Project	AtlantOS – 633211
Deliverable number	D8.12
Deliverable title	AtlantOS fitness for storm surge forecasting and warning
Description	Assessment of the observing system fitness for storm surge forecasting and warning in the Atlantic
Work Package number	WP8
Work Package title	Societal benefits from observing/information systems
Lead beneficiary	National disaster risk and environmental managers
Lead authors	Kevin Horsburgh (NOC)
Contributors	Jo Williams (NOC), David Byrne (NOC)
Submission date	12th April 2019
Due date	31st March 2019
Comments	Deliverable report was delayed due to discussion within the WP of the best context for linking AtlantOS observations to storm surge forecasting. We concluded the best observational context is the quality of tide gauge observations, which allows a strong link to be drawn between WP8 and activity in WP4

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n° 633211.

Stakeholder engagement relating to this task*

WHO are your most important stakeholders?	Private company – see below under "others" If yes, is it an SME or a large company ☐? ☒ National governmental bodies – responsible agencies for the issue of coastal flood warnings X International organisation – IOC GLOSS, IOC-WMO JCOMM ☐ NGO others Please give the name(s) of the stakeholder(s):
WHERE is/are the company(ies) or organization(s) from?	X Your own country X Another country in the EU X Another country outside the EU Please name the country(ies): All Atlantic coastal nations
Is this deliverable a success story? If yes, why? **If not, why?**	No, because not all coastal Atlantic nations who are vulnerable to coastal flood hazard have access to a storm surge and wave forecasting system. It is a priority of WMO-IOC JCOMM to encourage the development of such systems through follow on projects from the Coastal Inundation Forecasting Demonstration Project (CIFDP)
Will this deliverable be used? **If yes, who will use it?** **If not, why will it not be used?**	☒ Yes, to accelerate the development of coastal flood forecasting systems where they are most needed; and also to ensure (through IOC GLOSS) that the collection of sea level data around the Atlantic is available and fit for purpose for model development and improvement.

NOTE: This information is being collected for the following purposes:

1. To make a list of all companies/organizations with which AtlantOS partners have had contact. This is important to demonstrate the extent of industry and public-sector collaboration in the obs community. Please note that we will only publish one aggregated list of companies and not mention specific partnerships.
2. To better report success stories from the AtlantOS community on how observing delivers concrete value to society.

*For ideas about relations with stakeholders you are invited to consult D10.5 Best Practices in Stakeholder Engagement, Data Dissemination and Exploitation.

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Executive summary

AtlantOS WP8 seeks to demonstrate the value and societal benefit of the existing observing system in the Atlantic through eight pilot actions. This report provides a description of the necessity and value of high quality sea level measurements, from tide gauges, to support storm surge forecasting and warning systems. Coastal flooding is one of the most significant risks both globally and for Atlantic coastal nations with wide-ranging social, economic and environmental impacts. One of the biggest factors in extreme sea levels is storm surges – a large increase in sea level due to strong winds and low atospheric pressure during a storm. Storm surges, such as during the catastrophic 2017 hurricane season where over 3300 people were killed, can cause significant loss of life and economic damage. Many coastal nations around the Atlantic coastline have made substanital investments in coastal defences, storm surge and wave forecasting and sea level monitoring. Storm surge forecasting and warning systems depend heavily on high quality observations from tide gauges to validate and improve the models. A tide gauge system is essential to provide data to both enhance the performance of the model, and to make continuous improvement to the end-to-end warning system. Tide gauge data are also used in real-time during a storm event to develop the most accurate forecast. Storm surge forecasting is a perfect example of an end-to-end system for users of meteorological and oceanographic information in a complex value chain leading to societal benefit. In this context, the computer models are a value accelerator for the ocean observations. The impact of storm surges will continue to increase under rising sea levels. The international community needs to continue to support the develoment of effective systems for storm surge forecasting, particularly for vulnerable communities in developing countries. This demands reliable and affordable observation systems for storm surge monitoring at the national and regional levels.

