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Mud and sand effects on wave propagation over the French Guiana coasts

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Abstract:
The dampening effect of waves by soft mud layers is observed throughout the spectrum, in laboratory as well as on the Louisiana or Guyana coasts. Since the bi-layer theoretical approach of GADE (1958), several parameterizations have been proposed and implemented in wave numerical models but many efforts of calibrations and additional works are still required to obtain realistic representations of in situ processes.
The Guyanese coasts are impacted by the Amazon sediments discharge. In fact, 20 to 30% of these sediments migrate longshore either in turbid or in mud banks forms due to the waves and current combined actions. These mud banks cause rapid coastline variations, leading to accretion, erosion and submersion risks. The French operational wave forecasting system at coastal scale is based on WAVEWATCH III ®, using an unstructured grid that covers the French Guiana with a resolution of 200 m nearshore. A first version of this system has been implemented in 2017 in the framework of the HOMONIM project (History, Observation, Modeling sea levels, joint SHOM and Météo-France project). However this first version doesn't include the effects of the mud and sand banks on waves.
In this paper, we investigate the mud and sand effects on the wave propagation in order to improve the future version of the operational French Guiana configuration. Numerical tests on different bottom stress parameterizations are performed on a laboratory case, to assess the behaviour of WW3. A more realistic application on Guiana is carried out by the creation of a seabed map (grain size) and the use of a fine description of the characteristics and location of the mud banks, thanks to high resolution satellite imagery and in-situ data.
Keywords:
Wave, Mud, Sand, Modelling, Coastal hazard, Guiana, WAVEWATCH III.

1. Introduction

Guyana shoreline is characterised by muddy sedimentation continuously fed by deposits brought to the ocean by the Amazon, 800 km further south (Figure 1). At the mouth of the river, this intense sediment load is set in motion by the North Brazilian current and swell, and spread along the coast of Guyana during its ascent to the north. The deposited sediments form huge mud banks (up to 5 m thick, 10 to 60 km long, 20 to 30 km wide and 15 to 25 km apart) that migrate rapidly (1 to 5 km.y^{-1}) in low water depth (< 20 m) causing rapid coastline morphological changes which are difficult to predict. The mud banks present on the entire coast of Guyana quickly absorb and dissipate wave energy (about 70% and more, (WELLS & KEMP, 1986; WINTERWERP et al., 2007; GENSAC, 2012)).

In the HOMONIM project, the objective is to develop a wave forecasting model in order to better anticipate flooding from the sea and to improve warning systems on French metropolitan and overseas coasts. Initial configurations have been delivered since 2014. For the FrenchGuiana, a first version was released in 2016 (V1), based on the WAVEWATCH III ® (WW3, TOLMAN, 2016) model using an unstructured grid with a resolution of 200 m nearshore and 8 km offshore. However, this version does not include the effects of sandy and mud banks or current and water level variations on the waves. The objective of this paper is therefore to evaluate the effects of seabed sedimentary characteristics on wave propagation in order to improve the future version of the operational configuration for the French Guiana coastal area.

Numerical tests on different parameterizations are performed on the laboratory case of DE WIT (1995), to assess the behaviour of WW3. A more specific application on Guiana during winter storm 2016 is then carried out via the creation of a seabed map as well as a fine description of the characteristics and location of the mud banks, thanks to high resolution satellite imagery and in-situ data.

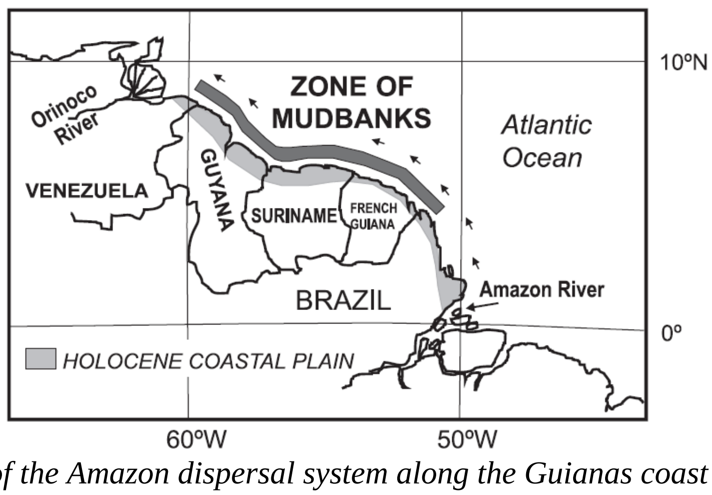

Figure 1. Map of the Amazon dispersal system along the Guianas coast (from ALLISON and LEE, 2004).

