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Satellite-Derived Estimates of Suspended $CaCO_3$ Mud Concentrations from the West Florida Shelf Induced by Hurricane Ian †

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Abstract: In the days following the passage of Hurricane Ian over the West Florida Shelf, a large plume of calcium carbonate ($CaCO_3$) mud slurry was observed extending from west of the Dry Tortugas and curving to the east into the Straits of Florida. This discreet target offered a unique opportunity to quantify the suspended mass of $CaCO_3$ in the slurry. Estimating the concentration of sediment in a plume of suspended $CaCO_3$ by satellite sensor observations has been stymied up to now owing to a lack of *in situ* suspended sediment measurements during storm events, as "sea truth" data for such events is difficult to acquire. However, the Particulate Inorganic Carbon (PIC) standard product provided by the NASA Ocean Biology Distributed Active Archive Center (OBDAAC) is based on Moderate Resolution Imaging Spectroradiometer (MODIS) observations of a plume of coccolith chalk released from a ship in the "Chalk-Ex" experiment. Due to the similarities (particle size, mineralogy, and reflectance properties) of the suspended chalk features and the Ian-induced slurry, we utilized this data product to make initial estimates of the concentration of suspended sediment in the plume.

Keywords: sediments; transport; hurricanes; ocean optics; carbon cycling

1. Introduction

One of the largest uncertainties in oceanic marine calcium carbonate ($CaCO_3$) cycling is the amount of shallow-water $CaCO_3$ that is transported from reefs, banks, platforms, and tropical continental shelves to deeper pelagic waters, where these sediments will be either deposited or dissolved, depending on water depth and the saturation state of the water column with respect to $CaCO_3$ [1,2]. Furthermore, primary physical mechanisms by which $CaCO_3$ sediments are transported from shallow environments to deep waters have not been fully characterized or quantified [3,4]. In contrast, the flux of biogenic pelagic $CaCO_3$ has been relatively well characterized using sediment traps and other methods, though uncertainties remain [5–11].

While it is clear—from both marine geological research [12–14], and more recently, satellite remote sensing observations [15,16]—that tropical storm system winds (e.g. hurricanes, typhoons, and cyclones) are capable of first suspending and subsequently transporting large masses of $CaCO_3$ sediments from shallow-water environments to the deep ocean, it has been quite difficult to quantify this important process. There are several reasons for this difficulty. These features are short-lived because the sediments sink relatively rapidly in the water column, and the high windspeeds inducing the transport are also locationally of short duration. The locations that sediment transport features will be generated from are dependent on reef and bank morphology, wind direction and windspeed of a storm, and even the rate and direction of movement of the storm. Furthermore, storms

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of this nature generate hazardous conditions, making *in situ* sampling problematic and dangerous.

Therefore, satellite remote sensing offers a useful alternative method for observing and characterizing $CaCO_3$ sediment transport events. The increasing availability of remote sensing data and imagery from multiple satellite instruments also makes event observations, once a fortuitous rarity, more common, inviting the potential for vastly improved quantification. In addition, these observations can provide answers to basic questions in carbonate process sedimentology which have gone unanswered for over 80 years.

1.1. Hurricane Ian's Interaction with the West Florida Shelf

Hurricane Ian formed in the Caribbean Sea from an African tropical wave in late September 2022. The system organized into a tropical depression on September 23, and achieved tropical storm strength on September 24 south of Jamaica, reaching hurricane strength on the next day. The storm moved northward over western Cuba, and on September 27, at Category 5 strength, passed over the West Florida Shelf before making a catastrophic September 28 landfall on the west coast of Florida near Sanibel Island and Fort Myers. Ian subsequently crossed the Florida peninsula and moved into the Atlantic Ocean, regained strength, and made a second landfall on the South Carolina coast.

Figure 1 shows the passage of Hurricane Ian over the West Florida Shelf, and the subsequent appearance of the shelf.