High quality tide gauge data form the basis of such a system. For the Atlantic and surrounding marginal seas the current availability of tide gauge data is highly variable in both extend and quality. Several countries in Europe, and also the USA and Canada, provide high frequency sea level data which are valuable scientifically and also in support of operational storm surge forecasting systems. Several linked activities in AtlantOS WP4 have improved the availability of sea level data across the Atlantic in previously data-poor areas and have highlighted the need to continue international efforts in this endeavour. AtlantOS WP4 delivered a comprehensive South Atlantic sea level observing site catalogue, and also implemented delayed mode quality control, documentation and secure archiving of data from 47 South Atlantic tide gauge sites to unify the quality of Atlantic sea level data. An Ocean Obs' 19 White Paper provides the blueprint for future improvements to Atlantic tide gauge data.

Introduction and context: storm surges and coastal flood hazards

Coastal flooding is one of the most significant risks both globally and for Atlantic coastal nations with wide-ranging social, economic and environmental impacts. It is estimated that by 2070, approximately 150 million people and $35,000 billion of assets will be exposed to a 1 in 100-year flood event. Any increase in flood frequency or severity due to sea level rise or changes in storminess would adversely impact society. For the European coastline, annual damages due to coastal flooding are estimated to increase by two to three orders of magnitude (from €1.25 today) by 2100 (Vousdoukas et al., 2018). Recent work by Jevrejeva et al. (2018) warns that without additional adaptation the UK alone would be exposed to flood risk of 6.5% of its GDP by 2100 if the worst greenhouse gas emissions scenario is realised. In Europe, long term investment in operational flood warning systems has largely ensured that fatalities due to coastal flooding are avoided, yet the damage to infrastructure and clean-up costs are still significant. For example, during storm Xaver (4-8 December 2013) which brought the highest ever observed water levels to many European coastlines, there was no loss of life due to coastal flooding. However, the financial impact due to the severe coastal flooding was estimated by Credit Suisse as being over 1.5 billion euros (Poljanšek et al., 2017).

Storm surges are the large scale increase in sea level due to a storm. They can increase sea levels by 3-4m in European coastal seas and they last from hours to days and span hundreds of square kilometres. They are caused by wind stress at the sea surface and the horizontal gradient of atmospheric pressure (Pugh and Woodworth, 2014), although the magnitude of any particular storm surge is influenced by many factors including the intensity and track of the weather system, bathymetry, and coastal topography. Coastal flooding occurs when some combination of high tide, storm surge and wave conditions is severe enough to overtop or breach coastal defences and cause inundation of low-lying areas. Extreme high waters around much of the Atlantic are normally caused by a combination of high tides and severe weather events (with the exception of the Mediterranean Sea where tides are small). Extra-tropical cyclones (the prevailing European weather systems) produce storm surges which can increase tidal levels by 3-4m in exceptional cases. Nearer the equator, tropical cyclones (hurricanes) can cause storm surges of up to 10m which continue to cause devastating loss across large parts of the Caribbean. The 2017 Atlantic hurricane season was catastrophic with over 3300 fatalities across the Caribbean and US due to hurricanes Harvey, Irma, and Maria. With estimated damages of approximately $300 billion, 2017 was the costliest tropical cyclone season on record.

To mitigate the effects of storm surges, many coastal nations globally have made significant investments in coastal defences, storm surge and wave forecasting and sea level monitoring. Typically, numerical weather forecasting models feed into computer models of storm surges and waves. The model forecasts are normally combined with real-time monitoring of coastal sea levels, and are interpreted by a team of forecasters. For a review of numerical methods for storm surge prediction (see WMO, 2011; Gonnert et al., 2001). Recent advances to storm surge forecasting include the increased use of ensemble forecasting (e.g. Flowerdew et al., 2010) to quantify the inherent uncertainty in short-term weather prediction. Multiple model runs are made, adjusting model parameters, to provide a range of outcomes that can then be used to judge the reliability of the forecast and provide a probabilistic approach to flood warning. Forecasting both for atmosphere and oceans requires many skills and many intermediate and technical operators. Experienced forecasters are required to interpret the model forecasts, provide a forecast tailored to user requirements, and explain the impacts of the forecast and end user activities. For many countries that are still developing storm surge warning systems, capacity building in these areas is the priority.