2. Method

WW3 is a third generation wave-averaged model that solves the 2D wave action balance equation for wave action density as a function wave number and direction. The source/sink term is expressed in terms of energy density and represents different physical processes available in the wave model:

$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{ds,w} + S_{ds,b} + S_{ds,br} \quad (1)$$

with S_{in} the atmospheric source function, S_{nl4} the nonlinear quadruplet interactions and $S_{ds,w}$ the dissipation by white capping. Other phenomena induced by the finite depth effects are taken into account, such as S_{nl3} triad nonlinear wave–wave interactions, $S_{ds,b}$ dissipation by bottom friction and $S_{ds,br}$ dissipation by depth-induced breaking.

The dissipation by bottom friction can be represented by different WW3 parameterizations:

- BT0: set to zero
- BT1: the classical empirical linear Jonswap parameterization (HASSELMANN *et al.*, 1973)
- BT4: a more realistic parameterization for sandy bottoms that is based on the eddy viscosity model by GRANT & MADSEN (1979) and a roughness parameterization that includes the formation of ripples and transition to sheet flow, adjusted with the SHOWEX experiment (ARDHUIN *et al.*, 2003).
- BT8: a parameterization for muddy bottom that follows DARYMPLE & LIU (1978); hereafter D&L
- BT9: a parameterization for muddy bottom that follows NG (2000).

The last two parameterizations have been implemented in WW3 by ROGERS & ORZECH (2013). The mud-induced dissipation is represented by a complex mud-induced wave number, k_{mud}, where the real part represents mud impact on the wavelength and the wave group velocity, producing shoaling/deshoaling effects, and the imaginary part is linked to the dissipation due to mud at each frequency by:

$$S_{ds,b} = - 2 \, \mathrm{Imag}(k_{mud}) \, C_{g,mud} \, E \quad (2)$$

where $C_{g,mud.}$ is the wave group velocity affected by mud and E the energy density. The two parameterizations differ by solving k_{mud}. The parameterization D&L treats the mud as a laminar viscous fluid and k_{mud} is a numerical solution found by solving Navier-Stokes equations on a two-layer model (GADE, 1958), using an iterative procedure. The parameterization of NG assumes the mud layer to be thin, and thus directly provides an analytical asymptotic solution of k_{mud} avoiding the costly iteration procedure. These parameterizations have been tested on an academic case (ROGERS & ORZECH, 2013) and recently for a realistic configuration (SAMIKSHA *et al*, 2017).

3. Laboratory test case of DE WIT (1995)

DE WIT (1995) carried out wave damping experiments in a 40m long wave and flow flume (experiment III, test 3). An 8m long false floor of 11.5 cm of depth is created so that a dense mud of a viscosity of $2.6.10^{-3}$ m²/s and a density of 1300 kg/m^3 can be placed inside. Waves with heights of 4.5 cm and periods of 1.5 s are generated from one side and measurements of wave height are performed at 6 locations inside the 8m zone. Measurements show that waves are damped and reach about 3.5 cm after 5m of propagation. We numerically reproduce this experiment with WW3 (figure 2).

