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Modelling the transport of sediment discharged by Colombian rivers to the southern Caribbean Sea

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Abstract

The three-dimensional transport of sediments released by the main rivers in the Colombian Caribbean basin is investigated using numerical model simulations. Different types of sediments (fine sands, very fine sands and coarse silts) were tracked by implementing SedimentDrift software, a subclass of the OpenDrift open-source trajectory framework. The simulations were forced with climatological winds from ERA-5 and currents from the Copernicus Marine Environment Monitoring Service (CMEMS). In situ measurements from the area were utilised in the evaluation of the forcing fields. The diagnostic analysis of ERA-5 and CMEMS at the evaluated stations in the Colombian basin led to the conclusion that these datasets are reliable; hence, they can be used for several oceanographic and coastal engineering studies. The sediment transport of non-cohesive particles at each river mouth is subject to the variability of local hydrodynamics, morphological features and the grain size, which determines the settling velocities. These factors were considered and evaluated in detail. Given the lack of available in situ information, the performance of the Lagrangian model is evaluated by comparing the resulting simulations with previous studies reported in the area for river plume dynamics. However, this study presents an initial analysis of the pathways that sediments of different sizes follow, from the river mouth to the seafloor. This approach is convenient given that the Colombian rivers deliver large amounts of sediment of various grain sizes, there are insufficient in situ data to assess the seasonal cycle of sediment transport and many aspects of the sediment dynamics are not fully resolved. The resulting simulations provide evidence of the importance of high-resolution ocean current data, given that this is the main factor determining the trajectories and dispersion patterns at seasonal scales.

Keywords Suspended sediment transport · Caribbean Sea; river discharges · Non-cohesive particles · Seasonal hydrodynamics · Lagrangian simulation

1 Introduction

In the southern Caribbean Sea, there has been an increase in productive activities, such as oil and gas exploration, marine renewables and the installation of networks of cables, pipelines and other infrastructure on the seafloor. For nations with coastal boundaries, all of these productive and emerging sectors are of great socioeconomic importance, and hence, all of these activities should be accompanied by environmental monitoring and the assessment of possible risks and impacts.

Hazardous marine events may occur at any time, and the scientific community, marine industry and governmental agencies must cooperate if they are to better understand and monitor the processes involved and mitigate the resulting, unpredictable damage (Camargo et al. 2019). It is essential that we improve the knowledge and tools for identifying these risks and set out strategies for hazard mitigation.

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The identification of possible sea hazards and geohazards is fundamental for the strategic planning of programmes and projects. To improve disaster risk and societal resilience, it is necessary to have a better understanding of natural and man-made disasters, in addition to developing novel concepts and technologies to counter these risks (European Marine Board 2019).

The Caribbean region is exposed to various natural sea hazards that make the region vulnerable to numerous impacts; these include storms and hurricanes, floods, landslides, earthquakes, tsunamis and volcanoes, causing devastation and negative socioeconomic impacts (Méheux et al. 2007; López-Marrero et al. 2013).

Marine geohazards can also jeopardise economic activities and civil infrastructure and may hamper the effective implementation of policies such as the Maritime Spatial Planning and Integrated Coastal Zone Management (European Marine Board 2019). However, with respect to geohazards in the southern Caribbean Sea, the availability of local studies and information is limited. Most published research papers have concentrated on earthquakes and volcanoes (López-Marrero et al. 2013).

Tsunami risks, due to giant submarine landslides off the Caribbean coast of Colombia, have been discussed by Leslie and Mann (2016). In this study, a series of giant (> 1000 km^3), previously unrecognised, Plio-Pleistocene age, submarine landslide deposits are identified, based on seismic reflection records. The source of the slides is interpreted as being the submarine slopes of the Magdalena River Fan. Tsunami modelling indicates a recurrent slide which would devastate Caribbean coastlines. Hence, geohazards are slowly gaining political attention, given the increasing amount of human activity being conducted offshore.

Subsea infrastructure, including communication and energy cables, oil and gas rigs and pipelines, are potentially at risk of damage and destruction due to these seafloor landslides, which could be triggered by storms, earthquakes, tsunamis and local processes that destabilise the seabed. Avoidance of hazardous areas is preferred but is not always an option (Clare et al. 2017). It is important to understand the processes that may cause seafloor instabilities in order to mitigate the risk posed by marine geohazards to strategically important, offshore infrastructure (Campbell 1999).

The theoretical basis for sediment transport along shorelines and offshore has not been fully developed. This is largely because, at the present time, we do not have a complete understanding of sediment transport, even under simple conditions, despite the efforts of many investigators (Dean and Dalrymple 2002).

Longshore sediment transport is mostly due to the wave-induced longshore current, whereas cross-shore transport is a result of water motion due to the waves and the undertow associated with breaking waves. Seasonal shoreline changes are usually considered to be caused by the incidence of storms and the associated seaward sand transport and nearshore storage (Dean and Dalrymple 2002).

The suspended sediment load (SSL) that is transported from the river mouths towards the coast is subject to wind action, waves and currents. The ocean and coastal water seabed is mainly formed by the settling of sediment particles out of suspension. Sediment settling is mainly determined by the particle fall velocity, availability and turbulence. Only coarse grades may settle under energetic conditions. The fall velocity of sediment particles depends on size and density. Because the density of different types of sediment is similar, the grain size becomes the determinant: the larger the grain size, the higher the fall velocity.

Alluvial sediments are derived from various terrestrial processes and human activities and comprise both cohesive (clay-sized and silt-sized) and non-cohesive (sand and gravel-sized) material properties (van Rijn 1993). The coarser sediments are deposited in the upper reaches of the river/estuary, while the fine sediment fractions are carried further downstream into the estuarine/coastal waters where salinity enhances aggregation, forming flocs that possess higher settling velocities. These aggregates are then deposited in areas where velocities are sufficiently small (Shrestha and Blumberg 2005).

The study of the settling (deposition) process led to the earliest general model of sediment distribution across the sea floor, with the size of sediment particles gradually decreasing with increasing water depth. The nearshore consists of sand that is gradually replaced by silt and then clay, in deeper water. This is based on the concept that the energy of ocean currents and waves decrease from shallow water to deeper water, and therefore, smaller particles can only settle to the bottom in less energetic, deeper water. The physical characteristics (size, shape, composition) and the distribution of sediment are the result of complex interactions between geological, oceanographic and biological processes (U.S. Geological Survey USGS 2001).

Understanding and predicting the transport and fate of suspended loads discharged by the rivers into the ocean is very important for science-based, sustained management of these systems (Pinto et al. 2012) and for several offshore commercial applications. However, the dynamic processes responsible for the transfer and dispersion of sediments involve complex flows such as wind and wave-induced circulation, density gradients and flows adjacent to structures. The lack of understanding of these processes in the Colombian Caribbean basin is partly explained by the lack of availability of high-resolution field measurements of currents, waves and the ocean floor.

Of interest to the scientific community and the productive sectors is the sediment dynamics of the Magdalena River delta and submarine alluvial fan, given that the SSL discharged (~ 142.6×10^6 t year^{-1}) is among the largest in the world and is of a comparable magnitude to those of rivers with greater drainage areas, such as the Orinoco in Venezuela (SSL = 150×10^6 t year^{-1}) and Huanghe in China (SSL = 150×10^6 t year^{-1}). The sediment flow of the Magdalena River constitutes a key element in the progradation and architecture of the Magdalena Delta, as well as the coastal morphodynamics and transfer of nutrients into the Caribbean Sea (Restrepo et al. 2017).

The transport, deposition and accumulation of the vast amounts of sediment released by local rivers into the southern Caribbean Sea is an important factor in shaping the ocean floor and could also be contributing to seafloor instability in offshore Colombia. There are more than 20 streams and rivers draining to the Colombian coast. The main rivers of this hydrological basin, which are considered in this investigation, are the Magdalena, Atrato and Sinú (Fig. 1, Table 1), with freshwater discharges of around 321.5 km^3 year^{-1} to the Caribbean (95% of the total) (Restrepo and Kjerfve 2004).

A large number of applications could benefit from the description of the sediment transport and deposition in this oceanic region, including science, environmental management, natural resources exploration and engineering. However, understanding and predicting the movement of sediment in coastal and shelf seas remains a difficult task. Several techniques have been applied to the determination of sediment transport pathways and its final fate. Such wide-ranging approaches include direct measurements, indirect estimations and the refinement and application of numerical modelling (Collins and Balson 2007).

Given that direct measurements of waves and coastal currents are scarce, or unavailable, in the Colombian basin, the application of Lagrangian particle tracking for modelling sediment in the ocean is a valid approximation. This approach has become increasingly common in several oceanic regions as the reduced cost of computer time and memory has made it feasible to couple 3D circulation models with a vast number of concurrent particle-trajectory calculations (Corell and Döös 2013). The off-line set-up, where output fields from circulation models are stored and used repeatedly, is an even more flexible and less time-consuming approximation, being ideal for the emergency preparedness purposes required by operational agencies (Dagestad et al. 2018).

Considering that there is a need for a comprehensive geohazard risk assessment in the Colombian basin, it is important to start by determining the 3D propagation and dispersion patterns and the deposition sites of sediments that are released by the main rivers in the Caribbean coast, under different metocean conditions. It is necessary to determine if there are areas of excessive accumulation within a year, which could lead to short-term instability of the seafloor.

In Colombia, the estimation of fluvial sediment transport and its natural and human-induced variability are important issues that have been analysed over the past three decades. However, the fate of the sediments after the suspended particles are discharged by the rivers into the ocean has received relatively little attention, given that there are few direct measurements of the suspended sediments and of the physical environment in the delta areas and the open sea. There is a need for the characterisation of the seasonal 3D dispersion patterns of sediments suspended in the water column, considering the trajectories and deposition sites, and how these are related with the hydrodynamics.

In this study, the sediment transport in the Colombian Caribbean basin is assessed by means of a Lagrangian

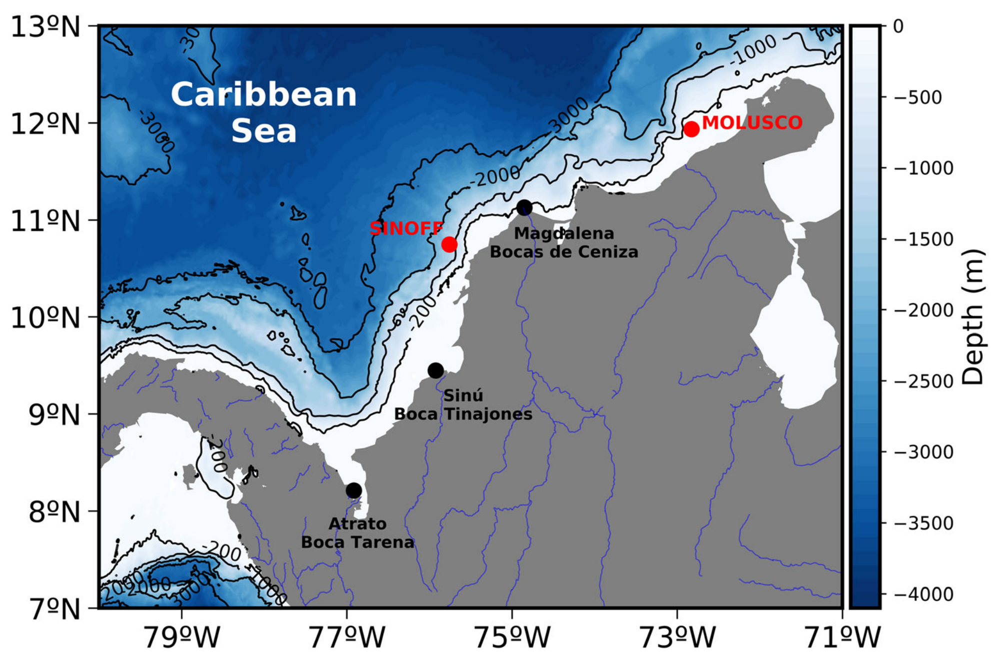


Fig. 1 The Colombian Caribbean basin. Location of Magdalena, Atrato and Sinú River mouths (black dots). Location of monitoring stations SINOFF with in situ measurements of ocean currents and Molusco (MOL) with records of currents and wind (red dots). The bathymetry data are from GEBCO-2019 (in metres). The isobaths of 200, 1000, 2000 and 3000 m are shown as black contours, and the main rivers are shown in blue

Table 1 Annual mean river runoff, suspended sediment load (SSL) and sediment yield for the main rivers in the Colombian Caribbean basin

River mouth	Location	Annual river runoff ($m^3\ s^{-1}$)[1]	Annual mean suspended sediment load	Annual mean sediment yield ($t\ km^{-2}\ year^{-1}$)[1]	Drainage basin area ($\times 10^3\ km^2$)[1]
Magdalena River (Bocas de Ceniza)	74.85° W; 11.1267° N	7200	390.86×10^3 t day^{-1} [2] 142×10^6 t $year^{-1}$(2000–2010) [2]	559	257.43
Atrato River (Boca Tarena)	8.266° N; 76.983° W	2570	30.84×10^3 t day^{-1} [2] ~ 11.3×10^6 t $year^{-1}$ [3]	315	35.7
Sinú River (Boca Tinajones)	9.4475° N; 75.923° W	373	8.62×10^3 t day^{-1} [2] ~ 6×10^6 t $year^{-1}$ (1963–1993)[1] 3.68×10^6 t $year^{-1}$ (< 2000), 2.35×10^6 t $year^{-1}$ (2000–2010)[2]	589	10.18

[1] Restrepo and Kjerfve (2000, 2004); Restrepo and López (2008); [2] Restrepo et al. (2016); Restrepo et al. (2017); Higgins et al. (2017); (Restrepo et al. 2014)[3]

modelling approach, which includes a set of hydrodynamic inputs from high-resolution models, different grain-sizes, release points and climatic scenarios. This study evaluates three very different coastal-delta areas, where an offline tracking-Lagrangian model is run, seeding sediment particles of different sizes, at each river mouth. The advective and dispersive three-dimensional (3D) transport of suspended sediment originating from these rivers is subject to the hydrodynamic forcing of ocean circulation and local winds. The trajectories, spreading patterns and deposition sites within the annual cycle are evaluated.

