AN ESTIMATE OF THE SEA LEVEL TREND ALONG THE TUNISIA COASTS

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ملخص
تقيّم هذه الدراسة مدى ارتفاع مستوى سطح البحر على طول السواحل التونسية على أساس الملاحظات التاريخية والحديثة لمقاييس المد والجزر الموجودة على السواحل التونسية وعلى الجانب الغربي من مضيق جبل طارق للفترة 1880-2018. تستخدم أيضًا سلسلة مستوى سطح البحر القائمة على إعادة التحليل والمحاكاة النموذجية للبحر الأبيض المتوسط. أولاً، تم إنشاء سلسلة تمثيلية واحدة لمنطقة المضيق الغربي لجبل طارق. بعد ذلك، يتم إنشاء سلسلة مستوى سطح البحر على طول السواحل التونسية على أساس افتراض أن الانخفاض الملحوظ في مستوى سطح البحر مقارنةً بذلك على الجانب الغربي من مضيق جبل طارق يظل عمليا دون تغيير عندما نعتبر فترات طويلة الأجل. تُظهر السلسلة ارتفاعًا واضحًا في مستوى سطح البحر متراكبً على تقلب عقدي متعلق بتذبذب شمال الأطلسي. بالنسبة لكامل الفترة، يُقدر ارتفاع مستوى سطح البحر بـ 1.5 +ملم / سنة بينما يقدر ب 3 +ملم / سنة للفترة الأخيرة 1980-2015. يرجع هذا الارتفاع في مستوى البحر في الفترة الأخيرة إلى التقلبات العقدية. تم تقديم توقعات الحالة المستقبلية لمستوى سطح البحر على طول الساحل التونسي على أساس تقديرات الاتجاهات الموجودة في هذه الدراسة.
الكلمات المفاتيح: ارتفاع مستوى البحر، الساحل التونسي، تقلبات عقدية.

RESUME
Une estimation de l'élévation du niveau de la mer le long des côtes tunisiennes : Cette étude évalue la variation du niveau de la mer le long des côtes tunisiennes sur la base d'observations historiques et récentes de marégraphes installés sur les côtes tunisiennes et celles du côté ouest du détroit de Gibraltar pour la période 1880-2018. Des séries du niveau de la mer basées sur des réanalyses et des simulations de modèles de la mer Méditerranée sont également utilisées. Tout d'abord, une seule série représentative de la région à l'ouest du détroit de Gibraltar est construite. Ensuite, la série du niveau de la mer le long des côtes tunisiennes est construite sur la base de l'hypothèse que la baisse du niveau de la mer observée par rapport à celle du côté ouest du détroit de Gibraltar reste pratiquement inchangée lorsque l'on considère des périodes temporelles longues. La série construite pour les côtes tunisiennes montre une élévation évidente du niveau de la mer superposée à une variabilité décennale liée à l'oscillation nord-atlantique (NAO). Pour l'ensemble de la période, la variation du niveau de la mer est estimée à +1,5 mm / an alors que l'estimation de la tendance est de +3 mm / an pour la période récente 1980-2015. Cette tendance plus élevée peut être attribuée, en plus d'une accélération effective de la montée des eaux, à la variabilité décennale. Des projections de l'état futur du niveau de la mer le long des côtes tunisiennes sont fournies sur la base des estimations de tendance trouvées dans cette étude.
Mots clés : Niveau de la mer, Elévation, Variabilité décennale, Côtes tunisiennes.

ABSTRACT
This study evaluates the sea level trend along the Tunisia coasts based on available historical and recent tide gauge observations for the period 1880-2018. The stations used are located in the Tunisia coasts and in the western side of the Strait of Gibraltar. Sea level series based on reanalyses and Mediterranean Sea model simulations are also used. First, a single series representing the western Strait of Gibraltar sea level evolution is constructed. Then, the sea level series along the Tunisia coasts is constructed based on the hypothesis that the observed sea level drop relative to that in the western side of the Strait of Gibraltar remains nearly unchanged when long term periods are considered. The constructed series for the Tunisia coasts shows an evident sea level rise superimposed on a decadal variability in connection with the North Atlantic Oscillation (NAO). For the whole period, the estimated sea level trend is +1.5 mm/year, whereas it is +3mm/y for the recent period 1980-2015. In addition to the widely accepted of the sea level rise acceleration during the recent decades, this higher trend may also be attributed to the effect of the decadal variability. Projections for the future state of the sea level along the Tunisia coasts are given based on the trend estimates found in this study.
Key words: Sea level, Trend, Decadal variability, Tunisia coasts.

