

A NUMERICAL STUDY OF THE SALINITY STRUCTURE OF A SHALLOW
BAY - CASE OF COPANO BAY, TX

A Thesis

by

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ABSTRACT

The Gulf of Mexico has 39 estuaries, in which most of them are characterized as bar-built, shallow bay estuaries. Located at the northwest Gulf of Mexico, the Mission Aransas Estuarine Research Reserve is an area with 750 km² with 6 bays. The second largest bay is named Copano Bay, an area with 200 km² that has two main river sources, from Mission River and Aransas River, which are the only source of fresh water to the system. The bay is opened at one tidal channel at the south that exchanges salty water with Aransas Bay. As part of the monitoring system for Copano Bay, we used the two stations located at the east and west sides of the bay to understand the temporal variability of salinity in the bay. Because the salinity pattern is not as well defined as the temperature profile, we used a 3D hydrodynamic model (ROMS) to analyze how changes in river discharge, precipitation and winds will affect the bay. After running the simulations for 5 years, from January/2010 to December/2014, we found that the salinity of the bay is controlled by flooding events on the upper bay and by tides on the channel side. During 'wet years' (2010 and 2015), the salinity is kept in a range between 10 gkg⁻¹ and 25 gkg⁻¹. For 'dry years', where the discharge is low, the salinity was kept in a range of 30 gkg⁻¹ to 45 gkg⁻¹, considered hypersaline conditions. The year of 2011, considered a 'transition year', had the lowest river discharge and precipitation, causing the salinity to increase at a constant rate. By comparing the east and west sides, we saw that the east side is barely influenced by river discharge, responding mostly to the tides, while the west side is mostly influenced by the river discharge. The flooding events are responsible for an increase in vertical and horizontal stratification. A closer look at local events showed the water column took longer to stabilize, after a change in wind due to a storm or front, under hypersaline conditions than under normal years.

DEDICATION

I dedicate this work to my parents Eduardo and Carmen, and to my sister Sofia. I wouldn't be who I am today without you, I wouldn't be here today without you and I wouldn't have accomplished anything without you. This thesis is for you, not for me.

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1. INTRODUCTION

Sturges and Lugo-Fernandez (2005) describe the Gulf of Mexico as "a jewel among the natural resources of the western hemisphere". The authors show how important the Gulf is in supporting fisheries, to the oil and gas industry, and how all kinds of ecosystems, including estuaries, wetlands, beaches, are combined together as a source of recreational, research and economical activities.

The circulation in the Gulf has many elements that make this region a very unique region to the study of physical oceanography. It starts in the deep water circulation with the Loop Current, the dominant current in the Gulf. According to Oey et al. (2005), the formation of Loop Current is at the Yucatan Channel, a region on the western side of the channel by the south of the Gulf. Being a western boundary current, the Loop Current can reach velocities of 1.5 to 1.8 ms^{-1} , as strong and important as the Gulf Stream.

One of the main characteristics of the current is the detachment of anticyclonic eddies from the main flow that drift to the west of the Gulf (Sturges et al., 2005). These eddies have approximately 300 km in diameter and can reach depths as deep as 1000 m. As they go further into the Gulf, there is a constant exchange between deep water and continental shelf waters. This process is responsible for the input of nutrients and fresh water in both directions and depends on the position of the Loop Current, the topography and on atmospheric forcing (Sturges et al., 2005).

Over the continental shelf, the flow responds to a series of processes, such as the seasonality of river discharge, winds, hurricanes and precipitation. According to Danchuk and Willson (2011), the discharge from the Mississippi river, the main contributor of fresh water to the Gulf, has its highest values during spring and lowest during fall. The smaller rivers and estuaries depend on precipitation and the volume of water of their contributors, which may vary depending on the

precipitation in regions that are sometimes far from the Gulf. There is also a variability in the wind pattern. Bianchi et al. (1999) says that during fall and winter, the wind flows from east and northeast towards southwest, and during spring and summer they flow from southwest towards northeast. Starting on June 1st until November 30th, the hurricane season is an important feature in the Gulf. Since the sea surface temperature increases during summer, the complex dynamics of the Gulf contributes to the generation and propagation of hurricanes that come from the Caribbean Sea. These events are often related to changes in the dynamics of the open sea and can cause many losses by reaching coastal areas.

Figure 1.1 shows a schematic representation of the circulation of Gulf of Mexico by showing the Loop Current, the warm-core eddy associated, the Yucatan Channel and the Gulf Stream along the east coast of the United States.

All these features combined together lead to a complex environment in which coastal and deep waters interact together creating a more susceptible environment to natural disasters such as hurricanes or algae blooms or man-made disasters such as oil spills. Understanding the dynamics of the Gulf of Mexico circulation from the Loop Current to the small bays is of major importance in preventing and remedying any harmful situation to the economy or to the health of the Gulf. As mentioned before, the Gulf has a well marked seasonality of river discharge, winds and even hurricanes. By knowing how these variables work together from a big (the entire Gulf) to a small (a small bay) scale can lead to answers when dealing with climate changes and oceanographic processes that are common in the Gulf.

The next sections will discuss the importance of the estuaries and bays in the Gulf, focusing on Copano Bay, a small and shallow bay located northwest of the Gulf.

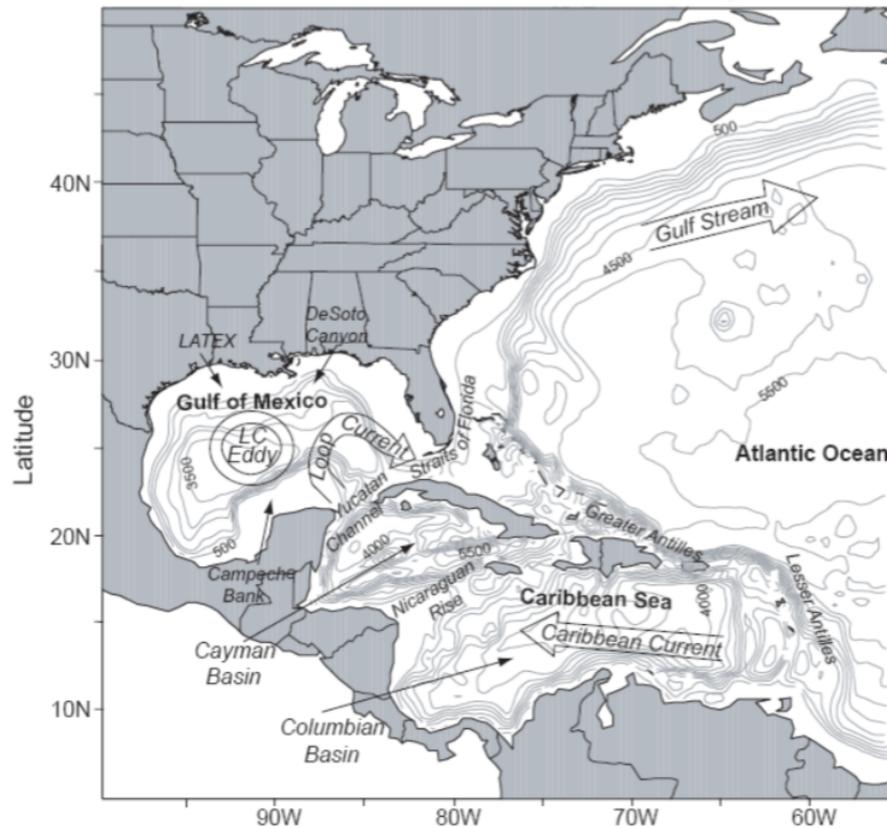


Figure 1.1: Schematic circulation of the Gulf of Mexico. (Oey et al., 2005)

1.1 The Estuaries of the Gulf of Mexico

Following the classification system proposed by Fairbridge (1980), which considers the physiography of each estuary, Bianchi et al. (1999) states that the Gulf of Mexico has four kinds of estuaries: bar-built, coastal plain, bar-built + coastal plain and sometimes deltas. The differences of each type result in different regimes of interaction between fresh and salty water. Thus, the authors also identified all types of estuaries according to the classification proposed by Pritchard (1955): salt wedges, partially mixed, vertically homogeneous and sectionally homogeneous.

Each one of the 39 estuaries in the Gulf are influenced by fresh water and sediment supply, winds, storms, hurricanes, rains, tides, interaction with coastal cur-

rents and some other processes in a short-term scale. Considering a long-term scale, they rely on changes in sea-level and climate changes. Even though tides in the Gulf do not have a big range (predominantly diurnal, microtidal environment), the tidal currents are still considered important for the circulation in many of the tidal inlets along the Gulf. It is important to understand that each estuary has its own geomorphology and characteristics, so each responds differently to local forcing conditions.

Among all the different types, the most common type of estuary in the Gulf is the broad, shallow, bar-built estuaries. Examples may be Aransas Bay, Galveston Bay and most estuaries northwest of the Gulf. According to Rayson et al. (2015), just like many estuaries in the Gulf, Galveston Bay has a small tide range (around 0.5 m) and a significant seasonality in the river discharge. At the same time, the authors also found that the mouth of the estuary can also depend on the variability imposed at the the mouth of the bay, where salty or less salty waters may enter the estuary depending on the conditions.

In a attempt to estimate the time scales in Galveston Bay, Rayson et al. (2016) used a three-dimensional hydrodynamic model under high discharge and low discharge conditions. The authors found longer residence time in the upper estuary and shorter residence time closer to the mouth of the estuary, a more dynamical region affected by tides and water level fluctuations caused by wind stress and barometric effects. The low residence times around the upper estuary responded to the increase in river discharge and high-flow conditions. The results showed that the residence time in the bay responded differently depending on the region of the bay. Due to the long distance between the Trinity River and the estuary mouth (around 60 km), the two regions responded separately, i.e. when the residence time was long close to the river (because of the low discharge) it was still short close to the Gulf.

Compared to Galveston Bay, the Aransas Bay estuarine complex has a simi-

lar dynamic. The main source of fresh water to the system is through Mission and Aransas Rivers, while the only source of salty water is through a tidal inlet in contact with the Gulf of Mexico. The distance between these two points is approximately 45 km and in between the two lies Copano Bay, a shallow and broad bay with one opened channel that exchanges water with Aransas Bay and with 2 main sources of river discharge.

The next sections will describe the characteristics of Aransas Bay estuarine system and Copano Bay.

1.1.1 Mission - Aransas Estuarine System

The Mission-Aransas National Estuarine Research Reserve (MANERR) is the Western Gulf Biogeographic part of the National Estuarine Research Reserve System (NERRS). The system is a network established in 1972 as part of the Coastal Zone Management Act, in which 28 coastal reserves, distributed in 21 states (Figure 1.2), are monitored in partnership with the National Ocean and Atmosphere Administration (NOAA). More information on the reserve can be found at - <http://missionaransas.org/>.

In addition to protect and study estuaries all over the country, the NERRS also focus on the study of climate changes, water quality, and habitat protection. To reach these goals, each station is managed locally by a university or local agency, considering that each estuarine reserve has different needs. The following are attributed to the NERRS according to federal regulations, 15 CFR Part 921.1(b) (Evans et al., 2015):

- Ensure a stable environment for research through long-term protection of NERR resources;
- Address coastal management issues identified as significant through coordinated estuarine research within the NERRS;



Figure 1.2: Map of the National Estuarine Research Reserve System. (Evans et al., 2015)

- Enhance public awareness and understanding of estuarine areas and provide suitable opportunities for public education and interpretation;
- Promote Federal, state, public and private use of one or more Reserves within the NERRS when such entities conduct estuarine research; and
- Conduct and coordinate estuarine research within the NERRS, gathering and making available information necessary for improved understanding and management of estuarine areas.

An important part of the monitoring system is the acquisition and distribution of oceanographic (water quality) and meteorological data for each station.

This type of data ensures a better monitoring of the estuarine conditions and help understand circulation patterns, the salinity gradient, how the nutrients are distributed throughout the bays and how atmospheric events, such as storms or even hurricanes, can affect the circulation.

This monitoring program in the Mission-Aransas NERR is made by five System-Wide Monitoring Program (SWMP) stations localized along the estuary, being two at Copano Bay (West and East), one at Aransas Bay, one at Mesquite Bay and one at the Ship Channel, an opening that connects Aransas Bay to the Gulf of Mexico.

Being one of the largest reserves (3rd in the country), the Mission-Aransas reserve is a complex estuarine system with approximately 750 km² of a range of diverse habitats such as woodlands and seagrass meadows (Evans et al., 2015). It is considered by Diener (1975) a typical Gulf of Mexico Estuary, where the bays are usually very shallow, ranging from 0.6 m to 3.0 m and are separated from the ocean by an offshore sand bar.

The system has a number of bays including Mission Bay as a tertiary bay, the farthest one from the Gulf, Copano, Port and St. Charles Bays as secondary bays and Mesquite, Aransas and Redfish Bays as primary bays, i.e., they are in contact with the Gulf of Mexico water, being responsible for the salinity exchange in the system (Evans et al., 2015; Pollack et al., 2011). This definition depends on the size, characteristics, and geologic origin of each bay. Figure 1.3 shows how the bays are distributed in the area, as well as the two water quality monitoring points maintained by the SWMP Mission-Aransas system.

Because of its dynamics, this estuarine system has a very low mixing efficiency ($e < 0.03$), a parameter that shows the fraction of the tidal prism that is available for mixing with the estuarine water. Also, according to Solis and Powell (1999), the residence time of the bay is approximately one year. The salinity in the system may vary due to changes in river discharge, precipitation and evaporation.

The system can also be affected by long-term oscillations. In a study to re-



Figure 1.3: Mission-Aransas National Estuarine Research Reserve.

late fresh water inflow and the effects on the oyster community, Pollack et al. (2011) also found correlations of El Niño Southern Oscillation (ENSO) and river discharge in the bay. According to the authors, between 2007 and 2008, there were periods of weak El Niño, followed by average conditions and then moderate La Niña, that lasted until mid-year in 2008.

This variability caused higher river discharge and lower salinities during the first months of 2007 (El Niño), followed by low precipitation and low river discharge in the following year, causing high salinity. The final conclusions from

citetpollack2011role were that the low salinities in 2007 lead to the decrease of oyster population, followed by a slow increase in the next year, where higher salinities helped the oysters against predators and their ecology supported the population recovery. The importance and a quantitative analysis of river discharge to the bays will be discussed in section 3.2.4.

Being the second largest bay in the Mission-Aransas estuarine system, Copano Bay is an important part of the system because it connects the fresh water discharge from Mission and Aransas rivers to the rest of the bays, being dependent on river discharge, tides, winds and other atmospheric conditions. The study of the circulation, salinity pattern and effects of river discharge on Copano Bay will be the focus of this current work.

1.1.2 Copano Bay

As mentioned before in section 1.1.1, Copano Bay is a secondary bay at the Mission-Aransas National Estuarine Research Reserve with a southwest-northeast orientation. Like estuaries in the mostwestern part of Gulf of Mexico, it is a shallow and broad estuary with an average depth of 2 m, average tidal range of 0.2 m and surface area of approximately 200 km² (Nañez-James et al., 2009). The bottom of the bay is mostly non vegetated, composed by sand and small portions of clay and silt (Britton and Morton, 2014).

According to a water quality report issued by Mott and Lehman (2005), Copano Bay is considered a molluscan shellfish growing area due to the presence of the Eastern Oyster (*Crassostrea virginica*). The area is used recreationally and commercially as a fishing area and for oyster farming. The surrounding areas of the bay are mostly higher grasslands, rural areas, developing areas and, no industries. The bay exchanges seawater with Aransas Bay through a 2.7 km channel located at the south side of the bay with approximately 3 m deep and has two main river sources, Mission River from the north and Aransas River from the west side. The location where the two rivers enter the bay can be seen in Figure 1.3.

Another contribution of the shallowness of the bay is that the circulation is highly dependent on the wind. Changes in the wind patterns are responsible for moving the water in or out of the bay. In case of northwesterly winds, tides are reduced at the bay, and most of the water is forced towards Aransas Bay. However, in case of southeasterly winds, water is pushed into Copano bay enhancing tidal activity. Mott and Lehman (2005) show a simple chart (Figure 1.4) with the proposed circulation pattern for Copano Bay based on a southeasterly wind regime, i.e. the most prevailing winds along Texas coast.

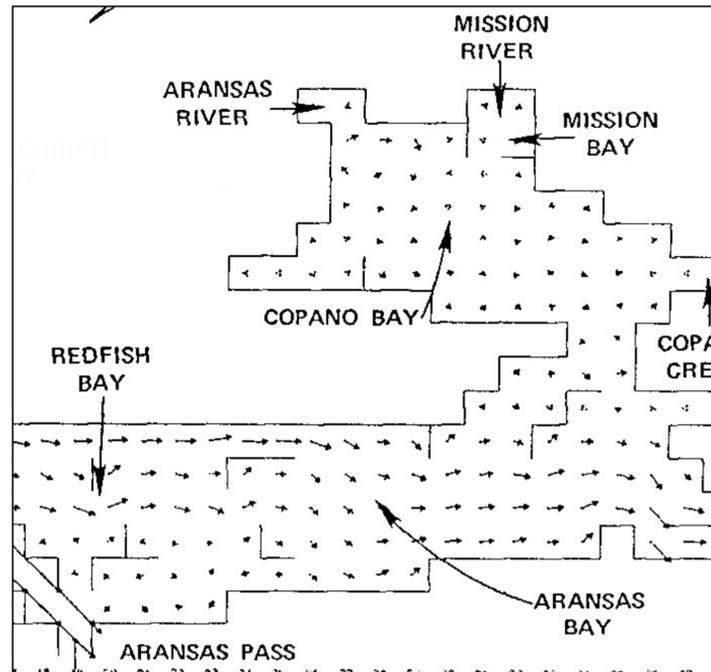


Figure 1.4: Water circulation in Copano Bay (Mott and Lehman, 2005).