Despite the feasibility and increased availability of regional warning systems, storm surges, tsunamis and other phenomena continue to cause inundation in the coastal zone, killing thousands annually and displacing hundreds of thousands more from their homes and communities. It is for this reason that the World Meteorological Organisation (WMO) and the Intergovernmental Oceanographic Commission (IOC) initiated the Coastal Inundation Forecasting Demonstration Project (CIFDP):
https://www.jcomm.info/index.php?option=com_content&view=article&id=167
The project was designed and overseen by the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) and the WMO Commission for Hydrology (CHy) with the objective of delivering to any requesting country a co-designed coastal inundation forecasting and warning systems at the regional scale and associated capacity building activities.

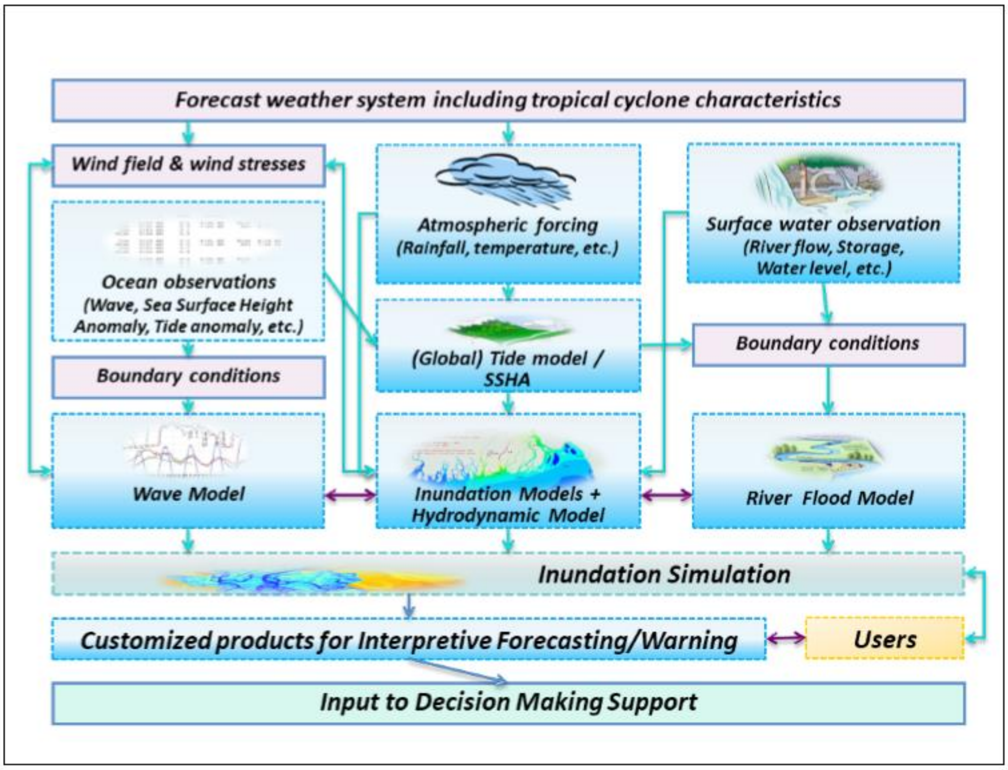

Figure 1. Schematic of the WMO-IOC Coastal Inundation Forecasting Demonstration Project (CIFDP) model configuration. All models depend critically on observations for their validation and practical use in real-time forecasting

One such CIFDP operational system has been developed on the island of Hispaniola. The Dominican Republic and Haiti, which together comprise Hispaniola, face the threat of tropical cyclones each hurricane season, with high storm surges, flooding, and large waves. The growing tourism industry in the Dominican Republic has increased the number of people exposed to this hazard, whilst Haiti has suffered devastating impacts with far-reaching humanitarian consequences from hurricane Maria in 2017 and hurricane Matthew in 2016. The USAID-funded CIFDP-Caribbean demonstration project was successfully completed in December 2018, with the main beneficiaries being the Dominican Republic, Haiti and other small islands. It was implemented by WMO and the Dominican Republic's national meteorological service (ONAMET) ensuring the maximum synergies of regional and national efforts. There is potential to further enhance this early warning platform and to extend it to other Caribbean nations.

