'OCEANS AND LAKES'

INTERUNIVERSITY MASTER IN MARINE AND LACUSTRINE SCIENCE AND MANAGEMENT

Quality Control of Sea Level Variation Observations and Tidal Predictions Based on the IOC Sea Level Station Monitoring Facility

Literature Review

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February, 2018

Thesis literature review submitted in partial fulfillment for master degree in Marine and Lacustrine Science and Management

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List of Acronyms

BODC – British Oceanographic Data Centre

D-M – Delayed mode information of data delivery

GCN – GLOSS Core Network

GLOSS – Global Sea Level Observing System

IOC – Intergovernmental Oceanographic Commission

IOTWS – Indian Ocean Tsunami Warning System

MSL – Mean Sea Level

PSMSL – Permanent Service for Mean Sea Level

RQDS – Research Quality dataset

RT – Real (near-real)-time data delivery

RTQC – Real time quality control

RSL – Relative Sea Level

QC – Quality Control

TGBM – tide gauge benchmark

TOGA – Tropical Ocean Global Atmosphere

TSLC – TOGA Sea Level Center

UHSLC – University of Hawaii Sea level Centre

VLIZ – Flanders Marine Institute

WOCE – World Ocean Circulation Experiment

1. Introduction

The notion that oceans are not static, but that the waters are continuously moving has been around since primordial civilizations. Archeologists were able to date the interaction of mankind and tides to approximately 2000 BC, through evidence of a *tidal dock* in the Gulf of Cambay (Cartwright, 1999). In addition, the connection between the moon and tides was documented by early philosophers in the Roman, Greek and Babylonian history, and can be found in many beliefs and superstitions of ancient sailors communities (Cartwright, 1999; Rappoport, 2012).

The science of sea level measurements and tidal observations had significant breakthroughs along the 18th, 19th and 20th century, developing with the emerging technology. Many coastal countries are experienced in controlling sea level measurements with tidal gauges, especially to monitor Mean Sea Level (MSL) and flooding protection purposes (Pugh, 1987). For example, regular measurements of sea level height have been done since 1682 and 1704 in the Netherlands and Scandinavia, respectively (Van Onselen, 2000). The Permanent Service for Mean Sea Level (PSMSL) holds long-term series of monthly and annual MSL for over a thousand stations worldwide, with the longest record being from 1806 from the Brest Station, France (IOC, 1985). In a higher sampling frequency, real and near-real-time sea level observations are registered at the Intergovernmental Oceanographic Commission (IOC) Sea Level Monitoring Facility.

The sea surface height can be explained as a superposition of tides, meteorological surges and the mean sea level (Weisse et al., 2011). Each of the components has different studies and applications. While the MSL is mainly studied through a long-term series, regarding the rise or subduction of sea level; meteorological residuals are applied in coastal defence projects and warning systems, which rely on near real-time or real-time measurements. The importance of continuous sea level monitoring is reflected in the growing number of worldwide projects and studies, which aim to build a global network of sea level observation.

2. Sea Level Variations

According to IOC (1985) the observed sea level can be decomposed in three main components: Mean sea level, described as the average of hourly values of sea level measured for at least a year; Tides, characterized by its periodicity, the tidal component is resultant of the gravitational attraction and rotation of the system earth-moon and earth-sun; And the meteorological residuals, or surge residual, which are the irregular non-tidal variations of the sea level caused by climatic fluctuations. Wind waves also influence the height of the sea surface; however this effect is usually filtered out in the measurements (Weisse et al., 2011).

The variations in the height of sea surface occur in a broad spatial and temporal spectrum (Weisse et al, 2011). The different periods and wavelengths of the variations can be linked to the source of energy. While the relative sea level is mainly affected by waves (Figure 1), with perturbations noticed in a window of seconds to days, significant changes in the MSL occurs in a lower frequency range and in a long-time scale. The latter refers to geological and long-term temperature changes, such as vertical land movements, ice melting and thermal expansion of sea water, all which cause a slow variation of the sea surface height (IOC, 2006; Pinet, 2009; Weisse et al., 2011).

