SCIENTIFIC REPORTS

OPEN

Observing storm surges from space: Hurricane Igor off Newfoundland

SUBJECT AREAS:
CLIMATE SCIENCES
OCEAN SCIENCES
PHYSICAL OCEANOGRAPHY
APPLIED PHYSICS

Received
10 October 2012

Accepted
30 November 2012

Published
20 December 2012

Correspondence and requests for materials should be addressed to G.H. (Guoqi.Han@dfo-mpo.gc.ca)

Guoqi Han[1], Zhimin Ma[2], Dake Chen[3], Brad deYoung[2] & Nancy Chen[1]

[1]Biological and Physical Oceanography Section, Fisheries and Oceans Canada, Northwest Atlantic Fisheries Centre, St. John's, NL, Canada, [2]Department of Physics and Physical Oceanography, Memorial University of Newfoundland, St. John's, NL, Canada, [3]State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Hangzhou, China.

Coastal communities are becoming increasingly more vulnerable to storm surges under a changing climate. Tide gauges can be used to monitor alongshore variations of a storm surge, but not cross-shelf features. In this study we combine Jason-2 satellite measurements with tide-gauge data to study the storm surge caused by Hurricane Igor off Newfoundland. Satellite observations reveal a storm surge of 1 m in the early morning of September 22, 2010 (UTC) after the passage of the storm, consistent with the tide-gauge measurements. The post-storm sea level variations at St. John's and Argentia are associated with free equatorward-propagating continental shelf waves (with a phase speed of ~10 m/s and a cross-shelf decaying scale of ~100 km). The study clearly shows the utility of satellite altimetry in observing and understanding storm surges, complementing tide-gauge observations for the analysis of storm surge characteristics and for the validation and improvement of storm surge models.

Hurricanes and tropical storms can cause damage to properties and loss of life in coastal communities and drastically change the ocean environment[1–3]. Some of the most severe impacts are associated with the storm surge. It is of high importance, therefore to monitor, understand and predict the storm surge caused by these storms. Tide gauges have been used to monitor the storm surge, and numerical models developed to forecast it[4]. Nevertheless, the cross-shelf structure of a storm surge has rarely been observed. Scharroo *et al.*[5] reported the first altimetric observation of a storm surge, but they did not go further on its features and mechanism.

The Island of Newfoundland is located adjacent to the mid Northwest Atlantic (Fig. 1). Occasionally, Atlantic tropical storms pass over the island and adjacent oceans in summer and fall. Tang *et al.*[6] using a linear model investigated the barotropic response of shelf circulation to an idealized moving storm off Newfoundland and Labrador. A barotropic ocean model was used to explain coastal sea level variations along East Newfoundland as a consequence of storm-generated barotropic gravity waves[7]. Wavelet analysis was used to explain the propagation of the sea level by Florence as free continental shelf waves[8].

Hurricane Igor, the strongest of the tropical cyclones in the 2010 Atlantic season[9], hit Newfoundland on September 21–22, 2010 (Fig. 1) and brought heavy rainfall and high water level. Coastal communities were isolated for an extended time. The storm caused enormous damage to roads and properties, the most severe in the past 75 years[9].

The Jason-2 satellite altimeter passed over the Grand Banks during Hurricane Igor's passage, thus providing a rare opportunity to study the storm surge by combining the satellite sea level observations with the tide-gauge data at St. John's and Argentia. Here we integrate the Jason-2 satellite altimetry with St. John's and Argentia tide-gauge data to investigate the storm surge along the Newfoundland coast and adjacent Grand Banks. Our main objective is to investigate and understand the temporal and spatial variability of the storm surge caused by Hurricane Igor. We will also show that the satellite altimetry provides important information of the cross-shelf surge structure, complementing the tide-gauge observations.

Results

Before the storm, the along-track sea surface topography (track number 226) relative to the Earth Gravity Model 2008 (EGM2008) had a typical pattern across the Grand Banks: an offshore slope near the coast, flat over the mid shelf, and an offshore slope at the shelf edge (Fig. 2a). For storm impacts, we will focus on sea surface height anomalies relative to the CLS01 mean sea surface topography (Fig. 2b).

The satellite-observed sea surface height magnitude and pattern during the storm are significantly different from those 10 days before. The storm surge at the location closest to the coast (about 25 km away) was 60 cm,

