Delayed-mode reprocessing of in situ sea level data for the Copernicus Marine Service

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Abstract. The number of tide gauges providing coastal sea level data has significantly increased in recent decades. They help in the issue of coastal hazard warnings, the forecasting (indirectly, through models) of storm surges and tsunamis, and in operational oceanography applications. This data is ~~often~~ automatically quality controlled in near-real-time, ~~as is the case~~ in the Copernicus Marine Service. ~~However, machine and visually inspected validation of historical sea level time series from these platforms is required. It has long been requested by the oceanographic community at large. As a result, a~~A new initiative seeks to provide ~~such validated~~delayed-mode reprocessed data for the Copernicus Marine Service, by developing a new ~~delayed-mode reprocessed in-situ sea level~~ product. ~~The existing~~ and upgrading the software ~~for the near-real-time product has been adapted to this end. After being visually controlled by a team with expertise~~used in ~~sea level reprocessing~~its automated quality control. Several new modules, such as buddy checking, detection of attenuated data, among others, ~~the~~are implemented. The new product was launched in November of 2022. The entire reprocessing is discussed, in detail. An example of the information that can be extracted from the delayed-mode reprocessed product is also given.

Keywords: sea level, ~~observation~~in situ, delayed-mode, software

1 Introduction

Sea level has long been in the public spotlight for being one major indicator of Climate Change ~~and~~. It is now an essential ocean ~~variable (https://www.goosocean.org/index~~variable[1]. ~~php?option=com_content&view=article&id=14&Itemid=114l).~~ Remote and in situ (non-~~situ~~remote) observations show that the sea level rise has been accelerating in recent decades (Nerem et al., 2018; Dangendorf et al., 2019). It raises ~~concern~~concerns about a corresponding increase in the magnitude, frequency and impact of coastal extreme events (Vousdoukas et al., 2018; Kirezci et al., 2020; Almar et al., 2021). Tide gauge data are an essential source of information to understand the contribution of different physical processes to sea level variations, at different timescales. Therefore, reliable delayed-mode reprocessed sea level data are crucial for validation of hindcasting and forecasting ocean models, for both short-term forecasts and long-term climatic studies.-

[1]https://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114l. ¶

In the past, the quality control of sea level measurements heavily relied on expert visual inspection, mainly done at national level by tide gauge network operators. This is still a key part of the process, but the community has increasingly adopted automation to detect low quality data, more quickly and exhaustively (IOC, 2020), both in near-real time (NRT) and delayed mode, depending on the application. Likewise, expert knowledge, ruled by physical formulation, can be partially translated into machine language. The combination of automation and an efficient algorithm can minimize the total cost of the quality control, and can make it possible to apply quality control to a large network of thousands of tide gauge stations. Up to now, automatic quality control was applied in NRT for in situ sea level data in the Copernicus Marine In Situ Thematic Assembly Centre (In Situ TAC). However, a more comprehensive and exhaustive quality control in delayed mode, including additional tests and validation methods of historical timeseries, was not performed, at a centralized site, for generation of a higher quality dataset in this service (Sea Level Reprocessed or Multi-Year product). This is essential to ensure a more reliable use of these data for scientific applications, including aggregation into existing datasets that download data from the In Situ TAC (Eurosea project. Deliverable 3.3), and it is the main achievement of the new product described in this manuscript, especially for those hundreds of stations where this reprocessing and validation of the historical timeseries is not available or done at national level.

2 The Copernicus Marine Service, the In Situ Thematic Centre (In Situ TAC) and the data dealt in the quality control

The Copernicus Marine Service provides regular and systematic reference information on the physical and biogeochemical ocean and sea-ice state for the global ocean and the European region seas (Le Traon, 2019; Copernicus Marine In Situ Tac Data Management Team, 2021). Four key application areas of the Copernicus Marine Service are:

- ~~As one of the cheapest, most readily monitored ocean variables, it is of no surprise that it was one of the first ones to be systematically measured. Tide gauge data are an essential source of information to understand the contribution of different physical processes to sea level variations at different timescales. Therefore, reliable delayed-mode reprocessed sea level data are crucial for validation of hindcasting and forecasting ocean models, for both short-term forecasts and long-term climatic studies.~~ maritime safety
- ~~The Copernicus Marine Service gathers the information of a network of tide gauges with other in-situ observations (Copernicus Marine In Situ Tac Data Management Team, 2021). Until November of 2022, these platforms were only included in the near-real-time data product, while a sea level delayed-mode reprocessed product was pressingly requested for model validation, comparison to remote-sensing measurements, among other functions.~~ marine resources
- marine and coastal environment
- weather, seasonal forecasting and climate

Observations are used by Copernicus Marine Service Thmatic Assembly Centres (TACs) to provide high-level data products, as well as by Copernicus Marine Service Monitoring and Forecasting Centres (MFCs) to validate and constrain their global and regional ocean analysis and forecasting systems. The sources for the data can be satellites or in situ.

The Copernicus Marine Service In Situ Thematic Assembly Center (In Situ TAC) is the main interface between the Copernicus Marine Service and the global, regional and coastal in situ observing networks. It collects, processes and carries out the quality control of the upstream in situ data, required to both constrain and directly validate modeling and data assimilation systems, and to directly serve downstream applications and services. The in situ network includes the network of tide gauges, argos, research vessels, moorings, gliders, surface drifters, among other methods of measurement. The in situ observations are for sea level, wave, temperature, salinity, currents, chlorophyll, oxygen, nutrients, pH and fugacity of CO_2. The In Situ TAC delivers NRT

[1]https://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114l.

products, that are delivered within 24 hours, having completed automatic quality processing, as well as scientifically assessed reprocessed products.

~~There~~ Until November of 2022, the tide gauges only provided NRT data product, while a sea level delayed-mode reprocessed product was pending. This functionality is also unavailable, up to date, in other major databases, such as the ones owned by the Global Extreme Sea Level Analysis (GESLA, which aggregates existing NRT data in In Situ TAC) and the Global Sea Level Observing System (GLOSS), which rely on national providers effort on quality control and processing. There is, currently, a contract under way to deliver this delayed-mode reprocessed sea level product for the Copernicus Marine Service (Product User Manual, 2022; Quality Information Document, 2022). A first release was made in November of 2022. Its product and the software used to carry out the quality control at that moment is described herein. The spatial coverage consists mostly of European waters, at this moment (Fig. 1). The most veteran tide gauges are in the Baltic and the Iberian-Biscay-Irish regions. Some of these stations still operate, and offer ~~historical~~ series of over 100 years. ~~Most data in the Mediterranean Basin had series shorter than one year, as of 2020. New tide gauges are emerging from Turkey and other Eastern Mediterranean countries. Some geographically non-European islands also contribute at the global level to this product, which will expand to include other stations of the Global Sea Level Observing System (GLOSS) and improve the global coverage by November 2024.~~

~~Stations in different regions experience different sea level variability (Pugh, 1987). Astronomical tides differ from one location to the next, depending on the extension of the sea basin and the degree of openness of the waters. For instance, the Mediterranean Sea has a relatively reduced semi-enclosed basin, with a smaller astronomical tidal component. On the contrary, the Atlantic coastlines are exposed to the open ocean and have a strong astronomical tidal component. Each region also experiences different atmospheric conditions, which influence storm surges. There can be meteo-tsunamis, seiches and other high frequency events, as well. Thus, each station can register a variety of total sea levels, astronomical tides and de-tided sea levels.~~

~~The~~ The time series used in this product span very different periods, ranging from 1886 in some Baltic stations, to dozens of stations that were installed as late as 2019 (Fig. 2). The newer sensors have different precisions, which tend to be in millimeters, compared to older sensors, used at some point in the century-long series, that can have a factual precision of centimeters. Following the Baltic area, more tide gauges were successively installed in the Iberian-Biscay-Irish region, the Mediterranean region, the Arctic, the North-West shelf, and more recently, the Black Sea region (Fig. 2). Most NRT data in the Mediterranean Basin had series shorter than one year, as of 2020. New tide gauges are being installed in Turkey and ~~3)~~other Eastern Mediterranean countries. Some geographically non-European islands also contribute, at the global level, to this product.

~~Up to now, the quality control of in-situ measurements has relied heavily on expert visual inspection. This is still a key part of the process, but the community has increasingly adopted automation to detect low quality data, more quickly and exhaustively. Likewise, expert knowledge, ruled by physical formulation, can be partially translated into machine language. The combination of automation and an efficient algorithm can minimize the total cost of the quality control, and this can make it possible to apply quality control to a large network of thousands of tide gauge stations (Eurosea project. Deliverable 3.3).~~

~~2~~3 The ~~near-real-time~~NRT: The ~~near-real-time~~NRT (L1) product and the SELENE software

~~The near-real-time~~ The NRT process (Fig. ~~4~~3) in Copernicus takes total ~~observed~~ sea levels at the original time sampling (as measured by the tide gauges), applies an automatic quality control test, and flags sea level data points, where appropriate. These series are transformed into an intermediate, 5-min sampled format, where short gaps (below or equal to 27 minutes) are interpolated. Then, a Pugh filter (Pugh, 1987) is applied to produce

[1]https://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114l.

hourly sea levels. In the Copernicus Marine Service, the original, automatically flagged total sea level and the hourly filtered total sea level are both available as ~~near-real-time~~NRT products.