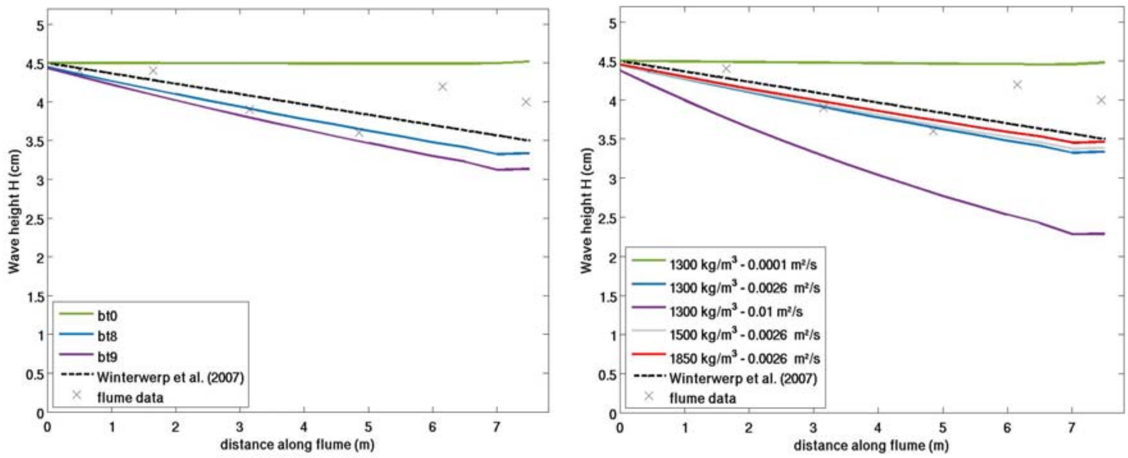

Figure 2. Wave damping on the Laboratory test case of DE WIT (1995) depending of the bottom parameterization (left) and in function of density in kg/m^3 or viscosity in m²/s (right).

This academic test was also conducted by WINTERWERP *et al.* (2007) with the Swan model. With no bottom dissipation (BT0), simulated waves keep a 4.5 cm height, whereas with a D&L (BT8) or NG (BT9) dissipation, waves damp along the flume, linked to mud interaction. D&L parameterization have the best good agreement with the data and also with the ones of WINTERWERP *et al.* (2007). Other tests show the importance of the choice of viscosity and the weak influence of the density.

4. Impact of bottom parameterizations on Guiana configuration

4.1 Presentation of the configuration

The mesh is composed of 32030 nodes and based on the 100 m resolution bathymetry carried out by the SHOM as part of the project (BISCARA, 2016). The selected resolution is 200 m near the coast of French Guiana with a lower resolution on the borders of Brazil and Suriname and about 8 km offshore. The operational wave model MFWAM, currently used for the forecast at regional scales with a resolution grid of 0.1°, provides the boundary conditions to WW3. The physical parameterizations corresponding to TEST 451 (ARDHUIN *et al.*, 2010) are used, modified to take into account some coefficients in the wind source and dissipation terms described in JANSSEN *et al.* (2014), and to be consistent with the version TEST 463, implemented

in the operational wave model MFWAM since November 2014 (see MICHAUD *et al.*, 2015 for further information). The spatial propagation uses the implicit N scheme (ROLAND, 2009). Wave spectrum is discretized on 24 directions and 30 frequencies exponentially spaced from 0.0345 Hz to 0.5473 Hz at an increment of 10%. In the version V1, the parameterization BT4 is used for bottom friction considering uniform and constant median size sediment D50 equal to 0.2 mm. The model is forced by the Arpege wind model at a resolution of 0.1° with a time step of 3 hours. We study the results with the different parameterizations during some events with strong swell of the 2016-2017 winter, and in particular on December 11th where swell originated from a local depression in North Atlantic, propagates until the Guiana coasts, reaching more than 2.5 m.
Two buoys from the Candhis network, located in the coastal zone of Guiana at 20 m of water depth (Cayenne buoy: 4°59'N;52°03'W and Kourou buoy: 5°23.252'N;52°35.536'W) recorded the wave parameters during these events (until 12/11 for Cayenne buoy) and are used to assess the performance of the model.

4.2 Sensitivity to the implementation of a granulometric map with BT4

A seabed sedimentary map (median grain size) has been established from the Shom database at a resolution of 50 m (figure 3), and is a review of all available sedimentological data, based on the primary work of PUJOS & FROIDEFOND (1995).