2 Colombian Caribbean basin: general physical context

The seafloor of the Caribbean Sea (Fig. 1) consists of several basinal areas (the Yucatan, Colombian and Venezuelan Basins), separated by shallower areas (the Nicaraguan Rise and Beata Ridge). The Cayman Trough is a narrow, very deep, linear basin immediately north of the Nicaraguan Rise; it is notable for being the site of contemporary sea-floor spreading. The floor of the main part of the Caribbean (i.e. the Venezuelan and Colombian basins) is underlain by a vast plateau of basalt which is not typical of oceanic crust, but which has close analogues elsewhere in the world ocean (Donnelly 1994).

Boundary conditions and factors such as sediment supply, freshwater inputs, energy from marine processes, accommodation space for sediment deposits, and density differences between river, estuarine, and coastal waters control the dynamics and architecture of the delta areas. The fluvial discharges play an important role in the hydrological cycle, the thermodynamic stability of the ocean and in biogeochemical cycles (Restrepo et al. 2016).

Some authors have highlighted the great influence that river regimes have on the dynamics of tropical deltas, especially those that experience a micro-tidal domain (e.g. Wolanski et al. 1998; Moskalski and Torres 2012; Wu et al. 2012). The contribution of freshwater affects the salinity distribution, the patterns of gravitational circulation and, consequently, alters the cycles of resuspension, transport and deposition of sediments. During high flow events, the transport of suspended sediments is usually high, leading to changes in deposition patterns within the delta. Furthermore, this large quantity of freshwater could move the saline wedge away from the delta and favour the flow of sediments towards the continental shelf (Restrepo et al. 2016).

The present-day discharge of suspended sediment into the oceans from Colombian rivers has a great impact on the world sediment budget (Milliman 1990; Milliman and Syvitski 1992). The Caribbean Colombian basin is principally drained by the Magdalena and Sinú Rivers, but it also receives the

Atrato drainage from the west of the Cordilleras. Major natural origins and controls of these river-borne materials include atmospheric inputs, chemical weathering of minerals, mechanical erosion of rock and soil particles and soil leaching (Restrepo and Kjerfve 2004).

The Magdalena is the main river in Colombia, and *Bocas de Ceniza* is its principal river mouth, located on the northern coast (Fig. 1). This tropical delta has a micro-tidal regime, with a mixed-diurnal tide ranging between 0.45 and 0.64 m (Restrepo and López 2008). The maximum and minimum water discharges are 16,000 and 1475 $m^3 s^{-1}$, during the June–December and January–September seasons, respectively. This river forms a 1690 km^2 triangular delta. The present delta mouth empties into a deep, offshore canyon with a steep slope (40°) (Alvarado 2005). It drains 39% of the total fluvial discharge estimated for the whole Caribbean littoral zone (378×10^6 t $year^{-1}$). It is one of the top 10 largest river-sediment discharges to the ocean (Restrepo et al. 2017).

The Magdalena River delta is a highly stratified estuary experiencing high stream flow, high freshwater discharges which exert a major influence on the stratified conditions of the deltaic and adjacent coastal waters, promoting the transfer of sediments from the river channel to the outer pro-delta through the upper layers of the water column (Restrepo et al. 2016). This river have been categorised as a wave-dominated delta system, where most of the bed loads initially deposited at the distributary mouths have been reworked by energetic waves and redistributed along the delta front by longshore drift (Coleman 1981; Restrepo and López 2008). According to the functional, morphological classifications of deltaic systems (e.g. Galloway 1975; Orton and Reading 1993; Hori and Saito 2005), the Magdalena delta has also been classified as a fluvio-wave dominated type (Restrepo et al. 2014; Higgins et al. 2016; Restrepo et al. 2018), given that this delta receives a water inflow of 205.1 km^3 $year^{-1}$ and 142.0×10^6 t $year^{-1}$ of suspended sediment (Restrepo et al. 2014).

The grain sizes of the suspended sediment have been measured by several authors, by considering different periods, depths and locations along the Magdalena River channel and mouth. In the deltaic front, a sediment core showed deposits of coarse silts (50–70%) and fine sands (10% of the net sediment weight) (Klingebiel and Vernette 1979). For the surface water layer, Restrepo et al. (2016) reported 76.4% of coarse silt, 16.5% clay and 7.1% of sand during the high river runoff season (November 2012). During the low river runoff season (April 2013), the coarse silt was approximately 65.4% of the total weight of the suspended sediments, with an increase in clay (32.7%) and a reduction in sand (< 2.0%). The grain size of the sediment found, particularly during the low flow season, increases the efficiency of sediment capture in the turbulent maximum zone (TMZ) since, on the convergence front, fine cohesive sediments are trapped and concentrated.

Torregroza-Espinosa et al. (2020) evaluated the sediment grain-sized distribution in the Magdalena River. They reported that, in the mouth section, 10.5% of the suspended particles corresponded to clay and very fine, fine, medium and coarse silt (highly cohesive sediment, < 63 μm); 84.7% was very fine and fine sand; and 4.8% was medium sand. In the estuarine section, 29.3% of the sediment comprised clay and very fine, fine, medium and coarse silt (highly cohesive sediment, < 63 μm), whereas 64.9% was very fine and fine sand and 5.8% medium sand. On average, the greater the distance to the river mouth, the more the coarse fraction diminishes in size.

The other rivers in the Colombian Caribbean basin exhibit relatively low freshwater discharges (~ 93.0 to 125.4 km^3 $year^{-1}$) and low SSL ($< 3.0 \times 10^6$ t $year^{-1}$). However, the transport and trapping of sediments suggests that a large fraction of sediments is deposited upstream, which plays a significant role in the morphological stability of deltas, estuaries and beaches (Restrepo et al. 2017).

The Atrato River, draining a basin of 35,700 km^2, occupies a considerable portion of the Pacific basin of Colombia, but it empties into the Caribbean via the Urabá Gulf, which is a relatively shallow region (mean depth approximately 20 to 40 m). Although this is a river-dominated delta with a bird-foot morphology (Vernette et al. 2002; Serrano-Suarez 2004), it shows the contribution of wave forces due to the low tidal energy present along its shoreline. Marshes, swamps and lakes are the most abundant features in this delta, and wave-deposited sand features, such as beaches and beach ridges, are scarce. Towards the wave-dominated end of the spectrum, there is a progressive decrease in river-dominated features, such as digital distributaries, bays and marshes, and an increase in wave-built features, such as beach ridges, spits, dunes and barrier islands (Restrepo and López 2008).

The Atrato, River in the Urabá Gulf, is by far the most diluted and is four times less mineralised than the large Magdalena and the other Caribbean rivers, as a result of its location in a very humid environment. The upper and middle sections of the Atrato are located in regions with very high annual rainfall. The sediment yield is comparatively low, because of the large size of the drainage basin and the alluvial flood plains, with an area of 5500 km^2 (Restrepo and Kjerfve 2004). For this river, a study of the effect of the wind and tidal regime on the plume was conducted by Montoya et al. (2017) from field data collected from 2004 to 2007 and a numerical model. The results revealed high spatial and temporal plume variability according to the magnitudes of river discharges, tidal cycles and wind stress. Both the observations and numerical simulations revealed that the highest vertical salinity gradients are near the surface, below the river's water layer, with a thickness of less than 2 m.

Information on the distribution of sediments by their grain size is scarce. García (2007) discussed the predominance of sands (150 μm) and finer sediment particles (< 63 μm). Sand-sized sediments are mainly located near the north-western coast of the Urabá Gulf. These two sizes were also used by Velásquez-Montoya (2013) in sediment transport modelling, considering a rainy and dry season.

The Sinú, along with the Magdalena and Atrato, is one of the most important rivers on the Caribbean coast of Colombia. Its delta is situated near the Morrosquillo Gulf and drains an area with a complex network of swamps, originating at an altitude of 3960 m and extending for 415 km. The Sinú delta, like the Atrato, is characterised by marshes and lakes, but the coastline is smoother and sand features, such as spits and beach ridges, are much more developed than in the Atrato. However, fluvial dominance is still evident and reflected by the pronounced cuspate form of the Sinú delta and by the mangroves which dominate the flanks of the bays and behind the sandy beaches of the delta shoreline (Restrepo and López 2008).

In contrast to the Magdalena River, which delivers all of its sediment over the continental slope and delta front (Ercilla et al. 2002; Torregroza-Espinosa et al. 2020), the Sinú delivers its sediment into the largest portion of the continental shelf forming the Tinajones delta, which has been categorised as river and wave dominated (Tabares et al. 1996; Serrano-Suarez 2004). Recent estimates of SSL showed an interannual decreasing trend for this river (Table 1). The annual mean SSL before 2000 was 36% higher than its annual average SSL between 2000 and 2010 (Restrepo et al. 2017).

A sedimentary study of the Sinú River by INVEMAR-GEO (2016) reported a predominance of fine sand-sized particles (greater than 85%). The percentage of mud-sized particles is highly variable, with ranges between 0.62 and 15.31%. The predominant textural group in the delta area is sand and, to a lesser extent, muddy sand. The sectors of direct influence of the river sediment particles, that are transported by jumping and suspension mechanisms, ratify the contribution from proximal areas.

It is considered that the sedimentary contribution would reach approximately 20 km from the main mouth in the western direction and approximately 15 km to the east. In the Sinú delta, Serrano-Suarez (2004) obtained an estimated net sediment accumulation of 161×10^6 m^3 and an estimated sedimentation rate of 2.83×10^6 m^3 year^{-1} for the 1957–1997 period. According to this study, most accumulation occurred in the subaerial delta (70%). Restrepo and López (2008) also showed evidence that, for the Sinú delta, there was coastline progradation during 1986 to 2002. Maximum accretion rates of 1300 m were present in the western part of the delta.

The river runoff and SSL of Colombian rivers and the hydro-climatology in this region are mainly controlled by the meridional migration of the Intertropical Convergence Zone (ITCZ), which, in turn, controls the dynamics of the trade winds, low-level wind jets and precipitation over oceans and landmasses (Poveda 2004). The local and regional atmospheric circulation patterns interact with the ITCZ and orography to establish the spatial and temporal distribution of precipitation in Colombia (Mejia et al. 1999).

The Caribbean Low-Level Jet (CLLJ), which is a fast-moving trade wind current (> 10 m s^{-1}) over the Caribbean Sea (Amador 1998, 2008), transports large amounts of moisture from the tropical Atlantic westward, into the Caribbean Sea and Central America (Fig. 2). The easterly CLLJ varies semi-annually, with two maxima in the summer (peaking in June–July) and winter (January–February) and two minima, in the fall (October) and spring (May).

The dominant surface wind-driven currents in the area are the Caribbean Current, flowing west-north-westward through the northern Caribbean (Wust 1963; Morrison and Nowlin Jr 1982) and the cyclonic circulation of the Panama-Colombia cyclonic Gyre (PCG) in the southwestern Caribbean Sea (Mooers and Maul 1998). The limb of the gyre that flows along the coast is known as the Panama-Colombia Countercurrent (PCC) (Pujos et al. 1986). Wind waves are also associated with the persistence and intensity of the CLLJ (Appendini et al. 2014; Salinas et al. 2019). The dry (rainy) season is related to energetic (weak) ocean waves.

In Colombia, the study of sediment loads and their underlying processes are still incipient, with the exceptions of the Magdalena, Atrato and Sinú Rivers (Restrepo and Kjerfve 2000, 2004; Restrepo et al. 2006; Restrepo and Syvitski 2006; Higgins et al. 2016; Restrepo et al. 2017). Those studies have highlighted the importance of the sediment loads of Colombian rivers in the global budgets of sediment supply to the oceans. However, few studies have evaluated the fate of the SSL after these sediments are discharged offshore (Pujos et al. 1986; Pujos and Javelaud (1991); Torregroza-Espinosa et al. (2020); Montoya et al. (2017); Escobar and Velásquez-Montoya (2018); INVEMAR-GEO 2015, 2016).

None of these studies of sediment dynamics have evaluated the trajectories and the location of the deposition sites of the different types of sediments that are discharged by the main rivers in the Caribbean Colombian basin, considering the seasonal changes in metocean conditions (winds/waves and ocean currents). Given that most studies cover specific periods (when measurements are available), there is still a lack of understanding of the monthly mean dispersion patterns of the suspended sediment that is discharged by the main rivers in this region.

3 Data and methods

To assess how the hydrodynamics influences the sediment transport of three rivers that flow into the Colombian Caribbean basin, a numerical model was used. This Lagrangian particle model considered the advection and diffusion processes. The available datasets from these river mouth deltas (or further offshore) are insufficient to evaluate seasonal patterns of sediment transport. The key objective of this study was to determine the pathways of the suspended sediments from the river mouth to the location where they settle on the seafloor, considering seasonal timescales.