Even though Copano Bay is a small bay, due to all external forcing such as winds, tides and river inflow, the salinity pattern in the bay can and will change depending on the meteorological conditions in a seasonal, monthly and even daily scales. The salinity patterns at Copano Bay will be discussed in the next section.

1.1.2.1 Salinity at Copano Bay

Figure 1.5 shows a 15 minute resolution time-series of salinity and temperature from Jan/2010 to Dec/2015. The data were obtained from stations Copano West and Copano East. The temperature profile, for all 5 years, shows a consistent pattern, with low temperatures (around 5 °C) during winter months, and high temperatures (around 30 °C) during summer. This pattern is repeated every year.

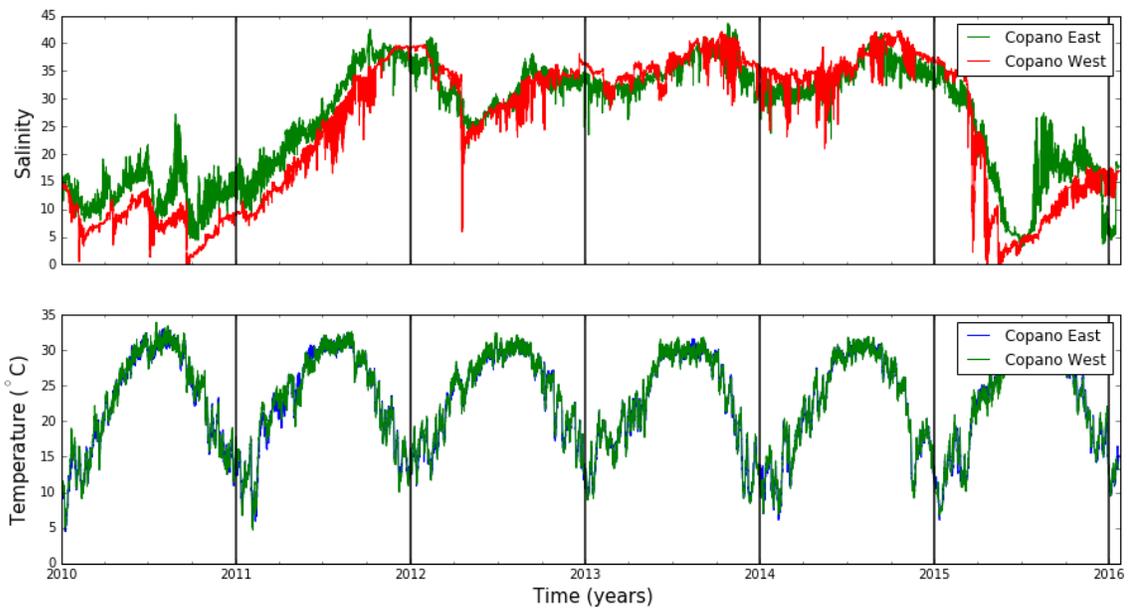


Figure 1.5: Surface salinity and temperature from stations Copano East and Copano West located at Copano Bay.

For salinity, however, there is not a defined pattern. The figure shows that between 2010 and 2011 salinity ranged from 5 gkg^{-1} to 15 gkg^{-1} , increased in 2011 and had its highest values between 2012 and 2015, ranging from 20 gkg^{-1} to hypersaline conditions, such as 45 gkg^{-1} . The year of 2015 had a similar pattern as 2010, with a range between 5 gkg^{-1} and 20 gkg^{-1} .

In a work about the salinity gradient in the MANERR reserve, Bittler (2011) observed a strong salinity gradient between the west side and the south channel of the bay in normal year conditions, such as 2008. The authors found lowest salinity (around 20) close to the river source and highest (around 30 gkg^{-1}) at the ship channel. This difference causes a zone of mixing between the fresh water coming from Aransas river and the salty water coming from Aransas Bay.

However, for a dry year such as 2009, the authors observed high values at all sites, even close to the river source. In these conditions, salinities were higher than 37 gkg^{-1} for the entire domain, with slightly higher values close to the river source, indicating a strong evaporation and low fresh water inflow. In case of a wet year, such as 2010, salinity is kept in a range of 10 gkg^{-1} to 20 gkg^{-1} along the bay, with the lowest values close to the river sources.

Figure 1.6 shows the three distinct patterns for salinity distribution in Copano Bay.

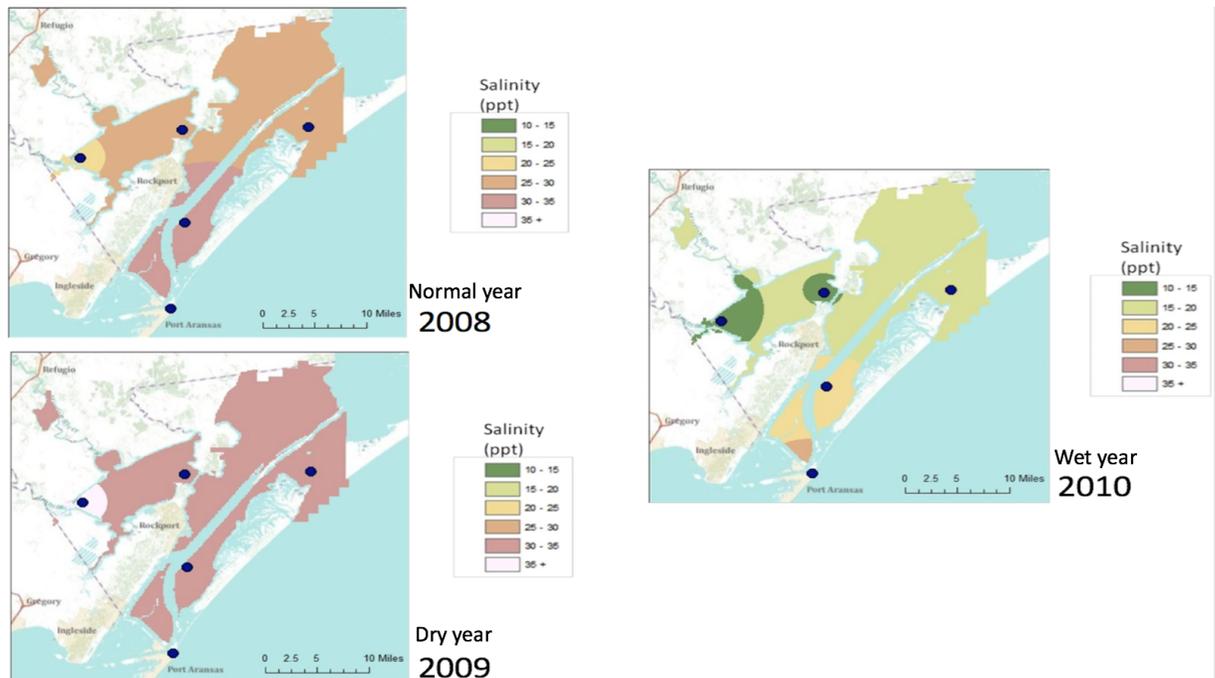


Figure 1.6: Salinity distribution for a normal year (2008), a dry year (2009) and a wet year (2010) according to Bittler (2011) .

Together with yearly fluctuations, Bittler (2011) also found daily fluctuations related to tidal fluctuations. As expected, the daily fluctuations were more evident close to the ship channel and decayed further into the bay. The response of the bay to a rapid decrease in salinity also showed differences between the two regions.

Figure 1.7 shows a sharp decrease in salinity in the Copano West station in a matter of hours (see November 23rd, 2009). At the same time, the station at Copano East also had a drop on salinity, but over a longer period. This decrease in salinity, due to a storm event or a jet of fresh water into the system, shows that horizontal stratification of freshwater may weaken the response of the bay depending on how far a point is from the river source. This rapid response of salinity profiles to storm and/or increased fresh water events was also discussed by Mooney and McClelland (2012). The other time series represent Mesquite Bay,

the Shipping Channel and Aransas Bay. All locations can be seen in Figure 1.3.

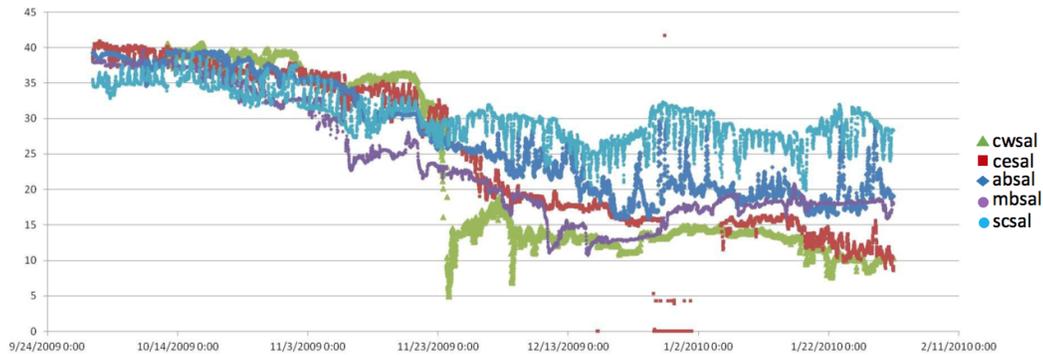


Figure 1.7: Salinity time-series in 5 different points in the Mission-Aransas estuarine system. The legends 'cwsal' and 'cesal' are for Copano West and Copano East points, respectively. The other points are 'mbsal' (Mesquite Bay), 'absal' (Aransas Bay) and 'scsal' (Shipping Channel). Source: Bittler (2011) .

Because one of the objectives of the current work is to use numerical modeling techniques to simulate the patterns at Copano Bay and compare with the real data, the next section will show a brief background on the current efforts of simulating hydrodynamics of the bay.

1.1.3 Ocean Modeling and Copano Bay

Reports dating back from 2010 (Gray (1987), Bittler (2011)) describe the state of the art of ocean models used at the Mission-Aransas estuarine system. Guthrie (2010) uses a variant of the BLEND model developed by Gray (1987), named TxBLEND, a 2-D model that uses the finite-element method and an unstructured grid to simulate velocities in both directions, salinity and sea level. To the new version, the Texas Water Development Board (TWDB) added tides, river inflow information from Texas, evaporation and salinity information for all seven major estuaries in Texas.

Other considerations mentioned by Guthrie (2010) are that the vertical stratification should be negligible due to shallowness of the bays, the fluid depth is small relative to the horizontal scale and density variations are also neglected. Due to the high resolution of the model output, TWDB has applied the model to a variety of projects, such as oil spill, environmental impact evaluations, salinity gradient in estuaries, ecological studies, among others. More information can be found at <http://www.twdb.texas.gov/surfacewater/bays/models/>.

With more advanced techniques and ocean models, there is currently an attempt to implement three-dimensional models for all major estuaries. The work of Zhang (2010) shows the implementation of the 3-D SELFE model to Corpus Christi Bay as a test for the TWDB. Like the TxBLEND model, SELFE also uses unstructured grid.

The problem with unstructured grid models is that they do not represent well vertical salinity gradients due to the loss of resolution at regions with low bathymetric gradient, such as Copano Bay, leading to a coarse resolution in places that are shallow and relatively flat. Because of the low capacity in simulating the effects of subtle changes in bathymetry or how the domain responds to winds and/or tides, the model will not be able to resolve vertical gradients of salinity and density, which are very important in regions under influence of river inflow, rain and evaporation, regardless the shallowness of the region. The next sections will show the implementation of a 3-D structured grid model to Copano Bay and the effectiveness of this model in resolving shallow and broad estuaries.

2. OBJECTIVES

In order to better understand circulation at Copano Bay and how the bay responds to different external forcing, my objectives are:

- Analyze the response of Copano Bay to changes in river discharge. As seen before in section 1.1.2, Copano Bay has two different sources of fresh water, but with no defined seasonal pattern, as we will show in Section 3.2.4. The way the bay responds to the fresh water input may change over the years after a higher or lower flooding event.;
- Characterize salinity behavior over the 6 years of simulation and compare the results to real data. As seen in Figures 1.6 and Figure 1.5, the salinity at Copano Bay responds differently to 'wet' and 'dry' years. Using the model output and real data, the long-term salinity pattern will be discussed, as well as short term changes that happen in a matter of hours, days and weeks due to specific events, such storms and fronts. .
- Compare the difference in salinity between the west and east side of the bay and between the surface and the bottom. The bay is constantly changing the dynamics because of strong winds, evaporation, precipitation, river discharge, and many other external conditions that can cause changes in water density. Specially for a shallow domain, we expect to find horizontal and vertical stratification since one side of the bay is close to a river source point and the other side is close to the opened boundary that exchanges water with Aransas Bay. ;

3. METHODOLOGY

In physical oceanography, data acquisition and field work are valuable resources to have a better understanding on the dynamics of a particular region. However, due to the high cost of oceanographic expeditions and due to the need of a long time-series of high resolution oceanographic data, a different approach is needed to represent the complexity of coastal and oceanic processes.

In this context, the use of numerical modeling allows the study of oceanography with a higher temporal and spatial resolution and the study of specific processes and regions. Also, with the advance of computer power, ocean modeling has become cheaper with time when compared to expeditions. Adding together a prior knowledge of the region, observation data and modeling, one can have a good overview of the processes in a region of interest. In this work, numerical modeling was chosen as a tool to analyze the processes related to Copano Bay described in sections 1 and 2.

3.1 The Regional Ocean Modeling System (ROMS)

The Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005) was used for the simulations. ROMS is a widely used model developed at Rutgers University together with other universities and oceanographic institutes. ROMS has been used for tidally driven estuaries, high-latitude processes, river plume dynamics and mesoscale activity Haidvogel et al. (2008).

ROMS is a free-surface, primitive equation model with terrain-following coordinate levels in the vertical (known as σ - coordinates) (Song and Haidvogel, 1994). This kind of coordinate is subject to an error due to the difference in the horizontal pressure gradient between two cells, which depends on the steepness of the bathymetry. However, by dividing the vertical component in a previously defined number of layers, we can have an increase in the resolution closer to the

surface or the bottom, depending on the experiment.

In the horizontal dimension, ROMS uses curvilinear coordinates that allows both spherical and Cartesian coordinates, on a Arakawa-C grid (Arakawa and Lamb, 1977). In this scheme, the velocities (u and v) are calculated in the center of the four faces, as seen in Figure 3.1.

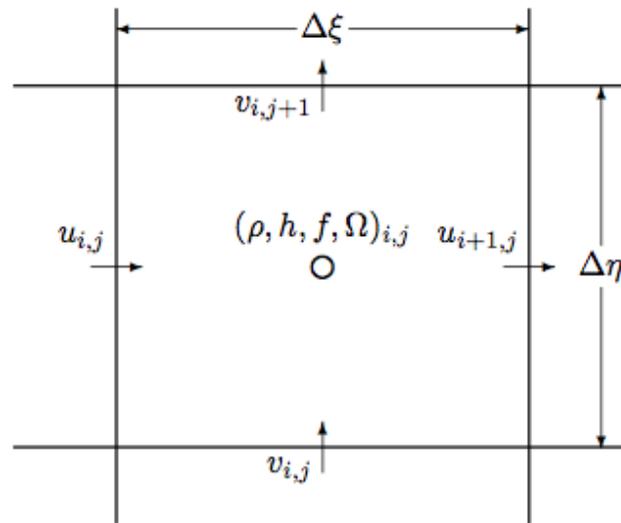


Figure 3.1: Cell of an Arakawa-C grid showing the points where the variables are calculated. Haidvogel et al. (2008)

According to Shchepetkin and McWilliams (2005), the time integration in ROMS comes from a decomposition of the variables in baroclinic and barotropic time-steps. The evolution of tracers (temperature and salinity) and the 3-D velocities u and v is calculated in the baroclinic time-step, also known as the internal model. The 2-D vertically integrated velocities $ubar$ and $vbar$ are calculated during the barotropic time-step, together with free-surface. This mode is also known as external mode. For every number of baroclinic time-steps there is a limited number

of barotropic time-steps and the average of the external mode is used to compute the values in the internal mode.

Haidvogel et al. (2008) and Warner et al. (2010) shows some other components of the model such as biogeochemical model, sea-ice coupling and sediment transportation and coupling with wave and atmospheric models.

3.2 Model Description and Configuration

In contrast to large scale oceanic models, coastal areas such as rivers and estuaries are constantly under influence of tides, river mixing, local winds, river plume and sediment transport. Depending on the geometry of the coastline, the size of the estuary, the seasonality of river discharge and changes in wind direction and speed, coastal regions have a shorter time-scale to adjust to these changes when compared to the open ocean.

In comparison to narrow estuaries, where a deep channel allows the exchange of fresh and salty water between the coast and the upper estuary, broad and shallow estuaries like Copano Bay behave more like the shelf seas. In this case, due to its shallowness, the system is more susceptible to subtle changes in the bathymetry, river input and processes such as precipitation and evaporation. Since the bay is in a constant process of adjusting to external forces, a more incisive approach is needed to understand how these subtle changes work in Copano Bay.

