TIDE GAUGE AND SATELLITE ALTIMETRY INTEGRATION FOR STORM SURGE PREDICTION

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ABSTRACT

Integrating coarse temporal sampling by the satellite altimeter in the deep ocean with the high temporal sampling at tide gauges in sparse location along the coast has been used to improve the forecast of high water in the North Sea along the Danish Coast and storm surges along the Northeast coast of Australia. Along with satellite altimetric data, we have tried to investigate high frequency signals (surges) using data from the past 20 years to investigate existence of ability to capture surges in the regions.

We have selected several representative high water events on the two continents based on tide gauge recordings and investigated the capability of the satellite altimeters to capture these in the sea surface height. On the European coast we find that when two or more satellites are available we capture more than 90% of the extreme sea level events.

In the Great Barrier Reef section of the Northeast Australia, we have investigated several large cyclones causing much destruction when they hit the coast. One of these being the Cyclone Larry, which hit the Queensland coast in March 2006 and caused both losses of lives as well as huge devastation. Here we demonstrate the importance of integrating tide gauges with satellite altimetry for forecasting high water at the city of Townville in North East Australia.

Key words satellite altimetry, sea level, storm surges.

1. INTRODUCTION

There is a vast difference between tide gauge and satellite altimetry in both temporal and spatial sampling patterns. Radar altimeters on board satellites measure sea level from a distance of 1000 km as well as wind speed and wave height over a 2 to 5 km radius.

The observations are confined along the ground tracks because of the fact that the satellite repeating the observations typically each 10 days. Tide gauges are fundamentally different which measuring in situ sea level each second to minute accurately at selected coastal locations.

However the data can be integrated to take advantage of the high temporal sampling of the tide gauges with the high spatial sampling of the satellite. Combining the data we have tried to investigate and detect storm induced high water signals in the two fundamentally different coastal regions prone to storm surges. One is the west-coast of Denmark in the North Sea and the other the Great Barrier Reef region in Northeast Australia for the past 20 years to investigate the ability of satellite altimetry to capture storm induced high water even hours to days in advance.

Exceptionally high sea level claimed many victims throughout the history of both Australia and the countries around the North Sea (Gill, 1982). The sea level variability in both the North Sea and Great Barrie Reef is dominated by ocean tides ranging. In the case of the North Sea it ranges above 4 m at some positions on the English east coast (Flather, 2000). The most important non-tidal contribution to sea level variations is weather induced surges which can act together with the tidal variations and cause flooding of the low lying regions on the coast. Surges are by nature much more difficult to predict than the tidal variations due to the dependence on the performance of the weather forecasts (Heaps, 1983).

Modern satellite altimeters have an accuracy which enables detection of surges both in terms of measuring the increased wind speed and wave height, but also in measuring the increased sea surface height. The ability to measure increased sea surface height is very important, as this parameter is a proxy for the vertically integrated heat content within the water column as this provides the reservoir of energy available to intensify a storm (Shay et al, 2000).

We have selected a tropical storm that hit the northeastern Australia in 2006 named cyclone Larry. This cyclone was not only very fierce but also limited in extend which makes it a challenge to capture from satellite altimetry. This investigation illustrates that we can capture the cyclone in sea level as well as the other parameters, but also that including the observation in a multi-regression model of the region leads to significant improved sea level forecasting at the tide gauge in Cape Fergusson (Townville).

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2. HIGHWATER IN THE NORTH SEA

The North Sea is a marginal sea to the Northeast Atlantic Ocean and surges normally propagate in a westerly direction from north of Britain and down through the North Sea until they hit the coast of Denmark. Figure 1 illustrates the location of the Hvidesande Tide Gauge recorder on the west coast of Denmark and the temporal variation of sea level at the gauge. We have computed the normal variation of sea level by computing the standard deviation of sea level – this is 49 cm - and then we marked all episodes where the sea level is higher than 2 times the standard deviation with green in Figure 1. Besides there are five episodes of sea level higher than 3 times the standard deviation that are marked with arrows.

The altimetric observations used here are taken from the Radar Altimetry Data System (RADS) in a special version where the satellite data has maintained the inverse barometer effects due to changes in sea level pressure in order not to remove part of the surge signal from the altimetry. This is also to be consistent with the water level recorders where the effects are also present. We have used available satellite altimetry data for the 1997-2001 period including the TOPEX/POSEIDON and ERS-2 satellites.

