SMOS sensing of Ocean surface response to Hurricanes

Potential for better prediction of Tropical Cyclone intensification

Progress meeting 1

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Accurate forecast of hurricanes can save lives and reduce serious economic losses. However, hurricane forecast, especially its intensity forecast, remains a challenging problem in modern numerical weather prediction.

=> Aim is to demonstrate that SMOS SSS data can be useful for improving hurricane forecasts and enhancing our understanding of oceanic processes involved in hurricane intensification.
3 major Aims for that study:

1) Based on analysis of Hurricane Igor case:

1.1-Demonstrate **first observations of SSS wake** behind a storm from Space

1.2-Emphasize the **potential of the synergetic use of observations**, now **complemented with SMOS data**, for improved physical understanding of Physical mechanism involved in ocean-atmosphere interactions at high winds => SMOS+SST+Color+Altimetry+in situ+physical modelling

2) Demonstrate that the **Igor case results can be extended to an Historical database of TCs**

3) Provide a **roadmap methodology on how Smos SSS products can be used to improve TC intensity forecasts**
Context & Review
Emmanuel, 2003

\[ |V_{\text{max}}|^2 = \frac{C_k}{C_D} \frac{T_S - T_0}{T_0} \left( k^*_S - k^* \right) \]

Ck: enthalpy coefficient
CD: drag coefficient
Ts: sea surface Temperature
To: temperature at the top of the troposphere
K: air enthalpy at 10 m height
Ks: air enthalpy at the contact of the ocean at temperature Ts

Carnot cycle in TCs
The pre-cyclonic SST is a very important parameter for TC intensification prediction. In fact=> all the thermal content of the upper ocean =>Index were introduced & are used to predict TC potential intensification:

Ocean heat Potential (OHC) or Tropical Cyclone heat Potential (TCHP)

\[ OHC = \int_0^{26} \rho C_p (T(z) - 26^\circ C) \, dz. \]
Negative feedback of the ocean cooling on the TC intensification

Wind mixing=>SST cooling=>TC intensity damping (Vmax)
Vincent et al, 2012
Lyold and Vecchi, 2010
2011
Potential impact of the upper ocean stratification in the Amazon-orinoco Plume region on hurricane intensification

The barrier Layer Concept: Control of salinity on the mixed layer depth in the Tropical Atlantic ocean

The oceanic mixed layer, which is typically defined as a layer of constant density and temperature, plays an important role as an interface for air-sea interaction mechanisms. It is normally assumed that the layer of uniform temperature is also the layer of uniform density. However, as noted earlier, in regions where the salinity dominates over temperature in the determination of the mixed layer density, the difference between the MLD and ILD is defined as the BL as it acts as a barrier to entrainment cooling and vertical mixing.

Strength of the stratification is dependent on the density gradient at the base of the ML.
The density stratification below the plume may inhibit surface cooling due to mixing under TCS and potentially intensify hurricanes.
Amazon and Orinoco River Plumes and NBC Rings: Bystanders or Participants in Hurricane Events?

AMY FFIELD => J CLIM 2007

TABLE 1. The distribution of 1960–2000 hurricanes by location. With increasing category (hurricane strength), an increasing (decreasing) percentage of hurricanes pass through (outside) the plume region. For example, for category 5 hurricanes, 68% passed through the plume region, while only 32% passed outside the plume region.

<table>
<thead>
<tr>
<th>Category</th>
<th>1960–2000</th>
<th>Through plume</th>
<th>Outside plume</th>
<th>All hurricanes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>No./total</td>
<td>No.</td>
<td>No./total</td>
</tr>
<tr>
<td>Category 1</td>
<td>17</td>
<td>17%</td>
<td>84</td>
<td>83%</td>
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<tr>
<td>Category 2</td>
<td>13</td>
<td>32%</td>
<td>32</td>
<td>71%</td>
</tr>
<tr>
<td>Category 3</td>
<td>18</td>
<td>45%</td>
<td>22</td>
<td>55%</td>
</tr>
<tr>
<td>Category 4</td>
<td>18</td>
<td>60%</td>
<td>12</td>
<td>40%</td>
</tr>
<tr>
<td>Category 5</td>
<td>13</td>
<td>68%</td>
<td>6</td>
<td>32%</td>
</tr>
</tbody>
</table>

IBTrACS - International Best Track Archive for Climate Stewardship
Influence of the Amazon/Orinoco Plume on the summertime Atlantic climate
Vizzy and Cook, JGR, 2010

Using a regional atmospheric model (WRF).