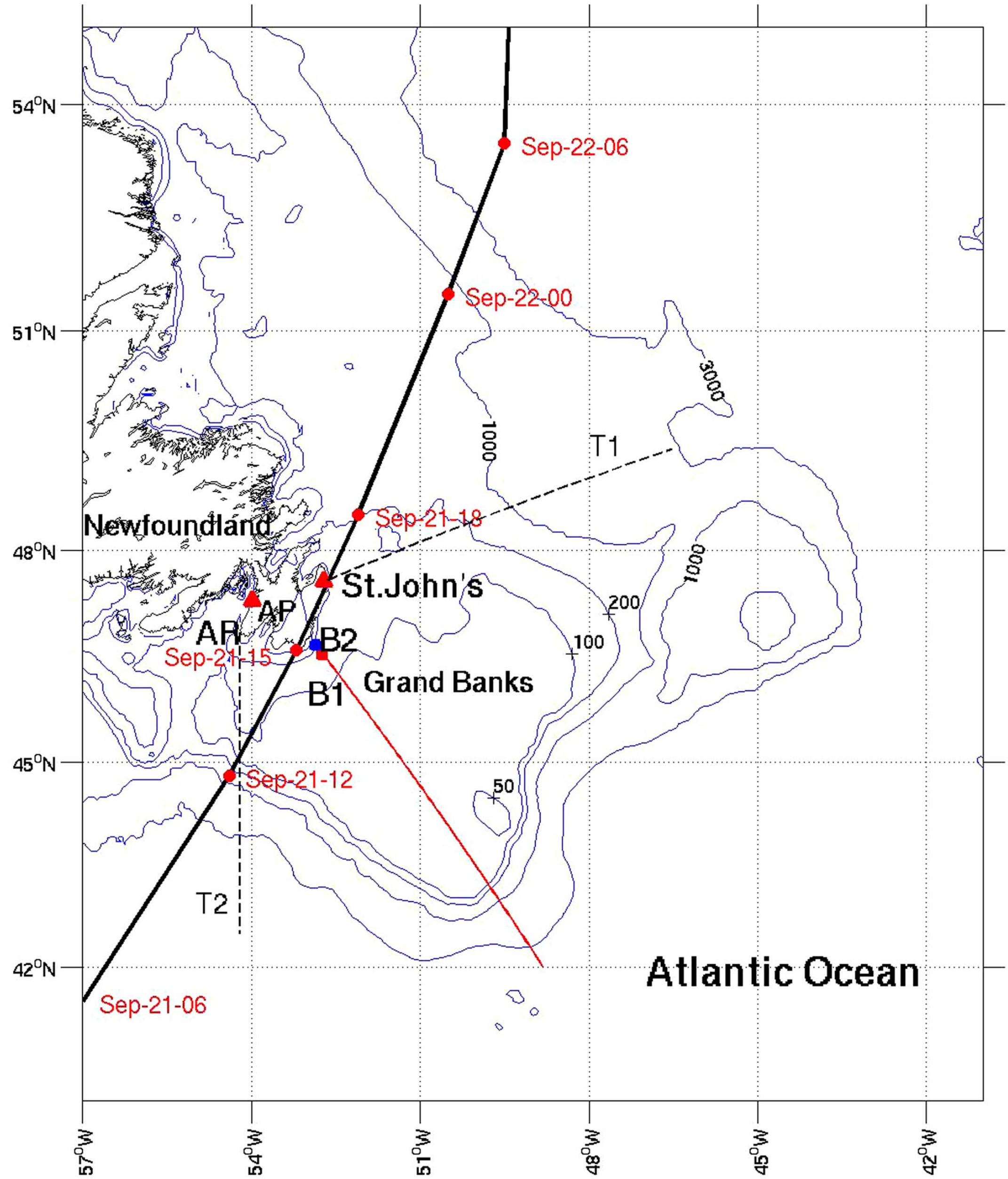

Figure 1 | Study area showing the Grand Banks and adjacent areas and the Hurricane Igor track based on Pasch R.J. and T. B. Kimberlain[9]. Red line is the Jason-2 satellite ground track, with B1 (red square) and B2 (blue square) depicting the locations of the inshore extent for 1-Hz and 20-Hz altimetric data, respectively. The two dashed lines are the selected cross-transects used to calculate the dispersion relationship for the continental shelf wave. AP: Avalon Peninsula. Tide-gauge stations at St. John's and Argentia (AR) are depicted in triangles.

resulting in a large offshore slope. At this location the sea level increased by 45 cm compared to that observed 10 days before. The along-track profile also shows a depression of 20 cm over the inner shelf. The surface height profile ten days after the storm was similar to the profile ten days before the storm, except that the sea surface height was about 10 cm lower.

The tide-gauge data at St. John's (which is about 89 km north of B1, Fig. 1) indicate there was a smaller surge (70 cm, Fig. 3a) at 15:30 September 21, 2010 before the storm arrival, followed by the maximum surge (94 cm) at 2:30 September 22, 2010 after the storm passage at St. John's. At the times of satellite passing, sea level difference between during- and before-the-storm was 80 cm; and that between during- and after-the-storm was 90 cm. It is not surprising to see the quantitative differences between the altimetry and tide-gauge data, in consideration of the large cross-shore sea surface slope near the coast (Fig. 2b, the blue solid curve) and the 25-km distance between B1 and the shoreline. The horizontal distance (about 89 km) with the sea level phase lag (see the next section) between B1 and St. John's is also a contributing factor. On the other hand, the tide gauge data show that sea level at St. John's after the storm (10-d after) was 10 cm lower than that before the storm (10-d before) (Fig. 3a), which supports the altimetric results.

Discussion

Storm surge is sensitive to many factors: storm intensity, translation speed, size (diameter of maximum winds), angle of approach to the coast, central pressure, and the shape and characteristics of coastal features such as bays and estuaries.

The predominant wind over the Grand Banks is from the southwest during the summer time[10]. When Hurricane Igor passed over