3.2.1 Model Grid

The grid used for the simulations has a maximum/minimum of latitude at 28.23°N /27.98°N and a maximum/minimum of longitude at -96,95°W -97,25°W, as seen in Figure 3.2. In the horizontal dimension, the grid is distributed in 607 points in the x-direction (approx 24 km) and 247 points in the y-direction (approx 10 km), which gives a horizontal resolution of 35 m. The vertical resolution is 20 σ -layers.

The grid bathymetry derives from soundings that took place during 1935 to

1991. The bathymetry data acquisition was part of a special project from the Hydrographic Survey Division at the National Ocean Service (NOS) to compile data that could be used for nautical charts, showing the most important features of each estuary (NOAA, 1998).

For the Aransas Bay estuarine system, there were 123,235 soundings, with a horizontal resolution of 65 m. The depth range was 2.0 m to 16.1 m. A shoreline relative to the Mean Lowest Low Water (0.3 m) was used to compute and interpolate the depths. More information on the bathymetry can be found at http://estuarinebathymetry.noaa.gov/bathy_htmls/G300.html.

The data was originally in Digital Elevation Model (DEM) format and were extracted and interpolated to the grid. The data from Coapno Bay only had a minimum depth of 0.5 m, and a maximum of 3.38 m, with an average depth of 1.15 m. The grid bathymetry can be seen in Figure 3.2.

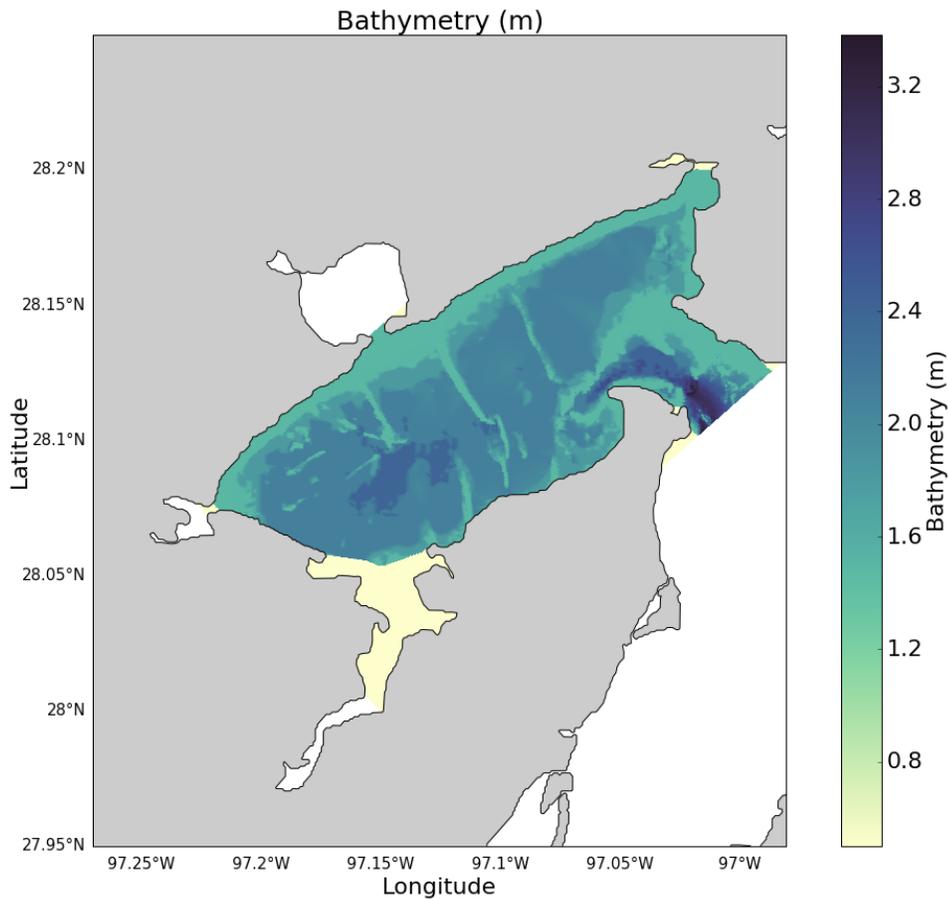


Figure 3.2: Grid bathymetry (m)

It is important to notice that Copano Bay has shallow bathymetry and has only one open boundary, which is the connection to Aransas Bay in the south channel. Because of that, some areas had to be cut off from the mask in order to better represent the dynamics of the bay by keeping only depths deeper than a minimum of 1.5 m. The removal of the masked regions did not affect the results and the particularities of the bay.

3.2.2 Atmospheric Forcing

The configuration used here for Copano Bay has a very high resolution model in such a small area. Due to its shallowness, the bay is more susceptible to even

small changes in the atmospheric forcing. Because the bay is so small, we assumed that the spatial resolution for the atmospheric conditions did not change over the domain. Therefore, we used one single point from the atmospheric model over the entire domain. The forcing evolved every-time step with a resolution of 3 hours.

The fluxes used to compute the atmospheric forcing were air temperature, precipitation rate, cloud coverage, air pressure, relative humidity, shortwave radiation and net surface freshwater flux were also added to the simulations.

All the data were obtained from the European Center for Medium-Range Weather Forecasts (ECMWF) global atmospheric reanalysis product known as ERA-Interim (Dee et al., 2011). The ERA-Interim dataset is the substitute of the previous reanalysis products ERA-15 and ERA-40 and the data are available from 1979 to present.

Part of the dataset for the ERA-interim product consists of a dataset previously used for ERA-40 product. Most of the data were obtained from both satellites and *in-situ* observations from ships, land stations, aircraft reports, buoys, pilot balloons and stations all over the world. More information on the input data can be found at Dee et al. (2011) and Uppala et al. (2005).

After the data are acquired, they are submitted to a quality control process to detect errors such as problems with the equipment, completeness of reports and error found when recording and/or transmitting the data. After this process, the meteorological data is assimilated using a 4-dimensional variation analysis (4D-Var) every 12 hours. The vertical resolution of the data is 60 vertical levels with 80 km of horizontal resolution. More information on the data and how to download can be found at: <http://apps.ecmwf.int>.

3.2.3 *Initial and Boundary Conditions*

Because we could not find any climatology data or any other model output to be used as an input data, the initial conditions of the model were based on the salinity and temperature gradients between Copano Bay East and West stations. The average temperature and salinity for January, 2010 was calculated and used to

represent the range of the gradient. Figures 3.3 and 3.4 show the initial conditions for the model, as well as the stations and the two main sources of river discharge.

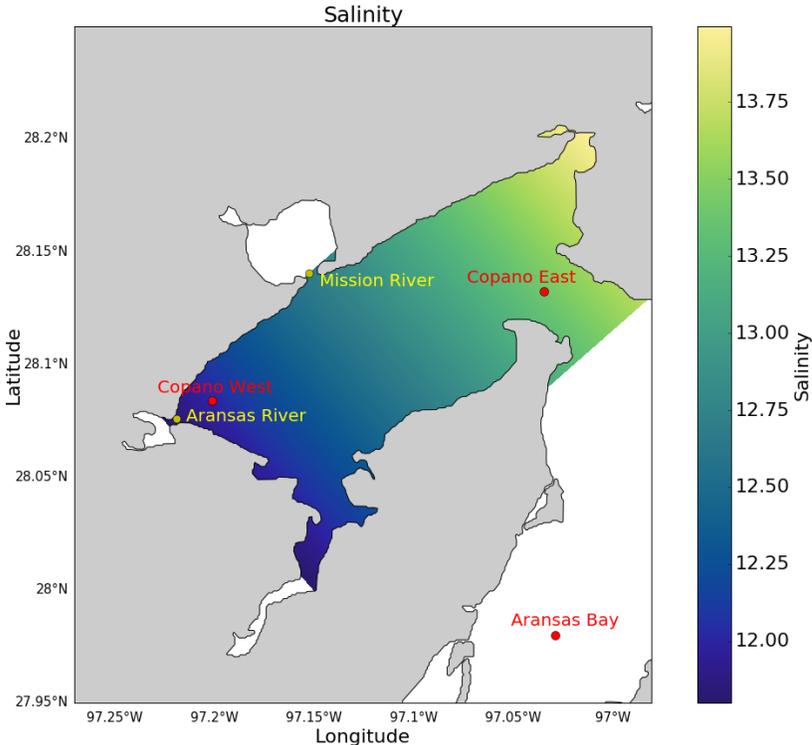


Figure 3.3: Initial salinity with Copano East and Copano West water quality stations.

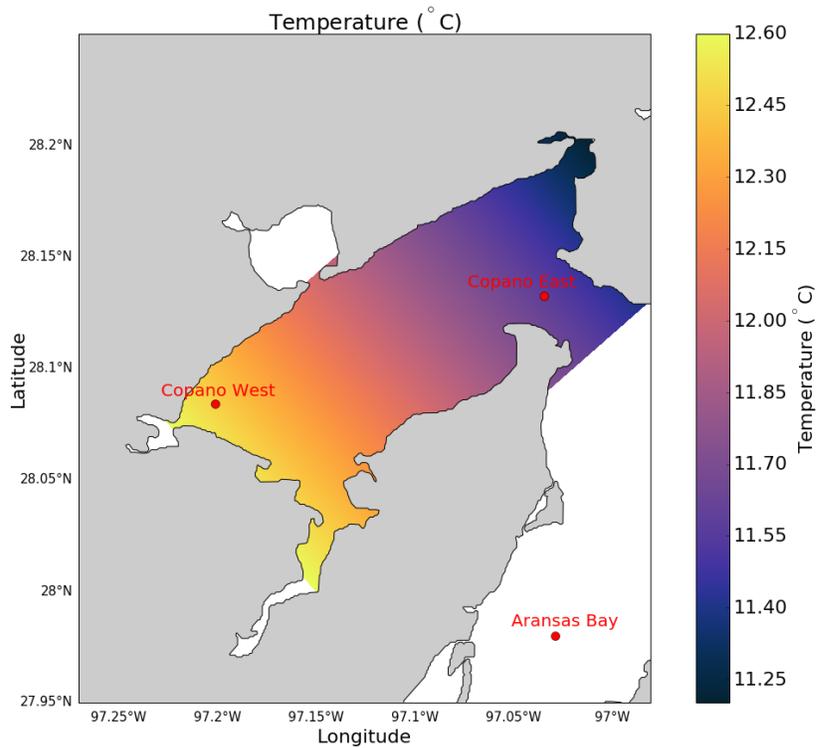


Figure 3.4: Initial temperature with Copano East and Copano West water quality stations.

The boundary conditions for the model were imposed through the southern boundary, location of the shipping channel.

For the free surface conditions, sea surface height data were extracted from the XTide software from David Flater (Flater, 2005). The data were taken from the Copano Bay State Fishing Pier station, located at 28,1138°N/97,0217°W. This software provides tides and currents predictions with resolution of one hour and, according to the author, the algorithm used is the same one used by the National Ocean Service in the U.S.

In order to better estimate meteorological tides and extreme events, *in situ* sea surface height (SSH) data were downloaded from a NOAA station located at Copano Bay. A low pass filter was used in the time series and the resulting series

was added to the XTide dataset. By doing that we were able to capture both the effects of tides and the effects of meteorological conditions in the sea level. Figure 3.5 shows the XTide series, the data, the low pass filter and the final SSH used in the model for the year of 2010. We applied the same procedures for all the 6 years of run.

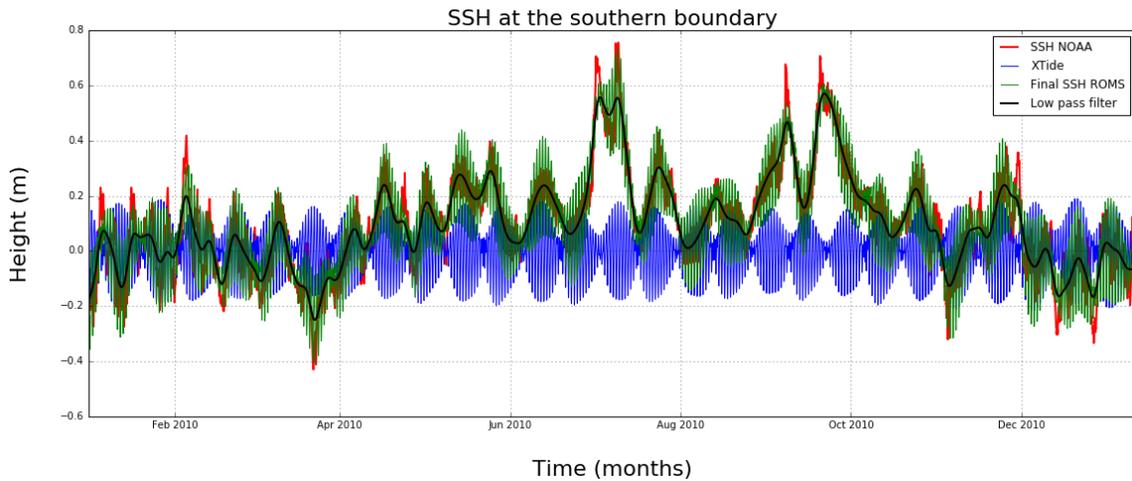


Figure 3.5: Sea surface height at the southern boundary for 2010.

The values of temperature and salinity were obtained from the Aransas Bay Water Quality station (MANERR Station 4) located at $97,0287^{\circ}\text{N}/27,9798^{\circ}\text{W}$ (NERRS, 2012), a station located just outside Copano Bay and close to the shipping channel. Six years of data were used with one hour resolution to be imposed to the southern boundary. The location of the Aransas Bay station is seen at Figures 3.3 and 3.4.

The reason why Aransas Bay station was used to provide salinity and temperature to the southern boundary was to make sure the conditions from the Gulf were well represented in the model, since this station is located close to the shipping channel with access to the Gulf waters.

3.2.4 River Forcing

The river discharge data were downloaded from the USGS Current Water Data for the Nation website (<http://waterdata.usgs.gov/nwis/rt>) with daily streamflow conditions in cf^3s^{-1} for both Aransas River and Mission River. The data were then converted to m^3s^{-1} . The discharge of both rivers can be seen in figure 3.6.

It is important to notice here the difference in between years. The annual reports from USGS Water Watch (<http://waterwatch.usgs.gov>) showed that 2010 and 2015 were considered 'wet' years when compared to the period between 2012 and 2014, called 'dry' years. These differences in river discharge throughout the years have a great impact on the salinity pattern in Copano Bay and will be explored in the next sections.

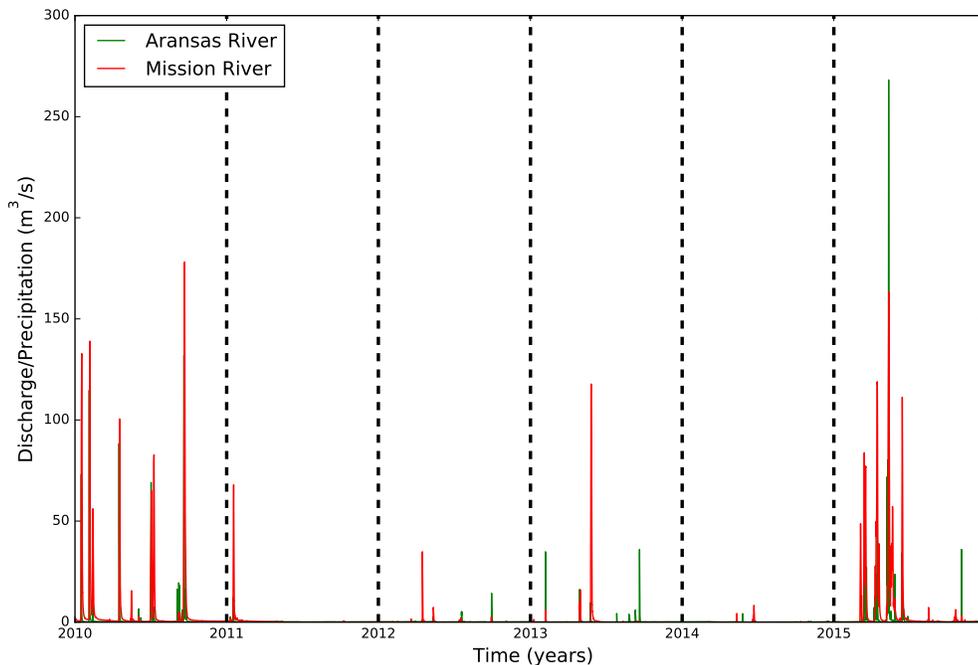


Figure 3.6: River discharge in m^3/s for Aransas River and Mission River

The discharges were then distributed in 4 river source points in the grid for each river in order to avoid model instability, representing the freshwater inflow from the north and from the west of the domain. The first and last points have 1/6 of the total discharge, while the second and third points have each 1/3 of the total discharge for a given time. This setup resulted in a gradient of water inflow along the river locations. The positions of the rivers are in Figure 1.3. Even though both rivers have a low discharge rate when compared to other rivers in the Gulf of Mexico, their contributions to the system are important to physical and biological processes in Copano Bay.

For both rivers, the salinity was kept constant at 0 to simulate fresh water inflow and a vertical discharge gradient was given being maximum at the surface and zero at the bottom.

Because of the seasonal variation in temperature throughout the year, the ERA-Interim air temperature of 2 m with a 3-hourly resolution was used to simulate the water temperature from both rivers. This approach was used due to the lack of data for river temperature in the region and due to the known interactions of the air-sea layers. The time-series was chosen for a point near Copano Bay and interpolated from a 3-hourly resolution to a 15-minutes resolution to match the river discharge.