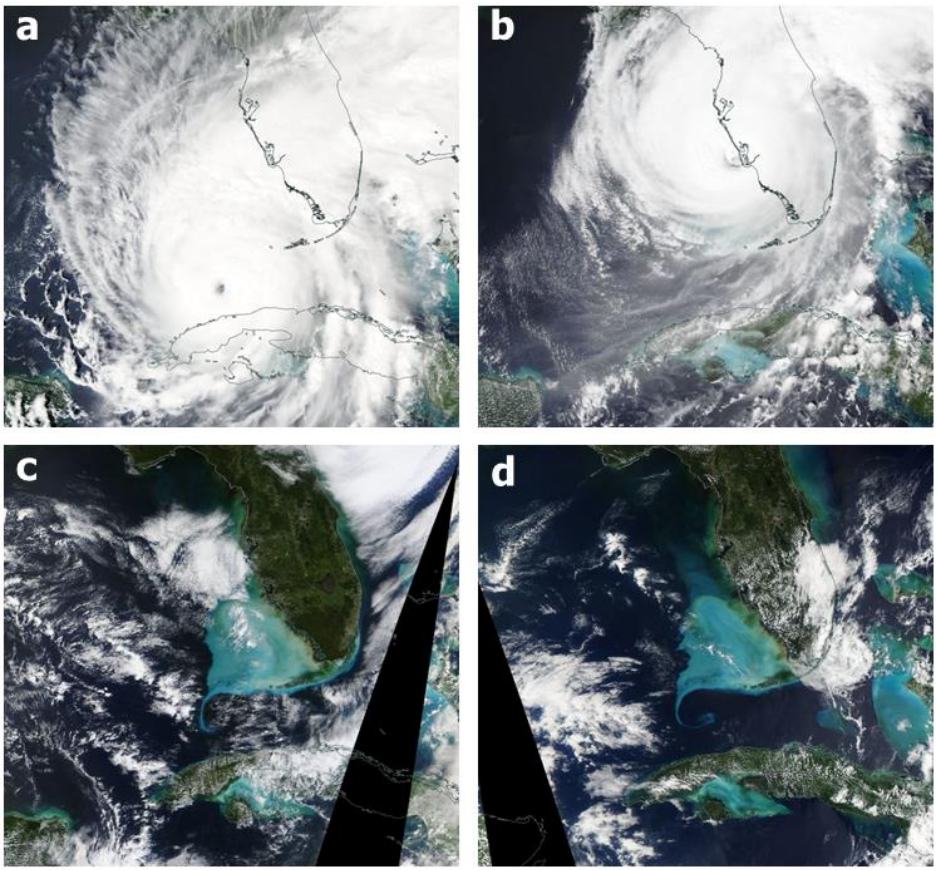

Figure 1. Images of the passage of Hurricane Ian over the West Florida Shelf. (**a**) September 27, 2022, MODIS-Aqua. (**b**) September 28, NOAA-20 VIIRS. (**c**) September 30, MODIS-Terra. (**d**) October 1, MODIS-Aqua.

Following the passage of Ian over the West Florida Shelf, the bright reflective "Maya Blue" color of the shelf sediments indicates widespread sediment suspension due to the water column stirring by Ian's high windspeeds. To the west of the Florida Keys and Dry

Tortugas, a high reflectance arcuate feature is indicative of a plume of suspended sediment mud. Sediments in this plume can be seen initially transported to the west, then curling to the east in the flow of the Loop Current as it enters the Straits of Florida. This plume will be discussed and analyzed in the remainder of this paper.

2. Materials and Methods

The images of the effects of Hurricane Ian on the West Florida Shelf were acquired from NASA Worldview [17]. RGB images were subset from the archived imagery acquired from the two Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the Terra and Aqua satellites, as well as imagery from the Visible Infrared Imaging Radiometer Suite (VIIRS) on the National Oceanic and Atmospheric Administration (NOAA) NOAA-20 polar-orbiting environmental satellite.

Imagery and data of the MODIS standard Particulate Inorganic Carbon (PIC) data product were acquired from the NASA Giovanni system [18]. This product is based on the "Chalk-Ex" remote sensing of suspended coccolithophore chalk experiment [19, 20]. Ocean color standard products in Giovanni are provided from the Ocean Biology Distributed Active Archive Center (OBDAAC) at Goddard Space Flight Center (GSFC). Subsequently, MODIS Level 2 daily PIC data files were acquired from the OBDAAC for analysis with the NASA software package Panoply [21].

3. Results: Analysis of the Hurricane Ian-Generated Sediment Plume

3.1. Giovanni Analysis of 8-day MODIS Level 3 Data

The first step of our analysis was an examination of MODIS-Aqua 8-day Level 3 data available in Giovanni. The 8-day PIC data file for the period September 30 – October 7, 2022 was selected, and the Florida and West Florida Shelf region was examined (Figure 2). This image indicated high values over the southern West Florida Shelf, attributable to sediment suspension and transport. It is difficult to distinguish in this image where suspended sediments are above deep water compared to suspension over shallower waters inside the shelf break.

Due to the potential combined signal of bottom effects and sediment suspension over the shelf, this analysis concentrated on the sediment plume feature located west and south of the Florida Keys and Dry Tortugas (Figure 3). This figure indicated that the maximum 8-day average concentration of PIC, in the form of $CaCO_3$, was at least 1000×10^{-5} mol/m^3. Because the sediment plume feature was only visible for the first four days of the 8-day period, it is possible to calculate an approximate daily concentration of $CaCO_3$, in both moles and grams per cubic meter. The four-day concentration would be 2000×10^{-5} mol/m^3 (0.02 mol/m^3), which is approximately 2 g/m^3 $CaCO_3$.