To achieve this goal, high-resolution oceanic and atmospheric data from global re-analysis were used, along with a Lagrangian model to simulate the three-dimensional (3D) dispersion and advection patterns of sediments from the river mouth to the seafloor, considering different grain sizes and metocean conditions. Forcing data from the re-analyses were validated against in situ measurements available for the area, in order to determine the ability of these models to represent realistic conditions. Seasonal maps of 3D scattering and areas of influence of the different size class sediments were analysed in detail in this work.

3.1 Bathymetry data: GEBCO_2019

The bathymetry data used in this study consisted of the latest product released by the General Bathymetric Chart of the Oceans (GEBCO), which has been developed through the Nippon Foundation-GEBCO Seabed 2030 Project. The GEBCO_2019 product provides global coverage, on a regular 15 arc-second grid (~450-m resolution) (Olson et al. 2014;

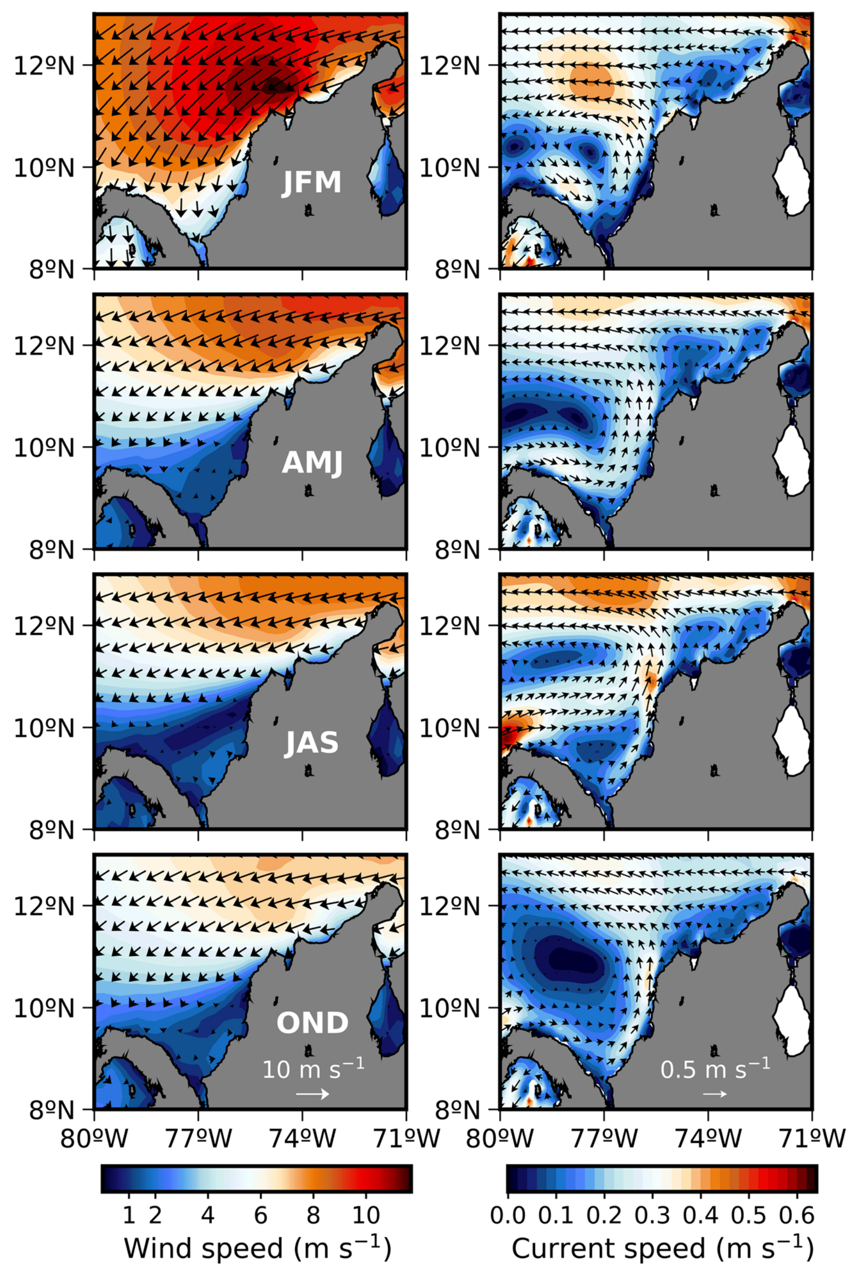


Fig. 2 Seasonal cycle of surface winds at 10 m above mean sea level (left panels) and surface currents (right panels) in the Colombian Caribbean Basin. Atmospheric data are from ERA-5 re-analysis. Ocean data from the Marine Copernicus Physical Analysis (CMEMS). Both seasonal means are estimated for the 2006–2019 period. The magnitude and direction are shown in colours and arrows. The scales are located on the bottom. JFM, January–February–March; AMJ, April–May–June; JAS, July–August–September; OND, October–November–December

GEBCO Compilation Group 2019). The data are available to download according to the Terms of Use provided at the Website of the project (https://www.gebco.net/).

3.2 Ocean currents from the Copernicus Marine Environment Monitoring Service

Velocity data used to force the Lagrangian model, and to describe the seasonal cycle of ocean currents in the Colombian Caribbean Basin, are from the operational Mercator global ocean analysis and forecast system at 1/12-degree horizontal resolution (approx. 8 km) with a regular longitude/latitude equi-rectangular projection. The product GLOBAL_ANALYSIS_FORECAST_PHY_001_024 of the Copernicus Marine Environment Monitoring Service (CMEMS) can be downloaded from the Website http://marine.copernicus.eu/.

This product includes hourly mean oceanic currents (eastward and northward sea water velocity) from the surface to 5000-m depth (50 geopotential vertical levels). Details of this analysis are described in the Product User Manual (CMEMS 2018). The common period of the atmospheric and oceanic datasets used as forcing fields is from 2007 to 2018. Using these data, an hourly climatology of the zonal and meridional components of the currents in the water column was calculated.

The physical, high-resolution analysis and forecasting system PSY4V3R1 uses version 3.1 of the NEMO ocean model (Madec and the NEMO team 2008). The advection of the tracers (temperature and salinity) was computed with a total variance diminishing (TVD) advection scheme (Lévy et al. 2001; Cravatte et al. 2007); it uses a free surface formulation. External gravity waves were filtered out using the Roullet and Madec (2000) approach. A Laplacian, lateral, isopycnal diffusion was used on the tracers, and a horizontal biharmonic viscosity was used for the momentum. In addition, the vertical mixing was parameterised according to a turbulent closure model (order 1.5 and mixing length of 30 m), as adapted by Blanke and Delecluse (1993). This reanalysis is forced with the atmospheric field taken from the ECMWF (European Centre for Medium-Range Weather Forecasts) Integrated Forecast System. Assimilated data include altimeter, in situ temperature and vertical salinity profiles and satellite sea surface temperature and sea ice concentration (CMEMS 2019).

3.3 Wind data from the ERA-5 re-analysis

The eastward and northward components of the surface winds used to force the Lagrangian model were from the ERA-5 global atmospheric re-analysis. This is the fifth generation atmospheric re-analysis of the ECMWF (C3S 2017). This re-analysis combined model data with observations from across the world into a globally complete and consistent dataset using the laws of physics (Hersbach et al. 2019). ERA-5 provides estimates for each hour of the day, worldwide, with a 0.25° horizontal resolution (approx. 27 km). This hourly output resolution is a significant improvement over its predecessor (ERA-Interim) and provides a more detailed evolution of particular weather events. The re-analysis data used for the estimation of the hourly climatology is from 2007 to 2018.

3.4 In situ data

Local measurements of ocean currents are available at two nearshore stations located in the Colombian basin: Molusco and Sinú-offshore (SINOFF7) (Fig. 1). The datasets were provided by the Colombian Petroleum Institute ECOPETROL (Colombian Petroleum Company) metocean database, which is part of their baseline information for offshore projects.

The SINOFF7 is a deep-water mooring (~ 1434 m) located on the central coast of Colombia, to the southwest of the Magdalena River. It was deployed to measure current speed and direction, seawater temperature and conductivity (Table 2). The oceanographic monitoring instrumentation comprised numerous sub-sea instruments and recorded ADCP and CTD measurements at different depths (FUGRO Global Environmental, and Ocean Sciences, Inc 2017).

Quality control procedures included the application of amended start and end times to remove invalid data recorded

Table 2 In situ data available in the Colombian Caribbean basin used in the validation of the global oceanic and atmospheric re-analyses

Station ID	Parameter	Location (bottom depth)	Depths and dates	Instruments
SINOFF7	Current speed and direction	10.746° N 75.758° W (~ 1434 m)	ADCP (34 to 380 m). 16/12/2015 to 31/05/2016	300 kHz WH ADCP and SBE 37 CTD at 52 m. 75 kHz WHLR ADCP and SBE 37 CTD at 413 m
Molusco	Current speed and direction and surface winds	11.935°N, 72.826°W (~ 60 m)	ADCP (12 to 52 m) from 4/9/2015 to 1/6/2017. Winds from 4/9/2015 to 5/4/2017	Real-Time Metocean Monitoring (RTMM) system: wind speed sensors (RM Young: propeller/vane wind monitor) and compass; barometric pressure; solar radiation; air temperature probe, TRIAXYS NW directional wave sensor Teledyne RDI, 300 Khz Workhorse ADCP downward, on lower bridle of 3 m buoy

during mooring deployment, drift, redeployment and recovery; comparison of valid data with logsheet start and end times to ensure that no timing drifts occurred; application of a degree correction for magnetic declination, to convert all directional data from magnetic to True North; removal of all zeros; and a final inspection of data quality by an experienced oceanographer, to identify and remove any remaining anomalous values outside of the physical limits of the region.

Additional quality control parameters for the ADCP data, including error and vertical velocity, percentage of good pings, echo intensity and beam correlation values, were performed. Records flagged with errors were removed from all data analyses (FUGRO Global Environmental, and Ocean Sciences, Inc 2017). In this study, the upper 400 m of ADCP data were analysed.

The Molusco metocean buoy, located in northern Colombia, is the largest record available for this area, with hourly ADCP current measurements (12 to 52 m) from September 2015 to June 2017 and surface wind data from April 2015 to April 2017. Several atmospheric and oceanic parameters were measured with a buoy-based Real-Time Metocean Monitoring (RTMM) system, located 43 km north-northeast of Riohacha, in La Guajira coastal zone (Woods Hole Group 2016).

Physically, the system consists of a 3-m buoy that serves as a surface platform to support a meteorological tower. The tower hosts the meteorological and atmospheric measuring suite as well as the telemetry equipment. The buoy is connected to an underwater bridle that hosts the current measuring instrument (ADCP) and is attached to a mooring line (Table 2).

The RTMM system measures and transmits current speed and direction throughout the water column (from approximately 13 to 57 m water depth), significant wave height, wave period and directional wave parameters, wind speed and direction, atmospheric pressure, air temperature and solar radiation. All of the directional data collected was referenced to Magnetic North. In post-processing, wind, wave and current directions were converted to True North. The value of magnetic declination for the area is 8.9° W (Woods Hole Group 2017).

The available in situ measurements were statistically compared with the re-analysis data, in order to determine the ability of the global models to represent real metocean conditions in this area. Several statistical parameters were estimated. These include the correlation coefficient ($r = \sigma(\mathrm{Obs}, \mathrm{Mod})/(\sigma\mathrm{obs}\ \ \sigma\mathrm{mod})$); the root mean square error ($\mathrm{RMSE}=\sqrt{1/N\sum_{t=1}^{N}\left(X^t_{\mathrm{mod}}-X^t_{\mathrm{obs}}\right)^2}$); the bias ($1/N\sum_{t=1}^{N}(X^t_{\mathrm{mod}}-X^t_{\mathrm{obs}}$); and the scattering index ($SI = \frac{\mathrm{RMSE}}{1/N\sum_{i=1}^{N}X^t_{\mathrm{obs}}}$, in %). In these equations, "obs" represents the buoy measurements and "mod" represents the re-analysis model data.

3.5 Numerical Lagrangian model

To effectively assess the impact of sediment input to coastal waters, it is necessary to predict their spatial and temporal distributions in the water column and in the sediment substrate. In order to do this, it is imperative to consider the interaction between sediment transport processes and the flow field (Shrestha and Blumberg 2005).

Sediment transport is a complex, multidimensional and dynamic process that results from the interactions of hydrodynamics, turbulence and sediment particles. Grain particles can be transported by currents (tide driven, density driven, wave driven or wind driven), wave motions and combinations of the two. Sediment transport models have been widely used in the scientific and engineering community to understand deposition by rivers into the ocean. The three-dimensional (3D) models are based on the 3D-mass balance equations or the convection-diffusion equations for suspended sediment transport (van Rijn 1989). The flow field and sediment concentration computations are integrated and computed for each time step. Both the horizontal and the vertical components of the sediment transport processes are considered, providing the most complete, quantitative representation of any hydrodynamic system.

Conventional Eulerian transport models predict the bulk flux of particles in the sea, ignoring their identity. However, for certain problems, a Lagrangian approach is required, as the identity of the particles is important. Lagrangian models represent substances released to the sea as regular releases of discrete particles, each representing a defined quantity of the released substance. Model particles move under the influence of currents simulated by numerical hydrodynamic models (Soulsby et al. 2011). This method provides an accurate and efficient means of resolving advection-dominated problems. Individual particle tracking permits visualisation of trajectories and settling patterns and can provide complementary information to that derived from Eulerian diffusion-based models (Corell and Döös 2013).