3.3 Experiments

As mentioned before in section 3.2.4, Copano Bay has two distinct patterns over the years, representing low and high salinity due to the river discharge. In order to capture the differences within each year, we decided to run the model for 5 years, from January/2010 to December/2015. Outputs of temperature, salinity, density, velocities (u , v , u_{bar} , v_{bar}) and SSH were saved every two 2 hours and all the simulations were made using the Texas A&M High Performance Research Computing (<http://hprc.tamu.edu/>).

3.3.1 *Analysis of Observations and Model Validation*

Before all the simulations, temperature and salinity data from Copano Bay West and East water quality stations were analyzed along the 6 years to check for any significant patterns. Also, river inflow and precipitation data were also analyzed to see if there was some correlation between all four parameters.

The model validation was made by choosing two different points in the model grid close to the Copano Bay East and West stations, and comparing the temperature and salinity values at the surface with the real data. Due to different resolutions between the two datasets, the resolution of the stations was adjusted to every 2 hours instead every 15 minutes to match the model's temporal resolution.

4. RESULTS AND DISCUSSION

4.1 Model Validation

As mentioned before in section 1.1.1, Copano Bay has two water quality stations named Copano East and Copano West. The salinity and temperature from these stations were used to configure the model's initial and boundary conditions and were also used as a reference to the salinity pattern of the bay. In order to assess our results we decided to use the time series from two points from the model located at the same location as the two water quality stations. Because the observation points were in a different resolution (15 minutes) we converted the data to a lower resolution (every 2 hours) to match the model's output. The time series comparison and a scatter plot comparing data and model output for temperature is shown in Figure 4.1.

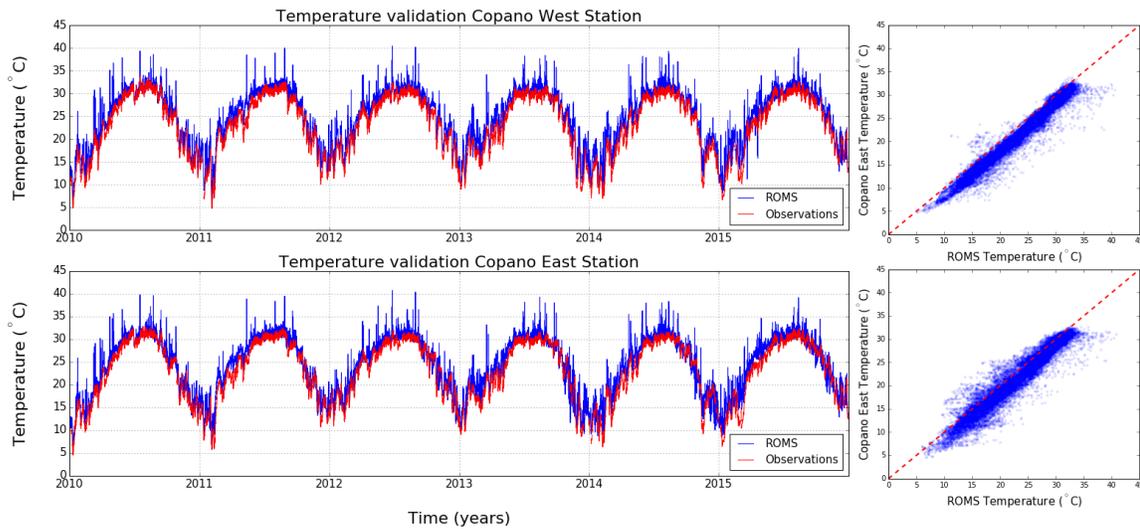


Figure 4.1: Temperature validation for the West and East sides of the bay.

From the figure, one can notice that the model represented well the seasonal

changes in temperature, with low temperatures during the winter and fall months, and higher temperatures during spring and summer. Since the temporal variability of temperature do not depend much on the river discharge, the temperature on the west side is similar to the east side. The correlation coefficient between the model's results and the observed data was $r^2 = 0.96$ for the east side and $r^2 = 0.98$ for the west side.

Figure 4.2 shows the comparison between the model output and the real data for the salinity at the surface. The upper panel shows that the model simulated well the changes in salinity over the years for the west side, but overestimated the values in some occasions, which can be seen in the negative values of the grey lines. The correlation coefficient for the west side was $r^2 = 0.91$. For the east side, the model also simulated the changes over the years when compared to the real data, resulting on $r^2 = 0.90$. Next to both panels there is the scatter plot comparing the data and the model results.

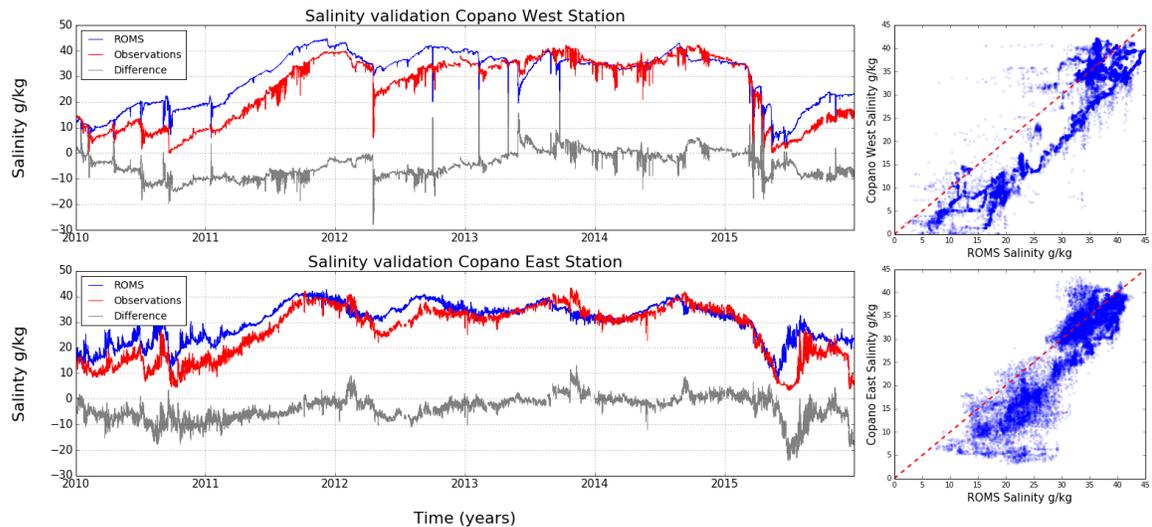


Figure 4.2: Salinity validation for the West and East sides of the bay.

As mentioned before, the use of a 2D model such as TxBLEND can result in a worse prediction in temperature when compared to 3D models such as ROMS. Figure 4.3 shows a comparison between ROMS and TxBLEND validations. For the west side at the surface, ROMS has a $r^2 = 0.91$, while TxBLEND has $r^2 = 0.78$ at Aransas Bay. Even though the periods are not the same, it is possible to see that ROMS resolves better the salinity variability in the bay, by following the right trend and episodic drops. The panels on the right show the comparison between models and real data for both models. ROMS tends to overestimate the salinity but the values are less sparse than the TxBLEND, which doesn't have a well defined pattern.

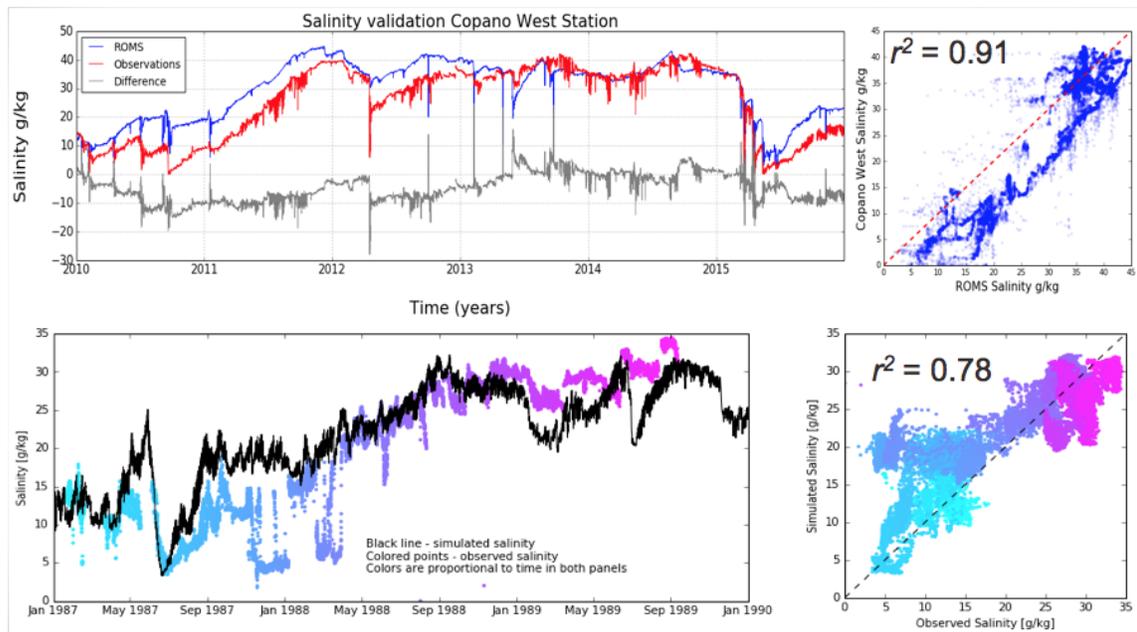


Figure 4.3: Comparison of surface salinity between ROMS and Copano West station between January/2010 and December/2015 and comparison between the TxBLEND model and the surface salinity at Aransas Bay between January/1987 and January/1990.

One of the objectives of this work is to investigate the differences between the east and west sides of the bay. Figure 4.4 shows the horizontal stratification between the east and west sides of the bay for surface salinity and temperature. As expected, the model captured the differences between the east and west for both parameters, despite overestimating the difference in salinity during some flooding events.

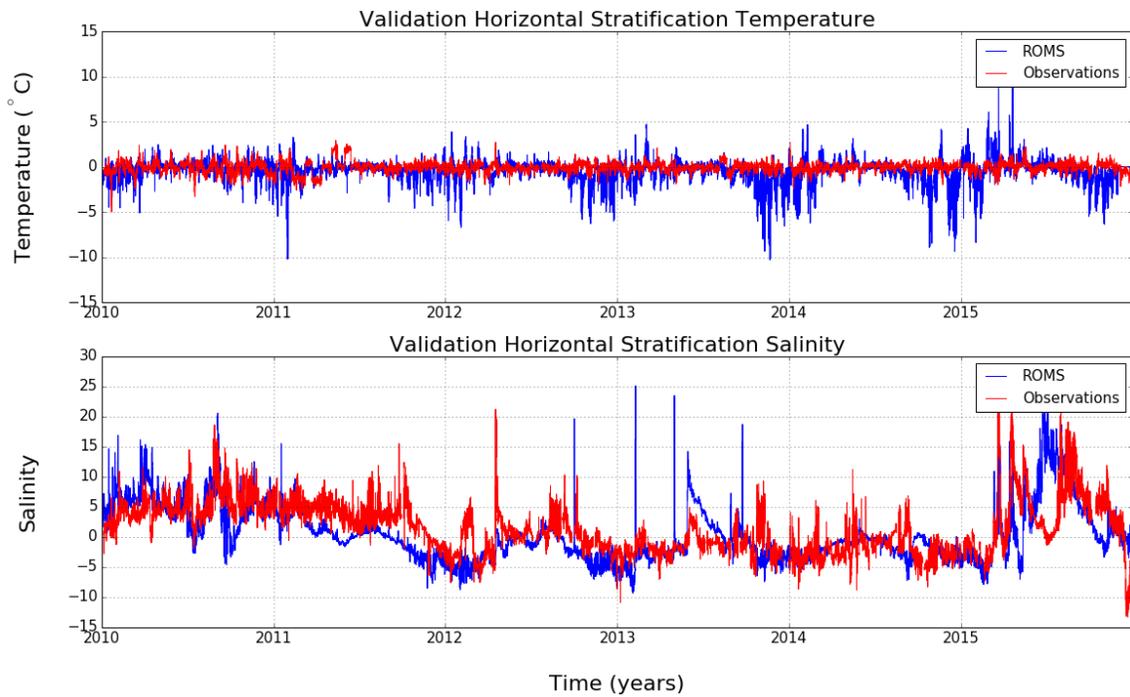


Figure 4.4: Differences between the Copano East and Copano West stations (red) and ROMS locations on the east and west side for surface temperature and salinity.

The model resolved the south channel of the bay and captured the horizontal stratification between the east and west sides of the bay. Also, the long-term salinity intrusion was accurately reproduced on the east and west sides, making it suitable for studying how external forcing such as river discharge, precipitation

and wind can alter the salinity in the bay.

4.2 Time Series Analysis of *in situ* data and model results

As discussed in section 3.2.4, there is clearly a difference in river discharge over the period between 2010 and 2015. In order to better understand how these differences affect the salinity patterns, salinity values (model and *in situ*) from the the east and west side of the bay, as well as precipitation and river discharge, were plotted as seen in Figure 4.5. The first row of the figure shows the salinity at the surface and bottom for the west side of the bay, while the second row is for the east side. The third row represents the difference of salinity values between the east and west side and the fourth row the differences between the surface and the bottom. For the fifth row, the precipitation data were integrated over the domain and converted to m^3s^{-1} to be comparable to the river discharge, which is also plotted as a sum of the discharge from Mission and Aransas rivers. Both points chosen to represent the model results were in the same location as the two water quality stations previously discussed. One point is close to the Aransas River discharge (west point) and the other point is close to the mouth of the bay (east point).

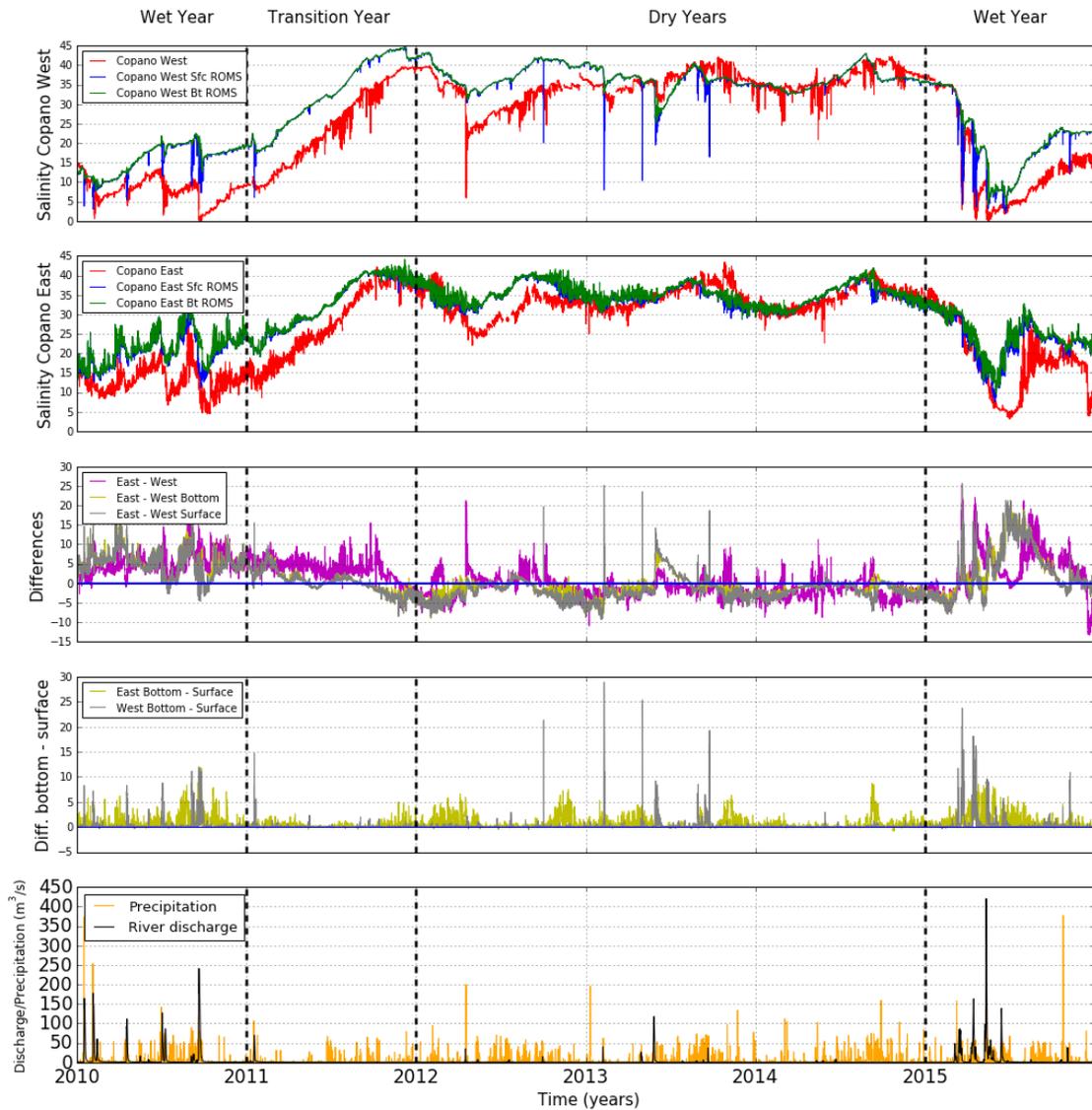


Figure 4.5: Salinity values for stations Copano East and West, precipitation in mm and river discharge in m^3s^{-1} for Aransas and Mission River (sum). All values are from 2010 to 2015.

