Density driven flows, due to hurricanes

A case study of hurricane Irma and Maria around Saint Martin

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TUDelft

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by

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in the scope of Additional Graduation Work, Research Project (CIE5050-09)
at the Delft University of Technology,

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Assessment committee: Prof. dr. J. D. Pietrzak,   TU Delft, supervisor
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Abstract

In this report a first assessment is made of the impact of hurricanes on Saint Martin. Two bays at the east coast of Saint Martin, Baie Orientale and Baie de L'Embouchure, are studied under the conditions of hurricane Irma and Maria, which both have passed over in September 2017. During these hurricanes the bays were exposed to large wind speeds up to $40 \ [m/s]$. Also the bays were subject to runoff due to large rainfall. The runoff has been flowing into the bays as fresh water, but also as high saline waters. This due to the salt ponds which are located in the region.

The model has been run in Delft3D and as result large wind-setup driven circulations were obtained. These circulations caused a drop of waterlevel during Irma and an increase under Maria. The saline and fresh waters discharged during the hurricanes were mostly kept onshore and is distributed over the two basins.

Preface

This report is written as part of the education program of Civil Engineering at the Delft University of Technology. The specific goal for this research is the course Additional Graduation Work Research Project (CIE5050-09). After following several classes on hydrodynamics and density driven flow my attention was awakened to density gradients and the flow they induce.

The reader with a background in fluid mechanics should be able to understand which processes are involved in the problem and which steps are made in the report to obtain the final result. The report can be used to obtain a first insight in the magnitude of flow velocities during hurricanes and the flow induced by density differences in the Carribean.

During the project prof. dr. J.D. Pietrzak supervised my work and hereby I would like to thank her for the feedback and meetings during the project.

H. Platell, BSc
Delft, October 2018

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1

Introduction

In the recent decades the concentration of carbon dioxide in the atmosphere has grown [5]. This change has been involved by the human interaction with nature. Therefore a lot of studies are performed studying the impact of human involvement. Due to this changing concentration the global temperature is rising, which has a huge impact on the global environmental properties. In the recent century has been seen that due to this global warming effect the sea level has been risen [16]. That the sea level will rise further is almost certain, but the magnitude is uncertain. Another effect of the global warming is the change of hurricanes. Large hurricanes will occur more often and beside the power of these larger hurricanes will increase [18].

Hurricanes have a big impact on the daily life on the population of the area involved, many houses will be destroyed due to the wind and flooding [1]. During hurricanes large wind speeds can be observed, which also causes higher waves to approach the coast. Beside this hurricanes will effect the local sea level, a hurricane extracts a lot of water from the sea which will result in heavy rains and large runoff values in the coastal areas [8].

1.1. Problem definition

In this the impact of hurricanes in the Carribean area will be studied. Explicitly will be looked at the hydrodynamic behavior in two specific bays, Baie de L'Embouchure and Baie Orientale, at the east coast of Saint Martin. Hurricanes impose a high wind velocity, which may lead to high velocities in the bays and eventually drying of some areas. These high water velocities can impact the sediment distribution in the coastal area, but also could have an affect on the sea grasses and coral reefs in the area.

The heavy rainfall during hurricanes will cause a runoff of fresh water into the coastal bays. A part of the coastline is sheltered by salt ponds. In the Carribean area a lot of salt ponds can be found [13], so also on Saint Martin [15]. These salt ponds have a unique behavior, they are relatively shallow and are mostly hypersaline (> 50 [ppt]) and the salinity value can rise easily to over 100 [ppt]. During sprint and summer the salinity rises, but in autumn this salinity drops [13]. This is mostly due to heavy rainfall during hurricanes. Due to hurricanes the salinity can drop in a small number of days with 20 [ppt] or more. This means that when the runoff enters the salt pond it should discharge a lot of salty water into the bays. This can be done by flooding or through a channel between the salt ponds and the bay.

In this study the water velocities under hurricane conditions will be investigated and the hydrodynamic changes due to runoff and discharges from the salt ponds will be looked at.

The situation will be modeled for the period of September, 2017. In this period Saint Martin was hit by two large hurricanes. Hurricane Irma on September, 6th and Maria on September, 19th. These hurricanes where both of category 5 [19] [20]. The damage of Irma on Saint Martin was very large and exceeded the damage of every earlier hurricane in that area. There were four people reported death and 23 injuries were found, beside a lot of structures, houses, hotels and even the airport were destroyed.

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1.2. Research and structure

In this research will be focused on the hurricane induced flow and the flow due to the runoff and density gradients. To answer this problem the following research question is formulated.

> What is the effect of hurricane Irma and Maria combined with the salinity gradients on the situation in Baie de L'Embouchure and Baie Orientale?

As support for answering these questions, the following subquestions are defined:

- What are the hydrodynamic conditions in Baie de L'Embouchure and Baie Orientale?

- How does the flow behave during hurricane Irma and Maria?

- How will the flow be affected by the salinity gradients in the system?

- To which locations will the fresh and saline water be distributed?

To obtain an answer on these research questions the report is built up in the following steps. First an area analysis will be performed, based on several datasets and aerial photos the conditions and observed changes will bee assessed. Next a model in Delft3D [6] will be created and the quantities given to the model will be discussed. With the Delft3D model in hand, results can be created and obtained for the behavior in September, 2017. These results are given in chapter 4. Finally a conclusion will be drawn and a discussion will be held.

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Area analysis

The area of interest are two bays at Saint Martin, which is an island in the northeast Caribbean Sea. The two specific bays are Baie Orientale and the smaller Baie de L'Embouchure (see figure 2.1). These are located at the east coast of Saint Martin in the northern (French) part.

Figure 2.1: Location of the area of interest at Saint Martin [11]

In figure 2.2 the area is shown in more detail. To the northern bay, Baie Orientale, one salt pond, Étang Chevrise is connected. Beside there is a smaller bay sheltered in the most northern part of the bay. This one is called Baie du Cul-de-Sac. Baie de L'Embouchure is located south of Baie Orientale and is much smaller. Two salt ponds are connected to this bay: Salines d'Orient and the bigger Étang aux Poissons. Note that the three salt ponds in the area are not all constantly connected to the sea. Sometimes the connection channel is dammed or dried up, as is noted in section 2.1.

In this chapter first the changes of the environment are discussed based on aerial photos, whereafter the hydraulic conditions, bathymetry, salinity, water temperature and tidal effects, are considered. Finally this chapter closes with a look on the wind and rainfall forcing.

Figure 2.2: Area of interest at Saint Martin (circles are indicating the connection between a salt pond and a bay) [11]

2.1. Aerial changes

Every coastal section is subject to environmental changes and therefore also Baie de L'Embouchure at Saint Martin. At different times an aerial photo of Google Earth is used to find these differences. First the main coastline of the southern bay is discussed.

In the first period from 2004 (figure 2.3) to early 2017 (figure 2.4) can be seen that the deeper part in the southern part has disappeared (as the black dot isn't there anymore). Just north of the mouth of Étang aux Poissons the coastline has eroded and therefore has moved more inland and the area seems to be more sandy. In the northern part there is a small channel connecting the inner part of the bay with the ocean. In February 2017 this channel seems to be more narrow and deeper compared to 2004. At September 11th, 2017 just after hurricane Irma has passed Saint Martin (so before hurricane Maria) another picture (figure 2.5) is taken. Unfortunately this picture is less clear, but it could be seen that the coastline is eroded in most parts of the bay and that the vegetation of the coastline is lost.

Figure 2.3: Baie de L'Embouchure, September 11th, 2004 [11]
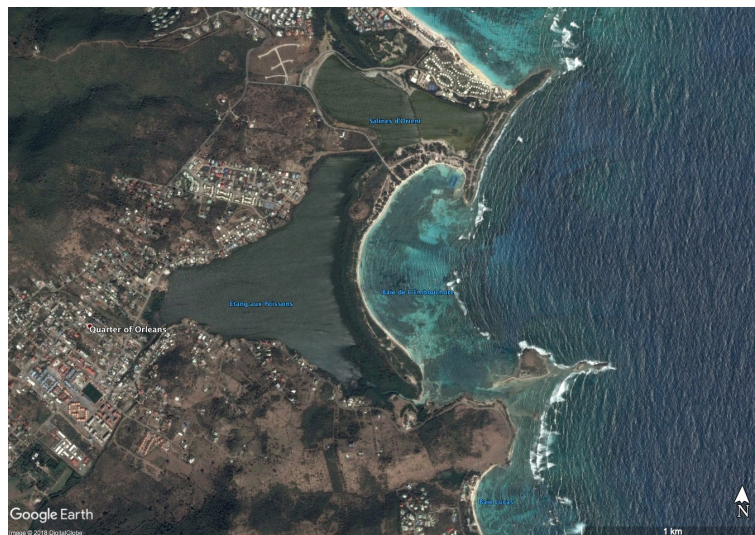

Figure 2.4: Baie de L'Embouchure, February 12th, 2017 [11]

Figure 2.5: Baie de L'Embouchure, September 11th, 2017 [11]

Figure 2.6: Mouth of Salines d'Orient, September 11th, 2004 [11]

Figure 2.7: Mouth of Salines d'Orient, February 28th, 2011 [11]

Now focus on the northern part of the bay where the salt pond, Salines d'Orient, mouths into the bay. In the early stages, 2004 (figure 2.6) and 2011 (figure 2.7) a connection between the pond and bay is established in the most eastern part of the bay. In February 2017 (figure 2.8 this connection is closed and/or dry. Comparing figure 2.6 and 2.8 results in the conclusion that the area of the bay ins't changed that much, beside the fact that just east of the tip the area has become more sandy. The final photo (figure 2.9) of this area shows that a new connection is created after Irma, just westwards of the old connection. The breach has resulted in a deposit of sand in the bay just before the mouth of the connection channel. In the salt pond some channels are formed to supply the water. Looking back at the stage of 2004, it could be seen that a kind of channel in the bay was already present near the breach, which indicates that there was a breach before at this location.

Figure 2.8: Mouth of Salines d'Orient, February 12th, 2017 [11]

Figure 2.9: Mouth of Salines d'Orient, September 11th, 2017 [11]

Figure 2.10: Mouth of Étang aux Poissons, June 16th, 2005 [11]

Figure 2.11: Mouth of Étang aux Poissons, April 1st, 2017 [11]

Next up the mouth of Étang aux Poissons is considered. Comparing 2005 (figure 2.10) with April 2017 (figure 2.11) results into the conclusion that the connection channel is meandering and that there is more sand in front of the mouth in April 2017. Consider the latest version of September 11th, 2017 (2.12) a lot of sediment is washed away compared to April and furthermore it seems to be that the connection channel is deeper after Irma.
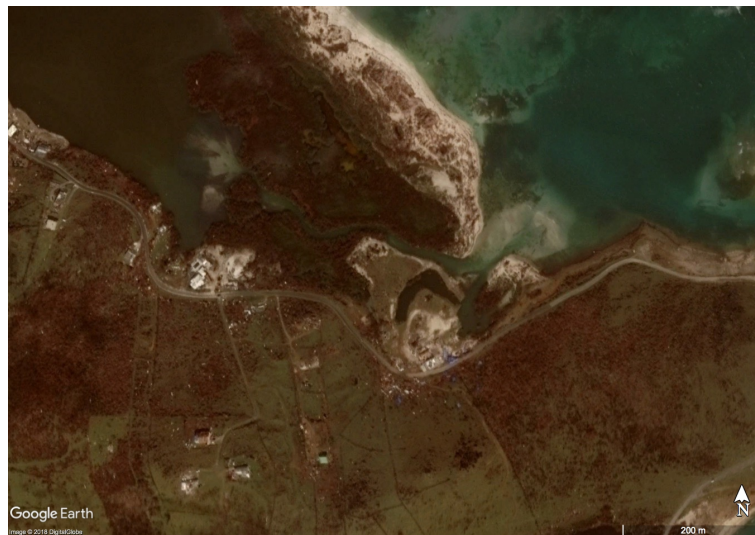
Figure 2.12: Mouth of Étang aux Poissons, September 11th, 2017 [11]
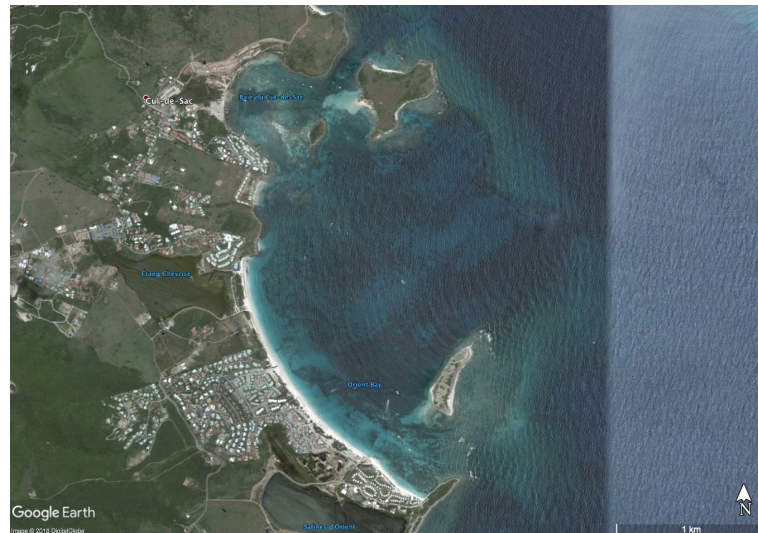
Figure 2.13: Baie Orientale, June 16th, 2004 [11]

Figure 2.14: Baie Orientale, February 12th, 2017 [11]

Baie Orientale is deeper compared to Baie de L'Embouchure and by comparing the pictures of 2005 (figure 2.13) with February 2017 (figure 2.14) there are no notable differences. Comparing this with the picture taken after Irma (figure 2.15), it seem that between Baie du Cul-de-Sac and the beach of Baie Orientale there is more sand on the bed, beside the beach is partly eroded and the vegetation on the coastline is washed away. Also note that in the northern part the tip of the island in the narrow opening between the island an Baie du Cul-de-Sac is smaller after Irma compared to before.

Figure 2.15: Baie Orientale, September 11th, 2017 [11]

Figure 2.16: Étang Chevrise, June 16th, 2005 [11]

Figure 2.17: Étang Chevrise, February 12th, 2017 [11]

Zooming in on the mouth of Étang Chevrise. Also no notable differences are obtained in the period of 2005 (figuer 2.16) to February 2017 (figure 2.17), beside the water level in the pond, which could simply explained by the different seasons that the pictures are taken. Extending the analysis to the picture taken after Irma (figure 2.18) the mud around the outlet of the pond has been eroded. Also notable is that most of the vegetation along the coastline around the pond is gone. This may indicate that Étang Chevrise has been flooded during hurricane Irma.

Figure 2.18: Étang Chevrise, September 11th, 2017 [11]
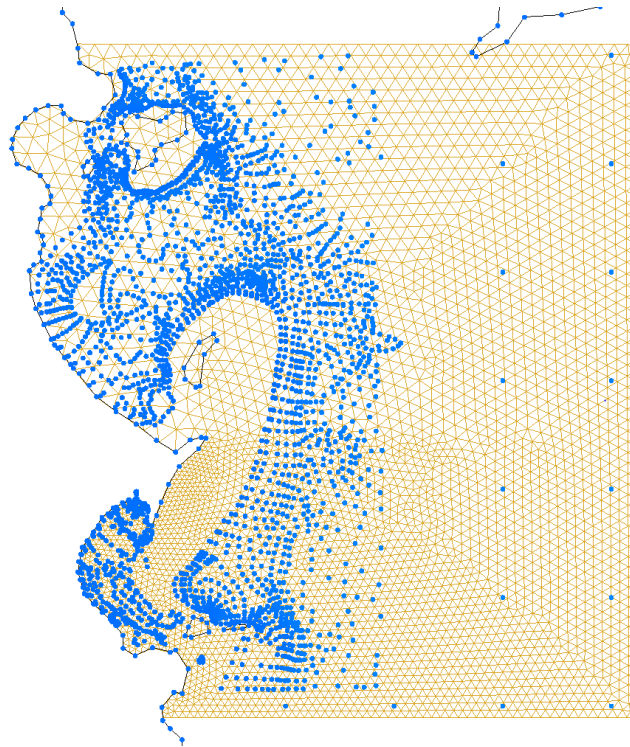
Figure 2.19: Available depth points and computational grid

2.2. Bathymetry

To setup a model of the area the bathymetry is needed. Therefore the land boundaries and depth profile are needed. To create the landboudary a file of the area is exported from the GSHHG database. This file is modified such that it can be used in Delft3D [6]. This work is performed by L. Keyzer [14].

For the depth multiple sources are combined to obtain one file containing points in the area with the corresponding depth. Therefore data from GEBCO and Navionics is used to create the depth profile on a coarse resolution. In Baie de L'Embouchure both GEBCO and Navionics have no detailed depth measurements. Therefore measurements are performed by NIOZ [17] in the scope of the SCENES [7] project. This data is corrected for the tidal differences, based on the analysis of section 2.5 and finally added to the depth file. Also the work to create the actual depth file is carried out by L. Keyzer [14].

Based on the land boundary a computational grid is created in Delft3D. On this computational grid the depth needs to bed defined on each node such that the calculation can be performed. Therefore the points from the depth file (figure 2.19) are interpolated using triangulation, a standard interpolation method of Delft3D. This results in the depth profile of figure 2.20.
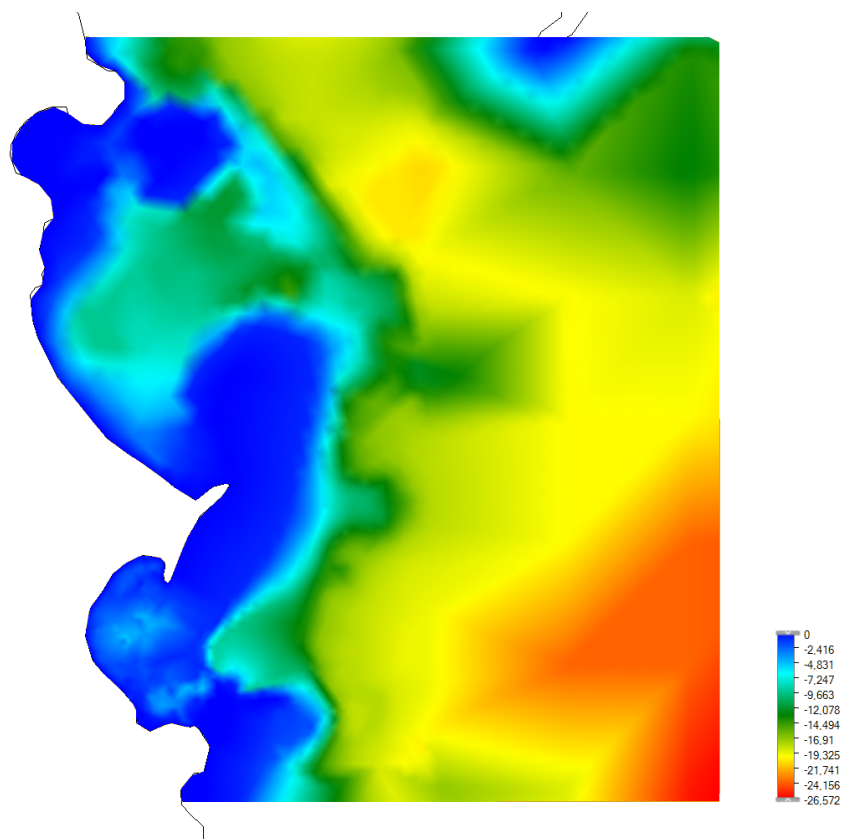
Figure 2.20: Interpolated depth on the computational grid

Sorry, but this image is confidential until publication of [17]

Figure 2.21: Measurement locations [11]

2.3. Salinity

To obtain insight in the influence of fresh water runoff during hurricanes, the background salinity is needed for use in the model. Therefore the salinity measures from NIOZ [17] are used. The measurements locations are given in figure 2.21 and the measurements themselves in figure 2.22. Note that time scale is changed for readability of the measurements. From the figure could be obtained that there is some spread in the salinity values, but that it is limited. The measurements are limited between $-$ [psu][1] and $-$ [psu]. Based on this data the salinity at location 1 is found to be $-$ [psu] ($\sigma = -$), at location 2 $-$ [psu] ($\sigma = -$) and location 3 $-$ [psu] ($\sigma = -$). This means that there is nearly no difference between the three locations.

This data is verified with the salinity measures from the model created by Mercator Ocean [10]. In figure 2.23 the salinity at two points near the east coast of Saint Martin are given as function of depth. Note that the variability along the vertical could be neglected and that model output is a little bit bigger compared to the measurements (around 0.2 [psu]). This implies that the measurements correspond to the values obtained from the Mercator Ocean model.

From the Mercator Ocean model also the salinity data during hurricane Irma and Maria can be obtained. Therefore the salinity is given in figure 2.24 at the closest point to the east coast of Saint Martin (also used in the previous figure), which is around one kilometer offshore between Baie Orientale and Baie de L'Embouchure. Closely after Irma (which passed at September, 6th) a drop in salinity could be seen. In one day the salinity drops 0.3 [psu] which is already restored in the day after. At September 19th Maria has passed by. At this day, a strong increase in salinity is observed with a magnitude of aprroximately 0.2 [psu].

The salinity in the area just before hurricane Irma is given in figure 2.25 and the difference with the next day is given in figure 2.26. The more saline waters in the north eastern parts are becoming less saline, due to the hurricane why the water around 34.6 [psu] is becoming more saline.

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[1]Sorry, but this data is confidential until publication of [17]

Sorry, but this image is confidential until publication of [17]

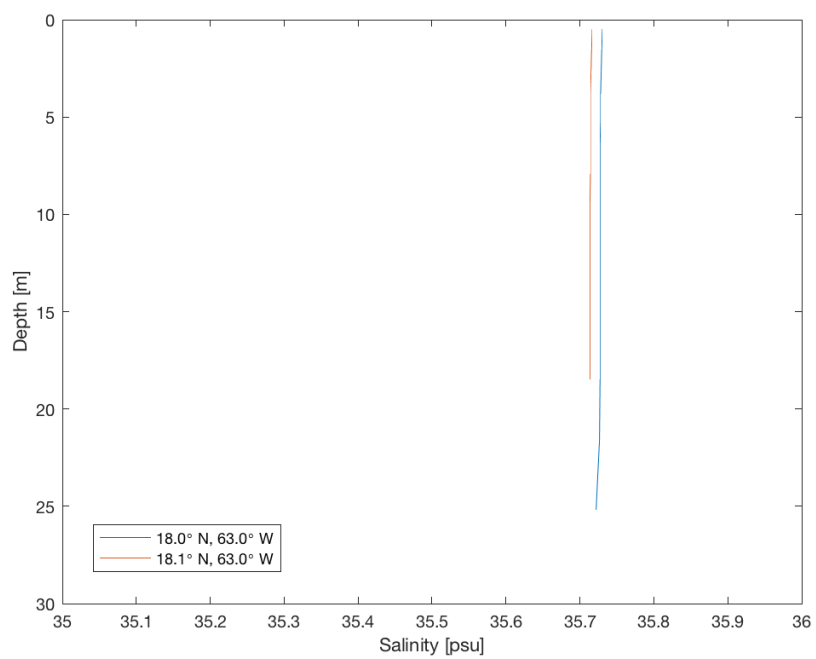Figure 2.22: Salinity measurements [17]

Figure 2.23: Salinity measures from Mercator ocean (mean of January 18th and 19th, 2016) [10]
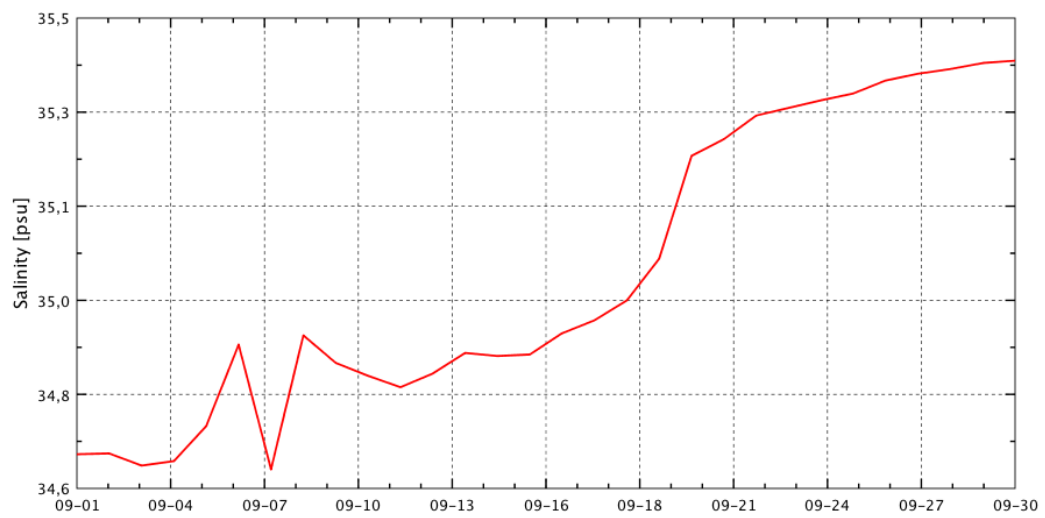
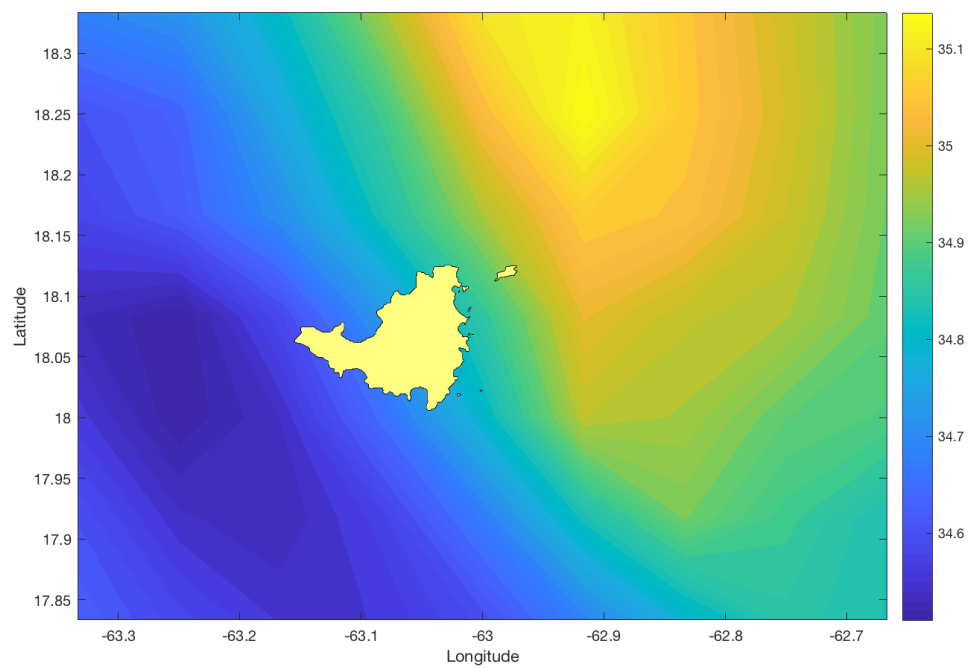Figure 2.24: Salinity measures from Mercator ocean (September 2017, $18.1°N$, $63.0°W$) [10]