In this study, the OpenDrift framework for Lagrangian modelling was used to predict the pathways and deposition of sediments in the Colombian Caribbean Sea. This offline tool allows the trajectories to be computed from the Eulerian model simulations. The framework allows for the ingestion of various forcing fields (scalar and vectorial) from various sources, including Eulerian ocean, atmosphere and wave models.

OpenDrift is an open-source, Python-based, Lagrangian particle modelling code developed at the Norwegian Meteorological Institute (MET Norway) with contributions from the wider scientific community (https://opendrift.

github.io/). It is described in detail in Dagestad et al. (2018) and supports a wide range of offline predictions. Object drift is decomposed into its downwind and crosswind components (Breivik and Allen 2008).

OpenDrift modules share several configuration settings which may be adjusted before a simulation, as well as some settings which are module specific. The Euler propagation scheme was selected, but the second-order Runge-Kutta scheme is also available (Dagestad et al. 2018). The 3D Lagrangian model performs the propagation with ocean currents and, possibly, additional wind drag. Hence, particles can move with the ambient current, advected wind drag, the Stokes drift, turbulent mixing and vertical advection. It is suitable for passive tracers; the particles may be buoyant and/or subject to terminal velocities and may be affected by vertical turbulent mixing. Particles could be oil droplets, plankton, nutrients or sediments. Buoyancy is expressed as a terminal velocity, which is the steady-state vertical velocity due to buoyant behaviour or sedimentation rates. It is usually a function of particle density, diameter and shape. Vertical particle displacement due to turbulent mixing is calculated using a random walk scheme (Visser 1997).

The SedimentDrift model used to track sediment particles was developed by MetOcean Solutions Ltd. This module is part of the OpenDrift framework. Each particle has properties such as position (longitude, latitude, depth) and a vertical settling velocity which is related to the grain size and density. The 3D motion of the sediment includes propagation with horizontal and vertical ocean currents, horizontal and vertical diffusions and additional wind drag, inherited from the base class.

Lagrangian simulations only include the non-cohesive sediment dynamics. Cohesive sediments in coastal waters come under the influence of various complex processes which are not solved by the model. This limits the overall understanding of the SSL delivered by rivers into the coastal zone of Colombia. Even though the predominant textural group in the delta areas is generally sand, followed by muddy sand, finer, highly cohesive sediments (silts and clays) have been reported for the Magdalena River mouth water-column section (Restrepo et al. 2016).

To simulate different types of sediment (classified by grain size), the SedimentDrift module requires the sediment settling velocity, as neither sediment transport nor deposition can be understood or modelled without knowing what the settling velocity of a particle of a certain grain size is. In the Lagrangian model, this is defined by the terminal velocities (m s^{-1}) to be used in the turbulent mixing. For very small particles, settling velocities in water can be estimated using Stokes' Law (Stokes 1851):

$$w = \frac{RgD^2}{C_1 \nu}$$

where w denotes the particle's fall velocity, R is the submerged specific gravity (1.65 in the case of quartz-density sediment), g is the gravitational acceleration, D is the particle diameter, C_1 is a constant with a theoretical value of 18 and ν is the kinematic viscosity of the fluid. To estimate R, the density of the quartz particles is 2650 kg m^{-3} and the average density of the seawater is 1025 kg m^{-3}.The fall velocities of non-spherical particles, rough particles or particles in very high concentrations are somewhat lower (i.e. C_1 is larger) (Raudkivi 1990). Stokes' law holds for particles with a Reynolds number (Re= $w\ D/\nu$) below a value of about 1.

Fine sand grains are small enough that viscous forces still play an important role in their subaqueous settling behaviour but large enough that the departure from Stokes' Law is significant and wake turbulence cannot be ignored. To simulate this type of sediment, the Ferguson and Church (2004) approximation for fall velocity as a function of diameter is used:

$$w = \frac{RgD^2}{C_1 \nu + \sqrt{0.75 C_2 RgD^3}}$$

$C_2 = 1$ is a constant in the Ferguson-Church equation and is valid for natural sand grains. These values of C_1 and C_2 give an excellent fit to existing experimental datasets for natural sands of non-spherical shape (Ferguson and Church 2004). At small values of D, the left term in the denominator is much larger than the one containing the third power of D, and the equation is equivalent to Stokes' Law. At large values of D, the second term dominates, and the settling velocity converges to the solution of the turbulent drag equation.

For the Lagrangian simulations, a Mercator projection grid basemap for the Colombian Caribbean domain (8°–13° N; 71°–80° W) is used. Particles were released on the sea surface at each river mouth (Table 1) on the first day of each climatological month. The uncertainty radius around the release point was defined as being 1000 m, in order to represent the river plumes. The simulations ended when all of the particles reached the coastline or the ocean floor. For the Magdalena River, the model time steps for the estimations and for the outputs were hourly. For the Atrato River, the time step was 1 min and for the Sinú River, it was 10 min.

Even though it is evident that the sediments that are discharged by these rivers are released at different depths along the water column, the influence of the high freshwater discharges as buoyancy inputs promote the transfer of sediments from the river channel to the outer pro-delta through the upper layers of the water column (Restrepo et al. 2016). The terminal velocities are also required in the seeding of the sediment particles. For fine sands (0.15-mm diameter), the terminal velocity in water at 20 °C is w = 0.0146 m s^{-1}; for very fine sands (0.081-mm diameter), the settling velocity is w =0.006 m s^{-1}; and for coarse silts (0.043 mm diameter), the velocity used is w =0.0016 m s^{-1}.

In these simulations, the number of particles seeded on the ocean surface is intended to represent the SSL of each river. Due to computer capacity restrictions, in these experiments, a maximum value of 10,000 particles was designated to the Magdalena River delta (Bocas de Ceniza), which has the highest SSL. The other two rivers were scaled to a smaller number of particles, considering their annual SSL. For the Atrato River delta (Boca Tarena), 790 particles were used and for the Sinú River delta (Boca Tinajones), 220 particles were simulated. Given that the SSL in the three rivers has varied significantly over the past decades, due to natural oscillations and human intervention (Restrepo et al. 2016), it was preferable to use the annual mean reported in the bibliography (Restrepo et al. 2016, 2017; Higgins et al. 2017) to simulate a specific number of particles released by the Magdalena, Sinú and Atrato Rivers each month.

Even though it would be desirable to have sufficiently long records of SSL for each river mouth, with which to construct climatology, the available data is scarce and insufficient to accomplish this. Hence, in these experiments, it was not intended to accurately represent the seasonality of the suspended sediments that are discharged by the main rivers in Caribbean Colombia, given that there are still several uncertainties in the information needed to address realistic SSL conditions. In the simulations, a constant value of Lagrangian particles was used but the metocean conditions do change each month.

In these simulations, data of wind and ocean currents used as forcing fields comprised the hourly climatology constructed from ERA-5 and Marine Copernicus, respectively. The variable “sea floor depth below sea level” was taken from GEBCO-2019. The effect of waves was calculated implicitly with the wind. The Stokes drift corresponding to actual depths was internally parameterised, based on the wind velocity (if this was not provided by the wave model) (Breivik et al. 2016). As wind-generated waves have a mean direction closely aligned with the local wind direction, it was neither practical nor desirable to disentangle the Stokes drift from the wind drag for the Lagrangian simulations.

In addition to the wave-induced entrainment, the Lagrangian elements are also subject to vertical turbulence throughout the water column, as parameterised with the numerical scheme described in Visser (1997). This scheme is generic within OpenDrift (Dagestad et al. 2018). Also, a random wind drift factor was specified, allowing an additional wind drag at the surface. The horizontal ocean diffusivity used was 0.1 m^2 s^{-1}, and vertical ocean diffusivity was 0.0001 m^2 s^{-1}.

Tidal circulation could be an important factor in sediment transport (Dyer 1998; Mathew and Winterwerp 2020) but, given that this region is characterised by a microtidal range (Kjerfve 1981; Torres and Tsimplis 2011), this forcing was not included in the simulations. Restrepo et al. (2016) made measurements in the Magdalena River mouth in two different seasons and concluded that, in this area, there was no evidence of currents induced by tides.

The bed load transport and the bottom sediment erosion and deposition properties are not represented by the sediment transport module. Also, calibration of the Lagrangian model was not performed, given that there are no direct measurements available in these river mouth areas, such as in situ estimations of vertical and horizontal turbulent ocean diffusivity, with which to perform the estimations.

However, the hydrodynamic model data used as the forcing fields was validated against in situ measurements within the Colombian Caribbean basin. Hence, it was expected that the resulting sediment trajectories and deposition sites were not far from present-day conditions. It is evident that there are limitations to this approach, given the scarcity of available data. Nevertheless, the Lagrangian modelling of sediment transport under different climatic scenarios resulted in valuable information regarding the 3D dispersion of the SSL discharged by the main rivers in the southern Caribbean Sea.

In order to obtain some geospatial properties of the sediments deposited each month, an ellipse that encloses the dispersion of particles was adjusted, using the methodology described in Preisendorfer (1988). This method delivers the major axis, minor axis and their orientation. With these parameters, an ellipse could be adjusted, and, from this, the following parameters determined: (a) deposit area. This parameter was estimated using the area method of an irregular polygon through the Gauss determinant (Beyer 1987). This method is applicable to any polygon with any number of sides, for both concave and convex polygons; (b) perimeter; (c) percentage of particles inside the ellipse; and (d) the orientation of the ellipse, relative to north, in a clockwise direction. This parameter gives us information about the direction of the deposit on the sea floor. The resulting ellipses allowed us to identify the area of influence of the fine sands, very fine sands and coarse silts that are discharged to the coast by the Magdalena, Sinú and Atrato Rivers. The patterns obtained from the Lagrangian simulations each month were then related to the hydrodynamic processes that dominate in this region.

4 Results

4.1 Validation of the forcing fields

To quantify the ability of the numerical hydrodynamic and wind models is the first step towards the assessment of the Lagrangian sediment transport, given that these models should be able to reproduce the observed metocean conditions occurring over the shelf and offshore areas of the Colombian basin. To determine the effectiveness of these re-analysis models, it would be desirable to have a network of stations along the coast, near to the river deltas; however, in the Colombian basin, in situ data of marine wind and currents are scarce. Nevertheless, the stations with data available for this study are located in two zones that represent different metocean conditions. On the northern Colombian coast, the Molusco buoy represents a highly energetic environment where coastal upwelling and strong winds and currents are dominant during the dry seasons. The SINOFF7 mooring is located further offshore in the central coast, outside of the upwelling.

In the evaluation of the wind speed from ERA-5, we considered local conditions and the distribution of the in situ data available from the Molusco metocean buoy (Fig. 3). Here, we consider that a bias of less than 1 m s^{-1}, a correlation coefficient above 0.8, an RMSE less than 1.5 and an SI of less than 20% are indicative of an acceptable level (Devis-Morales et al. 2017). A visual comparison indicates a good agreement between both datasets. Maximum wind speeds from the re-analysis were somewhat underestimated at this station. However, results from the statistical comparison show that ERA-5 re-analysis adequately represents the wind speed patterns and variability in this offshore area of northern Colombia (Table 3).

The ocean currents from the CMEMS re-analysis were compared with the ADCP measurements at SINOFF station at different depths (Fig. 4). The results clearly show that the model data is in good agreement with the available measurements in the upper water column, with high correlation coefficients ($r > 0.6$) and very small RMSE (< 0.1) and bias (< 0.05). The SI is low in the upper water column (< 0.76). This evaluation indicates that the model adequately represents the ocean hydrodynamics in this region (Table 3) and can be used as a forcing field for the Lagrangian sediment model. The diagnostic analysis of ERA-5 and CMEMS at the evaluated stations in the Caribbean Sea led to the conclusion that these datasets are reliable; hence, they can be used for several oceanographic and coastal engineering studies.

4.2 Seasonal patterns of sediment transport

4.2.1 The Magdalena River

Particles seeded at the river mouth (Bocas de Ceniza) on the first day of each month are forced with climatological wind and ocean current fields. The fine sands are transported towards the west-southwest during the dry season, when the CLLJ and ocean currents are intense. These sediments are rapidly deposited near the river mouth, at depths below 200 to 250 m. Less than 2% of released particles are advected towards the coastline. During the rainy season, when easterly winds and currents are relatively weak, the eastward coastal counter-current is a dominant feature, and hence, the dispersion of these particles changes direction towards the north-northeast. The vertical settling velocities of these coarse sediments dominate over the horizontal advection by the ocean currents; this type of sand reaches the seafloor in less than 6 h (Fig. 5).

Very fine sands are transported for longer horizontal distances before seafloor deposition. Seasonal variations of the transport pathways are due to the changes in the intensity and direction of the prevailing winds and currents. During the dry season, these suspended sediments are advected towards the west; February is the month with the largest horizontal advection. From May, the currents, and wind change direction and particles are transported northward or north-eastward.

These very fine sands are usually advected away from the continental shelf and are finally deposited at depths of up to 800 m, but seasonal variability is large. When currents are weak, particles are transported short distances and settle relatively quickly (around 12 h) on the seafloor. When winds and currents are intense, particles are advected large distances, taking at least 20 to 22 h to reach the ocean floor.