~~The~~ The quality control of tide gauge time series is performed with the SEa LEvel NEar-real time quality control processing (SELENE) software (Puertos del Estado, 2019). The original software was created in the 1990s, based on Fortran77 programming language and C-Shell scripts~~. It was implemented, operationally, in near-real-time (every 15 min)~~. It included quality control, filtering to hourly values and computation of non-tidal residuals~~. These de-tided sea level observations facilitate quality control of the total sea level time series, since tidal variations often dominate a sea level record, making subtle errors more difficult to detect~~. The ~~corrected time series were then used to improve~~NRT service (every 15 minutes) in the ~~sea level forecasts of~~Copernicus Marine Service now uses the ~~Nivmar Sea Level Forecasting system of Puertos del Estado (Álvarez-Fanjul et al, 2001; Pérez-Gómez et al~~SELENE software adapted to Python language~~, 2013)~~. ~~This was performed by means of a nudging technique, still operational today.~~

The SELENE software follows best practices, as defined by GLOSS (IOC, 2020). In NRT, it applies the L1 quality control level, as defined by the IOC (2020), including: out-of-range, spike detection, and stability tests. The quality control of SELENE software uses a series of station-configuration parameters. These are the maximum/minimum total/de-tided sea levels; the degree of the polynomial for spike detection, as well as the size of the window of time to be fit to the polynomial, and the maximum standard deviation allowed for the non-spike data; and the limit for the stuck-data (data that keeps being constant for an abnormally long time) to start to constitute one (that is, once the data is constant for as long as the limit time, it is considered to be stuck). ¶

Prior to the launch of the NRT operational service, a sensitivity test was carried out on tide gauges from Puertos del Estado. The data in the test had a sampling of 1 minute. The polynomial used for total sea levels was optimal when being of 2 degrees; the best window size was of 200 points (sampling points) and the maximum standard deviation was equal to 4. The polynomial used for de-tided sea levels was optimal as of 3 degrees; the best window size was of 500 points and the maximum standard deviation was equal to 5. The limit for stuck-data was equal to 10 points. The limits for the maximum and minimum total sea levels and the de-tided sea levels were given by an expert, for each tide gauge. This set of criteria was extended to the Iberian-Biscay-Irish region in the NRT automatised quality control in the Copernicus Marine Service. ¶

The original de-tiding module of SELENE is based on the Foreman tidal prediction package in Fortran77 (Foreman, 1977). The de-tided sea level observations facilitate quality control, since tidal variations often dominate a sea level record, making subtle errors more difficult to detect. On the contrary, bad data can easily present itself as abrupt changes in the non-tidal residual, while being told apart from the real extreme surges, which evolve more gradually. The corrected time series were then used to improve the sea level forecasts of the Nivmar Sea Level Forecasting system of Puertos del Estado (Álvarez-Fanjul et al, 2001; Pérez-Gómez et al., 2013). This was performed by means of a nudging technique, still operational today. However, the de-tiding module is only available in internal reprocessing in Puertos del Estado, but is not yet applied in operational NRT mode in the Copernicus Marine Service in situ NRT product, as it requires the computation of yearly tidal constants at each station in the Copernicus Marine Service. ¶

~~The~~ The interest of international tide gauge communities (such as the Copernicus Marine Service, GLOSS and EuroGOOS Tide Gauge Task Team) was for the SELENE software, first used in ~~applying this automatic algorithm to other tide gauge networks resulted in~~the Copernicus Marine Service as the ~~software being upgraded~~NRT quality control of total sea level, to be a modern, open-source (Python) and well-documented format. It ~~is~~had to be multi-platform (Linux, MacOS and Windows) and it is now used by some regions in the Copernicus Marine Service In Situ TAC, and by some national providers for purposes outside the Copernicus system.

~~The SELENE software follows best practices, as defined by GLOSS (IOC, 2020). In near-real-time, it applies the L1 quality control level, as defined by the IOC (2020), including: out-of-range, spike detection, and stability tests. It also includes a module for de-tiding, based on the Foreman tidal prediction package in Fortran77~~

[1]https://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114l. ¶

~~(Foreman, 1977). However, this module is not yet applied in operational near-real-time mode in the Copernicus Marine Service In Situ near-real-time product, as it requires historic tidal constants at each station, as a precursor to the process.~~

~~The SELENE software uses a series of station-configuration parameters. These are the maximum and minimum total sea level; degree of polynomial and other parameters for spike detection; parameters for the stuck-data test (data that keeps being constant for an abnormally long time), among others. Prior to this project, no study was carried out to calibrate the parameters for each station. Such a study needs to employ statistical analyses, while dealing with the physical oceanographic aspects.~~

~~3~~4 The delayed-mode: the reprocessed product (L2) and the ~~methodology~~ upgraded SELENE software

The delayed-mode reprocessing follows ~~the same~~a similar procedure as the ~~near-real-time~~NRT process (Fig. 3). The products (https://doi.org/10.48670/moi-00307) available in the first release of November 2022 comprise quality-controlled versions of the original series of total sea level and the hourly filtered series of sea level. These products end in December 2020, and are available for the 639 stations that were operational by that time. The series that, by December of 2020, presented less than one year of data, were excluded (Fig. 1). The reprocessed product has been assigned with corresponding metadata, to better identify the product from each station. An updated version of the SELENE software, developed in 2022, is used for the automated quality control. The reprocessing is complemented by visual inspection. The reprocessing can more accurately flag the bad or dubious data than the NRT product, which can only rely on automated quality control of a short moving time window (a few days), applied every 15 minutes. With the new tests implemented for delayed mode in the first release of this product, the reprocessing flags 1.9% of the sea level data as bad/dubious data, whereas the NRT automated quality control can flag about 0.3~~)~~% of the sea level measurements as bad/dubious data. In some tide gauges, the total sea level is already reprocessed by national providers. In this case, the data mode is read from the source metadata of each sea level file, and recorded as a station-configuration parameter. When the data mode is "reprocessed", the original flagging is considered to be correct, although some further automated and visual quality control is carried out, by default.

~~An updated version of the SELENE software is used for quality control.~~ The ~~reprocessing is complemented by visual inspection. The updated~~upgraded SELENE software contains a series of new modules. The changes can, in their turn, improve ~~near-real-time quality control as it includes new quality control tests and~~the NRT quality control~~ of non-tidal residuals (by providing yearly tidal constants)~~. A new version of the de-tiding module had been incorporated~~,~~ in Python language. The corresponding Python package is called uTide (Codiga, 2011), also based upon Foreman. It is used by other authors, such as Mélet et al. (2021), for tide gauge data reprocessing. uTide accepts non-uniform sampling frequencies. This flexibility comes in especially handy, since some time series uploaded to Copernicus Marine Service are not entirely uniform, in terms of sampling interval. ~~Apart from being a product itself, the de-tided sea level can help detect anomalous behaviour, such as in Fig. 5. These small errors~~Astronomical constants are ~~not easily detectable by visual inspection, and this automation can significantly reduce workload~~given for each year which large gaps (>0.5 week) add up to less than 1 month. ~~Other issues detectable with de-tided sea levels are clock malfunction and datum changes~~Also, ~~when combined with visual inspection. Hourly non-tidal sea level for the Iberian-Biscay-Irish region will be available by November 2023.~~

$$\log_{10}\frac{max(A)}{min(A)} \le 0.7$$

for all months, where A is the monthly amplitude of the M2 tidal component. If a year does not comply with these conditions and astronomical constants are not computed for that year, the de-tiding process can borrow the constants from up to three years previous or later than that year for its computation.

[1]https://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114l.

Hourly de-tided sea level and astronomical tide for the Iberian-Biscay-Irish region will be available as delayed-mode reprocessed products, in the Copernicus Marine Service, by November 2023. Neither of them contain the non-astronomical “tide”. That is, cyclical fluctuation of the sea level that are generated by non-astronomical phenomena. The de-tided sea level can, internally, help pinpoint anomalous behaviour, such as in Fig. 4. These small errors are not easily detectable by visual inspection, and this automation can significantly reduce workload. Other issues detectable with de-tided sea levels are clock malfunction and datum changes, when combined with visual inspection.

~~One of the~~ A new ~~modules~~module added to the SELENE software is the “buddy” checking~~ or neighbour test~~, applied to hourly de-tided ~~series~~sea levels and monthly mean sea levels. It has been implemented to compare the target station to neighboring stations within a range of 0.01º~~,~~ (approximately 1 km). Another ~~new~~ module is the detection of attenuated data. The attenuated data is easily detectable by a human, but it is ~~dedicated~~difficult to ~~identification~~have a machine tell it apart from neap tides. Neap tides are more centred around the the mean water level of ~~data displaying an erroneous~~the sea level, and attenuation ~~of~~usually presents itself as a fluctuation around a value far away from the ~~tidal signal~~mean water level. Specific testing had been carried out, to set the parameters and the ~~criterion for attenuated data~~criteria to tell the two cases apart. Because of the level of complication of the specific criteria, ~~in contrast~~the reader may refer to ~~neap tides (~~the Product User Manual~~)~~.