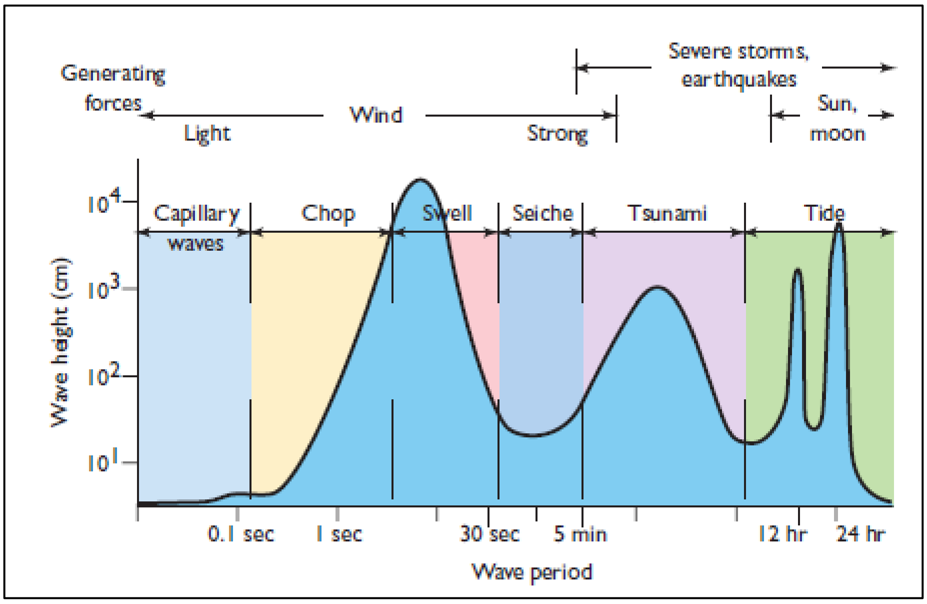

Figure 1. Spectrum of Sea Level Variations. Long-period variations (days to decades) belong to the low frequency range, and are not present in the illustration (Source: Pinet, 2009).

Waves are the main mechanisms disturbing the sea surface height. However, according to the generating forces and the amount of available energy, different waves can be formed (Figure 1). Surface waves can be generated by wind, severe storms and earthquakes or by the gravitational attraction between Earth-Moon-Sun. The former can generate different types of waves depending on the intensity of the wind, while the latter is the generating force of tides. Severe storms and earthquakes generate storm surges and tsunamis.

Starting with a calm wind over the water, the first waves to form are the capillary waves. These are small turbulent fluctuations in the sea surface, with surface tension being the major restoring force (Weisse et al., 2011). The intensity of the perturbations is proportional to the strength of the wind. With increasing speed of the wind, the height, wavelength and period of the capillary ripples also increase, and gravity becomes an important restoring force. When gravity replaces surface tension as the major restoring force, gravity waves are generated. While capillary ripples have wavelength shorter than 2 cm and period up to 0.1 seconds, surface gravity waves can be larger than 10 cm and last until 30 seconds. The differences between capillary and surface gravity waves are reflected in their speed: Whereas the speed of surface gravity waves increase with wavelength, the speed of capillary waves decreases with wavelength (Weisse et al., 2011). Surface gravity waves can still be subdivided in chops and swell. Apart from the different period (1-10 sec and 10-30 sec) and wavelength (1-10 m and up to hundred meters, for chops and swells, respectively), the main difference between chops and swell is the causing force: Although both are caused by winds, chops are the result of local winds, while swells are originated from distant storms (Pinet, 2009).

While chops and swell generate oscillations of 1 to 20 seconds, seiches and tsunamis range from minutes to hours. Seiches are standing waves, with wavelength ranging from meters up to hundreds of kilometers, which can be generated by wind, tsunamis or tidal resonances. They usually occur in closed and semi-enclosed coastal areas, such as bays, estuaries, lakes and habors. Seiches are characterized by the back and forth movement of the water, causing the water level to rise at one side of the basin, while the opposite side has a drop in water level (Pinet, 2009). Tides are the waves with the longest period, centered on 12 and 24 hours, and meteorological effects can last for several days. Tides, tsunamis and storm surges will be further discussed in the following sections.