To analyze what caused the lows and highs salinity values in each year, we decide to split the years into three different categories: 'wet years', corresponding 2010 and 2015, where salinity was kept in a normal range, 'transition year', which corresponds to 2011, where salinity went from normal values to hypersaline con-

ditions, and 'dry years', being the period between Jan/2012 and Dec/2014, which is a period with high salinity and low river discharge.

The first year, 2010, was considered a 'wet year'. The salinity on the west side had a range of 2.9 gkg^{-1} to 22 gkg^{-1} (average 16.5 gkg^{-1}) at the surface and 7.87 gkg^{-1} to 22.5 gkg^{-1} (average 16 gkg^{-1}) at the bottom. For the east side, the salinity range was 11 gkg^{-1} to 31 gkg^{-1} (average 20 gkg^{-1}) and 13 gkg^{-1} to 33 gkg^{-1} (average 21.6 gkg^{-1}) for the surface and bottom, respectively. The horizontal stratification between the west and east side is represented by the positive values of the third row. It is possible to see that the salinity on the east side is always higher than the west side, most likely due to the constant exchange between Aransas Bay and the east side. This difference can reach up to 17 gkg^{-1} . For the west side however, the proximity to the river discharge causes a lower salinity range. Another important feature is the difference in salinity between the bottom and the surface, even considering the shallow depths. The fourth row shows that high discharge periods cause a vertical gradient of salinity up to 12 gkg^{-1} between the surface and the bottom. This condition was observed on both sides, with a weaker stratification on the east side. To maintain this salinity pattern, the amount of freshwater into the system was record in comparison to all of the other 5 years. During 2010, a total volume of $122,924,676 \text{ m}^3$ of fresh water was added to the system, being $58,766,690 \text{ m}^3$ of river discharge and $64,157,986 \text{ m}^3$ from precipitation.

The second year, 2011, a transition year, showed the lowest gradients for salinity at the surface and bottom at both locations. The year started with one event of high river discharge and precipitation around mid January that contributed to a drop in salinity from 23 gkg^{-1} to 5.9 gkg^{-1} at the surface of the west location. From February to December, the river discharge was very low, leading to a volume of $1,993,222 \text{ m}^3$ of fresh water into the bay, while precipitation contributed with $29,472,207 \text{ m}^3$. The total input of freshwater for 2011 was $31,465,429 \text{ m}^3$, about one fourth of the volume of 2010. This low river discharge regime caused the salinity

to increase on both sides along the year, starting from 19 gkg^{-1} in January and going up to 44.7 gkg^{-1} (average of 32.5 gkg^{-1}) in December on the west side at the surface. The east side of the bay ranged from 19 gkg^{-1} to 42 gkg^{-1} (average of 31.4 gkg^{-1}). For the bottom, the gradients were also high. For the west side, the range of salinity was from 17.4 gkg^{-1} to 44.7 gkg^{-1} (average of 32.5 gkg^{-1}) and for the east side it was from 19 gkg^{-1} to 44 gkg^{-1} (average of 32 gkg^{-1}). A more careful analysis of the second row shows that the salinity on the east side increased until around October and stabilized, while the salinity at the west side kept increasing and reached approximately 45 gkg^{-1} . At some point, around November, the difference in salinity between the east and west was 0, indicating no horizontal stratification. After this point, the values became negative, indicating that the west side was saltier than the east side. Among all the reasons for the increase in salinity on the west side is the low river discharge, evaporation, and the fact that the water on the west side is farther from the tidal channel, so they are less influenced by the dynamics. As the surface became saltier at the west side, the difference between the bottom and surface also dropped, as indicated in the fourth row by the grey lines, reducing the vertical stratification.

The period called 'dry years', from 2012 to 2014, started with the west side being saltier than the east side. According to Valle-Levinson (2010), the regime where the upper estuary is saltier than the mouth, is called an inverse estuary. The author says that in cases where evaporation exceeds river discharge, a hypersaline condition is created, where the salinity increases landward, instead of decreasing as expected in a normal condition. Considering the entire period of the simulations, the river discharge had 1/3 the volume of the so called 'wet years' 2010 and 2015. The fresh water for the three years added together was $467,153,289 \text{ m}^3$ from precipitation and $43,089,241 \text{ m}^3$ from river discharge, resulting on a total of $510,242,531 \text{ m}^3$. The ranges of salinity for the west side at the surface and bottom were 7.9 gkg^{-1} to 43.2 gkg^{-1} (average 36.7 gkg^{-1}) and 25 gkg^{-1} to 43.2

gkg^{-1} (average 36.9 gkg^{-1}), respectively. For the east side the ranges were from 28 gkg^{-1} to 40 gkg^{-1} (average 34.9 gkg^{-1}) and from 29 gkg^{-1} to 41.6 gkg^{-1} (average 35.3 gkg^{-1}). During almost the entire period the west side was saltier than the east side, except when there were some increase in precipitation and some river discharge, as seen as the positive values in the third row, which follow the higher values at the fourth row. Thus, the horizontal stratification with the upper bay saltier than the mouth continued for a period of three years, indicating a long residence time for the bay. The vertical stratification followed the gradients caused by river discharge, specially between June/2012 and June/2013, where the higher precipitation and some river discharge caused some stratification, dropping the salinity from around 40 gkg^{-1} to 10 gkg^{-1} on the west side.

We assumed the bay as hypersaline by comparing the salinity of the bay with the salinity at Aransas Bay. Figure 4.6 shows *in situ* data of salinity at Aransas Bay, Copano East Bay and Copano West Bay for the period between Jan/2013 and Dec/2015. It is possible to notice that during the period the salinity inside the bay was slightly higher than the salinity at Aransas Bay, result of low evaporation, low precipitation and lower depths.

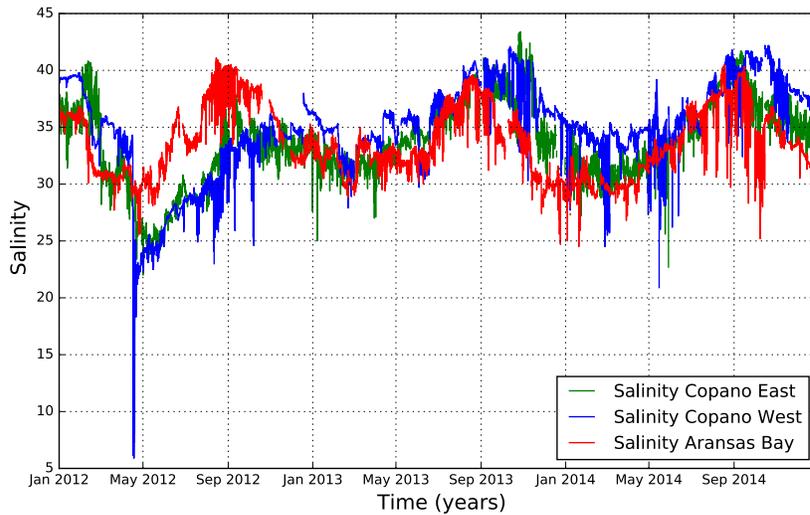


Figure 4.6: Salinity at Aransas Bay, Copano East and Copano West stations between Jan/2012 and Dec/2014.

The last year, 2015, was also considered a ‘wet year’, not much because precipitation, but because river discharge. The contribution of river discharge to the system was 50,883,113 m³ specially between March and July. The precipitation rate for the period was 599,207,079 m³, resulting on a total of 110,803,192 m³ of freshwater into the bay. During the first semester of 2015, the salinity decreased from 35 gkg⁻¹ to less than 10 gkg⁻¹ in a few months, where 95% of the total river discharge for 2015 was added to Copano Bay. As seen in the third row, after a few months, the difference between east and west became positive again, indicating that the east side was again saltier than the west side. The salinity range from the east side at the surface was 7.5 gkg⁻¹ to 33 gkg⁻¹ (average of 23.9 gkg⁻¹) and at the bottom was 9.4 gkg⁻¹ to 33.7 gkg⁻¹ (average of 24.9 gkg⁻¹). For the west side, the range was 1.9 gkg⁻¹ to 35.8 gkg⁻¹ (average 20.7 gkg⁻¹) and between 3.79 gkg⁻¹ to 35.8 gkg⁻¹ (average 21.4 gkg⁻¹) for the surface and bottom, respectively. The vertical stratification followed the river discharge and reached its maximum when river discharge was also maximum.

The classification proposed by Bittler (2011) that showed 2010 as a 'wet year' was also seen in the model's results, indicating that the model captured the horizontal stratification. As in 2009, considered a 'dry' year by the authors, the model also captured the hypersaline conditions and the horizontal gradient between the west (now saltier) and east (now fresher) sides. During the entire period analyzed, the salinity at the bottom was always higher than at the surface, even under hypersaline conditions. This indicates that the bay always has some vertical stratification, which can be stronger or weaker depending on the river discharge (west side) and the tides (east side). It is also important to notice here that in some periods high precipitation did not mean high discharge. In fact, the period between 2012 and 2014 had an average of 150,000,000 m³ of precipitation distributed over three years, but had a very low river discharge. The opposite is also true. Between March and July of 2015, the river discharge increased with no significant increase in precipitation. There are some factors that can explain this discrepancy:

- Both Aransas and Mission rivers receive water from other rivers in different regions of Texas that may have a different precipitation regime than Copano Bay;
- The river discharge is not measured at Copano Bay, but a few miles upstream, causing differences in what is measured and what portion of fresh water reaches the bay.

Understanding how interannual changes can influence the salinity dynamics at Copano Bay is important to look at changes in a long time scale. This information can be used to analyze climate changes, seasonal patterns and how the bay responds to an increase(decrease) in precipitation and/or river discharge. However, it is also important to understand the dynamics of processes that happen in scales that can vary from hours to weeks, such as a change in the wind direction due to a storm event, a subsequent increase in precipitation and river discharge,

and finally the adjustment of the bay to these events. Some examples of these episodes are the salinity drops in 2010 and some episodes between 2012 and 2014, where the salinity went from a hypersaline condition to low salinity (around 10 gkg^{-1}). The next sections will look deeper into the short time scale processes that cause the salinity to drop from 40 gkg^{-1} to 10 gkg^{-1} in a matter of days, causing changes in horizontal and vertical stratification.

4.3 Analysis of Local Events

The first case studied was during January of 2010. The top panel of Figure 4.7 shows how the wind direction changed over time, the second panel shows the precipitation and river discharge levels, while the third and fifth panels show the salinity at the surface and bottom for the west and east side, respectively. In order to analyze the horizontal stratification, the fourth panel shows the salinity difference between the east and west side. The dashed lines are used here to mark the moment when each event started, i.e. when the wind changed, when salinity started to drop on both sides.

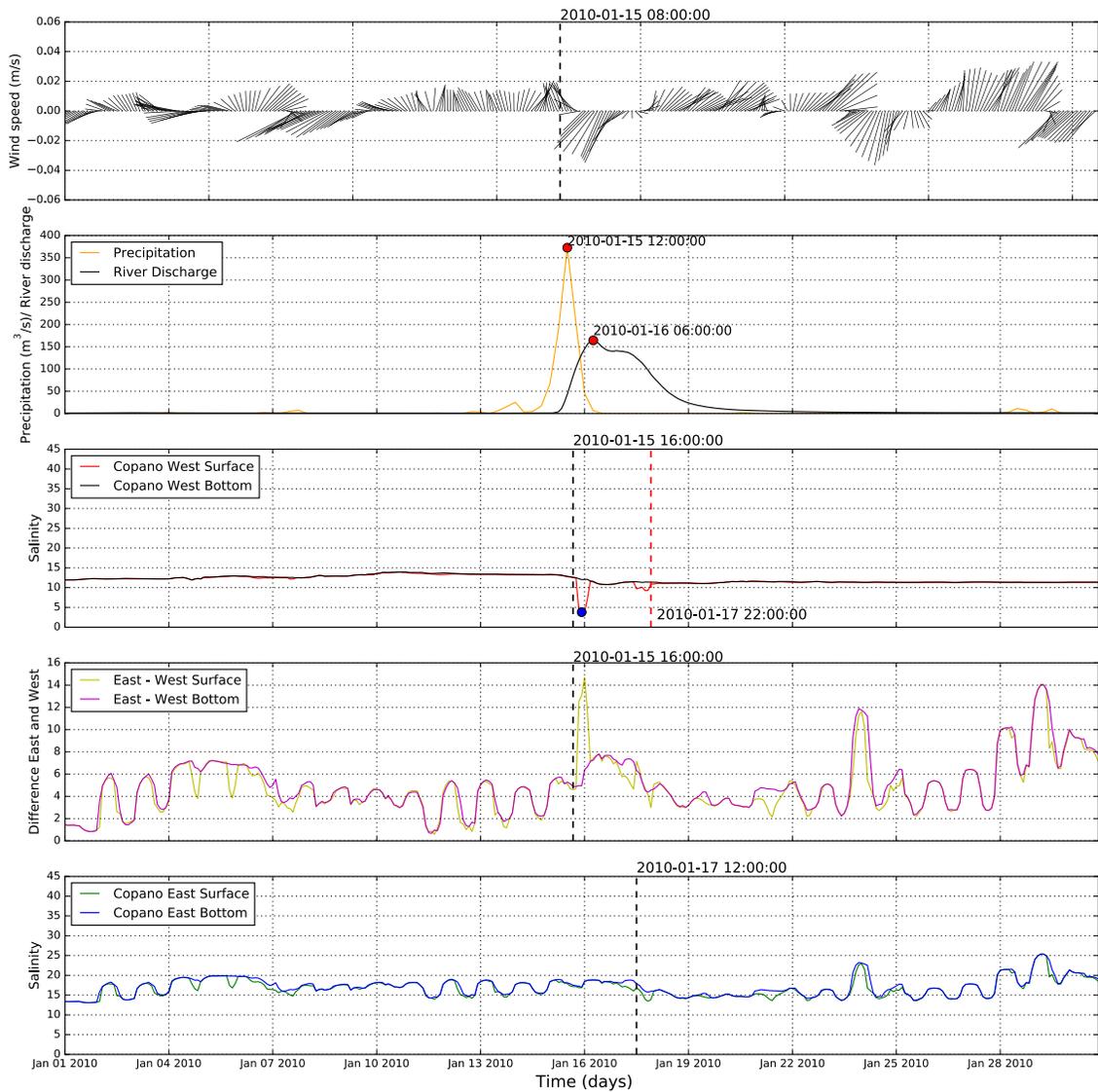


Figure 4.7: Representation of wind speed and direction, precipitation and river discharge, salinity on the west side, difference between the east and west sides and salinity for the east side for January of 2010.

As shown in the figure, around the 15th of January at 08:00 am, the wind direction changed from northwest to southwest, probably due to a front or a storm event. Followed by the change in wind direction, the peak of precipitation was 4 hours later, with almost 111,645 m³ of fresh water, represented by the red dot in

the figure. The second red dot shows the peak of river discharge, which happened 18 hours after the peak of precipitation. This input of fresh water reflected on the salinity on the west side 4 hours after the peak of precipitation. This response was stronger at the surface, where the salinity went from around 11 gkg^{-1} to 3 gkg^{-1} in a few hours, and went back to the previous value after 2 days and 6 hours, as indicated by the red dotted line. As seen in the black line at the third panel, the salinity at the bottom did not change with the fresh water input, indicating strong vertical stratification at that point. Before the salinity dropped, the difference between the east and west side for the bottom and surface was practically the same. As the wind started and the fresh water entered the bay, the difference increased to around 15 gkg^{-1} at the surface but did not change much at the bottom, increasing from 6 gkg^{-1} to 8 gkg^{-1} only. The difference also stabilized after approximately 2 day. Because of the constant exchange of salty water with Aransas Bay, the East side only responded to the fresh water input around 1 day after the peak in river discharge. Still, the changes in salinity were only seen at the surface, with a moderate drop from 16 gkg^{-1} to 13 gkg^{-1} , which shows that the freshwater is diluted closer to river source and doesn't have the strength to cause significant change at the mouth of the bay. The input of fresh water either from rain or river caused both vertical and horizontal stratification. Before the rain, the water was completely mixed, with the same salinity at the surface and bottom. The stratification started and lasted for only one day in response to the fresher water.

The figure for the second case has the same setup as the first one, but for a 'dry year'. As discussed before in section 4.2, in cases where the river discharge and precipitation are low, the salinity of the bay increased up to 45 gkg^{-1} , creating a hypersaline condition. The third panel of Figure 4.8 shows that the salinity dropped from 40 gkg^{-1} to 10 gkg^{-1} due to an increase in precipitation and (moderate) increase in river discharge.