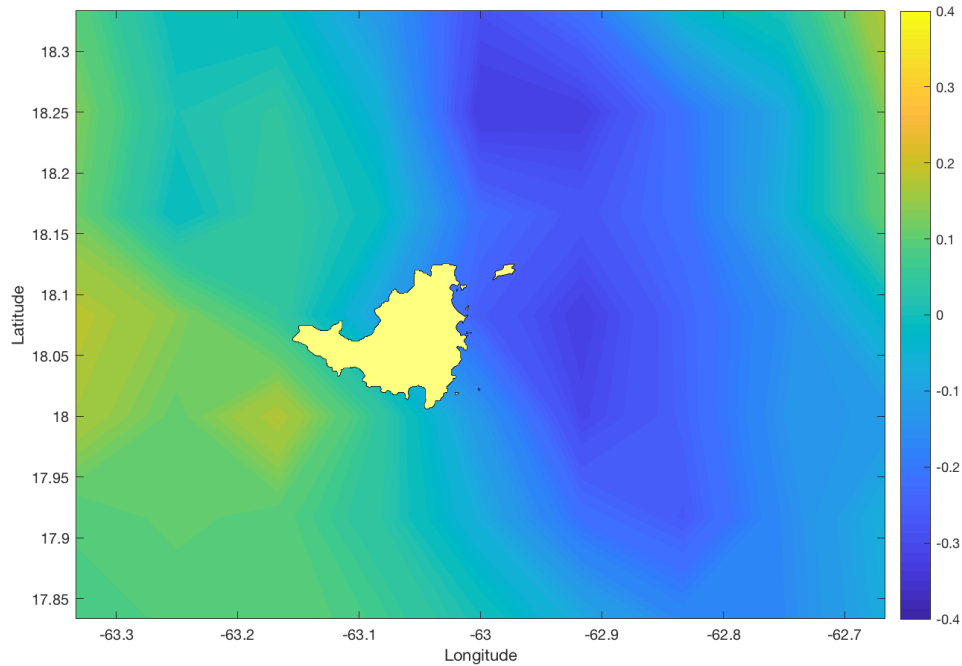Figure 2.25: Salinity measures [psu] from Mercator ocean, September 6th 2017 [10]

Figure 2.26: Salinity measures [psu] from Mercator ocean, difference between September 6th and 7th 2017 [10]

2.4. Water temperature

To study density driven flows, next to salinity also the water temperature should be studied. Therefore the measurements from NIOZ [17] are also used. The raw data is displayed in figure 2.27. After averaging these values per day 2.28, a more clear signal is obtained. It could be seen that water is warmer in summer and autumn, whereafter it cools down during winter and in spring it's starting to heat up again. Also the standard deviation per day is given (figure 2.29). From this could be seen that variability of temperature is higher at location 2 compared to 1 and lower compared to 3. Which could be explained by the fact that location 1 is more deep compared to location 3.

In figure 2.30 the temperature is displayed in September, 2017 of a location near the east coast of Saint Martin. From this time series could be obtained that after Irma and Maria the temperature drops around 0.7 degree Celsius.

Sorry, but this image is confidential until publication of [17]

Figure 2.27: All temperature measurements [17]

Sorry, but this image is confidential until publication of [17]

Figure 2.28: Temperature measurements averaged per day [17]

Sorry, but this image is confidential until publication of [17]

Figure 2.29: Standard deviation of the the temperature measurements per day [17]
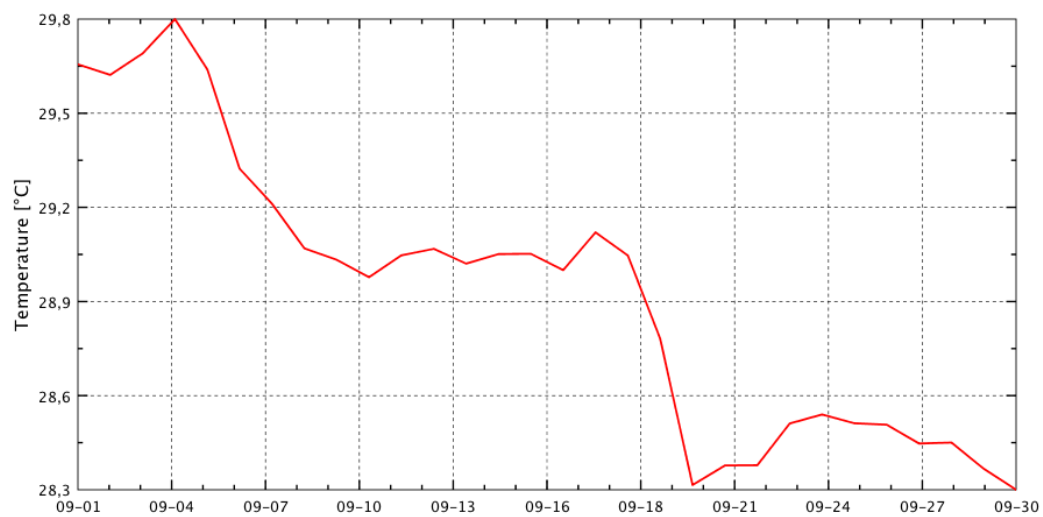

Figure 2.30: Temperature measures from Mercator ocean (September 2017, $18.1°N$, $63.0°W$) [10]

Figure 2.31: Location of Port de Galisbay at Saint Martin [11]

2.5. Tidal effects

At Port de Galisbay, a small port at the north coast of Saint Martin, (see figure 2.31) the water level is continuously monitored. This data is used to perform a tidal analysis. The data is obtained form the Intergovernmental Oceanographic Commission of UNESCO [12]. The raw data is shown in figure 2.32.

Next this data series can be loaded into the UTide [4], a Matlab script which return the tidal modes reported in table 2.1. The tidal signal in this area isn't strong (the tidal range is around 0.3 [m]. From this analysis the signal could also be reconstructed which is seen shown in figure 2.33.

Tidal mode	Amplitude
O1	0.058 [m]
K1	0.052 [m]
M2	0.051 [m]

Table 2.1: Amplitude of most important tidal modes

2.6. Wind

Based on the yearly climate summaries of the Meteorological Department St. Maarten [9], the average windspeed is 4.5 [m/s] and is mainly blowing from the east. The wind rose (figure) shows the distribution of wind speeds and directions based on the measurements at Princess Juliana International Airport (SXM).

From September, 2017 there is also some wind speed data available. From Windguru [21] a time-series is obtained with an interval of three hours. The speed is shown in figure 2.35. At September, 6th in the figure the highest wind speeds are given, this is the passing of hurricane Irma, which was a category 5 hurricane and passed right over the island, Saint Martin (figure 2.36). The second peek is
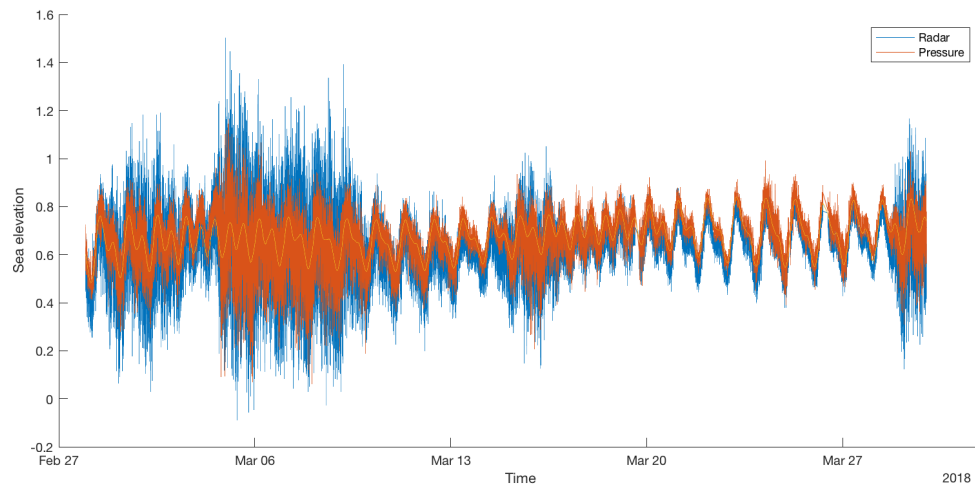
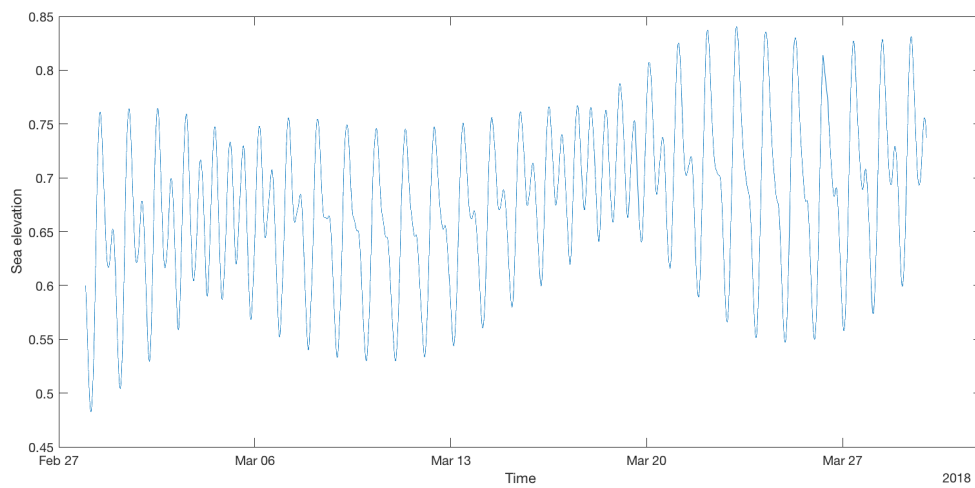Figure 2.32: Water level measurements from Port de Galisbay [12]
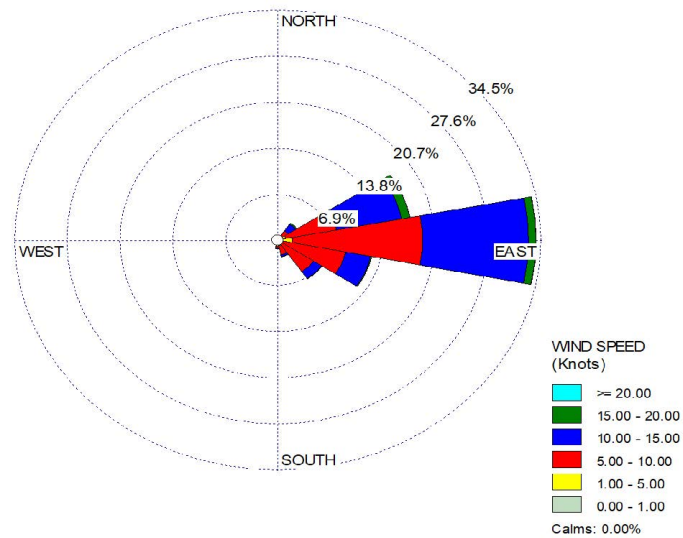

Figure 2.33: Tidal signal at Port de Galisbay

Figure 2.34: Wind rose of 2017 [9]

of hurricane Maria, which was also category 5, but passed on a larger distance (figure 2.37).

2.7. Rainfall

A hurricane will also induce a lot of rain. From Windguru [21] also the 3 hour interval rainfall is obtained, which is shown in figure 2.38. Also now two peeks can be obtained from hurricane Irma and Maria. The peek of hurricane Irma is larger compared to the one of Maria, but the higher rainfall intensity period takes longer during Maria.
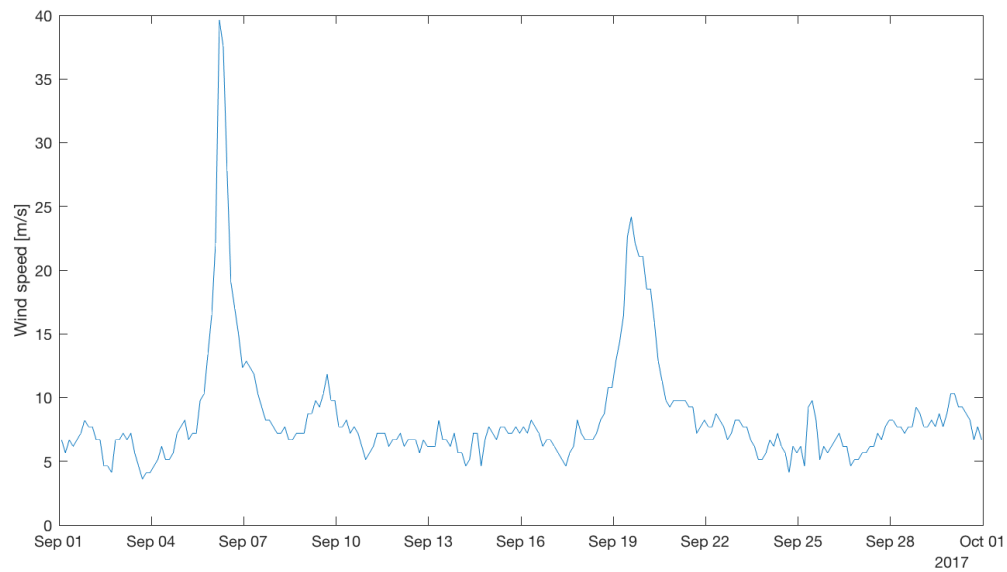
Figure 2.35: Wind speed September, 2017 [21]
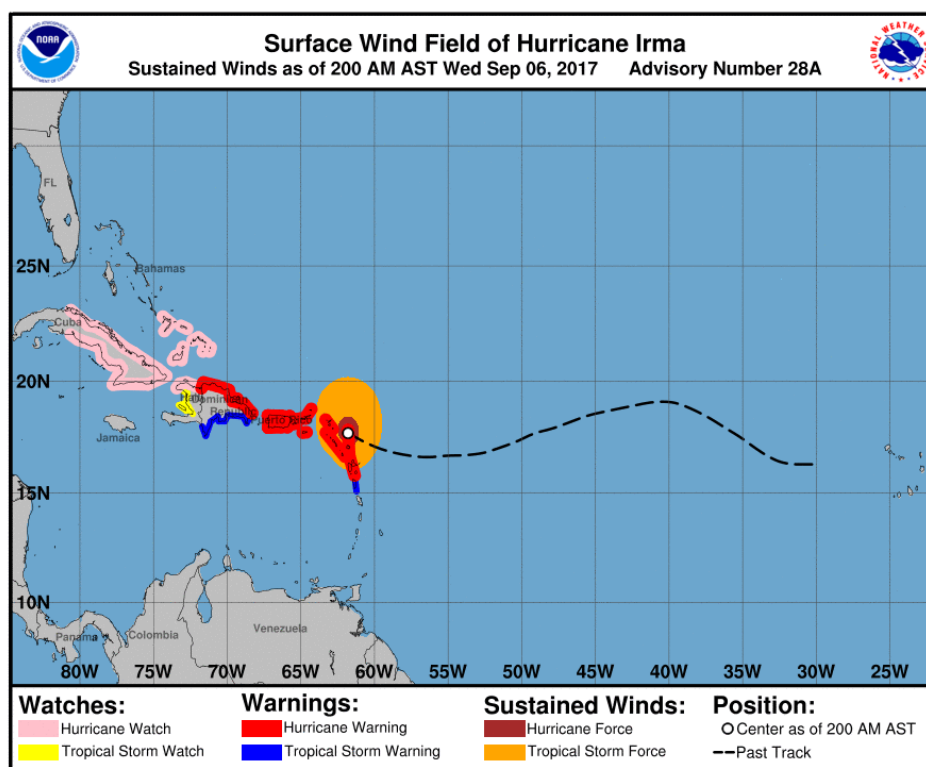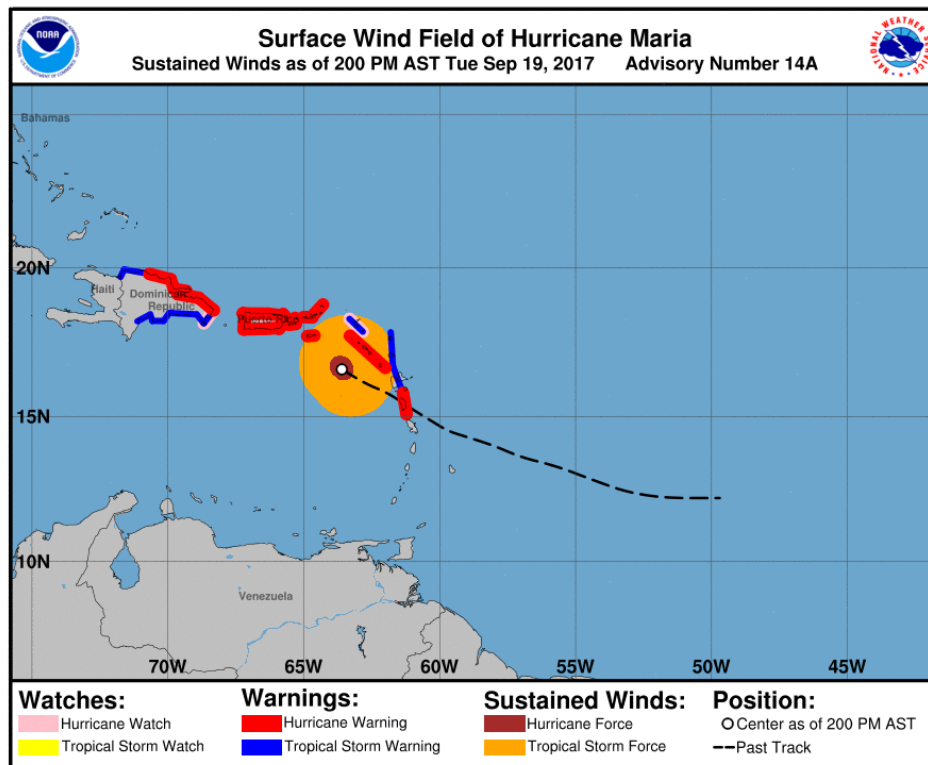

Figure 2.36: Path of hurricane Irma [2]

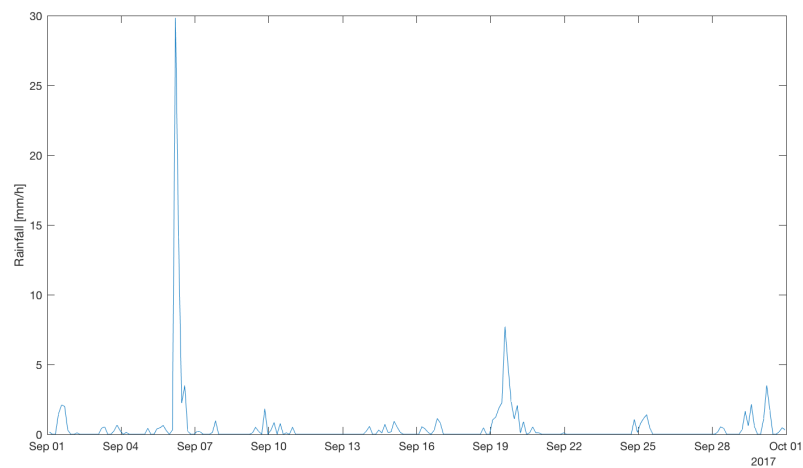Figure 2.37: Path of hurricane Maria [2]

Figure 2.38: Rainfall September, 2017 [21]

3

Model setup

To model the area of interest a model made in Delft3D will be created. The model is built in multiple steps. First a model will be made for an average situation in both bays. This is needed to verify the implementation of land-, tidal boundaries and the depth profile. The next step is to change the model to the conditions of September, 2017. Such that the impact of hurricane Irma and Maria can be studied. First only the wind speed is applied to the model, next the inflow boundaries are added, the last extension is to turn on the salinity module and specify these values. Each step for the September, 2017 models is first performed using a 2D-model, thereafter each of these models is extended to a multi-layer model.

3.1. Basic setup

In the basic set up, the land boundaries are loaded into Delft3D [6] and based on these a triangular computational grid is defined (see figure 3.1). On this grid the depth profile is interpolated, as stated in section 2.2 where the final result is obtained in figure 3.2.

Next the boundary conditions are added (for the exact location, see figure 3.2). The east boundary is the tidal boundary. The tidal modes from table 2.1 are added as astronomic water level boundary. Next the northern and southern boundary conditions should be defined. A tidal boundary as on the eastern boundary can not be applied here, because of the large difference in depth along these boundaries. Near shore the depth is much smaller and therefore the amplitudes of the tidal signal may change. A discharge or velocity boundary also couldn't be applied since there is no data available for these kind of boundary conditions. Finally is chosen for a Neumann zero boundary. This boundary doesn't disturb the flow and will make it possible to move up and down with the tidal signal

The time frame of this model is set from January, 1st midnight to January, 7th midnight and a time step of 20 minutes is taken. The model output is discussed next, to verify the result before moving on.

The tidal elevation of a point located near the eastern boundary is given in figure 3.3. When considering the elevation in the full domain, this is approximately equal over the complete domain and therefore not shown in detail.

Considering the results from figure 3.4 and figure 3.5 the mean flow is considered small and has no main direction. The amplitude of the velocity is in the second figure a little bit higher, which is due to the larger difference between low- and high tide, which could be observed from figure 3.3.

Next the windspeed is set to $4.5 \ [m/s]$, from an eastern direction. Other parameters of the model are not changed yet. The results are given in figure 3.6. These results have a flow which differs in other of magnitude compared to the situation without wind ($0.1 \ [m/s]$ vs $0.01 \ [m/s]$). The flow is now directed northwards offshore, while more nearshore it's directed southwards. In the bays the flow circulates.