3.2. Panoply Analysis of MODIS Level 2 Data for October 2, 2022

In order to further examine the concentration of in the Hurricane Ian-generated plume, three Level 2 MODIS PIC file subsets were acquired from the OBDAAC for the dates September 30, October 1, and October 2. The October 2 file was selected for analysis. The file was opened with NASA Panoply, and the color palette was selected and "tuned" to both visually and numerically bracket the highest PIC values in the plume (Figure 4). This process allowed the isolation of values in the plume, separate from the region to the north, which is less clearly defined as a single feature.

The results of this procedure indicate that the range of PIC values in the plume is about 0.017 - 0.029 mol/m^3. These values agree well with the value estimated from the 8-day data image from Giovanni, and thus indicate a maximum concentration of $CaCO_3$ in the plume of approximately 3 g/m^3.

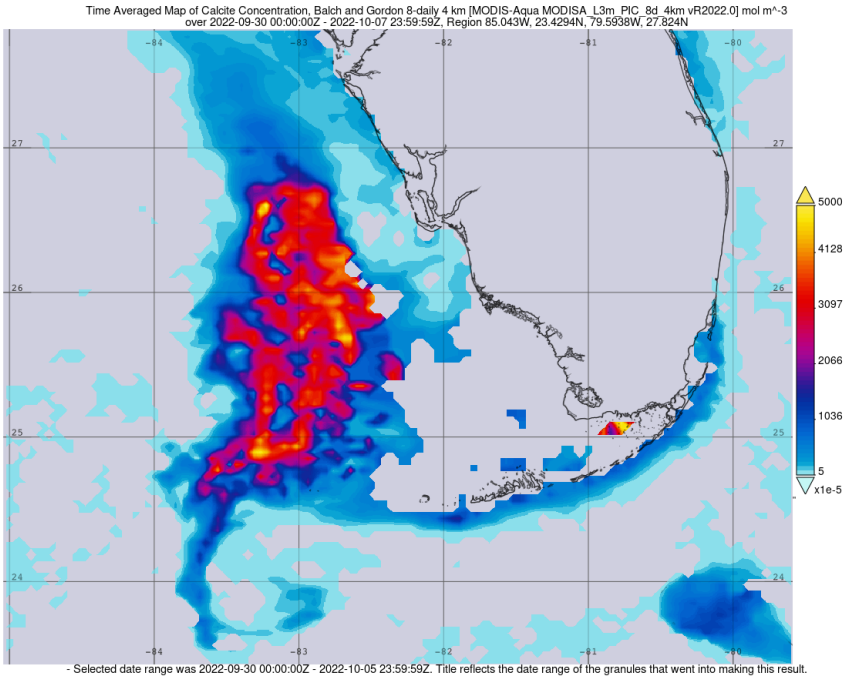

Figure 2. MODIS-Aqua 8-day PIC data image for the period September 30 – October 7, 2022, visualized with Giovanni. High values of the PIC variable over the West Florida Shelf are attributable to sediment suspension and bottom reflection.

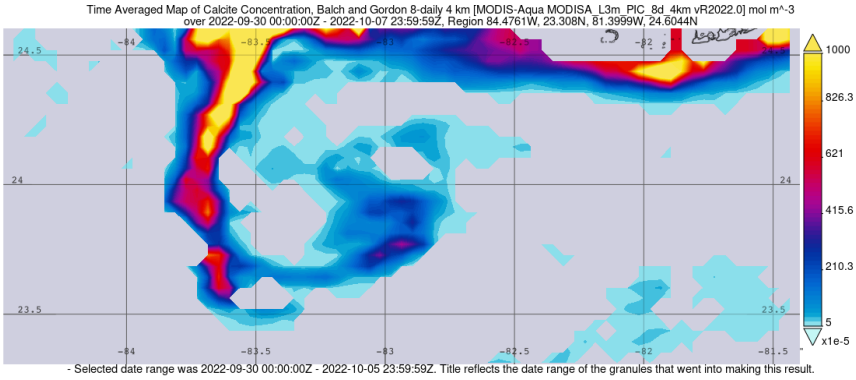

Figure 3. MODIS-Aqua 8-day PIC data image for the period September 30 – October 7, 2022, examining the region of the sediment plume extending from the southwestern edge of the West Florida Shelf. .