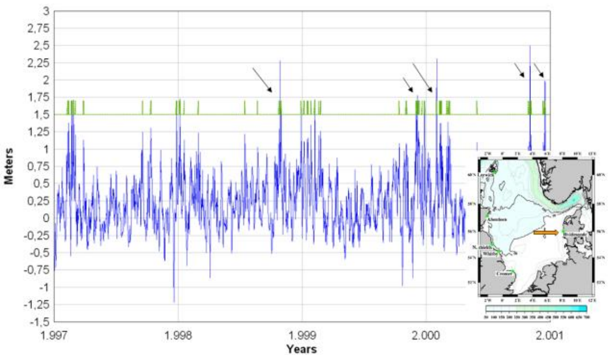

Figure 1. The location of the Hvidesande Tide Gauge recorder on the west coast of Denmark (insert picture) and the variation of sea level (in blue) at the gauge for the 1997-2001 period in meters. Episodes where the sea level is higher than 2 times the standard deviation is marked with green and 5 episodes of sea level higher than 3 times the standard deviation are marked with arrows.

The satellite ground tracks are shown in the inserted figure in Figure 2. Here the purple tracks illustrate the TOPEX/POSEIDON ground tracks and the red tracks illustrate the ERS-2 tracks. For each location along the satellite's ground track the four years of data were used to compute the standard deviation. This can be thought to represent normal conditions. Again we pick the instances where the altimeter-derived sea surface height is higher than two times the standard deviation. First we pick the data in the small box from TOPEX/POSEIDON and mark the instances of high water observed by the satellite altimeter. This is illustrated using the red line in Figure 2. It can be seen that this roughly captures half of the high water instances and three out of 5 of the instances of 3 times the standard deviation.

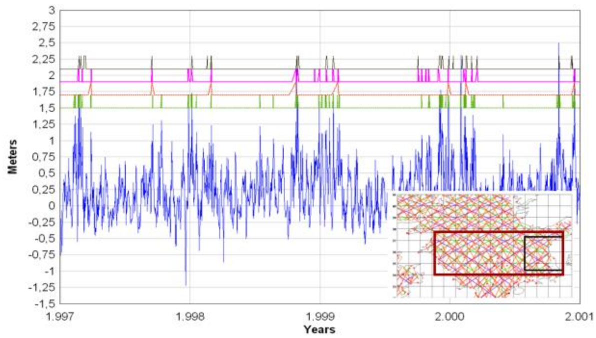

Figure 2. Tide gauge recordings (in blue) in Hvidesande for the 1997-2001 period in meters. Episodes where the sea level is higher than 2 times the standard deviation is marked with green. Episodes of high waver by the TOPEX satellite within the black box is marked in red. Episodes within the red box by the TOPEX satellite are marked with purple. Episodes of high water recorded by the ERS-2 satellite are marked with black.

The work by Høyer and Andersen (2003) showed that the surges propagate in a counter-clock rotation around the North Sea with a delay between Aberdeen at the northern mount of the in North Sea to Hvidesande. This is illustrated in Figure 3 which shows the temporal correlation between the tide gauge readings. We can consequently extend the box (in black) in Figure 2 to the extended box (in red) which should then capture the surge as it propagates across the North Sea in an easterly counter-clock rotation.

This is shown in purple in Figure 2. Several more instances are captured, but also a few ones that do not lead to high water in Hvidesande can be seen. However the TOPEX satellite only captures three of the 5 instances of 3 times the standard deviation or roughly 1.5 meters. As the propagation time of surge is 12 hours and the satellite repeats at 10 days with 6 tracks within the box we will have an observation from the TOPEX satellite roughly every 1.5 days which is why we do not capture all surges.

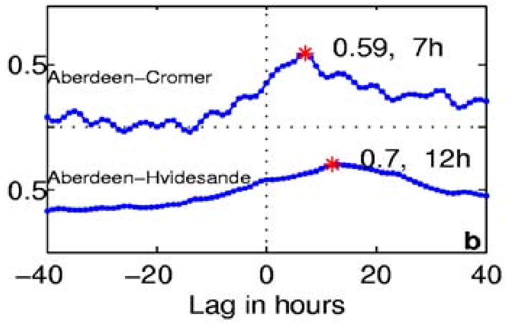

Figure 3. Cross correlation between the tide gauge in Aberdeen and the tide gauges in Cromer on the central east coast of Britain and the Hvidesande tide gauge in Denmark (scale 0-1). There is a clear 12 propagation time of the surge between Aberdeen at the northern mount of the North Sea to Hvidesande in Denmark.