Results from two ensembles: one with the plume SSTA removed, & the other with an idealized plume SSTA imposed,

=>reveal that the scale of the SSTA forcing is large enough to influence the summer climate over the tropical western Atlantic and Central America.

=>The presence of the plume increases the number of Atlantic basin storms by 60% (i.e., 4.66 more storms).

An increase in storm intensity also occurs, with a 61% increase of the number of storms that reach tropical storm and hurricane strength. However, these storms tend to be shorter lived and are associated with a 12% decrease in the number of tropical storm days.

Storm trajectories also shift westward over the western Atlantic associated with the presence of the plume, bringing them closer to the U.S. coast as both the steering winds and vertical wind shear over the Atlantic are modified.

These results suggest that the August storm systems may be more likely to track closer to the U.S. coast and/or over the Gulf of Mexico
Empirical Method to account for ocean stratification impact on TC intensity forecasting
Shay and Brewster, MWR, 2010

Ocean Heat Content (OHC) potential determination

Two-layer model

\[ g' = \frac{g(\rho_2 - \rho_1)}{\rho_2} \]

Average depth of the 20°C isotherm (climatology)

Sea surface height anomaly from altimetry

Determination of the depth of the 26°C isotherm

\[ H_{26} = \frac{H_{26}}{H_{20}} H_{20}, \quad \frac{H_{26}}{H_{20}} \]

Average depth of the 20°C isotherm (climatology)

Determination of OHC relative to the 26°C isotherm

\[ Q = \rho_1 c_p \int_{H_{26}}^{\eta'} [T(z) - 26°C] dz, \]

If \( h \) is the depth of the mixed layer (climatology), then:

From \( h \rightarrow n' \) : OHC prop to [(SST-26°C)h]

\( H_{26} \rightarrow h \) : OHC prop to [0.5(H_{26}-h)(SST-26°C)]

So with SST, SSHA and climatological profiles => OHC
Stratification parameter

\[ S = \sqrt{\frac{N_{\text{max}}}{N_0}}, \]

Equivalent OHC

\[ \text{OHC}_E = \text{OHC} \sqrt{\frac{N_{\text{max}}}{N_0}}, \]
A question is how SMOS SSS can help in better predicting \( S = \frac{N_{\text{max}}}{N_o} \)?
First Objective of the Study : analysis of Hurricane Igor case:

1.1-Demonstrate **first observations of SSS wake** behind a storm from Space

1.2-Emphasize the **potential of the synergetic use of observations**, now **complemented with SMOS data**, for improved physical understanding of Physical mechanism involved in ocean-atmosphere interactions at high winds

=>SMOS+SST+Color+Altimetry+in situ+physical modelling
What can we bring with SMOS data?

=> example for the Igor Case

A salty TC wake observed from Space
Right Plot: Llyod and Vecchi [2010]: the nondimensional term $V_{ts}/fL$, for translation speed $V_{ts}$, Coriolis parameter $f$, and characteristic length scale $L$ is a variable that can control the cyclone-induced SST response: from inertial oscillation theory we expect the maximum SST response to occur when $V/fL \sim 1$; Here we choose $L=R_{max}$ (the radius of maximum winds). The cyan area is indicating the period when Igor crossed the Amazon-Orinoco Plume.

=> Max SST response shall occur from ~15->20 Sep
Atmospheric Conditioning: vertical wind shear

Low wind vertical shear $(u(250\text{mb}-850\text{mb}))$ in the hurricane area:

⇒ the large scale atmospheric circulation was not conditioning the hurricane evolution.

