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Sea level trends and variability in the Adriatic Sea and around Venice

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Sea level trends and variability in the Adriatic Sea and around Venice

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Abstract

This paper provide a preliminary analysis of sea level (SL) changes around Venice from three tide gauges (one off-shore: AAPTF, one at the coast and one inside the lagoon: PS) to characterize the variability during 1993-2015 and SL trends. The results show that hourly SL observations overlap pretty well. Monthly SL means from the European Space Agency (ESA) Sea Level Climate Change Initiative (CCI) altimeter-derived product are also used. A comparison has been performed using the nearest CCI grid point to the location of AAPTF. Both data sets agree well in term of seasonality, with higher variability, with respect to AAPTF, observed in the altimetry record (centred RMSD 6.33 cm with a correlation of 0.75), than in the PS record (centred RMSD 1.03 cm, correlation 0.99). In the Adriatic Sea, trends are spatially higher than Global Mean Sea Level (GMSL) in most of the region, with a pronounced greater value than average in Venice, while 6.65 mm/yr are measured at AAPTF. A smaller trend has been found here from altimetry (4.25 mm/yr). The differences might be explained in terms of Vertical Land Motion (VLM) and/or uncertainty in this area due to the current CCI product that is based on open ocean altimetry. Reprocessing of along-track altimeter data sets with consistent coastal processing for all missions is expected to enhance SL accuracy and with a better refining of raw trends.

Keywords: *satellite radar altimetry, coastal altimetry, sea level, Adriatic Sea, Venice, tide gauge*

1 Introduction and study area

The Adriatic Sea, including the area around Venice, is an important laboratory for validating and applying satellite altimetry products since the calibration of the European Space Agency (ESA) ERS-1 altimeter (Scharroo, 2002). The area is frequently affected by storm surges because of its geographical position and geometry. The Sirocco wind blowing along the main axis of the basin rises up water in the Northern Adriatic that generates surges along the northern shorelines. The resulting surge signal is maximum in the northwestern part of the basin, especially at the city of Venice and its surrounding lagoon, where is it called "Acqua Alta" (high water). Also the northeastern side of the Adriatic Sea is subject to storm surges, mainly connected with the phenomenon of meteotsunami, a tsunami-like event enhanced and conditioned by specific meteorological forcing and geometry of the coast (Orlić 2015).

In Venice, the MOdulo Sperimentale Elettromeccanico (MOSE) barriers, due for completion in late 2021, were designed to protect the town and its lagoon from storm surges, and preserve its integrity from the ever more frequent high waters connected to the local eustatism and subsidence. The barriers will be raised, closing the mouths only when levels of 110 cm (that is the maximum level that still permits normal activities in town) are foreseen.

The City of Venice is today on average 30 cm lower than early 1900s (Cordella et al., 2010; Collini et al., 2017). In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), Church et al. (2013) predicted an increase in sea level (SL) between 18 and 59 cm during the next 100 years. The Sixth Assessment Report (AR6) is underway and a special report on the Ocean and Cryosphere in a Changing Climate (SROCC) will look at SL rise and implications for low lying islands, coasts and communities.

MOSE has been designed to work with an increase of up to 60 cm. Flooding could be further aggravated by the predicted rise in SL resulting from climate change. Understanding SL variability, in particular the relationship between storm surges and long-term SL changes as well as a better assessment of the climate-related contribution to local SL has particular relevance for local policymakers. It is thus of particular interest to have accurate SL observations to improve the scientific knowledge of past trends that might continue into the future. Climate-related changes of meteorological and marine variables are an important input to define future scenarios not only of MOSE infrastructure, designed to protect Venice from storm surges, but also of the coastal settlements of the northern Adriatic Sea. In this context an accurate definition of the actual SL rise cannot leave aside the estimation of the Vertical Land Motion (VLM), as even little rates of VLM can exacerbate the effects of the SL rise and quicken the attainment of specific thresholds requiring actions in the coastal zone local planning.

Satellite radar altimetry is designed to measure height profiles at sea in the along-track direction, with a coverage organized as a mesh of ground tracks, including also zones with no tide gauges (TGs) around. Until a few years ago, satellite radar altimetry was not sufficiently exploited for SL research in the Adriatic Sea. The ESA eSurge-Venice project permitted to exploit altimeter data to improve the modelling and forecasting of storm surges (De Biasio et al., 2016; Bajo et al., 2017; De Biasio et al., 2017). The ESA Climate Change Initiative (CCI) now provides a SL Essential Climate Variable from which to get a much clearer picture of regional trends and year-to-year variations (Legeais et al. 2018).