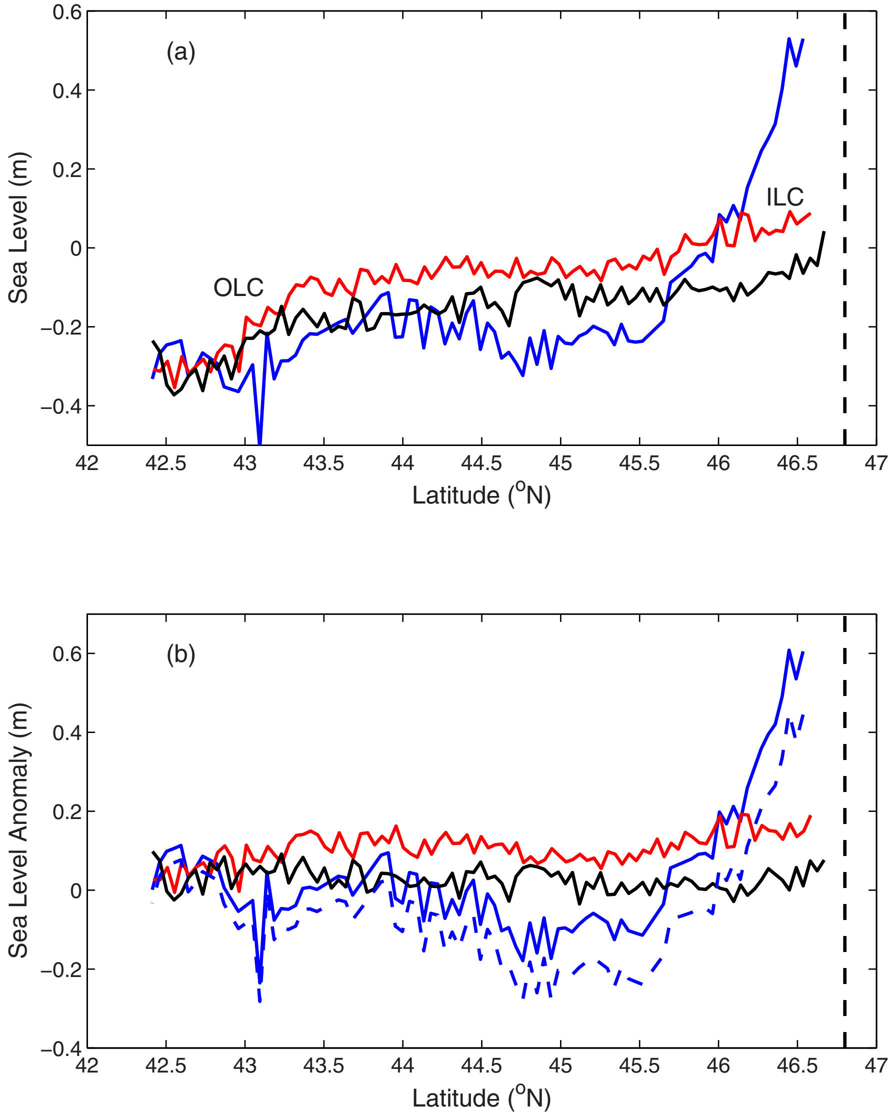

Figure 2 | (a) sea surface height relative to the EGM2008 geoid and (b) sea surface height anomalies relative to the CLS01 mean topography along a track across the Grand Banks observed by Jason-2 before (red), during (blue) and after (black) Hurricane Igor. The blue dashed curve in (b) is the sea surface height anomalies with the inverse barometric effect corrected. The satellite pass time during Hurricane Igor was around 2:22 September 22, 2010. The location of the coastline is also depicted (dashed line). ILC: Inshore Labrador Current. OLC: Offshore Labrador Current.

the Grand Banks, the maximum sustained (1-minute) wind was around 35 m/s. The detailed wind pattern based on the NCEP NARR wind fields (Fig. 4) also shows upwelling favorable winds off St. John's as the storm was approaching and passing by in the afternoon of September 21, and downwelling favorable winds off the northeast Newfoundland coast in the morning of September 22. The diameter of the core of intense winds was estimated to be 180 km when Hurricane Igor passed over the Grand Banks, which is close to the historical average of 200 km for this region[6].

The pre-storm sea surface height profiles along the satellite track (Fig. 2a) were representative of typical summer circulation features over the Grand Banks. Geostrophically the nearshore sea surface slope is associated with the inshore Labrador Current through the Avalon Channel and the shelf-edge slope is associated with the offshore Labrador Current along the southeast Grand Banks edge[11,12].

When the storm was approaching Avalon Peninsula from the south (Fig. 1), it first generated smaller surges at Argentia at 14:30 September 21 (Fig. 3b) and at St. John's at 15:30 (Fig. 3a). As the storm moved over the Avalon Peninsula, it lowered sea level nearshore as observed at St. John's by the tide gauge (Fig. 3a). At the same time water piled up over the southeast Grand Banks where the mean water depth is relatively shallow (~50 m). As the storm moved farther away toward the northeast, the direct storm effects over the southeast Grand Banks gradually dissipated; while on the left side of the track the storm (green vectors, Fig. 4) setup sea level along the northeastern coast of Newfoundland. This sea level setup propagated equatorward along the coast and lead to the second (higher) peak at St. John's at 2:30 September 22, 2010 (Fig. 3a). A sea level depression was observed by the altimetry around 2:22 September 22, 2010 between the propagating surge along the coast and the relatively high sea level over the southeast Grand Banks (Fig. 2b).

The dynamic response of the coastal and shelf seas to a moving storm is complex. There have been several model and observational studies off Newfoundland[6–8]. A study based on a linear barotropic model identified directly wind-driven motion, shelf waves and inertia-gravity waves off Labrador and Newfoundland[6]. In the other studies, the coastal sea level setup and propagation around the Newfoundland coast were attributed to continental shelf waves[8] or gravity waves[7] induced by passing storms.