INTRODUCTION

Most in situ and satellite-based observations show an evident rise of the sea level in the Mediterranean Sea (e.g., Tsimplis and Spencer, 1997) but superimposed on interannual/interdecadal variations. For example, between the 1960s and 1990s the sea level trend in the Mediterranean was zero or even negative (Tsimplis and Baker, 2000). Changes in sea level trend may also occur in some parts of the Mediterranean basin as was the case of the lowering of the sea in the Eastern Mediterranean Sea after 1999 (Vigo et al., 2005; Fenoglio-Marc, 2001).

Comparing the trends in different locations in the Mediterranean Sea, Bonaduce et al. (2016) have shown that local sea-level changes were large and very different; the highest values were found in the central Mediterranean Sea, in the Adriatic, and along the Tunisian coasts probably in relation to large positive anomalies they found in some locations among them the area along the Tunisian coasts. The attribution of sea level changes was examined by several authors (e.g., Tsimplis et al., 2008). Atmospheric pressure, mass and steric effects all contribute but at different levels.

Among trend estimates in the Mediterranean Sea Zerbini et al (1996) found 1.1 mm/year for the longest records in Marseille (1885-1989) and Trieste (1905-1990). A higher trend is found for Napoli (for the period 1896-1922), 2 mm/year and Venezia (for the period 1889-1913), 1.8 mm/year. For the more recent period 1993-2012 Bonaduce (2016) estimated the Mediterranean Sea level trend as 2.44 mm/year based on both satellite and tide gauges. When using the tide gauge data only the trend was even higher, 3.5 mm/year. For Marseille the trend based on tide gauges is found 3.26 mm/year much higher than the above-mentioned trend found by Zerbini et al. (1996).

The sea level in the Mediterranean is characterised by large interannual and decadal variability. The behaviour was investigated by several authors and has been shown to be linked to the North Atlantic Oscillation (NAO). Tsimplis et al. (2013) showed that the variability in the basin sea level and its mass component is dominated by the winter North Atlantic Oscillation through its effect on atmospheric pressure and local wind field changes. Tsimplis and Josey (2001) showed a high correlation between the sea level on northern Mediterranean coasts and the inverse of the NAO index. They attributed this relationship to pressure effects and to the alteration in the evaporation–precipitation balance.

For the Tunisia coasts very few estimates are available. Saidani (2007) and Essouissi (2007) showed that the mean sea level at the Sfax harbour grew by a mean value of 17 cm between 1946 and 2006. Those estimates are based on one single annual mean value in 1946-1947 and 8-year tide gauge observations covering the period 1999-2006. To our knowledge, no other estimates of the sea level trend along the Tunisia coasts are available. In this paper, we provide an estimate of the sea level trend along the Tunisia coasts based on historical and recent observations in three Tunisia coasts tide gauge stations but also in five stations in the western side of the Strait of Gibraltar, a key area for the sea level in the Mediterranean Sea. Reanalyses and model simulation are also used in the sea level derivation. The next section presents the data, the model used and the method followed. Section 2 shows the derived sea level evolution and the trend estimate. The paper ends with a conclusion.

MATERIAL AND METHODS

One key feature in the sea level of the Mediterranean basin is its dependence on the global sea level through its connection to Atlantic Ocean. To a large extent, the sea level in the Mediterranean basin follows that in the area west of the Strait (for instance the Gulf of Cadiz). However, differences may result from the time-space variations of the atmospheric pressure, the steric effect and the water circulation. The three-dimensional thermohaline circulation exercises dynamical constraints on the narrow strait leading to a permanent sea level drop relative to that in the Atlantic side by nearly 120 mm (e.g. Harzallah, 2009). The present paper takes advantage on the parallel variations of the sea level in the western Atlantic area and in the Mediterranean Sea when time scales of several years are considered. We combine available sea level observations along the Tunisia coasts and adjust them to the sea level in the Atlantic sea level considering a quasi-permanent sea level drop across the Strait of Gibraltar based on the reanalyses and model simulation data. The trend is then estimated based on the resulting series.