4. Discussion

Concentrations of particulate matter with values of 2-3 grams per cubic meter may seem very high to those accustomed to open ocean values of milligrams to micrograms per cubic meter. It should be noted, however, that what is being examined here is a suspension of sediment in seawater, termed a "slurry". The primary sediment component of the slurry in this case is fine-grained $CaCO_3$ sand and silt, which is easily suspended in the current flow generated by Ian's winds. The distance of transport by the plume indicates that the sediments are likely in the sand and silt size category, and thus will settle slowly in the water column.

This value can be compared to other mass concentration estimates for suspended sediments. Conrad Neumann measured sediments in the Bight of Abaco suspended by winds following a storm in the Bight of Abaco with an average value of ~2 g/m^3. [22]

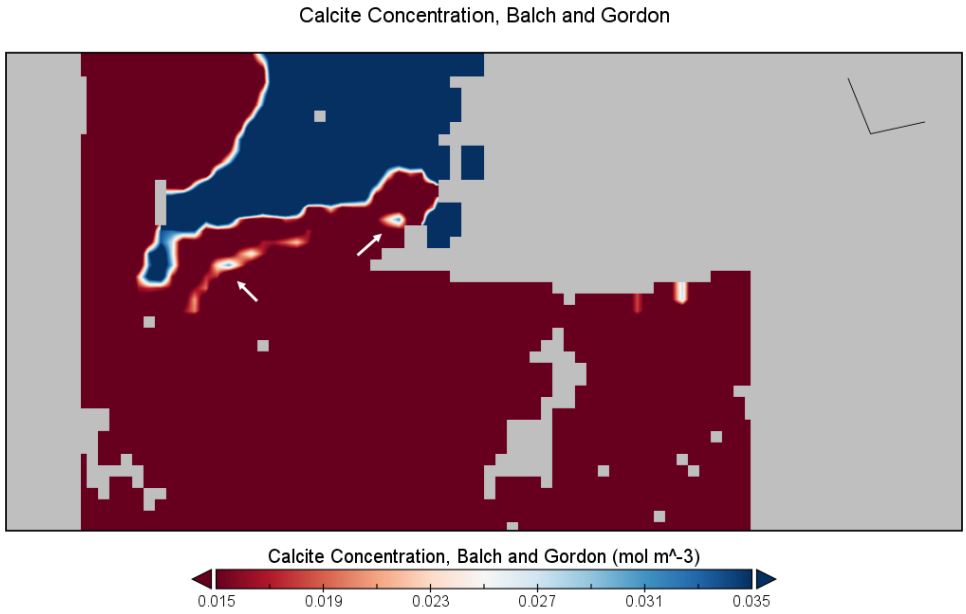

Figure 4. Image of MODIS-Aqua PIC data (Balch and Gordon algorithm) for October 2, 2022. The highest values of PIC in the plume are indicated with arrows. The black line chevron at upper right is the southwesternmost coast of Florida.

Using an empirical algorithm, Acker et al. [16] estimated the mass concentration of two hurricane-generated carbonate sediment plumes in pelagic waters as 0.42 and 0.71 g/m^3. Thus, this initial estimate for the Ian-generated plume is similar in magnitude to these values, even though this event – the interaction of Category 5 hurricane winds with shallow shelf sediments – is rare and unusual. It can also be noted that sediment plumes forming in this location have been observed before, including the passage of Hurricane Wilma in 2005 and recently, the passage of Hurricane Idalia in 2023. The bottom morphology and geography thus appears conducive to the formation of a density flow when sediments are suspended by elevated windspeeds.

Our use of the PIC data product as a proxy for suspended sediment concentrations is a first step in the process of developing improved quantitative estimates for storm-induced sediment transport. We expect that there is a similarity of optical properties between a suspension of coccolithophore chalk, as was done for Chalk-Ex [19] and a mixture of carbonate shelf sediments. These materials are certainly similar, both compositionally and in their appearance when suspended in seawater, as numerous images of coccolithophore blooms attest. The primary differences would be the homogenous particle size of the chalk compared to the mixed particle sizes in a sediment suspension; and the potential difficulty of extending the PIC algorithm, derived from an open water suspension of chalk, to the higher mass concentration of sediments in the mud slurry created by Ian.

5. Conclusions

In this paper, we have examined a unique feature caused by the passage of Hurricane Ian over the West Florida Shelf. Our examination has produced useful first-order estimates of sediment mass concentration in this feature. As researchers endeavor to examine similar events with the eventual goal of quantifying this process on a global scale – and to use this quantification to advance understanding of the importance of this process to both ocean carbonate chemistry and carbonate sedimentology – this first step indicates that remote sensing observations are the best way to accomplish this goal.

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