~~Finally, an exhaustive study was carried out, to calibrate the parameters for SELENE. Specifically, a sensitivity test has been performed, and the goodness of the results has been controlled by expert visual inspection. This process has been repeated for each one of the 909 files of various sampling frequencies, from the 639 stations in the Copernicus Marine Service In Situ TAC. The selection of the parameters followed the application of unified criteria. For instance, the limit for stuck data depends on the precision of the data. These customized parameters can improve the performance of SELENE by successfully detecting spikes, even in difficult cases (Fig. 6).~~

Finally, a sensitivity test was carried out, to calibrate the station-configuration parameters used by SELENE, on the tide gauges in the Copernicus Marine Service. A unified criterion for station-configuration parameters is created. It is designed to be further used on other regions of the planet. The limits for maximum and minimum total sea levels are the mean water level plus or minus the 99th percentile of the total sea level in the whole time series. The limits for maximum and minimum de-tided sea levels is the same as for the total sea level, but the mean water level is set to be null, as it is eliminated from the data during de-tiding. The polynomial, used to detect spikes in the total sea level, is of 2 degrees; the maximum standard deviation allowed for non-spikes is equal to 3. The window size of total sea level data to be fitted to the polynomial depends on the frequency of sampling. The greater the sampling frequency, the more the elements that should be within the window (see Product User Manual for details). The window for fitting de-tided sea levels is double that of the window for total sea levels. This is because the total sea level has cyclicities caused by astronomical tides, whereas the de-tided sea level does not have such cyclicity. These customized parameters can improve the performance of SELENE by successfully detecting spikes, even in difficult cases (Fig. 5).

The limit for stuck-data starts with 10 points. Then, the limit can be more lax in the case of worse precision (in centimeters, instead of millimeters) or when the data is flagged as “stuck” in over 50% of the total time series. This situation is commonplace for older tide gauges. If, despite the modifications to the limit of stuck-data, the total sea level is still being flagged often during a visual inspection, the time series can be classified as having “many stuck” or “too many stuck”. In this case, the limit can be further modified, depending on the sampling frequency (Product User Manual).

The processing speed of the first Python version of the SELENE software (currently used in the NRT service) was slower than that of the original Fortran77 code in Puertos del Estado. This was only sustainable on a time window of 15 minutes, the one used for NRT quality control. However, this fact hampered the reprocessing of extensive series in a delayed-mode reprocessed product. In the upgrade of the SELENE software, the computational cost of the Python-based algorithm has been reduced ten-fold. One change is that, while the version of SELENE used in the NRT process tackled all time *t* to find spikes, the delayed-mode reprocessing starts the

[1]https://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114l.

detection of spikes only in specific cases. The increment of data at the time *t* must be larger than 100 millimeters, and greater than the following value

$$\frac{1}{50}\,\frac{\left|slev_{max}-slev_{min}\right|}{3},$$

~~The processing speed of the first Python version of the SELENE algorithm was slower than that of the original Fortran77 code. It hampered the reprocessing of extensive historical series. During this project, the computational cost of the Python-based algorithm has been reduced ten-fold. In addition, the reprocessed product has been assigned with corresponding metadata, to better identify the product from each station. Product enhancements~~where $slev_{max}$ and $slev_{min}$ are ~~planned such as improvement of the geographical coverage, by including stations from~~ the ~~GLOSS network in 2024. Time extensions of the product to six months prior to the respective release will be regularly provided. Future goals for the reprocessing service include product validation with satellite altimetry,~~maximum and ~~to carry out a feasibility study on the inclusion of vertical land motion corrections, based on Global Navigation Satellite System (GNSS) receivers~~minimum total sea levels. -

~~4~~5 Possible applications

The reprocessed total sea level product has many applications for scientists and coastal stakeholders. As an example, seasonal extreme water levels can be computed, normalized (divided) by the tidal range. Seasonal relative maximum sea levels derived in this way could help highlight regions at most risk of flooding. Alternatively, seasonal relative lowest water levels can also be useful to remind harbours to keep their maintenance on schedule, to ensure ~~its~~their channels have enough draft for ships to circulate freely.

~~From~~ From hourly (filtered) total sea level, the maximum and minimum values for each season are computed. The values for all stations are scaled, to share a single ~~zero~~mean water level. These extreme sea level parameters are subsequently divided by the tidal range at each station, in order to produce the relative extreme sea levels. The tidal range is computed as the difference between the ~~historical~~ 99th percentile and the ~~historical~~ 1st percentile of the whole time series. The relative maximum and minimum hourly total sea levels in each season are shown in Figs. ~~7~~6 and ~~8~~7, respectively. Note that the used series are the ones that by December of 2020 presented a time interval longer than one year. Moreover, each series has a different length, as shown in Fig. ~~3~~1.

~~The (absolute) highest water levels, according~~According to the European Environment Agency and to the reprocessed sea level data, the (absolute) highest water levels are in the Iberian-Biscay-Irish area and the Northwest-shelf. The areas with the most extreme water levels are the British coasts in the Irish Sea, as well as the French coast in the English Channel. Some high-water levels are typical in the Frisian Sea, near the German-Denmark border. This area, too, is heavily influenced by the Atlantic Sea. However, ~~these regions~~the Iberian-Biscay-Irish area and the Northwest-shelf are geographically and technologically more prepared for such ranges of sea level, since they are typically macro-tidal. Attention must be paid to micro-tidal and meso-tidal areas with large percentage increases in sea level, for small changes can induce floods in them.

~~The~~ The Strait of Kattegat (between the east coast of Denmark and the South-western coast of Sweden, located at 56.82ºN, 11.39ºE) ~~suffers from~~exhibits the highest relative sea levels in Spring, Autumn and Winter (Fig. ~~7~~6). Furthermore, during the Autumn-Winter, the phenomenon of high relative sea levels extends to the neighboring Gulf of Bothnia (the gulf between Sweden and Finland, located at 62.33ºN, 19.55ºE). The Strait of Kattegat also presents the lowest relative sea levels in Autumn and Winter (see Fig. ~~8~~7). The North-western Mediterranean displays high relative sea levels in Spring, Autumn and Winter. It is known that some of these regions, like Barcelona, in the North-western Mediterranean, have a history of engineering challenges for coastal protection,

[1]https://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114l.

like during Storm Gloria (Pérez Gómez et al., 2021). Similarly, Denmark and Sweden had taken steps to improve their protection against floods, because of the historical flood in 1872 (Hallin et al., 2021; Fredriksson et al., 2018). The ~~improvements~~upgrades were not always based on engineering, but also on changes in the structure of the economic system, insurance policies, among others. Much more information can be drawn from the reprocessed sea level data. All this will improve communication between stakeholders.

~~5~~6 Conclusions

~~The Copernicus reprocessed sea level product is especially useful to the oceanographic community. The quality of the data can determine both the veracity of the conclusions and the correctness of the decisions to be taken. The delayed-mode reprocessing is based on the near-real-time process, the existing software and visual inspection for quality control. There were several improvements and adaptations in the automated part, such as the adaptation of the de-tiding module from Fortran77 to Python language, the implementation of the buddy checking, the detection of attenuated data, and the calibration of parameters for the SELENE software. ¶~~

~~An example of a possible use for these reprocessed sea level data is given. It helps map the risk areas for high and low relative sea levels, per season of the year, in Europe. Temporal and geographical extensions are planned for the present service. There will also be improvements for the de-tiding module, tests on comparison with altimetry and inclusion of Global Navigation Satellite System land vertical motion corrections. ¶~~

The Copernicus delayed-mode reprocessed sea level product is crucial for validation of ocean models, for both short-term forecasts and long-term climatic studies (reanalysis). The quality of the data can determine both the veracity of the conclusions and the correctness of the decisions to be taken. The Copernicus Marine System already has a service of operational automated quality control of NRT data, which detects spikes, stuck data, among other errors. It uses a software called SELENE. ¶

The delayed-mode reprocessed product described here was first available in November of 2022, and was obtained by applying an upgraded version of SELENE software, in delayed mode, including additional tests and visual inspection of the whole time series by an expert in sea level data. The mentioned upgrade includes an adaptation of the de-tiding module from Fortran77 to Python language, the implementation of the buddy checking of hourly de-tided and monthly mean sea levels, the detection of attenuated data, and the creation of a criterion for determining the station-configuration parameters used in the quality control. The criterion was obtained after carrying out sensitivity tests on each module of the SELENE software, such as the spike detection test and the stuck-data test, intended to be applied to the whole planet. The upgrade to SELENE has increased the ability of automatically flagging bad data by 1.6%, as compared to the automated quality control in the NRT process. The computational cost of the upgraded software is also 10 times lower, if comparing the shared modules. This faster speed is possible due to, in part, the pre-selection of data to apply spike detection. ¶

The new delayed-mode sea level product is of major interest for the scientific community and other data aggregators using In Situ TAC sea level data, and more broadly for coastal and local decision-makers, such as coastal engineers intensively using tide gauges data to design coastal and port infrastructures. It is also an added-value product for those regions or countries where quality control of historical records is not performed at national level. Product enhancements are planned, such as improvement of the geographical coverage, by including stations from the GLOSS network in 2024. Time extensions of the product to six months prior to the respective release will be regularly provided. Future goals for the reprocessing service include to compare monthly mean sea levels to altimetry, as well as a feasibility study on the inclusion of vertical land motion corrections, based on Global Navigation Satellite System (GNSS) receivers.

¶

Competing interests

[1]https://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114l. ¶

The contact author has declared that none of the authors has any competing interests.