This work will report on the initial assessment of the quality of the ESA SL CCI products in the Adriatic Sea and in particular around the city of Venice (Fig. 1). TGs available around Venice and Trieste provide an accurate independent source of SL information to be used as reference of long-term SL variability at the coast. In this work, we focus on SL changes at long term scales (trends).

2 Data and methods

A TG records how the SL is changing relative to the land on which it is installed. SL is generally provided as a measurement relative to an arbitrary and local reference. By convention, in the Venice area such reference is the Zero Mareografico di Punta Salute (ZMPS), i.e. the historical reference benchmark of the Mean Sea Level (MSL) in Venice for twenty-five years 1885 -1909. The Venice tide gauge installed at “Punta della Salute”, indicated as “VENICE PS” or simply “PS” henceforth, supplies one of the longest SL records of the Mediterranean Sea. The SL time series of the historical TG of VENICE PS dates back to about 1875. The monthly means are also available in the Permanent Service for Mean Sea Level (PSMSL) on-line archive (Holgate et al., 2013).

The VENICE PS TG is operated by the Venice Tide Centre (Centro Previsioni e Segnalazioni Maree - CPSM, Venice Municipality). As the TG is situated in the city centre inside the Venice Lagoon, far from any satellite altimeter track, we adopted for this study the SL record supplied by the CPSM TG installed in the ACQUA ALTA off-shore platform (AAPTF: 45° 18' 51.29" N, 12° 30' 29.69" E) of CNR (see Fig. 1). The AAPTF record begins in 1974 and is still continuing. It is very useful for the forecast of storm surges in Venice as the SL signal is observed about 50 minutes in advance with respect to VENICE PS. As the AAPTF record presents gaps in the satellite altimetry era (e.g., 1993 is almost completely missing), we used the SL record registered in another TG of the CPSM, namely VENICE Diga Sud Lido, indicated as "DSL", whose position is also shown in the map of Fig. 1, to integrate the AAPTF record. The three TGs cited so far are well maintained and constantly monitored, and report the "equivalent" SL height observed at VENICE PS. Moreover, the AAPTF and DSL TGs have very similar average delays of the tide (Ferla et al., 2007) with respect to PS, thus facilitating the integration of the two time series where needed. The assumption is supported by the plots in Fig. 2. The hourly values of the two TGs have been processed in monthly aggregation to determine the centred (unbiased) RMS difference, the linear correlation coefficient and the bias of the two SL time series. The three statistical parameters span a very narrow range of values, with a variability which is influenced mostly by seasonality: respectively [2, 5] cm, [0.98, 0.99] and [-2, +2] cm. The longest gap in the AAPTF record is the whole 1993 year. Looking at the three plot in the years immediately before (1991, 1992) and after (1994, 1995) the year 1993, the three statistical parameters are well inside the ranges given above. Therefore, the replacement of the entire year of sea level measurements at AAPTF with those taken at DSL seemed to us a reasonable choice. Shorter gaps were filled in the same way, making similar assumptions. In order to be comparable to satellite altimetry records, the TGs hourly records have been reduced to daily means applying the Doodson's X0 filter (Shirahata et al., 2016) following PSMSL guidelines. The daily means were then used to calculate the monthly means.

Since 1990's, a series of radar altimetry missions accumulated a satellite-based record of SL that is now long enough to estimate trends. Sea Level Anomaly (SLA) is obtained by subtracting the Mean Sea Surface (MSS) to the Sea Surface height (SSH), referred to ellipsoid, corrected for various effects (including tides and meteorological forcing to avoid aliasing). The ESA CCI project on "Sea Level" has reprocessed these altimeter data over 1993-2015 to provide homogeneous SL for all altimetry missions (Legeais et al. 2018). The v2.0 dataset was released in December 2016, with details provided at http://www.esa-sealevel-cci.org/products (Quartly et al., 2017). The ESA SL CCI products are generated using open ocean altimetry data, selecting improved satellite orbits and updated geophysical corrections, adopting a new calculation of the mean sea surface used as reference, reducing instrumental drifts and biases, in order to further reduce the error budget and provide a consistent unbiased SL record for long-term change studies. These products include along track SLA at 1 Hz (around 7 km) and monthly gridded time series of multi-mission merged SLA at a spatial resolution of 0.25° (around 25km) from which some oceanic indicators (e.g., trends) are derived. The gridding process is described in Ablain et al. (2017). Also, it should be noted that CCI products are not corrected of the empirical TOPEX drift correction (Beckley et al, 2017).