2.1. Tides

The response of the ocean to the gravitational attraction of the Sun and the Moon is a rhythmic rise and fall of sea level, named tide (Open University, 1999; IOC, 2006). In reality, the high and low of sea level is the movement of the tidal wave, the longest wave in the ocean. The rising and falling of a tidal wave is referred to as flood and ebb tide, respectively (Open University, 1999). Another important characteristic of tides is that they propagate as a shallow-water wave, thus their speed varies in function of the local water depth and gravity acceleration (Pinet, 2009).

When analyzing a record of sea level measurements, two important features of a tidal wave can be recognized: the tidal range, which is the height difference between a consecutive high and low level; and the tidal period, the time difference between one low (or high) and the next low (or high) level (Pugh, 1987). Those are the result of the well defined periodicity of the tides, which also allows for the easy identification of tidal movement in sea level records (Open University, 1999). The regular period and range of tides make it possible to predict their behavior.

It is possible to classify tides as diurnal, semidiurnal and mixed regimes in function of its periodicity. Figure 2 illustrates the different tidal patterns that can be found around the word. Most of the coasts are dominated by a semidiurnal tide, which has a tidal cycle of approximately 12 hours and 25 minutes (e.g. Kilindini and Bermuda, Figure 2). In such locations there are, usually, two lows and two highs tides in a day. In a few places, like the coast of Karumba (Australia), the tide has a period of approximately 24 hours with only one high and one low tide in a day, characterizing a diurnal tide. Other coasts, like the case of Musay'id (Persian Gulf), have a mixed regime, where the diurnal and semidiurnal components have similar magnitude, and their relative importance changes through the month (Pugh, 1987).

