Sea Tide Analysis Derived by PPP Kinematic GPS Data Acquired at David-Drygalski Floating Ice Tongue (Antarctica)

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Abstract.
One of the most important ice-stream of the Victoria Land (VL) is the David Glacier, which produces 100 km long floating sea-ward ice tongues in the Ross Sea, the Drygalski Ice Tongue (DIT). The ice-tongue slides down into the sea increasing its velocity rates and together with ice-stream movement sometime produce characteristic ice-quakes. This paper shows the effects of the sea tidal variation on both horizontal and vertical components of movement at a portion of DIT. Ocean tide is usually modelled by a series of harmonic coefficients (amplitude and phase), which are estimated through several systems of measurement. For the study area, these data are made available by the Antarctic Tide Gauge (ATG) database. Moreover, tidal data recorded by a multiparameter underwater tide gauge, which was installed at Mario Zucchelli Station (MZS), the Italian Antarctic Base, in February 2006, are being processed again.
The kinematic Precise Point Positioning (PPP) processing was adopted for the analysis of 24 days of acquisition performed with a GPS receiver located in the initial part of DIT, about 46 kilometers seaward from the Ice Fault David Cauldron. The analysis of harmonic tidal components has shown that PPP solutions show correct values of diurnal and semi-diurnal tidal components and therefore can provide valuable information in the coastal area covered by ice tongues.

Keywords: Tide analysis, Kinematic Precise Point Positioning, glacier mechanics, Antarctica.

1 Introduction

Antarctica is a continent almost entirely covered by ice and therefore particularly sensitive to climate change. The Antarctic ice coverage includes continental glaciers and marine ice shelves, which influence Earth's energy balance through their high

albedo. For this reason, the decrease in the volume of the ice mass would lead to an increase in the global temperature.

Glacier dynamics depend on several effects (bedrock and ice surface topography, snow accumulation, fault alignments in the bedrock, dry or wet basal condition, ice temperature, weather conditions, etc). When the ice flows are fed by very large drainage basins, such as those of the plateau areas of Eastern Antarctica, the flows become very fast and concentrate towards the coast in narrow "rivers of ice", which are called ice-streams.

The Drygalski Ice Tongue (DIT), 75°30' S, 163°50' E, is the seaward eastward extension of the David Glacier into the Ross Sea. It is about 100 km long and 14-24 km wide, and it is fed by the David Glacier and the Larsen Glacier, along the coast of Victoria Land (VL), more than 100 km far from Mario Zucchelli Station (MZS), the Italian base in Antarctica (figure 1). The David-Drygalski Glacier and DIT are the most important glaciers of VL.

In Terranova Bay there is a large area of open water produced by very strong katabatic winds (polynya), which persists throughout the winter. The David Glacier is the most massive drainage glacier for Talos Dome and Dome C in the East Antarctica sector. From Transantarctic Mountains start strong winds that blow downslope, driving the sea ice eastward. The dominant ice drift pattern in the area is northward, so DIT prevents the Terra Nova Bay from being repopulated with sea ice.

The DIT evolution was monitored and studied for glaciological and geophysical purposes [1, 2], and oceanographic ones [3-6].

Remote sensing and past geodetic GPS surveys showed that the terminal part of the DIT is characterized by high superficial velocities, up to 700 m/year [7-12].

In general, the fluctuation of the ice sheets depends on the processes in the subglacial environment. The extension variation of the ice shelf affects tides and alters the speed of movement of glacial tongues [13-16].

The study of the behaviour of the Antarctic ice balance is important for understanding the variation of the global marine level, which affects the flow of ice from the continent to the ocean.

Furthermore, DIT acts as a blocking feature to the upper sea, forcing surface current. The local ocean circulation is affected by tidal excursion, which plays a role on in terms of pumping and local supercooling [5].

Shear seismicity along the ice-bed interface is a function of the sliding motion of glaciers, the flow speed and is affected by the tide behaviour [17-24]. The DIT is in hydrostatic equilibrium year-round, but falling tide behaviour produces acceleration of the Ice Tongue.