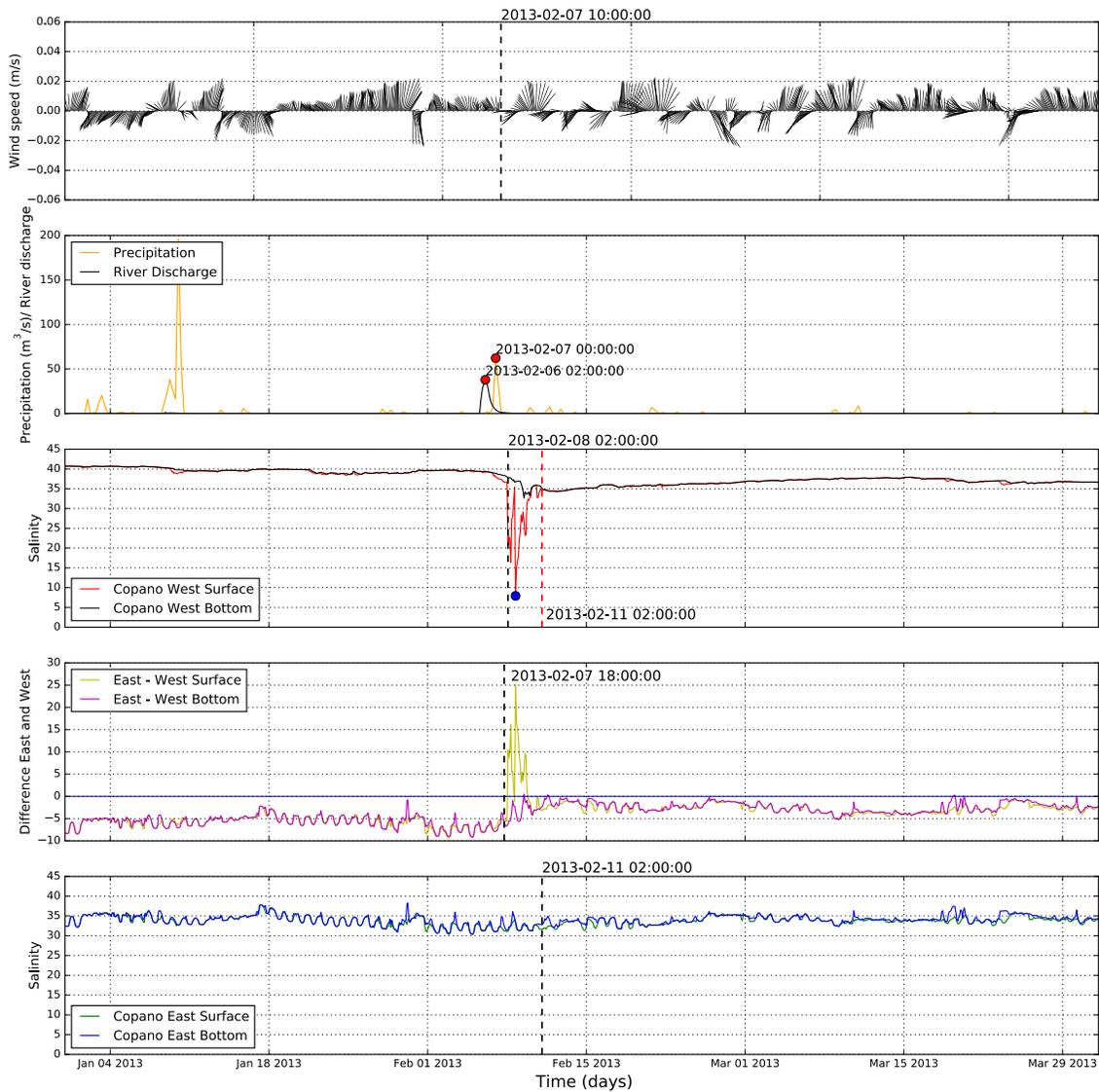


Figure 4.8: Same as Figure 4.7 but for February/2013.

First, the northern winds weakened for a few days and changed the direction on 02/03/2013 around 10:00 pm. The response from precipitation started on the same day, where the peak reached $60 \text{ m}^3\text{s}^{-1}$ of fresh water. A day before the wind changed, the river discharge had its peak with $40 \text{ m}^3\text{s}^{-1}$. The third panel shows that the bay went from a mixed environment to a stratified one after two days of

the maximum river discharge. This event dropped the salinity from hypersaline (40 gkg^{-1}) conditions to fresh water values (around 8 gkg^{-1}). Just like the last case, salinity dropped at the surface, while the bottom did not respond instantly to the input of fresh water, dropping only 5 gkg^{-1} . The time interval from the moment where salinity at the surface dropped and went back up close to the previous values was around 3 days. A comparison with the previous case, where the estuary recovered in 1 day, indicates that due to the high gradient imposed by the fresh water input, the hypersaline condition would take longer to be stable again. The fourth row shows that due to the drop in salinity, the estuary went from an inverse estuary to a normal estuary, where the upper bay was fresher than the mouth of the bay. The maximum difference of salinity between the two stations were approximately 25 gkg^{-1} , showing the sensibility of the high salinity to the fresh water. On the east side, the response from precipitation and river discharge was felt 3 days after the west side, and only with an increase in the difference between the surface and the bottom.

The last case here presented is during May of 2015. During this period, the river discharge reached its maximum in 6 years, with a fresh water input of $420 \text{ m}^3\text{s}^{-1}$ around May 12th. Figure 4.9 shows the third case.

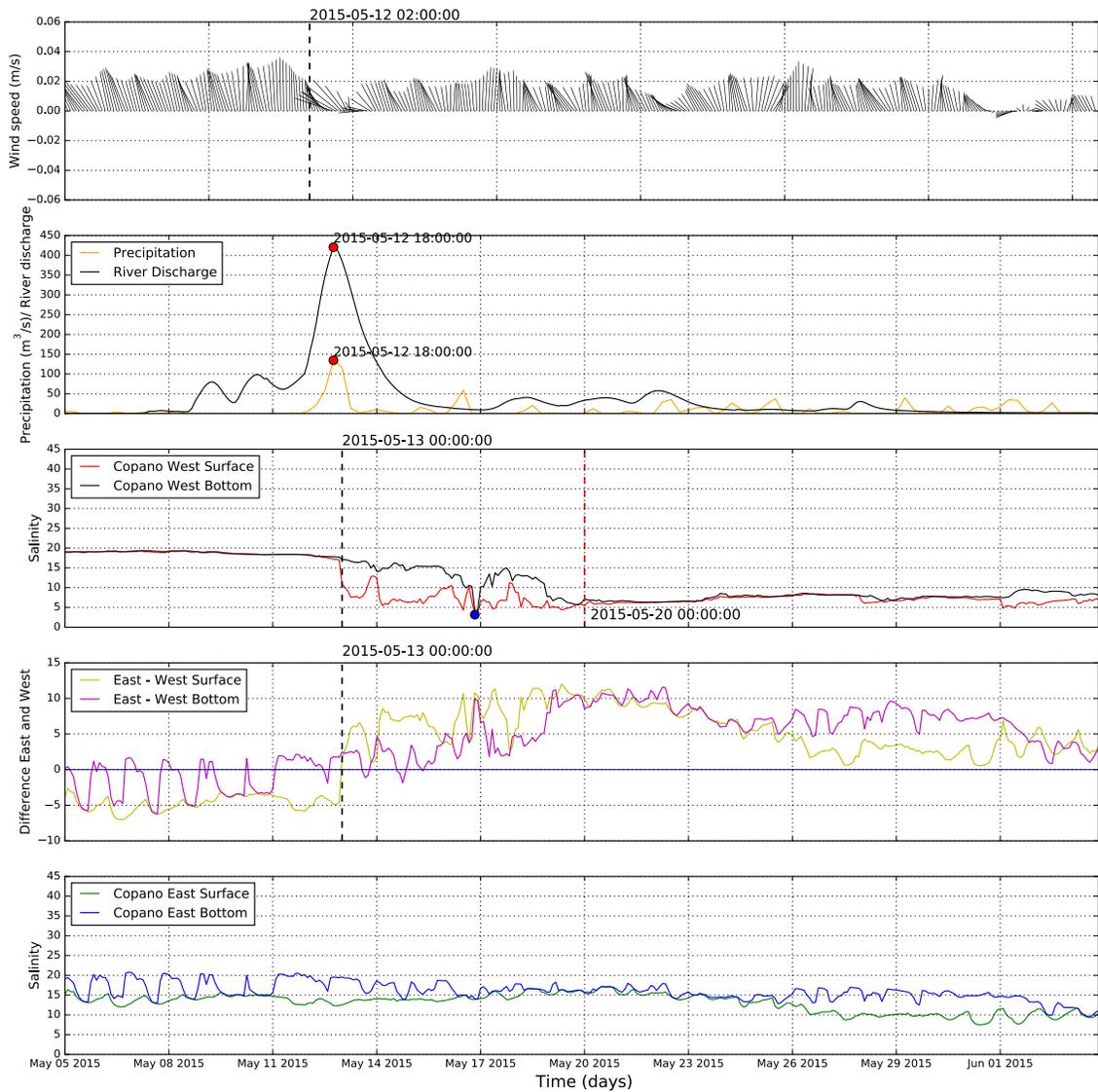


Figure 4.9: Same as Figure 4.7 but for May/2015.

As seen in the figure, around 05/12/2015, the wind changed the direction from northwest to west. After a few hours, there was the peak of river discharge and precipitation with approximately $514,381 \text{ m}^3$ (precipitation + river discharge) of fresh water into the bay. The response of the salinity on the west side was one day after the river discharge, causing the salinity to go from 20 gkg^{-1} to less than 5

gkg^{-1} . This drop on salinity continued for almost a week before the water column was mixed again. It is important to notice here that Copano Bay started 2015 as a hypersaline bay. The fourth row of the figure shows that before the fresh water input, the west side was saltier than the east side and it was necessary a high amount of fresh water to make the west side fresher again and for the salinity to stay stable. This change only occurred after this high discharge and high precipitation event. The positive values in the fourth row indicate that the estuary went from an inverse estuary to a normal estuary after the dried period. Also, one can notice that the salinity on the west side dropped from 20 gkg^{-1} to 10 gkg^{-1} and became stable with a lower salinity than before. This shows that for a higher river discharge than the average flux, the salinity on the west side will not be able to recover to the same value as before even after the vertical stratification has ended. The east side of the bay barely responded to the big amount of fresh water, having only a small drop on salinity of 5 gkg^{-1} , which resulted in a weak vertical stratification.

From the three cases presented here, there is a relationship between the amount of fresh water that was put into the system, the salinity previous to the event, the gradient caused by the fresher water and the amount time the west side of the bay took to recover from that fresh water. As discussed before, the first case shows that even with an amount of approximately $138,016 \text{ m}^3$, the salinity stabilized after 1 day. This is due to the low gradient (around 7 gkg^{-1}) between the fresher water and the previous water in the bay. However, for the second case, the salinity dropped from 45 gkg^{-1} to approximately 10 gkg^{-1} (gradient of 35 gkg^{-1}) with an input of approximately $7,240 \text{ m}^3\text{s}^{-1}$ (river + precipitation peaks) and went back to normal after 3 days, showing that even for a small input of fresh water, the gradient caused by the low salinity water in comparison to the hypersaline condition will take longer to adjust. In the third case, the salinity went from a inverse estuary situation to a normal situation with the input of approximately $514,381 \text{ m}^3\text{s}^{-1}$

of fresh water added to the system.

Thus, it is clear that for the estuary to restore its salinity, it depends on the amount of fresh water, specially through river discharge, the lowest salinity reached during the event, the gradient caused by the drop on salinity, the evaporation and the salinity before and after the storm event. How some of these parameters can be used to estimate after how long the bay can adjust to specific events will be now discussed.

The blue dots in the last 3 figures represent the lowest salinity reached for the west side of the bay after the precipitation and river discharge events. After this point, we assumed that the salinity started recovering and reached stable values, leading to a mixed water column again. The time between this point and to reach a stable condition varied among the 3 different cases. The first case had a lag of 2 days, the second case a lag of 2 days and 08 hours and the last case the lag was 3 days and 08 hours. By using the lowest value of salinity during the event, the number of hours that the salinity took to stabilize and the salinity value considering a mixed water column, we decided to use an exponential decay function to check the rate of salinity change per hour. Here, the amount of time needed for the salinity to recover is less than before, since in this case we started counting from the moment the salinity reached its minimum value, which is different from when the salinity dropped in the first case. Equation 4.1 is as follows:

$$S(t) = S_0 - (S_0 - S_f)(e^{-t/\tau}) \quad (4.1)$$

Here, $S(t)$ is the salinity changing over time, S_f is the lowest salinity after the river discharge and S_0 is the salinity before (or after) the fresh water event, considering a mixed water column where the salinity at the surface and bottom are the same. t is the number of hours and τ is the mean lifetime. This last variable is related to the exponential decay constant λ as in $\tau = 1/\lambda$.

We applied Equation 4.1 to 4 different cases (3 cases mentioned before and

1 other case) in order to estimate a generic value for τ , which could be used to estimate the time the west side of the bay would take to go from stratified to completely mixed. For each case an exponential decay curve was generated from the lowest salinity point to the stable salinity value. The time t was chosen based on difference of hours between the two points, while the value for S_0 was used as an average of salinity values of a period after the salinity stabilized. Here, we considered the values before and after the fresh water input would be similar. Figure 4.10 shows the curve and parameters for 4 different cases, as well as the salinity between the lowest value and the time where the water column was mixed.

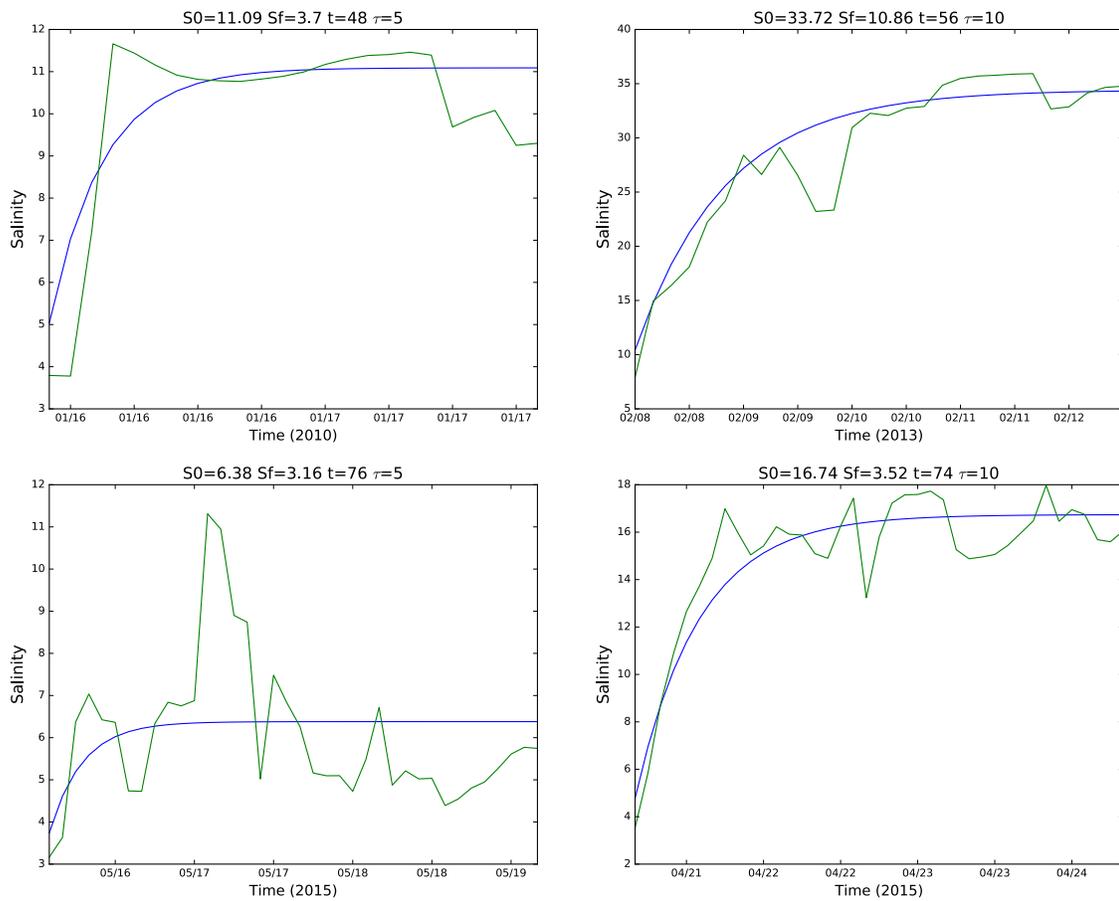


Figure 4.10: Four different cases of salinity estimated growth based on different initial conditions.

The salinity gradient between the lowest value to the stable value reflects each different regime. The first case, top left on the figure, the lowest salinity was at 3.7 gkg^{-1} and stabilized back in 11.09 gkg^{-1} after 2 days. The second case, top right in the figure, shows the minimum salinity as 10.86 gkg^{-1} but a higher stable salinity at 33.72 gkg^{-1} . The salinity values took approximately 2.5 days to be reestablished. The third case, represented by the left lower panel, shows that the salinity took around 3.5 days to be maintained around 6.38 gkg^{-1} , after a minimum of 3.16 gkg^{-1} . The last case here shows that the salinity recovered from approximately 3.52 gkg^{-1} to 16.74 gkg^{-1} in 3 days. Even though different values of τ were used, we roughly estimated a value of 10 hours to be used to estimate the change in the salinity over a certain period. In this case, for Copano Bay, even for different regimes, where the salinity can be as high as 45 gkg^{-1} or as low as 2 gkg^{-1} , Equation 4.1 can be re-written as:

$$S(t) = S_0 - (S_0 - S_f)(e^{-t/10}) \quad (4.2)$$

Just a reminder that the equation is only an approximation, since it is a rough estimate of the salinity. Since the salinity pattern also depends on other parameters such as the distance from the mouth and the currents, equation 4.2 can be used to first estimate how salinity changes over time after an event of fresh water discharge and to compare how the west side of the bay responds in comparison to the east side. As seen in the 3 different cases presented here, the response of the east is weaker than at the west side, since it depends more on the salinity from Aransas Bay, and not much from the salinity at the west side.