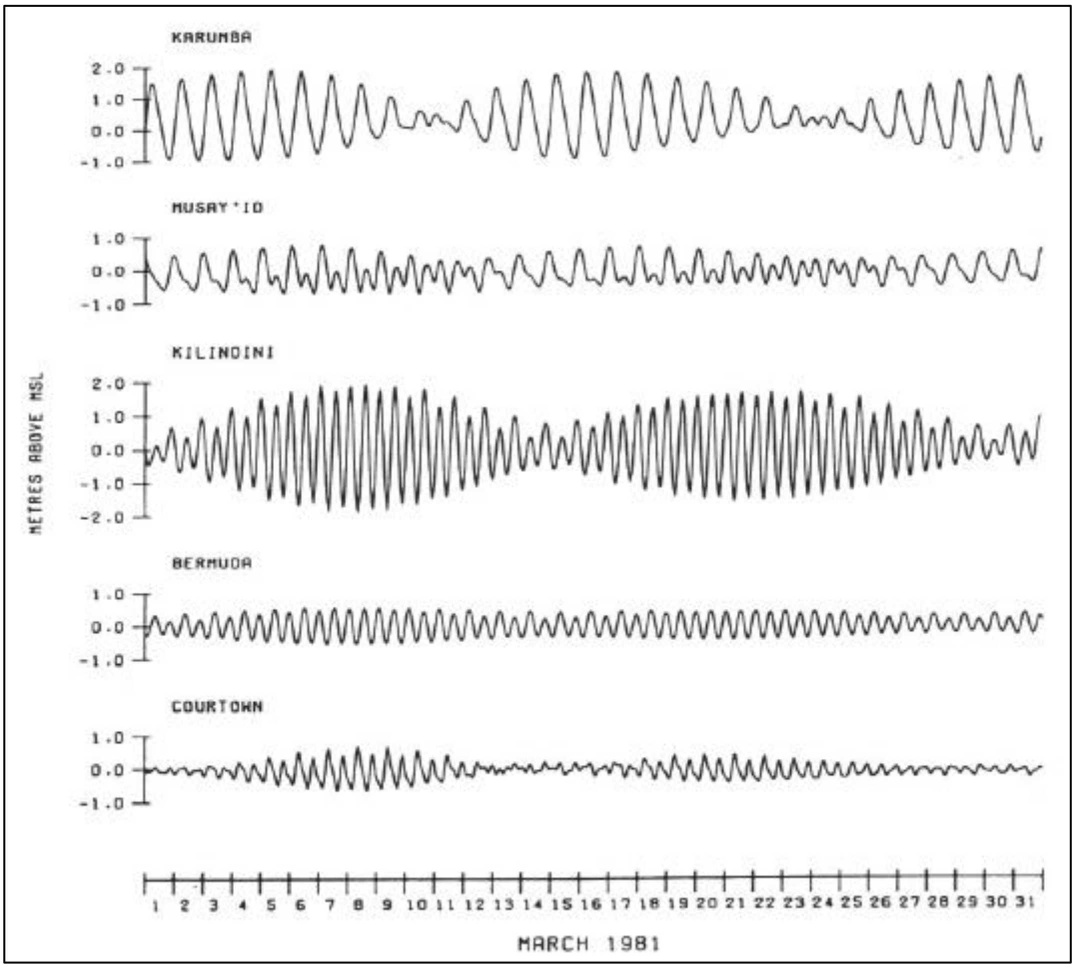

Figure 2. Tidal levels at five stations, showing the different tidal regimes that can be found around the world. Karumba (Australia) has a diurnal tide, Musay'id (Persian Gulf) has a mixed tide, and Kilindini (Mombasa) and Bermuda have a semidiurnal regime. Courtown (Irish Sea) is an example of tidal distortion due the shallow water effects. (Source: Pugh, 1987; IOC, 2006).

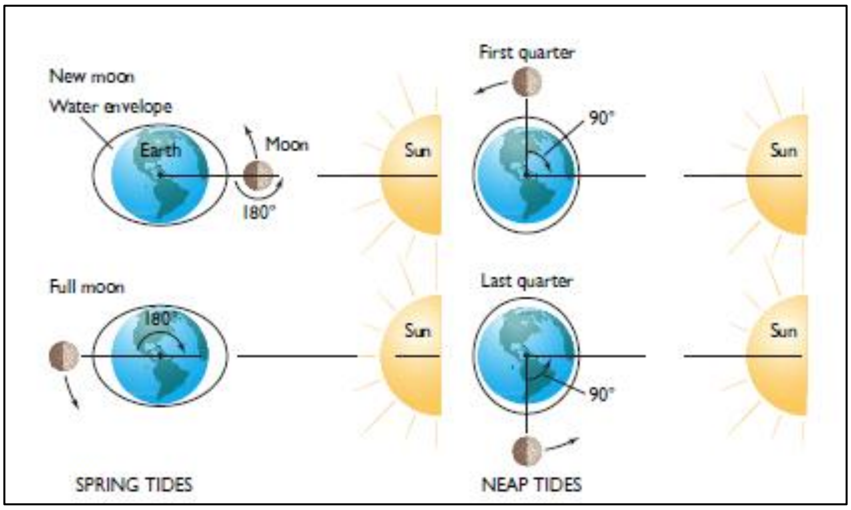

Figure 3. Effect of the Moon phases on tides. During new and full Moon, the alignment of the Moon and Sun result in spring tides. During the quarter-moons, the Sun and the Moon form a 90° resulting in neap tides. (Source: Pinet, 2009).

A fourth case is illustrated in Figure 2 for the city of Courtown (Irish Sea). When the tides reach relatively shallow waters, the tidal pattern can suffer strong distortions (Pugh, 1987). The shallow waters of the Irish Sea interact with the tidal propagation, creating a tidal range of more than a meter during spring tide. On the other hand, during neap tide the tidal range is of a few centimeters. The tides on some coasts along the English Channel, the Dutch coast and the North Sea also suffer from shallow water distortions.

