Report on the potential origin of the SCTLD in the Florida Reef Tract

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ABSTRACT

For about six years, the Florida Reef Tract (FRT) has been experiencing an outbreak of the Stony Coral Tissue Loss Disease (SCTLD). Although the epicenter of the propagation of the disease has been identified off the coast of Miami-Dade County in 2014, the origin and identity of the agent responsible for the initiation of the epidemic remain unknown. A potential scenario is that this agent was transported to the first-affected coral colonies within material driven by currents. The goal of this preliminary study is therefore to identify the potential sources of such material. Backward and forward particle tracking from May to September 2014 suggested that fine matters suspended in the water column generated by phase III of the expansion of Port of Miami (November 2013 - March 2017) might have been transported south, to the first-identified diseased colonies. However, sediment modeling showed no sediment transport south to the dredged channel during our simulated period. An extension of the simulated period is therefore required to determine whether hydrodynamics allowed sediments to reach the first-affected colonies prior to May 2014. Besides, the modeled impact of sediments on the reefs located north to the dredged channel suggest that the SCTLD outbreak might have been initiated north to the reefs where it was first observed by Precht et al. (2016). Further propagation studies would assess the feasibility of disease transmission from the north to the south of the dredged channel.

INTRODUCTION

Coral diseases are a major threat to coral reef ecosystems and have led to significant declines in coral cover especially within the Caribbean region (Richardson et al. 1998, Sutherland et al. 2004, Aronson and Precht 2001, Harvell et al. 2007, Miller et al. 2009, Brandt et al. 2009). A novel coral disease called the Stony Coral Tissue Loss Disease (SCTLD) gave rise to an outbreak that is now threatening the last vestiges of coral throughout the Florida Reef Tract (FRT). First documented off the coast of Miami-Dade County in the summer of 2014 by Precht et al. (2016), the SCTLD has since spread throughout the entire FRT with the exception of the Dry Tortugas. The initial exponential growth among reefs from the disease epicenter (Precht et al. 2016) and the persistent subsequent linear rate of spread of SCTLD (Muller et al. 2020), north along South Florida reefs and south into the Florida Keys, indicates that water currents may play a role in disease transmission. To date, SCTLD has been observed affecting over 20 different stony corals species. Unfortunately, SCTLD has not remained isolated in the Florida reef tract and has now been recorded in Mexico (Alvarez-Filip et al. 2019), the USVI (Blondeau et al. 2020) and several other locations around the Caribbean. The continued persistence of the outbreak, the high number of species affected, and the large geographical range of reports of the disease suggests that SCTLD is the largest coral disease outbreak ever recorded.

To date, the causative agent of the disease remains unknown. Although the epicenter of the disease has been identified by Precht et al. (2016), little is known about how the disease was initiated on the first-contaminated reefs. Assuming that the agent was brought to these first colonies within material transported by currents, the potential sources of such infectious material may be found using virtual particle backtracking. Backtracking methods are often used for pollution tracing (Spivakovskaya et al. 2005) and can also be applied to identify larval spawning sites (Christensen et al. 2007) or hatchling areas (Batchelder et al. 2006). Further, they provide a more efficient way to identify material sources compared to forward tracking approaches (Christensen et al. 2007). With the latter methods, sources of infectious materials are identified by releasing virtual particles at candidate locations and considering the small proportion of particles that reach the colonies of interest (Allain et al. 2003). Forward tracking therefore requires larger numbers of particles and is less likely to unveil unexpected sources as particle release locations are given as input of the simulation. As in the case of forward tracking, diffusion cannot be ignored in backtracking in order to account for dispersion processes in the ocean (Batchelder et al. 2006). Backtracking is therefore not able to pinpoint unique origination points for the infectious material. Instead, it provides a probability density map with potential source locations. That map can then be combined with other sources of information to narrow down the search.

To accurately backtrack the trajectories of infectious materials in the vicinity of the colonies identified by Prechts et al. (2016), a realistic picture of the water circulation at the reef-scale is required. High spatial resolution is therefore needed to capture small-scale flow features such as recirculation eddies around reefs and islands that increase material retention and deflect water currents (Wolanski, 1994; Burgess et al., 2007; Figueiredo et al., 2013). Spatial resolution should be well below 1 km in dense reef systems, which is unaffordable in regional ocean models due to large computational cost induced. In this context, unstructured-mesh ocean models, which can locally increase the resolution, are good candidates to represent ocean circulation at reef scale as they allocate computational resources only where they are most needed (Lambrechts et al., 2008; Thomas et al., 2014, 2015).