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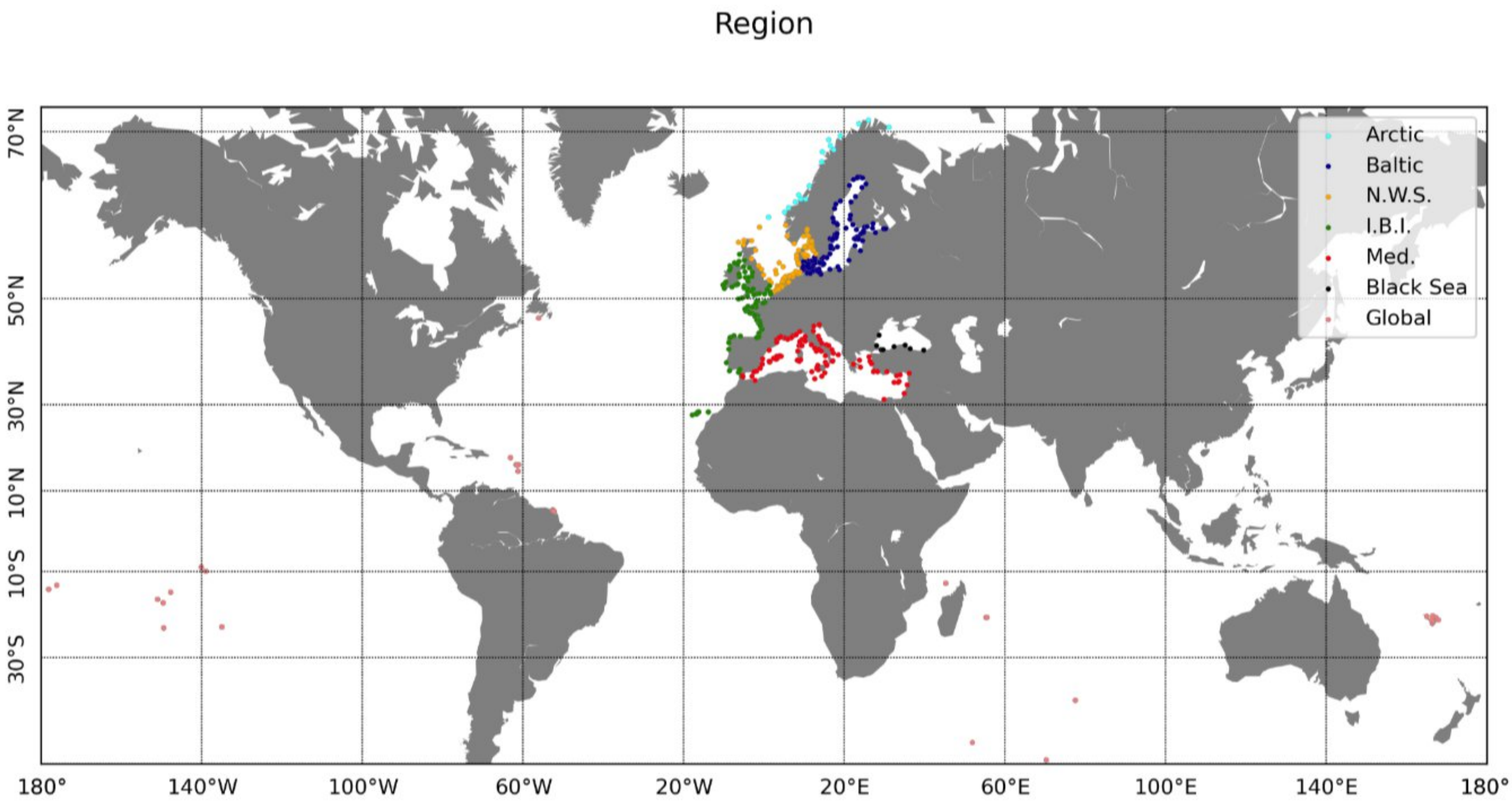

Region
70°N
50°N
30°N
10°N
10°S
30°S
180°
140°W
100°W
60°W
20°W
20°E
60°E
100°E
140°E
180°
Arctic
Baltic
N.W.S.
I.B.I.
Med.
Black Sea
Global

1

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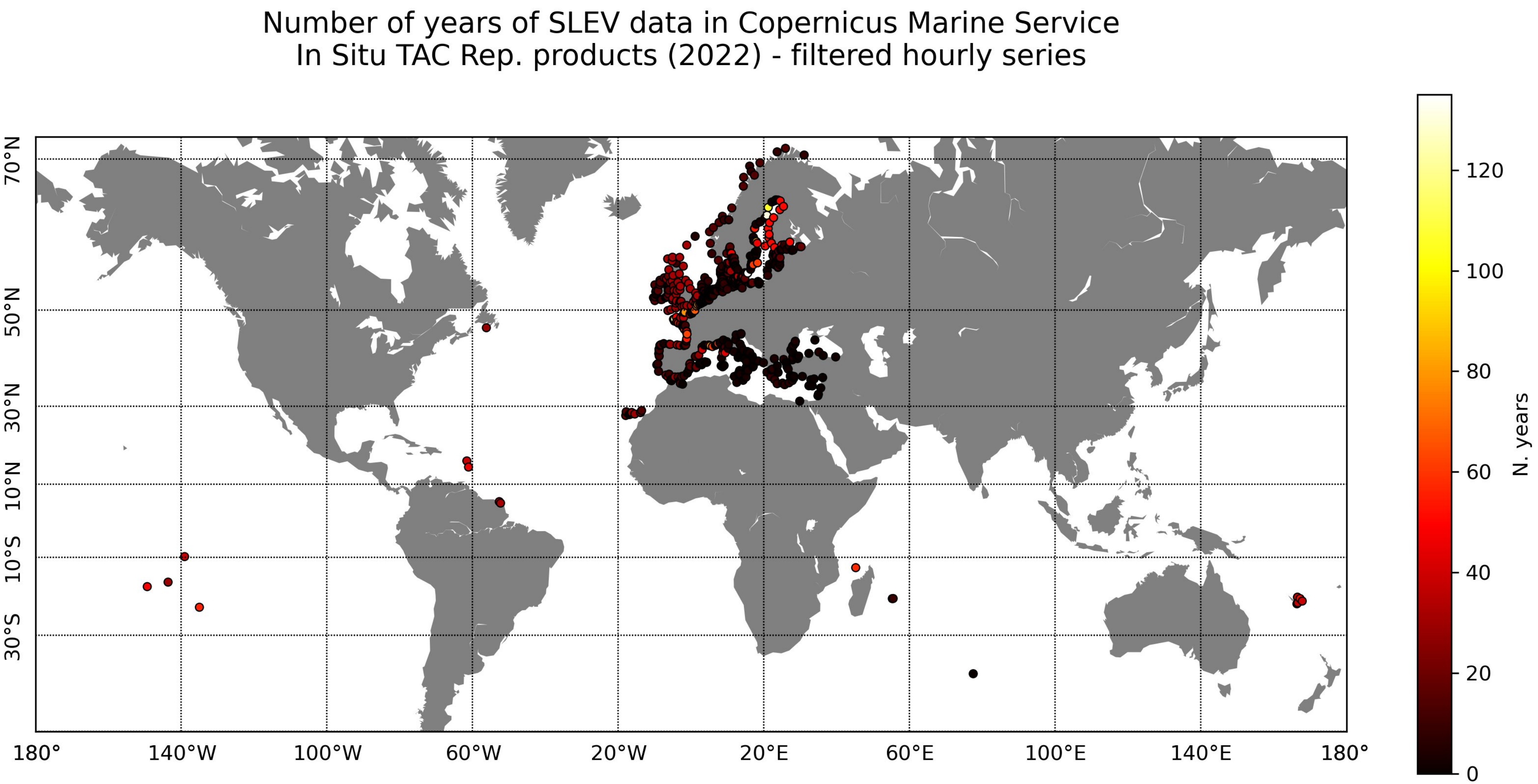

~~Fig. 1 Network of tide gauges in the Copernicus Marine Service In Situ TAC showing data integration by each of the regions (colours). Source: Quality Information Document, Issue 1.0.~~

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Fig. 1 Time series length of tide gauges that are included in the reprocessed product, first release of November of 2022.

