Use of ICESat altimeter data for ocean monitoring: An Evaluation

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Oscar Garcia
Texas A&M University Corpus Christi.

(Mentor)
Dr. Daniel Jacob
NASA Goddard Space Flight Center.
Laboratory of Hydrospheric and Biospheric Sciences

INTRODUCTION

The birth of a hurricane, called cyclogenesis, occurs when an atmospheric cyclone is created as air is warmed by anomalously warm sea surface temperatures, exceeding 26° Celsius. As the air rises, an atmospheric low pressure cell is created in such a way that if this low pressure cell is near the equator, it will produce counter-clock wise rotating winds around the low pressure center, an effect of the Earth's rotation (Shay 1998). As warm water temperatures persist, heat and moisture continue to be transferred from the ocean to the atmosphere allowing hurricanes make progress on their paths.

Additionally, the intensification of hurricanes involves a combination of favorable atmospheric conditions such as trough interactions and vertical shear. For a long time the upper ocean thermal structure was thought to play only a marginal role in hurricane intensification (Goni et al. 2003). However, after a series of events where the sudden intensification of hurricanes occurred when their paths passed over oceanic warm features, it is now important to consider that the upper ocean plays a crucial role in this process. The hurricane heat potential, a parameter introduced by Leipper and Volgenau (Leipper and Volgenao 1972), is proportional to the integrated vertical temperature from the sea surface to the depth of the 26°C isotherm. Consequently, regions of warmer sea surface temperatures and deeper 26°C isotherms have higher hurricane heat potential than their surrounding waters. The tropical North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico are regions where hurricanes build and intensify. Here, the ocean dynamics are highly variable in space and time and characterized by the presence of warm currents, meanders, and eddy formation, often with very high hurricane heat potential values during the summer months.

Remotely sensed data, including sea surface temperatures (SSTs) and sea surface heights (topography) are now being used as part of a suite of tools to predict rapid intensification of tropical cyclones. SSTs are measured on a clear day using infrared satellite remote sensing techniques (Digby and Antczak 1999). But during a storm, clouds block the infrared signal, and the determination of the ocean's surface temperature becomes much more difficult. Satellite-based radar altimeter measurements are used to indirectly estimate the sea's height anomaly and to make an estimate of the thickness of the warm water layer. An increase of 1 cm in sea level represents heating of 1° C for a 100 meter column of sea water. Combined with prior temperature data, an estimate of upper layer heat content from the altimeter data are now being routinely generated (Zumpichiati et al. 2005). However, due to the 4 km footprint of the radar pulse, data closer to the coast cannot be used due to land contamination. The ICESat laser altimeter, with a footprint of 70 m provides data much closer to the coast. Therefore, the purpose of this work is to analyze the ICESat satellite ocean product (GLA 15) and compare it to the radar altimeter data from TOPEX/Jason, While the main objective is to supplement the radar altimeter measurements of oceanic mesoscale variability, the initial objective is to investigate whether anomalies in the surface topography could be detected satisfactorily by the ICESat Geoscience laser altimeter for identifying zones where intensification of hurricanes occurred. In the region bounded by 100° to 60° west longitude and from 0° to 40° North latitude the GLAS data is compared to radar altimetry. With significant mesoscale variability due to the Loop current and warm core eddies in the Gulf of Mexico, Caribbean and Atlantic (where many of the hurricanes rapidly intensify and affect the coastal zones in the Gulf of Mexico), and in the Eastern Pacific, where anomalies such as the Costa Rica Dome exist this region provides a good test case.

BACKGROUND

Satellite altimetry has proven to be a useful tool to study eddy dynamics by acquiring continuous global coverage of sea level anomaly (SLA) fields. Unlike AVHRR imagery, altimeter data are unaffected by cloud obscuration and provides information on the vertical ocean structure if complemented by historical hydrographic data (Goni et al. 2003). Given the relatively slow translation speeds of mesoscale ocean features of a few kilometers per day, the surface height data from the altimeter detects and locates warm features, usually identified as positive SHA values. (Shay et al. 2000). Since positive SHA corresponds to higher oceanic heat content, this information is being used in the prediction of hurricane intensity.

