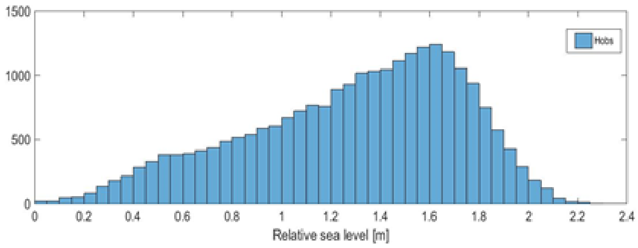

Figure 3. Histogram of sea-level data sets

2.2. Harmonic analysis

The standard tool for tidal analysis is usually based on HA, and Utide was selected to calculate all tidal constituents (Codiga 2011). HA codes model tidal heights $h(t_j)$ as a function of time t_j, with known tidal constituent frequencies f_k and unknown amplitudes a_0, $a_{1,k}$ and $a_{2,k}$; thus,

$$h(t_j) = a_0 + \sum_{k=1}^{n} [a_{1,k} \cos(f_k t_j) + a_{2,k} \sin(f_k t_j)].$$

Several experimental calculations using the UTide software tool (Codiga 2011) are performed (not shown) with different options of the iteratively reweighted least squares (IRLS) and the ordinary least squares (OLS) methods separately for the two observational periods. They show a minimal effect on the obtained results. Here, we show in Table 2, the most common tidal harmonic constituents - daily O1, K1, P1, Q1, sub-daily M2, S2, N2, K2 and three long-term constituents MF, MSF, SSA with their accuracy evaluation. Phase lags are referenced to Greenwich. More detail for practical application and interpretation of tidal analysis and prediction is provided in Parker (2007).

3. Results

The obtained results (Table 2) show that the most significant tidal amplitudes are the principal lunar M2 and principal solar S2. Diurnal constituents K1 and O1 also dominate the amplitudes. The significant differences between our results are not discovered, which confirm that the TG data obtained at the BGLIV station are reliable. Calculated values for 2(M2+S2) = 1.20 m, 2(K1+O1) = 1.04 m, and the tidal form factor F= (K1+O1)/(M2+S2) = 0.86, which shows that the prevailing tides are mixed.

Table 2. Tidal constituents at BGLIV station on Livingston Island and their accuracy estimation

Tidal component		Amplitude [cm]	Error [cm]	Phase [°G]	Error [°G]
Daily	K1	26.2	0.1	23.5	0.2
	O1	25.9	0.1	6.1	0.2
	P1	8.1	0.1	16.0	0.8
	Q1	5.7	0.1	358.0	1.2
Sub-daily	M2	39.6	0.1	191.0	0.2
	S2	20.6	0.1	249.0	0.3
	K2	5.9	0.1	246.0	0.7
	N2	5.3	0.1	153.0	0.9
Long-term	MF	5.5	2.2	286	22.5
	MSF	2.5	2.0	274	46.5
	SSA	9.1	2.2	97.6	11.8

The harmonic constituents are determined from the sea level data of the TG station LIVMAR at the Spanish base (Vidal et al. 2012; Oreiro et al. 2014; Jigena et al, 2015) close to the TG BGLIV, agree well with our results. In practice, the values of the main daily and sub-daily tidal components are the same within the accuracy they are estimated. The small residuals could be attributed to local forcing by wind stress and air pressure fluctuations (inverse barometer effect). The water level variations are exclusively driven by astronomical tides. The values of the long-term dominant harmonics have larger amplitudes for the local area of the Bulgarian base in comparison with those estimated from the Spanish TG LIVMAR, which is located in the south-southwest direction of the South Bay on t Livingston Island. The values of the estimated phases differ by about 50° for the diurnal and about 100° for the half-day tidal components. This fact can be explained by the LT (UTC - 3h) used in the data processing, in which registrations are made at sea level through TG BGLIV at BAS.

Further, we compare our results with the published main tidal constituents from global Tidal Analysis using different data sources for the Antarctic Peninsula (Padman et al. 2002; Oreiro et al. 2014; Howard et al. 2020; Weikang et al. 2021). They are also in good conformity with the main tidal constituents obtained through global and regional tidal models developed in the last two decades. The established differences in the amplitudes are of the order of ± 4-5 cm, with what accuracy the tidal components are presented in the global and regional models

4. Discussion

The HA is one of the most popular methods to investigate the tidal regime and its change. This study provides the first results of tidal harmonics using the 15-minute sea-level records; the results show high consistency with the results estimated with the HA method and the independent regional tidal solution for the Livingston Island. The obtained results are auspicious to be used for further analysis and comparison with the satellite altimetry data and to be assimilated into numerical models for regional and local weather and ocean forecasting. Changes in tidal characteristics over time are usually associated with local changes in morphology and tidal currents. In addition to morphological changes and SLR that affect the propagation pattern of tidal currents (which depend on water depth and the shape of coastlines and bays), the changes in mixed layer depth are caused by the warming of the upper ocean layer may induce additional unknown baroclinic changes in currents (Llanillo et al. 2019).