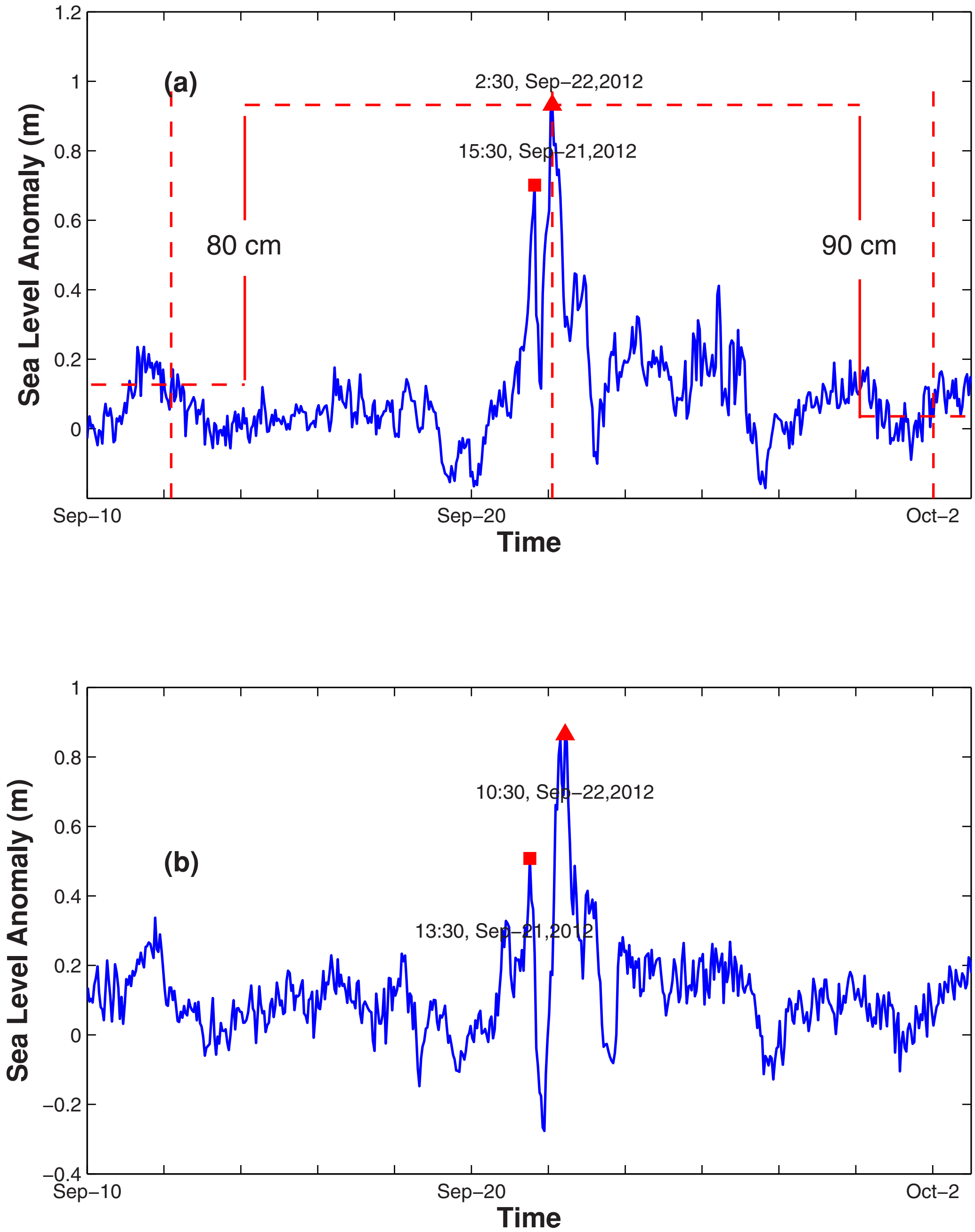

Figure 3 | (a) Residual tide-gauge sea level anomalies at St. John's, and (b) Same as (a) but at Argentia. The vertical dashed lines indicate the times of the satellite passing before, during, and after Hurricane Igor. The solid triangles (squares) indicate the maximum surges (initial peaks) at St. John's and Argentia.

The lag between the maximum sea levels at the two stations is 8 hours (Fig. 3). After the storm's passage, the maximum correlation between the sea level anomalies of St. John's and Argentia occurs if the latter is lagged by 7–8 hours (Fig. 5a). The correlation is calculated based on the sea level time series from 01:30 September 23 to 01:30 September 27, 2010. The sea level data on September 21–22, 2010 are removed to minimize the impacts of forced waves. Based on these time lags and the along-coast distance of 327 km, the average propagation speed of the surge is estimated to be 11–13 m/s, which is much lower than the phase speed of a barotropic Kelvin wave for this region. From the phase speed, the cross-shelf e-folding scale is estimated to be 100–120 km (the Coriolis parameter of 1.0632e-4 s^{-1} at 47°N). By fitting the altimetry sea surface height profile over selected coastal segments to an exponential function, the cross-shore decay scale is estimated to be 96±6 km (Table 1). Thus, the phase speed based on the altimetric data is about 10 m/s. The extrapolated surge height at the coast is 101±2 cm. Note that it took approximately 2 hours for the surge peak to propagate from St. John's to where the altimetry crossed the coast, during which time the sea level at St. Johns dropped about 12 cm. Even with this factor taken into account, the extrapolated surge is consistent with observations at St. John's.