Regarding the tidal range, another pattern can be noticed. Every fourteen-day period, the tides increase and decrease cyclically. This variation is directly related to the phase of the Moon, and its position in relation to the Sun (Figure 3). When there is full and new Moon, the Moon and the Sun are aligned, in a way that both tide-raising forces act constructively. This results in maximum tidal ranges, referred as spring tide (syzygy). During the quarter-Moon phases, the Moon and the Sun form a 90° angle, resulting in a destructive interference of the forces. Thus, the tides reach minimal tidal ranges, characterizing a neap tide. The relationship between tides, Moon and Sun can be explained through the Equilibrium Model of Tides. Good discussion of such model can be found in Pugh (1987), Open University (1999) and Pinet (2009), among other works.

2.2. Meteorological Residuals

When the tidal pattern is removed and the slow changes in the MSL are neglected, the meteorological residuals are the remaining disturbances on sea level measurements (Horsburgh & Wilson, 2007). Also known as non-tidal components, the residuals include storm surges and tsunami events, with significant rise and drop of sea level height (Weisse et al., 2011). Opposite of tides, they are irregular, unpredictable and associated with destructive events. Thus, the understanding of residuals and their interaction with sea surface height is extremely important.

Storm surges refer to the response of the sea level to intense meteorological conditions (Horsburgh & Wilson, 2007). Strong winds and atmospheric pressure act on the sea surface, transporting large water masses away or towards the coast. While the latter is responsible for an increase in sea level height and is known as positive surges, the former causes a decrease in sea surface height and is called negative surge (Weisse et al., 2011). Usually, the most destructive positive storm surges are associated with tropical cyclones, such as Hurricane Katrina and Irma (Weisse et al., 2011). Although storm surges have a variable range of spatial and time scale, they usually last for a few hours and reach about 50 km. When related to extra-tropical storms, the surges have larger and longer scales (Talley et al., 2011). Storm surges differ from other wind-generated waves (chops and swell) by the period of the oscillations (Dube, 2002).

Another important mechanism influencing sea level height in coastal areas is tsunamis. This low-frequency ocean waves are generated by sudden shifting of the sea bed, such as submarine earthquakes and landslides, and characterized by having very long wavelength, around hundreds to thousands of kilometers (Steward, 2002). This special feature of tsunamis makes them behave as shallow-water waves, even though they are generated in deep waters. As a shallow-water wave, the speed of propagation is a function of local water depth (Talley et al, 2011). Therefore, they can travel thousands of kilometers in short time periods, being unnoticeable in deep waters. Another special remark about tsunamis is that they spread radially from the origin point, thus one seismic event can generate tsunamis that reach different continents. When they get to coastal waters, their velocity suffers a relative strong decrease, while their height increases. Tsunamis can be greater than 10 meters high, leading to catastrophic events (Pinet, 2009). After the extensive damages of the 2004 Indian Ocean tsunami, efforts rose to learn more about these waves, and how to minimize their destructive effects. As a result, regional warning systems were built, and coastal defence strategies are growingly being included into policies.

2.2.1. Previous Works

Extreme sea level has always been a hazard for coastal areas, especially for low lying countries such as those bordering the Southern North Sea. Regarding this issue, Weisse et al. (2011) presented a review on the available knowledge of extreme sea level hazards and protections in the Southern North Sea. The authors concluded that past works have focused on understanding the different factors that cause sea level variations and how their interaction leads to extreme sea levels. However, there is still a lack of knowledge on the long-term variations and potential future changes of sea levels. According to the review, future studies should comprise improving the understanding of past changes in extreme sea levels, and assessing potential future regional changes and their consequences. Also, the variability of the changes should be incorporated in defense plans, resulting in flexible adaptation strategies to cope with extreme sea levels.

Regarding storm surges in the North Sea, an interesting study was presented by Horsburgh & Wilson (2007). The authors used data from five tide gauges along the North Sea coastline of the UK to investigate the tide and storm surge interaction. They showed that the highest meteorological residuals and the highest tidal levels do not occur simultaneously. On the contrary, the astronomical high water prevent the generation of local surges. The meteorological residuals are affected by the tidal state and are predominant during the rising tide. The authors suggest that flood risk and coastal management plans should recognize the dependence of tide and surge, and change the misconception that tide and surges can be coincident.