The time and location of the initiation of the SCTLD in the FRT, as identified by Precht et al. (2016), coincide with the phase III of the expansion of the Port of Miami (POM), conducted between November 2013 and March 2015. The dredging activities performed during the expansion of the port are estimated to have killed > 560,000 corals within 0.5 km, with impact extending over 5-10 km and sediment plumes covering up to 11 km² of coral area (Barnes et al. 2015; Cunning et al. 2019). Considering the proximity of the first-contaminated colonies to the POM and the large impact radius of the expansion works, the causative agent of the SCTLD might have been transported to the first-contaminated colonies within sediments resuspended by dredging operations. This assumption may be assessed by modeling the transport of sediments from the dredge sites. As in the case of backtracking, the impacted zone is then highlighted by sediment distribution.

The objective of this study is to use virtual backtracking to identify the source of infectious material driven by currents that might have initiated the SCTLD outbreak on the reefs identified by Precht et al. (2016). These backtracking simulations are complemented with sediment transport simulations in order to assess the effect of the dredging activities conducted during the expansion of the POM. Finally results of both backward and forward simulations are compared to identify possible zones of overlapping particle distributions.

MATERIAL AND METHODS

Hydrodynamic and particle-tracking models

Our goal is to identify sources of infectious material that could have been transported by ocean currents on the first contaminated reefs. This requires an ocean model that provides a realistic large-scale circulation while also resolving small-scale flow features down to the scale of individual reefs. In this study, we use the unstructured-mesh depth-integrated coastal ocean model SLIM[1] to simulate ocean currents over an area that includes the FRT but also the Florida Strait and part of the Gulf of Mexico (Fig. 1). By using an unstructured mesh, we can locally increase the model resolution hence concentrate computational

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[1] https://www.slim-ocean.be

resources near the reef of interest. SLIM has already been successfully applied in complex coastal systems such as the Great Barrier Reef (Lambrechts et al., 2008; Thomas et al., 2014) and is well suited to shallow-water flows. Details of the model formulation and validation are provided in Frys et al. (2020).

Simulations are performed with the same mesh used to model the propagation of the SCTLD in the FRT. The model resolution depends only on the distance to the coast but we distinguish between the coastlines along the FRT where we impose a maximum resolution of 100 m and the other coastlines along which the finer resolution is 2500 m. The mesh has been generated with the open-source mesh generator GMSH (Geuzaine and Remacle, 2009) and has about 7×10^5 elements. The coarsest elements, far away from the FRT, have a size of about 10 km. An illustration of ocean currents simulated on that mesh are shown in Fig. 1. It shows how a 100-m spatial resolution allows us to simulate fine-scale details of the flow near the POM, such as the acceleration of currents between islands.

The simulated currents can then be used to model the transport of the material responsible for the initiation of the SCTLD outbreak. As this material can be of a different nature than the one responsible for the subsequent spread of the disease between reefs, we assume that it can be positively, neutrally and negatively buoyant. SLIM being a barotropic model, it produces depth-averaged currents that can be used to transport neutrally-buoyant material that remains within the water column. However, these currents must be modified to correctly represent the dynamics of material evolving in the surface and bottom boundary layers. Surface currents being influenced by wind-generated waves, they are estimated by adding 1.5% of the wind speed to the simulated depth-averaged currents with a windage angle of 45° to the right. This parametrization has been shown to be an accurate approximation of wave-induced Stokes drift and quasi-Eulerian surface currents by Ardhuin et al. (2009). It will be used to model the transport of positively-buoyant particles. For negatively-buoyant particles, we use bottom currents, which are obtained by taking 60% of SLIM currents velocity with a veering angle of 15° to the left. This is an approximation based on observations of bottom currents and whole water column current profiles in the shallow waters (<15 m) of Hawk Channel in the middle Florida Keys by Smith (2009), as well as observations obtained during the Atlantic Ocean Acidification Testbed project (Gramer pers. comm.). It is also consistent with the theory of current veering in the bottom Ekman layer, albeit that was previously observed in deeper (30-90 m) coastal waters, e.g., by Perlin et al. (2007) and Kundu (1976).