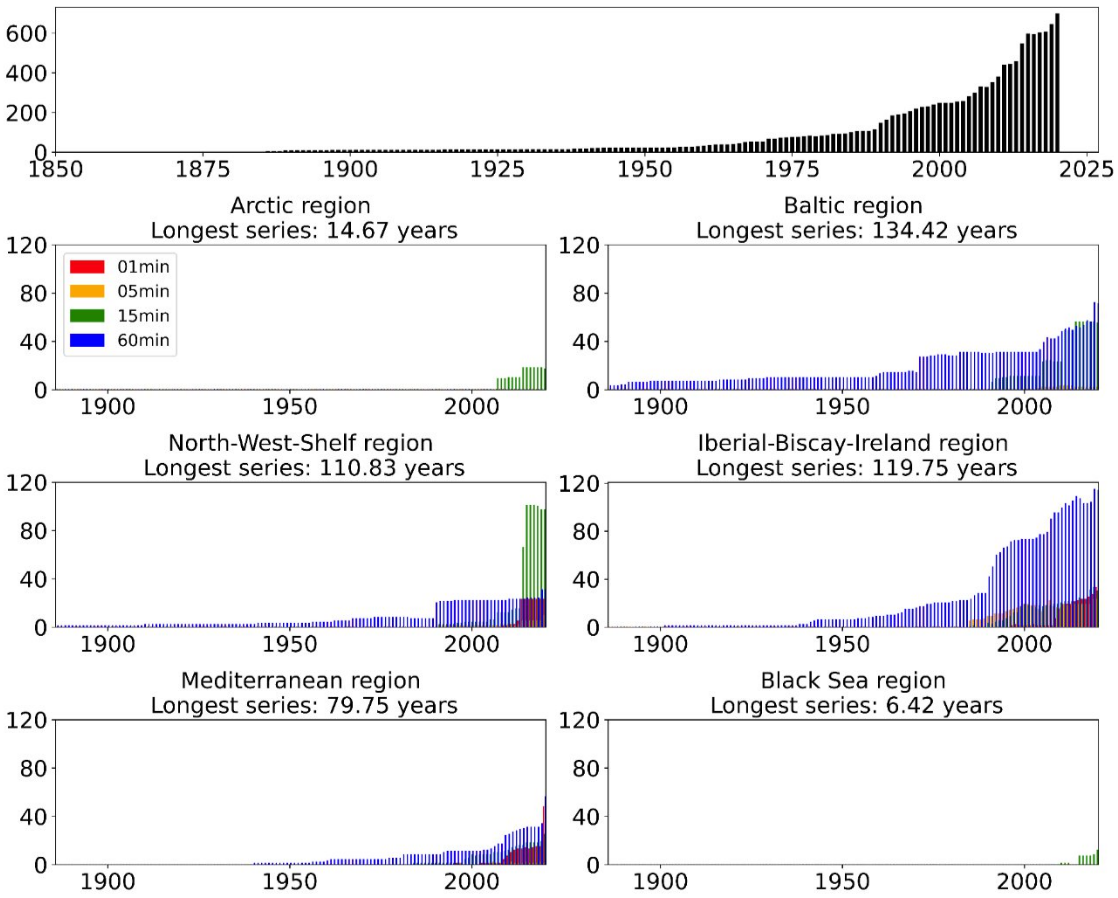
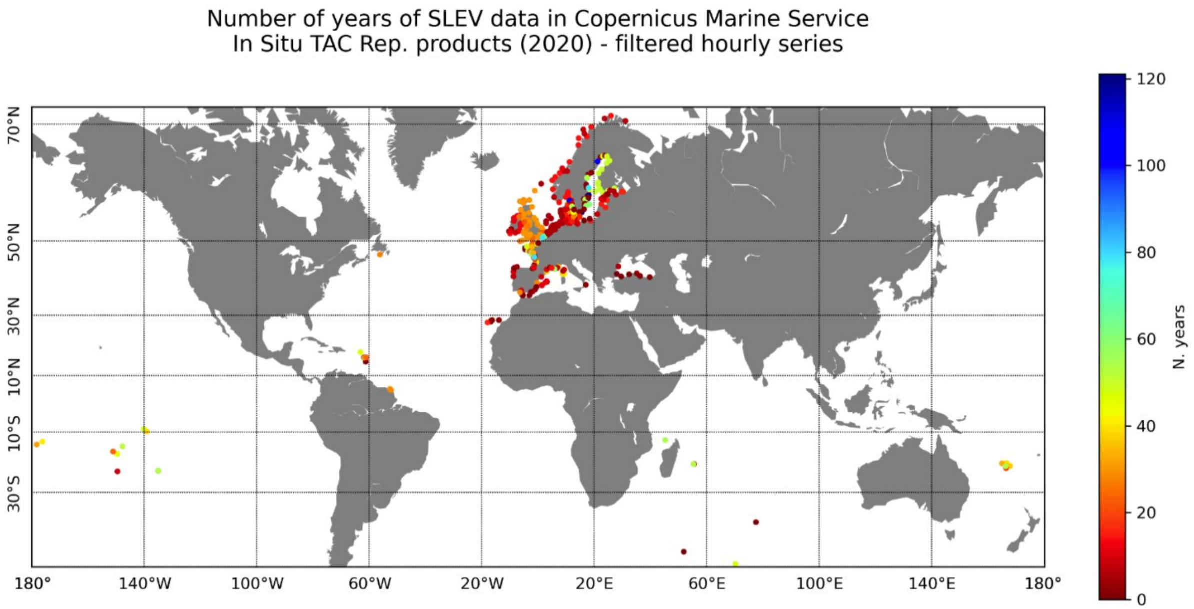
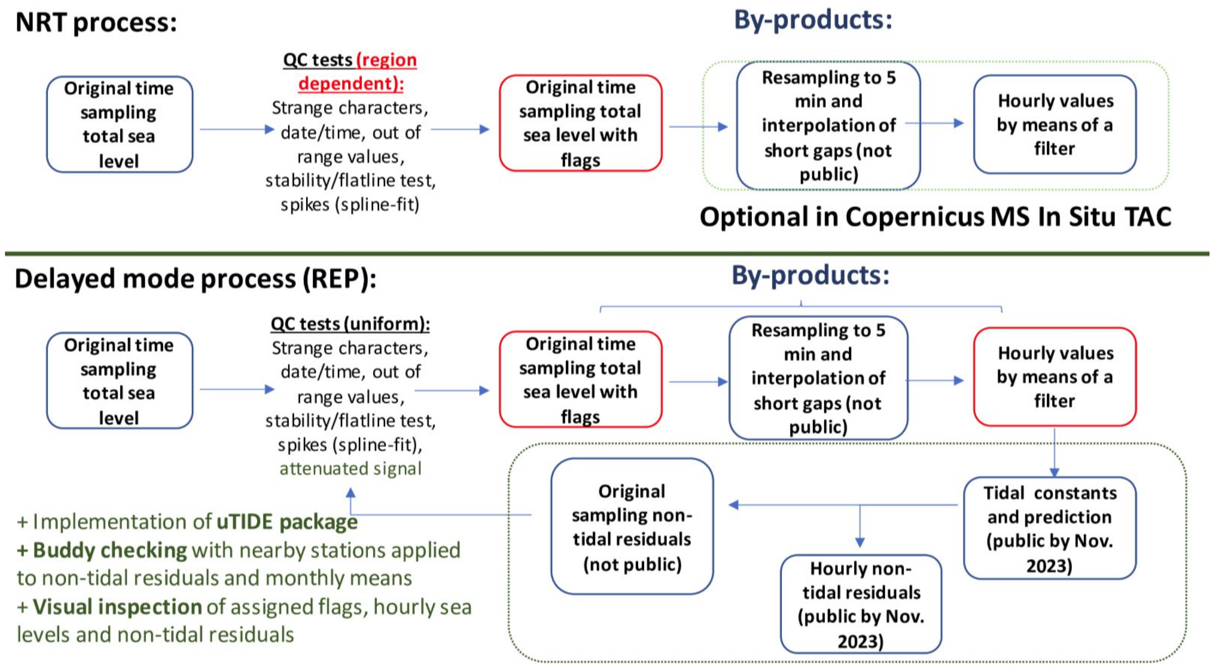


Fig. 2 Evolution of the number of tide gauges per year in Copernicus Marine Service In Situ TAC. ~~It~~The figure includes the series that span less than one year at the end of 2020. Product name: INSITU_GLO_PHY_SSH_DISCRETE_MY_013_053. ~~Source: Quality Information Document, Issue 1.0.~~



~~**Fig. 3 Time series length of tide gauges that are included in the reprocessed product, first release. Source: Quality Information Document, Issue 1.0.**~~

Delayed mode QC and data processing (L2, IOC-UNESCO, 2020 GLOSS standards)



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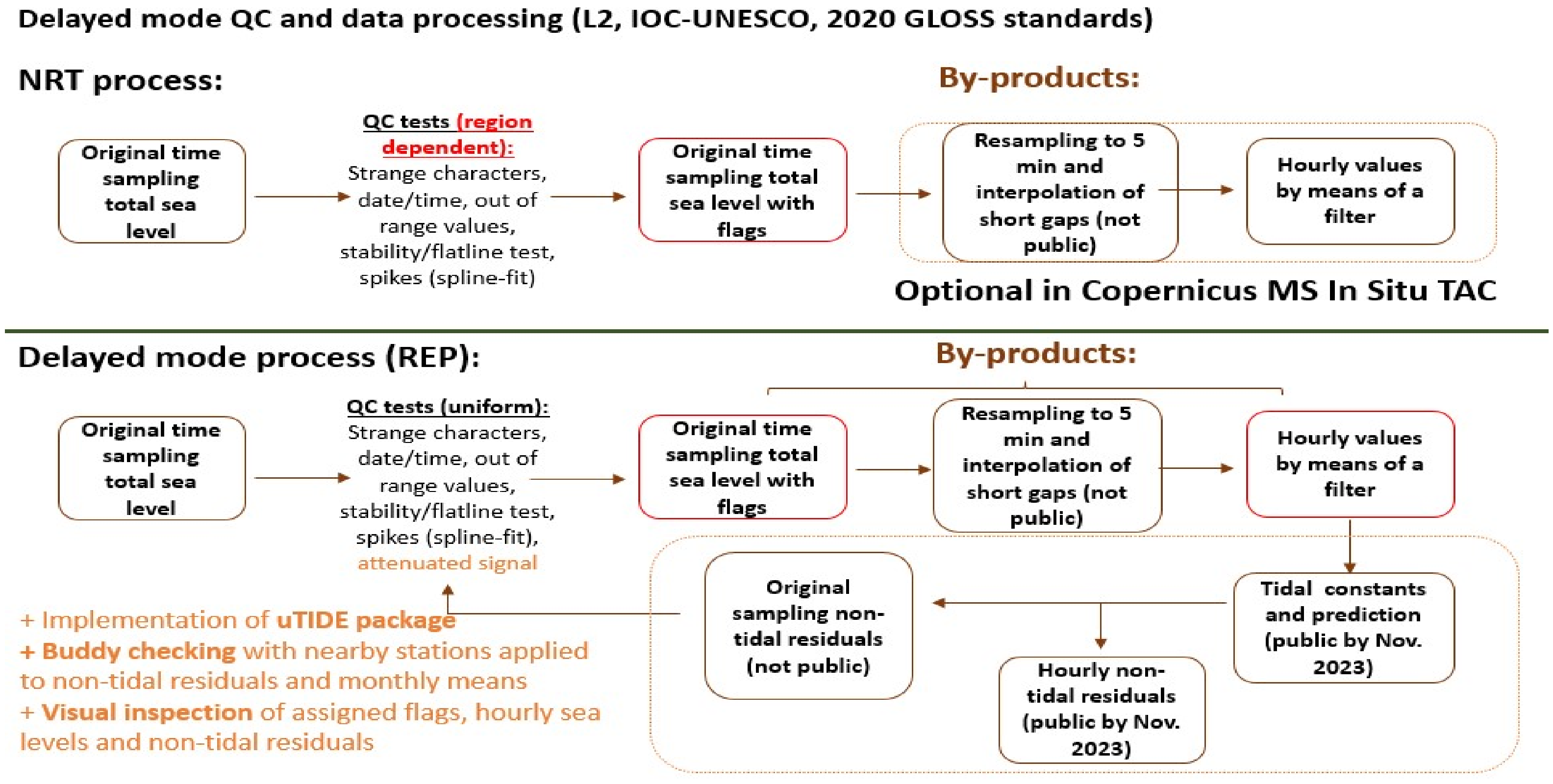
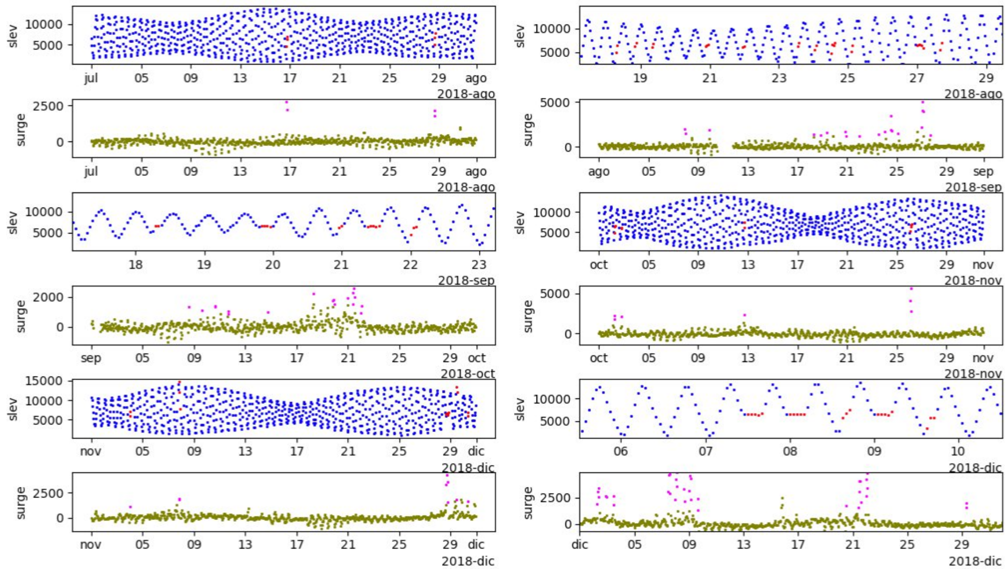