Continental shelf waves are often generated after large-scale storm events move across or along a continental shelf[13]. In the present case, the altimetric sea level anomalies have one node across the Grand Banks (Fig. 2b), providing direct evidence that the observed storm surge is in the form of the continental shelf wave generated by Hurricane Igor. Furthermore, an analysis of the sea level anomalies

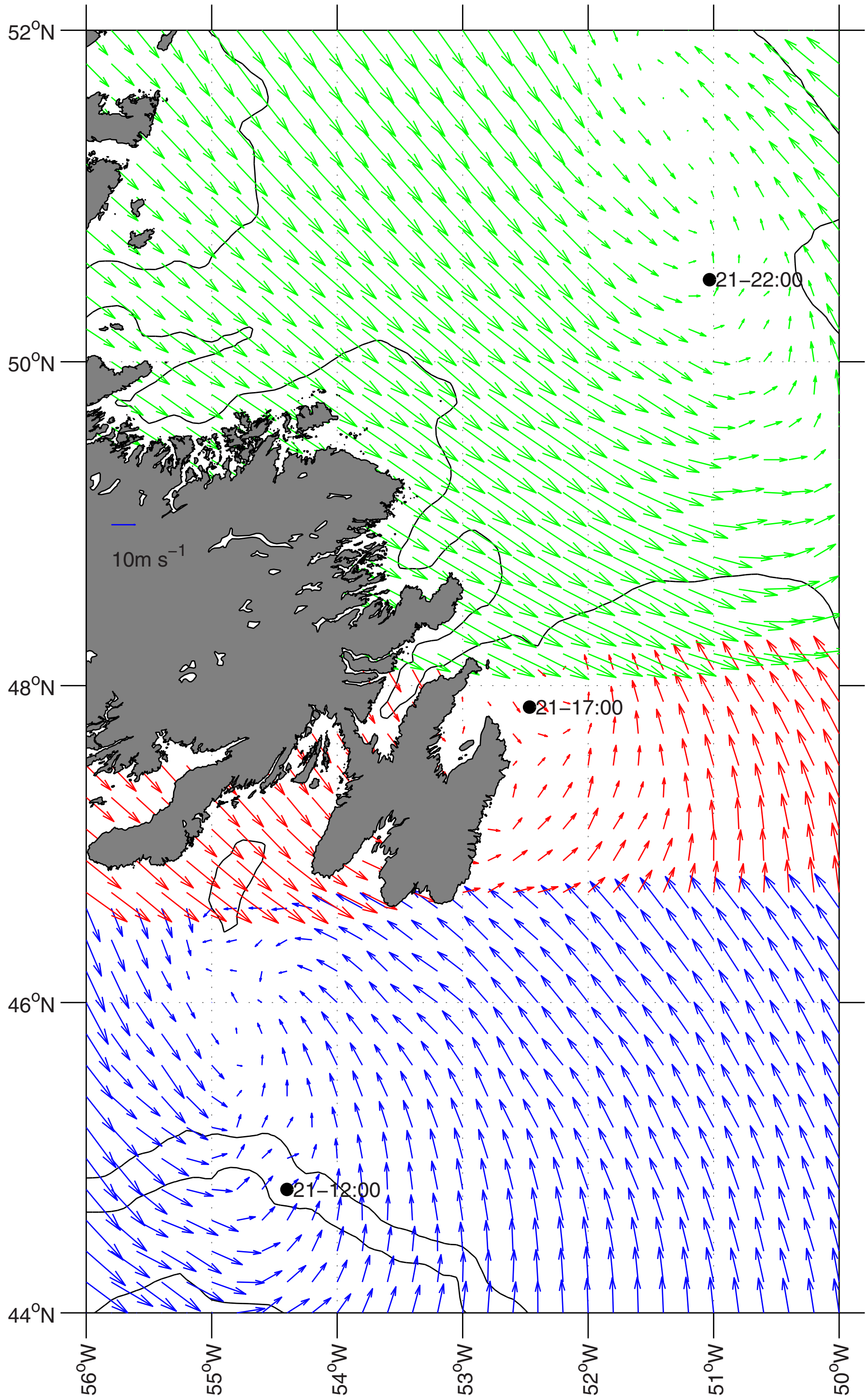

Figure 4 | NCEP NARR wind fields at 12:00 (blue), 17:00 (red) and 22:00 (green) on September 21, 2010. The hurricane track locations based on Pasch R.J. and T. B. Kimberlain[9] are also depicted (solid dots).

after the storm (from 01:30 September 23 to 01:30 September 27, 2010) indicates that the oscillation is dominant at a period of about 48 hours at St. John's, i.e., 0.5 cpd, but at about 1.3 cpd at Argentia where the oscillation at 0.5 cpd is also notable (Fig. 5b). Next we determine the dispersion relationship of the first-mode continental shelf wave for two selected cross-shelf sections: one near St. John's and the other at 54.17°W near Argentia (see Fig. 1 for location). The calculation is carried out using barotropic continental shelf wave theory[14]. Based on the theory, the phase speed is about 19 m/s at 0.5 cpd near St. John's and about 12 m/s at 1.3 cpd near Argentia (Fig. 6). The theoretical phase speed near Argentia is close to that observed (10 m/s from altimetry and 11–13 m/s from tide-gauge data). Note that this shelf wave theory assumes a straight coastline and uniform depth in the along shelf direction; while the Newfoundland Shelf has complex coastline and bottom topography. The dispersion curve also indicates that the maximum possible frequency at St. John's is much lower than that at Argentia. We argue that the sea level setup generated north of St. John's propagated equatorward along the Newfoundland coast as a free continental shelf waves causing the maximum surge peak at St. John's and subsequently at Argentia.