TC Intensification shall have been dominantly driven by ocean-atmosphere interactions.
Oceanic Pre-Storm Conditions: SST and TCHP

Figure 1: (a) TMI-AMSR microwave satellite-derived SST composite image of the Amazon plume region revealing the SST conditions the 10 September 2010 before the passing of Hurricane Igor, a category 5 hurricane that attained wind speeds of 136 knots in September 2010. The magenta and cyan contours are indicating the 28°C and 29°C levels. The black curves is the contour of the sea surface salinity at 35.75 deduced from SMOS data prior the storm, delineating the horizontal extent of the Amazon-Orinoco Plume (see Figure 2). Color-coded squares mark the successive hurricane eye positions and maximum 1-min sustained wind speed values.

(b) Tropical Cyclone Heat Potential (TCHP) derived by AOML for the 10 September 2010. TCHP is defined as a measure of the integrated vertical temperature from the sea surface to the depth of the 26°C isotherm and is derived here from AVISO SSA and historical 1992-2006 in situ temperature profiles.

Intensification starts over the 28°C waters. The plume is warmer ~29°C. TCHP along track is favorable for hurricane intensification and max over the plume.
**Atmospheric Forcing During Igor**

Note: GFDL model winds have been well compared to other wind obs in IGOR (see our 2012’s JGR)

**(a)** Maximum surface wind speed at 10 m height during the month of september estimated from NAH/GFDL hurricane model. The thick and thin black curves are indicating the hurricane eye best-track and locii of maximum surface wind, speed respectively. The thin dotted black curves are the radii of wind speed equal to 34 knots. The magenta and gray-blue contours are indicating the pre and post hurricane plume horizontal extent (contours at SSS=35.75 pss), respectively.

**(b)** Corresponding Wind Power Index \( WPi \).

Where \( WPi(x,y) = \left( \frac{\int_{t_0}^{t_0+3\text{days}} \int_{x_0-3\text{day}}^{x_0+3\text{day}} C_{D10}(x,y,t)u_{10}(x,y,t) \, dt}{\int_{t_0}^{t_0+3\text{days}} \int_{x_0-3\text{day}}^{x_0+3\text{day}} C_{D10}(x,y,t)u_{10}(x,y,t) \, dt} \right)^{\frac{1}{3}} \) and \( (x_0,y_0) = [35^\circ\text{W},17^\circ\text{W}] \)

is a location where Igor was a Tropical Storm and \( t_0 \) is the date of maximum wind.

CD is determined from Kudryavtsev and Makin [2011] (follows obs by Powell et al. 2003; 2006; Jaroz et al 2007) => significant saturation and even decrease at high wind.
In between blue curves: spatial locations around the eye track for which the wind exceeded 34 knots during the passing of the hurricane.
The max wind is on the right-hand side along the red curve but we will look also at properties along its symmetrical counterpart on the left hand side.
The color is indicating to: the day in September for which the maximum hurricane-induced wind speed occurred according to GFDL model.
=>this plot is not meant to be published.
Igor Wake synergetic Observations from Space
Figure 2: Two SMOS microwave satellite-derived SSS composite images of the Amazon plume region revealing the SSS conditions (a) before and (b) after the passing of Hurricane Igor, a category 5 hurricane that attained wind speeds of 136 knots in September 2010. Color-coded circles mark the successive hurricane eye positions and maximum 1-min sustained wind speed values in knots. Seven days of data centered on (a) 10 Sep 2010 and (b) 22 Sep 2010 have been averaged to construct the SSS images, which are smoothed by a 1° x 1° block average.
Surface wakes of Hurricane Igor

Figure 4: Surface wakes of Hurricane Igor. Post minus Pre-hurricane (a) Sea Surface Temperature (ΔSST) (b) Sea surface Salinity (ΔSSS), (c) Sea Surface Density (Δσ₀) and (d) Sea Surface CDOM absorption coefficient. The thick and thin curves are showing the hurricane eye track and the locii of maximum winds, respectively. The dotted lines is showing the pre-hurricane plume extent. ΔSST, ΔSSS, Δσ₀ wakes were only evaluated at spatial locations around the eye track for which the wind exceeded 34 knots during the passing of the hurricane.