Fanjul et al. (2001) presented Nivmar, a storm surge prediction system for the coast of Spain. The system uses as a base the ocean circulation Hamsom model and harmonic tidal predictions calculated from a regional tide gauge network, Redmar. Besides being used to predict tidal elevations, the tide gauge information is used to validate the system and perform data assimilation, correcting possible errors of the model. The authors used 5 months of sea level data to validate the system. Results showed that the sea level predictions from Nivmar are correct and reliable. In addition, it also pointed out the importance that tidal gauges information can have to add accuracy in a storm surge forecasting system. In another research, Staneva et al. (2016) also discussed methods for reducing the uncertainties in storm surge models. Although the authors focused on using a wave-dependent approach to improve the model, they also mentioned the possibility and importance of using in situ sea level measurements to improve the forecasting.

The Indian Ocean tsunami of 2004 was a disaster of great magnitude, which showed the emerging need for tsunami warning systems, not existent at that time. (Merrifield et al., 2009). After this event, the Global Sea Level Observing System (GLOSS) project added to their aim the development of the Indian Ocean Tsunami Warning System (IOTWS). Their tidal stations became essential components of other tsunami warning networks, such as the ones in the Pacific, Caribbean, Northeast Atlantic and Mediterranean (GLOSS, 2012). Although there was no tsunami warning system in the region in 2004, there were already a number of tide gauges installed by national and international organizations. Merrifield et al (2005) and Leonard (2006) presented analysis of the tsunami recordings by the tide gauges. The authors showed that, even with data being transferred only at hourly frequency, early warnings could be generated from one station to the neighbouring locations. However, when planning a tsunami warning system, real-time transmission is an important requirement.

The existing tide gauges in 2004 had sampling intervals from 1 to 10 minutes. Leonard (2006) was able to show that sampling rates longer than 4 minutes are not representative of the tsunami waveform. On the other hand, sampling rates of 1 minute successfully recorded the main features of the tsunami. Stations that had a sampling interval of 2 minutes were adequate to register the amplitude of the tsunami. Moreover, the author recommended that for the purpose of tsunami warning, tide gauges should have a maximum sampling rate of 1 minute, and that at least 4 samples per minute is required for modeling purposes.

3. Measuring the Sea Level

In situ measurements of sea level are conventionally collected from a tide gauge, which records sea level height in relation to a fixed point, namely a tide gauge benchmark (TGBM) (Van Onselen, 2000). Therefore, a tide gauge records the relative sea level (RSL) and not the absolute sea level. RSL provides information of the local sea level change, which will determine the risk of flooding of a coastal community (Holgate et al., 2013). Thus, it is a very important measure for society. Besides the real variation of water level, the RSL signal is also affected by vertical land movement (Zerbini, 2000). Local crust displacements can be caused by tectonic events, oil and groundwater extraction, among others. GPS systems installed at the tide gauge stations can be used for monitoring vertical crustal shifts. Such technique allows the removal of datum shift’s influence on sea level data (Zerbini, 2000).

Historically, sea level observations were collected from float tidal gauges with analogue charts. With the advance of technology, new measuring methods were developed. Nowadays, in addition to the basic float gauge, pressure, acoustic and radar systems are new technologies used for measuring sea level. According to IOC (2006), current sea level stations around the world use one or more of the following measuring technologies:

1. Acoustic Gauges: Acoustic systems calculate sea level height based on the travel distance of a sonic pulse. They can be positioned directly in the open air, inside a protective well, or attached to a sounding tube;
2. Pressure Gauges: Pressure systems convert the subsurface pressure into water height. They can be subdivided in pneumatic bubbler gauges, sensor gauges with a single or multiple transducers, and pressure transducers in stilling wells;
3. Float gauges in a stilling well: This system determines the sea level in relation to the length of the float wire to the benchmark. The stilling well allows for filtering of the waves;
4. Radar Gauges: Radar technologies use the transit time from a pulsed radar wave to compute the distance to the sea surface.

More detailed information on types of tidal gauges can be found in Manual II, IV and V for Sea Level Measurement and Interpretation (IOC, 1985, 1994, 2016).