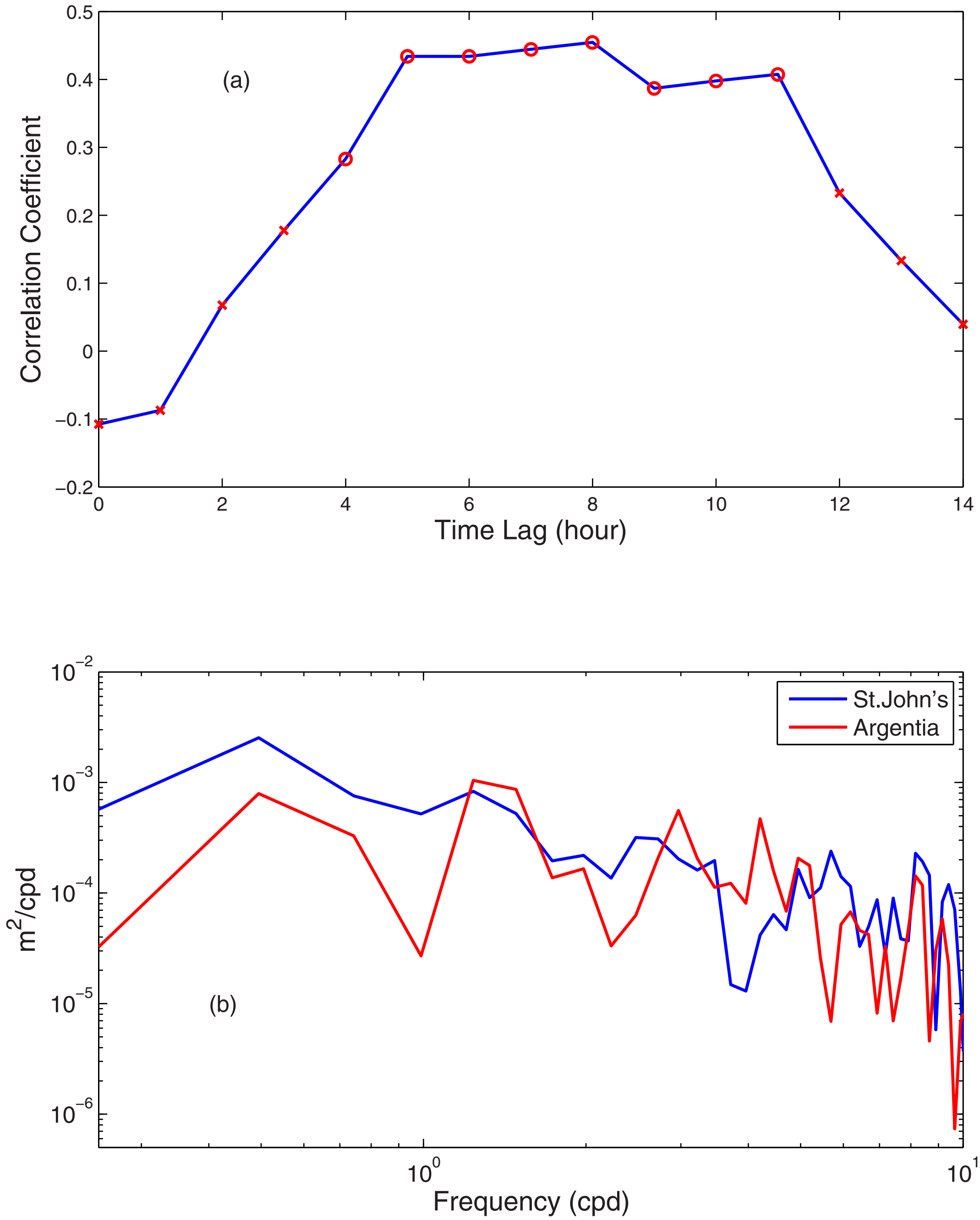

Figure 5 | (a) Lagged correlation coefficients (open circles: significantly different from zero at the 99% confidence level; crosses: insignificant) between the sea level anomalies at St. John's and Argentia, with the latter lagging the former. (b) Power spectral density of the sea level anomalies at St. John's and Argentia.

The continental shelf wave speed in the present study is consistent with previous results for the Canadian Atlantic shelves based on numerical models and sea-level observations. The shelf wave speed from numerical modelling is 11 m/s for the Labrador and Newfoundland shelf edge[6] and 16 m/s for the Scotian Shelf[15]. Thiebaut and Vennell's[7] analysis of tide-gauge data obtained a phase speed of 16 m/s for a free continental shelf wave propagating from the Newfoundland Shelf to the Scotian Shelf.

To conclude, satellite altimetry and tide gauge data at St. John's observed a maximum surge of about 1 m at 2:30, September 22, 2010, hours after the passage of Hurricane Igor. The post-storm sea level variations seem to be associated with propagating first-mode continental shelf waves generated off northeast Newfoundland after the storm passed by St. John's. The shelf wave propagated at an average speed of ~10 m/s, with a cross-shelf e-folding scale of ~100 km. The present study shows that satellite altimetry is able to observe storm surges, providing important information for analysing surge characteristics. This information is also useful for validating and improving storm surge models.

Our study also indicates that within a few tens of kilometres from the coast quality altimetric data may not be available from the standard 1-Hz product and that it is usually coincidental for a single nadir altimeter to observe a storm surge. Nevertheless, there are emerging efforts to integrate various satellite observations for storm surges such as the European Space Agency's eSurge consortium (http://www.storm-surge.info/esurge-consortium). The ongoing coastal

Table 1 | Cross-shelf exponential length scale of the sea level variation and extrapolated coastal surge by fitting the Jason-2 1-Hz and 20-Hz observations. The inshore extents for the former and latter are 46.535 and 46.696°N, respectively

	Length Scale (km)		Coastal Surge (cm)	
Offshore Extent (°N)	1-Hz	20-Hz	1-Hz	20-Hz
45.518	98	83	100	94
45.574	103	98	99	90
45.429	101	96	99	90
45.385	93	95	102	90
45.340	94	92	102	91
45.296	88	94	104	91
Mean ± Standard Deviation	96 ± 6	93 ± 5	101 ± 2	91 ± 1

altimetry initiatives will surely improve the utility of altimetry near the coast[16]. The experimental Jason-2 20-Hz data are closer to the coast (about 20 km closer in this case), from which we obtained coastal surge and exponential cross-shelf length scale consistent with those from the standard 1-Hz data (Table 1). The nadir altimeter constellation and the wide-swath ocean altimetry[17] on the planned Surface Water and Ocean Topography mission will provide much better capability for monitoring storm surges from space.