The modeled current velocities for the 3 types of material are then used in our particle tracking model. In this model, the position $\mathbf{x}_i$ of particle i is updated through time as follows:

$$d\mathbf{x}_i = \left(\xi \mathbf{u}(\mathbf{x}_i, t) + \nabla K(\mathbf{x}_i, t) + \frac{K(\mathbf{x}_i, t)}{H(\mathbf{x}_i, t)} \nabla H(\mathbf{x}_i, t) \right) dt + R\sqrt{2K(\mathbf{x}_i, t) dt} \quad (1)$$

where $\mathbf{u}$ is the current velocity, H is the modeled total water depth, K is the local diffusivity field and R is a random number following an uniform distribution between -1 and 1. The parameter ξ that multiplies the velocity $\mathbf{u}$ is equal to 1 (resp. -1) for forward (resp. backward) tracking simulations. On the other hand, the sign of the dispersion terms depending on the diffusivity K remains positive for both forward and backward simulations as random walk processes are time reversible (Christensen et al. 2007). All modeled particles are initiated with a given mass, that they lose continuously on the mesh elements that they cross on their trajectories. The distribution of the particle mass on the mesh at the end of the simulation defines the zone of dependence (resp. influence) of the location where particles are released for backward (resp. forward) tracking. This probability distribution is computed by normalizing the cumulated particle mass per surface unit obtained on each element at the end of the simulation. Taylor (1921) showed that for diffusive processes, the spatial accuracy on particle position $\mathbf{x}$ after transport time t follows $\sqrt{4Kt}$. Therefore, uncertainties grow and the modeled particles tend to become more widespread when going backward (resp. forward) in time with backtracking (resp. forward tracking), as shown in Fig. 2. As the SCTLD was first observed on September 26, 2014 by Precht et al. (2016) on the Virginia Key (VK) site highlighted in Fig. 1, this site serves as a release point for the backtracked particles in this study.

Impact of dredging activities

To assess the impact of the expansion of the POM on coral reefs, we focus on a destructive practice called “rock shopping”, performed using a Cutterhead Suction Dredge (CSD) during the project. The CSD is a floating platform equipped with a rotating cutter that pulverizes rock into fine colloidal sediments. While used in a conventional way, the loosened material is fed into a pumping system driving the material and water slurry away from the platform, on a barge or in a floating pipeline. The majority of the dredge material was then transported to the US Environmental Protection Agency designated Ocean Dredge Material Disposal Site (ODMDS) located 4.7 nautical miles offshore. However, the suction mechanism was turned off during non-conventional rock-chopping activities in order to pre-treat very hard rock contained in the Anastasia and Fort Thompson formations between December 2013 and May 2014. The Army Corps commissioned a report that provides a back-of-the-envelope estimating this practice could have resulted in up to 33 cm deposition over 874,121 m² of reef surrounding the outer entrance channel (Jocelyn Karazsia, pers. comm.).

To model the impact of these dredging activities, we simulate the transport of sediments produced during the non-conventional rock-chopping operations performed during our simulated period on 05/04/2014 and 05/05/2014. The simulations are performed in forward time using Eq. 1, with a modified advection term $\mathbf{u}'$:

$$\mathbf{u}' = \begin{cases} \mathbf{u} & \text{if } M \geq 1 \\ \max\left\{\frac{\mathbf{u}}{C_s}\left(10 - \frac{7}{\sqrt{M}}\right)\right\} & \text{otherwise} \end{cases} \tag{2}$$