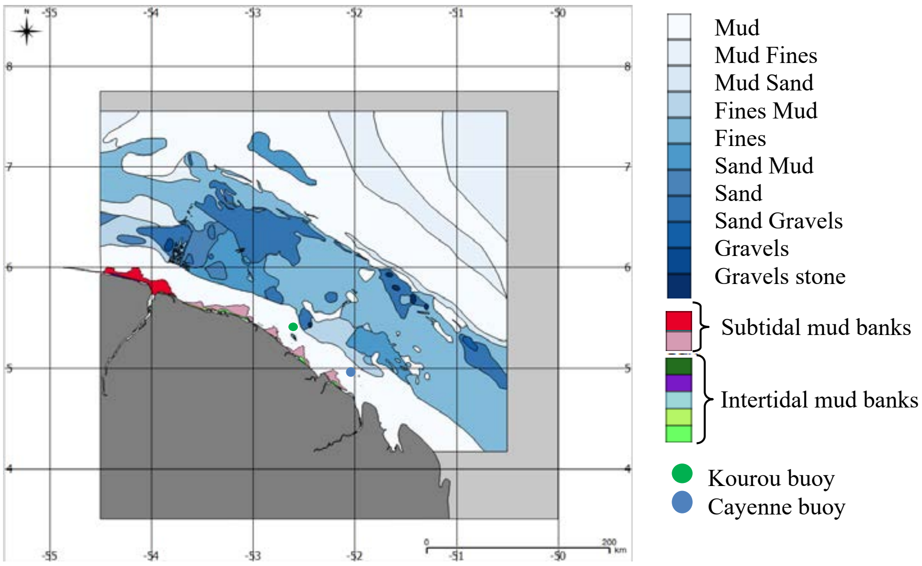

Figure 3. Map of sediment type from the Shom database and positions of intertidal (green) and subtidal (red and pink) mud banks in September 2016 from the work of A.GRONDIN (JACQ, 2017). The locations of Candhis buoys are also indicated.

As suggested by ROLAND & ARDHUIN (2014), we prescribed the bottom friction parameterization created from the "SHOWEX" experiment (ARDHUIN et al., 2003a) instead of the classical empirical linear Jonswap parameterization (HASSELMANN et al., 1973), and a constant Nikuradse roughness length of 12 cm is applied for rocks. This modified bottom friction has limited impact on Hs (figure 4) on the winter swell events except at the West coast of Guiana where the significant wave height Hs can decrease by more than 20 cm (up to 50 cm) during winter storms. On the Kourou buoy (figure 5), Hs is decreased with the seabed sedimentary map, while the bias with the observation increases (table 1). Direction (not shown) is not modified.

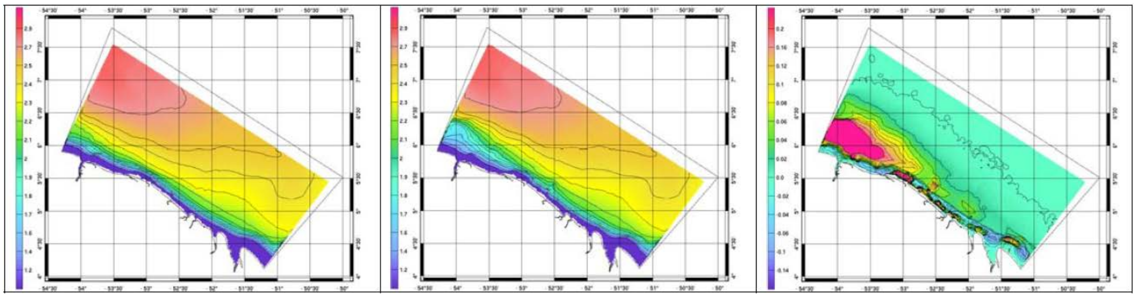

Figure 4. Map of significant wave height on December 11th at 3 a.m. with a simulation using BT4 and a constant median size sediment V1 (left), BT4 and a seabed sedimentary map (center) and the difference between the first and the second one (right, scale saturated to 20 cm).

4.3 <u>Sensitivity to the implementation of a mud banks map with BT8/9</u>

The median grain size map used in section 4.2 with BT4 considers that the entire nearshore zone is muddy. However, a cartography of the Guianas mud banks produced by A. GRONDIN for the month of September 2016, by analyzing the different spectral bands of the Landsat 8 satellite images shows mud banks alternating with sandy or rocky bottom. The coverage and the spatial (30 meters) and temporal resolution of these data (16 days) make it possible to map at an appropriate scale to apprehend the structure of the mudbanks. In shallow waters, subtidal banks are not visible, but their boundaries can be determined indirectly. Passing over these banks, the wave breaks, leaving whitecaps visible on the satellite images. The presence of subtidal mud banks is thus marked by a strong attenuation of the swell. In addition to its damping, the swell is slightly diffracted. We implement the position of these mud banks, and we consider the thickness δ_m in a first guess equal to 50 cm inside the mud and 0 cm outside, the mud viscosity ν_m equal to 0.0076 m²/s and the density ρ_m equal to 1310 kg/m^3, (the mud parameters are assessed from literature). The selected values are given in Table 2. Computations for sensitivity tests were carried out with δ_m =0, 0.2, 0.5 and 1 m, ν_m=0.01, 0.0076 and 0.001 m2/s and ρ_m = 1310, 1500, 1850 kg/m^3, for BT8 and BT9 parameterizations.