Apart from the *in situ* measurements from tide gauges, sea level can also be obtained via satellite altimetry. While tide gauges provide a local signal of the coastal sea level, satellite altimeters supply sea level data with a global spatial coverage (Vinogradov & Ponte, 2011). Another significant difference between the two methods lies on the type of sea level provided. As explained before, tide gauges measures the relative sea level. In comparison, the altimeter data gives the geocentric, or absolute, sea level height (IOC, 2016). Notwithstanding the difference, there is a high correlation between the two types of sea level data (Vinogradov & Ponte, 2011), allowing the use of the altimeter information for quality control of the tide gauge measurement, and vice-versa (Leulietteet al., 2004).

According to Woodworth et al. (2017), different types of sea level datasets can be obtained in relation to frequency and latency. On one side of the spectrum there is very high-frequency data, with sampling intervals of minutes or less. This data is used for the detection of rapid processes, such as tsunamis, storm surges and seiches. For such purpose, the data is delivery in real (or near-real)-time (RT), with no time for quality control. On the other side of the spectrum, there is low-frequency datasets, which regards sampling intervals from 6 and 15 minutes to 1 hour. This information is delivered in a delayed-mode (D-M), allowing for complete and quality control of the data. The D-M data ensures scientific research quality, and can be used for studies of storm surges, ocean tides, extreme sea levels, among other coastal processes. The PSMSL calculates the monthly and annual MSL from the hourly values of sea level. The mean values are used for studies on the variability of sea level in a longer time scale (decadal to secular), and to derive sea level rise curves (Van Onselen, 2000). Data can also be delivered in a fast mode, within days to weeks of the measurement, passing by a small quality control. Such data can be used for satellite altimetry validation, among other purposes.

3.1. Global Sea Level Networks

The 1980s and 1990s were marked by the expansion of *in-situ* sea level data acquisition and management (Rickards & Kilonsky, 1997). Major regional and global sea level databanks developed during those years, evolving to the present GLOSS. In the 80s, the World Climate Research Programme introduced the Tropical Ocean Global Atmosphere (TOGA) project, with the University of Hawaii Sea Level Centre (UHSLC) being an important actor of it (Woodworth et al., 2017). In 1985, the project resulted in the TOGA Sea Level Center (TSLC), which had a broad spectrum, covering sea level studies in the tropic Pacific, Indian and Atlantic oceans.

Also in the 80s, the IOC started the development of GLOSS. The initial aim of the project was to gather information of sea level, and supply monthly mean sea level to PSMSL and other international programmes, like the World Ocean Circulation Experiment (WOCE) (Merrifield et al., 2009). The main centers responsible for handling the sea level information of WOCE was the UHSLC and the British Oceanographic Data Centre (BODC) (Rickards & Kilonsky, 1997). While the latter acted as a ‘delayed data centre’, providing research quality controlled data after months to years of the data collection; the former acted as a ‘fast data centre’, providing minimal quality controlled data after weeks to months of the data collection. Both centers already had experience with collecting, processing and distributing sea level data before the implementation of WOCE, and continue up to today to perform these activities, but now in cooperation with GLOSS.

GLOSS was a successful project, expanding from its original purpose to form a worldwide tide gauge network (Holgate et al., 2013). The programme also set technical standards for the installation of tide gauge stations, apart from providing training and guidance in the topic. Currently, the network is composed of around 300 stations worldwide, called the GLOSS Core Network (GCN) (GLOSS, 2012). Expanding from the GCN station and regional tsunami warning networks, the IOC Sea Level Station Monitoring Facility was formed, hosted by the Flanders Marine Institute (VLIZ , Belgium). This network provides real time sea level measurements from, currently, 879 stations around the world. The information collected is transferred to the UHSLC and BODC, responsible for Research Quality dataset (RQDS) and D-M quality control, respectively (Woodworth et al., 2017). While the real-time data processing and storing is carried out by VLIZ , the long-term quality controlled sea level records is handled by the PSMSL.