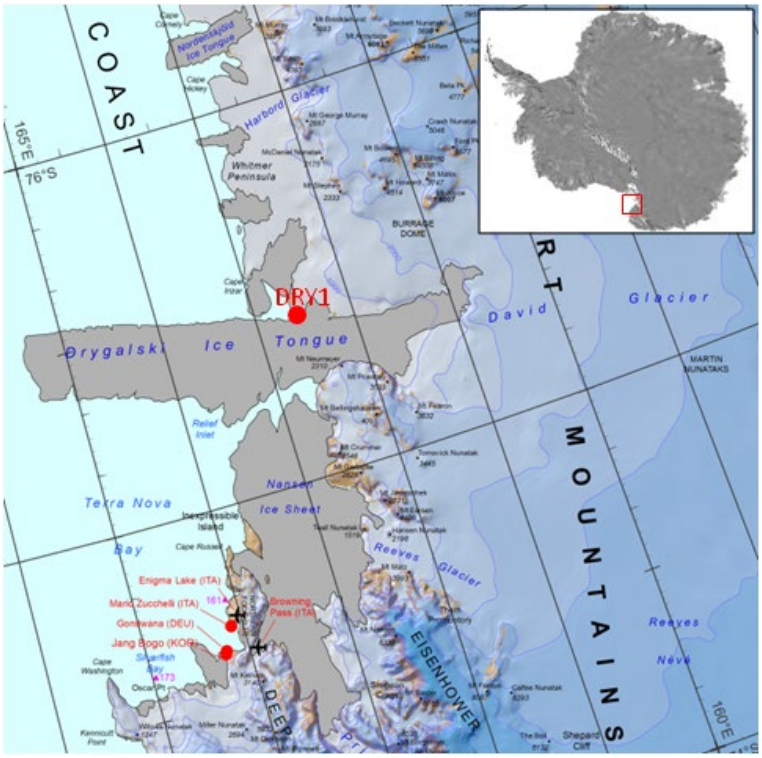

Fig. 1. Map shows the Drygalski Ice Tongue (DIT). DRY1 is the GPS station located in the initial part of DIT (modified from "Map 16: Victoria Land, Edition 3", Polar Geospatial Center, USA). The location of the tide gauge of Cape Roberts is off the map, 170 km far southward DIT.

Tidal observations are the basic water level readings, usually coming from tide gauges, which are instruments that allow most accurate analysis.

Satellite altimetry is a remote sensing suitable technique for measuring tidal changes.

Ice Cloud and Land Elevation Satellite (ICESat) have been running since 2003 using the GLAS Geoscience Laser altimeter System [25]. The system provides water level in Antarctica with accuracy greater than 20 cm [26].

The research purposes are to show the effects of the sea tidal variation on both horizontal and vertical components of movement at a portion of DIT.

Ocean tides in the area of the DIT were obtained using a single GPS receiver and compared with those obtained from the tide gauge placed near MZS [27]. In Antarctica this technique was previously adopted successfully by several authors [19, 28-31].

King and Aoki [32] presented a similar approach to obtain tidal observations on floating ice using a single GPS receiver and processing GPS data based on the Precise Point Positioning. In this case, there is no need for a GPS reference station that acquires continuously and the method provides quite similar precision allowing of diur-

nal and semi-diurnal tidal constituents, which can be assimilated into numerical tide models.

GNSS data processing and tidal analysis procedures are described in sections 2 and 3.

2 GNSS data processing

During the 2005–06 Austral Summer (21st Italian Expedition to Antarctica) two GPS antennas (DRY1 and ICF1) were installed on the Drygalski Ice Tongue [19]. The collected dataset resulted in 24-hour 15-second GNSS data in compressed RINEX format. The observation periods were 24 and 34 days respectively. Only the point DRY1 was located downstream of the grounding line of the David Glacier, and therefore was reprocessed in this analysis. For the installation of the geodetic GPS station on the ice, an aluminium tube of 13 cm diameter and 3 m long was used, and driven in the ice of about 1 m. To fix the antenna on the top of the pole was used an aluminium adaptor designed to allow the self-centering of the geodetic antenna. A solar panel was used as power supply for the GPS receiver for several days.

Dual-frequency GPS daily observations were analysed firstly by Danesi et al., [19]. In this case, a differential approach was used, adopting the kinematic module TRACK of GAMIT-GLOBK post processing software [33]. Vice versa, in this study a PPP approach was adopted using the Bernese GNSS software, Version 5.2 [34], to calculate the kinematic position of DRY1 GPS antenna.