The essential role of sea level observations for storm surge models

All storm surge forecasting and warning systems depend critically on high quality observations – mostly from tide gauges - for their development, validation and successful application. The primary purpose of validation is to monitor the consistency of outputs and to identify steps that may be taken to improve the quality of a forecast. In practice, the most commonly compared variable is sea level (or derived storm surge measures, see below) and the observational data are obtained from tide-gauge networks. Although not a routine choice, the verification of horizontal currents is also feasible using data from instruments such as acoustic Doppler current profilers (ADCP). When comparing observed and modelled sea levels, the differing nature of the two datasets must be taken into account. The majority of storm surge models are based on a regular latitude-longitude grid, where the model point at which sea level is calculated is half a grid cell away from the modelled representation of the physical coastline. For models of medium or coarse resolution this may necessitate extrapolation of the model variable. Since the model output represents average conditions over several time periods, then some averaging of observations over time may also be required; an averaging period of five to fifteen minutes is recommended.

Most commonly, to validate storm surge models, the non-tidal residual and skew surge are compared against observations from tide gauge data – typically at a number of ports along a coastline. Non-tidal residual is the time-series difference between the water level that would be expected due to the tide alone, and the actual water level observed/modelled including the atmospheric surge component. Skew surge is the difference in height of the expected peak at high tide and the total peak water level cycle (e.g. de Vries et al., 1995). Correct manipulation of the tide gauge data is as important as the quality of the observations. Within AtlantOS Task 8.2 (deliverable D8.1) we provided a systematic approach to isolating storm surge from tide gauge records. In regions with significant tidal range, storm surges represent the greatest threat when they coincide with tidal high water. Williams et al. (2016) showed how storm surges and high tides interact, providing the first systematic proof that any storm surge can occur on any tide. The lack of observed storm surge dependency on water depth emphasizes the dominant natural variability of weather systems. As well as providing an improve metric for numerical model validation this work also helped advance statistical methods for estimating extreme water levels. The AtlantOS D8.1 work also confirms that the skew surge is the most useful measure of storm surge. Hence each tidal cycle has one predicted high water value and one associated skew surge value. The advantage of using the skew surge for model validation is that it is a simple and unambiguous measure of the storm surge and that the effect of the meteorological forcing is integrated over a tidal cycle.

For storm surge model validation, non-tidal residual water level is calculated by subtracting the model total water level output from a tide-only run (i.e. no atmospheric forcing) of the same period. The tide gauge observations are processed in a similar way by subtracting a harmonic tide prediction from the gauge measurements. For both model and observational data, the skew surge is calculated by adding the residual onto the harmonic tide prediction, identifying the peak in water level at each tidal cycle, and comparing it to the expected tide-only peak level. It is worth noting that the observed skew surge values comprise both the genuine storm surge generated by the weather systems but also small, additional error terms related to imperfect tidal predictions.

Comparisons with observational data will usually take the form of a set of statistics, calculated monthly. The parameters of interest for sea levels are the correlation, the mean error (which can reveal model biases), the maximum error and RMSE. More concise verifications can be obtained via a specified skill score which normally takes the form of a ratio between the instantaneous model error and the departure from a reference or background value. An example selection of validation metrics (O'Neill et al., 2016) used to validate a new UK storm surge model was:

- Root mean square (RMS) error
- Mean error (bias)
- Maximum error—the largest error (positive or negative) that occurs anywhere in the time series
- Scatter index—defined as σE/σO where σE denotes the standard deviation of model-observation error and σO is the standard deviation of the observations. This provides an indication of the non-systematic error
- Normalised standard deviation σM/σO i.e. the ratio of modelled to observed standard deviation. This indicates how well the models represent the observed range of water level changes regardless of any overall bias
- Quartile-quartile (Q-Q) data
- Correlation coefficients

Figure 2 shows the use of Scatter Plots and Q-Q plots in the comparison of metrics at the Newlyn tide gauge in the UK from two storm surge models of the northwest European shelf (from O'Neill et al., 2016)