3.2. Measurements Quality Control

Quality Control (QC) is necessary to maintain common standards and allow consistency and reliability of archived data (BODC, 2007). In relation to real-time data, QC ensures credibility and value of the data (IOOS, 2016a). The quality of the data can be a subjective issue, as it depends on the purpose of its use (Emburi, 2004). For example, data points used for the studies of tsunamis and storm surges would be smoothened out for the study of tides and sea-level rise, thus the definition of high quality data for such studies would be different. In conclusion, bad data should not be deleted from the original dataset, but tagged with a quality flag, so that the final decision to use the data is up to the user.

The level of QC is expressed in data quality flags. These flags indicate the reliability of the data, and should always be mentioned in the metadata to ensure consistency and reliability of the data (IOOS, 2017). An important practice during QC is that a flag should not override the information from a previous test (IOOS, 2016b).

Sea Level QC can be divided in three levels: Real-time Quality control (RTQC); Level 1 (after 1 hour to 1 month); and Level 2 (months to years). Level 1 and 2 of the IOC Sea Level Stations is performed by the UHSLC and the BODC, respectively.

For tsunami monitoring systems, sea level data need to be provided in real time, without delays. For such purposes, RTQC is minimum (IOOS, 2016b). When programing automatic RTQC, it is important that out-of-range checks do not remove real events, such as tsunamis. Thus, only a few checks to detect the functionality of the tide gauge are applied in the RTQC (IOOS, 2016b). Near-real time QC (RTQC1) is applicable within hours to a maximum of a week from the acquisition of the data, and is highly recommended (IOOS, 2016b). It consists of a series of checks in the raw data, such as detection of spikes, gaps, out-of-range values and stability checks (GLOSS, 2011). The raw data is kept and flagged according to those tests. After the tests, the suspicious values can be removed and a new “clean” dataset is created with interpolation methods, if necessary. The new dataset, consisting of the interpolated series, is the one considered for the next QCsteps.

The second level of data processing (RTQC2) consists of tidal analysis, computation of harmonic constants, calculation and inspection of residuals, identification of extremes values and the generation of daily, monthly and annual means (GLOSS, 2011). This “additional” level of QC is highly desirable (IOOS, 2016b). Usually, for such treatments at least one year of data is necessary, and hourly values are used. Additional checks, such as comparison with models, predictions and neighbouring tide gauges should be done in this stage (BODC, 2007).

3.3. Applications

Sea level height is an extensively used oceanographic parameter (Merrifield et al., 2009). Besides the growing interest in sea level height due to sea level rise and climate change, the observations are also important for the understanding of ocean dynamics and tides (Rickards & Kilonsky, 1997; Van Onselen, 2000).The latter is an essential factor influencing marine and geological processes (Pugh, 1987). For practical purposes, the continuous monitoring of sea level is applied in coastal defence projects, such as coastal erosion protection and tsunami and storm surge warning (Holgate et al., 2008).

Coastal tide gauges have been the main technique used for sea level measurements during the past century (Rapper, 2000). Initially used for the construction of tide tables and assessment of flooding risks, the continuous sea level measurements can also be used for studies on ocean transport, currents and circulation, trends in sea level variations and the impacts of sea level rise (Ali Khan & Rabbani, 2005; GLOSS, 2012; Holgate et al, 2013). In addition, the sea level information can be used to give information of the local sea surface and to predict local sea level height (Fanjul et al., 2001). Another important application of tide gauge measurements is the calibration of satellite altimeters (GLOSS, 2012). All the possible applications of sea level data (including the one not mentioned previously) are inter-dependent, thus an efficient tide gauge station is able to provide information for all the diverse purposes (GLOSS, 2012).

Although not the main element of early warning systems for tsunamis and storm surges, tide gauges have recently become a part of such programs (Holgate et al., 2013). Following a seismic event, water level stations can be used to inform, in real-time, how the tsunami is developing (Merrifield et al., 2005). In addition, sea level measurements are extremely useful for the validation of tsunami models. Currently, automatic warnings are generated by the IOC Sea Level Monitoring Station Facility based on the tide gauges data.

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