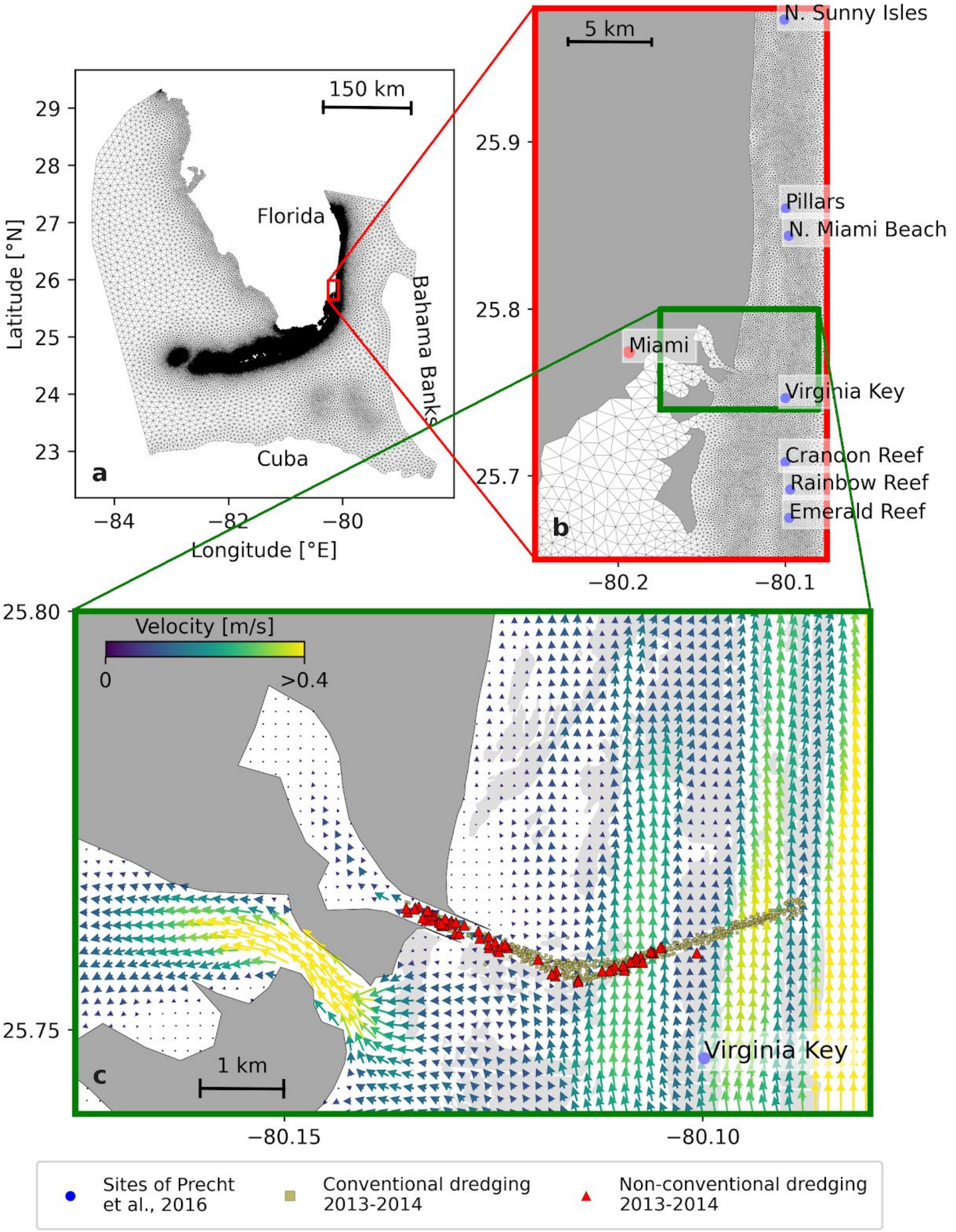

Figure 1. Model computational mesh **(a)** and close-up views around the POM **(b)** with a snapshot of the currents on September, 25 2014 at 00:00 near the Port of Miami **(c)**. Reefs are shown in light grey while the sites where Precht et al. (2016) first observed the SCTLD in 2014 are highlighted by blue dots. The dredging operations conducted during the Port of Miami Phase III expansion works are indicated by red triangles (non-conventional operations) and dark khaki squares (conventional operations).

where C_s is the dimensionless Chézy coefficient for rough turbulent flow and $M = \theta/\theta_{cr}$ is the ratio between the adimensional skin shear stress and the critical Shields parameter (Soulsby, 1997). When mean currents are strong enough to erode seabed ($M \geq 1$), sediments are suspended within the water column and transported by barotropic currents. Otherwise, sediments are moved as bedload transport.

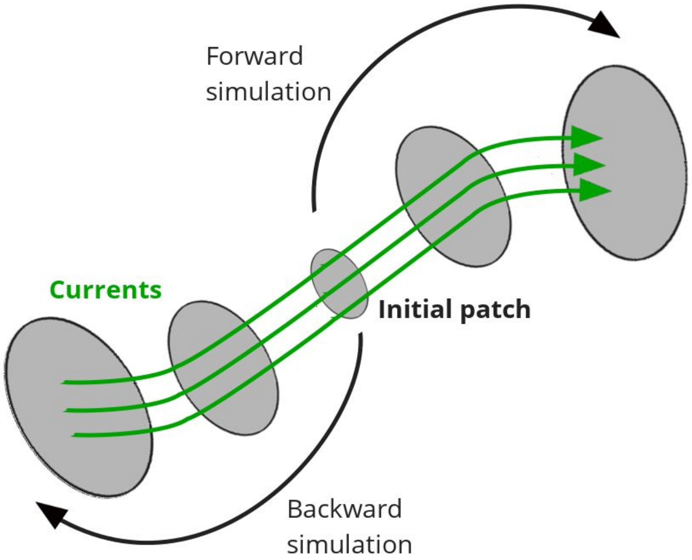

Figure 2. An initial patch of particles is transported forward in time by following the current velocity (shown in green), hence indicating where it will go. The same patch can be transported backward in time by reversing the direction of the velocity, hence indicating where it came from. In both cases, diffusion processes tend to spread out the patch and increase the uncertainty on the particles' position.