3 Results

As an example, the raw time series of SL hourly values at VENICE PS is shown in Fig. 3 (upper panel). The blue line is SL. The astronomical tide contribution (red line) and the residual difference (green line) after subtracting it from the SL are also reported. In order to compare the time series of in-situ data to the satellite-based SL measurements, the exact composition of the atmospheric corrections applied to the altimetry record has to be carefully considered, as the altimeter path delay explained by other climatological variables might have been already accounted for. For example the MSL atmospheric pressure (Fig. 3, bottom panel) and the wind stress. The atmospheric loading is well observed by TG measurements: 1 mbar increase of the local MSL pressure roughly corresponds to a drop of 1 cm in the SL, owing to the inverse barometer effect.

Monthly means of SL height at the AAPTF and VENICE PS that overlap the CCI reprocessed period (1993-2015) are shown in Fig. 4. The raw trends are also indicated. The references are arbitrary for sake of readability. VENICE PS and AAPTF overlap pretty well: the centred RMSD is 1.03 cm, and the linear correlation reaches 0.99. Recent trends (6.29 mm/yr at VENICE PS and 6,65 mm/yr at AAPTF) are more marked with respect to those calculated from the whole datasets (1941-2017 and 1975-2016 respectively) and not showed here. TG measurements register VLMs that are mixed with SL variations.

From the perspective of satellite altimetry, sea level observations highlight that rising is not geographically uniform worldwide (Nerem et al. 2018). A marked spatial variability of SL trends is observed in the Mediterranean Sea (Bonaduce et al. 2016). Some negative trends observed in the Ionian Sea and south-east of Crete, are supposed related to important changes in the circulation observed since 1990s. In the Adriatic Sea, trends are spatially higher than Global Mean Sea Level (GMSL) in most of the region, with a pronounced greater value than average around Venice (Fig. 5).

A comparison has been performed using the nearest CCI grid point to the location of AAPTF (Fig. 2). As the CCI dataset is available during the time frame 1993-2015, monthly time series and trends of SLA (altimetry) and SL (tide gauge) are referred to this period (Fig. 6). Both data sets overlap pretty well in term of seasonality, with lower variability observed in the altimetry record (centred RMSD 6.33 cm with a correlation of 0.75).

As shown previously, 6.5 mm/yr are measured at AAPTF. A smaller trend has been found from altimetry (4.25 mm/yr). Both trends are much higher than GMSL which is around 3.3 mm/yr (Legeais et al., 2018). Fenoglio et al. (2012) found around Venice 5.6 ± 1.6 mm/yr over a shorter period (1993-2008) and using only Envisat, TOPEX/Poseidon and Jason-1/2 satellite missions. Rocco (2015) found 4.02 ± 1.18 mm/yr from a TG inside lagoon: however, the SL measured by TG was corrected for VLM over the CCI period 1993-2013. It is important that the GPS time frame overlaps completely with the CCI data record.

Our analysis shows that TG and altimetry sea level time series are comparable and the difference between the two trends might be related to vertical land movements. The VLM in the Venice area has been investigated in many studies, over different periods, showing high spatial and temporal variations (e.g., Tosi et al. 2002). In addition to VLM, other aspects need to be investigated, e.g., de-seasoning, serial auto-correlation, removal of IB effect, including error estimation.

4 Discussion and concluding remarks

In this paper, we analysed hourly sea level observations from three tide gauges around

Venice in the northern Adriatic Sea. The hourly data were then converted in monthly values and compared with the altimetry dataset from the ESA Sea Level CCI. The comparison spans 23 years (1993-2015) using the nearest CCI grid point to the location of AAPTF, during which the trends are also estimated. Our results show that hourly observations match well, while, trends, computed from tide gauge data, slightly differ from altimetry data set, because of local VLM. However, the coastal zone needs special treatment, and the increased uncertainty in this area is not reflected in the trend error in the present version of the Sea Level CCI, which is based on open ocean altimetry. During the CCI+ phase (2018-2019) the objective is to extend the satellite-based sea level climate record to the coastal zone with quality comparable to the open ocean. At the same time, the focus will be expanded also to include the VLM signal identification in the TG time series, as this quantity, if accurately estimated, could provide the final tool in closing the balance between in-situ- and altimetry-based estimate of SL rise.