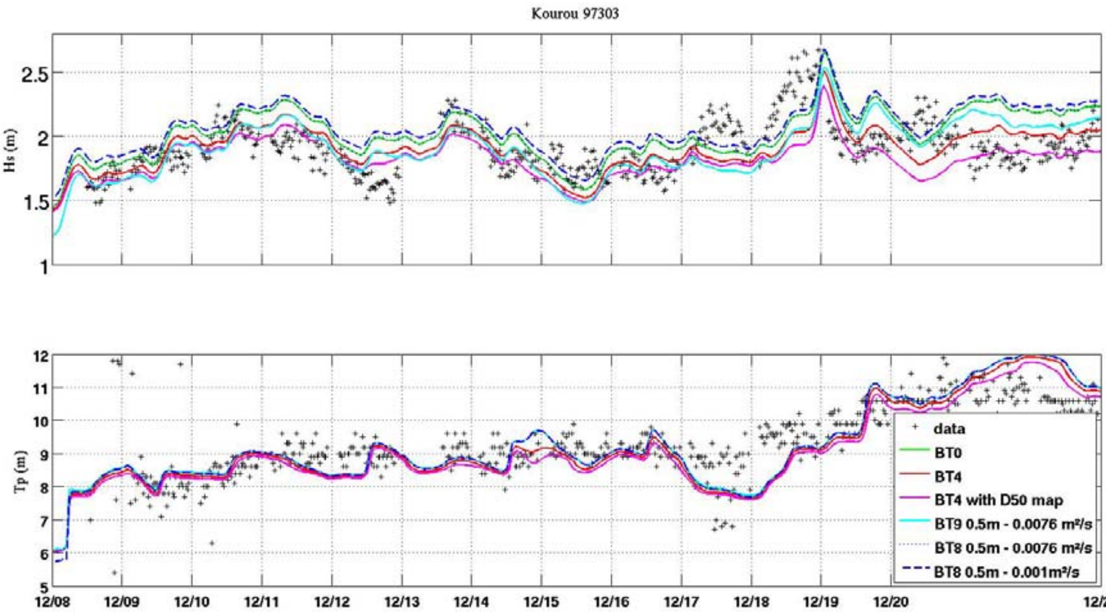

Figure 5. Times series of observed and simulated significant wave height and period at Kourou buoy in function of bottom friction parameterization.

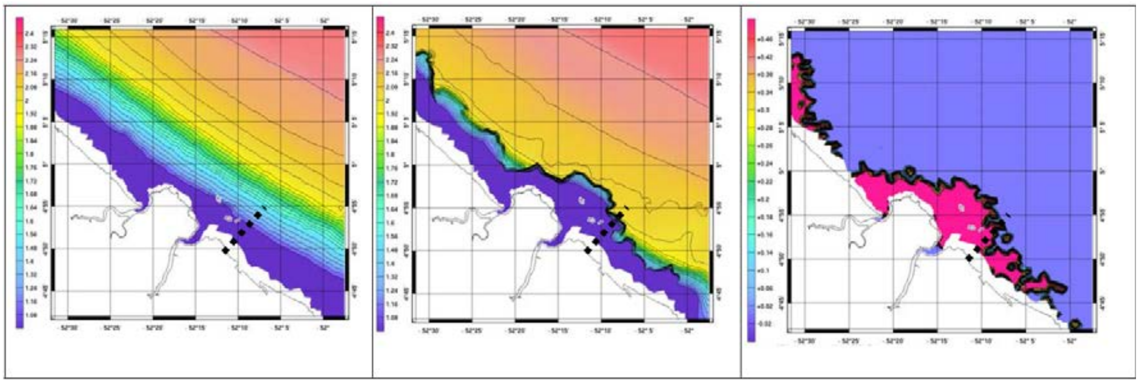

Figure 6. Map of significant wave height on December 11th at 3 a.m. in front of Cayenne with a simulation using BT4(left), BT8 with 0.5m of mud thickness (center)and the mud thickness (right). Transect of figure 6 is indicated by a dashed line.