For the Atlantic area the study uses monthly tide gauge sea level series obtained from the permanent service for mean sea level (Holgate et al., 2013; PSMSL, 2016). Six stations located in the Gulf of Cadiz west of the Strait of Gibraltar (Bonanza, CadiazII, CadizIII, Huelva, Lagos and Tarifa) are used to construct one single series representative of this area. Series of CadizII and Tarifa are rescaled to the Lagos one by adjusting their average over the overlapping period. Then series of Huelva, Bonanza and CadizIII are rescaled to those of the rescaled Tarifa series on their corresponding overlapping period. The resulting rescaled series is shown in Fig.1. They show close oscillations and low frequency variability. Close inspection also shows coherent in-phase variations of the large annual cycle. A composite is obtained averaging the different series for a given month. The use of averages is justified by the in-phase annual variations which lead to minor effects of annual means. The resulting annual series (hereafter labelled Atlantic sea level) is obtained. Finally, the average over the 1958-2007 period, considered here as reference period, is removed.

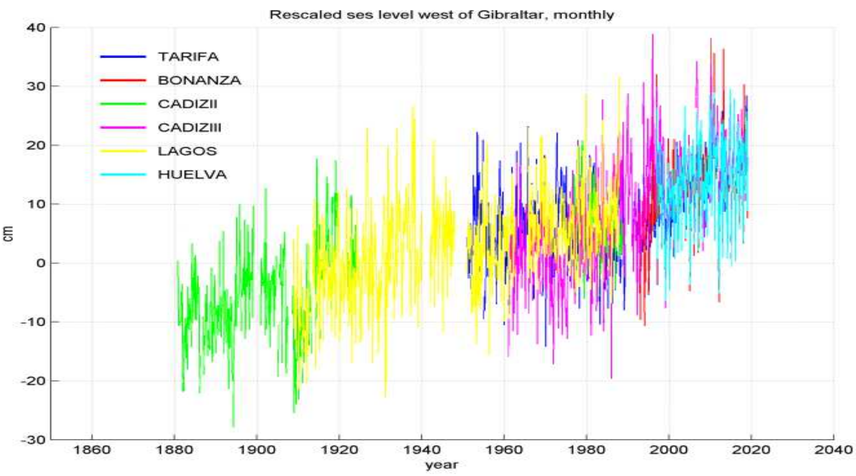

Figure 1: Tide gauge data rescaled so as to obtain a coherent series representing the time evolution of sea level in the western side of the Strait of Gibraltar (see the PSMSL web site to obtain the station locations).

The sea level along the Tunisia coasts is derived using the above-mentioned tide gauge series at Sfax harbour for the period 1999-2007 provided by Hydrographic and Oceanic Centre of the National Marines, Tunisia. Additional historical tide gauge series obtained from the PSMSL ancillary file (data which are not included in the main database) are also used for La Goulette, Soussa and Sfax stations. The above-mentioned sea level measurement in Sfax for the 1946-1947 period (Installed by the French Hydrographic Service to compute tidal ranges) is also included. Information on the historical sea level evolution can be found in Lucienne (2014). Finally, series for the neighbouring Lampeduza station east of the eastern Tunisia coasts are also used for the period 2001 to 2015.

Sea level series based on reanalyses and model simulation are also used. The ORAS4 ocean reanalyses (Balmaseda et al., 2013; Mogensen et al., 2012) are used for the period 1959-2007. The data used are available on a gridded set over the entire Mediterranean, including the Atlantic zone west of Gibraltar. Series at the same geographical locations as those of the tide gauges mentioned above are extracted from the ORAS4 reanalyses and used here.
For model data, the INSTMED06 model (Alioua and Harzallah, 2008) is used. The model was previously applied to Mediterranean Sea studies (e.g., Gualdi et al., 2013; Harzallah et al., 2014; Harzallah et al., 2016). The model covers the entire Mediterranean Sea and the western side of the Gibraltar Strait. The average model resolution is coarse (1/6°) but it is strongly increased at the Strait of Gibraltar (the narrowest section is represented by three grid points). The strait minimum depth is 230 m. The model uses open boundaries in the Atlantic limit with a radiation condition. The simulations performed in this study use the atmospheric forcing fields downscaled by the Arpège Climate model from 1958 to 2007 (hereafter labelled INSTM-ERA) and those from the MPI model for the period 1958 to 2005 (hereafter labelled INSTM-MPI). The ORAS4 sea level and hydrographical analyses in the Atlantic domain are used as boundary conditions in the INSTMED06 model. Here also the series of the tide gauge stations are extracted from the two simulated sea level fields.
The Tunisia and Lampeduza station series are rescaled relative to the Atlantic ones considering the average sea level drop from ORAS4 when available otherwise to the Atlantic sea level series. Finally, one single series representing the sea level evolution along the Tunisia coasts is obtained averaging the sea level values of the derived series of the Tunisia stations. After 2017 the Lampeduza series is considered.