RESULTS

Backtracking results for each type of current are shown in Fig. 3. Particles were continuously "released" from the VK reef, starting on September 26, 2014 and the transport model was run in reverse time until May the 1st, 2014. As a consequence of the northerly flow of the Florida Currents, virtual particle mass concentrations are larger south of VK for all three types of currents. Due to the effect of winds, surface currents are the only transport mode that allows elements produced in Biscayne Bay to contaminate the sites identified by Precht et al. (2016). Mean and bottom currents, on the other hand, are more strongly impacted by the Florida Current, which prevents neutrally or negatively buoyant contaminants produced in the bay to reach the monitoring sites of Precht et al. (2016) . The Florida Current also prevents material from the offshore Dredging Material Deposition Site to reach the reefs on the shelf, as Fig. 3 shows no virtual particle mass on the ODMDS for all three types of currents.

VK’s dependence zone, for the 3 types of current, intersects the region where dredging operations were performed during our simulated period (Fig. 2). This indicates that all 3 transport modes might have allowed suspended particles produced by the expansion works of the Port of Miami to reach the first contaminated reefs observed by Precht et al. (2016). More specifically, the non-zero virtual particle mass concentrations at the locations where non-conventional dredging activities were performed on 05/04/2014 and 05/05/2014 (red triangles) with mean currents suggest that neutrally buoyant elements produced during these operations might have reached VK reef. Forward sediment simulations from May, 4 to September, 26 2014 were therefore performed to estimate the propagation of the pulverized rocks produced by rock-chopping. Although large particle concentrations are observed on the reefs located north to the dredging sites, sediments were barely transported southward (Fig. 4). Due to the impact of the Florida Current on local circulation, southward currents are too weak to resuspend sediments in the water column. This leads to sediment being almost exclusively transported north by the currents.

These sediment simulations were complemented by forward tracking of suspended particles continuously released at the non-conventional dredging sites located inside the dependence zone of the VK reef (see Fig. 3). Although the corresponding rock chopping operations were performed outside our simulated period, forward particle tracking might serve as a proxy to estimate whether dredging operations prior to May 2014 might have impacted the VK reef. Fig. 5 shows that the boundary of the influence zone of the particles released on the non-conventional dredging sites intersects the site of VK. This confirms the results obtained by backtracking simulations in Fig. 3 and suggests that the site of VK might have been reached by particles produced by the rock chopping sites, provided that they are sufficiently fine to remain suspended most of the time inside the water.