The CODE products such as satellite orbits, 30-second clocks, and Earth orientation parameters (EOP) were used in the calculation along with the IGS products for the atmosphere modelling. The solution discussed in this paper was calculated using 900 seconds as the observable sampling interval and does not take into account the atmospheric tidal loading (ATL) corrections.

In figure 2 is reported the comparison between the differenced post processing approach, obtained at the time of the measurements using the module TRACK of GAMIT-GLOBK post processing software, and the new PPP processing using the Bernese GNSS software, Version 5.2. The time series are quite similar and the processing following a PPP approach using the Bernese GNSS software furnish a cleaner solution.

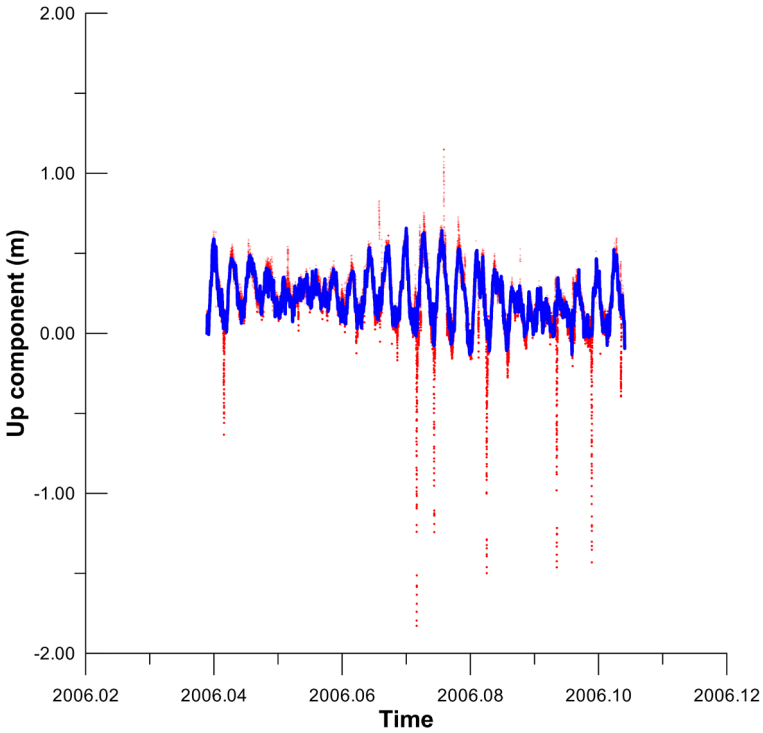

Fig. 2. Comparison between the differentiated post processing approach obtained in 2008 at the time of the measurements using the module TRACK of GAMIT-GLOBK post processing software (red points), and the new processing made in 2019 following a PPP approach using the Bernese GNSS software, Version 5.2 (blue points).

Considering that 10 years have passed between the differentiated solution and the PPP solution, and that in recent years considerable improvements in analysis methods and in the quality of ancillary products (ephemeris, clocks, PCV models, etc.) have been achieved, we can still consider of good quality the kinematic differentiated solution obtained using a reference station at a distance of over 100 km. Despite the many outliers, now absent in the undifferentiated analysis, the amplitudes and the phases of the signals were also identified in this first analysis. The actual precision achievable using the PPP kinematic approach in the same conditions of those described in this study can be considered at 5 cm level [32].

3 Tidal analysis

The water level variation is mainly a function of the gravitational interactions between earth, moon and sun. Tidal frequencies are characterized by defined parameters. The purpose of tidal analysis is to reproduce significant and stable absolute tidal parameters representing the tidal regime of the observation place. These parameters are called tidal constants to indicate their stability over time.

The quality of the parameters is also a function of the quantity of data and their temporal extent. The water level changes at both tidal and non-tidal frequencies. Sea level can be modified due to weather conditions, such as evaporation, solar radiation, wind and atmospheric pressure changes. These effects must be added to those derived from the astronomical ones.

The aim of the tide analysis is to separate these two components and to estimate predictable water level. In this study the calculated tidal parameters have a relative non-absolute meaning: they were estimated using a short series of GNSS data collected on DIT (DRY1 24JD), [19].

The closest tidal gauge to DRY1 is placed at Mario Zucchelli Station (MZS), [35]. It is maintained by the Italian Geodetic Observatory in Antarctic (IGOA) in the frame of the Italian National Program for Antarctic Research (PNRA, Programma Nazionale di Ricerche in Antartide). The harmonic tidal parameters used for the comparison were extracted from Goring, Pyne [27].