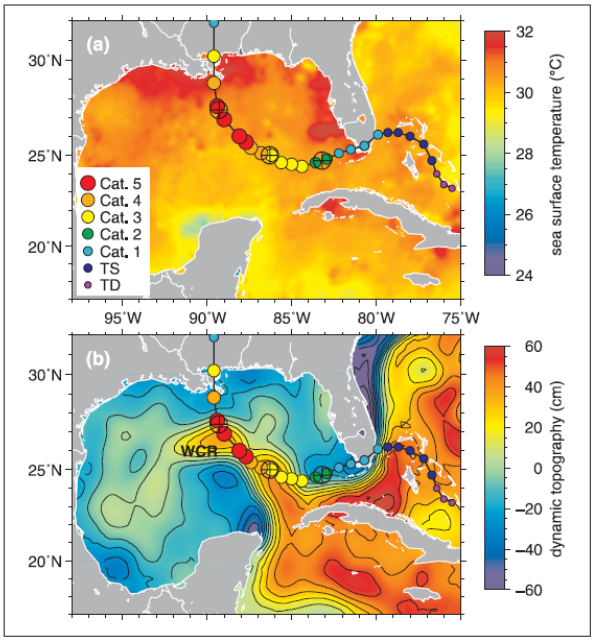


Figure 1. The location and intensity of Katrina at intervals of six hours (circles indicate data from National Hurricane Center advisories) show two intensification events. (a) Intensification is not correlated with sea surface temperature (from POES high-resolution infrared data). (b) In contrast, the intensifications correlate well with highs in the ocean dynamic topography (from Jason 1,TOPEX, Envisat, and GFO sea surface height data).The Loop Current can be seen entering the Gulf south of Cuba and exiting south of Florida; the warm-core ring (WCR) is the prominent high shedding from the Loop Current in the center of the Gulf.The crosshair symbols on the storm tracks show the storm position at the times of the three rows of panels in Figure 1. (Katrina) (Scharroo et al. 2005)

As shown in Fig.1, hurricane Katrina intensified over areas of anomalously high dynamic topography rather than areas of unusually warm surface waters. In the case of Katrina, the oceanic mesoscale features were tracked since the storm's formation. The example from Katrina suggests that any increase in hurricane intensity may be more directly correlated with variations in the thickness of the warm layer. Due to storm induced mixing in the upper ocean and direct heat loss to the storm, the upper ocean heat content reduces significantly as shown in Fig.2.

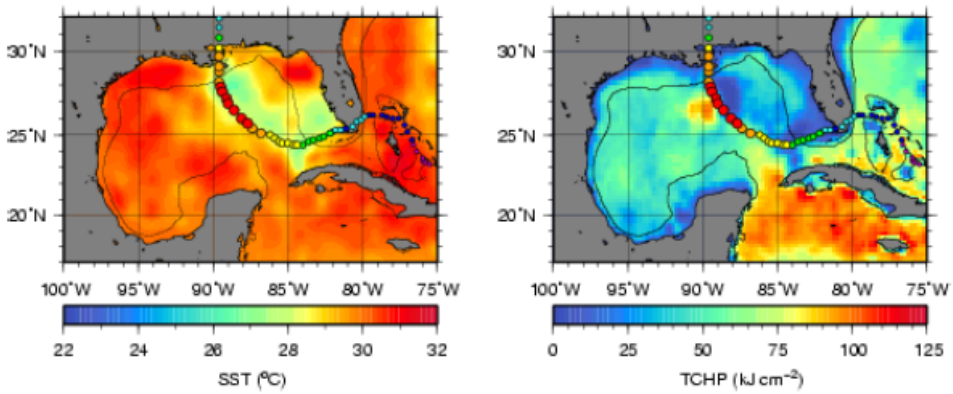


Figure. 2. The cooling of the surface waters in the GOM is observed by the decrease of the sea surface temperature values under the storm. This cooling is more pronounced to the right of the track, where winds are usually stronger. The passage of the cyclone produces a strong mixing of surface waters and upwelling of deeper and cooler waters. This can be observed in the reduction of the values of the TCHP field under the cyclone, which is more evident to the right of the track when the cyclone was more intense (NOAA 2005).