4.3.1 East vs West

As seen before in sections 4.2 and 4.3, there is a difference in salinity comparing the east and west side of the bay. In normal conditions, the east side is saltier than the west side due to the proximity of the west side to the river discharge.

However, this situation may change into an inverse estuary considering a period of low river discharge and precipitation, causing the west side to be saltier than the east side.

Based on the 3 cases shown before, this section will show model results to discuss how far the fresh water plume goes into the east side depending on the wind, amount of fresh water and the time scales. Following Figure 4.10, we will also discuss the adjustment of the estuary for each case.

Figure 4.11 shows the evolution of the surface salinity after a river discharge event during January/2010. The first panel to the left shows the salinity on the west side around 12 gkg^{-1} and around 17 gkg^{-1} on the east side. It is possible to see the line of 15 gkg^{-1} around the tidal plume. Following the time line to the second panel, the wind starts to change from northwest to southwest at 01/15 22:00 pm, followed by the peak of river discharge 10 hours after that. The peak was distributed in $100 \text{ m}^3\text{s}^{-1}$ from Mission River and $61 \text{ m}^3\text{s}^{-1}$ from Aransas river. A day after the change in the wind direction, the fresh water plume reached its maximum distance further from the river point, which is represented by the fourth panel, pushing the 15 gkg^{-1} water into Aransas Bay. This point of intrusion can be seen in figure 4.7 as the salinity on the east side had a small drop. The fourth panel also shows the wind weakened allowing the plume to go further into the bay. The discharge continued high, around $140 \text{ m}^3\text{s}^{-1}$ decreasing after 2 days, where the plume was mainly concentrated to the north and west sides of the bay, probably due to the wind (fifth panel). The last panel shows that on the 22nd day of January the river discharge was low and the salinity on the west side was lower than the first panel due to the fresh water input. This value (around 10 gkg^{-1}) continued stable during January showing that the west side is less influenced by the tides. The salinity at the east side followed the tidal regime and the input of saltier water from Aransas Bay. As seen in the last 3 panels, the plume was retracted due to the intrusion of fresher water into the system, specially from Mission River.

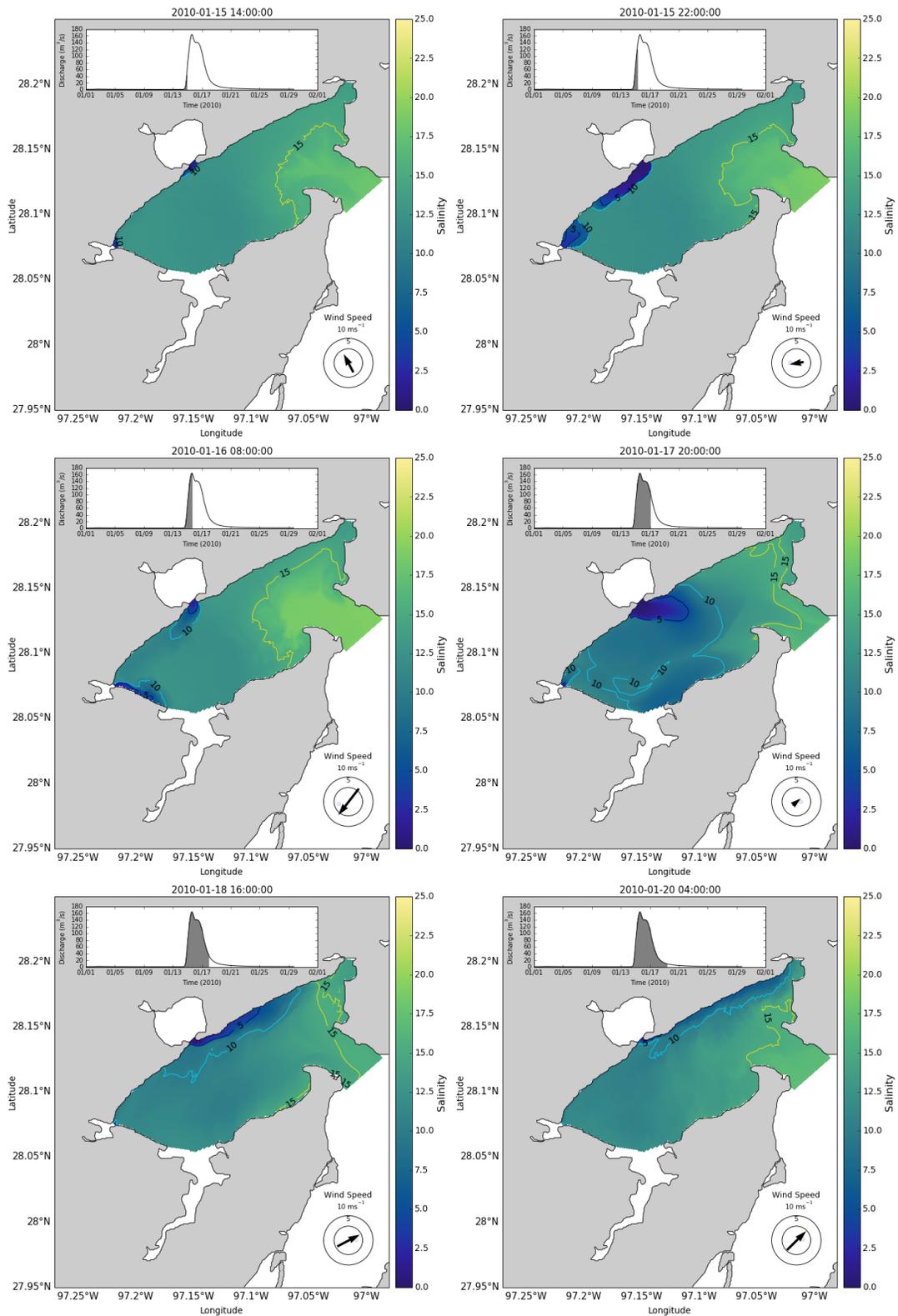


Figure 4.11: Evolution of a river discharge event during January/2010.

The second case took place during Feb/2013. The first panel of Figure 4.12 shows the salinity at the west side around 41 gkg^{-1} , i.e. higher than the east side. After two days when the wind changed directions from northwest to southwest, the maximum river discharge came on the 6th with $40 \text{ m}^3\text{s}^{-1}$ of fresh water ($34 \text{ m}^3\text{s}^{-1}$ from Aransas River and $6 \text{ m}^3\text{s}^{-1}$ from Mission River). As discussed before, since the measurement of fresh water discharge is not at Copano Bay, there might be a lag of time before the fresh water actually enters the system. In this case, the lag was 2 days after the peak of river discharge, as seen in the fourth panel. The fifth panel shows that the fresher water was limited to the northwest side of the bay, with salinity around 30 gkg^{-1} . After 6 days of the peak of river discharge the west became saltier than the east side again. There are a few considerations about this case. First, the fresh water turned the estuary from an inverse estuary to a normal estuary, with the upper estuary fresher than the mouth. The salinity took around 6 days to go back to the previous value, i.e. around 40 gkg^{-1} , which shows that since the salinity decreased to values as low as 10 gkg^{-1} , it took more time for the estuary to recover and go back to a hypersaline condition. Also, the amount of river discharge in this case was 1/4 the amount of the first case. Before we showed that the input of fresh water caused the salinity on the west side to stay lower than before even after the river discharge ceased and the wind turned back to northwest direction. This is not the case here. The salinity profile shows that this volume was not enough to sustain the low salinity values just like the first case. With no influence from fresh water, the east side remained with salinity around 32 gkg^{-1} during the entire period.

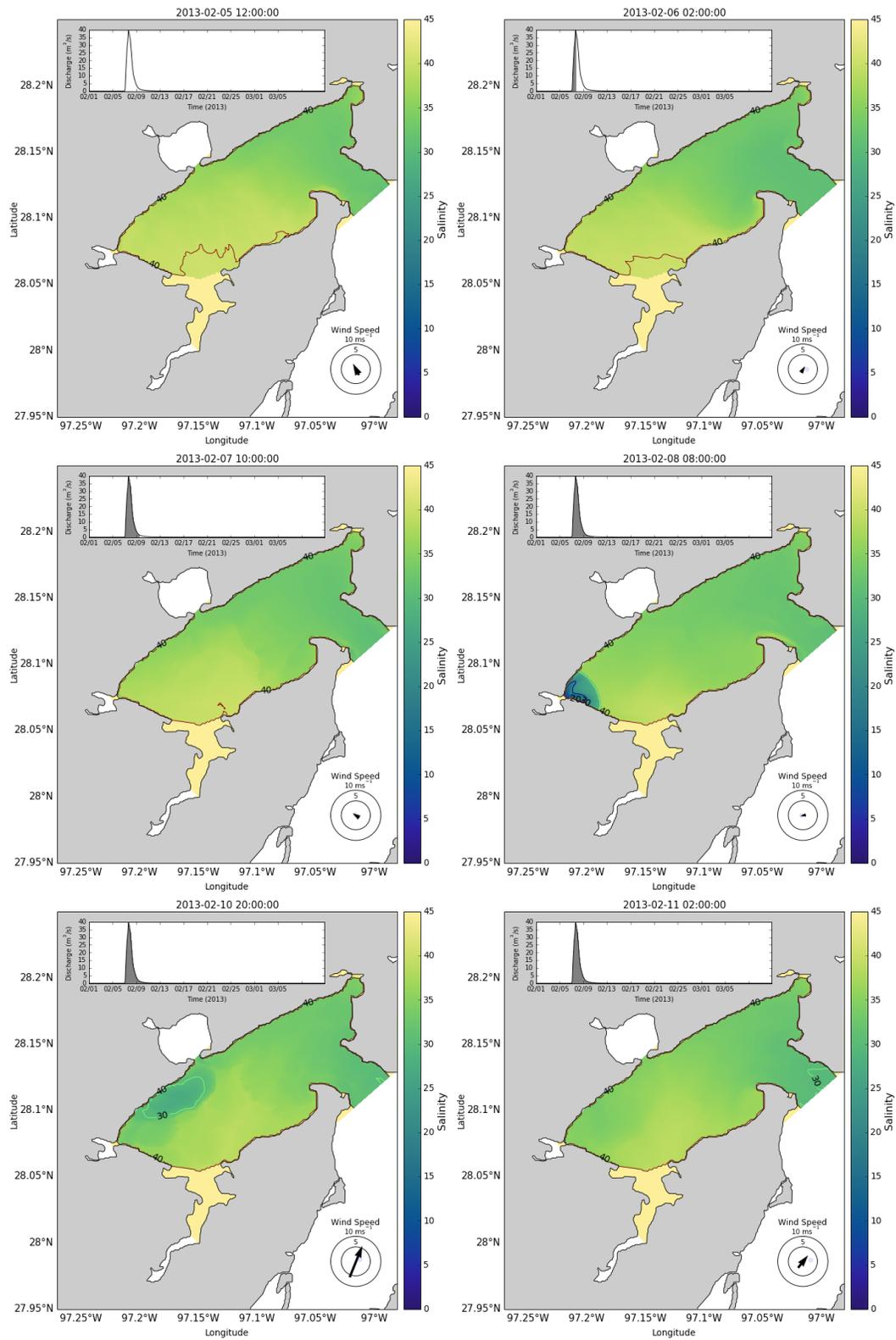


Figure 4.12: Evolution of a river discharge event during February/2013.

The amount of fresh water necessary to change the estuary from a hypersaline regime to normal conditions was discussed before in Section 4.2. The last case shows how this change happened because of the highest input of river discharge in 6 years. The first semester of 2015 added a high volume of fresh water to Copano Bay, which changed the salinity from 45 gkg^{-1} to 20 gkg^{-1} . However, even with the high flux of fresh water in the bay, the inverse estuary condition lasted for other 5 months into 2015, only changing after a high discharge event. This first panel of Figure 4.9 shows that the salinity at the west side is higher than the east side (20 gkg^{-1} compared to 13 gkg^{-1}). The river peak was at 05/12 20:00 pm, with $420 \text{ m}^3\text{s}^{-1}$ of fresh water into Copano Bay, being $267 \text{ m}^3\text{s}^{-1}$ from Aransas River and $153 \text{ m}^3\text{s}^{-1}$ from Mission River. The first signal of fresh water started after 6 hours of the river discharge peak and the wind changed direction after two days as seen in the fourth panel. With a huge amount of fresh water in the Bay, the plume reached its maximum 4 days after the wind changed. The salinity in front of Aransas and Mission River was as low as 5 gkg^{-1} . This change in the regime caused the salinity on the west side to decrease from 20 gkg^{-1} to 10 gkg^{-1} in a matter of days, causing the estuary to switch from inverse to normal. Just like the first case, the big volume of fresher water helped by keeping the low salinity along the bay for a longer period, specially on the west side. The east side did not change much even with the decrease in salinity on the upper bay, keeping a range between 15 gkg^{-1} and 20 gkg^{-1} . This might be related to the wind pattern, where the northwest winds kept the river plume closer to the river mouths.

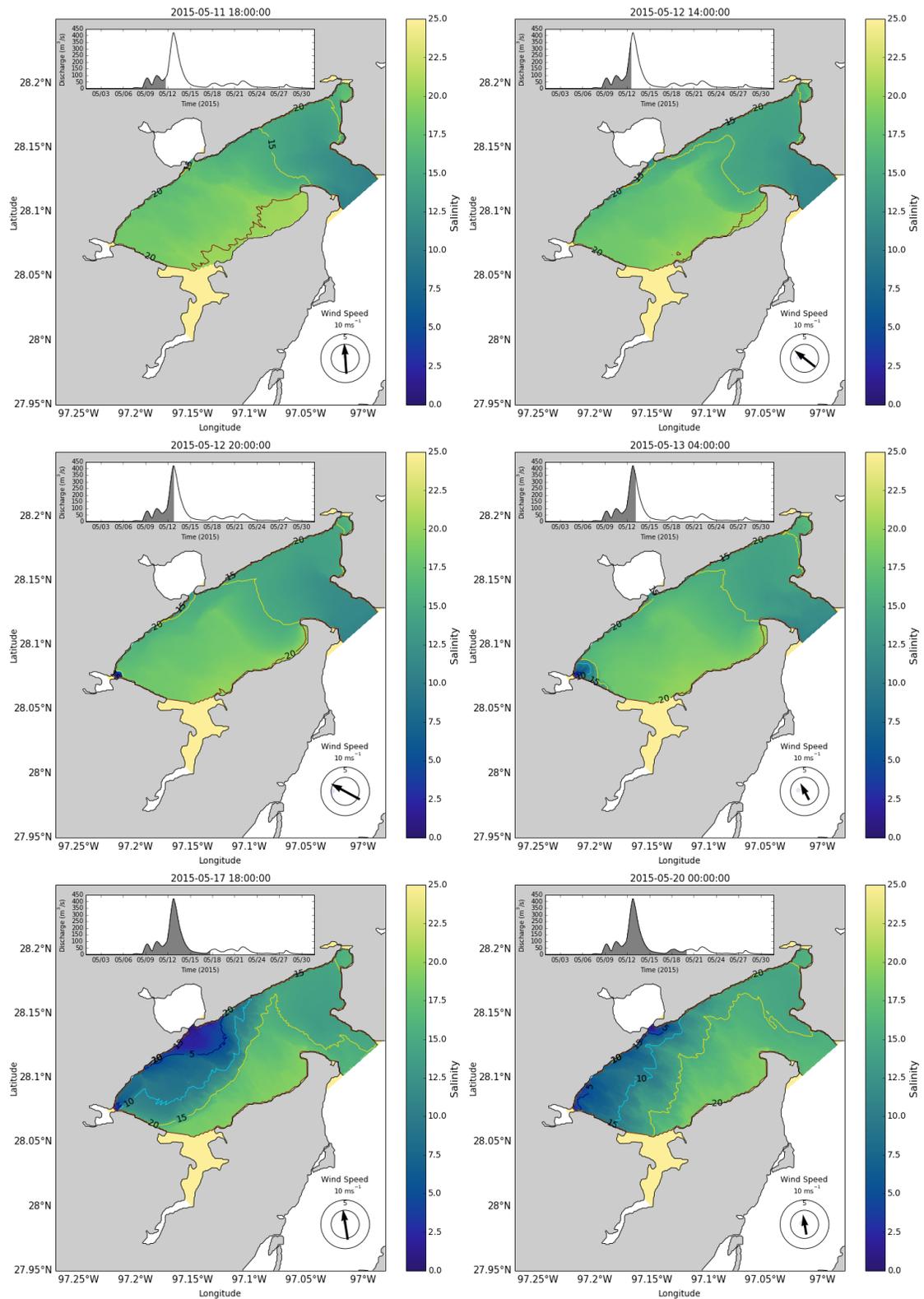


Figure 4.13: Evolution of a river discharge event during May/2015.

A number of factors can and will influence the changes in salinity at Copano Bay, such as tides, river discharge, evaporation and precipitation. Due to the low depth, the bay is constantly influenced by wind changes, which can come with an increase in precipitation and/or river discharge. This change will cause vertical and horizontal stratification that will be intensified because of the dynamics. As seen in the first and last case, a high river discharge can cause a decrease on the salinity of the upper bay, but do not affect much the east side of the bay, which is more influenced by the tides and the salinity from Aransas Bay. The results show that even though the two locations (east and west) are relatively close (around 20 km), they are still separated by the dynamics, where the west side is highly influenced by the river and the east side by the tides. These assumptions are confirmed because of the low depth, considering the fact that a small change on the surface will affect the whole water column. The second case shows that the salinity stayed high along the west side because of the low interaction with the tidal plume and almost no river discharge. The 3 years period only confirm the results shown by Bianchi et al. (1999), who estimated a residence time of one year for Aransas and Copano Bay.