Coastal altimetry has demonstrated that if standard products are reprocessed with dedicated algorithms, reliable data can be obtained up to few kms from the coasts (Vignudelli et al., 2011). Therefore, additional along-track data sets with consistent coastal processing for all missions and derived products dedicated to coastal regimes will be used to evaluate their current capabilities and perspectives for usage in long term sea level research studies.

Acknowledgements
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Figure legends

Figure 1: The Adriatic Sea and in particular the area of investigation (northern part) around City of Venice. Selected tide gauges: CNR Acqua Alta Platform (AAPTF), Venezia Punta della Salute (VENICE PS) and Venezia Diga Sud Lido (VENICE DSL). Also shown the closest CCI grid point to AAPTF

Figure 2: Centred root mean square difference, linear correlation and bias of the AAPTF and VENICE DSL tide gauge records. Monthly statistics of hourly data.

Figure 3: VENICE PS record. Top: tide gauge hourly time series. Blue: sea level. Red: astronomical tide. Green: difference. Bottom: mean sea level pressure.

Figure 4: Sea level monthly means records of AAPTF and VENICE PS during the altimetry era (1993-2015). References are arbitrary for sake of readability.

Figure 5: Map of sea level trends in the Adriatic Sea from the CCI product (1993-2015).

Figure 6: Monthly means records of AAPTF SL and altimeter SLA (closest grid point). References are ZMPS for the AAPTF, and MSS for SLA.