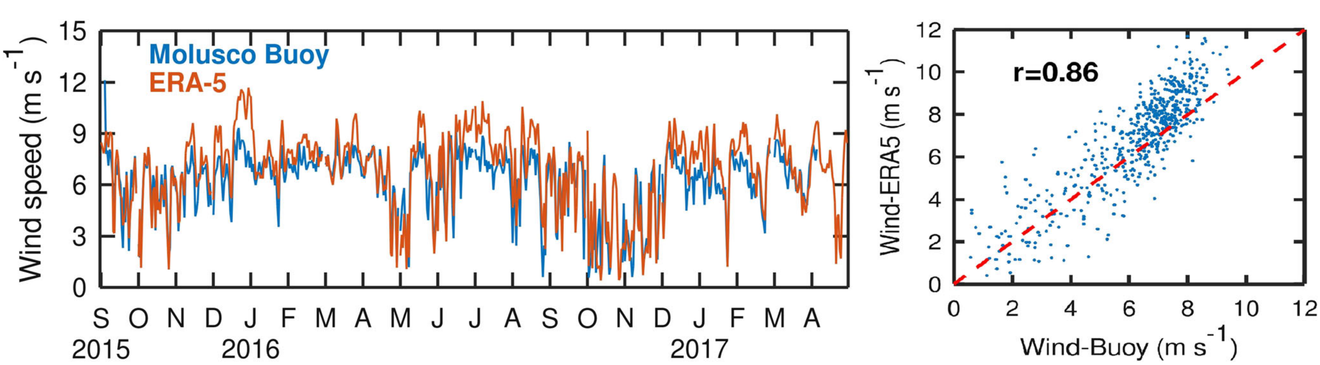


Fig. 3 Wind speed time series at Molusco station, measured in situ (blue) and extracted from the ERA-5 re-analysis (left panel). Dispersion diagram between the buoy and the re-analysis datasets including the correlation coefficient (right panel)

Table 3 Statistical comparison between re-analysis data and in situ measurements in the Caribbean Colombian basin

Datasets	Variable	RMSE	Bias	SI
Molusco buoy vs. ERA-5	Surface wind speed	1.34	− 0.63	0.02
SINOFF7 buoy vs. CMEMS	Currents at 34.4 m	0.08	0.02	0.76
	Currents at 40.3 m	0.07	0.01	0.59
	Currents at 55.7 m	0.07	− 0.01	0.52
	Currents at 65.8 m	0.06	− 0.01	0.53
	Currents at 77.8 m	0.07	− 0.02	0.76
	Currents at 92.3 m	0.09	− 0.02	1.16
	Currents at 109.7 m	0.09	− 0.01	1.86
	Currents at 130.6 m	0.09	0.01	3.05

RMSE root mean square error (m s^{-1}); Bias (m s^{-1}); *SI* scattering index

Coarse silts remain suspended in the water column for 5 to 7 days before reaching the seafloor, being transported by the currents for long distances. During the dry season, these particles are advected towards the west in the upper 200 m and are then diverted towards the east by the coastal counter-current, until they reach the seafloor at approximately 500-m depth. During the rainy season, the upper 200 m of sediment transport is towards the north, and then it is advected eastward or north-eastward. During the peak of the rainy season (October), most of the sediment is transported towards the east while slowly migrating vertically to reach the seafloor at around 500-m depth.

The sediment trajectories for the peak dry season (February) and the rainy season (October) provide clear evidence that the ocean currents are an important factor in controlling the 3D dispersion in the Magdalena River plume (Fig. 6). Intense flows from the Caribbean current and the northern limb of the Panama-Colombia cyclonic circulation move sediments westward during the dry season. The easterly winds and ocean currents weaken during the rainy season and the coastal counter-current intensifies, driving the sediments along the coastline, towards the north and northeast.

The horizontal distances that these particles travel depend on the settling velocities, which force the sediments towards the seabed. Fine and very fine sands move with the upper layer currents while rapidly reaching the seafloor. In the case of coarse silts, it can be seen that subsurface currents, which are driven by density gradients, have a direct effect on the trajectories at around 200-m depth. During the dry season, the sediments are transported westward in the upper layer, changing direction as they sink and move back towards the east, along with the counter-current.

This Lagrangian simulation allows us to understand the general sediment dynamics of this delta. From the resulting seasonal dispersion patterns of each sediment type, we constructed the mean ellipses that delineate their areas of influence (Fig. 7). This procedure allows us to estimate several properties of interest, such as the minimum/maximum distance travelled by the particles, the average area of the depositional sites, the perimeter of the ellipses and the percentage of particles within the ellipses.

For the fine sands, large seasonal variability can be observed with short trajectories (< 1 km) during the months when winds and currents are relatively weak and longer distances (around 10 km) during the windy months. The area of these ellipses ranged from 12 to 15 km^2, with perimeters of 18 to 20 km. The orientation of these ellipses is elongated towards the north (northeast or northwest) during the dry season and towards the southeast/southwest during the rainy season (Table 4).

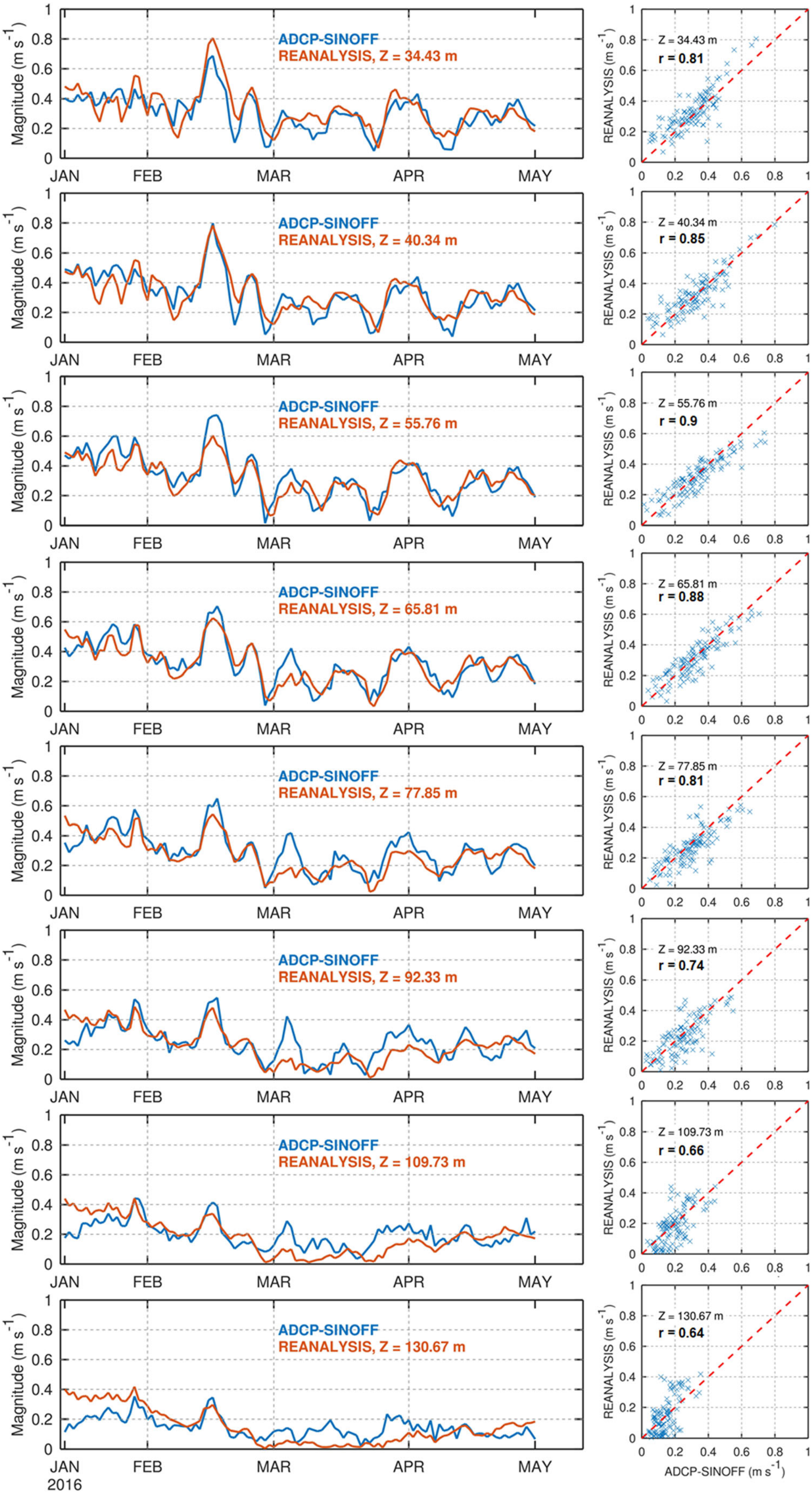
Very fine sands travel longer distances before settling on the seafloor, with maximums ranging from 11 to 32 km, covering an area of 15 to 68 km^2 and with perimeters of 21 to 65 km. February is the month when the largest dispersions coincide with the strength of the wind and ocean currents. The orientation of the ellipses was generally towards the north (northeast or northwest) except for May, June and September.

Coarse silts also travelled long horizontal distances (from 16 to 44 km), with dispersion plumes covering an area of 12 to 60 km^2 and perimeters ranging from 15 to 28 km. The mean orientation of the ellipses varied from month to month: in November, January, March to May and August, these were oriented towards the north while, during the remaining months, these acquired a southward orientation.

4.2.2 The Atrato River

The sediments released by this river are rapidly deposited on the seafloor due to the shallow depths encountered near the mouth and the relatively weak ocean currents (> 0.1 m s^{-1}) and winds (< 5 m s^{-1}) that prevail in the Urabá Gulf all year-round (Fig. 8). Fine sands settle near the river mouth (< 40-m depth) in less than 1 h. The very fine sands reach the seafloor in ~ 2 h, while the coarse silts take around 8 h to settle on the bottom, due to the horizontal advection that occurs during some months.

The resulting ellipses obtained from the horizontal dispersion of fine and very fine sands show very circular patterns


ADCP-SINOFF
REANALYSIS, Z = 34.43 m
Z = 34.43 m
r = 0.81
ADCP-SINOFF
REANALYSIS, Z = 40.34 m
Z = 40.34 m
r = 0.85
ADCP-SINOFF
REANALYSIS, Z = 55.76 m
Z = 55.76 m
r = 0.9
ADCP-SINOFF
REANALYSIS, Z = 65.81 m
Z = 65.81 m
r = 0.88
ADCP-SINOFF
REANALYSIS, Z = 77.85 m
Z = 77.85 m
r = 0.81
ADCP-SINOFF
REANALYSIS, Z = 92.33 m
Z = 92.33 m
r = 0.74
ADCP-SINOFF
REANALYSIS, Z = 109.73 m
Z = 109.73 m
r = 0.66
ADCP-SINOFF
REANALYSIS, Z = 130.67 m
Z = 130.67 m
r = 0.64
Magnitude (m s^{-1})
REANALYSIS (m s^{-1})
ADCP-SINOFF (m s^{-1})
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◀ **Fig. 4** Time series of ocean current magnitude at different depths, at the SINOFF station, measured in situ (blue) and extracted from the CMEMS analysis (left panels). Dispersion diagram between the buoy and the model data including the correlation coefficient (right panels)

and little variations during the annual cycle, indicating that the ocean currents and winds have little effect on the transport of these types of sediments. The coarse silts showed more elongated ellipses oriented towards the north, during the rainy season, indicating that winds and currents are important factors in the transport of very fine sediment.

The area of influence of the sediments released by the Atrato River is located near the coastal zone, with sedimentation occurring at depths between 35 and 45 m. Fine sands travel from 50 to 180 m before reaching the seafloor, covering an area of 12 km^2 and in a north-north-western orientation (Table 5). Very fine sands travelled 145 to 360 m in the water column before settling on the bottom, but the ellipses and area covered by these sediments were similar to the fine sands.

The coarse silts were advected by the ocean currents from between 600 and 1300 m, even though during a few months of the rainy season (September and October), the horizontal dispersion was higher (2.5 km) due to the strengthening of ocean currents in this area. The resulting ellipses were around 12.4 km^2, oriented towards the northwest (Table 5).