Next the result is shown specific for the southern bay (figure 3.7). The flow is circulating in the bay, and there is a strong flow around the tip of the northern barrier. The flow in the bay is clearly following the depth profile.
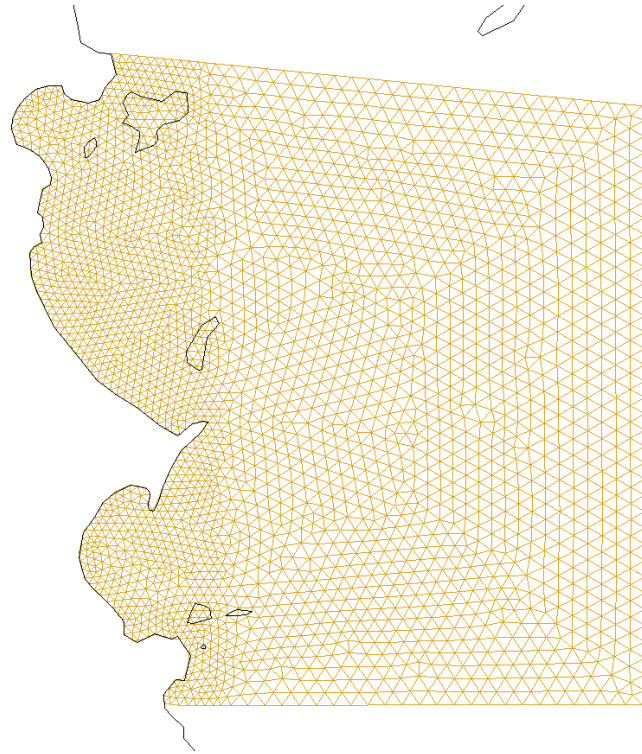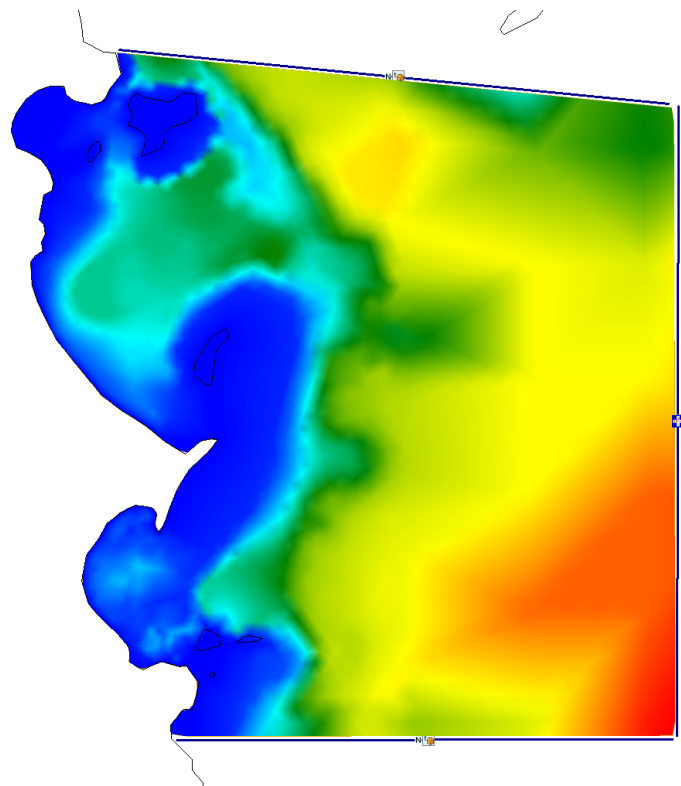
27

Figure 3.1: Computational grid

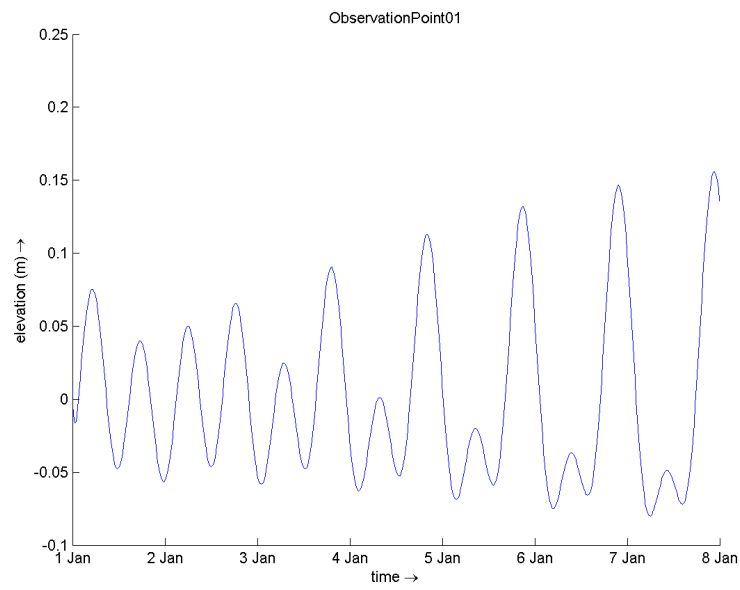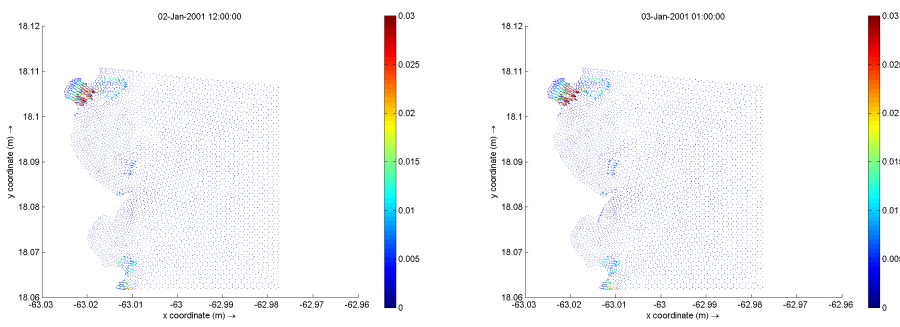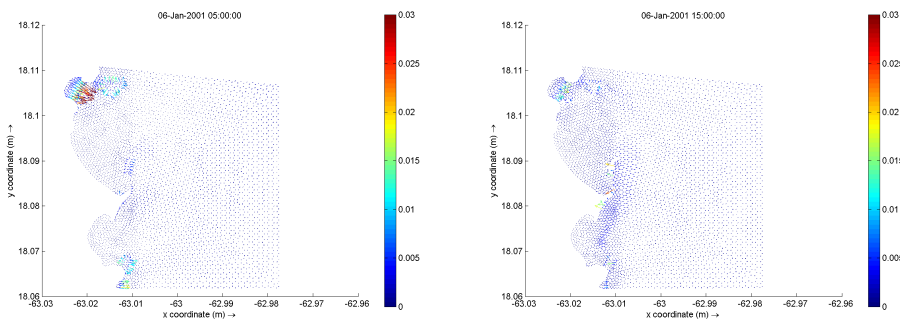Figure 3.2: Depth profile and boundary conditions

Figure 3.3: Elevation at eastern part

Figure 3.4: Flow velocity (in m/s) January, 2nd at 12:00 and January, 3th at 01:00

Figure 3.5: Flow velocity (in m/s) January, 6th at 05:00 and January, 6th at 15:00
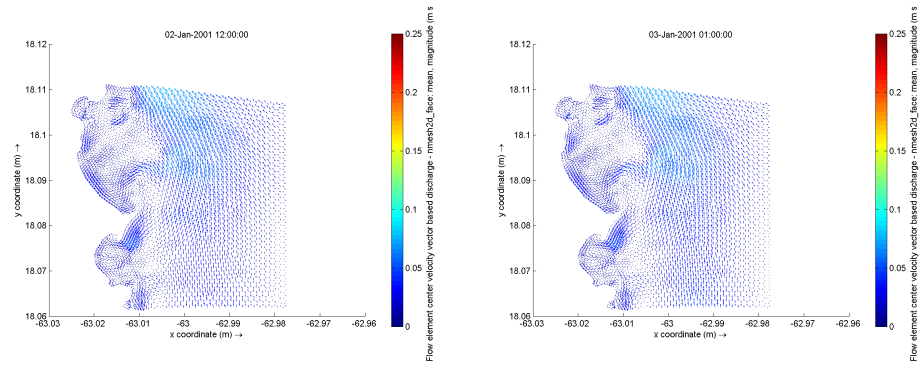
Figure 3.6: Flow velocity (in m/s) January, 2nd at 12:00 and January, 3th at 01:00 (model with wind)
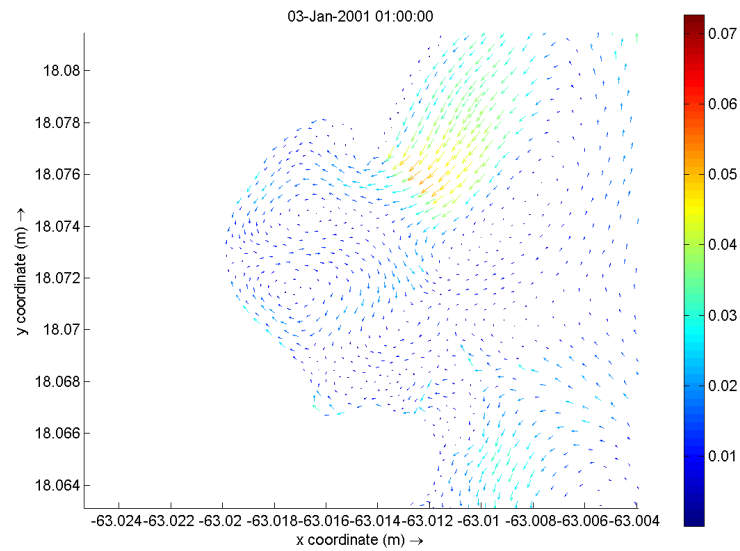

Figure 3.7: Flow velocities (in m/s) in Baie de L'Embouchure at January, 3rd at 01:00
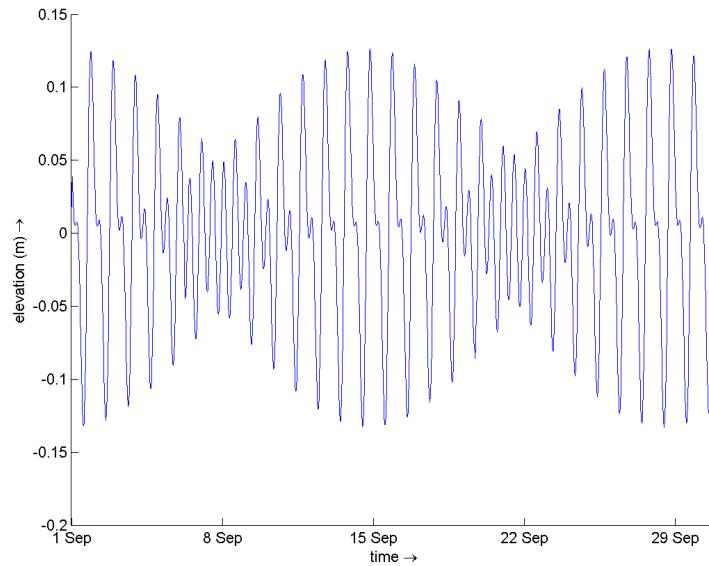
Figure 3.8: Waterlevel, at eastern boundary

3.2. Setup for September, 2017

The model is changed for the conditions of September, 2017. Which is the timeframe of interest, while hurricanes Irma and Maria have passed the island during this time period. The model now runs from September, 1st up till September, 30th with time steps of 20 minutes. The tidal boundary is updated with the correct phase and the wind speed of section 2.6 is applied. The updated results at the eastern boundary now shows the new tidal signal (figure 3.8).

Moving on, five inflow boundaries are added at the coastline. The locations of these boundaries are shown in figure 3.9. The inflow in the bays is caused by rainfall. To determine the inflow discharge, the following approach is used. The rainfall from section 2.7 is multiplied by the complete area of Saint Martin (88.4 [km^2] [3]) and thereafter divided by the length (58.9 [km] [3]) of the coastline. This results into a discharge per meter coastline, the discharge through a specific boundary can now be determined by multiplying this discharge per meter with the length of the specific boundary. The first boundary is the one in Baie du Cul-de-Sac, which is 1.2 [km] long. The next boundary is the outflow channel of Étang Chevrise. This salt pont represents 0.5 [km] (which is the sheltered coastline by this pont). Going further south the third inflow boundary can be found at the beach of Baie Orientale, this part is 0.9 [km] long. In Baie de L'Embouchure two salt ponds have their outflow channel. For Salines d'Orient a factor of 2.2 [km] is used and for Étang aux Poissons this is 1.4 [km], which are also representative for the sheltered coastlines by these ponts.

The next step is to turn on the salinity module of Delft3D. The initial salinity applied to the model is 34 [ppt]. The inflow boundaries connected to salt pont are given a salinity value of 50 [ppt], while the others (which are directly due to runoff) is 0 [ppt].

Finally all models made for September, 2017 are extended to a multi-layer problem. The calculations are performed on a set of ten layers.
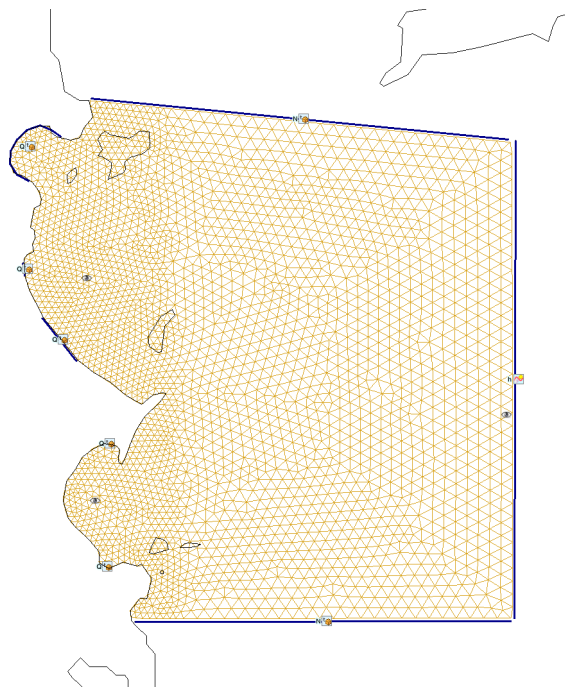
Figure 3.9: Inflow boundary conditions

4

Results

In this chapter the results from the final model (multi-layer model with wind, inflow and salinity) are discussed. In appendix A the results for the partial models are given and discussed. In this chapter the water level will be treated first, whereafter the velocity profiles will be discussed. Finally the salinity distributions will be shown.

In the results different cross sections will be used. These sections are shown in figure 4.1. In the figures cross section 1 of Baie Orientale and cross section 1 of Baie de L'Embouchure are seen from the east, while the others are seen from a southern direction.

Note that the model is exposed to extreme conditions (a large hurricane, with high wind speeds and massive discharges), but that the domain is limited. This means that the boundary conditions are maybe influencing the problem too much and that in further studies the domain should be extended.

4.1. Water level

The water level in both bays is mainly influenced by the tide and wind. The tidal signal could be obtained near the eastern boundary, where it's a boundary condition. For the period of September, 2017 this signal is found in figure 4.2. In Baie de L'Embouchure (figure 4.3) the tidal signal is also visible. Two anomalies can be found in this figure, the first around September, 6th, which is the impact of hurricane Irma. This hurricane had an offshore directed wind, which explains why the water level has dropped. The second anomaly is hurricane Maria, September, 19th. Here the water level has increased, due to the onshore wind. In figure 4.4 approximately the same results are found for Baie Orientale. These results are more or less matching the results form the results from the single layer model with only wind (see section A.1.1). The main difference is that the peek of hurricane Irma is lower in this case, this is due to the change from single- to multi-layer models where the stress in the water column is better carried over from one layer to another.
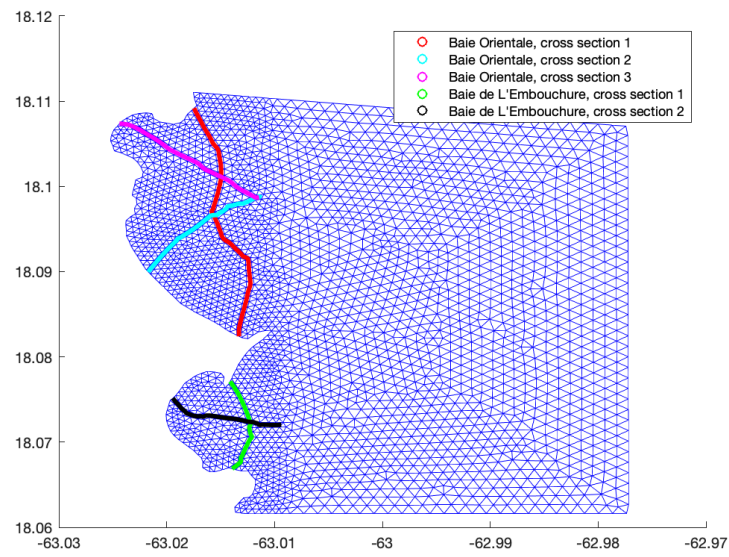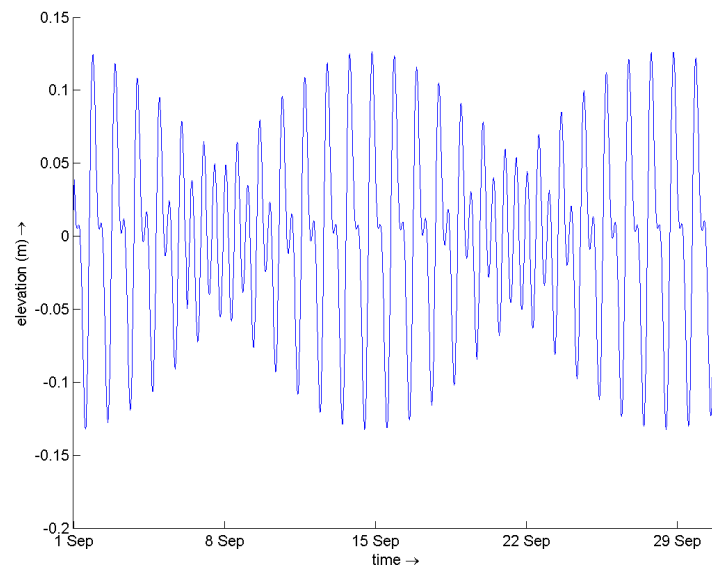
Figure 4.1: Location of the slices

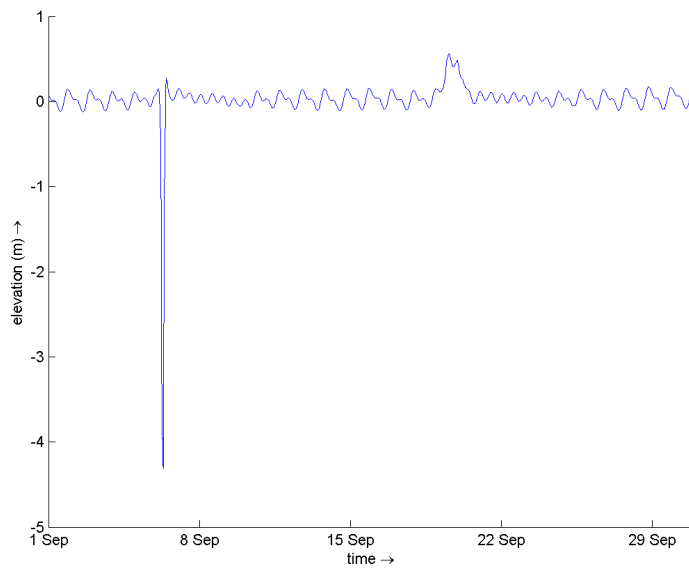Figure 4.2: Water level, at eastern boundary
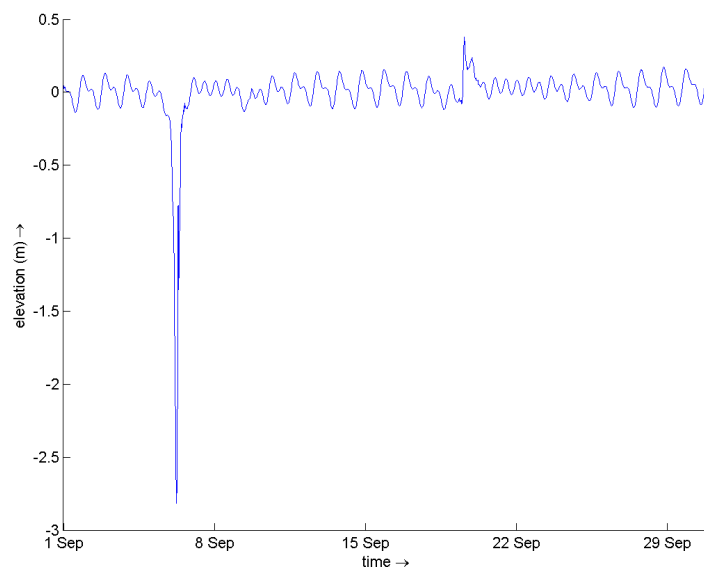
Figure 4.3: Water level, in Baie de L'Embouchure

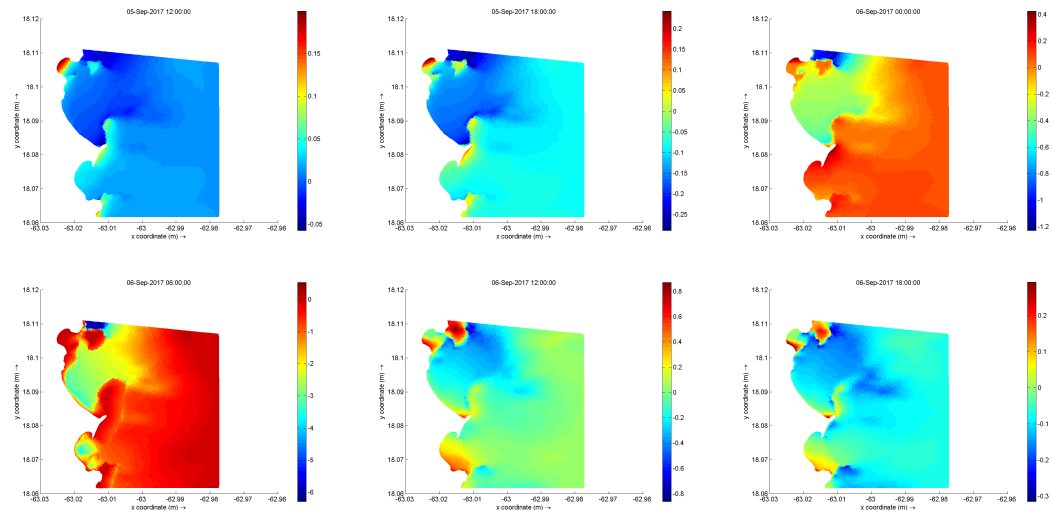Figure 4.4: Water level, in Baie Orientale

Figure 4.5: Water level (color scale in m) during Irma from 3D model wind, inflow and salinity

Next the water level during hurricane Irma and Maria will be discussed in more detail. Note the significant different behavior of both hurricanes, where Irma induced a water level drop, Maria has imposed a rise. The first time frame of figure 4.5 shows a relative flat water level distribution in the modeled area, as is the case when the model is exposed to only tide and a constant wind speed. Six hours later could be seen that the water level is Baie Orientale has dropped. The water level in de most southern part of this bay is lower compared to the middle due to the southern wind and wind setup. In Baie de L'Embouchure a small slope is obtained where the higher water level in the northern part (also due to wind setup). Also note that the water level near the tip between both bays and in Baie du Cul-de-sac is higher compared to the surrounding area. This is also due to the southern wind and the blocking effect of the coastline in these parts. At the start of September, 6th the same state is found only the values are further increased, which matches the higher wind velocity around this time. At six o'clock the wind has turned a little bit more offshore. That results in a pretty low water level in both bays, Baie de L'Embouchure contains nearly no water any more (also see figure 4.10). Baie du Cul-de-sac has also dried out (figure 4.12) and in the main part of Baie Orientale the water line has been withdrawn. In the next time frames the bays are slowly filling again and will finally result in a normal state. Note that at September, 12th Baie du Cul-de-sac is filled with fresh water due to rainfall and is flooding it's volume in Baie Orientale.

During hurricane Maria the first time frame (of figure 4.6) is a normal situation. In the next two steps of six hours the water level near the coast is increasing due to a stronger onshore wind. The level of September, 19th 06:00 is approximately constant up to September, 20th 00:00, whereafter it's slowly dropping, to finally return to it's normal state. The wind setup in the bays can also be distinguished from figure 4.14 and 4.16.
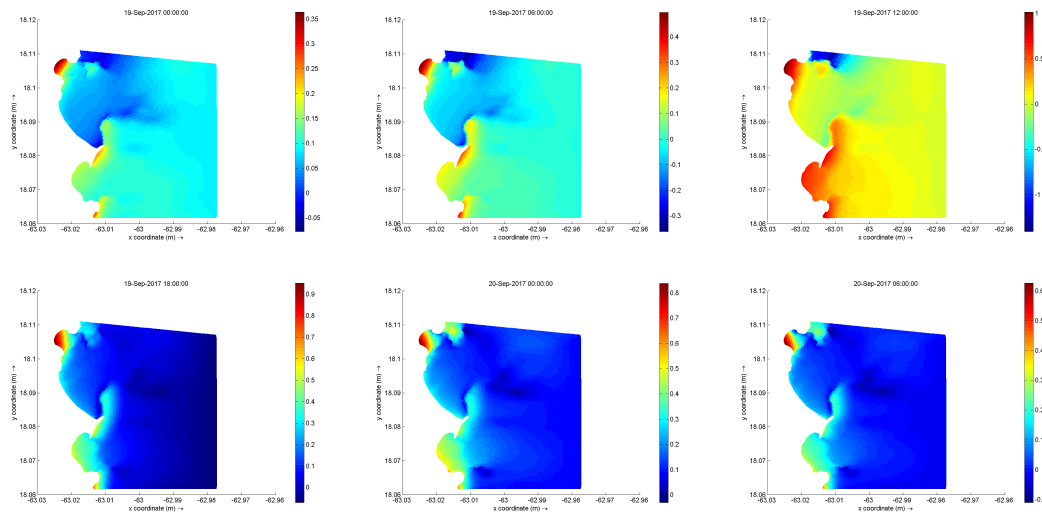
Figure 4.6: Water level (color scale in m) during Maria from 3D model wind, inflow and salinity
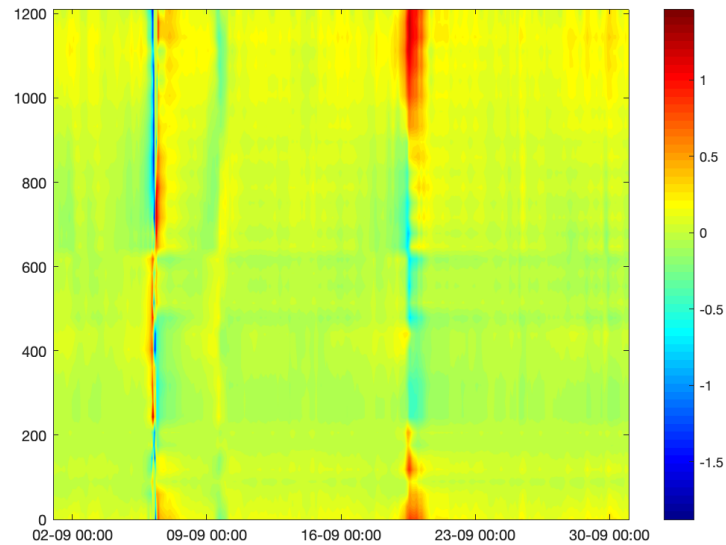
Figure 4.7: Velocity (in m/s, onshore directed is positive), at the entrance of Baie de L'Embouchure from 3D model with wind, inflow and salinity

4.2. Velocity

In figure 4.7 and 4.8 the velocity over cross sections 1 for both bays is given. In this figures the vertical mean velocity is given based on the multi-layer model. The velocity profile under non hurricane conditions is as expected and matching the result of the basic model from section 3.1. In Baie de L'Embouchure the flow in the northern part is directed onshore, in the middle part the flow is directed offshore and in the last 150 meters at the southern part the flow is directed onshore again. Baie Orientale shows an onshore directed velocity in the parts from $0-300$ [m], $700-1100$ [m] and $2300-2500$ [m], while in the other parts the velocity is directed offshore. From these two figures could be obtained that hurricane Irma has an impact which lasted a shorter time compared to Maria. Irma has induced in the beginning an offshore directed velocity in the northern part of Baie de L'Embouchure and a smaller onshore directed velocity in the southern part, this matches with the lower water level in the southern part and the higher level in the northern part. When the water is filling up Baie de L'Embouchure again the flow is onshore over main part of the basin. The peek of onshore velocities is found approximately 400 meters south of the northern tip of the bay. In Baie Orientale Irma shows first an offshore directed velocity (with a peek between the coast and an island in the northern part), whereafter the water is flowing back into the basin a large onshore directed velocity is found in the northern area. Hurricane Maria shows a strong inflow in Baie de L'Embouchure in the northern part of the bay. In the deeper, middle part the mean flow is directed offshore, which sound logical with a wind setup orthogonal to the coast. These results matches the results from the multi-layer model with only wind forcing (section A.1.1), the structure of inflow and outflow is the same but the velocity peeks during the hurricanes are larger in this case.