For the analysis and prediction of water levels in tidal waterways the World Tides and World Current 2013, program described in: John D. Boon Marine Consultant, LLC [36], were adopted.

This analysis permits the evaluation of a water level time series into its tidal harmonic components, relative to the Mean Sea Level (MSL), using a selective least squares harmonic reduction, and employing up to 36 tidal constituents. This program adopts HAMELS method (Harmonic Analysis MEthod of Least Squares) [36] to analyze the level time series, which achieves a progressive reduction in variance adding harmonic specific astronomical terms to a general least squares model [36].

After the evaluation of tidal harmonic constants using measured observations, prediction of the astronomical tide is produced. Differences between predicted and observed tides make it possible to detect residuals signals mainly due to non-tidal effects.

In table 1 are shown the estimated values of amplitude and phase of sea-tide components: forecast value at MZS and the estimated ones from the PPP time series.

In figure 3 are reported the vertical movements derived by the PPP analysis of 24 days acquired at DRY1, compared with the forecast sea tide signal derived by the same dataset.

Table 1. Forecast ocean-tide described by 8 principal harmonic components included in the ATG database for MZS, and estimation of the same parameters from PPP time series observed at DIT.

Tidal Components	Forecast sea-tide derived by ATG database for MZS		Observed PPP at DIT	
	Amplitude (cm)	Phase ° (Greenwich)	Amplitude (cm)	Phase ° (Greenwich)
Q1	4.1	146.0	2.8	108.2
O1	18.3	169.6	10.8	189.7
P1	6.0	204.8	1.8	187.9
K1	16.8	204.2	9.9	226.4
N2	4.4	228.8	3.4	178.8
M2	6.9	336.3	4.0	354.8
S2	5.9	304.7	5.1	342.0
K2	2.5	329.1	1.3	181.1

4 Results

The diurnal declinational tides K1 and O1 are the most important tides which occur once a day. In the Ross Sea as well as in the coasts between 65° W to 140° E there is a tide cycle per day, the lunar phases do not affect the tides. This confirm Thiel et al., [37], who firstly showed that the Ross Sea tide is diurnal and the solar component is predominating. Tides amplitude in the Ross Sea reduces every 13.66 days, corresponding to the Moon's crossing of the equator [27].

Robinson et al., [38] demonstrated that the amplitudes of the diurnal tidal constituents in the Ross Sea are larger than in the adjacent Southern Pacific Ocean, indicating the existence of a diurnal resonance related to the shape and depth of the sea.

The tidal levels observed are given by the sum of the astronomical effects due to the motion of the Moon and the Sun and to the weather contribution, which can play an important role that can change the sea level.