RESULTS

The derived sea level along the Tunisia coasts is shown in Fig.2 (red thick line). The first striking feature is the similarity with the Atlantic sea level including the decadal variability. The resemblance remains evident for the historical period before 1960. The ORAS4 series in the Atlantic zone agree with the tide gauge Atlantic series; the trends of both series are very close. The model series from the two simulations (green and cyan lines) agree well with that from ORAS4 (yellow line) and with the Atlantic series. The sea level along the Tunisia coasts exhibits an evident regular increase superimposed on the decadal variability. The sea level obtained from the recent observations at the Sfax station and those of the Lampeduza station are coherent in term of their mean values and their variations show some similarities.

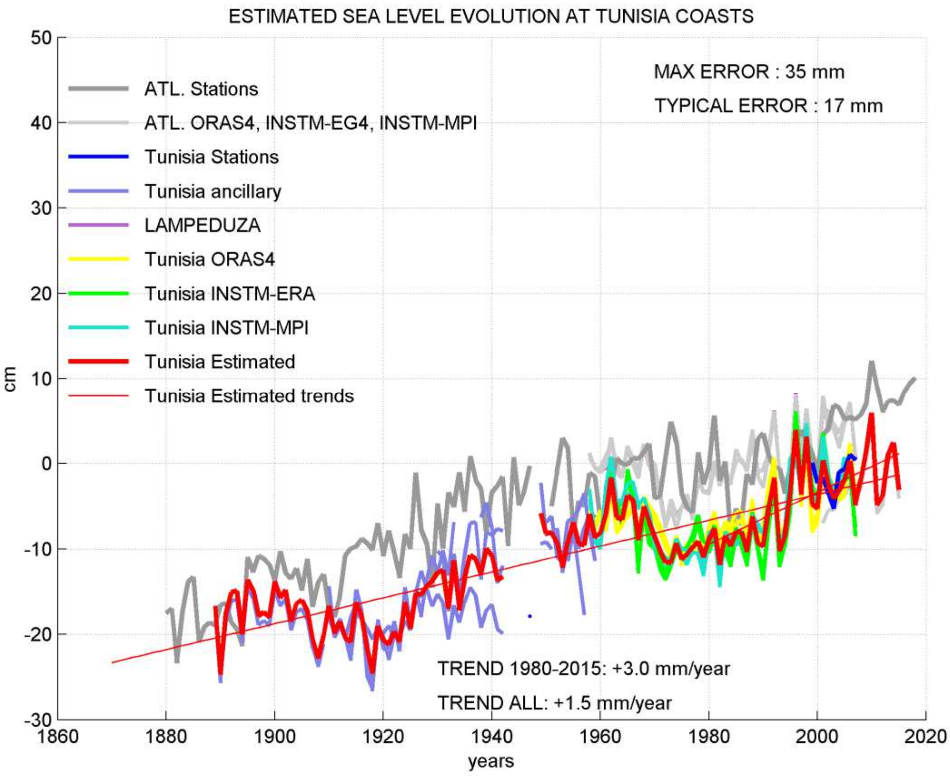

Figure 2: Gray lines; Sea level series in the area west of Gibraltar. Other colours: Sea level series along the Tunisia coasts (the magenta line corresponds to Lampeduza series). The thick red line corresponds to the derived sea level that represents the sea level along the Tunisia coasts. Trend estimated are shown as well as maximum and standard deviation of the sea level drop variation between the Atlantic and the Sfax station from the ORAS4 reanalyses.