Figure 1 Click here to download Figure Figure-1-area-of-investigation.png

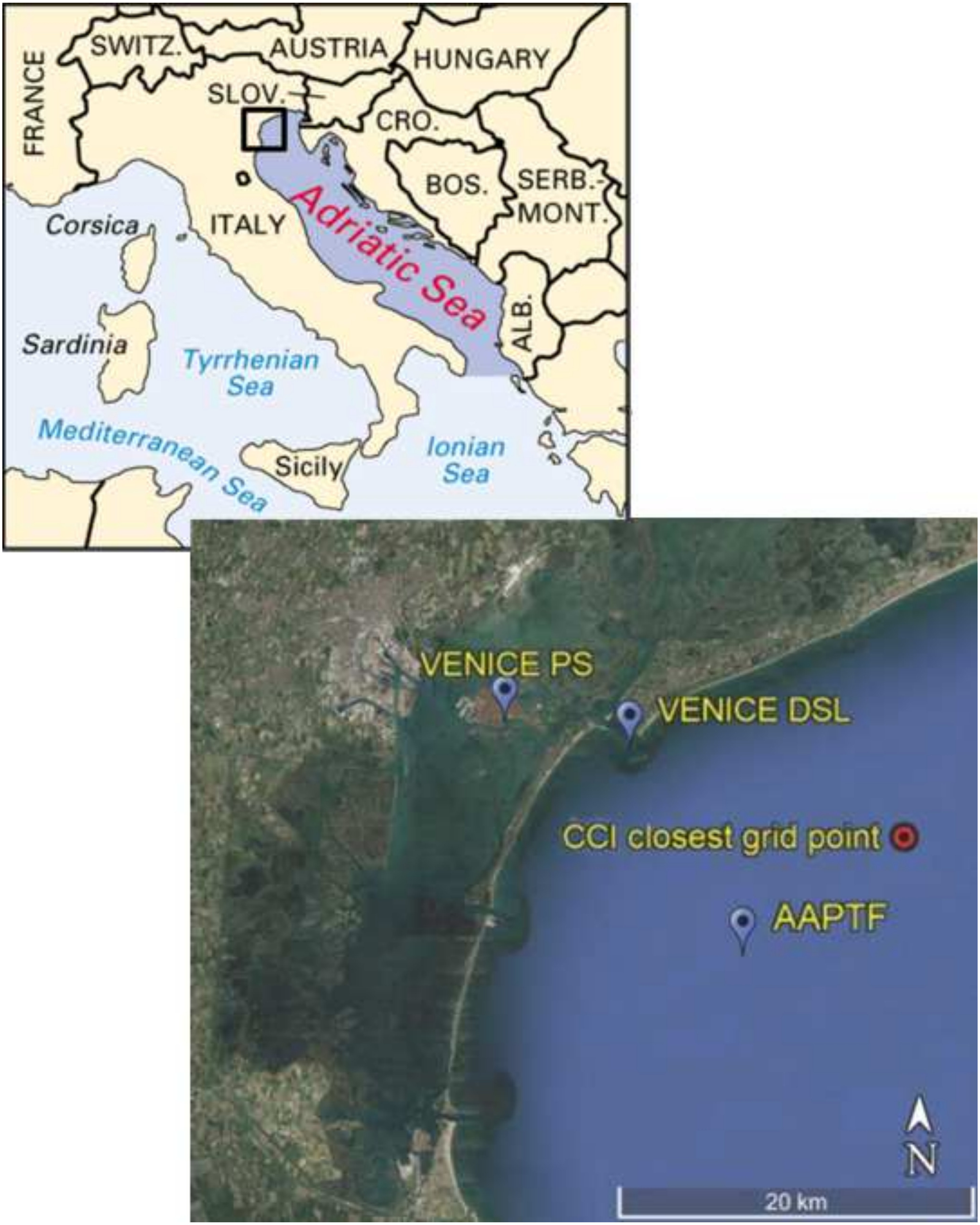


Figure 2

Click here to download Figure Figure-2-statistics-of-hourly-data-at-AAPTF-and-DSL.png