Shay et al. (2000) have reported a similar case for the intensification of Hurricane Opal (October 1995) while crossing a warm core eddy in the Gulf of Mexico. It was found that for the same SST, the upper ocean heat content will be significantly higher, as determined by the upper ocean temperature and the depth of the thermocline, which is reflected in the dynamic topography. The heat content therefore is more relevant to storm intensification.

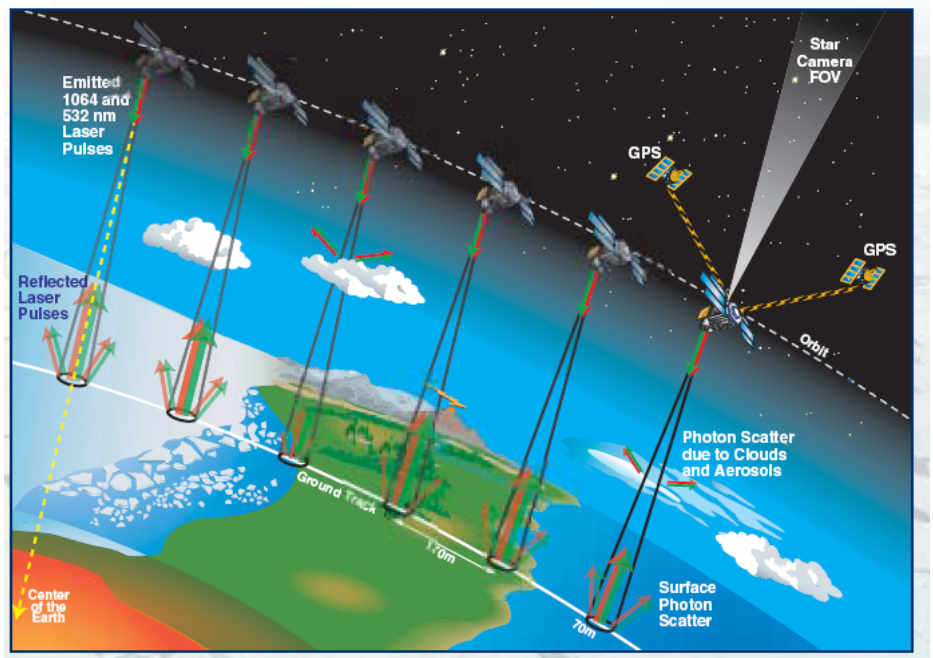
ICESat Altimetry:

In this present work it is analyzed the relation between data coming from 2 systems of satellites, the newer ICESat and the most used and recognized radar altimeter satellite systems of JASON and Topex/Poseidon. The overall goal of this research is to merge the data from these two types of altimeters, to provide data coverage and heat content all the way to the coast. In this section, the GLAS features are briefly reviewed.

GLAS on ICESat satellite:

ICESat was launched on a Delta-2 rocket from Vandenberg AFB at 0045 UT on January 13, 2002, into a 600km altitude orbit with a 94° inclination. The inclination was chosen to provide coverage of changing ice features in West Antarctica allow comparison of derived elevations at crossover points (intersections between ascending and descending tracks) that are commonly used in altimeter analyses. The primary purpose of the GLAS instrument on the

ICESat mission is to detect ice elevation changes that are indicative of changes in ice volume (mass balance) over time. (Carbajal and Harding 2001)



Schematic illustration of the GLAS instrument making measurement from ICESat while orbiting the Earth. Graphic by Deborah McLean.

Figure 3 GLAS has three lasers (designated Laser 1, 2 and 3) mounted on a rigid optical bench, with only one laser operating at a time (Magruder et al. 2003). Each laser produces a 1064 nm pulse for altimetry and lidar, but a doubler crystal produces a 532 nm wavelength pulse, which yields a more sensitive determination of the vertical distribution of clouds and aerosols.

The operating laser pulses at 40 Hz and the transmitted laser pulse illuminates a spot on the Earth's surface with a diameter of 65m, except when optically thick clouds obscure the surface. Successive spots are separated on the Earth's surface by 172 m.