The sea level rises at a mean rate of 1.5 mm/year from 1889 to 2015 (127 years). The sea level would have increased by 19 cm during this period. For the period 1946-2006 the sea level increase corresponds to 9.2 cm, a value lower than the 17 cm estimated by Saidani (2007) and Essouissi (2007). This is attributed to the relatively low sea level value in 1946/1947 relative to the trend line, hence enhancing the trend in their estimations. The trend is slightly higher than that shown by Tsimplis and Baker (2000), +1.1 mm/year for the period 1960-1997 based on tide gauge series in the Atlantic side. It is also higher than the same trend value obtained by Zerbini et al (1996) for the Marseille (1885-1989) and Trieste (1905-1990) records. It is very close to the global sea level trend from observations, 1.5 mm/year for the period 1901-1990 (Church et al, 2014).

For the recent period 1980-2015 the results show that the sea level increases at a higher rate, 3.0 mm/year. However, this rather high rate may be in part attributed to the decadal oscillations (see Zerbini et al., 1996) corresponding to the transition from the low to high phase during the 1980-2015 period. For the more recent period 1993-2015 Taibi and Haddad (2019) estimated the sea level trends based on tide gauges in the Mediterranean and found most values ranging between +3 and +6 mm/year. Trends based on altimetry are much less, mostly ranging between +2.5 and +3.5 mm/year. Our estimate of the trend for the same period is smaller, +2.1 mm/year. Bonaduce et al. (2016) found trends in the same order for the period 1993-2012. The trend for Marseille was for example +3.3 mm/year based on tide gauge data.

The trend estimate along the Tunisia coasts is mainly based on the hypothesis that the sea level drop of the Tunisia area relative to the western Strait of Gibraltar remains unchanged when averages over decades are considered. To investigate the limits of the sea level drop, the difference of the sea level series between the Atlantic side and at the Sfax station is calculated and the limits of its fluctuations relative to its mean value estimated. The maximum of sea level drop fluctuation is 35 mm. The standard deviation is 17 mm. Hence the sea level estimate along the Tunisia coasts has a typical error related to the sea level drop fluctuations of 17 mm. It is lower than the typical error of the derived sea level series along the Tunisia coasts (36 mm). This indicates that the sea level along the Tunisia costs is estimated with relatively high accuracy. We also note that the impact of the correction of vertical land motion is relatively small, in the order of -0.2 mm/year (Taibi and Zerbini et al.

1996; Haddad 2019). The estimated rate will marginally change when the correction is included. Baker et al. (1995) showed that for Mediterranean stations series spanning at least 40 years, trend errors are less than 0.5 mm/year. The length of derived Tunisia coasts series is 127 years; the error would therefore be much less. The trend obtained here, +1.5 mm/year is in the same order as those of the longest series shown by the sorting of the Mediterranean trends according to the record length (Zerbini et al., 1996).

As is the case for most Mediterranean series, the derived sea level along the Tunisia coasts exhibits a large decadal variability with episodes of relatively high and low values. During the high sea level episodes (around the dates: 1900, 1929, 1962, 1996), the sea level drop relative to the Atlantic side almost vanishes. To investigate its link to the NAO, values of minus the NAO index (Jones et al., 1997) were plotted in Fig.3 for January and annual values. For comparison, the trend-removed and normalised Tunisia sea level series are also plotted. There is an evident resemblance between the Tunisia sea level and the NAO index. The high sea level episodes clearly correspond to the low values of the NAO suggesting the evident impact of NAO on the sea level variability along the Tunisia coasts. During such episodes, low atmospheric pressure (and possibly other associated meteorological phenomena, as winds and water budget) leads to the shown rise of the sea level by the inverse barometer effect. The impact of NAO on the decadal variability is clearly illustrated with annual NAO index values; that on the interannual variability is more evident in the January values of the NAO index. Hence, both interannual and decadal variations of the sea level along the Tunisia coasts are linked to the NAO.