Energetic conditions in the dry season and extreme events in the Caribbean Sea increase SSC and reverse the sediment dynamics in the gulf. In this case, northerly winds and waves

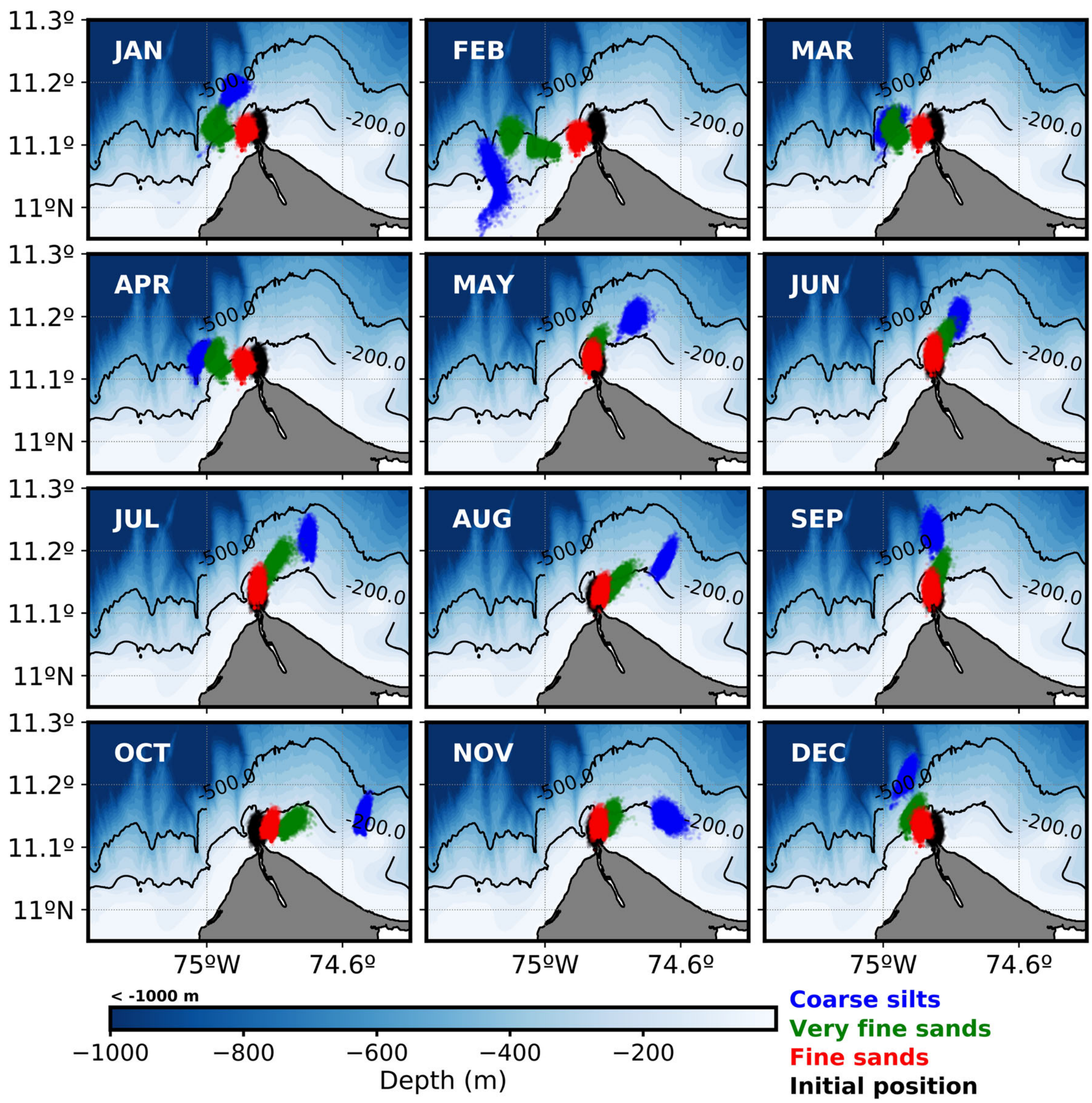

Fig. 5 3D scattering of fine sands (red), very fine sands (green) and coarse silts (blue) released at the Magdalena River mouth each climatological month. Simulations with SedimentDrift®. The bathymetry of GEBCO-2019 is shown in colour (depths in m). Ten thousand particles were released on the sea surface (black dots). The sediment settling position on the seafloor is shown

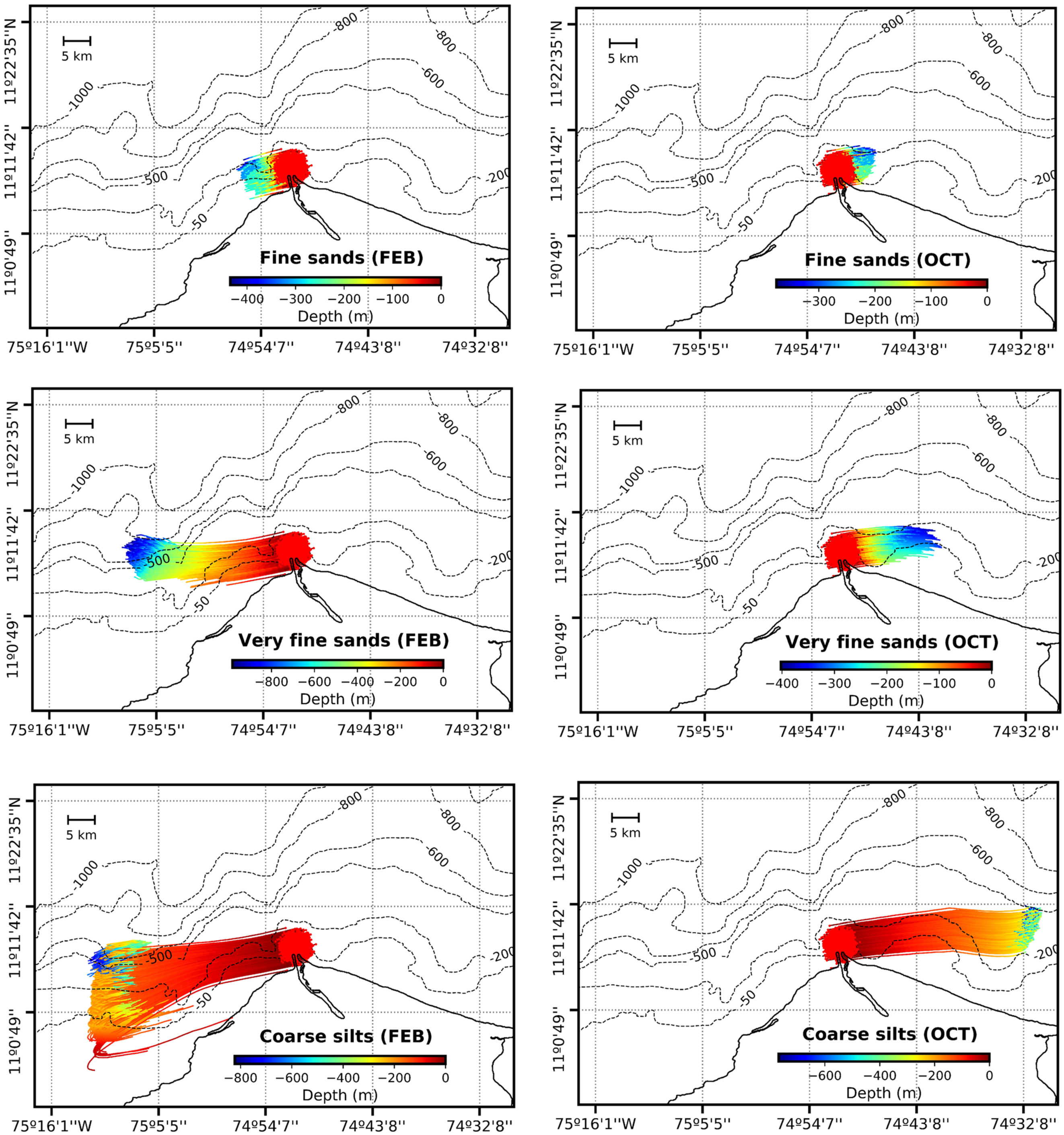

Fig. 6 3D trajectories of fine sands (top), very fine sands (centre) and coarse silts (bottom) released at the Magdalena River mouth during February (peak of dry season) and October (peak of rainy season). The depth of the particles along their trajectories is shown in colour. Simulations with SedimentDrift®. The bathymetry of GEBCO-2019 is shown as contours (depths in m)

block river plumes from travelling north, and suspended sediments have a southerly littoral drift. This is clearly evidenced in the coarse silts (orange and green ellipses), which remain in the water column for a longer period before reaching the seafloor (Fig. 8).

4.2.3 The Sinú River

The sediments released by the Sinú River rapidly sink towards the seafloor with little horizontal advection by ocean currents. Fine sands and very fine sands reach the bottom (around 10–

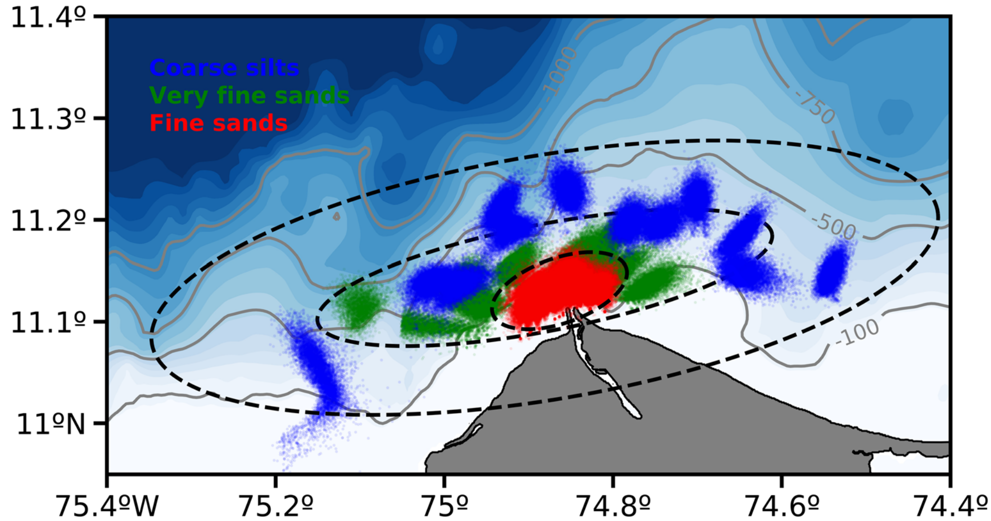

Fig. 7 Average area of influence of sediments released at the Magdalena River mouth, calculated from the ellipses of the dispersal clouds. Simulations with SedimentDrift®. The fine sands are shown in purple, the very fine sands are shown in red and the coarse silts in blue. The bathymetry is from GEBCO-2019. The isobaths of 100, 500 and 1000 m are shown as grey contours

15-m depth) in less than 1 h and 3 h, respectively. Coarse silts remain in suspension longer (13 to 23 h) before settling on the seafloor (25 to 35 m), depending on the season. During the rainy months (September to November), these very fine sediments are transported towards the northeast, parallel to the coastline, due to the counter-current, which intensifies during this season (Fig. 9).

The dispersion ellipses showed that fine and very fine sands varied very little during the annual cycle, sinking near to the river mouth, with very similar areas of influence. The silts evidenced monthly spatial variations related to local metocean conditions, with some horizontal spreading towards the north, northeast and southwest. Table 6 summarises the properties of the ellipses generated for the three types of sediments.

On average, the fine sands move between 200 and 300 m from their point of origin, covering an area of approximately 11.6 km^2 (with a perimeter of ~ 1250 km). The orientation of the ellipses ranged between 346° and 4°, indicating the tendency of the particles to disperse northward (NNW to NNE).

Very fine sands disperse between 400 and 900 m from their point of origin, in front of the Sinú River mouth. The resulting ellipses of the scatter clouds cover an area of about 10.8 km^2 and a perimeter of ~ 1180 km, with a preferential orientation towards the NNW (318°).

The coarse silts dispersed between 1.4 and 4.8 km, before settling on the seabed. The advected particles covered an area of about 11.7 km^2 (a perimeter of 1188 km). The resulting ellipses had a predominant orientation to the north, ranging between 330° and 21°.

5 Discussion

The ability of the numerical hydrodynamic and wind models used to force the Lagrangian sediment model was assessed by the statistical evaluation of these datasets. This analysis indicated that re-analysis models agreed well with the measurements in the two locations with in situ data available; hence, we are confident that these forcing fields represent the hydrodynamics in this ocean basin and the data can be used to model the sediment transport.

However, it is clear that these two stations are not representative of the entire Colombian basin. It would be desirable to have a monitoring network of stations along the coast, with which to perform the validation of the re-analysis models, but this is a limitation in this region. Nevertheless, the two moorings are located in two distinct coastal zones of Colombia: an upwelling area with strong winds and currents and a coastal zone located outside the upwelling dynamics but influenced by the warm, less saline waters of the southwestern Caribbean basin.

The winds and ocean currents encountered in each river mouth determine the sediment dynamics. During the dry and rainy seasons, these are the main features that trigger the transport of sediments from the river mouths towards the open ocean. However, each type of sediment responds differently, given their settling velocity. This explains why the sands are rapidly deposited near the river mouths, even though winds and currents are intense, while coarse silts remain suspended for longer in the water column during seasons of weak flow.