In the previous section was already seen that Baie de L'Embouchure has (nearly) dried during hurricane Irma. The first time frame of figure 4.9 a normal situation is shown. The top layer (on the left) shows an onshore velocity. In the bottom sigma-layer an outflow is shown in the middle, deeper part. The flow in the northern part of the bottom layer is also onshore directed. The middle layer has approximately the same structure as the bottom layer. From the first cross section of figure 4.10 can also be seen that the onshore velocity is found in the more shallow parts of the basin and that the offshore directed flow is found in the deeper parts. During the first time frames during Irma the (September, 5th 18:00 and September, 6th 00:00) a southern wind is forces on the bay. The top layer is flowing to the north, while there a return flow could be obtained in the lower layers of the deeper parts of the basin. This flow is due to wind setup and in the cross section this return flow could be clearly obtained. At six o'clock the the flow seems to be completely random, which is due the numerical errors
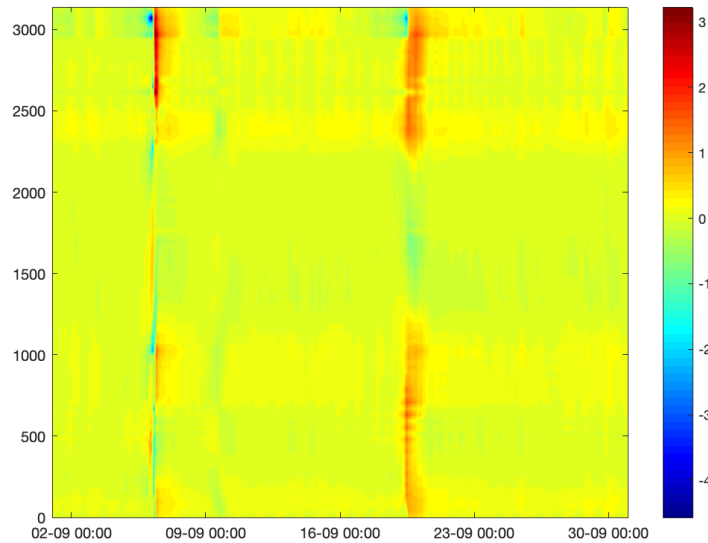
Figure 4.8: Velocity (in m/s, onshore directed is positive), at the entrance of Baie Orientale from 3D model with wind, inflow and salinity

and the very low water depth in the basin (see cross section 2 of figure 4.10). In the next time frame the flow has turned by the change in wind direction. The upper layer is now going to the south, while the lower layer has a northward directed velocity. This can also be seen in the cross section. The flow in this bay during Irma is mainly affected by the wind. The high saline water discharges have a small impact on the flow velocities of an order op 0.03 $[m/s]$.

Next the results of the model are compared with the observations made using Google Earth (in section 2.1). From the aerial changes was obtained that the coastline has withdrawn for a couple of meters, which could be matched with the high velocity found near the coast in all model layers. The velocity parallel near the coast at the bed can involve the mobility of sediment and the higher velocities in the upper layers make sure that the sediment is moved away from the coast and cann't settle again on the bed. In the outflow near Salines d'Orient a deposit of sand just southeast of the connection channel was observed. This matches with the early stages where the bottom layer was southward directed and the velocity in the upper layer to the west. Also the later stages where the flow at the bottom layer was going to the northeast and the top layer was going south, corresponds with the southeast deposit of sediment. Finally the outflow of Étang aux Poissons was discussed, here sediment was washed away and the connection channel may be deeper after Irma. This matches the high velocities in this area, which induces a higher mobility of sediment, which may also finally result in a larger connection channel and a loss of sediment in this area.
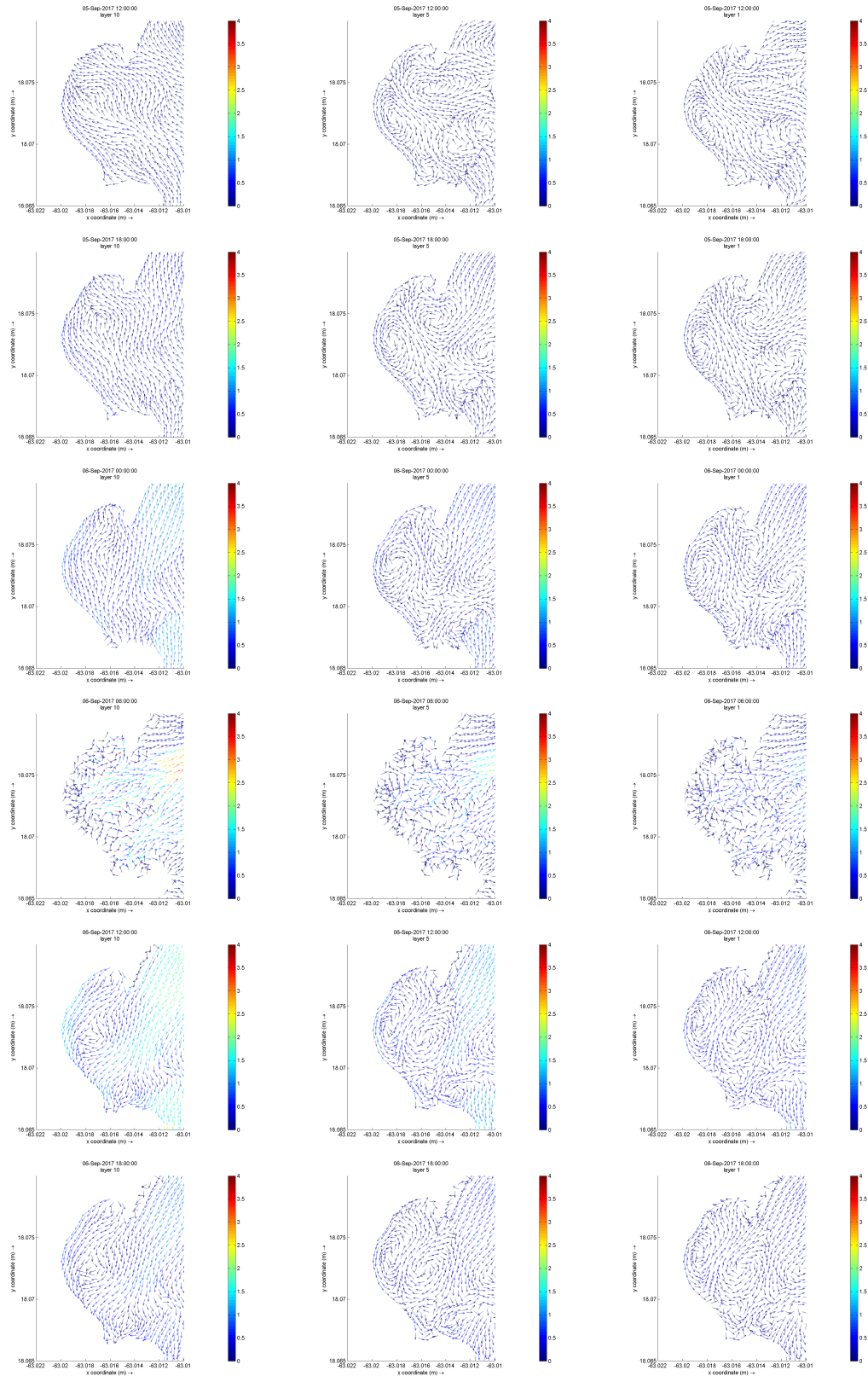
Figure 4.9: Velocities (magnitude color scale in m/s and direction of vector) in Baie de L'Embouchure during Irma from 3D model wind, inflow and salinity
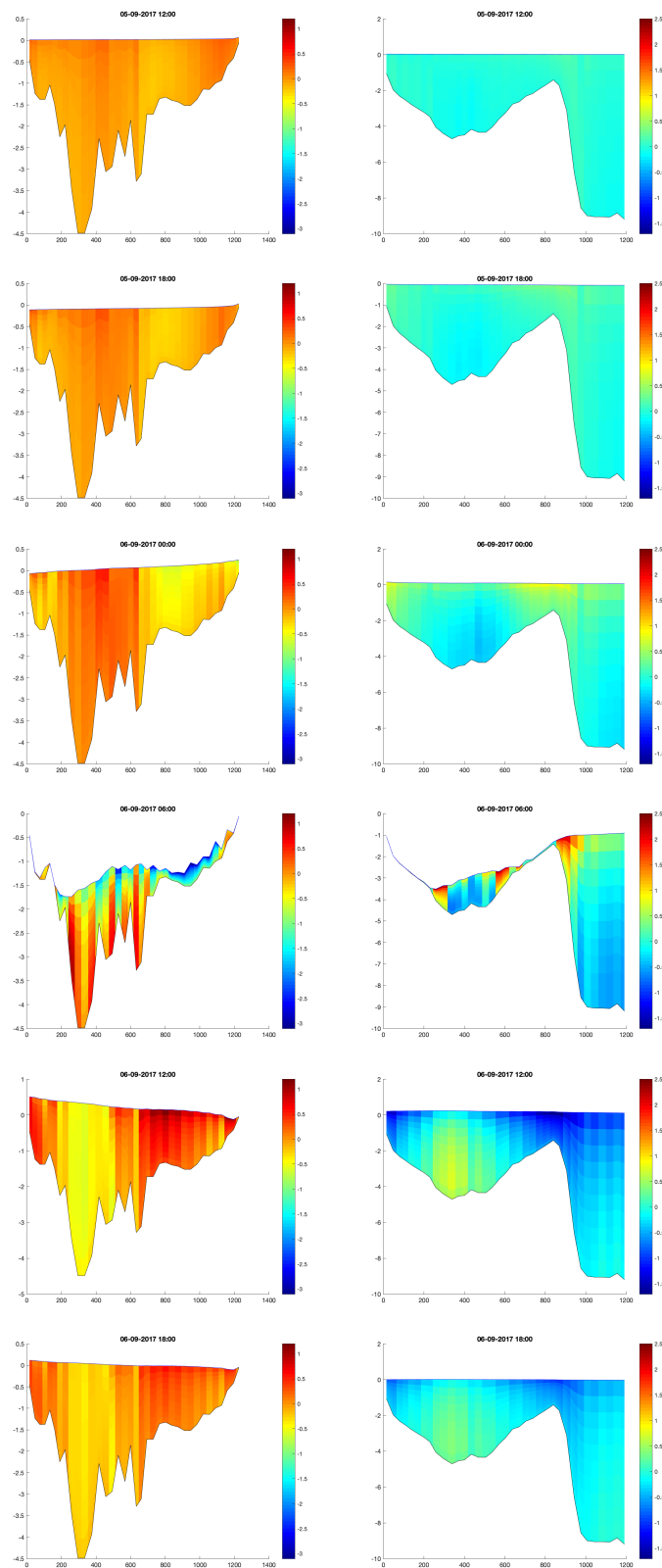
Figure 4.10: Orthogonal velocities (color scale in m/s, positive inwards directed) in cross sections (1 and 2) of Baie de L'Embouchure during Irma from 3D model with wind, inflow and salinity

In Baie Orientale (first time frame figure 4.11) also a northwards directed flow is obtained in the top layer. In the deepest sigma-layer layers a circulation is found, in the shallow part a northward directed flow is seen and in the deeper parts a southern directed flow is obtained. This behavior can be explained by a circulation due to wind setup and can also be seen in the third cross section of figure 4.12. In the second time frame a stronger flow is found near the coast which pushes water to the gap between the coast and an island just north of Baie du Cul-de-sac. At September, 6th 06:00 the wind is more offshore directed and therefore in the main part of the basin the flow is directed to the northeast in the top layer and a return flow is found in the bottom layers. This effect can also be seen in the cross section of this time frame, where the onshore velocities are found in the lower parts and the offshore velocities in the upper parts. When the bay is filling again the flow in the top layer is mainly directed in a southern direction, with a strong flow near the coast. All sigma-layers near the coast have these southern direction, but in the deeper parts a return flow is found. This also could be explained by the wind set-up. The main flow properties are dependent on the wind direction, but the effect of inflow discharges with salt and fresh water are giving an effect up to $0.5\,[m/s]$ (also see section A.2.3). The near coast velocity in the basin is mainly influenced by this forcing in a northward directed. In other words, when the main flow is directed northwards near coast this is increased by the water discharges, but while the flow is mainly directed southwards the flow velocity is reduced.

From the overview discussion (for Baie Orientale) in section 2.1 was concluded that the beach was eroded and that sand became more visible in the area. The eroding coast matches the simulations where higher nearshore velocities where found during Irma. Near the mouth of Étang Chevrise mud was eroded, which can also be induced by the higher velocities near the coast. The high velocity discharges in the region between Baie du Cul-de-Sac and the island located in front, matches that observation that the tip of the island is smaller in the aerial pictures taken after Irma.
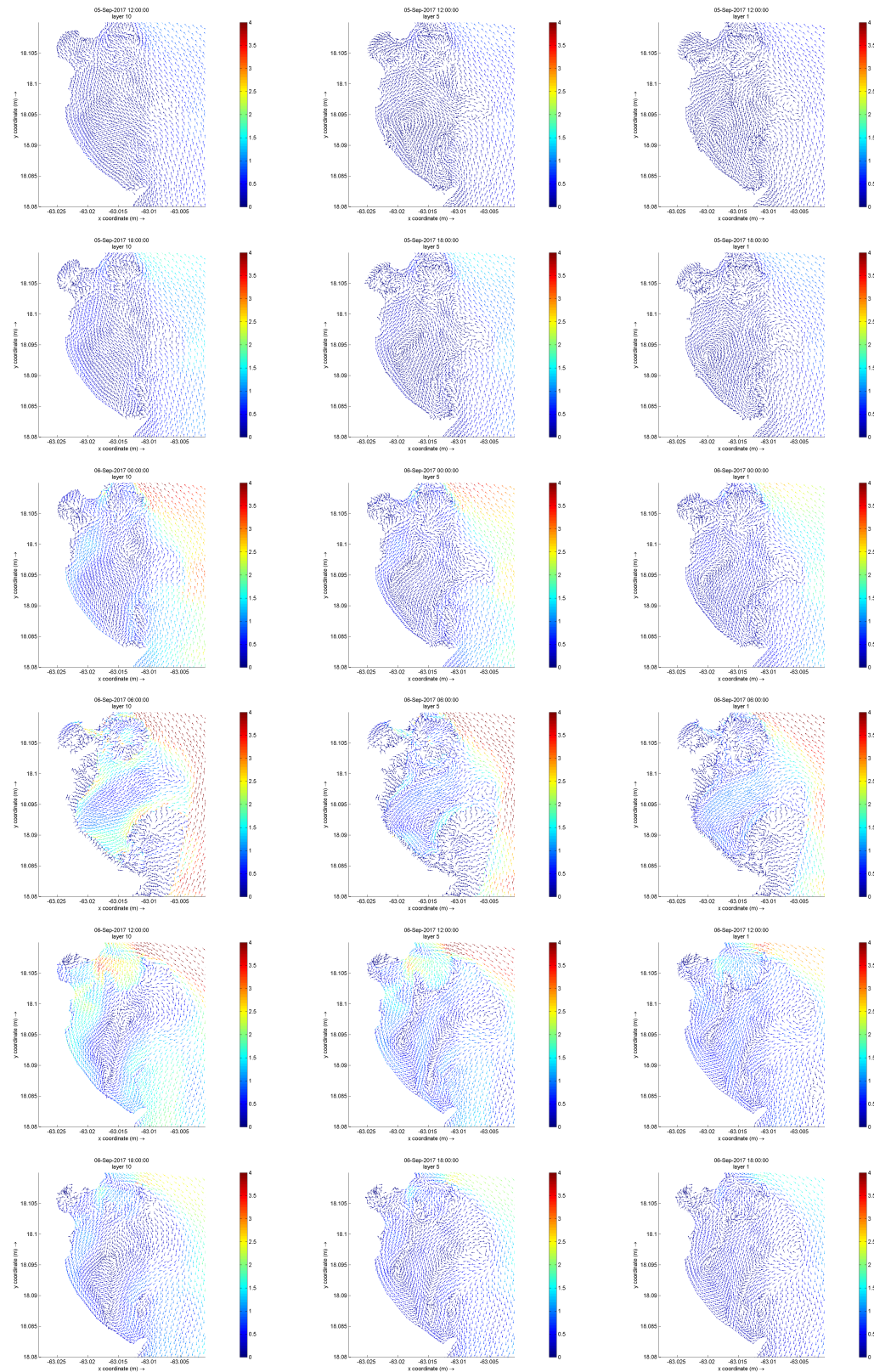
Figure 4.11: Velocities (magnitude color scale in m/s and direction of vector) in Baie Orientale during Irma from 3D model with wind, inflow and salinity
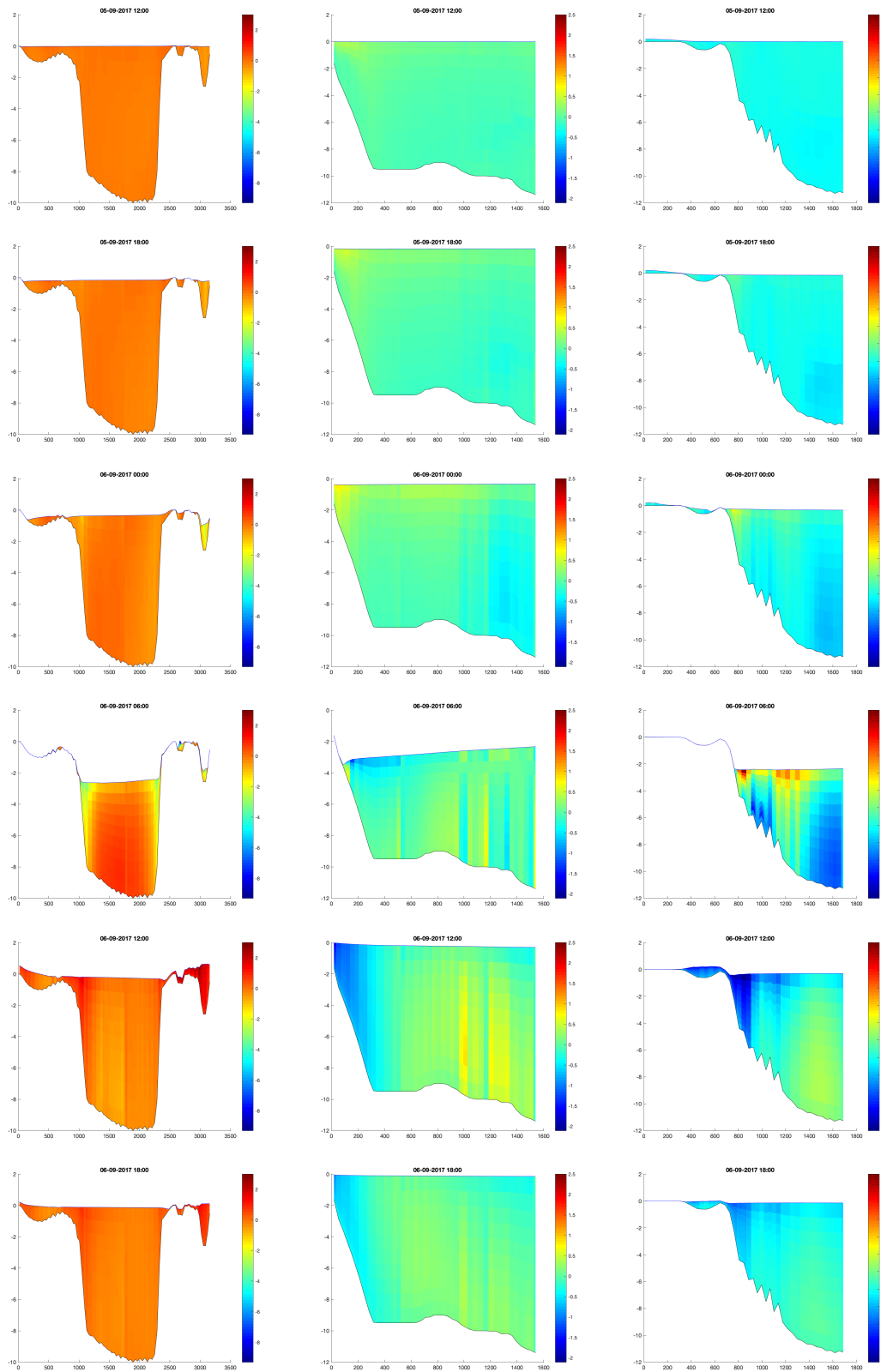
Figure 4.12: Orthogonal velocities (color scale in m/s, positive inwards directed) in cross sections (1, 2 and 3) of Baie Orientale during Irma from 3D model with wind, inflow and salinity