ΔSST, ΔSSS, Δσ₀ wakes were only evaluated at spatial locations around the eye track for which the wind exceeded 34 knots during the passing of the hurricane.

Six days of data centered on t₀–(+4) days have been averaged to construct the pre (post)-cyclonic quantities. Here

\[ a_{cdom} = a_d + a_g \]

ag: CDOM (dissolved matter)
ad: non living particulate organic material, bacteria, inorganic material and bubbles
Figure 8: Differences in sea level (elevation in red, depression in cyan) between successive Jason-1/2 altimeter tracks before and after the Igor passage. Only tracks roughly perpendicular to the Igor track have been pictured. Numbers above the tracks give the day for one altimeter track after the Igor passage, the sea level difference being then computed using the altimeter track for the previous 10-day cycle. Igor eye track is materialized with the blue line, and squares and numbers indicate the Igor location for the day at 12Z. The blue dashed-line is indicating the track of the tropical storm Julia. The magenta-colored symbols give the location of several Argo floats providing vertical profiles in Igor wake (see figures 9). The black dots indicate the pre-storm location of the Amazon/Orinoco plume boundaries.
Validation of sat observation with In Situ Observations
Figure 9: Positions of the nine Argo floats providing salinity and temperature profile measurements within the high-wind (>34 knts) wake of Igor before and after the storm passage (labeled A1 to A9). The location of the profilers before and after the storm passage are indicated by black and magenta symbols, respectively. The corresponding number of days between the date of the ARGO float profile measurements and the date of the local highest wind during Igor passage are indicated in the legend (before/after the storm). The storm eye track is shown as colored circles, indicating the days in September along track with the code provided in the colorbar. The orange and gray-blue contours are indicating the pre and post hurricane horizontal extent of the Amazon-Orinoco plume, respectively.
Figure 6: Satellite (left) and in situ (right) post minus pre-hurricane (a-b) Sea surface Salinity (ΔSSS) and (c-d) Sea Surface Temperature (ΔSST) (°C) at 10 Argo-float locations (colored circles) along the hurricane high-wind path. The orange and gray-blue contours are indicating the pre and post hurricane plume horizontal extent (contours at SSS=35.75 pss), respectively. In (a) the numbers in black boxes are some selected ARGO-profile WMO identifier.

Note: the Argo float selected here all have measurements at ~5 m depth within the 10 days before and after Igor passing. The temporal averaging of the sat data may explain the differences with in situ obs (which are only available once before & after)
**Figure 7:** Comparison between Satellite and *in situ* estimates of the Pre minus Post storm changes in (a) sea surface Salinity $\Delta$SSS, (b) Sea Surface Temperature ($\Delta$SST) (°C) and (c) sea surface density $\Delta\sigma_o$ at the Argo-float locations (colored circles) along the hurricane high-wind path.

Root-mean-square deviations over the 9 samples of 0.37, 0.4°C and 0.34 kg.m$^{-3}$ for surface salinity, temperature and density, respectively
Insight into mechanisms & obs consistency:

Q1: how to evidence impact of plume stratification on SST cooling?

Q2: why Sea Surface Trough from altimetry is ~symmetric on both sides of storm track & sea surface response is not?
Figure 9: Median observed sea surface changes in (a) temperature, (b) salinity, (c) density and (d) CDOM absorption coefficient as a function of the Wind Power index (WPi). The median quantity values were estimated over WPi bins with width of 0.2. The red color indicates the variable estimated in the open ocean domain (the red domain shown in the inlet of subplot (c)) and the blue color indicates the variables estimated in the plume waters.
The Plume ssts with $W_{pi} < 3$ are dominantly located on the left-hand side of the Storm. So for an equivalent $W_{pi}$ value there is a clear reduced cooling on the Left hand side of the plume compared to open-ocean waters

$\Rightarrow$ Good demonstration of the cooling inhibition by pre-storm ocean stratification
About the ΔSST in the TC right hand side at Wpi >3

Apparently, the reduced cooling amplitude at high WPi values (>3) is similar within the plume to what is observed outside the plume in open-ocean waters.