Fig. 43 Flow chart of NRT (near-real-time) process and delayed-mode reprocessing.



slev
10000
5000
jul 05 09 13 17 21 25 29 ago
2018-ago
19 21 23 25 27 29
surge
2500
0
ago 05 09 13 17 21 25 29 sep
2018-sep
18 19 20 21 22 23
oct 05 09 13 17 21 25 29 nov
2018-nov
2000
sep 05 09 13 17 21 25 29 oct
2018-oct
15000
nov 05 09 13 17 21 25 29 dic
2018-dic
06 07 08 09 10
dic 05 09 13 17 21 25 29

1

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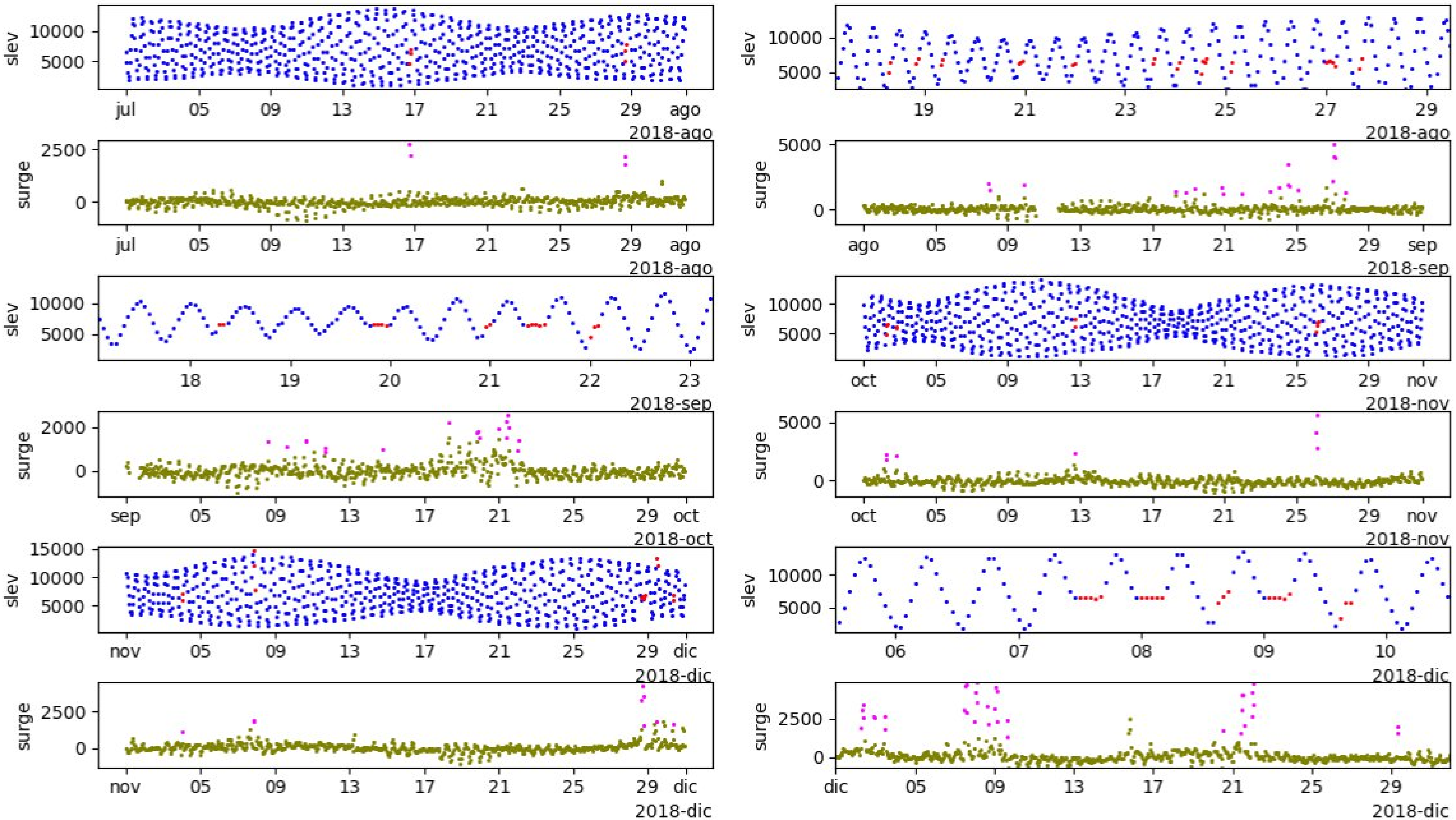

Fig. ~~5~~4 Example of detection of bad data in the total sea level ("slev", in millimeters), with the help of de-tided sea level ("surge", in millimeters). Subplots for the total sea level, in August, September and December are zoomed in to see the detection of bad data. Bad data are shown in red in the total sea level, and in pink in the de-tided sea level.

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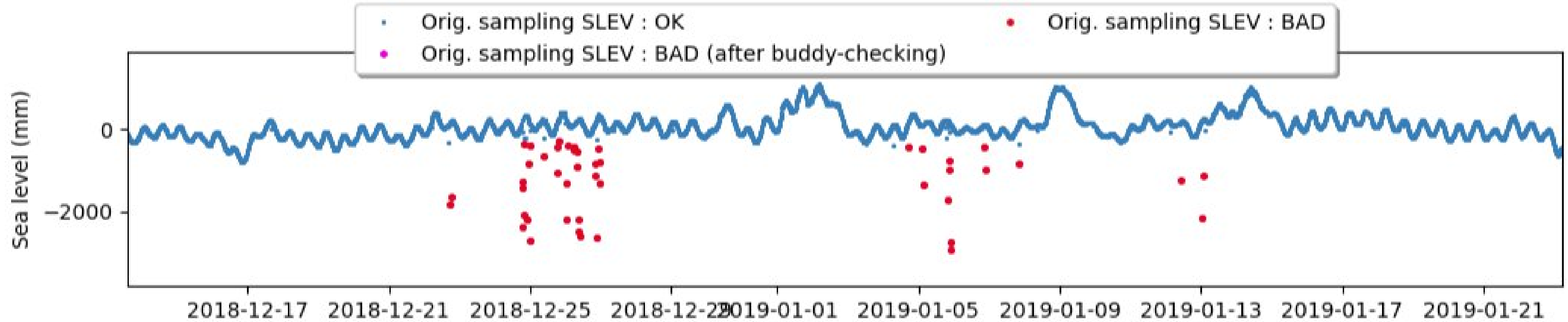