The flow is also effected by hurricane Maria. In the first time frame of figure 4.13 the same 'normal' conditions are found as just before Irma. Maria has imposed a large eastern wind velocity on the basin. This means that the normal wind set-up and circulations in the basin are more intense. At September, 19th 12:00 higher velocities are found in the bay up to $2\ [m/s]$ in the upper layer, but the flow structure is pretty much equal in both situations. This bigger wind-setup induced circulation can also be obtained form the cross sections. High offshore velocities are found in the deeper parts, and onshore velocities in the more shallow parts. In the next two time frames (18:00 and September, 20th 00:00) the flow is more directed southwards due to a change in wind direction. The highest velocities are found near the northern tip of the bay. In the final shown time frame the flow speed is reduced and the flow is approaching it's normal state.
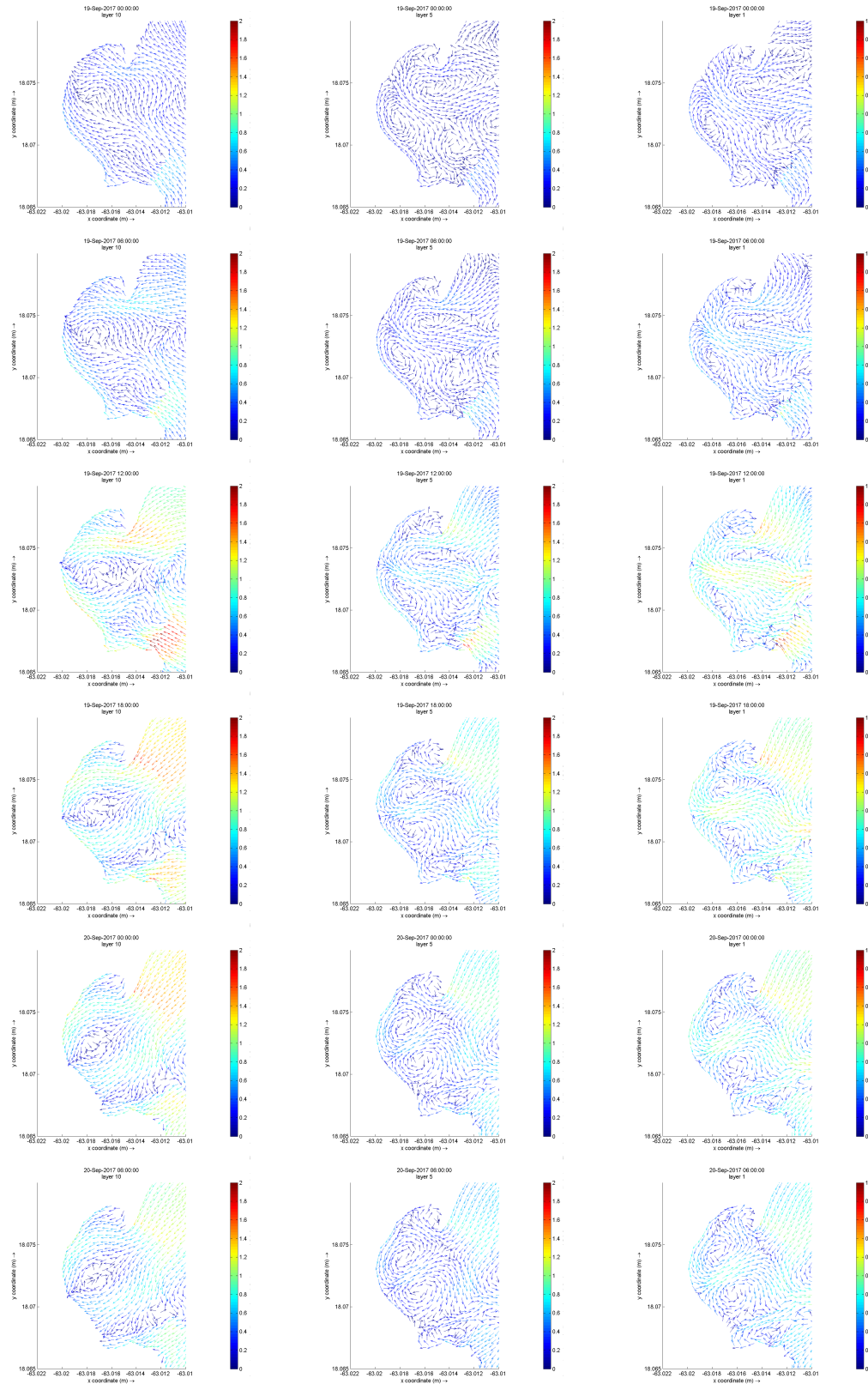
Figure 4.13: Velocities (magnitude color scale in m/s and direction of vector) in Baie de L'Embouchure during Maria from 3D model wind, inflow and salinity
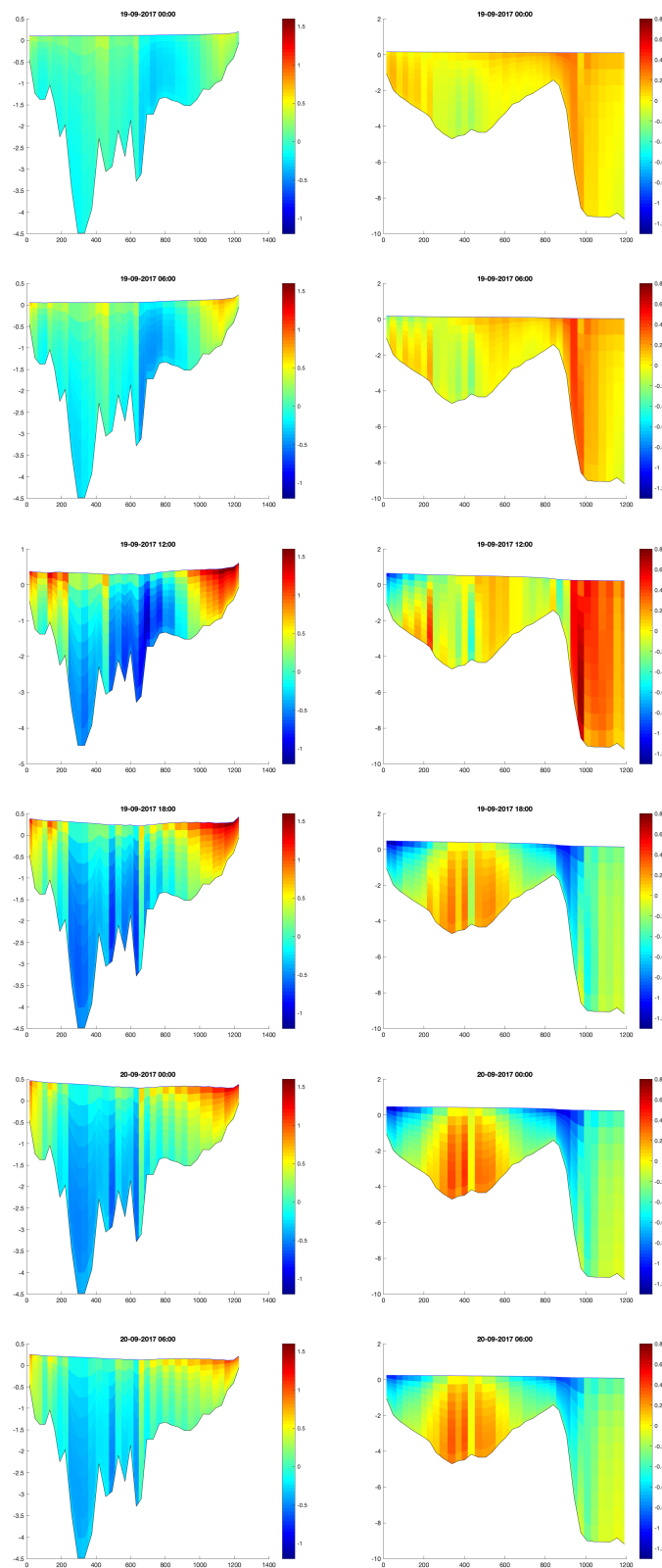
Figure 4.14: Orthogonal velocities (color scale in m/s, positive inwards directed) in cross sections (1 and 2) of Baie de L'Embouchure during Maria from 3D model with wind, inflow and salinity

In Baie Orientale the wind setup has also strengthened during Maria. In the time frame of September, 19th 12:00 could be clearly distinguished that the nearshore velocity has increased to around $1.5\ [\mathrm{m/s}]$, but also that there is a clear return flow established in the middle part of the basin for the lower sigma-layers. This flow has clearly strengthened during the hurricane. This effect could also be seen in figure 4.16, where there is a stronger return flow in the deeper parts. The other time steps have the same behavior and are mainly different in terms of velocity magnitude, which is directly dependent on the wind speed and the induced wind set-up circulation.
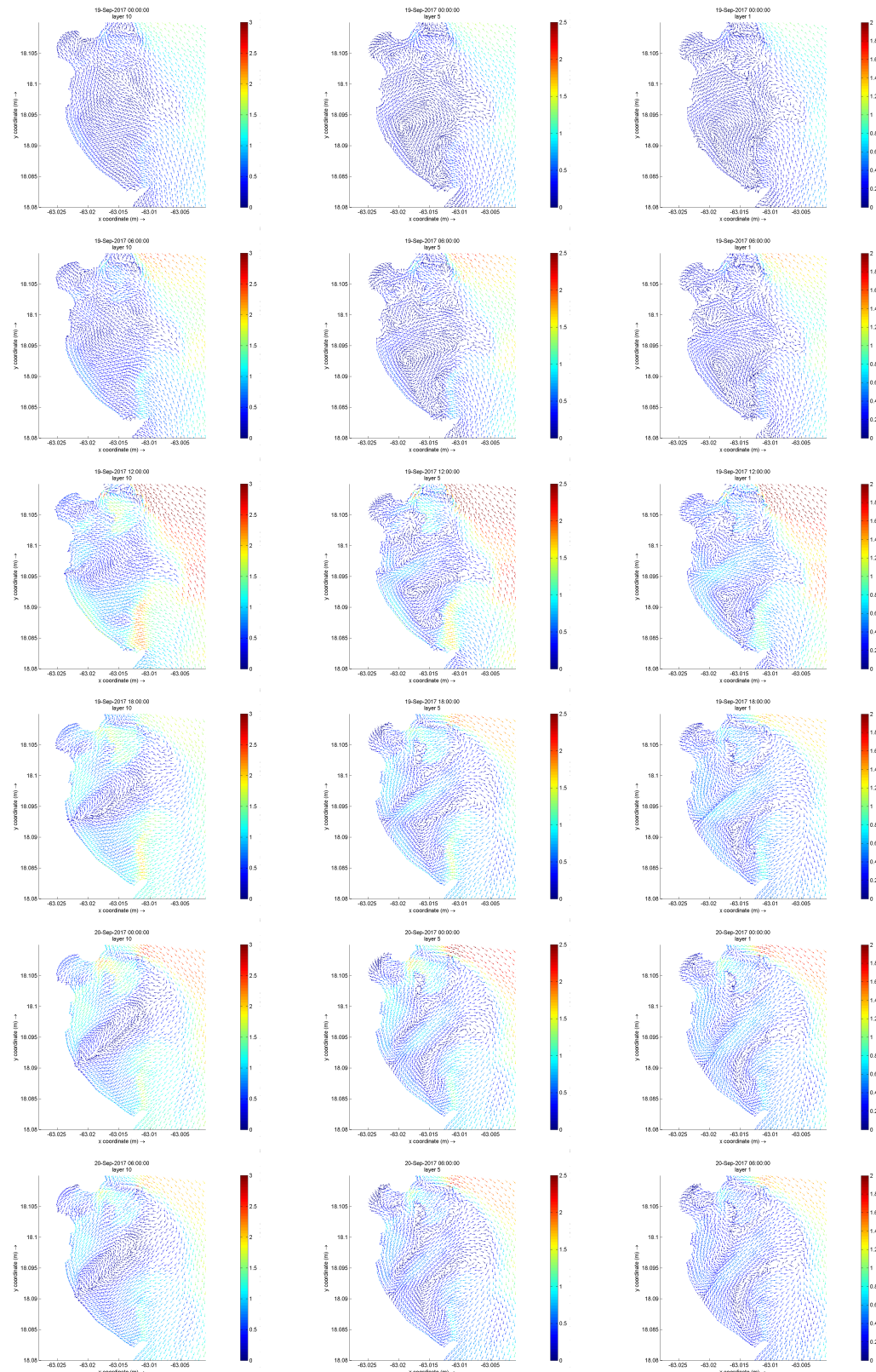
Figure 4.15: Velocities (magnitude color scale in m/s and direction of vector) in Baie Orientale during Maria from 3D model with wind, inflow and salinity
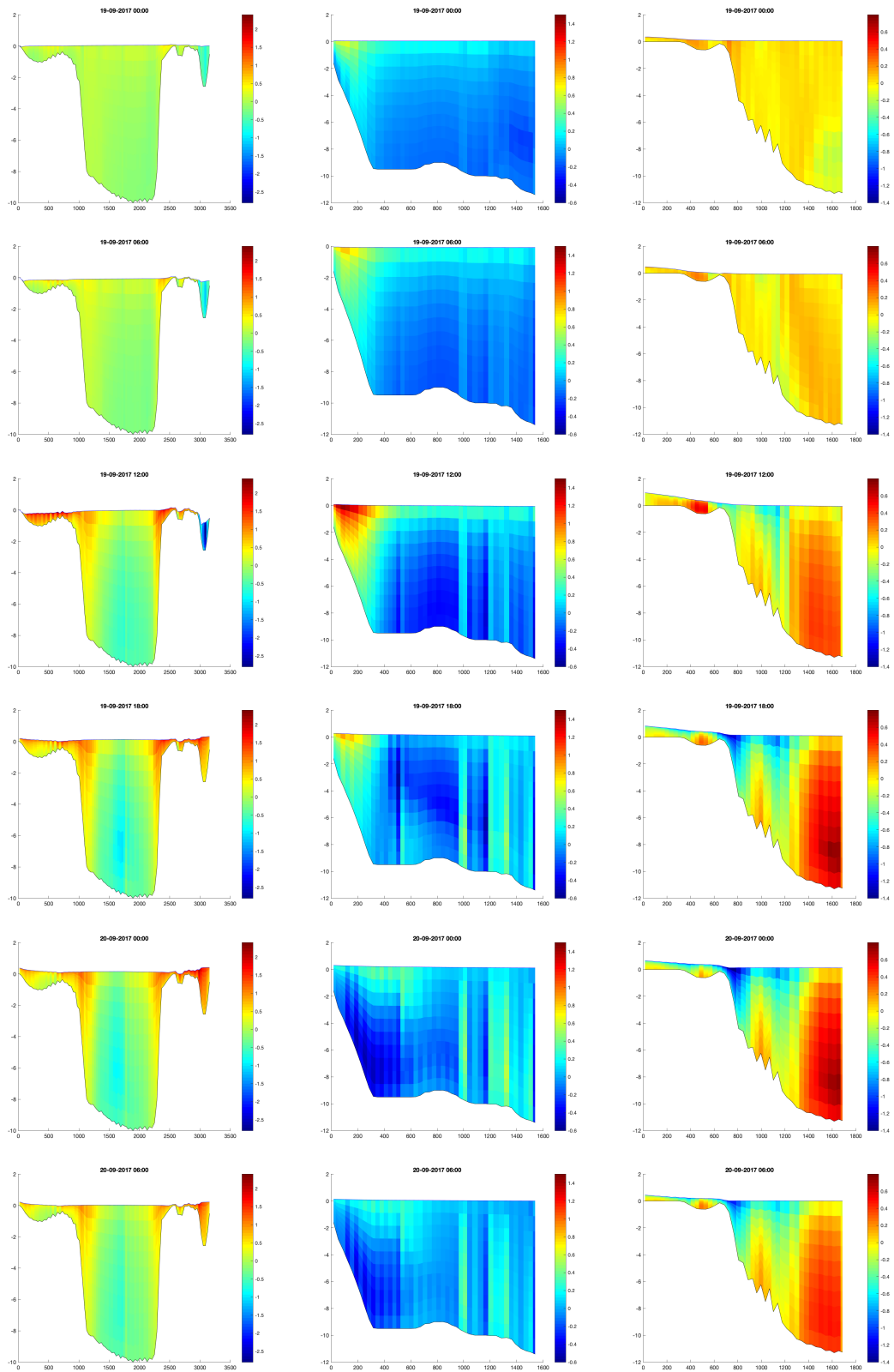
Figure 4.16: Orthogonal velocities (color scale in m/s, positive inwards directed) in cross sections (1, 2 and 3) of Baie Orientale during Maria from 3D model with wind, inflow and salinity

4.3. Salinity

In figures 4.17, 4.18, 4.19 and 4.20 the salinity results are given during Irma. The first thing what could be observed is that the results are approximately equal in each layer, in other words the salinity gradient in vertical direction is approximately zero. Under normal conditions Baie de L'Embouchure is filled with more salty water compared to the ocean. During Irma, first more fresh water is pushed into the bay, but next due to the high outflow (induced by the rainfall) the salinity rises. This salt water is pushed northwards by the wind. A few hours later the salinity in the bay has dropped and only high values are observed near the mouths of the salt pond. This low salinity is induced by the wind coming from the north and pushing a lot of water with a lower salinity value into the bay. In Baie Orientale fresh water is found near the beach and in the sheltered bay in the north. That this bay is fresh during normal conditions implies that there is nearly no exchange with the other parts of the bay. During Irma, the fresh water outflow is higher and more fresh water is found in the nearshore region, which matches the higher velocity in this area. In the timeframe of September, 6th 06:00 also the influence of Baie de L'Embouchure could be found. At later stages the salinity drops and the fresh water discharged from the coast is kept in the bay. When these result are compared with the result from the single layer model, a much higher concentration of high saline and fresh water is found in both bays. It seems that the single layer model mixes much faster in the horizontal plane, compared to the single layer model. The main behavior that the saline water from the Baie de L'Embouchure is flowing to the north and a concentrated outflow of fresh water is found from the beach in Baie Orientale is equal in both cases.