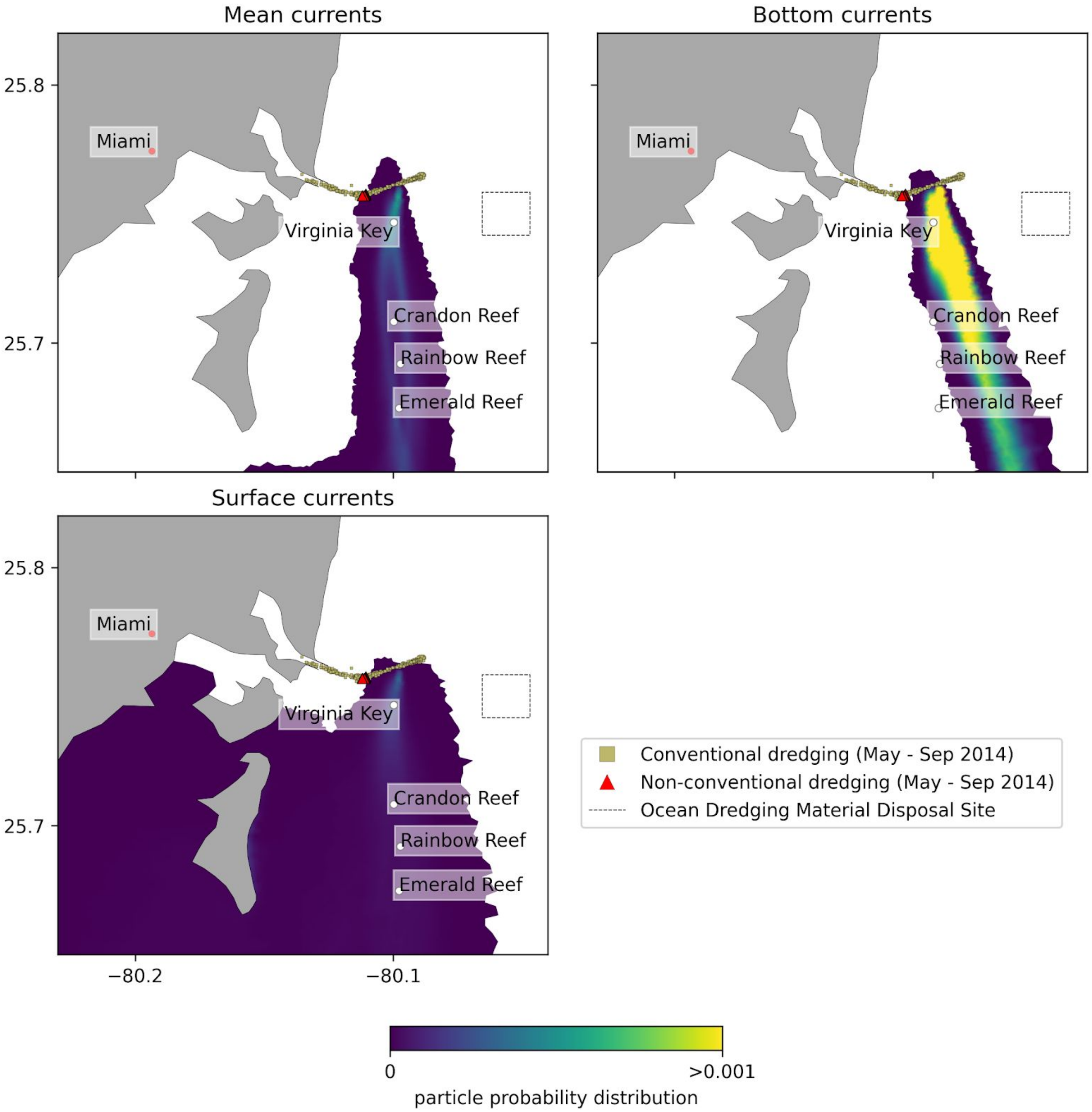

Figure 3. Particle concentrations obtained with mean, bottom and surface currents for the backtracking simulations starting at Virginia Key. All 3 simulations show that particles that arrived on Virginia Key could have originated from the dredging operations in the navigation channel leading to the Port of Miami.