The high WPi zone intercepting the pre-storm plume corresponds to an area which has been strongly eroded by the wind-induced mixing. It's associated with ΔSST similar to open ocean zones at same WPi but with much higher ΔSSS.

Consequently, it is a zone with maximized surface density increase Δσ.

The saturation of ΔSST in open ocean waters at WPi >3 is potentially associated with the fact that the curve is built by averaging both pre-plume and post-plume conditions. The nondimensional parameter Vts/fR is significantly differing between both zones. To account for that fact, may be we could weight the WPi by Vts/fR (see slide 3, right plot)? But by construction, WPi shall include that effect.
Figure 10: Vertical Profiles of Temperature (black circles) and Salinity (blue circles) measured before the storm (filled circles) and after the storm (open circles) at four ARGO floats with WMO # (a) 4900818, (b) 4900321, (c) 6900590 and (d) 4900819. The depths $D_\sigma$ and $D_{T_02}$ of the pre-storm mixed layer (depth where $\sigma(z=0) - \sigma(z=10m) > \Delta\sigma$ equivalent to 0.2 degC decrease in T at salinity=S(z=10m) are indicated by horizontal dashed lines. The thickness of the pre-storm barrier layer is defined as $D_{T_02} - D_\sigma$ and is indicated by the gray shaded area.
Figure 11: Vertical Profiles of Density measured before the storm (red circles) and after the storm (black squares) at four ARGO floats with WMO # (a) 4900818, (b) 4900321, (c) 6900590 and (d) 4900819. For each Argo float, the pre-storm stratification represented by the Brunt-Vaisala frequency N(z) is illustrated by the blue dotted curves. The depths $D_\sigma$ and $D_{T,0.2}$ of the pre-storm mixed layer (depth where $\sigma(z=0) - \sigma(z=10m) > \Delta \sigma$ equivalent to 0.2 degC decrease in T at salinity=S(z=10m) are indicated by horizontal dashed lines. The thickness of the pre-storm barrier layer is defined as $D_{T,0.2}-D_\sigma$ and is indicated by the gray shaded area.
Apparently, the thick BL & high stratification below the plume Reduced the mixing induced by the TC on the left-hand side => Reduced cooling on that side

But we have to understand left-right asymmetries
Asymmetries in surface response signatures

Symmetry in depth-integrated sea level trough
Oceanic response to TC mixing: 2 major mechanisms

=> Review Longuet-higgins, 67, Geisler, ..Price, (81,2009,..)
Ginis & Sutyrin 96, Ginis 2002…Shay..

- Barotropic component
- Baroclinic component

Barotropic component

Figure 2. The sea surface elevation (left, centimeters) and current velocity field (right, m s\(^{-1}\)) calculated from a single layer model, with depth of h=250 m. The hurricane wind stress was moving from the right to the left with a speed, 5 m s\(^{-1}\). The crosses indicate the initial and 6-day center positions.
Baroclinic component

Strong asymmetry in surface currents

**Figure 1** The displacement of the layer interface (left, meters) and current velocity field (right, m s$^{-1}$) calculated from a 1 ½ reduced gravity model with initial depth $h=100$ m. The dashed contours indicate upward displacement. The hurricane wind stress was moving from the right to the left with a speed, 5 m s$^{-1}$. The crosses indicate the initial and 6-day center positions.