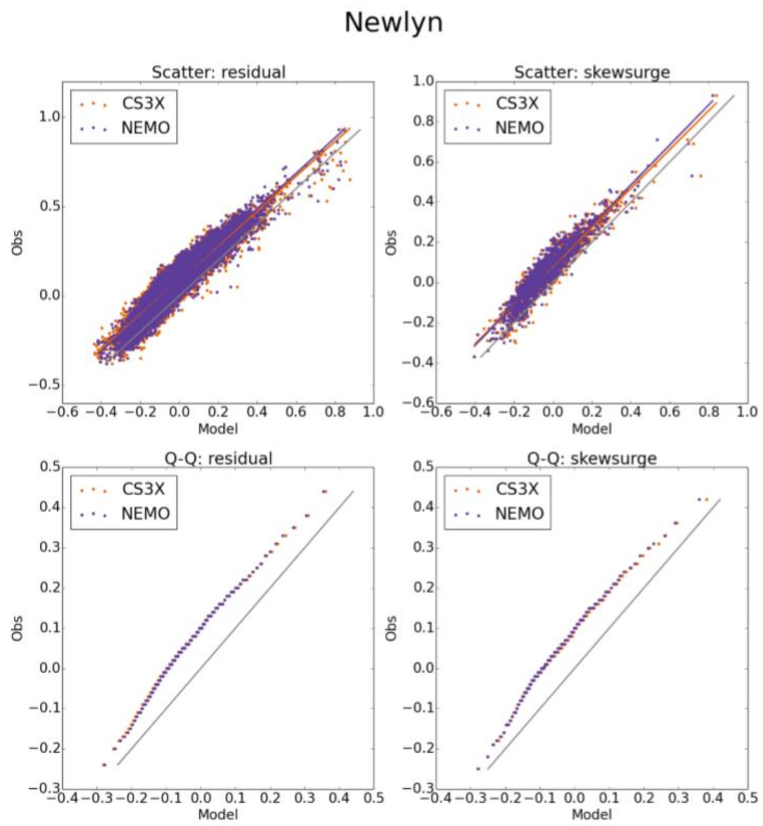

Figure 2. Comparison of NEMO and CS3X storm surge models at Newlyn tide gauge (UK). Scatter plots (top) and Q-Q plots bottom of the non-tidal residual (left) and skew surge (right) against tide gauge observations for one-year model run

The role of storm surge models in the ocean observations value chain

Storm surge forecasting is a perfect example of an end-to-end system for users of meteorological and oceanographic information in a complex value chain structure

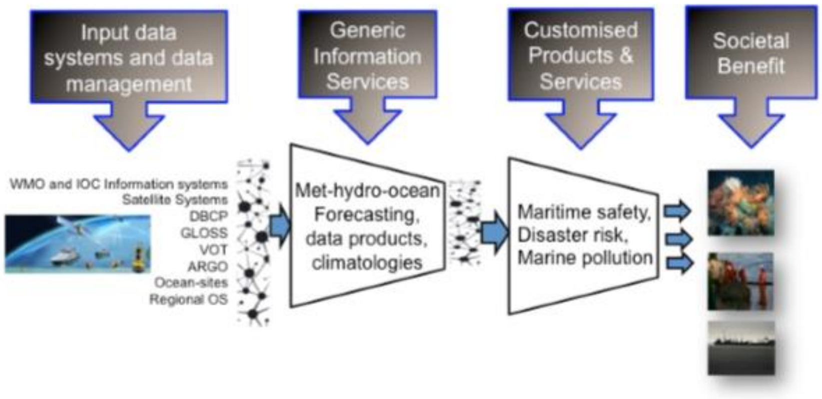

Figure 3. The metocean end-to-end system at multiple time and space scales and for multiple users (from Pinardi et al., 2018)

Internationally, the coordination of this complex value chain is performed by JCOMM which provides coordination of end-to-end systems, from ocean observations to metocean operational services such as storm surge forecasting (an overview of these activities is provided in a recent Ocean Obs' 19 White Paper, Pinardi et al., 2018). This flow of information in Figure 3 makes clear how ocean observations can be utilised in warning systems that deliver societal benefit. Models can be considered the 'value accelerator' for observations. Storm surge forecasting exemplifies the flow of tide gauge data along the value-added chain, from the collection and distribution of observations in near-real time and delayed mode, the production of generic data information products by modelling, to the further customization of such products for the final end-users to deliver societal benefit.