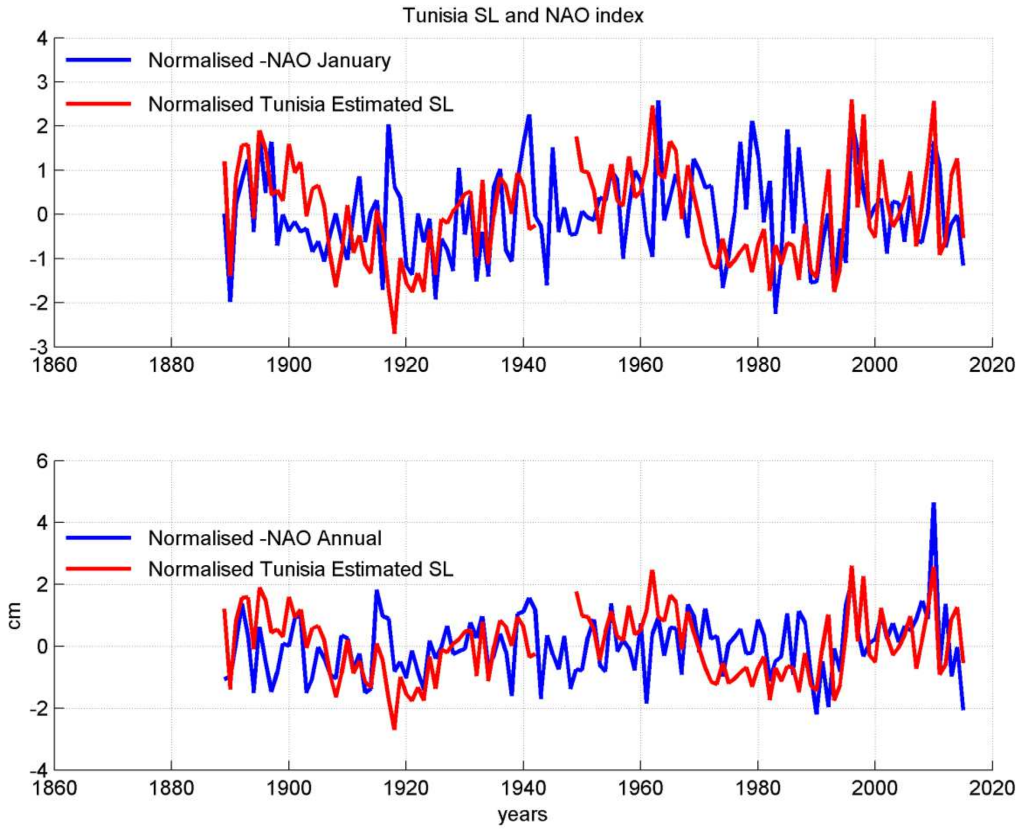

Figure 3: Red: derived sea level along the Tunisia coasts. Blue: inverse of the NAO index for January (upper) and annual (lower) values. Both series are centred and normalised. The trend of Tunisia sea level series is removed.

CONCLUSION

Available observations from tide gauges in three Tunisia stations are used together with those in the key area west of the Strait of Gibraltar to derive a series representative of the sea level along the Tunisia coasts for the period 1889 to 2015. The derivation also makes use of the ORAS4 reanalyses and model simulation using the INSTMED06 model. The neighbouring Lampeduza station series is also used. The resulting series show an evident sea level rise superimposed on a large interannual and decadal variability. This variability is found linked to the NAO. Episodes of high sea level reaching that in the

Atlantic side are shown to correspond to the low NAO phase. This may be attributed to the low atmospheric pressure through the inverse barometer effect.
For the entire period the sea level trend is estimated as +1.5 mm/year, slightly higher than Mediterranean Sea longest records trend estimates. For the recent period 1980-2015 the trend is higher, +3 mm/year, but this may be attributed to a large part to the decadal variability; the period considered indeed corresponds to the transition between the low and high phases. Error estimates are obtained using the typical deviations of the sea level drop of the sea level series at the Sfax station relative to that in the Atlantic side. It is shown that the typical error in the derived sea level along the Tunisia coasts (17 mm) is lower than its typical variations (37 mm). The sea level is hence derived with relatively high accuracy.
To our knowledge, this is the first time a long record representing the sea level evolution along the Tunisia coasts is obtained and an estimate of the sea level trend is provided. The series can be used in several applications for the scientific purposes but also for economic sectors. A first insight to the projection of the future state of the sea level along the Tunisia coasts indicates that if the trend remains unchanged, the sea level would increase from 1880 to 2100 by 33 cm and from 2020 to 2100 by nearly 12 cm. If the 1993-2015 trend rate is considered the sea level rise will increase by 46 and 17 cm, respectively. The series will be updated in the future when new observations will be made available.

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