Global changes in tidal properties may have significant spatial variations since different mechanisms may dominate different coasts. Recent studies highlight that mean SLR, intensifying coastal threats at some locations (see, e.g., Pickering et al. 2017), modifies tidal propagation in shallow waters. Further long-term sea-level observations at the TG BGLIV could be used to study time-dependent changes in tidal amplitudes under climate change conditions.

The research activities at the BAB envisaged for the next Bulgarian expedition to Livingston Island include re-establishing the tide gauge, performing precise GNSS levelling to link with TGBM and GNSS site KOH2 for long-term vertical datum control (Alexandrov and Pashova 2021). The IOC (2020) recommendations for the management of in-situ sea level monitoring stations will be taken into account when restoring the TG station and ensuring its smooth operation. Data can be recorded with improved time resolution, for example, every 1 minute, which will increase their amount, accuracy and ability to be used in the study of short-term high-frequency processes lasting from minutes to hours captured by the TG sensor.

5. Conclusion

Many factors can be taken into account when analyzing data from GT sea-level registrations that can give a clearer picture of actual water surface fluctuations and the relationship to the SLR and global climate change. To study the exact mechanism of how changes in shallow water in the bay in front of the BAB and changes in the wave field can affect the tidal variability in the local region require the installation of other equipment and additional research. Initial ocean parameters measurements (salinity, temperature and conductivity) were made during the 2019-20201 campaign near the shore and inland in front of the base. These data were pre-processed and will be used in future joint analyzes and comparisons with data from other sources. Furthermore, changes in the tidal characteristics over time are usually associated with local morphology and tidal currents. In addition to morphological changes and SLRs, which affect the pattern of tidal currents depending on the depth of the water and the shape of the shores and bays, additional unknown baroclinic changes in the currents may be caused by warming of the upper ocean layer. In this regard, hydrographic measurements in the

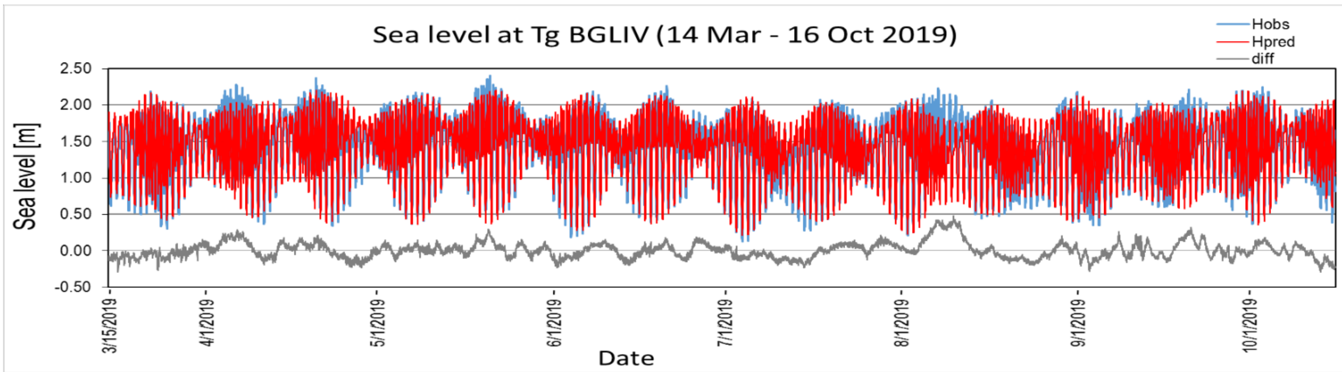

Figure 4. Sea level data, predicted tides and their residuals for the period 14 Mar – 16 Oct 2019 using UTide software

area of the Bulgarian base were performed to prepare a bathymetric map (Alexandrov 2019; Alexandrov and Pashova 2021).

In the last three decades, Bulgarian scientists working on the harshest continent on the Earth have contributed to the implementation of several international and national projects related to the current earth science topics. Seven Bulgarian surveyors contribute to the development of geodetic science and practice in the extreme conditions of Antarctica. They are part of the established experts who have contributed to the study and development of human knowledge about our planet. The construction of a permanent tide gauge station in the BAB "St. Kl. Ohridsky" area is essential for multi-disciplinary studies. TG BGLIV will be used for long-term research; the data will be processed, archived and analyzed together with those from other observations performed regularly. Its maintenance requires the provision of good logistics, providing a constant power source of energy for its year-round operation and finding a suitable data transfer in near or real-time to a Centre of the Bulgarian Antarctic Institute in Sofia, which are in progress.

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