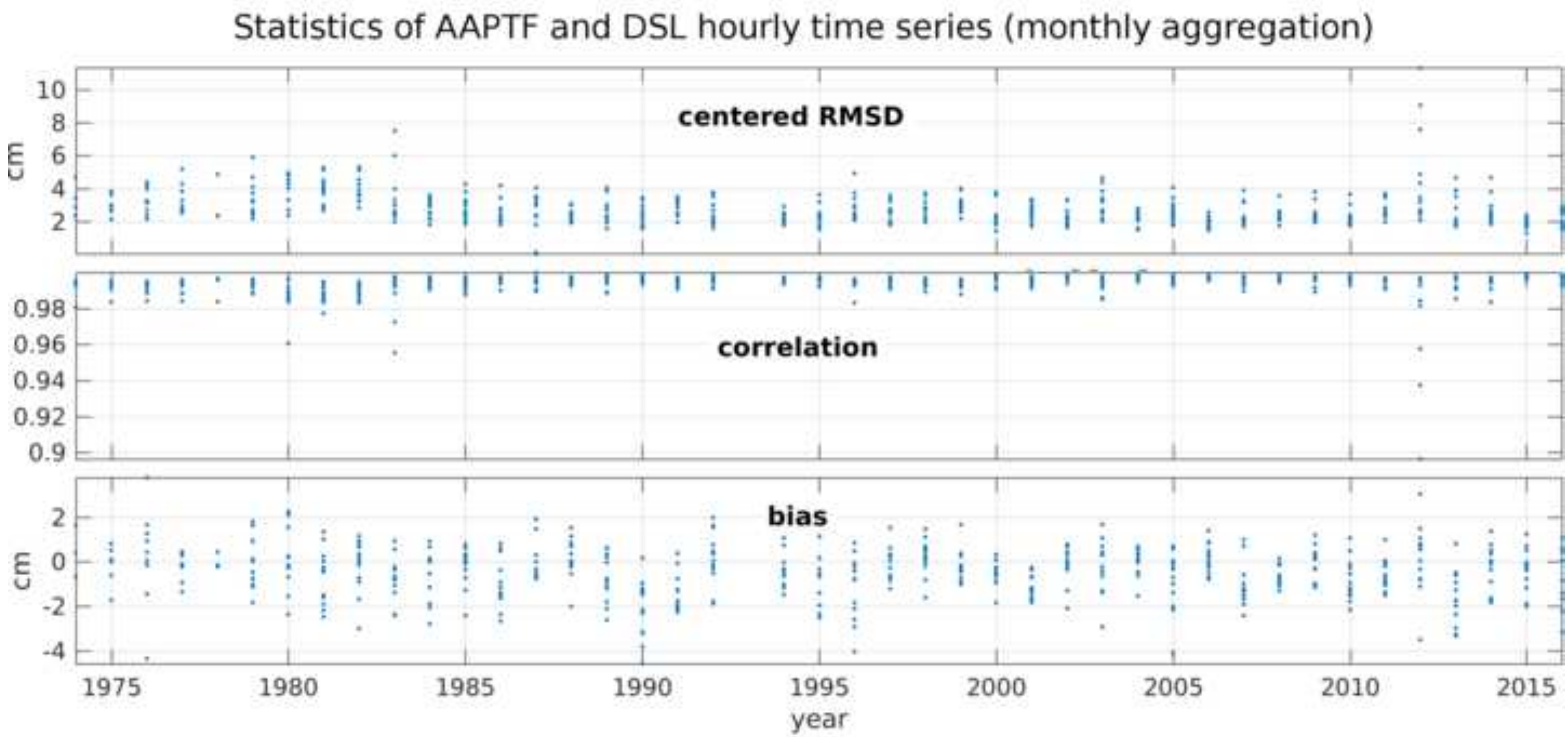
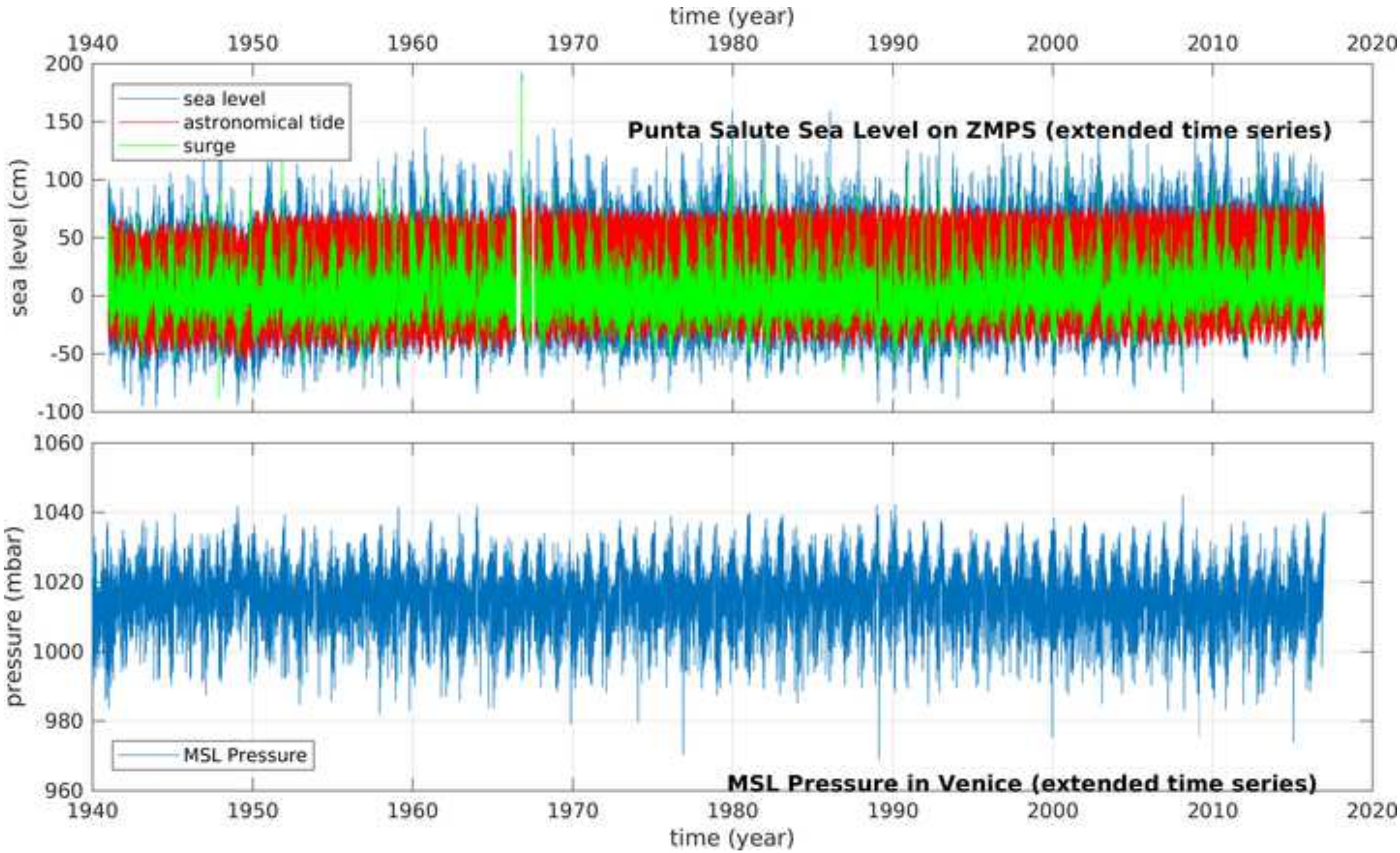