It is rare for a nadir satellite altimeter to capture storm surges generated by hurricane and tropical storms off Newfoundland. The chance off tropical coasts is higher, though remains limited. Storm surges in the Gulf of Mexico were observed by altimeters during Hurricane Katrina 2005 and Hurricane Isaac 2012 (Fig. 7). The altimetric results are in approximate agreement with nearby tide-gauge measurements. The average difference (satellite minus tide gauge) for the five comparisons is 14 cm, with a standard deviation of 6 cm. In addition to errors from altimetry itself, the discrepancies can be attributed to the differences between altimeter track and tide-gauge locations. Overall, these two examples show consistent accuracy of altimetric measurements with that of the Hurricane Igor case, pointing to the robustness of satellite altimetry in observing storm surges.

Methods

Satellite altimetry data. We have used standard 1-Hz altimetric sea surface height data along a Jason-2 satellite track (track 226) across the southeast Grand Banks (Fig. 1). The satellite has an exact repeat cycle of 9.9156 days. The satellite passed over the region around 2:22 am, September 22, 2010 UTC, a few hours after the passage of Igor's eye by St. John's. The altimetric sea surface height data are corrected for atmospheric and oceanographic effects except for the atmospheric pressure and wind effects, unless specified otherwise. We focus on the sea surface height anomalies

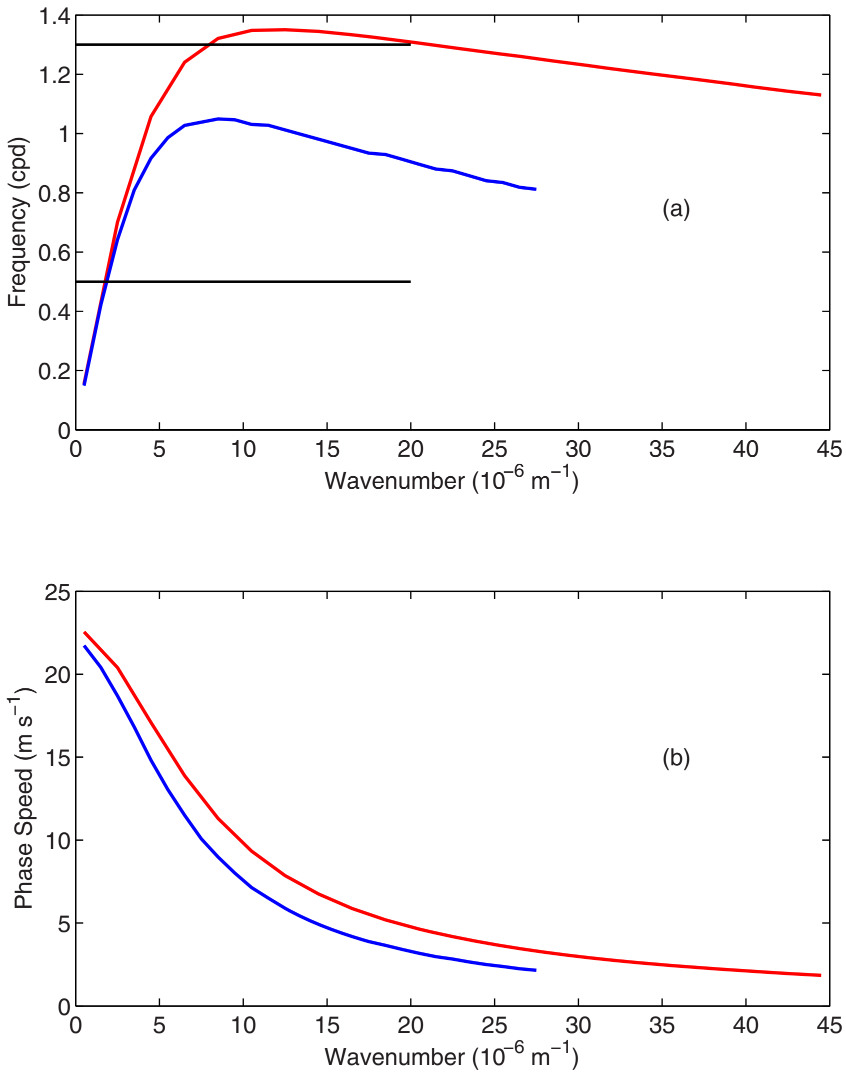

Figure 6 | (a) Dispersion relationships for first-mode continental shelf waves and (b) phase speed as a function of the wavenumber at two transects near St. John's (blue curve) and Argentia (red curve) (See Fig. 1 for location). The two horizontal lines in (a) indicate the dominant frequencies of 0.5 and 1.3 cpd at St. John's and near Argentia, respectively.