This effect mostly drive the asymmetry in SST & SSS responses
Modeling the barotropic component
In the plume region for Igor

According to Ginis and Sutyrin (1996), the sea surface elevation $\xi$ generated by a hurricane is formed by a combination of four physically different processes:

$$\xi = \xi_c + \xi_d + \xi_a + \xi_b$$

The first term on the right-hand side ($\xi_c$) represents the elevation geostrophically balanced with the depth-averaged currents. The second term ($\xi_d$) describes the elevation caused by wind stress divergence. The third term ($\xi_a$) describes the sea surface elevation, associated with the inverted barometer effect, and the last term ($\xi_b$) represents the influence of the baroclinic response. The elevation generated by the inverted barometer effect moves with the

$$\xi_c = -f \int_{-\infty}^{\gamma} \bar{u} dy$$

$$\bar{u} = -2y \int_{b1}^{b2} \frac{\tau_{\theta}(r)}{(r^2 - y^2)^{1/2}} dr$$

$\Rightarrow$ Consistent comparisons between Model trough in Igor wake & altimeter observations
Modeling the baroclinic component
In the plume region for Igor

The slower the storm, the more symmetric the SST response

Forward translation speed of Igor

Igor Slow over the plume V~3-5 m/s

Undergoing task, use a 1D model with & without equivalent plume
Stratification to reproduce surface wakes SST asymmetries
Objective II of the study:

Demonstrate that the **Igor case** results can be **extended to an Historical database of TCs**
Historical Surface Properties: June through November

*National Oceanographic Data Center (NODC): 1896-2009+ARGO 2009-2010*

**Average Salinity**

- Amazon & Orinoco Plumes

**Average Temperature**

- 28°C
- 35.7

- 28.5
- 28
- 27.5
- 27
- 26.5
Historical Surface Properties: June through November

NODC

Average Salinity

Longitude averaged sections (blue box)

Ibtracks 1851-2010

Average numbers of TC tracks per 1° square

Number of Tracks

Depth (m)

Salinity

Latitude

Number of Tracks

Depth (m)

Temperature

Latitude
The historical density of Hurricane tracks show maxima which coincide with climatological maxima in subsurface Salt-driven stratification (max of $N(z)$): causal effect?
Re-analysis of TC tracks that crossed the plume within a radius of 200 km over period 1998-2010

I Used TMI-AMSRE to characterized the DSST following exactly E.Vincent method (i.e. within Radius < 200 km) => Classified Dsst as function of Vmax and distinguished Overpasses Dsst domaines on plume waters & open ocean
Using a mask based on the historical extent of the Plume (green domain)
Example Hurricane Ivan
2 - 24 September 2004  (cat 5, cat 3 au Bahamas)

The blue domain is the $R < 200$ km

Vmax [knots]

Dsst [$^\circ$C] from TMI/AMSRE

Apparent reduced cooling in the plume
Other example %Hurricane Emily (cat 5) %11-21 July 2005

Here again, apparent reduced cooling in the plume
Statistical analysis all tracks 1998-2010

Slow storms

Fast storms

Apparenty, SST cooling inhibition in plume waters as observed in Igor is confirmed by an historical dataset

As expected, the impact is stronger for slow moving storms
Third Objective of the study:

Provide a **roadmap methodology on how Smos SSS products can be used to improve TC intensity forecasts**

Idea:
Can SMOS SSS can be used to derive Nmax and constraint OHC ?
Profiles data

- 20,000 ARGO profiles (1997-2011)
- 100,000 NODC profiles (WOD09: 1913-2009)
  - high & low resolution CTD
  - glider data
  - profiling floats
Mean values 0-10m over August-October
Climatologic mean profiles in & out of the Plume over August-October
Climatologic median profiles over August-October
SSS & SST (0-10m) as a function of Nmax in the Plume

In Plume - August-October

SSS (psu)

Nmax (cph)

SST (degC)

Nmax (cph)
Empirical model: \( N_{\text{max}} = f(\text{SSS}) \)
Pre-Igor Conditions

1 week Before IGOR

(a)

Empirical model:
\[ N_{\text{max}} = f(\text{SSS}) \]
Excellent consistency between SMOS deduced Nmax & in situ!
$S = \sqrt{\frac{N_{\text{max}}}{N_o}}$

**Equivalent OHC**

$$\text{OHC}_E = \text{OHC} \sqrt{\frac{N_{\text{max}}}{N_o}}$$
Conclusions:

Submit a paper soon

Write a dteil review