Figure 3



time (year)
1940
1950
1960
1970
1980
1990
2000
2010
2020
200
150
100
50
0
-50
-100
sea level (cm)
sea level
astronomical tide
surge
Punta Salute Sea Level on ZMPS (extended time series)
1060
1040
1020
1000
980
960
pressure (mbar)
MSL Pressure
MSL Pressure in Venice (extended time series)
1940
1950
1960
1970
1980
1990
2000
2010
2020
time (year)

Figure 4

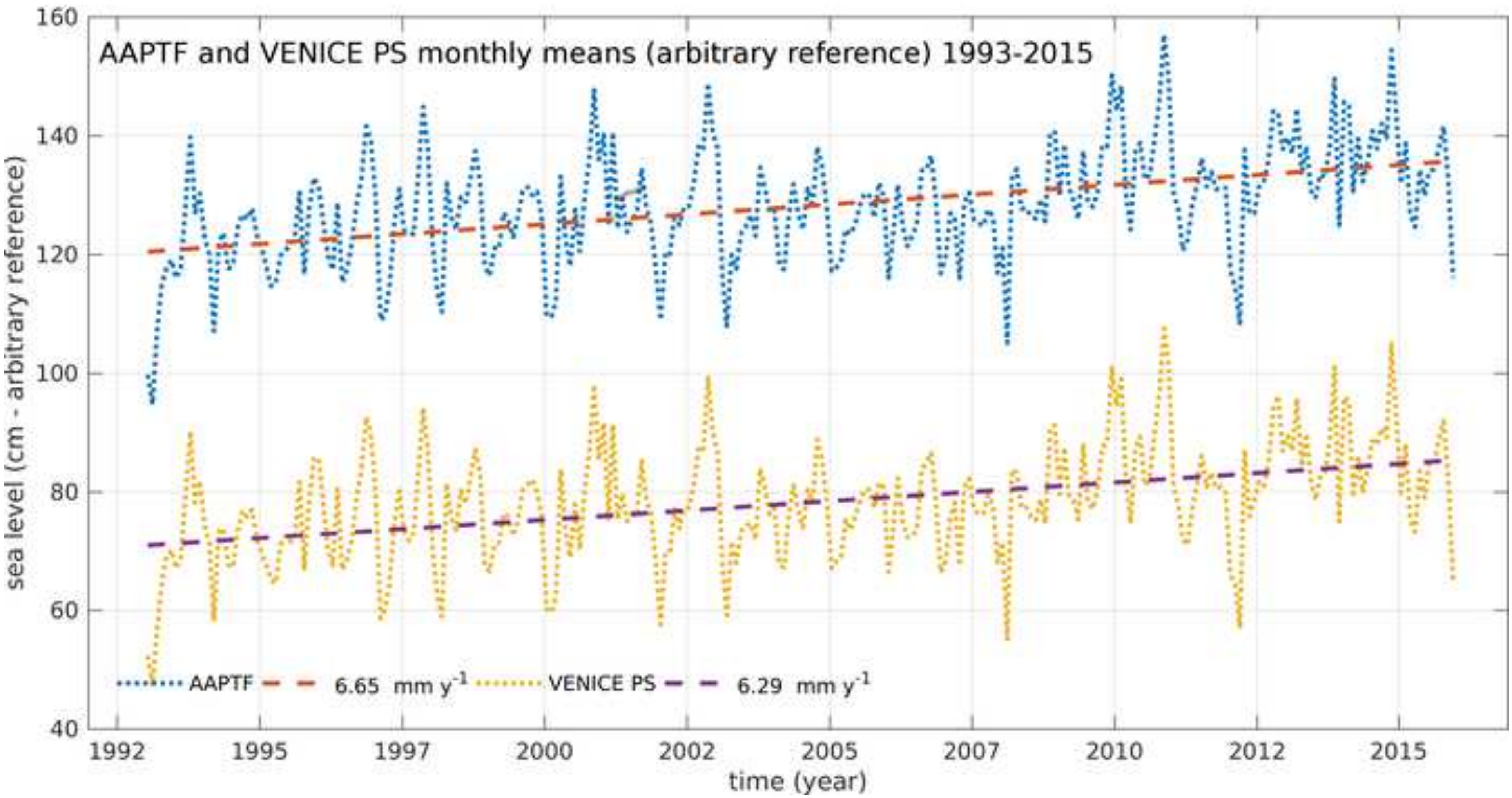

AAPTF and VENICE PS monthly means (arbitrary reference) 1993-2015
sea level (cm - arbitrary reference)
160
140
120
100
80
60
40
AAPTF
6.65 mm y-1
VENICE PS
6.29 mm y-1
1992
1995
1997
2000
2002
2005
2007
2010
2012
2015
time (year)