Atlantic tide gauge networks and capabilities

A tide gauge network for storm surge monitoring is of key importance in providing data to enhance the performance of operational hydrodynamic tide–surge models. Data can be used in the verification of the models and for data assimilation into them. Such a network clearly has to be capable of remote telemetry on a near real-time basis to be used operationally.

The need for sea level data within multi-hazard warning systems is not the only reason for sea level measurements. As well as long term scientific research into sea level rise (due to climate change) there are many practical reasons for such data, as outlined in IOC (2016). For example, major ports and coastal cities require sea level monitoring for operational reasons. The tide (and sea level in general) has always been an important factor in port operations. Standards for sea level measurement are set out by the GLOSS programme of IOC (IOC, 2012). Only through such a network (of sea level specialists as well as infrastructure) can best practice in sea level monitoring be transmitted around the world for adoption by national agencies within their own networks.

A requirement for a tide gauge in GLOSS is for it to be capable of measuring instantaneous sea level to better than 1 cm in all conditions of tide, waves, currents, and weather. There are fundamentally four types of measuring technology in routine use (IOC, 2006):

- A stilling well and float: where an enclosed well filters out high frequency wave signals
- Pressure systems: where sub-surface pressure is monitored and converted to height
- Acoustic systems: where the transit time of a sonic pulse is used to calculate distance to the sea surface
- Radar systems: similar to acoustic transmission, but using radar frequencies.

There are practical constraints that govern the choice of an instrument for a particular application (IOC, 2006). These include cost, degree of difficulty of installation, ease of maintenance and repair, availability of real time communications, engineering skills and capabilities required, etc. Whilst many North Atlantic countries have highly developed sea level networks which are used (amongst other things) for storm surge model validation, other Atlantic countries, particularly in West Africa and South America have not installed tide gauge technologies to the same level.