ICESat spends most of its lifetime over the ocean acquiring a vast amount of information on sea surface characteristics. The shape of the GLAS return-pulse waveform determined primarily by the surface-height distribution within the footprint, which is small enough to be affected by individual large waves. (Urban and Shutz 2005)

Each clear-weather GLAS return pulse provides estimates of average surface elevation and of surface heights distribution within the corresponding 70-meter footprint, at a rate of

40/second. However, these footprints, in general, cover less than one of the longer ocean waves, and it is necessary to include information from many consecutive footprints to infer sea-surface elevation and wave height. Surface elevation is obtained by averaging the elevation of these many footprints, and the maximum wave height are given by the highest and lowest surface elevations inferred from the all the pulse widths for wavelengths less than twice the footprint diameter. (Brenner et al. 2003)

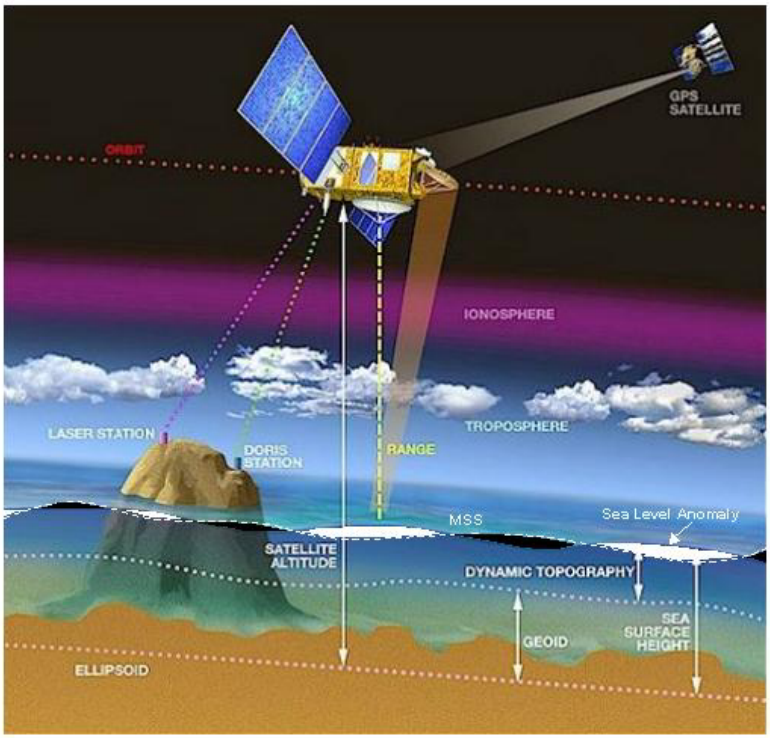


Figure 4 Satellite Altimetry Principle: Altimeters permanently transmit signals at high frequency (over 1700 pulses per second) to Earth, and receive the echo from the sea surface. This is analysed to derive a precise measurement of the round-trip time between the satellite and the surface. The ultimate aim is to measure sea level relative to a terrestrial reference frame. This requires independent measurements of the satellite orbital trajectory, i.e. exact latitude, longitude and altitude coordinates. Adapted from: http://www.aviso.oceanobs.com/html/alti/principe_uk.html

Goals and Objectives:

- Generate maps of sea surface elevations subtracting the geoid model used from ICESat in order to identify sea level anomalies (SLA) due to mesoscale features in the Gulf of Mexico.

- Compare the altimetry measured from ICESAT to the altimetry measured by other satellites during corresponding periods and cycles in order to find differences or systematic errors.
- Merge data from Jason-Topex-ICESat in order to be able to analyze the heat budget in coastal zones.

Methodology:

Data obtained from the GLAS server at NASA Goddard Space Flight Center and the NSIDC are used in this study. Both the data sources provide access to the same data although the data from GLAS server is more readily accessible from GSFC.