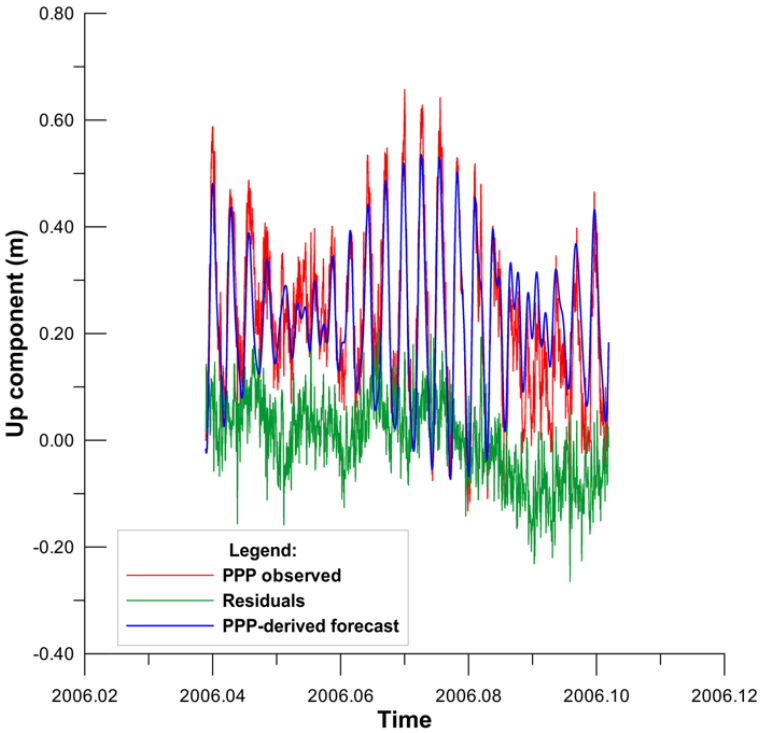

Fig. 3. Comparison between observed PPP time series at DIT and forecast sea-tide, computed by Q1, O1, P1, K1, N2, M2, S2, K2 harmonic coefficients estimated intrinsically by PPP time series. The residuals show the differences between the forecast signal and the observed one.

While the astronomical tide is predictable, the weather effects that produce variation in air pressure and wind induced effects are not easily predictable. Their presence is highlighted by the differences found between the expected and the observed tides (derived by GPS data).

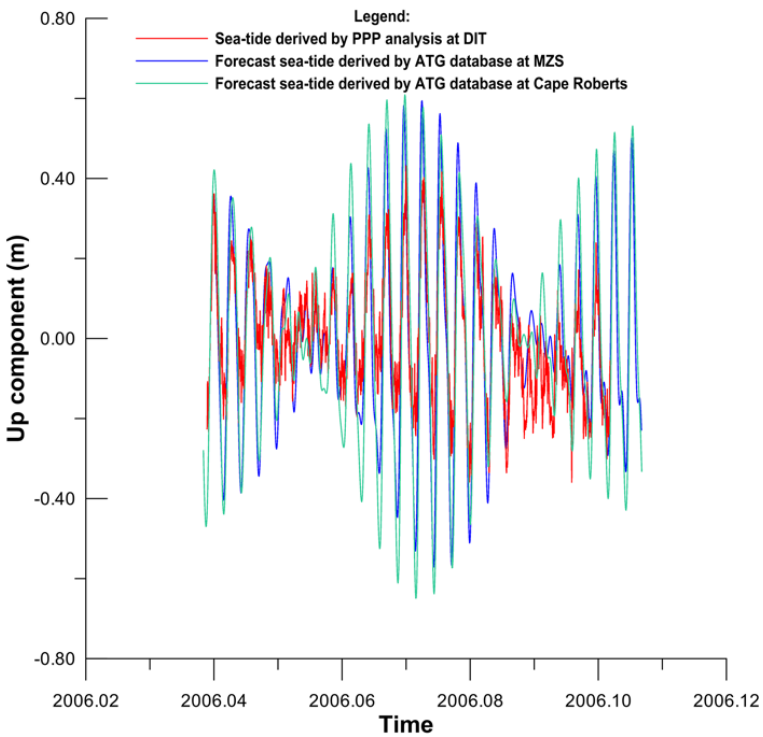

Fig. 4. Comparison between sea-tide observed by means of PPP time series acquired at DIT and the forecast sea-tide, computed by published Q1, O1, P1, K1, N2, M2, S2, K2 harmonic coefficients in ATG database for two sites: MZS (about 100 km Northward of DIT) and Cape Roberts (about 170 km Southern DIT).

Two main results are pointed out by this experiment:

1. The right amplitude and phase of sea tide response of the ice tongue, which is reduced in amplitude with respect to forecast waited signals (figure 4 and figure 5); DRY1 GPS station is located about 30 km seaward with respect to the estimated position of the grounding line. In this position, considering the elevation of the GPS point above sea-level, the submerged thickness of the ice is roughly 600 m at the DRY1 position. Due to ice thickness and lateral friction with respect to the rocky walls in which it expands inside a fjord, the amplitude of observed ice-tide at DRY1 is reduced.
2. Horizontal velocity of ice flow increases and decreases seaward, as a response of tide amplitude changes (corresponding to the Moon's crossing of the equator). In particular, in figure 6 can be observed a delay of about 1-2 days between the high tide observed in the maximum amplitude tide phase with respect to the higher horizontal velocity of the ice.