Lagrangian modelling is a valid initial approach, in the aim of understanding the basic sediment dynamics in these river deltas. However, limitations in this methodological approximation have been identified, which could affect the resulting spreading patterns of the different sediment classes. These include the simplifications made in the estimation of settling velocities, the use of a constant number of particles seeded on the ocean surface in a year and the lack of understanding of some processes that are not resolved by the model, such as re-suspension, bed load transport and erosion. Also, cohesive

Table 4 Properties of ellipses generated for fine sands (FS), very fine sands (VFS) and coarse silts (CS) per climatological month

Month	Sed.	MIN dist (km)	MAX dist (km)	Area (km^2)	Perimeter (km)	Orientation (degrees)
Jan	FS	0.1	8.2	14.1	20.1	14.8
	VFS	5.8	19.1	30.7	30.0	341.8
	CS	6.5	28.7	24.8	28.1	32.2
Feb	FS	1.0	10.2	15.1	20.8	14.3
	VFS	11.6	32.1	68.3	65.7	348.2
	CS	22.1	44.2	59.7	27.9	201.0
Mar	FS	0.5	8.6	14.4	20.2	14.2
	VFS	6.7	17.5	24.8	27.3	325.7
	CS	6.8	22.2	23.4	28.1	27.1
Apr	FS	0.2	9.1	14.6	20.4	358.8
	VFS	7.5	17.5	22.2	25.3	325.0
	CS	12.3	24.2	18.0	24.8	25.9
May	FS	0.0	5.4	13.0	19.0	142.6
	VFS	0.0	9.5	16.9	23.2	135.5
	CS	4.5	23.6	19.8	25.4	25.6
Jun	FS	0.0	6.1	14.7	20.3	171.8
	VFS	0.2	11.7	18.0	24.8	136.0
	CS	5.3	15.8	17.0	23.7	136.3
Jul	FS	0.0	6.5	15.1	20.7	165.0
	VFS	0.2	18.1	24.5	31.8	39.2
	CS	14.8	23.3	15.5	23.0	175.6
Aug	FS	0.0	6.2	12.1	18.7	137.9
	VFS	1.1	17.5	17.2	27.4	31.5
	CS	14.8	29.1	14.1	23.4	41.9
Sep	FS	0.0	6.2	14.4	20.1	186.6
	VFS	0.3	10.8	19.7	26.0	144.7
	CS	5.9	17.0	20.2	24.9	207.0
Oct	FS	0.7	8.1	11.8	18.5	44.0
	VFS	5.2	18.8	17.7	26.6	21.6
	CS	30.6	37.8	12.2	15.9	151.7
Nov	FS	0.0	5.4	13.0	19.1	159.5
	VFS	0.6	13.0	15.4	21.5	37.9
	CS	17.1	33.4	25.2	27.6	346.2
Dec	FS	0.3	8.7	15.2	20.7	337.5
	VFS	3.6	11.7	16.8	22.9	40.0
	CS	9.9	17.2	14.6	20.8	138.5

The minimum (MIN) and maximum (MAX) distance recorded by the sediment particles from the Magdalena River mouth, the seafloor area of the sediments deposits, the perimeter of the ellipses and the orientation of the sediment cloud are included

sediment dynamics are not considered; the inertial effect of buoyant feathers and the effect of stratification are not solved by the model. These are important factors which could have an impact on the 3D dispersion and settling patterns. If local measurements of SSL, ocean currents, winds and waves become available in these river deltas, it is recommended that further studies of the processes that were not resolved in this study are performed.

For the Magdalena River, it is evident that seasonal patterns of the fine sands are generally deposited near the mouth, on the continental shelf. From their initial position, these particles are transported by ocean currents, to a maximum distance of 5 to 10 km (depending on the season), before reaching the seafloor, in less than 6 h. Very fine sands take 12 to 22 h in settling over the continental slope (~ 400 m), being transported greater horizontal distances by ocean currents

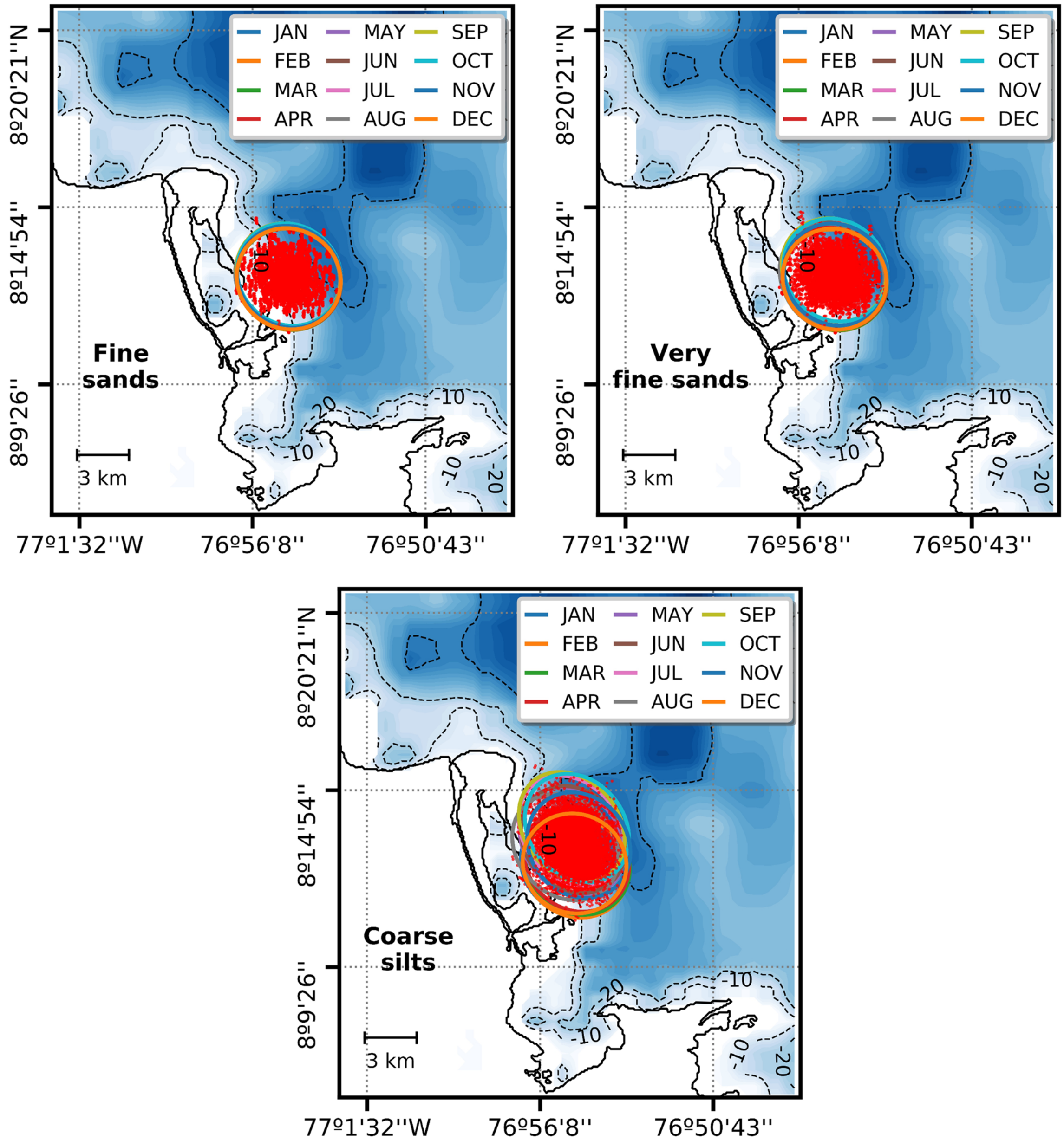

Fig. 8 Average area of influence of sediments released at the Atrato River mouth, calculated from the ellipses of the dispersal clouds. The fine sands are shown in the top-left panel, the very fine sands in the top-right panel and the coarse silts in the bottom panel. Simulations were conducted with SedimentDrift®. The bathymetry of GEBCO-2019 is shown in colour (depths in m). Seven hundred ninety particles were released on the sea surface at the beginning of each climatological month

(10 to 32 km). The coarse silts remain suspended in the water column for several days (5 to 7), before reaching the ocean floor. These very fine particles are advected by the upper layer currents and the subsurface counter-currents for tens of kilometres (15 to 44 km) and could remain near the bottom for hours, or even a few days, before finally settling.

Hydrodynamic patterns vary seasonally, and hence, the sediments change their trajectories and sedimentation zones each month. During the dry season, energetic winds and ocean currents are able to transport the sediments large distances, especially the silts which are advected towards the southwest in the upper 200 m and are then transported towards the northeast by the subsurface counter-current. In contrast, the rainy season is characterised by weak easterly winds and a stronger, shallow coastal counter-current, which occupies the upper 600 m of the water column during these months. These combine to favour advection of sediments towards the north and northeast.

The transport patterns obtained with the Lagrangian model are in agreement with the results from an oceanographic expedition made at the Colombian coast in 1981 (Pujos et al. 1986), in which the authors identified two hydrodynamic

Table 5 Properties of ellipses generated for fine sands (FS), very fine sands (VFS) and coarse silts (CS) per month

Month	Sed.	MIN dist (km)	MAX dist (km)	Area (km^2)	Perimeter (km)	Orientation (degrees)
Jan	FS	0.0	0.1	12.0	1822.5	333.8
	VFS	0.0	0.2	12.1	1823.7	332.3
	CS	0.1	0.5	12.0	1825.8	327.9
Feb	FS	0.0	0.1	12.0	1820.4	334.6
	VFS	0.0	0.2	11.1	1815.3	333.0
	CS	0.1	0.5	12.0	1819.8	330.6
Mar	FS	0.0	0.1	12.0	1820.7	334.1
	VFS	0.0	0.1	12.0	1821.5	332.6
	CS	0.0	0.4	12.0	1821.8	328.4
Apr	FS	0.0	0.1	12.0	1823.9	332.5
	VFS	0.0	0.1	12.1	1826.7	330.0
	CS	0.0	0.4	12.4	1832.5	320.8
May	FS	0.1	0.2	12.1	1831.4	329.7
	VFS	0.2	0.4	12.2	1840.5	326.4
	CS	0.7	1.6	12.7	1667.1	222.9
Jun	FS	0.1	0.2	12.1	1831.2	329.8
	VFS	0.2	0.4	12.1	1835.9	327.4
	CS	0.9	1.6	12.6	1665.3	223.7
Jul	FS	0.1	0.3	12.2	1839.2	326.8
	VFS	0.3	0.7	12.3	1849.8	323.9
	CS	1.2	2.4	12.9	1680.1	223.0
Aug	FS	0.1	0.2	12.1	1833.3	330.3
	VFS	0.2	0.4	12.2	1840.5	327.4
	CS	0.7	1.4	12.6	1850.9	317.7
Sep	FS	0.1	0.3	12.2	1838.3	326.9
	VFS	0.3	0.7	12.3	1848.0	324.1
	CS	1.4	2.5	12.9	1678.2	222.8
Oct	FS	0.1	0.3	12.1	1834.4	327.4
	VFS	0.3	0.7	12.2	1841.4	324.8
	CS	1.4	2.4	12.7	1667.8	221.9
Nov	FS	0.0	0.2	12.0	1826.0	330.4
	VFS	0.1	0.3	12.1	1829.6	328.3
	CS	0.6	1.2	12.3	1658.6	224.0
Dec	FS	0.0	0.1	12.0	1818.9	335.8
	VFS	0.0	0.1	11.9	1815.8	336.5
	CS	0.1	0.3	11.8	1813.3	340.1

The minimum (MIN) and maximum (MAX) distance recorded by the particles from the Atrato River mouth, the seafloor area where the sediments were deposited, the perimeter of the ellipses and the orientation of the sediment cloud are all included

features that have a direct effect on the suspended sediment dispersion: the Caribbean Current that transports upper layer sediments towards the west, and the coastal counter-current which moves deeper particles towards the northeast.

The results also coincided with those in Restrepo (2014) and Restrepo et al. (2018). The transport patterns indicate that the ocean currents are very efficient at moving the river plume, so the sediments are rapidly advected offshore during both the dry and wet seasons. The Magdalena River sands are deposited over the continental shelf in the delta front, while finer sediments are advected by the coastal hydrodynamics towards the pro-delta and are deposited away from the littoral.

Montoya-Sánchez et al. (2018) estimated the percentage contribution of mass transport given by ageostrophic processes (wind-driven) and by geostrophic currents (driven by density gradients) to the total current in the Colombian basin, within the annual cycle. These results indicated that, in general, ageostrophic processes are dominant (> 50%) near the central

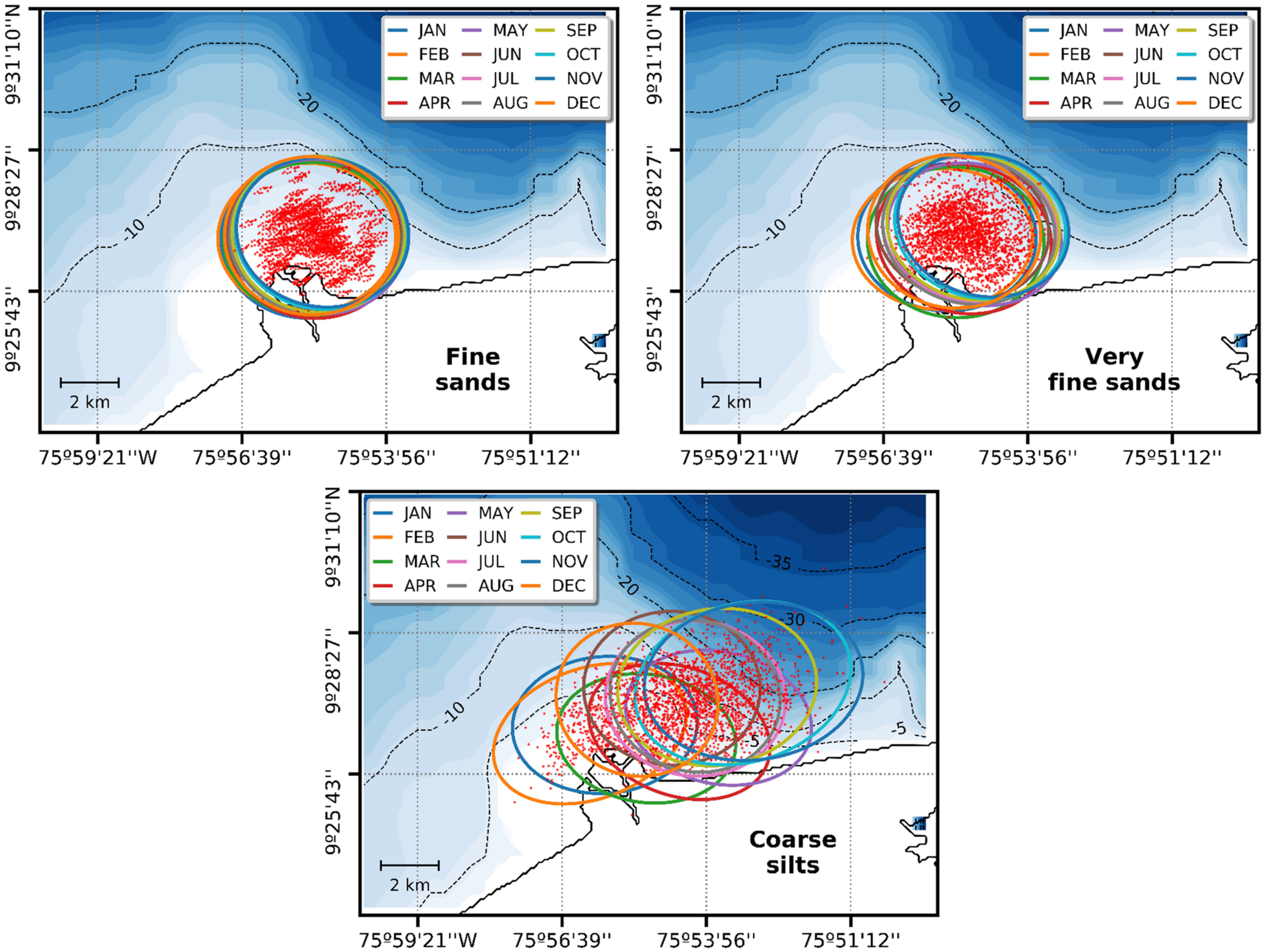

Fig. 9 Average area of influence of sediments released at the Sinú River mouth, calculated from the ellipses of the dispersal clouds. The fine sands are shown in the top-left panel, the very fine sands in the top-right panel and the coarse silts in the bottom panel. Simulations were carried out with SedimentDrift®. The bathymetry of GEBCO-2019 is shown in colour (depths in m). Two hundred twenty particles were released on the sea surface at the beginning of each climatological month