Therefore it is important to include an additional satellite in the investigation. The result using the ERS-2 satellite is shown with black in Figure 2. It can be seen that all episodes of high water higher than 3 times the standard deviation is now captured. This illustrates the fundamental importance of having more than one satellite for capturing surges in the North Sea due to the speed and nature of the surges.

In the following investigation we have tried to capture a tropical cyclone in the north east of Australia. These tropical cyclones generally have larger footprint and longer period (up to ~7 days) than mid latitude storms, therefore they will be easier to capture from satellite altimetry as will be illustrated.

3. GREAT BARRIER REEF AND TROPICAL CYCLONE LARRY

Severe Tropical Cyclone Larry made landfall at the tropical north Queensland coast near Innisfail on Monday 20 March 2006. Figure 4 shows the track of Larry (top panel), photo-like image of Larry acquired by the Moderate Resolution Imaging Spectro-radiometer (MODIS) on NASA's Aqua satellite with an overlapped altimetry pass (Jason-1, pass 149 of cycle 154) on March 19 2006 (lower right panel) and altimeter along-track sea level anomalies and their standard deviations (lower left panel). The tropical cyclone low developed over the eastern Coral Sea and reached cyclone intensity during the early hours of 18 March and continued on a general westerly course towards the Queensland coast. Larry rapidly strengthened in the following 48 hours reaching hurricane-force intensity at 12:00 UTC 18 March and peaking at 56 m/s (110 knots) at 12:00 UTC 19 March as it marched gradually westwards towards the coast as also illustrated in Figure 4.

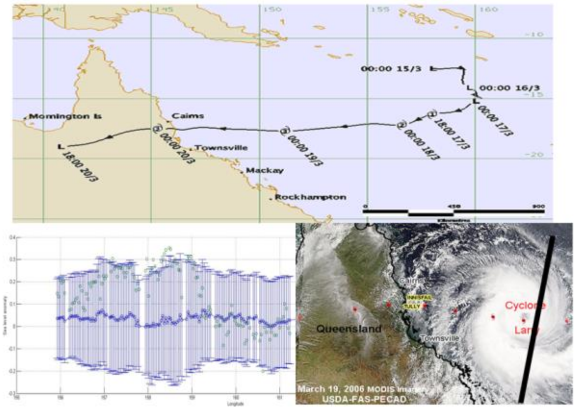

Figure 4. The tropical cyclone Larry that hit the Queensland coast in March 2006. The upper figure shows the path, category of Larry and the dates of the cyclone. The lower left picture shows the retracked sea surface height along the track overlaid the MODIS picture to the right. In the lower left figure, altimeter along-track mean sea level anomalies (SLAs) around zero are shown in blue circles, their 2 times standard deviations are shown in blue bars, and observed SLAs during the cyclone Larry are shown in green circles. Most observed SLAs are higher than 2 times standard deviations when satellite crossed the cyclone near longitude 158°E.

Figure 5 below illustrates the data available from the standard processed archives performed by the international space centers. Here altimetric tracks within 12 hours and 500 km of the tropical cyclone Larry are shown. The figure shows all three parameters derived from satellite altimetry: the sea surface height (left), wind speed and significant wave height (left pictures).

It is obvious that a lot of the data are missing. This is mainly caused by the heavy rain associated with the cyclone. This makes the satellite recording of power vs time (waveform) not looking like a standard Brown waveform and hence it is not retracked by marked as an error. However, the waveform can be illustrated using the Deng et al. (2012) waveform retracking system (reference). This is shown in the lower left part of the figure 4. The section shown in figure 4 corresponds to the track in Figure 5. The blue dots and lines marks the mean and two times the standard deviation of the sea surface height and the green marks the observed sea surface height by the satellite the day Larry crossed the track. The high sea surface height associated with the cyclone Larry is clearly seen. However, it only stands out marginally from two times normal sea surface variability. This is because non-tidal variability within this section of the Pacific is largely influences by the El Nino – La Nina signal in sea level.

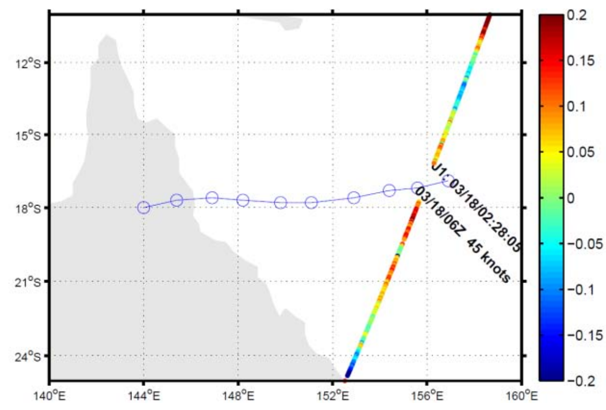

Figure 5. Altimetric observations from the standard processed altimetric archives showing only altimetric track within 12 hours and 500 km of the tropical cyclone Larry. J1 denotes Jason-1 satellite and the tropical storm track and Jason-1 satellite altimetry observed times are shown in UTC. The figure to the left shows the path of the cyclone and the sea surface height (in m).