The salinity distribution during Maria is given in figure 4.21 and 4.22. The saline waters discharged in Baie de L'Embouchure are kept in the bay, due to the onshore wind velocity the wind is not able to leave the bay. Also the wind velocity during Maria is lower compared to Irma, which induces less mixing in the bays and induces a more concentrated pulse. The fresh water released in Baie Orientale is spreading in the bay, as could be seen in figure 4.22. The salinity is dropping starting onshore and finally also more offshore. The same happens in the other direction first the salinity drops in the northern parts of the bay and finally also in the southern parts. The amount of fresh water becomes so big that it starts moving to the other bay, (the wind is also a little bit directed to the south). This induces a lower salinity value in Baie de L'Embouchure. Where in figure 4.21 could be seen that the fresh water is coming from the north east.
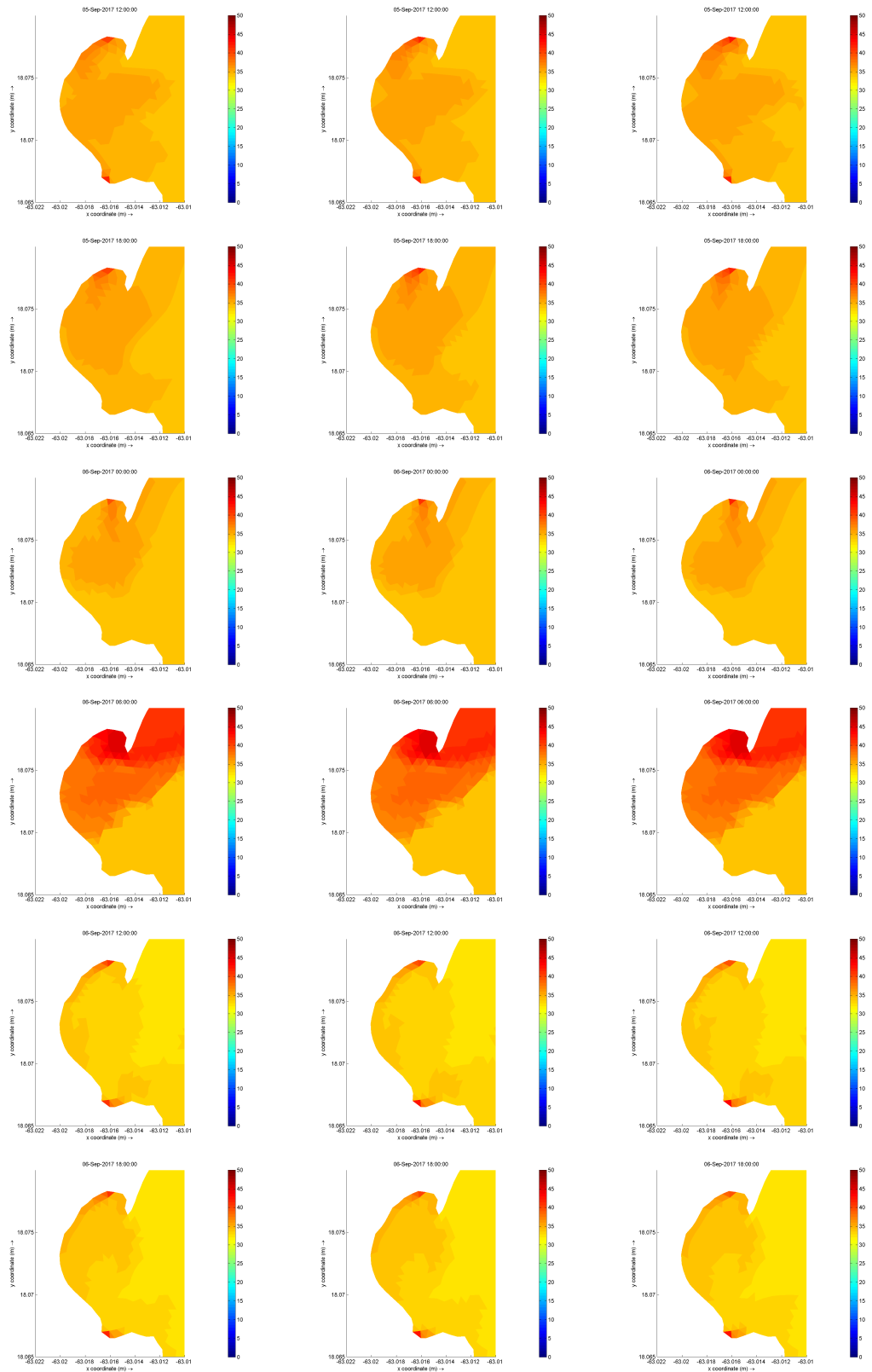
Figure 4.17: Salinity (color scale in psu) in Baie de L'Embouchure (layer 10, 5 and 1) during Irma from 3D model wind, inflow and salinity
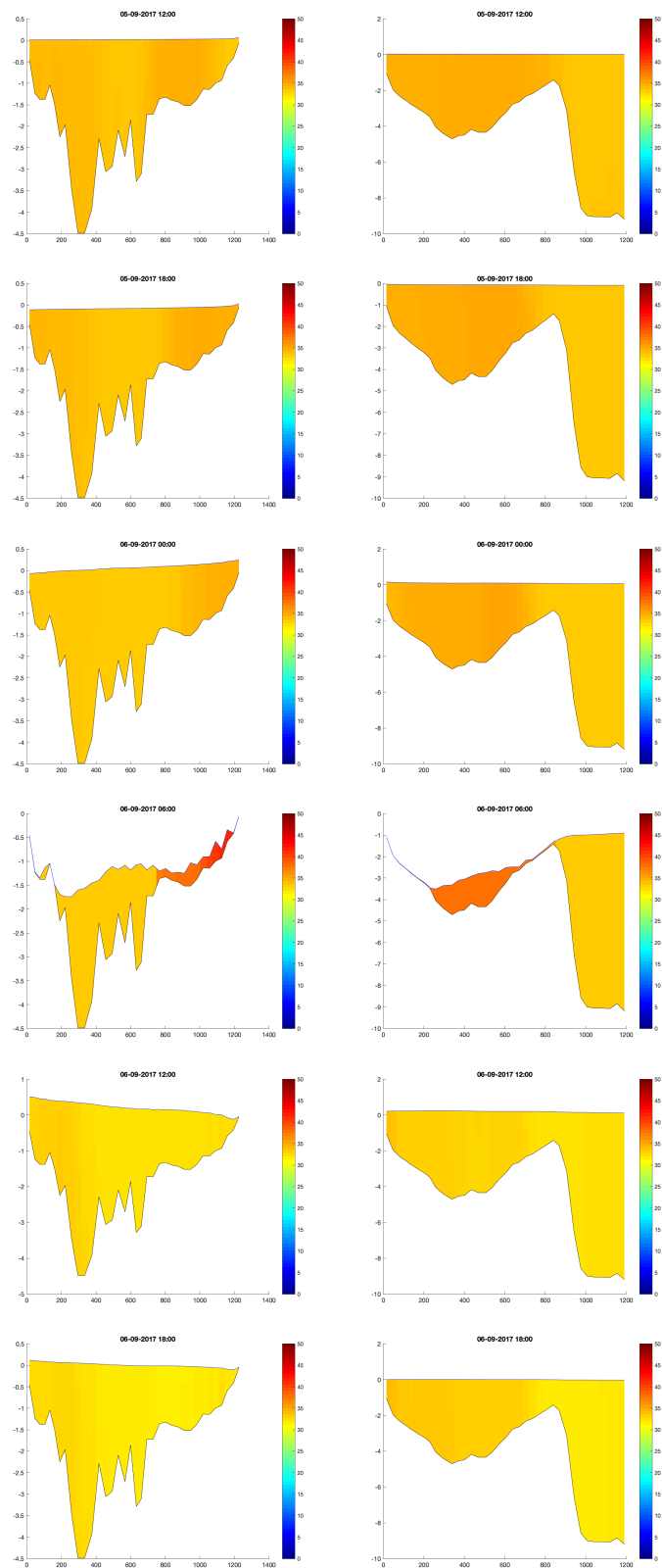
Figure 4.18: Salinity (color scale in psu) in cross sections (1 and 2) of Baie de L'Embouchure during Irma from 3D model with wind, inflow and salinity
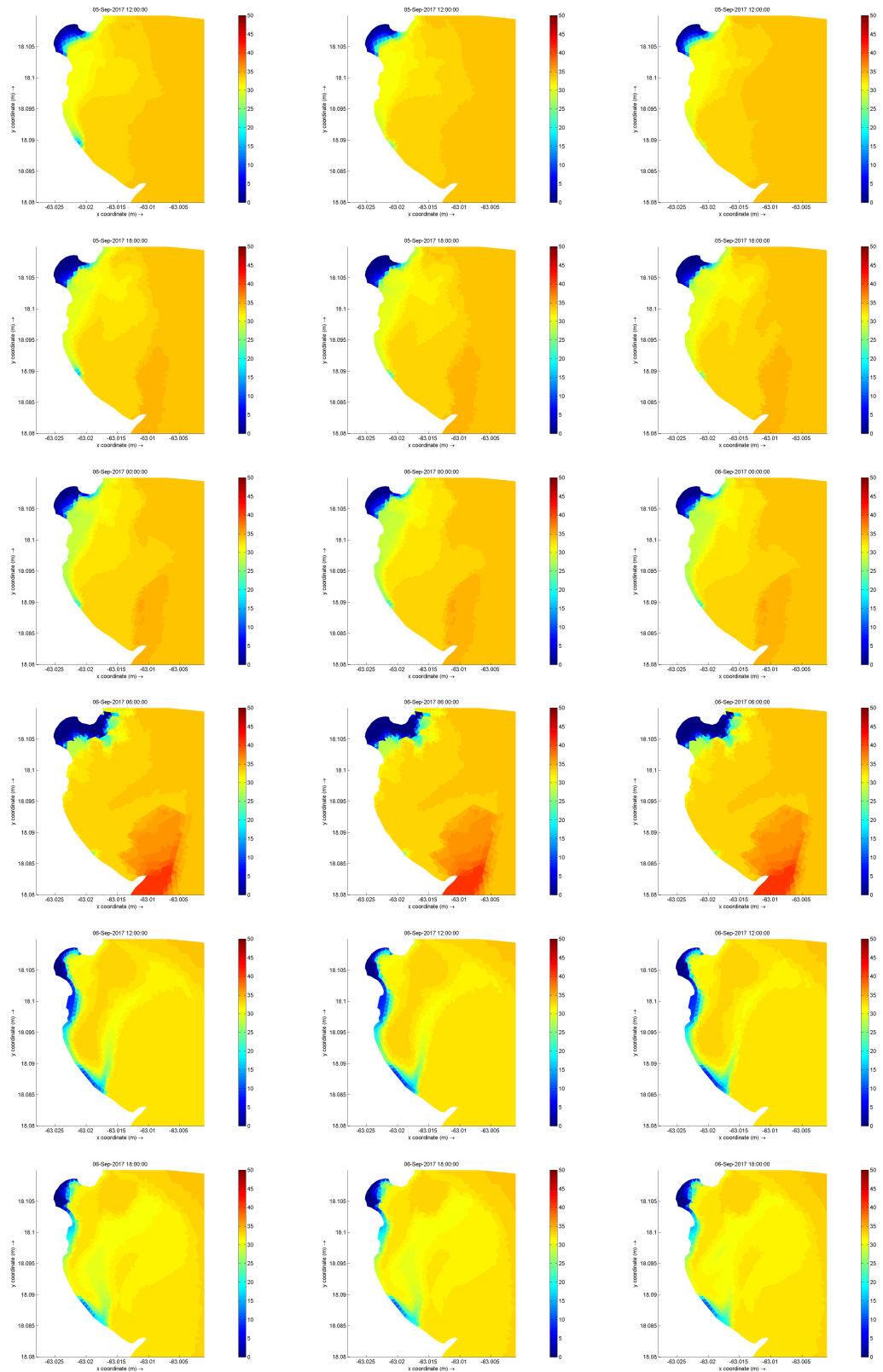
Figure 4.19: Salinity (color scale in psu) in Baie Orientale (layer 10, 5 and 1) during Irma from 3D model with wind, inflow and salinity
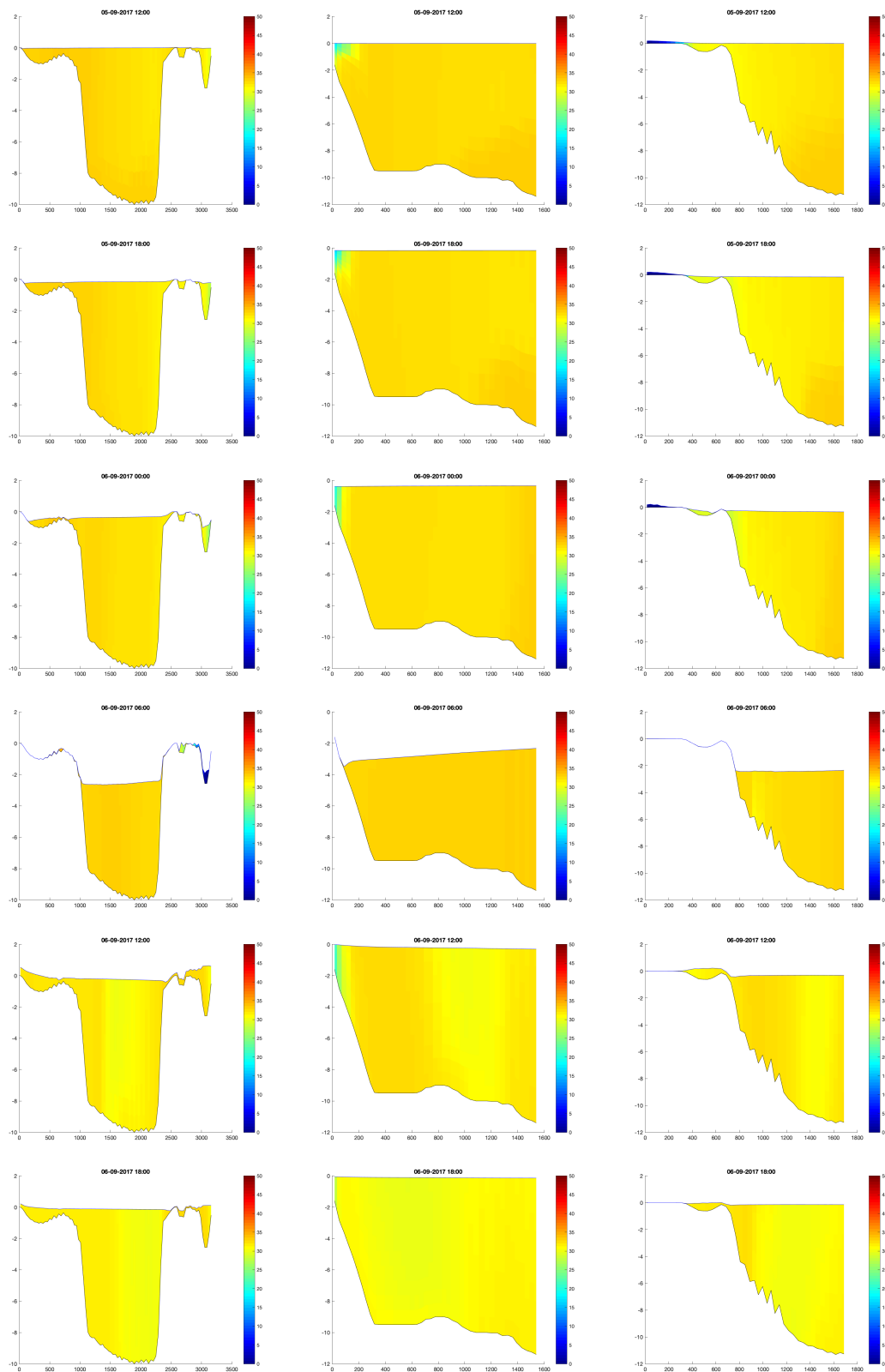
Figure 4.20: Salinity (color scale in psu) in cross sections (1, 2 and 3) of Baie Orientale during Irma from 3D model with wind, inflow and salinity
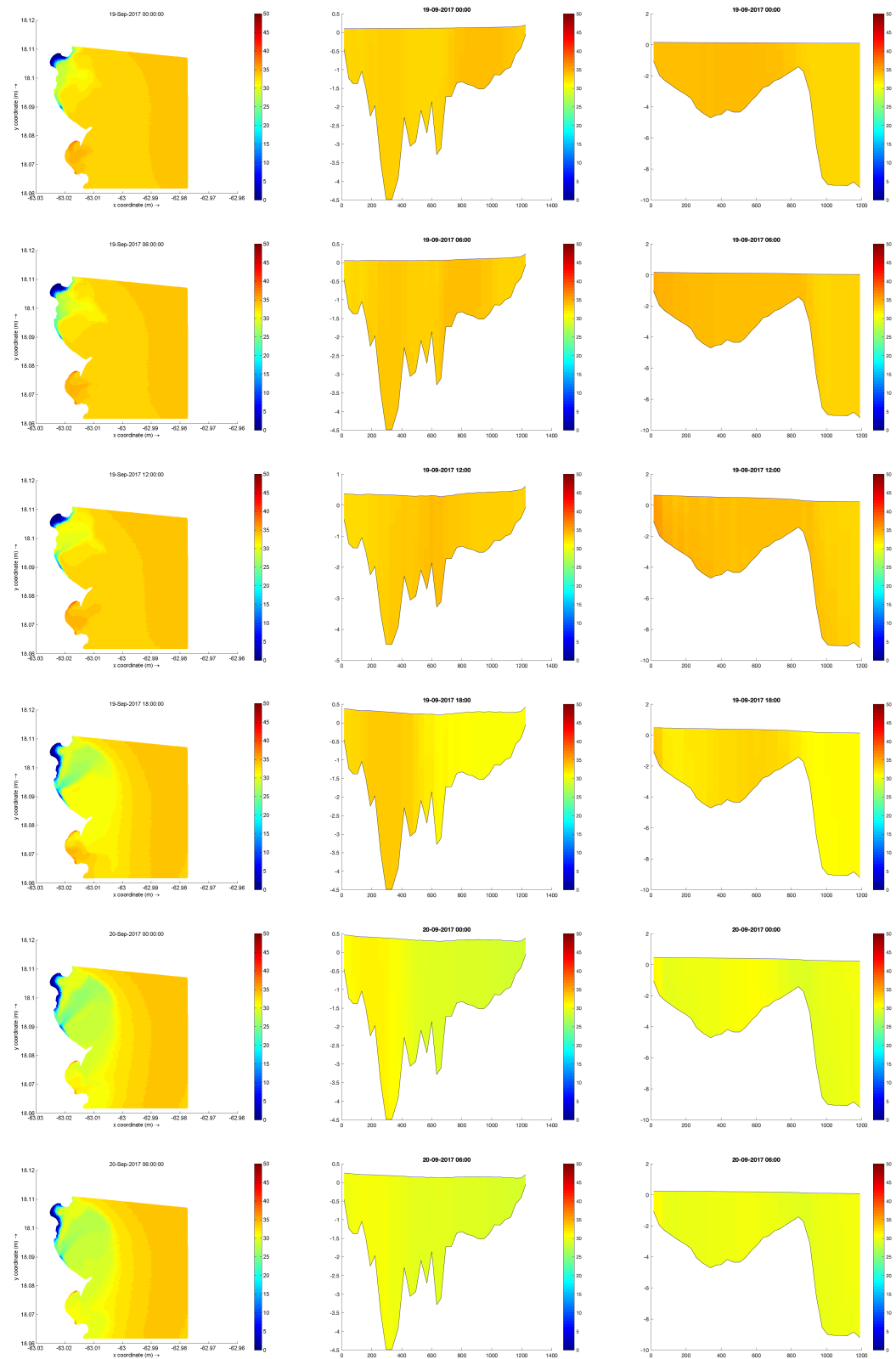
Figure 4.21: Salinity (color scale in psu) in top layer and in cross sections (1 and 2) of Baie de L'Embouchure during Maria from 3D model with wind, inflow and salinity
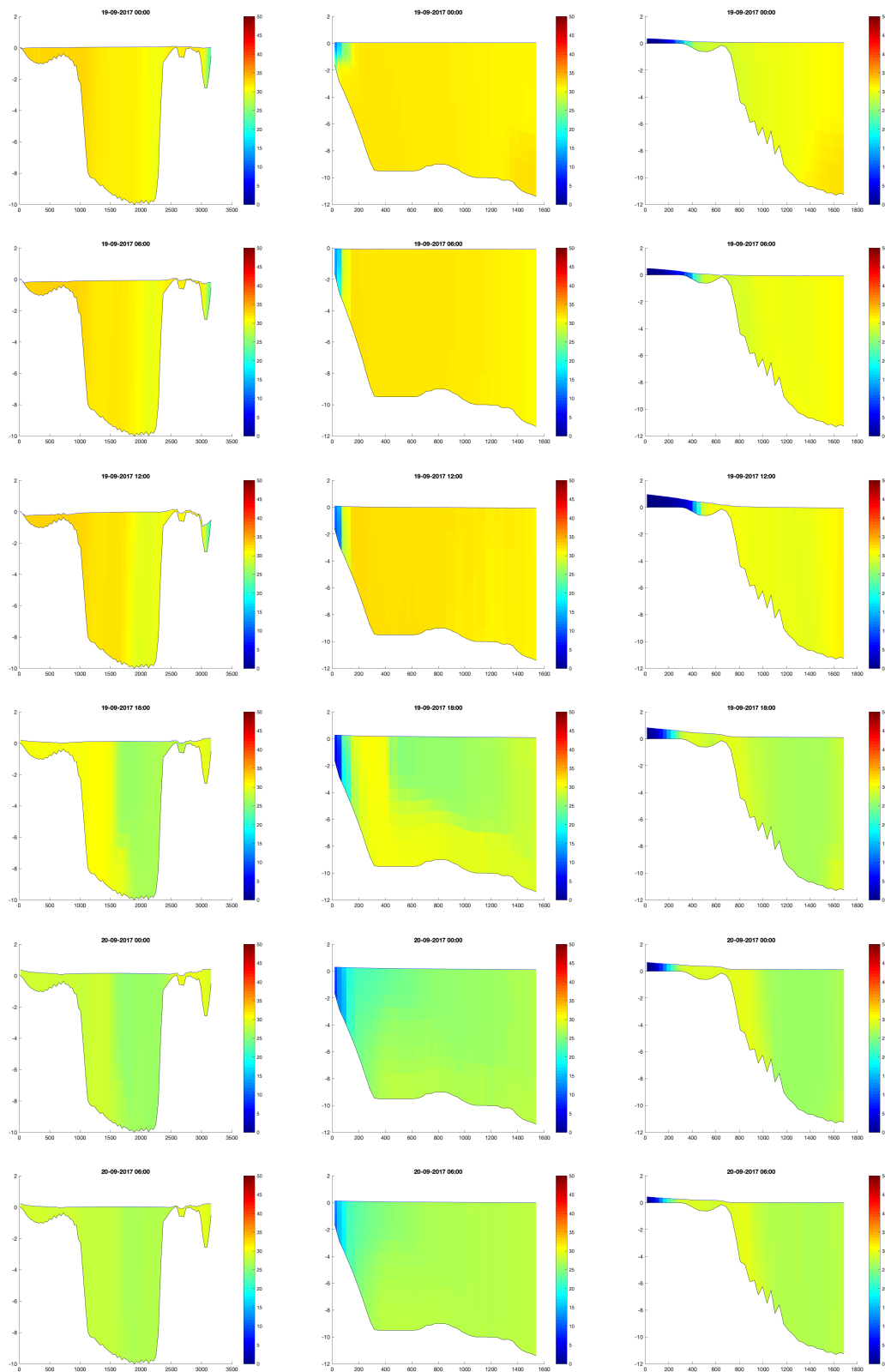
Figure 4.22: Salinity (color scale in psu) in cross sections (1, 2 and 3) of Baie Orientale during Maria from 3D model with wind, inflow and salinity

5

Conclusion

This situation around Saint Martin, and so for Baie de L'Embouchure and Baie Orientale, shows a small tidal range. The amplitude is around 0.15 [m]. The normal conditions show a wind from the east with a speed of 4.5 [m/s]. This wind induces a wind set-up to the coast and is more important in terms of flow velocity compared to the tidal effects. Under hurricane conditions this wind speed can increase up to 40 [m/s]. The two hurricanes gave both a different effect, while Irma was passing right over Saint Martin, Maria went further south. The wind of Irma (compared to Maria) was more intense, higher maximum and shorter total duration, and had more varying wind directions. Under normal conditions the salinity is constant in the basins and the influence of fresh and salty waters could be neglected.

Under normal conditions wind set-up was already the dominant effect, under hurricane conditions with faster winds this effect is even stronger. This implies that the flow during the hurricanes is faster compared to the normal situation and that the structures can mostly be explained by the wind set-up. Hurricane Irma showed a lot of drying in both bays. The water level dropped a couple of meter and Baie de L'Embouchure was nearly completely dry (as found in the model). Maria showed a complete different effect, due to the other wind direction a lot of more water was pushed to the coast and the water level has risen. In a simpler way, Maria has only strengthened the normal circulation and didn't gave any new flow structures.

The salinity gradients found in the normal situation are most of the time even not noticeable, and so no large density gradients are found. This implies that the density driven flows in these situations can be neglected. During the hurricanes a larger amount of rain will fall and so also the discharge into the bays has to rise. This imposes that the gradients are lager and some flow speed can be observed. In Baie de L'Embouchure only a small flow speed induced by salinity was obtained, but in Baie Orientale some larger flows can be found. The flow nearshore is modified with an amount of 0.5 [m/s].

In all model stages could be observed that the salinity gradient along the vertical is approximately zero. This means that water column is well mixed. Under hurricane Irma, Baie de L'Embouchure is filled with a lot of salt water. This is due to the outflow of two salt ponds in this bay. The southern wind has moved a lot of this salt water further north into Baie Orientale. In Baie Orientale a lot of more fresh water is found. This is mainly in the near shore area. During hurricane Maria the system is dominated by the fresh water from Baie Orientale. First this bay become filled fast, while next this water is pushed to Baie de L'Embouchure.

The main effect of hurricanes is the larger wind set-up. There is a huge difference in effect on both bays due to the different hurricanes and their different wind direction. Salinity gradients are mostly not driving the flow, but there are some local disturbances near the coast in Baie Orientale which are due to this gradients. The salt itself is well mixed over the vertical and is spreading in both bays and not necessarily gone directly. During hurricane Irma the salt water has moved to Baie Orientale and during Maria the fresh water was moving to Baie de L'Embouchure, this means that the bays are influencing each other.

6

Discussion

In the current model only wind, tide and inflow effect are taken into account. Under normal condition is seen that waves have an important impact on the area [14] and it'll be good to take them into account. Under hurricane conditions the waves will have a big impact as during hurricane Maria, the wind direction was east and so probably also the wave conditions. During Irma the wind was directed offshore and so waves are expected to have a smaller impact on this situation.

Density driven flow is caused by density gradients. Density in shallow water is dependent on salinity and temperature. The effects of salinity are now taken into account, but the effect of temperature is not investigated. It can be worth it to add this process to the model, the water temperature of the ocean, salt ponds and rain/runoff can be completely different.

The current domain of the model is limited offshore. This limit can be taken too close to the shore, since the water level is given at the eastern boundary. If the wind set-up will be larger in reality, especially during hurricanes, only the astronomic tidal boundary wouldn't be sufficient and/or influencing the results too much. Therefore it would be worth to extend the domain and when possible update the boundary condition with an actual water level

Finally the model can be improved by improving the dataset. The amount of data available during hurricanes is not that much and there is no way to validate the current model results. Even eyewitnesses will be hard to get during the peek of the hurricanes. Also the numerical model used can be checked better, numerical errors are likely to occur and the effect of drying is that it's hard to limit these errors.

Bibliography

[1] Bertinelli, L., Mohan, P., and Strobl, E. Hurricane damage risk assessment in the caribbean: An analysis using synthetic hurricane events and nightlight imagery. *Ecological Economics 124* (2016), 135 – 144.

[2] Cangialosi, J., Latto, A., and Berg, R. Tropical cyclone report, hurricane irma. *National Hurricane Center* (Jun 2018).

[3] Central Intelligence Agency. The world factbook central intelligence agency. `https://www.cia.gov/library/publications/the-world-factbook/geos/sk.html`. [Online; accessed 12-05-2018].

[4] Codiga, D. UTide. `https://nl.mathworks.com/matlabcentral/fileexchange/46523-utide-unified-tidal-analysis-and-prediction-functions`, Mar 2017. [Online; accessed 12-04-2018].

[5] Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., and Totterdell, I. J. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature 408* (11 2000), 184 EP –.

[6] Deltares. Delft3D Flexible Mesh Suite.

[7] Dijkstra, H. A. Scenes. `http://www.staff.science.uu.nl/~dijks101/SCENES/`, 2018. [Online; accessed 12-05-2018].

[8] Emanuel, K. A. The theory of hurricanes. *Annual Review of Fluid Mechanics 23*, 1 (1991), 179–196.

[9] Etienne-LeBlanc, S. Climatological summary 2017 and hurricane season review, Apr 2018.

[10] E.U. Copernicus Marine Service Information. Operational mercator global ocean analysis , global ocean 1/12° physics analysis and forecast updated daily. `http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_ANALYSIS_FORECAST_PHY_001_024`. [Online; accessed 28-04-2018].

[11] Google LLC. Google Earth Pro.

[12] Intergovernmental Oceanographic Commission. Sea level station monitoring facility. `http://www.ioc-sealevelmonitoring.org/station.php?code=stmt`. [Online; accessed 12-03-2018].

[13] Jarecki, L., and Walkey, M. Variable hydrology and salinity of salt ponds in the british virgin islands. *Saline Systems 2*, 1 (Feb 2006), 2.

[14] Keyzer, L. Predicting the impact of sea-level rise in baie orientale and baie de l'embouchure, 2018.

[15] Les Fruits De Mer. Notes on conservation and selected areas of interest. `http://www.lesfruitsdemer.org/guides/the-incomplete-guide-to-the-wildlife-of-saint-martin/notes-on-conservation-and-selected-areas-of-interest/`. [Online; accessed 15-03-2018].

[16] Nicholls, R. J., and Cazenave, A. Sea-level rise and its impact on coastal zones. *Science 328*, 5985 (2010), 1517–1520.

[17] van Katwijk M.M.; van der Heide T.; van Tussenbroek B.I.; Dijkstra H.A.; van Western R.; Pietrzak J.D.; Candy A.S.; Katsman C.A.; Riva R.E.M.; Slobbe C.; Klees R.; Herman P.M.J.; Bouma T.J., J. R. Stability of Caribbean coastal ecosystems under future extreme sea level changes (SCENES): sub-project C., 2018. [In preparation].

[18] Webster, P. J., Holland, G. J., Curry, J. A., and Chang, H.-R. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science 309*, 5742 (2005), 1844–1846.

[19] Wikipedia. Hurricane Irma. `https://en.wikipedia.org/wiki/Hurricane_Irma`, 2018. [Online; accessed 10-10-2018].

[20] Wikipedia. Hurricane Maria. `https://en.wikipedia.org/wiki/Hurricane_Maria`, 2018. [Online; accessed 10-10-2018].

[21] Windguru. Windguru, St. Martin. `https://www.windguru.cz/archive.php?id_spot=3604`, 2017. [Online; accessed 10-05-2018].

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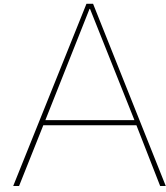
Extended results

In this appendix the results from the model steps are discussed. These are the models created to verify the influence of different conditions on the model and the reference model to assess the impact of the density differences. First the single layer models are discussed, whereafter the multi layer models will be discussed.

A.1. Results from single layer models

Three single layer models are made, in the first model only the wind conditions are added beside the forcing of the tidal boundary. The second model also involves the inflow boundaries implied by rainfall and the last model also contains information about salinity.

A.1.1. Wind

In chapter 3 the water level near the eastern boundary was already shown. This observation point only contains the tidal signal. In figure A.1 and A.2 the water level at two points more nearshore are shown. The first observation point is in Baie de L'Embouchure and the other in Baie Orientale. In the water level the tidal signal can be clearly distinguished, which is a little bit deformed from the signal of figure 3.8. From the two nearshore signals two anomaly events can be observed. Around September, 6th (hurricane Irma) the water level has been decreased, while during Maria the water level has been increased. This difference is due to the different wind direction, during Irma this was mainly south-south-east (which is offshore directed), while during Maria the wind was from the east, which is onshore. Beside the windspeed during Irma was much higher, due to the fact that Irma has passed right across Saint Martin, while Maria passed on a larger distance (see section 2.6).

In the first plot of figure A.3 an approximately normal situation is shown: low velocities and a constant water level across the area. Six ours later the water level has went down, mainly in the nearshore area. At the start of September, 6th the water level in the northern bay has dropped a lot. The main flow direction is in the northern direction. At six o'clock the main flow direction is still northwards, but the amplitude has grown. The water level in both bays has now dropped significant. In figure A.4 the water depth at this time is shown. In large parts of the bays the depth is (near) zero, which means that it has dried out in these areas. At midday the water level is clearly growing to it's normal level and at the beginning of the evening it's normal.
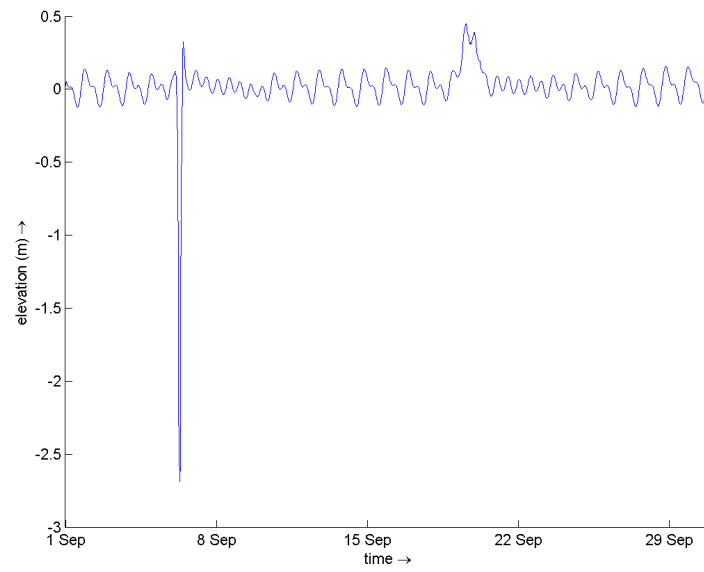
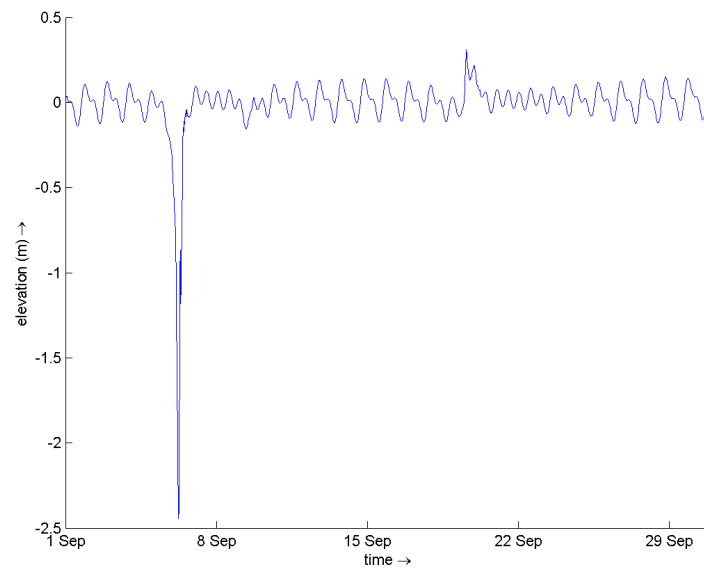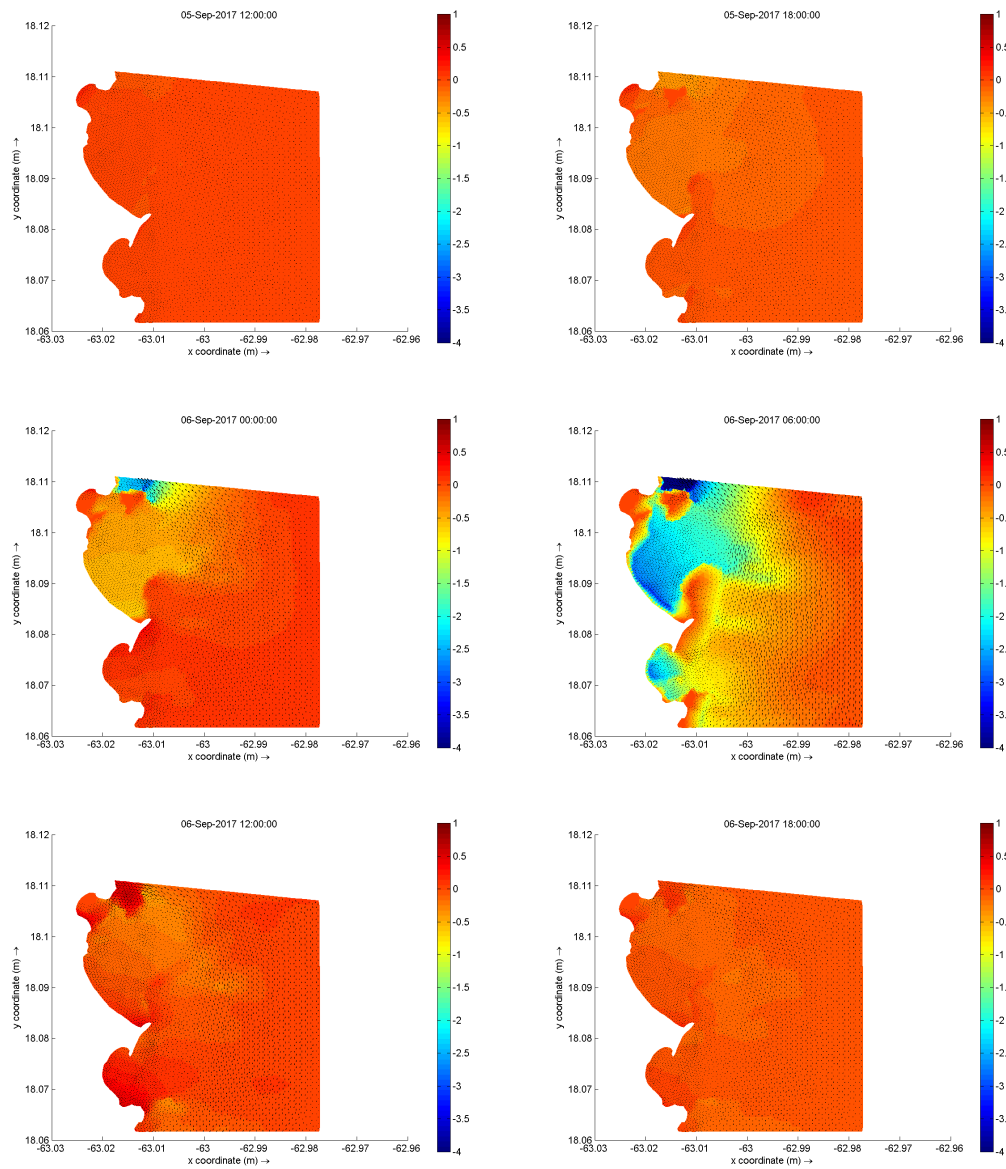Figure A.1: Water level, in Baie de L'Embouchure