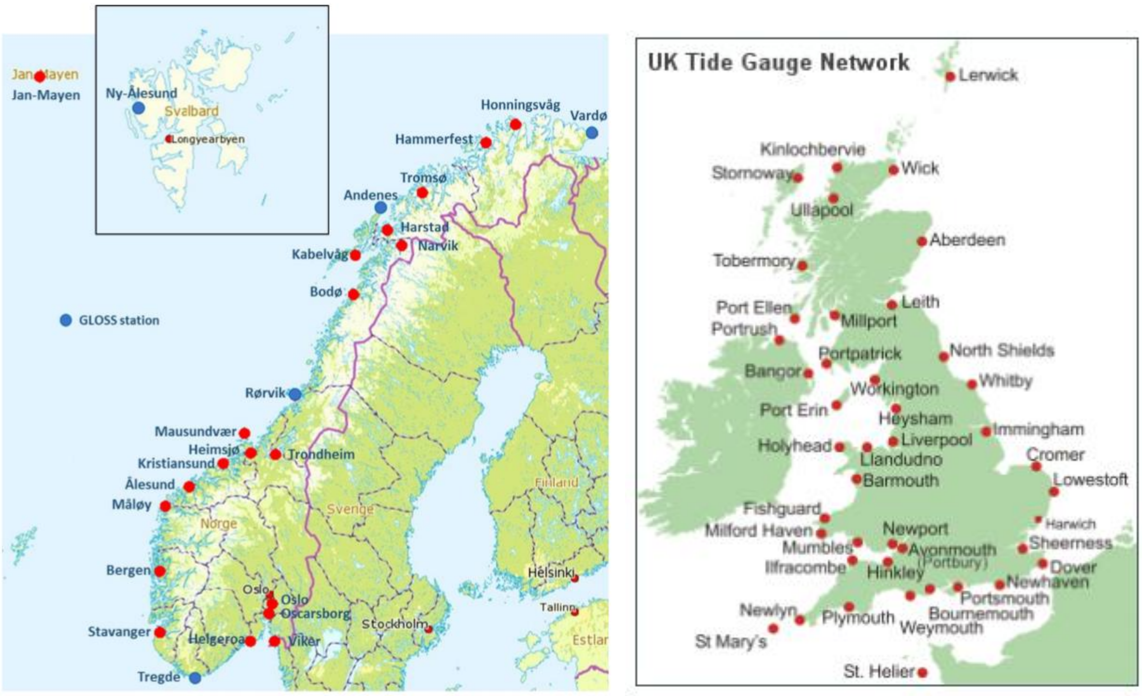

Figure 4. Examples of dense, well-instrumented tide gauge networks: Norway (left) and UK (right)

New technologies, radar in particular, are reducing the investment required to achieve GLOSS standard sea level monitoring. Radar tide gauges have some advantages over traditional systems in that they make a direct measurement of sea level. However, power consumption may be relatively large in radar systems if used on a continuous basis in a rapid sampling mode. This may limit its use in some applications (e.g. tsunami warning), but it is a very adequate tool for monitoring storm surges.

Sea level data acquired by a tide gauge may be required in near real time or in delayed mode depending on the application. For example, a storm surge or tsunami warning system may require the data to be transmitted to the competent authorities in a very short time. On the other hand, for some scientific research, it is often only necessary to recover the data annually. Real time transmission demands the installation and maintenance of reliable telemetry networks. A further requirement of the GLOSS system is that any tide gauge maintain an accurate level with reference to some geodetic network. High-precision levelling will need to be made between all the marks of the local network at regular intervals. For GLOSS purposes, the recommendation is that the exercise be repeated at least annually, with results fully documented by the responsible agency. The exact frequency of required levelling will depend on the geology of the area. For full detail see IOC (2006)

Tide gauge data gaps and mitigation actions under AtlantOS

Whilst tide gauge data are readily available from Canada, the USA and many European Atlantic coastline countries, the same is not true for countries surrounding the South Atlantic. A key deliverable from WP4 of AtlantOS (deliverable D4.1) was to develop a comprehensive South Atlantic sea level observing site catalogue (including sensors, benchmarks, maps and images) building on the IOC GLOSS Station Handbook and European Sea Level Service Observing Site specification. This new catalogue represents a first attempt at listing all tide gauge stations in the South Atlantic, Caribbean, Gulf of Mexico and a small section of Antarctica. The metadata these listings were created from are stored in a relational database for ease of update and querying. The beginnings of the catalogue came from the holdings of the Global Sea Level Observing System (GLOSS) data centres. There are several different data streams operated under GLOSS. These are:

- Sea-level monitoring facility (Flanders Marine Institute, VLIZ).
- Fast mode data centre (University of Hawaii Sea Level Center, UHSLC).
- Delayed mode data centre (British Oceanographic Data Centre, BODC).
- Mean Sea Level (Permanent Service for Mean Sea Level, PSMSL).

The listings of these data centres were interrogated to create a list of known stations. The next stage was to extract information from the National and Regional reports made to the GLOSS Group of Experts (GLOSS GE) meetings, as well as the data available from the GLOSS ODINAfrica project. The final stage was to make a web search for tide gauges and tide gauge networks in all the countries that bordered the areas of interest. When designing the catalogue, a decision was made to include hyperlinks for the more detailed fields such as benchmark information, as including all the descriptions in one field would make it very large. Where possible, links to originators' station documentation have been included: this should help the record stay up to date as changes won't be needed when originators update their information. The intention is now to update the catalogue at regular intervals through the forum of the GLOSS GE which convenes many of the tide gauge operators from the Caribbean and South America. This will keep momentum in increasing the availability of South Atlantic tide gauge data.