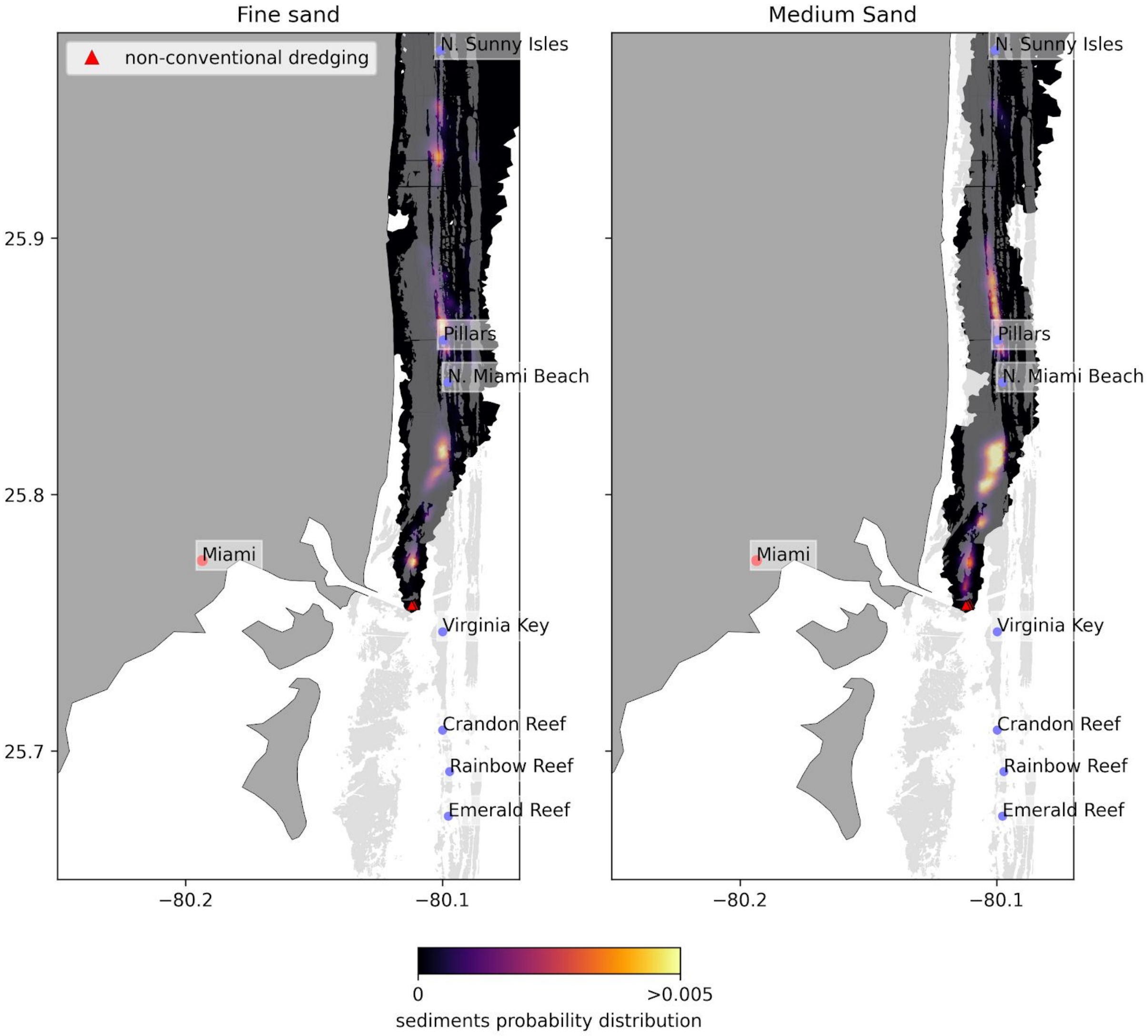

Figure 4. Simulation of the transport of sand particles released at the locations where non-conventional rock chopping was performed (red triangles) on 05/04/2014 and 05/05/2014. Coasts and islands are displayed in dark grey while reefs are shown in light grey.

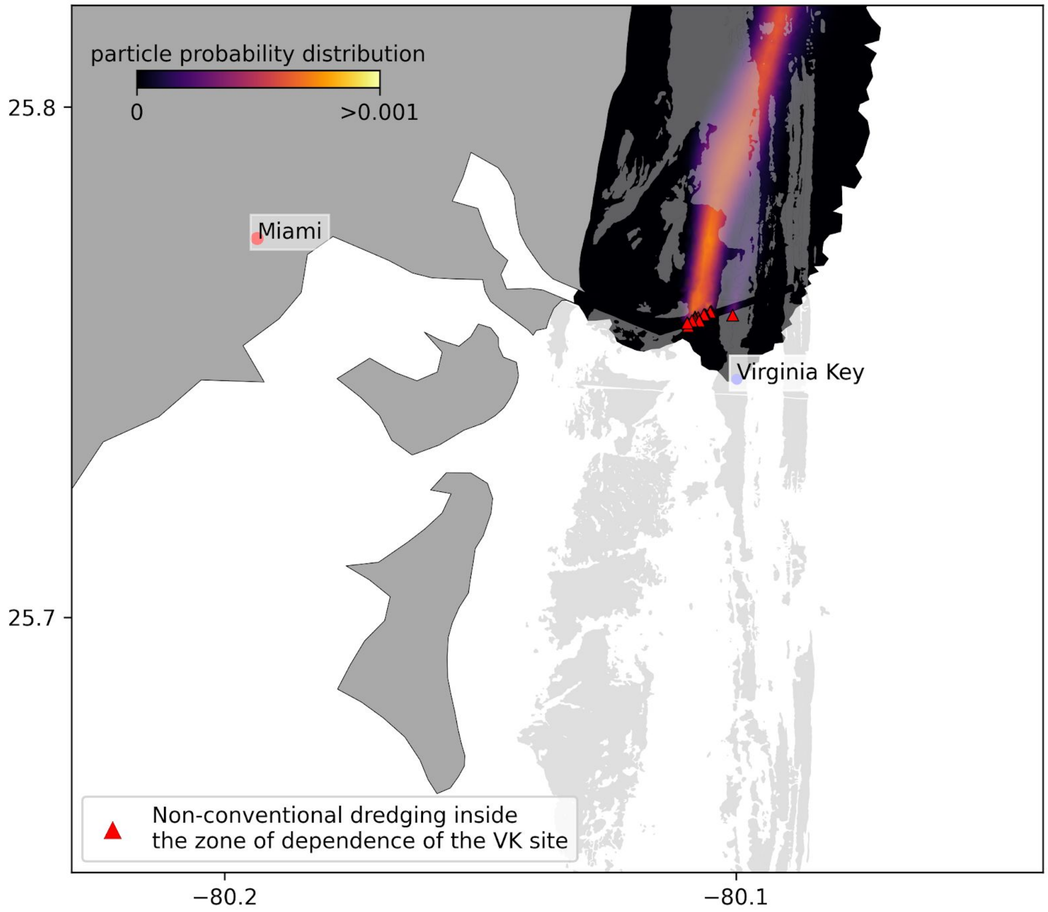

Figure 5. Forward tracking of neutrally buoyant particles released from the non-conventional dredging sites inside the zone of dependence of the site Virginia Key, highlighted in Fig. 3.