Figure A.2: Water level, in Baie Orientale

Figure A.3: Water level (color scale, in m) and velocities (vectors), during Irma from 2D model with wind
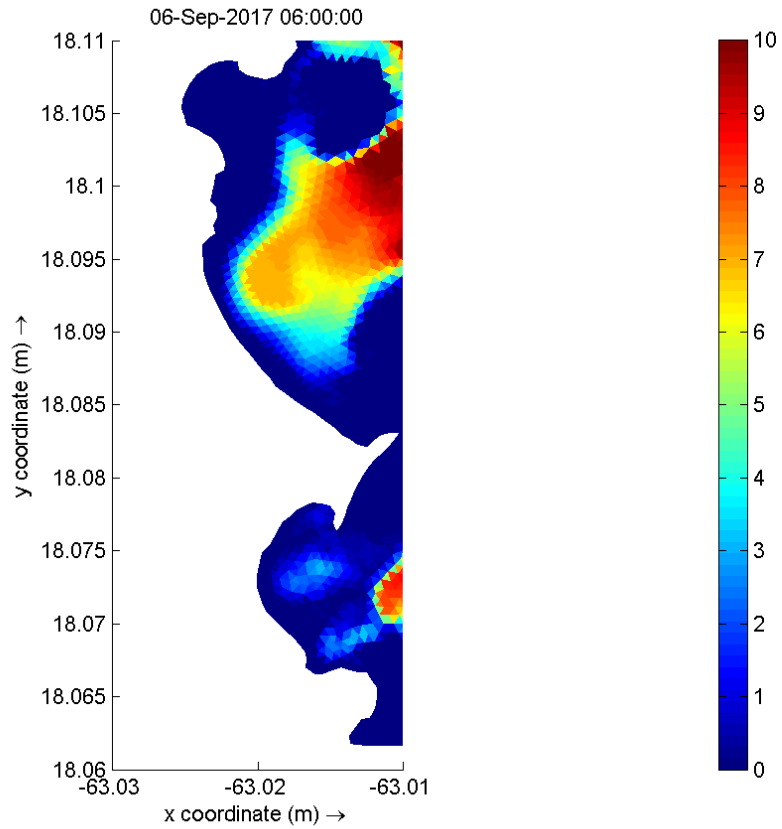
Figure A.4: Water depth (in m)

Looking in more detail to the situation in Baie de L'Embouchure (figure A.5), could be obtained that the water level is at all times except September, 6th 06:00 constant in this area and between -0.5 [m] and 0.5 [m]. From the plot of six o'clock could be obtained that the water level has dropped to a maximum of -3 [m]. The discharge at September, 6th 00:00 and 06:00 is directed offshore and has a larger amplitude compared to earlier stages. In later stages the flow is directed into the bay (to restore the water level).
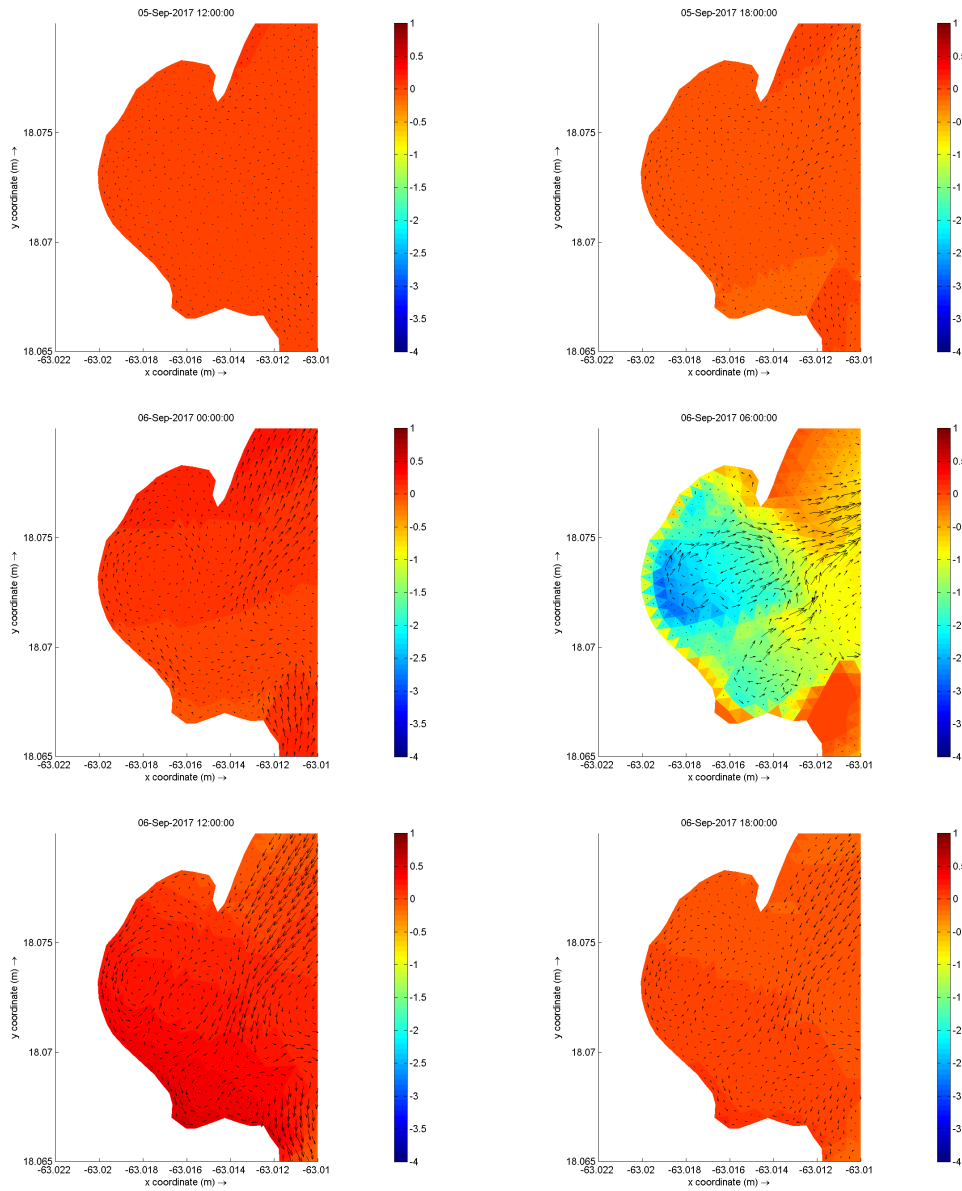
Figure A.5: Water level (color scale, in m) and velocities (vectors) in Baie de L'Embouchure, during Irma from 2D model with wind
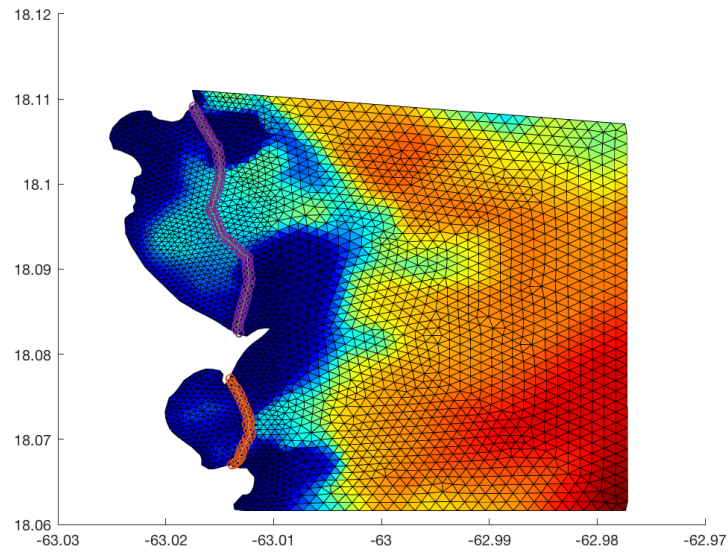
Figure A.6: Location of the slices

Next two slices are taken in the area, at the entrance of both bays. The exact locations are shown in figure A.6. On these slices the orthogonal velocity is determined. For Baie de L'Embouchure (figure A.7) could be seen that in normal situations the flow is directed onshore at the northern part of the bay and that in the southern part it's offshore directed. During hurricane Irma, some high, offshore directed velocities can be observed, but also some large inflow velocities. Hurricane Maria has a long period with high, onshore directed velocities and is much less offshore directed, compared to Irma. In Baie Orientale (figure A.8) there are high onshore directed velocities during Irma and Maria. During Maria the peek is lower, but the period of increased velocities is larger.
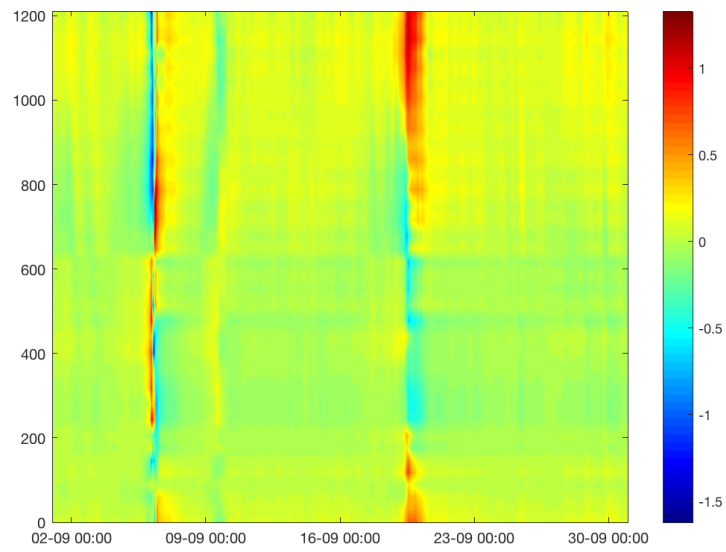
Figure A.7: Velocity (in m/s, onshore directed is positive), at the entrance of Baie de L'Embouchure from 2D model with wind
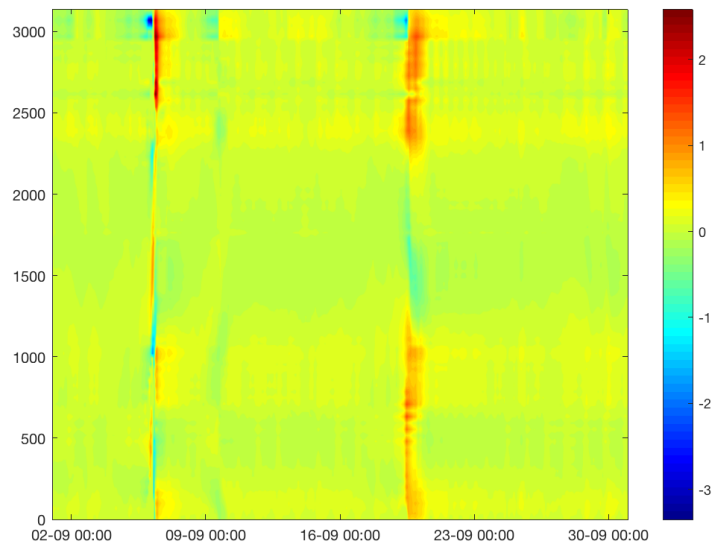

Figure A.8: Velocity (in m/s, onshore directed is positive), at the entrance of Baie Orientale from 2D model with wind
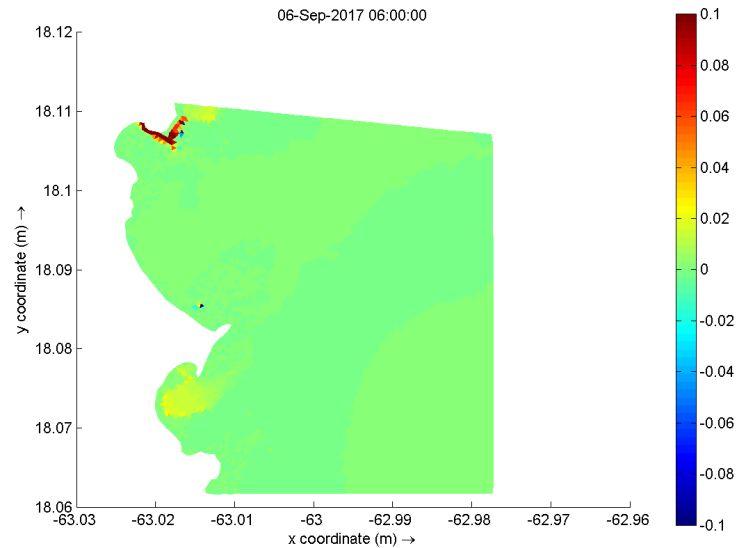
Figure A.9: Difference in water level (in m) due to adding inflow properties to the model

A.1.2. Wind and inflow

In the next model inflow properties are taken into account. These are the five inflow elements as discussed in section 3.2. The difference is water level is very small (order of 0.01 $[\mathrm{m}]$) compared to the previous model. Figure A.9 shows an example of this difference. From this could be obtained that the water level is a little bit higher near the inflow boundaries, as you would expect. Also the velocities are compared but there the difference is even less notable.

A.1.3. Wind, inflow and salinity

In the case with salinity the water level shows (nearly) exact the same result as the model with wind and inflow properties, therefore these differences are not of interest. In figure A.10 the difference in velocity amplitude and direction is shown. The difference is mostly around 0.05 $[\mathrm{m}/s]$ or less, but from the first two and last two pictures a circulation in the northern bay can be obtained, which is clearly related with the location of the inflow.

Finally the results of the salinity distribution are discussed. In the first figure (of A.11) could be seen that the northern part of Baie Orientale is less saline, due to the inflow in this area and the sheltered geographic position of this part of the bay. Baie de L'Embouchure has some high saline peeks near the inflow points of the two salt ponds, beside note that the complete is more saline compared to the area. Due the northward directed wind (and so flow velocities) the saline waters are moved to the north from Baie de L'Embouchure, as could be seen in the second and third figure. From the timeframe of September, 6th 06:00 could be seen that there was a lot of rainfall. The tip between the tow bays has now high saline waters (which was pushed northwards from the Baie de L'Embouchure by the wind), but also in Baie Orientale could be obtained that the fresh water discharges are moving into the bays. In the final two result could be seen that a more normal situation is reached (first figure), but note the 'channel' formed from the fresh water discharge of the beach in Baie Orientale.
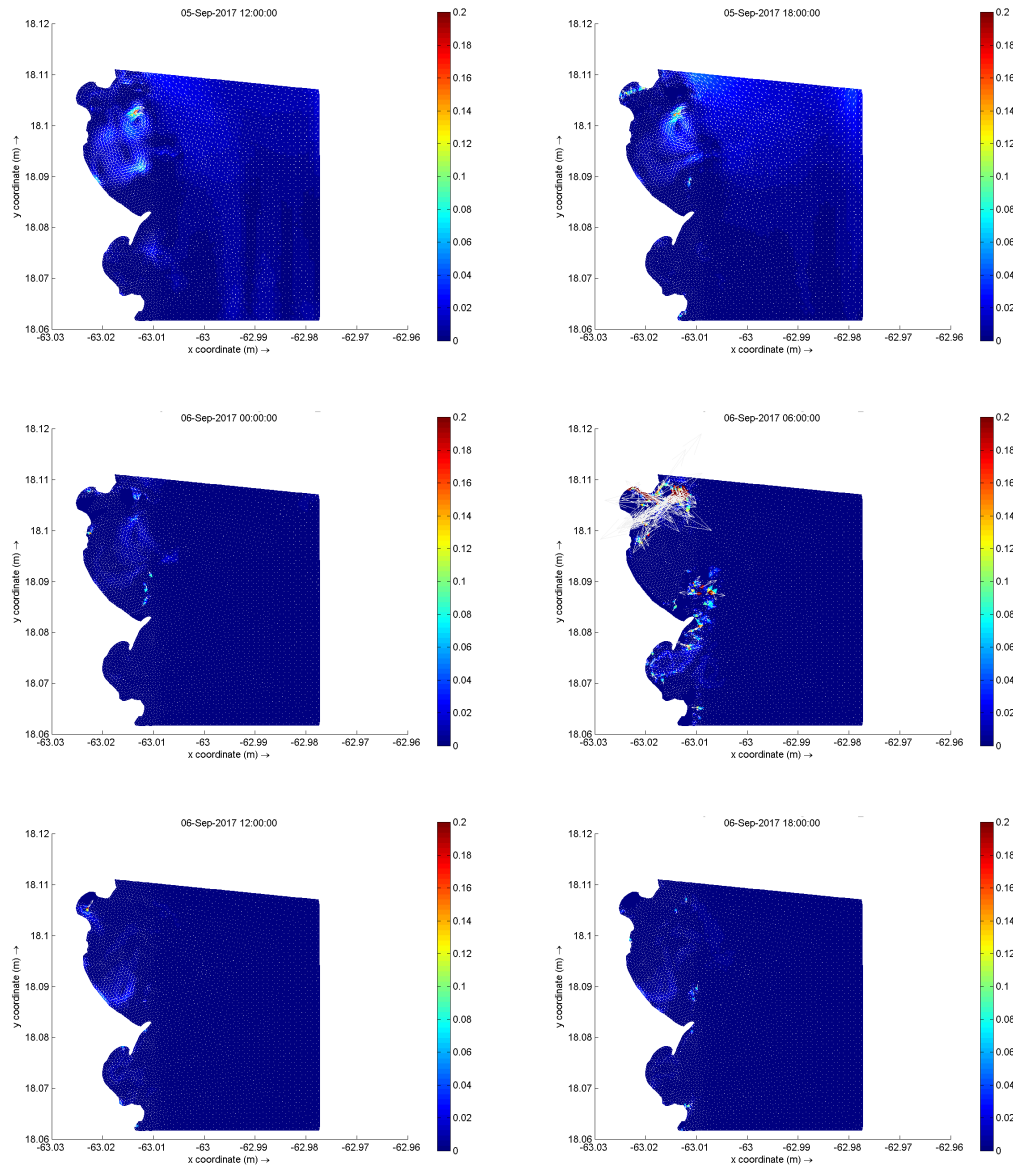
Figure A.10: Difference in velocity (color scale, in m/s) during Irma. Comparison between 2D model with only wind and wind, inflow and salinity
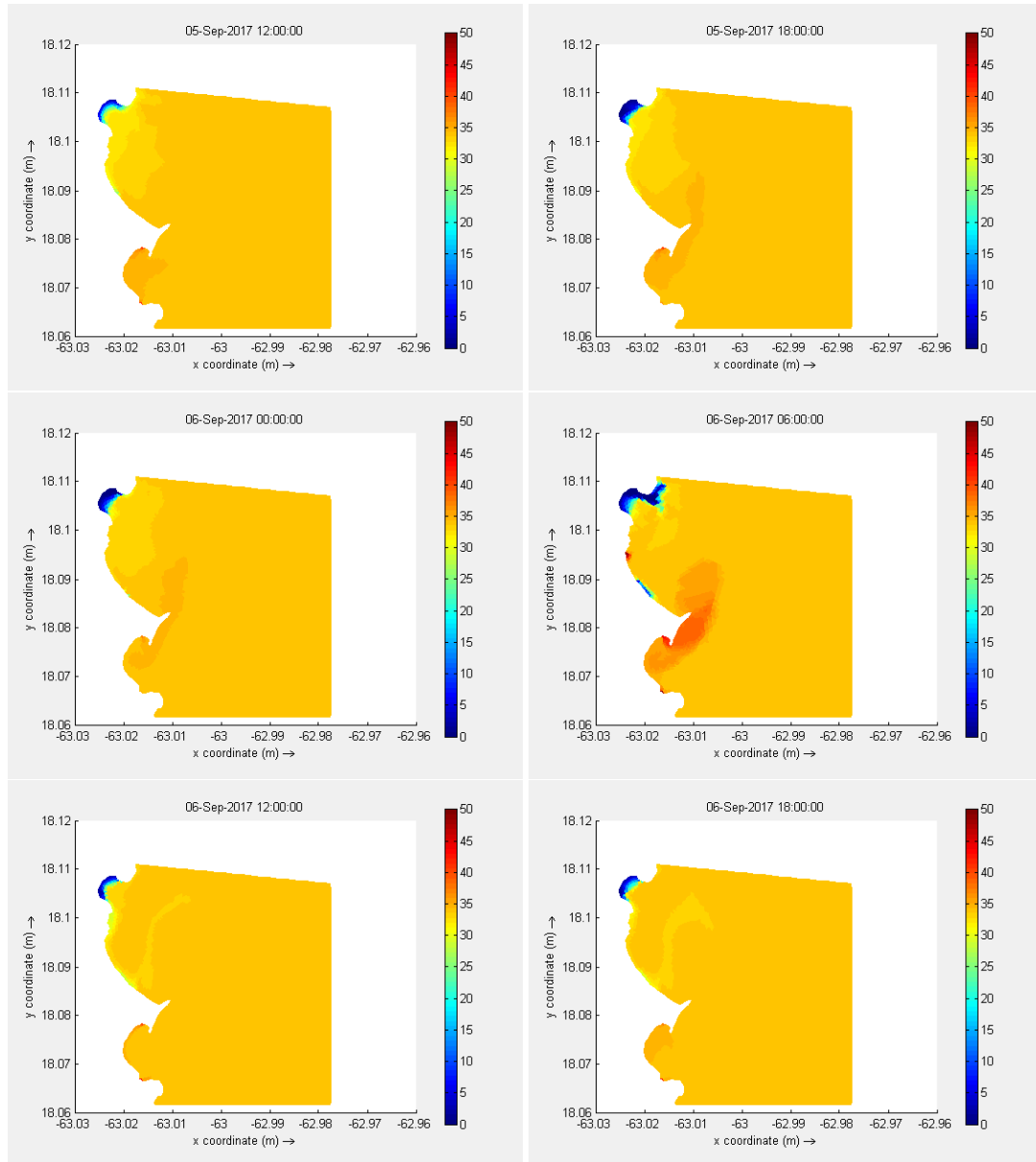
Figure A.11: Salinity (color scale, in psu) and velocities (vectors), during Irma from 2D model with wind, inflow and salinity

Hurricane Maria

Beside the results for hurricane Irma, also results are made for hurricane Maria. This hurricane has less impact on Saint Martin. Therefore the flow velocities and water levels obtained are lower (see figure A.12). The first two figures show a relatively normal situation, in the third figure the flow speed to the north is increased and the water is pushed to the coast, the water levels are rising in both bays. At September 19th, 18 o'clock the water level is a little bit lower but the main flow directions has turned to the south. This is due to the change in wind direction. In the fifth figure the water level is again lower compared to the previous time step but the flow speed to the south has increased. Finally the flow returns to a normal situation.