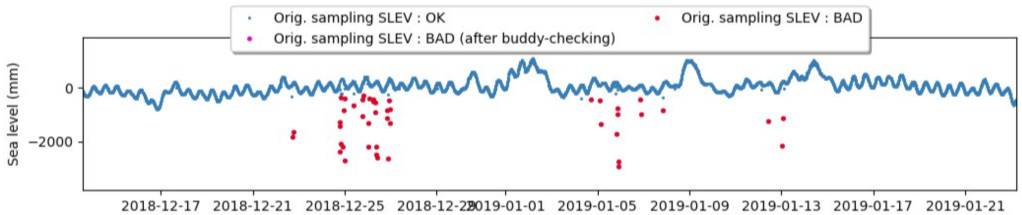
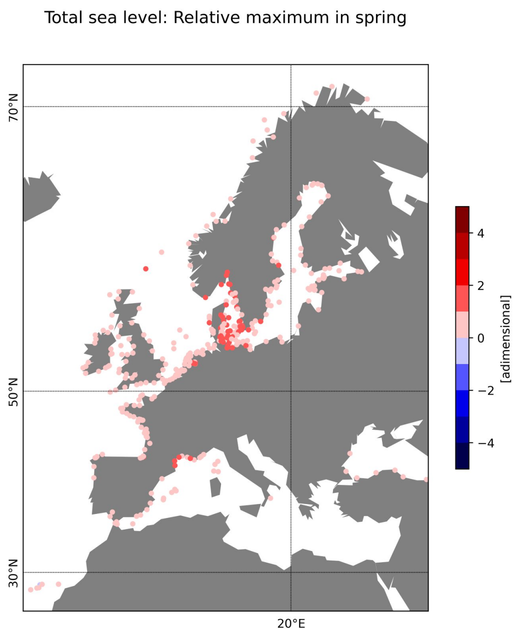
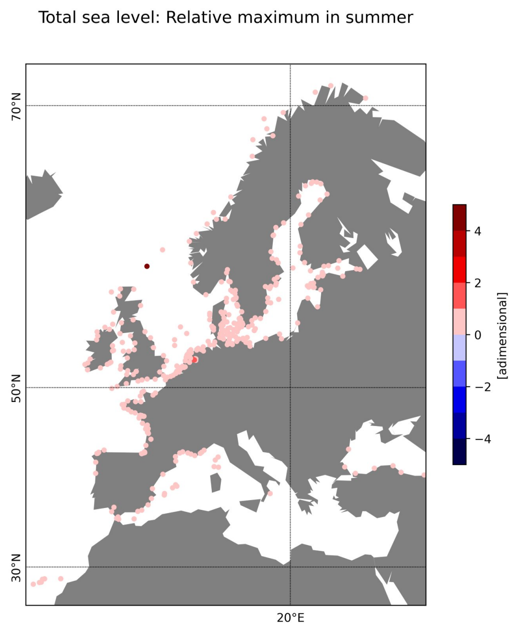
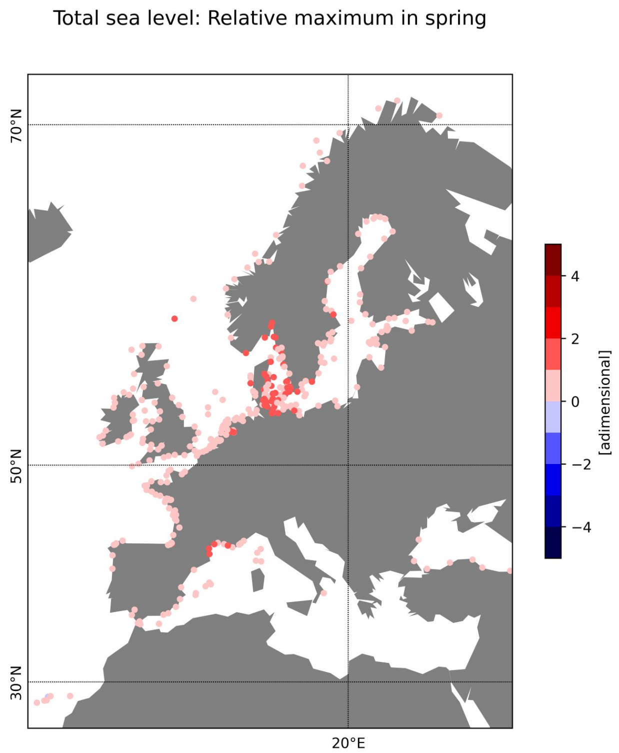
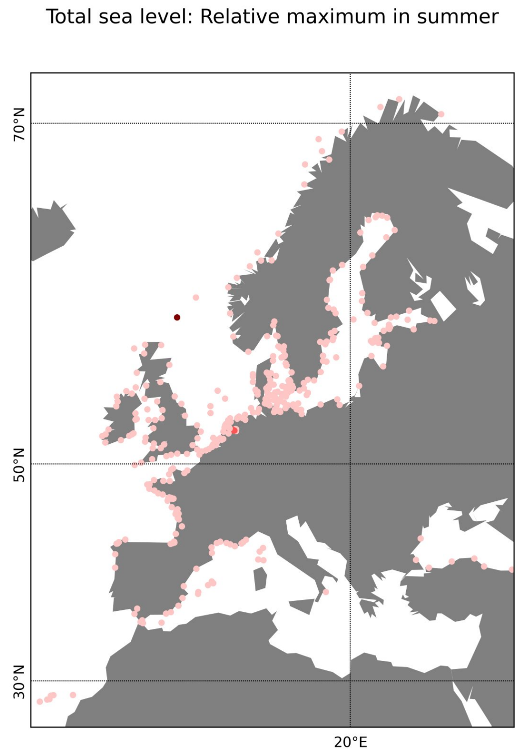


Fig. 65 Example of spike detection in the total sea level level


Total sea level: Relative maximum in spring
70°N
50°N
30°N
20°E
4
2
0
−2
−4
[adimensional]


Total sea level: Relative maximum in summer
70°N
50°N
30°N
20°E
4
2
0
−2
−4
[adimensional]


Total sea level: Relative maximum in spring
70°N
50°N
30°N
20°E
4
2
0
−2
−4
[adimensional]