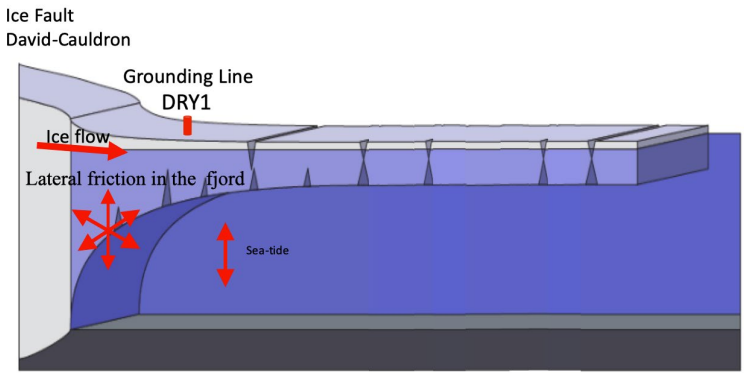

Fig. 5. Scheme of a float ice-tongue, derived by [39], introduced to point out a possible interpretation of figure 4, where two tide gauges located the first Northward and the second Southward with respect to DIT show amplitudes of sea-tide greater than the values observed at DRY1.

5 Conclusions

In this paper the tidal harmonic constants were determined using post-processed GPS observations according to the PPP procedure and to a standard differentiated approach. The PPP technique is very effective because GPS base station is not required, and this option is particularly useful for acquisitions in remote areas, such as Antarctica, where the number of GNSS permanent stations is limited.

The differences between the predicted and the observed tides were analyzed. The PPP derived elevation time series confirms the diurnal characteristic of the sea tide in the DIT area, with small semidiurnal component.

The tidal calculation compared to the predicted tide evaluated using the parameters published in Goring and Pyne [27], shows an excellent match only in terms of phases of the tide signals, but not with regard to the sea tide amplitude forecast.

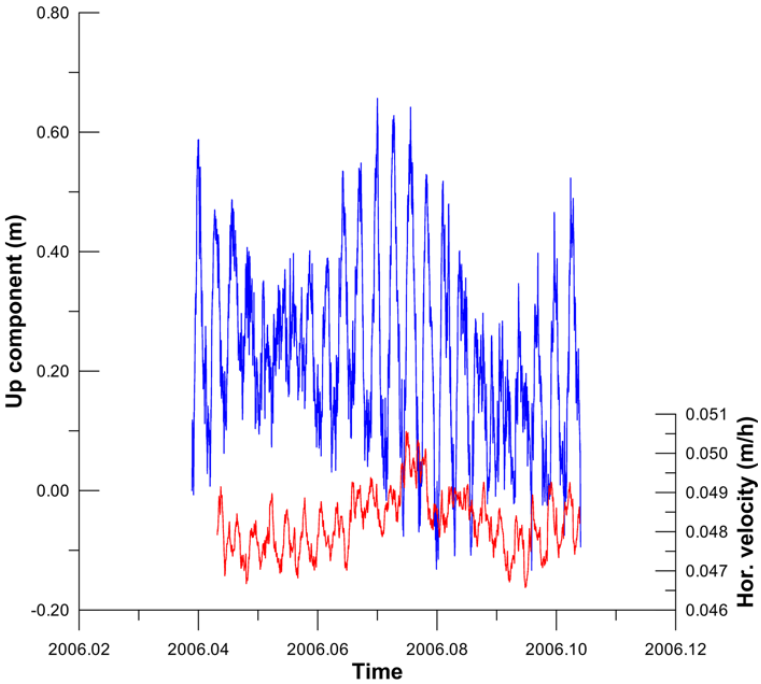

Fig. 6. Analysis of the horizontal velocity of the ice-tongue at DRY1, with respect to the phases of the vertical amplitude of sea tide. As can be clearly point out by the figure, the horizontal ice velocity increases with the increment of the tide amplitude. This effect could be interpreted with a minor friction of the glacial mass coming from the David, due to the greater elevation of the floating ice near the grounding line.

The differences highlighted are attributable to a number of coexisting factors, including the distance between the observation points, the time difference of the measurements, the weather effects related to solar radiation, wind, and atmospheric pressure changes. Nevertheless, the main effect observed is the reduction of the sea tide amplitudes, which could be due to the considerable ice thickness of the floating ice-tongue at DRY1 and to lateral friction with the rocky walls, where it expands within a fjord. In fact, they could act as resistant forces to tidal stress, up to reduce the tidal amplitude observed on the floating ice tongue

The PPP technique applied in coastal areas covered by ice tongues can provide valuable information as tide gauge instrument and contributes to the definition of dynamic models of floating glaciers.

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