DISCUSSION AND CONCLUSIONS

We have developed a hydrodynamic model to determine the origin of potential external agents driven by currents that could have triggered the SCTLD outbreak in the FRT. Starting from the location where the disease was first observed on September, 26 2014 by Precht et al. (2016), we modeled the trajectories of virtual particles backward in time. These results showed that material produced in the dredged channel during phase III of the expansion of the POM could have reached VK. These results are confirmed by forward tracking of particles released from the non-conventional dredging sites in the channel. Moreover, modeling of the sediments produced by the non-conventional rock chopping activities conducted in May 2014 showed that the pulverized rocks they produced might have impacted all the northern monitored reefs. Finally, our simulations indicate that the sediments dumped at the offshore disposal sites used during the expansion works should not have played a role in the initiation of the outbreak.

For all modeled currents, the zone of dependence of the site of VK intersects the channel in which dredging operations were performed during the expansion of the POM. This suggests that the disease might have been initiated on the monitoring site by material produced by the dredging activities between May and September 2014. Infected coral colonies on the reef might then have acted as a source of infectious material and spread the disease to the neighboring reefs, leading to the propagation derived by Precht et al. (2016). Moreover, the dependence zone obtained with barotropic currents includes the sites where rock-chopping activities were conducted without pumping the loosened material produced at the beginning of May 2014. Due to the large amount of dredging material they released in the water column, these non-conventional activities are likely sources of contaminants to the VK reef.

Forward tracking simulations between May and September 2014 confirm that material produced in the dredged channel might have reached VK during this period. However, the fact that the VK reef is located on the boundary of the zone of influence of these points indicates that only extremely fine sediments that barely deposit on the seabed might have reached and contaminated VK. It is therefore unlikely that material produced by non-conventional dredging during May-September 2014 did initiate the epidemic on VK. This is confirmed by sand transport simulations that showed that southward currents during the simulated period were not strong enough to resuspend and propagate sediments.

Nonetheless, the sediment simulations showed that the non-conventional dredging activities of May 2014 impacted the reefs north of the channel. The zone predicted to be impacted by sediments by our simulations matches what Barnes et al. (2015) and Cunning et al. (2019) reported from satellite imagery, with rock chopping affecting reefs located more than 10 km away. This far exceeds the 150 m announced by environment assessment performed prior to expansion works (Florida Department of Environmental Protection, 2012; National Marine Fisheries Service, 2011; U.S. Army Corps of Engineers, 2004). Such results indicate that dredging activities might have caused substantial damages to corals over a large area. First, resuspended sediments might have increased the turbidity over reefs, causing adverse effects on local coral communities (Barnes et al. 2016). Moreover, the modeled bed loads of Fig. 4 suggest that the rock chopping operations might also have been at the origin of coral sediment burial. Such damages should have strongly reduced coral resistance to infections and therefore favoured the onset of the SCTLD on the reefs.

Based on these preliminary results, we identify 2 main questions that would need to be answered in future modeling studies. First, although the modeled currents of May-September 2014 did not drive exchanges of sediments between the non-conventional dredging sites and VK, backtracking results show that a significant part of the dredged channel lies within the dependence zones of the sites identified by Precht et al. (2016). Therefore, currents should be modeled during the whole December 2013 - May 2014 period to determine whether the winter/spring ocean circulation could have allowed stronger exchanges of sediments between the non-conventional dredging sites and VK. Second, sediment transport simulations showed that reefs located north to the dredged channel were strongly impacted by non-conventional rock chopping. These reefs might therefore have been contaminated before VK and hence served as a source of infectious material to neighbouring reefs. Further studies are needed to determine whether currents in December 2013 - September 2014 might have propagated the SCTLD causative agent from the northern reefs to VK.

Answering these two questions would allow us to evaluate the initial dynamics of the disease and to determine whether the VK reef might be the first infected site or if the outbreak is more likely to have been initiated on the northern reefs.

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