coast, where the Magdalena River mouth is located. However, during the windy and dry season, the ageostrophic circulation (mainly Ekman transport) extends along the coast and offshore, while during the rainy season, its extension is reduced. Hence, the sediment transport by wind driven currents is a predominant feature in this area, but, during the rainy season, the geostrophic currents have an influence in the trajectories and 3D spreading, moving the particles towards the northeast.

The simulations clearly resemble the 3D advection and diffusion processes, as the sediment particles sink towards the bottom. Nevertheless, there are limitations to this methodological approximation that could affect the resulting patterns, but, given that there are no local measurements, the relative importance of each process was not assessed. There are several physical features not considered in the analysis, such as re-suspension, bed load transport and bottom sediment erosion, which are not represented by the model. The use of a constant number of particles each month and their seeding on the ocean surface are limiting factors that need to be considered. We did not attempt to represent the seasonal changes of the SSL but the influence of the seasonal metocean variability on the sediment transport.

The assumptions made in the estimation of the settling velocities from Stokes' Law could influence the results. The use of a mean (constant) value for the sea water and particle densities is not a realistic approximation; the use of a mean temperature, instead of a temperature profile, will affect viscosity and will affect velocity estimations; non-spherical particles are not simulated. Flakes will settle more slowly than spheres with the same density. Angular grains will generate small turbulent eddies that retard their settling velocity. All of these restrictions and limitations are noted and considered in the discussion of the resulting sediment spreading and deposition patterns.

Using remote sensing, Vargas-Cuervo (2016) showed a large patch of suspended sediment concentrated in the frontal

Table 6 Properties of ellipses generated for fine sands (FS), very fine sands (VFS) and coarse silts (CS) per month

Month	Sed.	MIN dist (km)	MAX dist (km)	Area (km^2)	Perimeter (km)	Orientation (degrees)
Jan	FS	0.0	0.1	11.9	1280.4	4.1
	VFS	0.1	0.3	11.2	1190.2	358.0
	CS	0.6	2.1	10.8	1192.2	4.4
Feb	FS	0.1	0.2	11.4	1208.7	1.4
	VFS	0.3	0.6	10.8	1141.3	2.2
	CS	1.0	3.0	11.2	1144.9	21.0
Mar	FS	0.1	0.1	11.6	1244.4	2.3
	VFS	0.2	0.4	11.4	1218.1	355.6
	CS	0.6	2.4	9.9	1218.9	351.1
Apr	FS	0.1	0.2	11.9	1281.3	356.9
	VFS	0.3	0.6	11.2	1210.5	343.9
	CS	1.1	3.9	10.3	1212.7	338.9
May	FS	0.2	0.3	11.5	1248.8	346.9
	VFS	0.5	1.3	10.5	1155.8	341.4
	CS	2.2	4.8	10.6	1159.3	346.8
Jun	FS	0.1	0.2	11.6	1245.2	356.0
	VFS	0.3	0.7	10.7	1182.1	345.7
	CS	1.1	3.2	11.6	1182.2	359.0
Jul	FS	0.2	0.3	11.7	1267.3	356.6
	VFS	0.5	1.0	10.8	1177.4	345.2
	CS	1.6	5.2	12.0	1178.5	354.5
Aug	FS	0.2	0.3	11.7	1267.9	357.3
	VFS	0.4	0.8	10.9	1197.5	344.1
	CS	1.5	4.6	11.0	1196.8	342.7
Sep	FS	0.2	0.4	11.6	1261.8	351.8
	VFS	0.6	1.0	10.7	1178.6	345.1
	CS	2.2	7.5	13.4	1184.5	8.5
Oct	FS	0.3	0.5	11.2	1231.4	348.7
	VFS	0.8	1.7	10.6	1174.1	343.4
	CS	2.6	8.8	14.9	1183.7	17.2
Nov	FS	0.3	0.5	11.0	1208.8	348.1
	VFS	0.9	2.1	10.5	1167.7	341.6
	CS	3.0	10.5	14.8	1180.5	7.6
Dec	FS	0.0	0.1	11.8	1275.2	358.3
	VFS	0.08	0.33	11.34	1237.67	351.2
	CS	0.35	1.79	10.62	1232.92	332.6

The minimum (MIN) and maximum (MAX) distance recorded by the particles from the Sinú River mouth, the seafloor area where the sediments were deposited, the perimeter of the ellipses and the orientation of the sediment cloud are included

area of the Magdalena River delta, which agrees well with the area of influence of the sediments released by this river as simulated by the Lagrangian model. Similar results were obtained with the satellite data obtained by Torregroza-Espinosa et al. (2020), for the temporal variability and spatial extent of the diffuse and solid sediment plumes of this river. These authors proposed that the wind speed and direction are the most important variables influencing the suspended sediment concentrations and the attributes of this river at seasonal scales. However, the deep counter-current is responsible for the advection and spreading of the very fine sands and coarse silts, providing evidence of the relative importance of ocean currents in the 3D displacement of the SSL discharged by this river. Hence, it is clear that the wind-driven currents and the geostrophic currents have an influence on the sediment dynamics in this coastal region.

Compared with the Magdalena River delta, which has a very short continental shelf and a complex submarine canyon system, the Sinú River delta has very different morphological features that determine the resulting sediment transport patterns. The large extension of the very shallow continental shelf (< 50 m) favours the rapid migration of these particles towards the seafloor. Also, the hydrodynamics are less intense and so the sediments released by this river are advected short horizontal distances each month. The sands reach the ocean bottom in a few hours, having been advected by the currents to only 1 or 2 km. The silts are transported a maximum distance of 2 to 10 km (depending on the season) taking less than a day to settle on the ocean floor. In this coastal area, the eastward counter-current is responsible for the northward and northeastward transport of sediments. During the rainy season, when this current intensifies, the very fine particles are advected further away from the river mouth towards the northeast.

The resulting sediment transport obtained with the SedimentDrift Lagrangian model coincided well with the study presented by INVEMAR-GEO (2016), in which a sedimentary analysis of this river was performed. In this report, the authors evidenced coarse grain sediments (fine sands) near the river mouth and finer sediments (very fine sands) in the southern flank of the river mouth.

The sediment distribution pattern encountered in this delta is largely determined by the river runoff, which varies during the dry and rainy seasons, but is also influenced by the wind patterns and coastal currents that predominate in this region. However, as previously discussed, the density gradient produced by the river runoff induces a reduction in the ocean current.

The Sinú River Delta acts as a barrier, which reduces the speed of the coastal currents. This effect is best seen in the eastern part of the delta and especially in the dry season, when the winds come from the north and ocean currents are considerably higher. Due to the speed-reducing effect and mixing, the sediment content carried by the current is deposited on the delta fraction, generating accretion. In this season, the currents in front of the Tinajones Delta are weaker than on the northwest side; however, they keep their course (INVEMAR-GEO 2016).

During the rainy season, currents reduce the speed due to the relaxation of the easterly winds. Nevertheless, the delta-barrier effect is still present. Coastal currents have a northeastward direction and are stronger on both sides of the delta front, inducing the rapid deposition of fine sands in front of the river mouth.

The sediment plume of the Sinú River has been investigated using MODIS-Aqua satellite observations (INVEMAR-GEO 2015), and these results coincided well with the simulations obtained in this study for coarse silts. During the dry season, the river plume is advected towards the southwest along the coast, due to the prevailing wind and currents that are intense in these months. However, during the rainy season, when easterly winds and currents are relatively weak, the sediment plume is advected further offshore, towards the north and northwest, coincident with the intensification of the coastal counter-current.

The Atrato River delta is considerably different from the other two rivers analysed in this study, given that it is located in a shallow, semi-enclosed bay with maximum depths of around 75 m in the north and less than 40 m in the mouth area. Winds and currents are also relatively weak in this region; hence, particles released by the river settle rapidly on the seafloor. Sand reaches the bottom very near to the river mouth (< 360-m horizontal distance) in less than 2 h. Silts may take up to 8 h before reaching the seabed, being advected larger horizontal distances. Depending on the season, these very fine sediments are transported towards the north less than 600 m (in dry months) and up to 2.5 km (in rainy months), driven by the surface currents.

The dispersion patterns obtained with the Lagrangian SedimentDrift model agreed with results from the measured and modelled, suspended sediment concentrations (SSC) in the Urabá Gulf (as reported by Escobar and Velásquez-Montoya 2018). During the rainy season, the Atrato River turbidity plume of very fine sediment extends northward and dominates the sediment dynamics in the gulf. Most of the discharge from the river is transported to the north of the mouth by buoyant jets. In Fig. 8, the light blue ellipses (October and November) are elongated towards the North, along the coastline. The finer sediments move further north of the river delta during these months.

6 Conclusions

Sediment transport in tropical, coastal regions is a complex process which requires a detailed analysis of local oceanographic and hydrological conditions that are not necessarily well-known and have been poorly described because of scarce data availability. Due to these limitations, a 3D modelling approach was established to give a first-hand, qualitative evaluation of the pathways of the sediments released by the main rivers in the Colombian Caribbean basin. The forcing field data is the key element that determines the successful performance of the simulations. The validated forcing fields used in the simulations adequately represent local metocean conditions.

In spite of the limitations encountered with this Lagrangian model, it is evident that the resulting dispersion patterns of the sediment released by the main rivers in Colombia will be useful in the identification of possible geohazards which could damage subsea infrastructure near the Colombian coast. The continuous accumulation of sediments in certain areas could trigger seafloor instabilities and landslides. This information should be taken into consideration in future offshore projects that have been planned in this oceanic basin.

The results from the SedimentDrift Lagrangian model in this investigation were compared against previous studies available for the areas of interest. The broad agreement with expected trends indicates that this is a reasonable methodological approximation. Seasonal patterns are well reproduced, given that the forcing fields represent adequately local conditions.

Limitations encountered in this study, that need to be addressed in the future, include the analysis of re-suspension, bed load and littoral transport, given that the SedimentDrift simulations stop when the seeded particles reach either the seafloor or the coastline and remain there for several time periods. The vertical velocities of the flow field are not included in these simulations and these could be an important factor driving sediment transport in the coastal upwelling areas of the Colombian Caribbean basin. Coastal defence structures were also not included in the preparation of the grids; hence, differences between our results and actual sediment transport along the coast are expected. However, the lack of data is the most problematic issue that needs special attention in order to calibrate and improve the simulations.

Nevertheless, the results obtained with the Lagrangian transport model allow us to conclude that this tool can be used for numerous applications in science and environmental management. Sediment particles can also act as pollutant and nutrient carriers. This model can also be used for studies of pelagic egg dispersion, oil drift, search and rescue, the impact of dredging, water quality and microplastics.

Although these initial results are a qualitative assessment of the sediment transport released by the main rivers in Colombia, the applicability of the modelling methodology to complex cases was demonstrated. In the future, with a more representative set of data, quantitative studies could be performed, considering morphological evolution. Furthermore, the methodology can be used to evaluate different designs of defence structures in order to propose a more efficient solution for the coastline retreat and intense erosion observed in recent years in several coastal areas.

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Data availability The data used in this study are mainly third-party data. Most of the data used in this paper allow public access (credits and URL in the paper). These datasets are from international, well-known databases. In situ data used to validate the re-analyses models belong to Ecopetrol and do not have public access.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

Consent to participate All authors agreed to participate in this study.

Consent for publication The authors hereby consent the publication of this original work in the *Ocean Dynamics* Journal.

Ethics approval Not applicable.

Code availability Authors have used open-access software in the preparation of this work.

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