Figure 5

Click here to download Figure Figure-5-sea-level-trends-Adriatic-sea-from-CCI.png

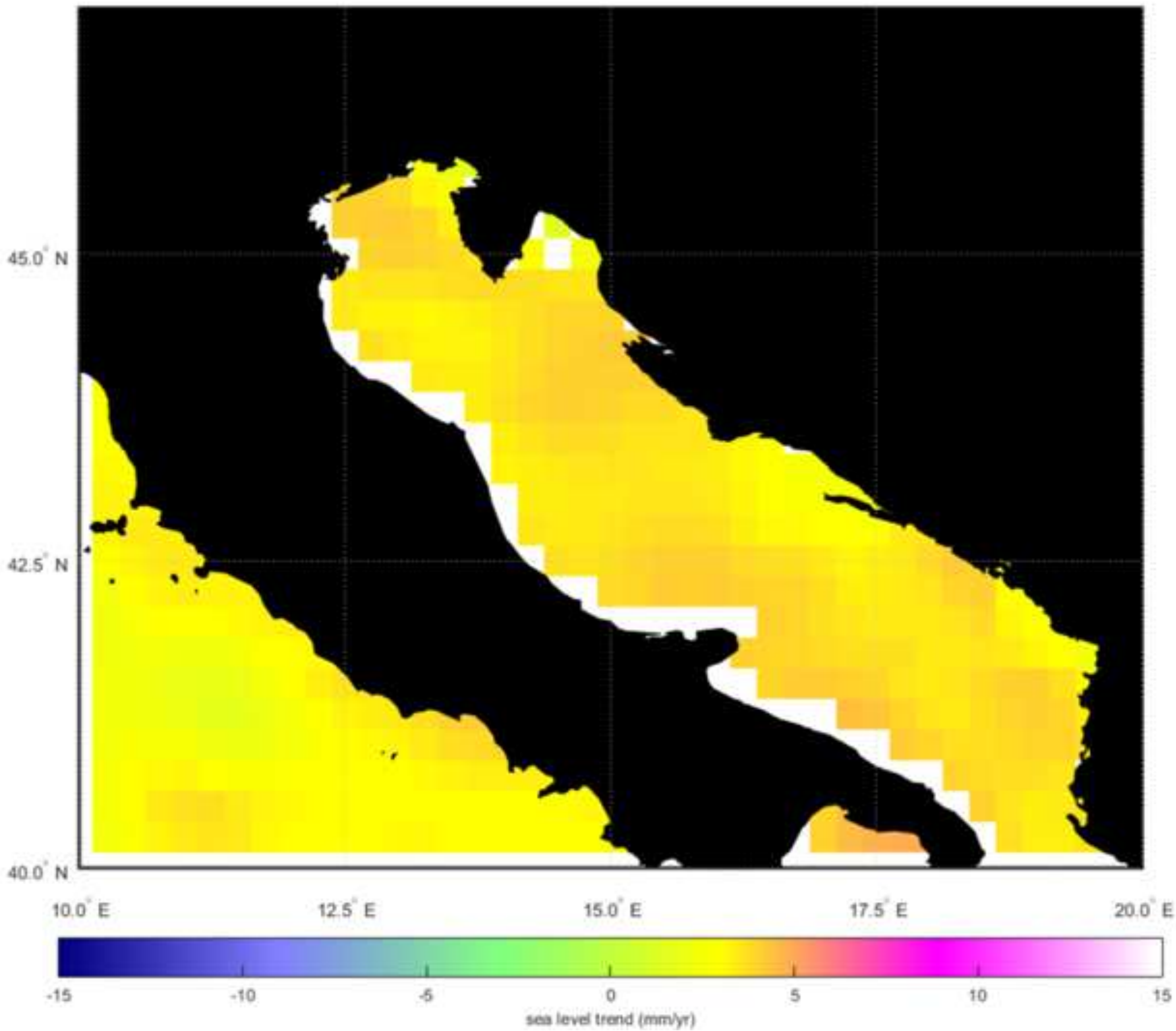


Figure 6

Click here to download Figure Figure-6-monthly-means-and-trends-AAPTF-and-altimeter.png