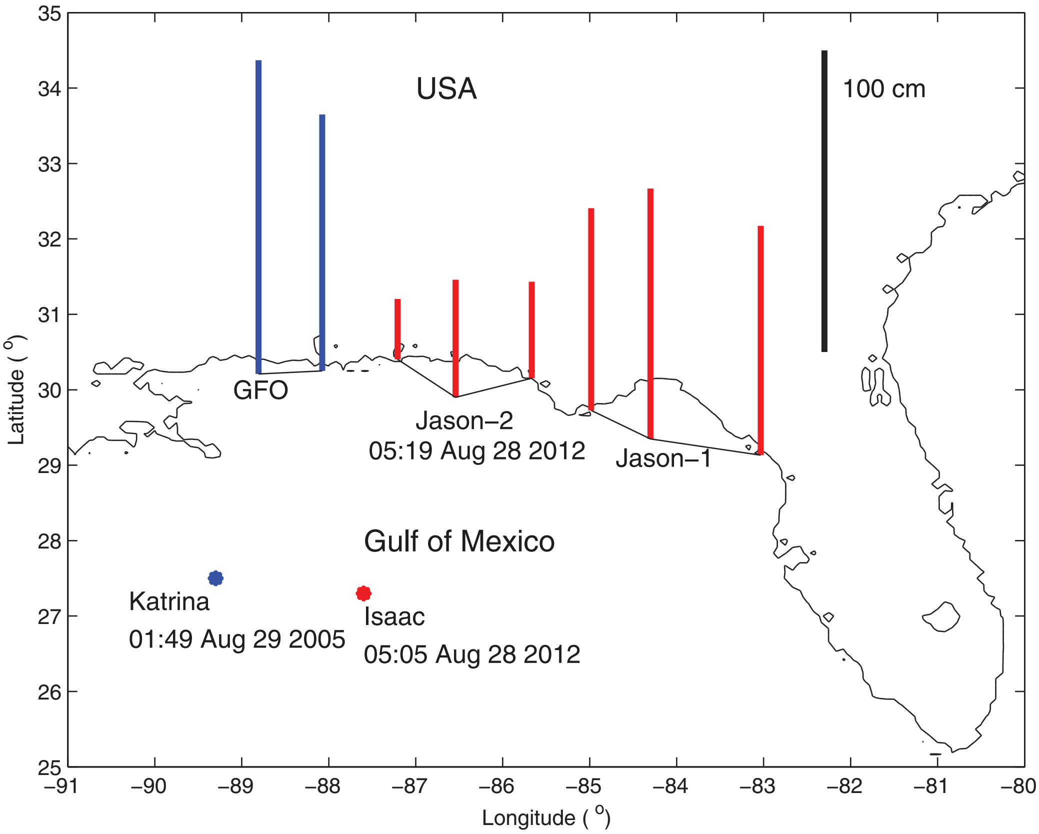

Figure 7 | Altimetric (thick vertical line) and tide-gauge (thin vertical line) observations of the storm surge in the Gulf of Mexico during Hurricane Katrina (blue) and Isaac (red). Storm centres at the time of comparison are depicted in dots. The Jason-2 and corresponding tide-gauge observations were at 05:19 August 28, 2012. The time is in UTC. GFO: Geosat-follow-on.

relative to the CLS01 mean sea surface (Fig. 2b), but also used the sea surface height relative to the EGM2008 geoid (Fig. 2a). Experimental 20-Hz Jason-2 data have also been used for a brief comparison.

We have fitted the altimetric along-track sea surface height anomalies corrected for the inverse barometric effect (Fig. 2b, dashed curve) to an exponential function to determine the dynamical length scale of the storm surge in the cross-shelf direction. The coastal surge is then determined by adding the fitted value to the inverse barometric effect at the coast.

Tide-gauge data. Hourly sea level data at St. John's and Argentia tide-gauge stations (Fig. 1) are from the Canadian Hydrographic Service. The tide-gauge data from January 1 to December 31, 2010 were de-tided and residual sea level anomalies were produced relative to the long-term mean sea level. We also used de-tided NOAA (National Oceanic and Atmospheric Administration) tide-gauge data along the northern Gulf of Mexico coast during Hurricane Katrina 2005 and Hurricane Isaac 2012.

Wind data. We used the 3-hourly wind and pressure fields from the North American Regional Reanalysis (NARR) project which is an extension of the National Center for Environmental Prediction (NCEP) Global Reanalysis over the North American Region (http://www.esrl.noaa.gov/psd/). The NARR model includes the very high resolution NCEP Eta Model (32 km/45 layer), in conjunction with the Regional Data Assimilation System which assimilates precipitation and other variables.

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Acknowledgements

G.H. acknowledges the support of the Canadian Space Agency Government Related Initiatives Program. B.D. acknowledges the support of the Natural Science and Engineering Research Council of Canada. D.C. is supported by grants from the Ministry of Science and

Technology (2010DFA21012), the State Oceanic Administration (201105018), and the National Science Foundation (91128204) of China. The 1-Hz and 20-Hz altimeter products are from the Radar Altimeter Database System and from AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data). The tide-gauge data are from the Integrated Data Management Service, Fisheries and Oceans Canada and from the National Ocean Service, NOAA. The hurricane track data are from the National Hurricane Center, NOAA.

Author Contributions

G.H. conceived the concept and framework, conducted the data analysis, interpreted the results and wrote the manuscript. Z.M. and N.C. contributed to the data analysis and prepared some figures. D.C. and B.D. contributed to the interpretation and reviewed the manuscript.

Additional information

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Han, G., Ma, Z., Chen, D., deYoung, B. & Chen, N. Observing storm surges from space: Hurricane Igor off Newfoundland. *Sci. Rep.* **2**, 1010; DOI:10.1038/srep01010 (2012).