Total sea level: Relative maximum in summer
70°N
50°N
30°N
20°E

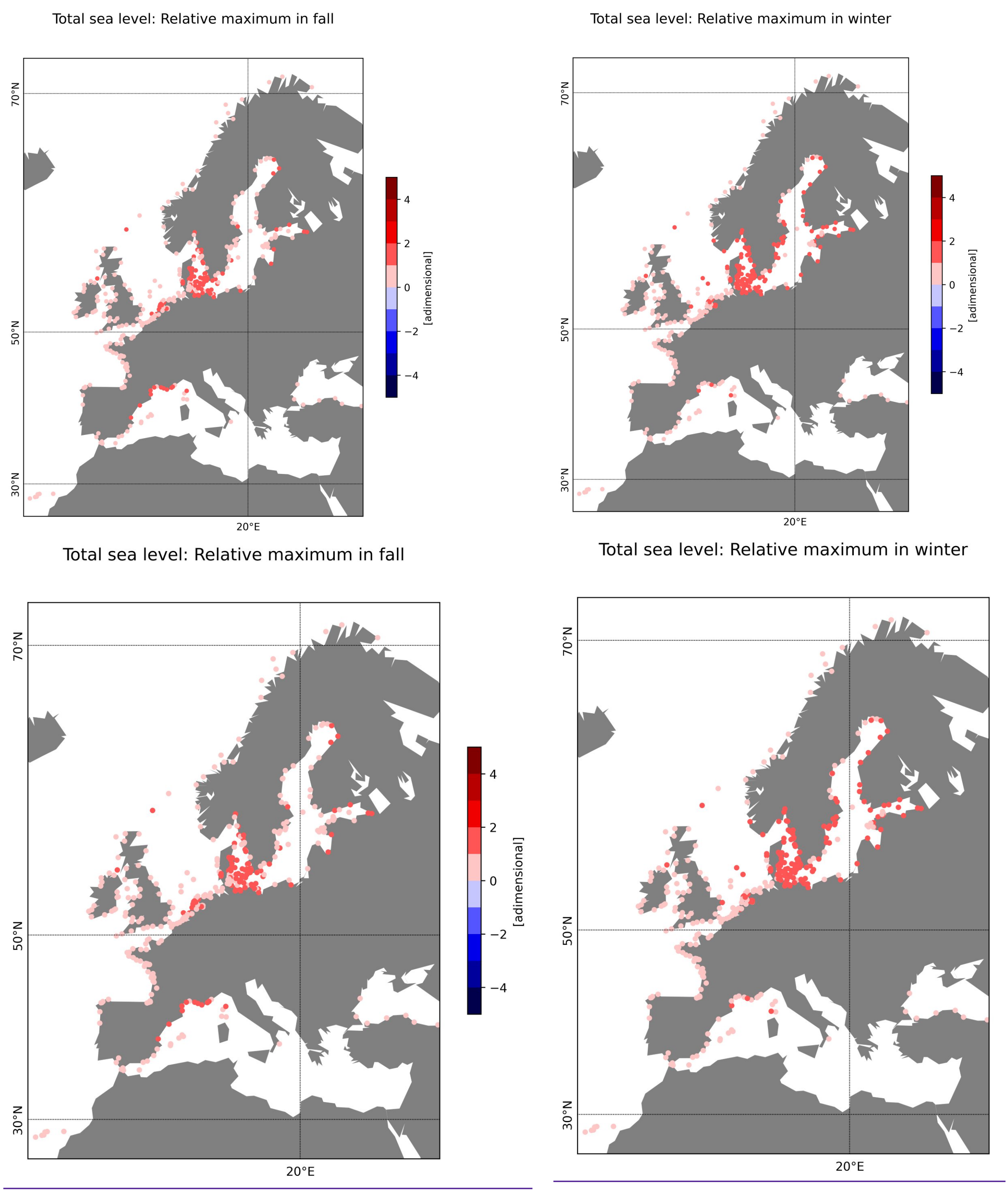
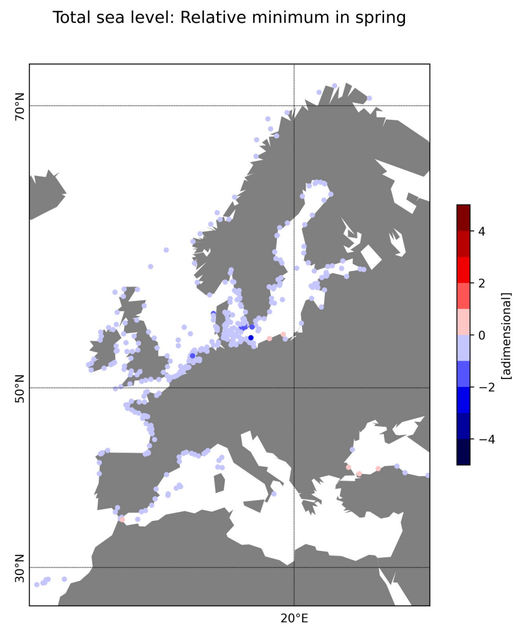
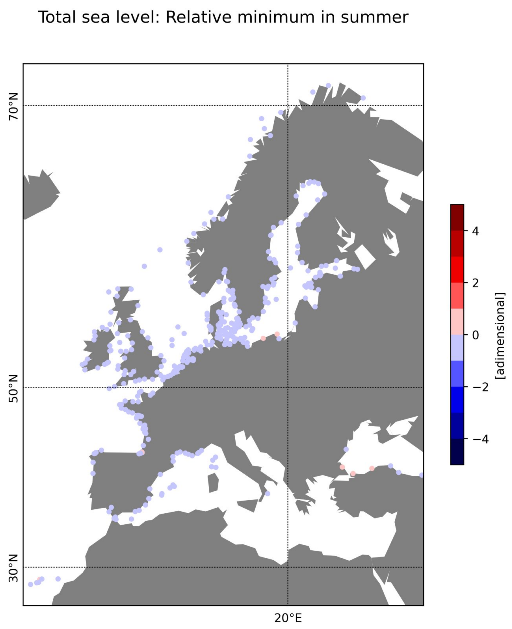
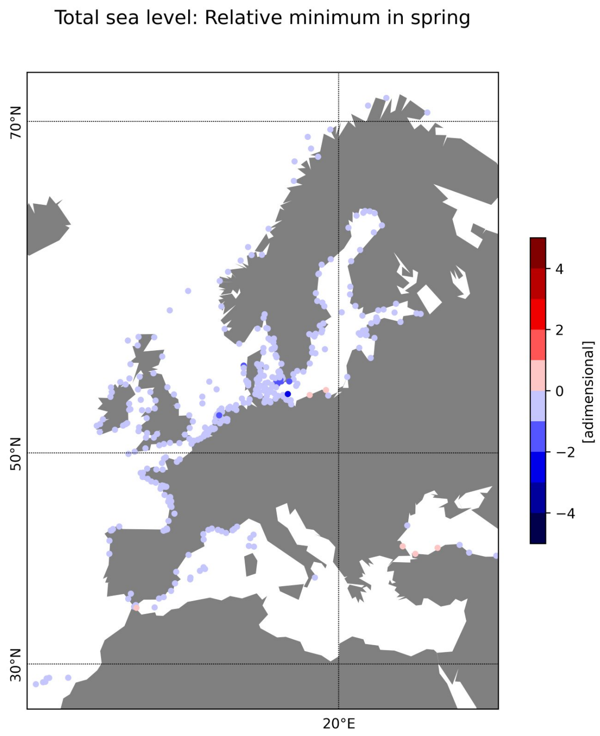
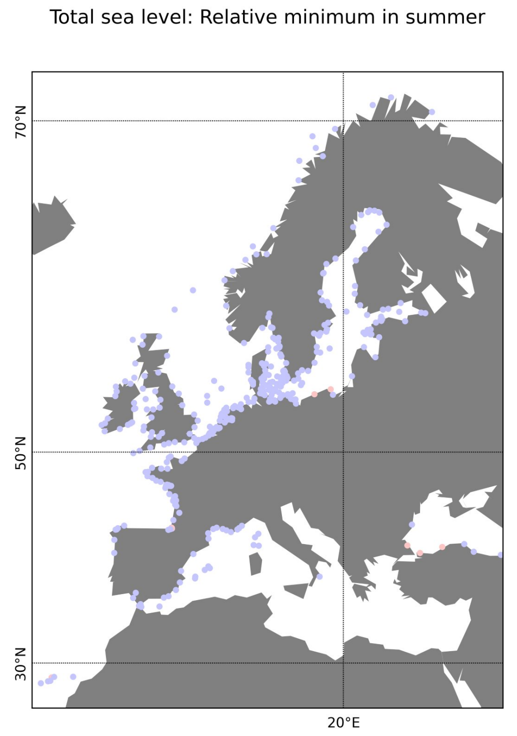


Fig. 6 Relative maximum sea levels (maximum sea levels at each station, divided by the corresponding tidal range), in each season.


Total sea level: Relative minimum in spring
70°N
50°N
30°N
20°E
4
2
0
−2
−4
[adimensional]


Total sea level: Relative minimum in summer
70°N
50°N
30°N
20°E
4
2
0
−2
−4
[adimensional]


Total sea level: Relative minimum in spring
70°N
50°N
30°N
20°E
4
2
0
−2
−4
[adimensional]


Total sea level: Relative minimum in summer
70°N
50°N
30°N
20°E

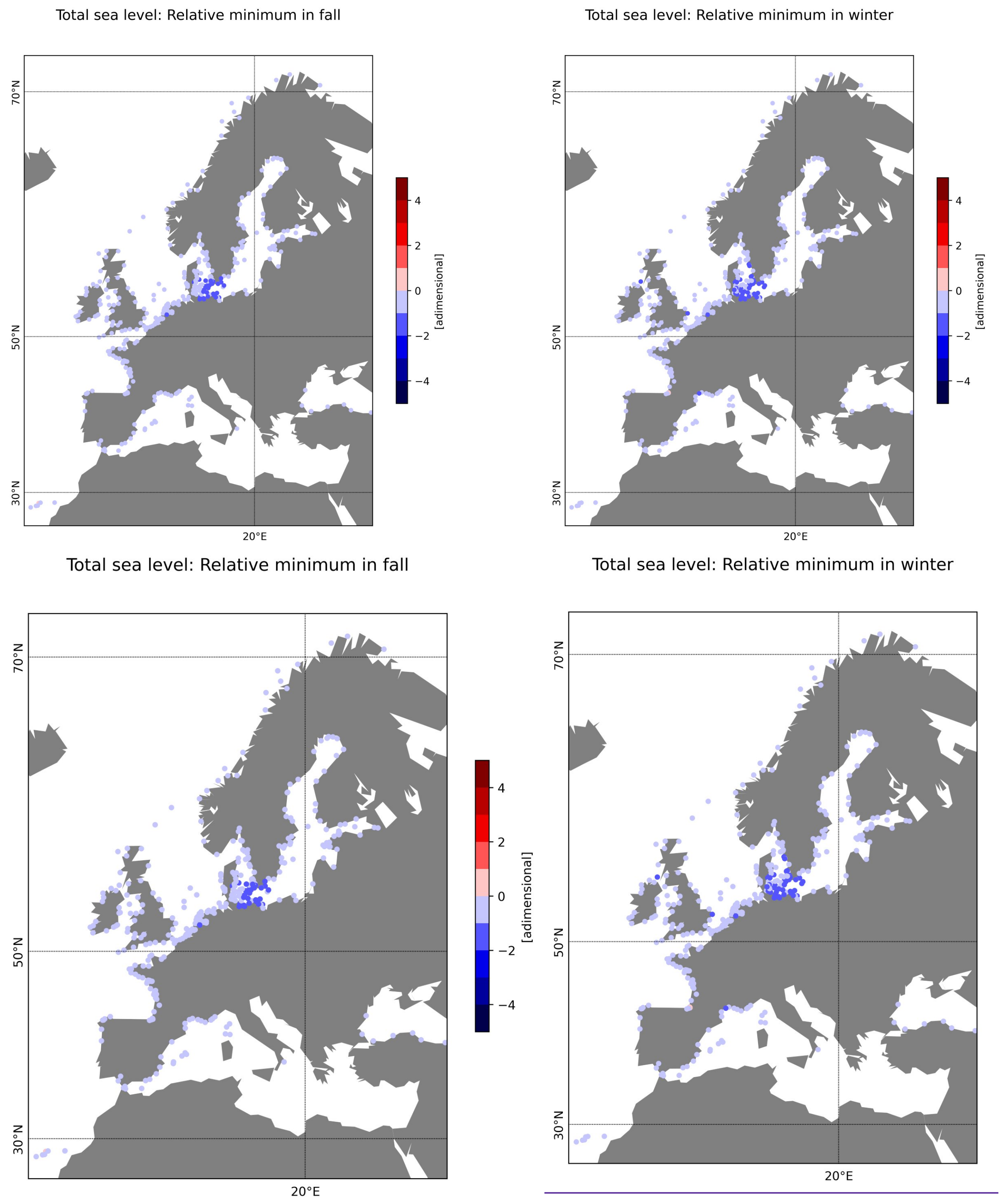


Fig. 87 Relative minimum sea levels, in each season.