Between hurricane Irma and Maria is a huge difference, while Irma blowed the water back to the sea, the winds of Maria were pushing the water towards the coast. Irma was more intense based on flow velocities, wind velocities and water levels but the effect of Maria was visible over a longer time.
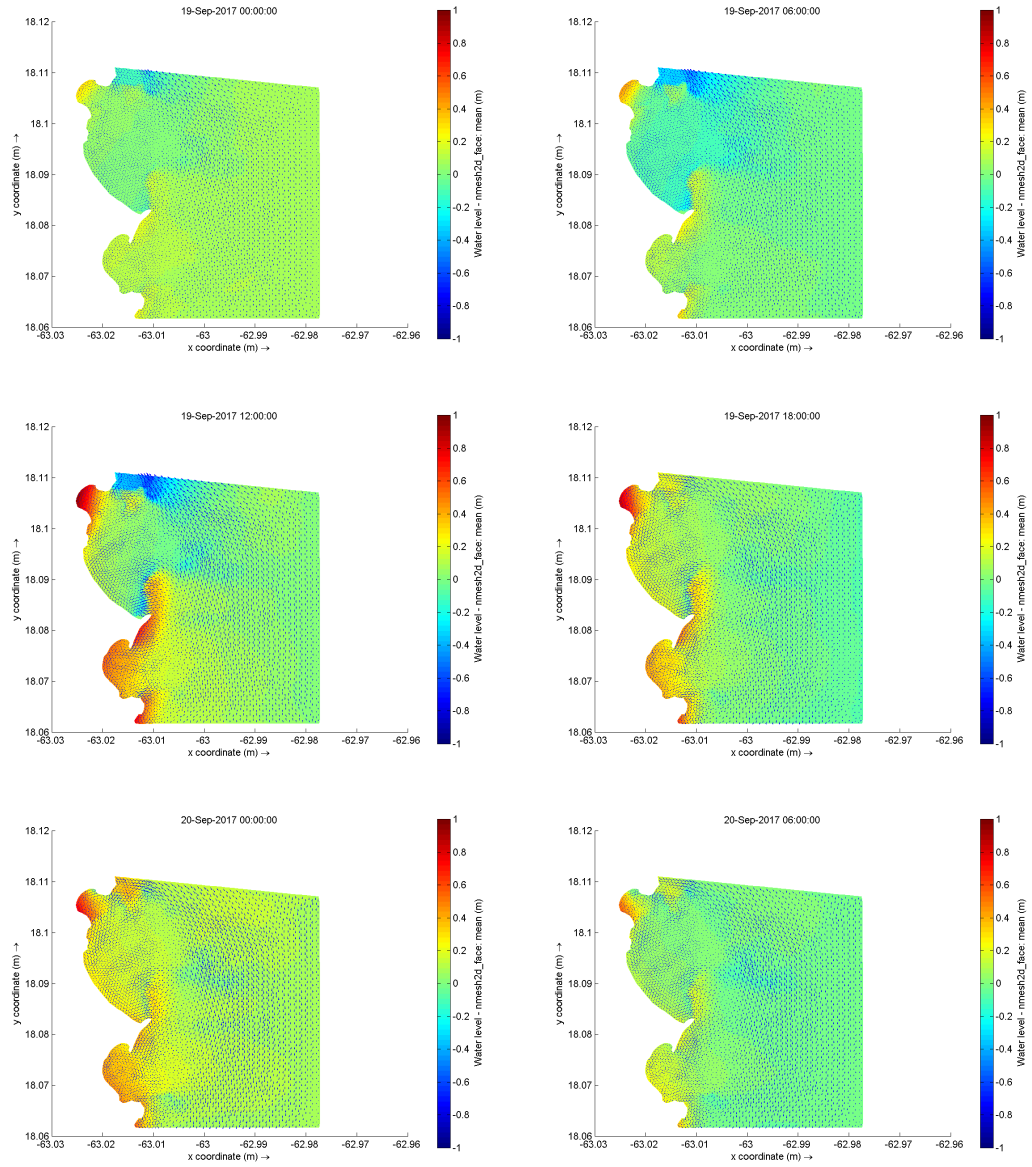
Figure A.12: Water level (color scale, in m) and velocities (vectors), during Maria from 2D model with wind, inflow and salinity

A.2. Results from multi layer models

Similar to the single layer models, three different multi layer models are created. Again first only the wind is involved, whereafter inflow and salinity are added.

A.2.1. Wind

The multi layer model with wind has given the same water levels in both bays as in the single layer model. The velocities in both bays during hurricane Irma are given in figure A.13 and A.14. From the first time step in both bays can be obtained that the main flow in the upper layer (layer 10) is directed onshore, while in the deeper layers more circulations are found. These circulations are similar to flow patterns found in the single layer models. The mainly onshore directed flow in the upper layer can be explained by the wind direction and the circulation normally expected with wind setup.

Due to the changing wind direction of Irma, the flow in the basins is in the upper layer directed northwards, while in the bottom layer it's directed the other way around, also this is due to the process of wind-setup. The maximum flow velocity in the timeframe of September, 6th 00:00 is around $1.5\ [m/s]$ which is more compared to the $0.8\ [m/s]$ from the 2D model. The frame of six o'clock is a little bit strange, but can be explained by numerical errors. The water level in the basins is so low, that it's difficult to calculate the correct flow speeds (actually there is no water to flow). Next the water flows back in with speeds up to $2.0\ [m/s]$ in the upper layer. The flow in the upper layer is directed to the south due to current wind direction. In Baie Orientale a strong flow is obtained near the coast, which may be explained by the topology. The circulations found in the deeper layers are different when they're compared to before Irma.
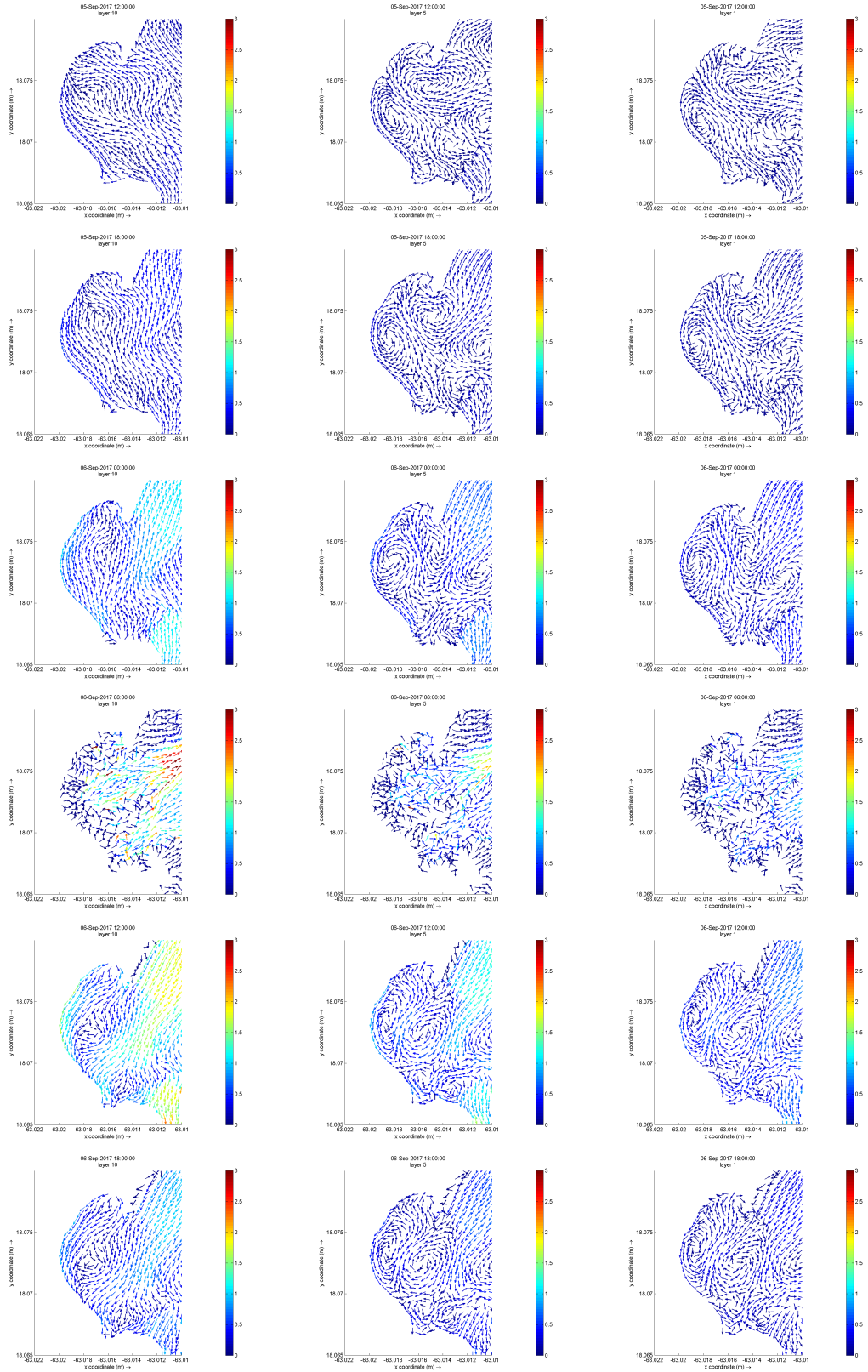
Figure A.13: Velocities (magnitude color scale in m/s and direction of vector) in Baie de L'Embouchure during Irma from 3D model with wind
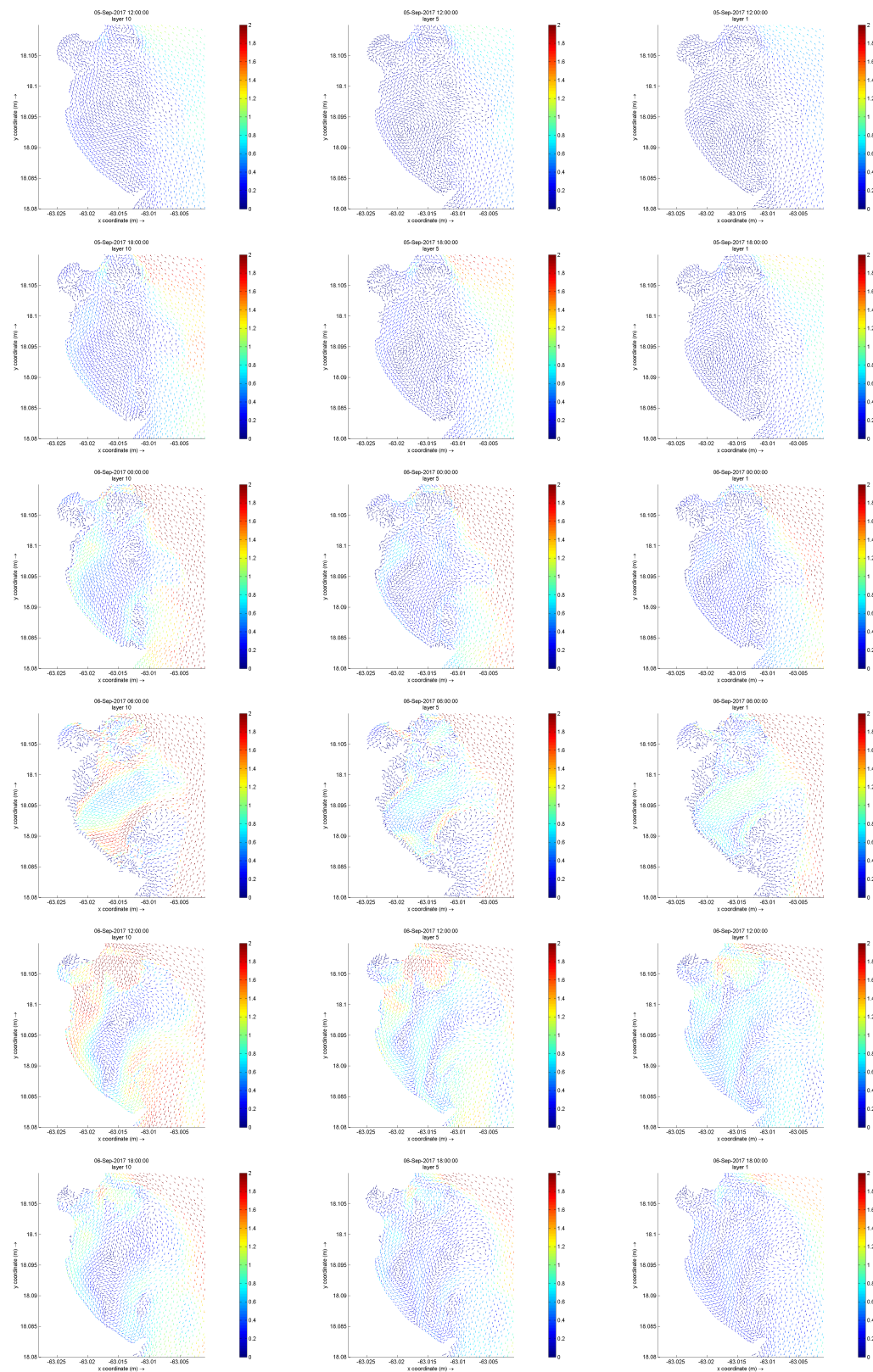
Figure A.14: Velocities (magnitude color scale in m/s and direction of vector) in Baie Orientale during Irma from 3D model with wind

In figure A.15 and A.16 the velocity in different cross sections are shown. This velocity is the orthogonal velocity compared to the slice of the bay taken. In Baie de L'Embouchure the higher velocities going into the bay are found in the deeper parts of the entrance. This inflow is strengthened during the hurricane as can be seen at September, 6th 00:00. Also the wind setup could be distinguished from the water level in the bay. While under normal conditions the flow velocities are relatively low, the flow velocities at this moment are higher. The wind setup has induced a flow directing north at the water surface, mainly in the shallower parts in the bay. In the deeper parts a strong return flow is found. During the hurricane it's clear that the bay has dry points and the water depth has decreased significantly. After the hurricane the wind direction has changed and the wind setup is just the other way around, also the inflow into the bay has now turned to be an outflow. The water setup has also induced the opposite flow pattern in the second slice. In Baie Orientale the inlow at the entrance of the bay is approximately zero. During Irma their is high inflow velocity up to 3 $[m/s]$. The first slice shows some small velocities in the bay, while the second slice has much higher northward directed velocities at the surface and a large return flow in the deeper part of the bay. At the final time frame shown the exchange flow between the bay and sea is relatively small again, but in the other direction a flow circulation due to wind setup is observed.

A.2.2. Wind and inflow

Between the model with wind only, the same difference are obtained as when moving from wind to wind and inflow in 2D. From the flow velocities could be extracted that the extra boundary conditions are having an effect on the flow and are working. Based on the little relevance this model is not discussed.

A.2.3. Wind, inflow and salinity

The main results of the multi-layer model with salinity properties is discussed in the main part of the report, in this section only the differences between the previous model and this model are discussed.

In figure 4.9 and 4.11 the flow velocities during Irma are given. These results are pretty similar compared to the results from the multi layer model with only wind forcing. In Baie de L'Embouchure the maximum velocity difference is 0.03 $[m/s]$, while in Baie Orientale this is a lot larger. This difference is given in figure A.17, wherefrom could be obtained that the flow directly from the coast is increased, which is due to the inflow with density difference. This can also be obtained from figure 4.12 where the near coast velocity is increased with approximately 0.5 $[m/s]$.
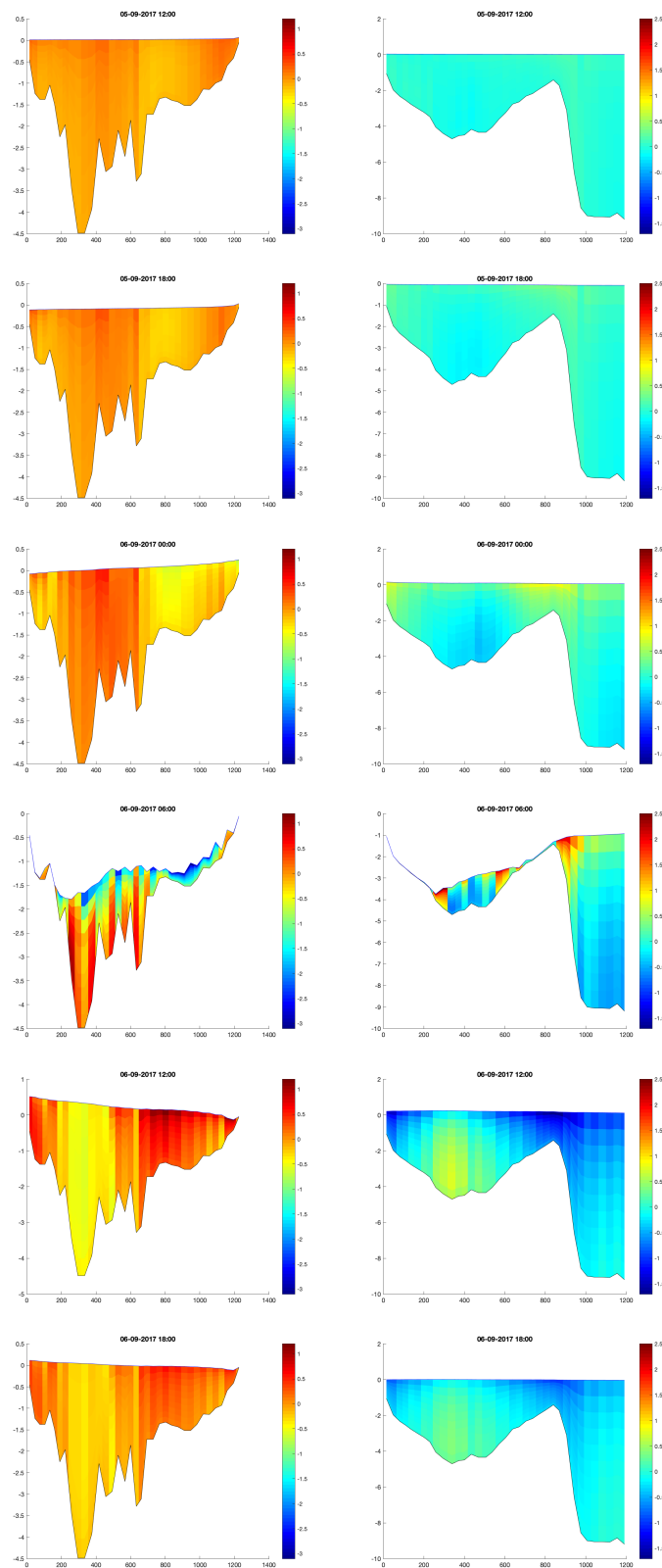
Figure A.15: Orthogonal velocities (color scale in m/s, positive inwards directed) in cross sections (1 and 2) of Baie de L'Embouchure during Irma from 3D model with wind
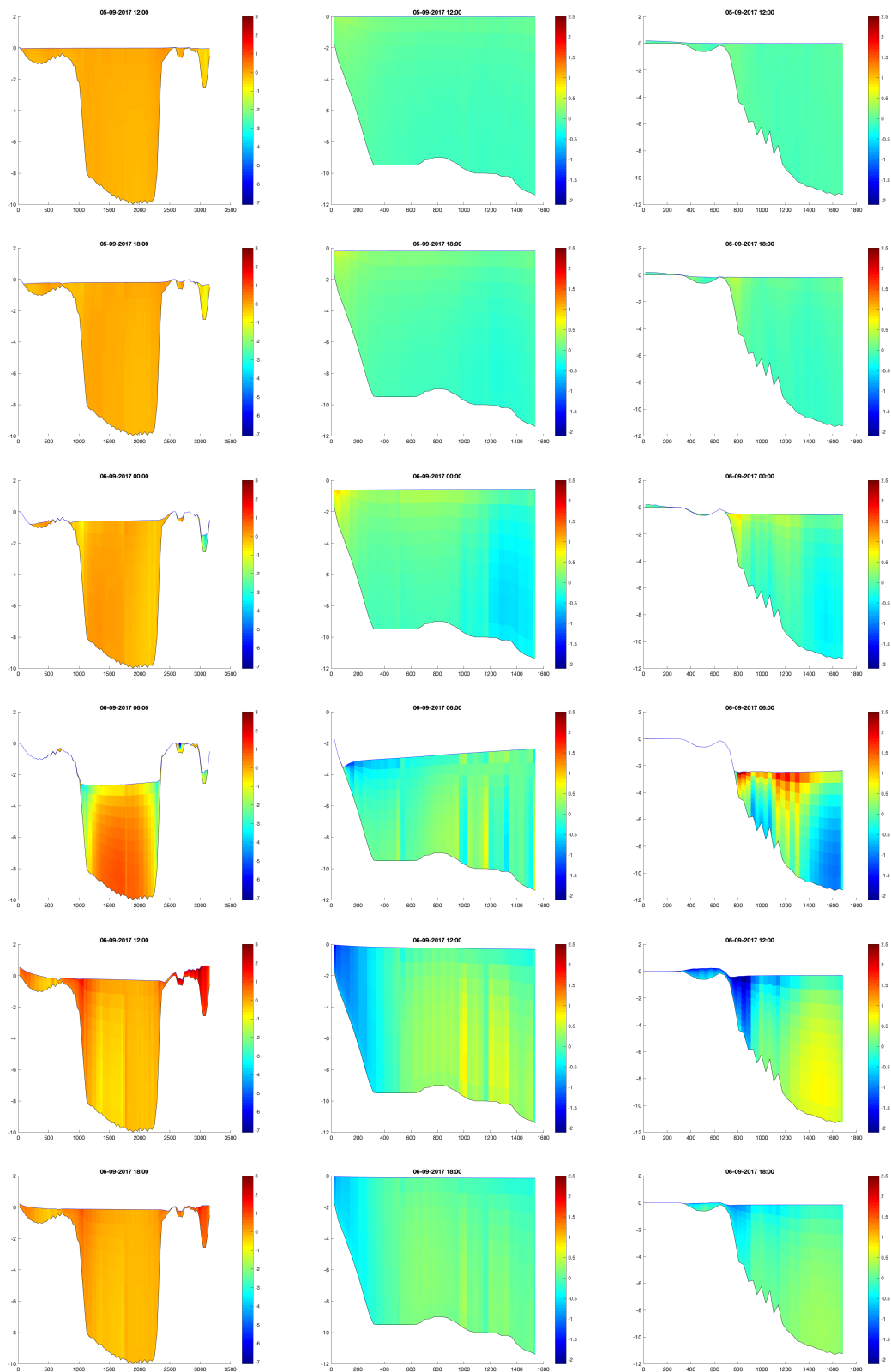
Figure A.16: Orthogonal velocities (color scale in m/s, positive inwards directed) in cross sections (1, 2 and 3) of Baie Orientale during Irma from 3D model with wind
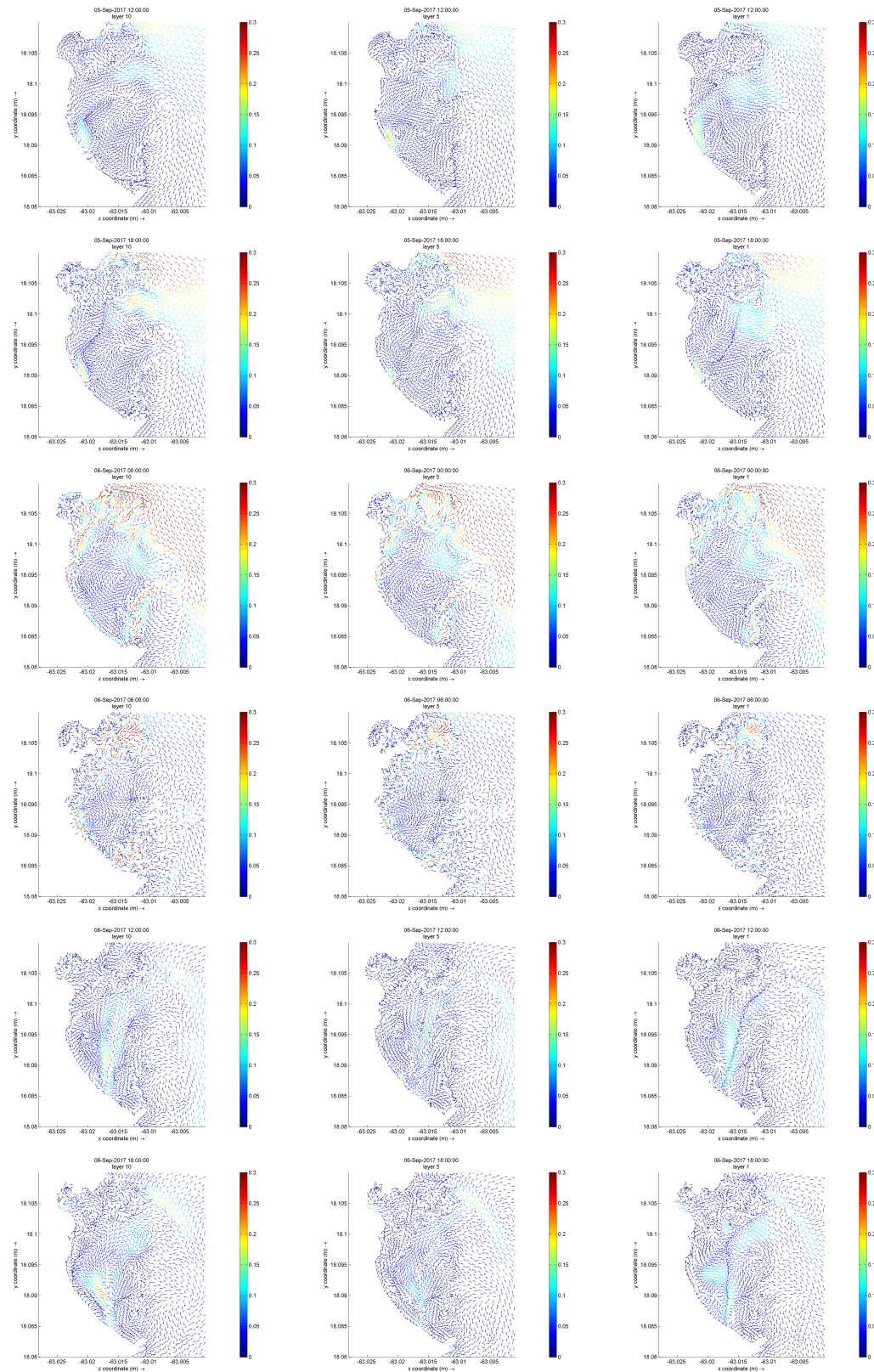
Figure A.17: Velocity difference (magnitude color scale in m/s and direction of vector) in Baie Orientale during Irma from 3D model with wind, inflow and salinity compared with 3D model with wind