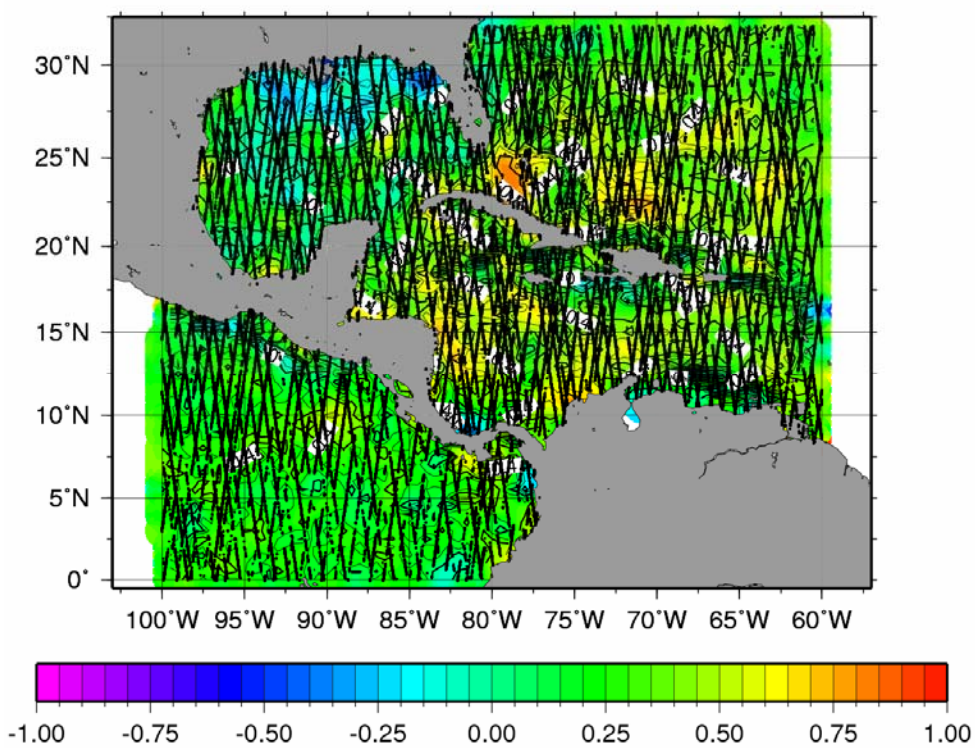


Figure 5 Satellite Altimetry Data coming from ICESat in the corresponding 2A period.

There have been 26 releases for the data. Each of those releases includes different calibrations, corrections, or model modifications that have been performed. The relation of those releases can be consulted at http://nsidc.org/daac/icesat/. From all the ICESat releases, only the latest 26 datasets were in this study.

Laser Identifier	Days in Operation	Start Date	End Date
1A	38	2/20/2003	3/29/2003
2A	55	9/24/2003	11/18/2003
2B	34	2/17/2004	3/21/2004
2C	35	5/18/2004	6/21/2004
3A	37	10/3/2004	11/8/2004
3B	36	2/17/2005	3/24/2005
3C	35	5/20/2005	6/23/2005
3D	35	10/21/2005	11/24/2005
3E	34	2/22/2006	3/27/2006
3F	32	5/24/2006	6/25/2006

TABLE 1. Campaigns, periods, and data coverage from ICESat is summarized in this table. In Yellow are the periods processed with the latest 26 releases.

Future work will analyze the merging of this data to investigate intensification of these hurricanes using the ICESat and compare results with Jason and T/P results.

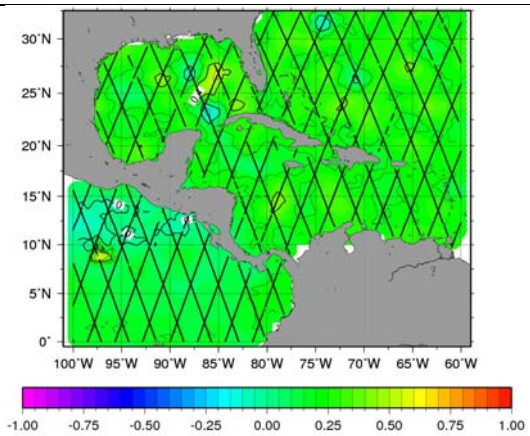
YEAR	PERIOD	NAME	TYPE	ICESAT LASER
2003	24-29 sep	Juan	H	2A
2003	26 sep- 07 oct	Kate	H	2A
2003	01-09 oct	Nora	H	2A
2003	02-08 oct	Olaf	H	2A
2003	20-26 oct	Patricia	H	2A
2004	22-24 may	Agatha	T	2C
2004	8-10 oct	Matthew	T	3A
2004	11-13 oct	Lester	T	3A
2004	19-25 may	Andres	T	3C
2004	17-22 jun	Blanca	T	3C
2005	8-13 jun	Arlene	T	3C
2005	15-25 oct	Wilma	H	3D
2005	26-31 oct	Beta	H	3D