The retracked altimeter observations for an extended period around the cyclone Larry have been entered into a multi-regression model (Høyer and Andersen, 2003; Cheng and Andersen, 2012; Deng et al., 2012) along with the data from 7 tide gauges in Figure 6. The tide gauge at Townsville near Cape Ferguson (not shown) has not been used as we want to estimate sea surface height in this gauge (Townville) using the multi-regression model as this was where cyclone Larry entered land.

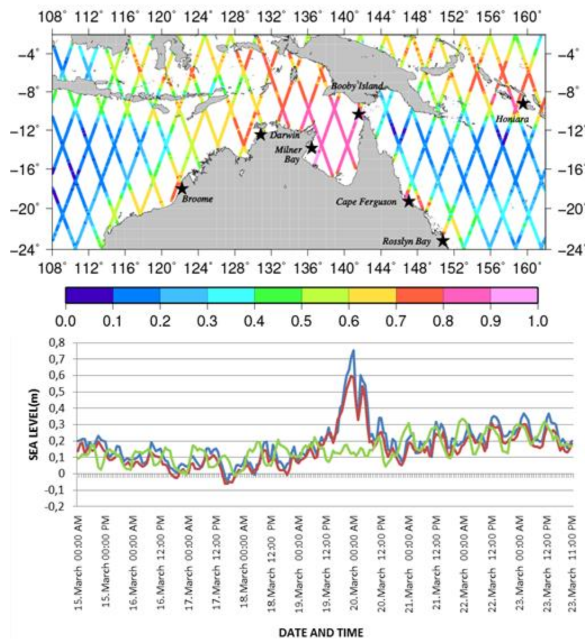

Figure 6. Upper figure shows the location of the 6 gauges used for predicting sea level at Townsville (near Cape Ferguson). Also the temporal correlation of non-tidal signal between the tide gauge observations and satellite altimetry is colour coded in the figure. The lower figure shows the sea level observed at Cape Fergusson (blue) and predicted using a multi-regression model from the 6 other tide gauges only (green) and from including satellite altimetry (red).

Figure 6 also illustrates the performance of the multi-regression model on predicting sea level. The upper figure coded in colours illustrates the spatial distribution of hindcast skills, which presents the proportion of the sea level observed by altimetry that is explained by tide gauges through the multivariate regression model. It is seen that the hindcast skill is close to 1 while closing to the various gauges and also high throughout the bay of Carpathia whereas it is close to zero away from the coast in eastern coast of Australia. This illustrates that the tide gauges are representing sea level variations close and in some case also far from the coast (bay of Carpathia). In this investigation the tide gauge in Cape Fergusson was also included.

The lower part of Figure 6 illustrates what happens when the tide gauge in Townsville is used for comparison of observed and predicted sea levels during the days of Cyclone Larry. The observed sea level at the Townsville is shown in blue and the predicted using a multi-regression model from the 7 tide gauges is shown in green. A multi-regression model taking the satellite altimetry into account is illustrated in red. The importance of including satellite altimetry is very clear and it increases the correlation between the observed and predicted sea level significantly.

CONCLUSION

The DTU10MSS Mean Sea surface (based on the previous DTU model DNSC08MSS) is presented and proposed to be used as a vertical reference in sea navigation.

We have illustrated the importance of combining the coarse temporal sampling by the satellite altimeter in the deep ocean with the high temporal sampling at tide gauges in sparse location. We have selected several representative high water events on the two continents based on tide gauge recordings and investigated the capability of the satellite altimeters to capture these in the sea surface height. On the European coast we find that when 2 or more satellites are available we capture more than 90% of the extreme sea level events.

Cyclone Larry hit the Queensland state of Australian north of Townville in March 2006. Examining the data delivered by the space agencies illustrated that most of the data within and close to the cyclone was rejected as they were flagged as invalid. However a careful reediting of the data enables to reveal that the data could be used in a multi-regression model to forecast sea level at the tide gauge Townville. The importance of including satellite altimetry is very clear and it increases the correlation between the observed and predicted sea level significantly.

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