WP4 of AtlantOS (deliverable D4.2) also developed a harmonised data management plan for all Atlantic tide gauge data, including the Caribbean and Gulf of Mexico. This data management plan clearly specifies the steps required to ensure that tide gauge data are managed effectively from the point of collection through real-time transmission, automatic near-real-time quality control and availability, to delayed mode, scientifically quality controlled data. The same work also implemented delayed mode quality control, documentation and secure archiving of data from 47 South Atlantic tide gauge sites to unify the quality of

Atlantic sea level data (for full details see AtlantOS D4.2). Over the last 10 years there has been an increase in the number of tide gauges providing near real time data, but resource constraints have meant that these data are not undergoing quality control and thus are not being delivered to some of the GLOSS data centres. As part of AtlantOS WP4, these data were quality controlled to international standards (e.g. Reverdin et al., 2017) by experienced data managers at the GLOSS delayed mode data centre. The screening process included:

- Producing a tidal analysis and comparing M2, S2, N2, K1, O1, and Z0 constituents with previous data series, adjacent sites and the Admiralty Tide Tables for the closest site
- Looking for spikes, gaps, timing errors and datum shifts
- Comparing with previous series from the same site
- Comparing with neighbouring stations covering the same period
- Other parameters, such as sea temperature and atmospheric pressure, can be displayed at the same time to aid quality control
- Checking the statistics produced, i.e. mean sea level, with those produced in previous years

High frequency data from the work will be made available through the GLOSS delayed mode data centre (www.bodc.ac.uk) and monthly and annual mean sea level data will be available to download from PSMSL (www.psmsl.org). As well as being available for the validation and improvement of new storm surge models in the region, these data serve multiple purposes. Long term series of sea level data are rare and unrepeatable measurements. They make an important contribution to climate science (sea level rise), oceanography (changes in currents, tides and storms surges) geodesy (national datum) and geophysics and geology (coastal land movements). Data from PSMSL are used in all the Intergovernmental Panel on Climate Change(IPCC) assessment reports. The data identified through AtlantOS WP4 contribute to several of the IOC vision and High-Level Objectives (2014-2021) such as creating effective early warning systems, preparedness for coastal flood incidents, and increased resiliency to climate change and variability.

Concluding remarks

The impact of storm surges will continue to increase under rising sea levels. Mean sea level rise will continue to be the dominant control on trends in future extreme water levels and coastal flooding. The IPCC Fifth Assessment Report of Working Group I (IPCC, 2013) concludes that it is very likely that there will be a significant increase in the occurrence of future sea level extremes by 2100, with the increase being primarily the result of the increase in mean sea level. Whilst the observational evidence is still inconclusive, possible future changes in weather patterns may further influence likelihoods of severe storm surges through changes in the frequency and severity of severe weather. Any increase in extreme sea levels will result in critical flood defence thresholds being reached more frequently and therefore the risk of flooding will increase. Consequently, we require consistent baseline systems for storm surge monitoring at the national and regional levels for the development of effective warning systems, as well as for robust coastal planning and adaptation.

High quality tide gauge data form the basis of such a system, and for the Atlantic (and surrounding marginal seas) the current availability of tide gauge data is variable in both extend and quality. Several countries in Europe, and also the USA and Canada, provide high frequency sea level data which are valuable scientifically and also in support of operational storm surge forecasting systems – these being run by their respective national meteorological agencies. It should be noted that in most cases, operational storm surge forecasts require an harmonic tidal prediction to be added to a model-derived storm surge prediction. This approach is necessary wherever the complexity and range of the tide is not amenable to accurate tidal modelling, and is used in the UK, Germany and in the US for official hurricane storm surge predictions. High quality tide gauge data are equally essential for the production of these tidal predictions and for a complete understanding of any errors therein (and see Williams et al., 2018 for a good description of tidal error analysis). Many of the activities of AtlantOS WP4 have (1) improved the availability of sea level data across the Atlantic in previously data-poor areas and (2) highlighted the need to continue international efforts in this endeavour.

The GLOSS Group of Experts has submitted a community white paper abstract to the OceanObs'19 conference which will outline a forward looking plan for the GLOSS programme. The conference has the main goal of developing, "effective strategies for a sustained, multidisciplinary and integrated ocean observing system, and to better connect user communities and observers". The white paper provides the agreement and the framework for future improvements to Atlantic tide gauge data.

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