Table 2. Hurricanes covered by measurements from ICESat in the corresponding periods of time are summarized in the following table.

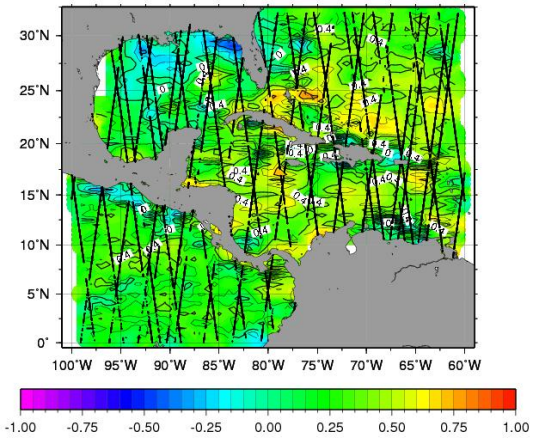
The GLA 15 dataset consisting of sea surface elevations either from NSIDC or from NASA GLAS is contaminated by data over land and Ice that must be removed before our analysis. Due the nature of the geolocation of the data (separated 170 m each footprint of 70m diameter), they were analyzed using the full 40 Hz, 20 Hz, and 1 Hz of frequencies in order to recognize the noise produced by tides and coastal waves. The best result was obtained working with 1 Hz. The data were filtered depending on geolocation. IDL was used for this task. They were also filtered with maximum 1m of altimetry avoiding land data contamination for the interpolations. Grid generation of ICESat periods were performed with several interpolation methods using Matlab, R, and GMT. Best results were obtained using GMT. Due to the repetition

cycles from ICESat (90 days) and the limitation in the data as it is described in table 1 (subsets of 55, 33 and 35 days), datasets were split in the corresponding TOPEX/POSEIDON and JASON cycles.

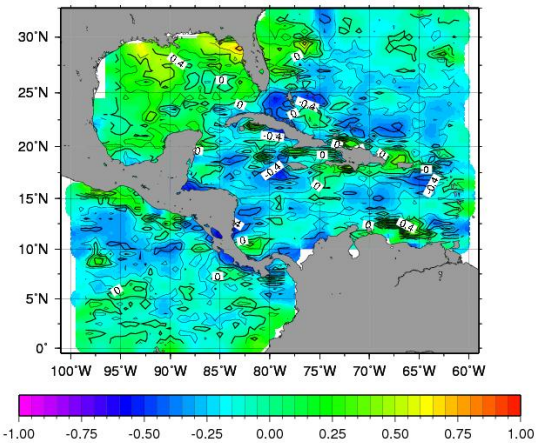
When the Geoid is subtracted from the Elevation in the ICESat dataset, maps show the height variations of the sea surface level. There is no well defined Mean Sea Surface for the ICESat GLAS data because there is data mainly from non-repeating orbits. Because of this, the heights from the ICESat (elevation minus geoid) were first compared against the SLA for the corresponding cycles of Jason and Topex. Results show a systematic error from 20 to 30 cm (Fig.?).