Implementing the mud friction parameterization induces a fast wave damping in mud banks (figures 6 and 7). This damping is similar with δm = 0.2 or 0.5 m, and has a strange pattern with 1m, linked to the limit of the two parameterizations that are not suitable for large mud thickness, in weak water depths. Increasing the viscosity increases the damping, and vice-versa. BT9 bottom friction is slightly stronger than BT8. Candhis buoys are not located in mud banks so the results with BT8 are quite similar than with BT0. The best comparisons between simulations and measurements at

Kourou buoy are thus obtained with BT0 or BT8 parameterizations (Table 1), i.e. with no bottom friction, maybe linked to a possible underestimation of the external forcings.

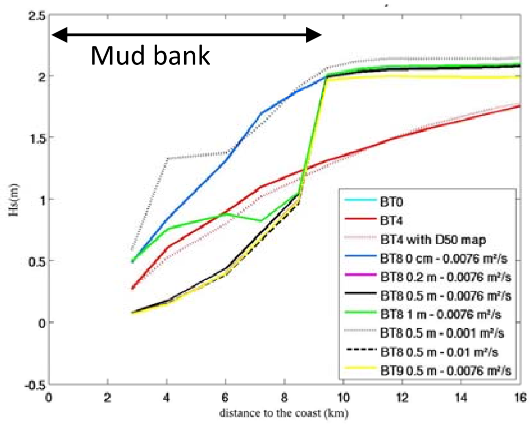

Figure 7: Simulated Hs with different bottom friction parameterizations, depending on the mud thickness (m) and viscosity(m²/s), along a transect crossing a mud bank.

Table 1: Statistical results of the simulations with different parameterizations compared to measurements at Kourou buoy.

Parameterization	*Parameter*	*Bias*	*Correlation*	*RMSE*	*SI*	*Max. error*
BT0	*Hs*	*0.02*	*0.92*	*0.17*	*0.13*	*0.8*
	Tp	*-1*	*0.30*	*2.52*	*0.25*	*9.32*
BT4	*Hs*	*-0.03*	*0.91*	*0.17*	*0.13*	*0.90*
	Tp	*-1.21*	*0.29*	*2.63*	*0.26*	*9.34*
BT4 with D50 map	*Hs*	*0.07*	*0.91*	*0.18*	*0.14*	*0.97*
	Tp	*-1.37*	*0.28*	*2.68*	*0.26*	*9.34*
BT8 v_m=0.0076 m²/s	*Hs*	*0.02*	*0.92*	*0.17*	*0.13*	*0.8*
	Tp	*-1*	*0.3*	*2.52*	*0.25*	*9.32*
BT9 v_m=0.0076 m²/s	*Hs*	*-0.1*	*0.91*	*0.21*	*0.16*	*0.86*
	Tp	*-0.96*	*0.3*	*2.47*	*0.24*	*9.29*
BT8 vm =0.01 m²/s	*Hs*	*0.02*	*0.92*	*0.17*	*0.13*	*0.8*
	Tp	*-1*	*0.30*	*2.52*	*0.25*	*9.32*
BT8 vm =0.001 m²/s	*Hs*	*0.12*	*0.92*	*0.2*	*0.15*	*0.68*
	Tp	*-1.4*	*0.26*	*2.94*	*0.29*	*9.47*

5. Conclusions

In this paper, we evaluate the impact of sand and mud on the wave propagation over the French Guiana. At coastal scale, ahead of breaking zone where bottom interacts with waves, the parameterization of ARDHUIN *et al.* (2003) is important to correctly represent the sand effects. At nearshore scale in mud banks, the D&L or NG parameterizations allow to reproduce the wave damping, but efforts remains to be done to improve the knowledge of the mud banks, their thicknesses, densities and viscosities to calibrate the model. Offshore campaigns are planned by the Propa-H and Shom teams in the coming years. Work is also underway on the determination of the location of the mud banks from spatial images.

6. Acknowledgements

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