SLA from Topex



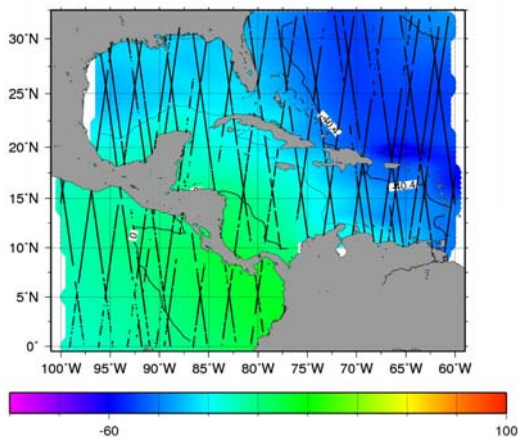
Altimetry from ICESat = Geoid Substracted to Elevation from ICESat



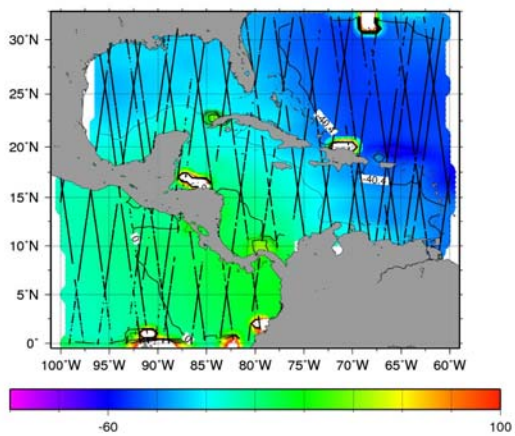
Substraction SLA Topex minus Altimetry ICESat

Topex/Poseidon and Jason have been generating a history of Mean Sea Surface during the last two decades. The Mean Sea Surface from Jason was computed for each point in the footprints of ICESat using Fortran and considering a frequency of 1 Hz.

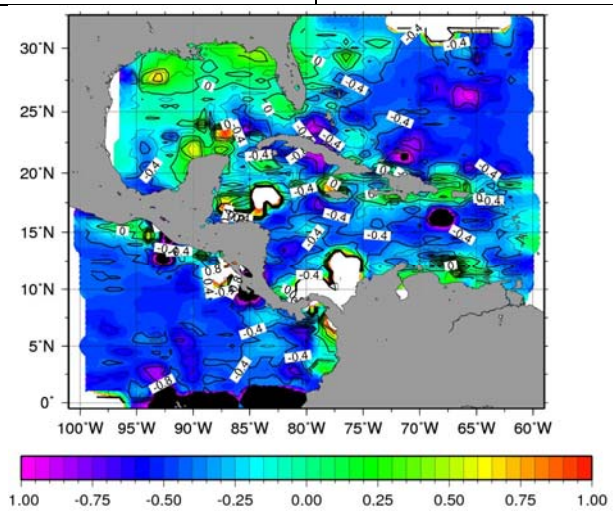
To register the GLAS elevation data to that of Jason and TOPEX, the MSS from Jason and TOPEX were interpolated for ICESat ground track for the following periods of time: Cycles 407, 408, 409, 411, 422 and 423 from Topex/Poseidon and Cycles 64, 65, 66, 67, 78, 79, 80, 140,141 and 142 from Jason. This MSS from Jason and T/P is then substracted from the elevation in ICESAT and then compared with the SLA from Jason and T/P. A consistent error from 20 to 30 cm also was seen in all the corresponding periods compared, described in table 3.



Elevation from ICESat



MSS computed used Jason data in ICESat



Subtraction of Elevation ICESat minus MSS from Jason

Conclusions:

The nature of data coming from ICESat allows identification of Sea Level Anomalies. ICESat calculations of sea level and mesoscale variability are demonstrated and compared to calculations from TOPEX/POSEIDON and JASON Satellites. A systematic error from 20 to 30 cm between ICESat altimetry and Jason SLA was observed and could be explained by the differences in the geoid and tide models used for each satellite. After fixing this difference, ICESat is able to match TOPEX/POSEIDON and Jason detection of major sea level anomaly and mesoscale variability features in the area under study.

The same systematic error from 20 to 30 cm between ICESat and Jason was observed using the Mean Sea Surface from Jason in the geolocation of ICESat spots and subtracting this MSS from ICESat's elevations.

In order to compute the exact bias between the ICESat and Jason, one would need to perform the crossover analysis. Future work will include combining datasets from ICESat and Jason to review the behavior in the mixing layers in coastal zones. Future work will also include analyzing intensification during the paths of hurricanes that were covered for the ICESat periods and review altimetry in zones where the intensification was increased.

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