Besides the amount of fresh water, the adjustment of the bay also depends on the initial salinity before the event. The first and second case had a difference between the lowest salinity and the initial salinity of 10 gkg^{-1} to 15 gkg^{-1} . For the second event, this difference was 30 gkg^{-1} . The second case took a longer time to recover from the drop on salinity when compared to the other two cases, showing that to mix the water column from 10 gkg^{-1} to 40 gkg^{-1} takes longer than to mix from 10 gkg^{-1} back to 20 gkg^{-1} .

Regarding the vertical stratification, the east side is weakly stratified due to the (mostly) higher salinity from Aransas Bay, but it is not influenced by the west side at all. The salinity pattern on this side will indeed be similar to the west side over the years, but the local events have more influence over the west than over

the east side. The west side, on the other hand, can be highly stratified and for a long period depending on the amount of fresh water. Even though it's stronger, the stratification on the west side is more dependable on atmospheric forcing and river discharge, while the stratification on the east side is more constant, only depending on the tidal cycle. The rate in which the salinity respond to sporadic events can completely change the dynamics of the bay, which will have influence over biological and chemical processes in the bay.

4.4 Property Histograms

For this section we used the volume-weighted probability density function (PDF) to calculate the portion of salinity, temperature, density, vertical stratification and horizontal stratification for each time step (8 hours resolution) over the 6 years of simulations. This function is based on a range for each variable (known as bins), where the total volume of water in each class of a determined property can be computed by multiplying the PDF by the total volume of the bay. The output is a histogram that shows the range in which the concentration of a property is higher.

In order to exemplify the analysis, Figure 4.14 shows the histograms based on the PDF analysis for the first case from Section 4.3, which took place during January/2010. Starting from the analysis of salinity, the figure shows that for the first week of the month, the salinity of the bay was around 13 gkg^{-1} , followed by the density, which showed only one major density class with water around 15 kgm^{-3} . After the first week, the temperature of the bay dropped from $13 \text{ }^\circ\text{C}$ to around $7 \text{ }^\circ\text{C}$, which caused density to increase and split in two different water masses, one with 15 kgm^{-3} and another one with 17 kgm^{-3} . This drop in temperature, probably due to a front or storm, was not followed by salinity, which was kept constant around 13 gkg^{-1} . Also, this first drop barely affected the vertical and horizontal stratification, considering the fact that the horizontal stratification kept a constant range between $10^{-5.5}$ and 10^{-6} and the vertical stratification practically followed the

tides.

As mentioned before, without any river discharge, the vertical stratification in the bay is controlled by the input of salty water from Aransas Bay, which mostly affects the east side. The west side remains mixed most of the time. By mid-January a flood event happened with an input of $160 \text{ m}^3\text{s}^{-1}$ of fresh water into the bay. For the temperature, this event only caused a minor drop, but not enough to stop the constant increase rate. For salinity, however, one can notice some parcel of water with salinity lower than 10 gkg^{-1} and also a slight drop in salinity around the 15th from 12 gkg^{-1} to 10 gkg^{-1} . The other parameters also responded to this input of fresh water. The horizontal stratification increased the range from $10^{-5.5}/10^{-6.0}$ to $10^{-5.0}/10^{-5.5}$, indicating the west side was now fresher than the east side. This decrease in salinity after the river discharge expanded the salinity range in the bay, where the lower limit is now around 10 gkg^{-1} and the upper limit around 15 gkg^{-1} , showing that the amount of fresh water was big enough to cause a decrease in the overall salinity of the bay (before the range was from 12 gkg^{-1} to 14 gkg^{-1}). The vertical stratification also had a peak during the flooding event, which was shown before as the difference between the salinity at the surface and at the bottom. Following the drop on salinity at the west side, the density only dropped by 1 kgm^{-3} , but now with a bigger range between 15 kgm^{-3} and 17 kgm^{-3} . This new range resulted in two different water masses as seen around the 20th day of the month. Around the 25th, the temperature dropped again causing a slight increase in density but without a change in salinity. It is important to notice here that the density of the bay follows the salinity profile, as expected, but without a river event, the salinity doesn't change much, meaning that small changes in density are caused by the temperature, since the two are inversely proportional, i.e. an increase in temperature causes a decrease in density.

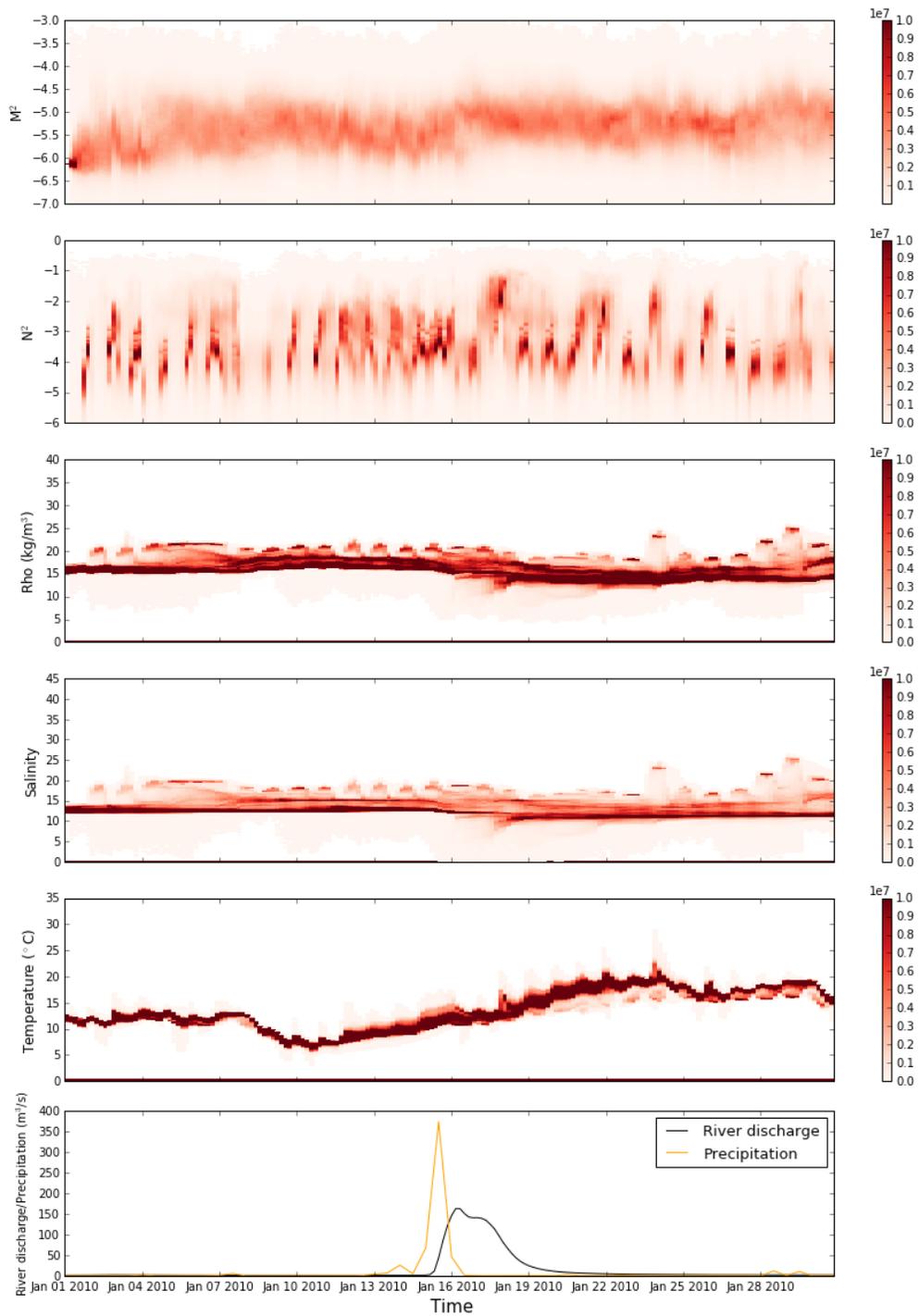


Figure 4.14: Volume-weighted probability density function for horizontal stratification (M^2), vertical stratification (N^2), density (Rho), salinity, temperature and river discharge (m^3s^{-1}) for January/2010 .

Now we follow the same analysis for each year. Again, the same approach used in Section 4.2 will be used here, where each period is considered as a 'dry year', 'transition year' or 'wet year' depending on their characteristics. Figure 4.15 shows the histogram plot for each property and how they changed over the years.

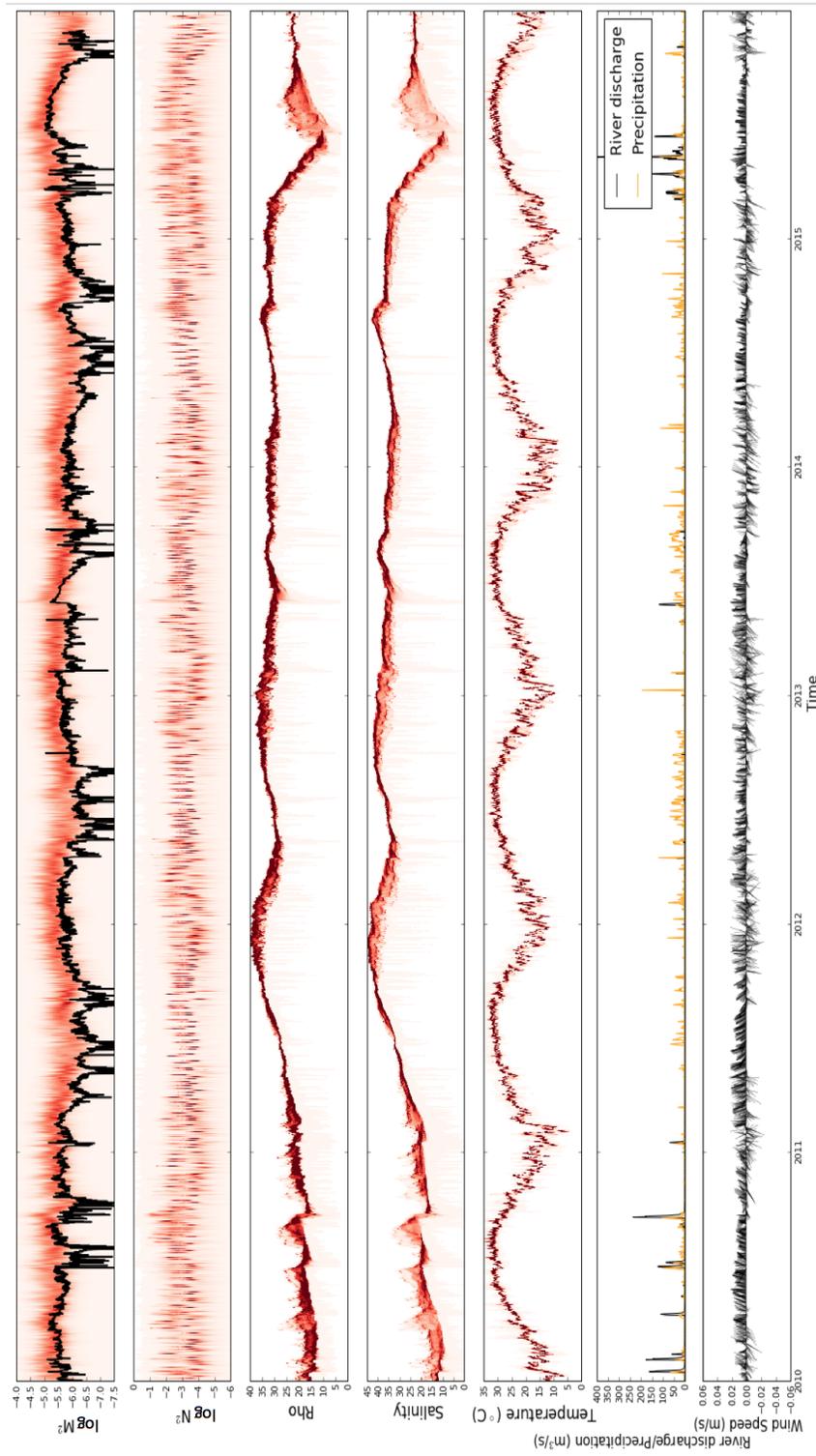


Figure 4.15: Volume-weighted probability density function for horizontal stratification (M^2), vertical stratification (N^2), density (Rho), salinity, temperature and river discharge (m^3s^{-1}) between Jan/2010 and Dec/2015.

The year of 2010 started with two events of high river discharge in January/2010 and February/2010. These events caused a drop on salinity on the west side, resulting on two different water masses, one with density below 15 kgm^{-3} , which occupied the west side of the bay, and one with density values around 17 kgm^{-3} , occupying the east side of the bay, in constant exchange of salty water with Aransas Bay. This scenario lasted for around 6 months, where the density followed the salinity trend. As seen in the figure, there were some local events (March/2010, June/2010 and Aug/2010) that caused changes in salinity, density, temperature and horizontal stratification. These events are usually associated to a front or storm event that caused the water temperature to go down. As seen between March/2010 and April/2010, the horizontal stratification increased coinciding with a decrease in temperature and increase in density and salinity. During these periods, there is no dominant water mass and the salinity and density are spread over a larger range. After these events, an increase in river discharge and precipitation collapsed the the salinity and density range, resulting on one single water mass in the bay, as seen between July/2010 and mid-August/2010.

The response to a high river discharge event around September/2010 caused a maximum of horizontal and vertical stratification, followed by a rapid decrease. This pattern can also be seen in Figure 4.5, third row, where right after the difference in salinity at the surface between the east and west side reached its maximum, around 20 gkg^{-1} , the west side recovered faster than the east side due to strong winds that collapsed the horizontal stratification, causing the difference between them to go negative, i.e. the west side was saltier than the east side. During the following months the horizontal stratification increased again followed by the constant increase rate of salinity and density. As mentioned before for the first case, the density follows the salinity pattern, but it's the temperature that will have effect on small and more subtle changes in density. During 2010, as a result of high precipitation and river discharge, the range around vertical stratification

was high throughout the year, with changes depending on the river discharge.

The year of 2011 had only one major river discharge event, which was around mid-January/2011. This event was followed by a slight drop in salinity and density, but did not affect much the stratification in the bay. By the beginning of February/2011 the temperature dropped from 25 °C to 5 °C causing a small increase in density, which led to two distinct water masses in the bay between February/2011 and March/2011. Because of the low river discharge and relatively low precipitation, the salinity and density of the bay increased at a constant rate, while the temperature followed the expected pattern, i.e. high temperatures during summer and lower during winter. During this period, the horizontal stratification decreased, considering that the west site only became saltier over time. As discussed before, from October/2011 to December/2011, the salinity on the east side of the bay stabilized around 40 gkg⁻¹, while the salinity on the west side kept increasing, what caused an increase in the horizontal stratification over the last three months. During this period one can see that the density split in two distinct water masses, one less salty on the east side (around 40 gkg⁻¹) and one saltier on the west side (around 45 gkg⁻¹). The small perturbations in density in the last 2 months were mainly caused by changes in temperature. The vertical stratification had its lowest range during summer months, where the winds are more stable and point north. Between the first and last three months, the range of vertical stratification increased due to changes in wind direction, fronts and storms. This response from the winds can also be seen on the low range of temperature during spring and summer.

The third period, named before as 'dry years', is the period between January/2012 and December/2014. It started in 2012 with practically no river discharge and two distinct water masses between January/2012 and mid-April/2012. The water mass with the higher salinity, which started on the west side, occupied a larger portion of the bay, as seen in the upper limit of the density and salin-

ity profiles. During this period, the horizontal stratification had a slight increase and only started to drop around May/2012, after a high precipitation event. This event reduced the difference between the west and east sides, which resulted in one main water mass in the bay. This condition coincided with a period with higher and more constant precipitation rates, which kept the salinity and density stable for 5 months. By the end of the year, as precipitation levels decreased, the horizontal and vertical stratification increased, since the west side became saltier than the east side again. Again, changes in temperature caused perturbations in the density levels. The following two years, 2013 and 2014, had a similar pattern as 2012. Both years started with two different classes of salinity and density, had an increase in vertical and horizontal stratification due to river discharge and/or rain events, which unified the two water masses in the bay, reducing the stratification for a few months, and had final months with increasing stratification and density. Just like 2011, the range for vertical stratification was lower during summer and higher during fall and winter.

From the three 'dry years', one can notice that the salinity and density patterns respond to river discharge and precipitation by decreasing the difference in salinity between the west and east sides. However, since the volume of fresh water into the system is so small when compared to the total volume of the bay, this response will not cause a drastic change in salinity and/or density, meaning that the fresh water can reduce the stratification for a few months, but the evaporation will eventually cause the west side to be saltier than the east. During three years the bay alternated between an inverse estuary, which coincided with the fall and winter months, and a normal estuary, which coincided with the rainy seasons, between spring and summer.

The last year, 2015, had the maximum river discharge, which caused the estuary to go from an inverse estuary pattern to a normal one. The year started with the salinity around 35 gkg^{-1} and density around 32 kgm^{-3} . These values only

changed around March/2015, when the river discharge and precipitation started, followed by an gradual increase in horizontal and vertical stratification. Until May/2015, the west side of the bay was still saltier than the bay. After this month, with a maximum river discharge of $400 \text{ m}^3\text{s}^{-1}$ around mid-May/2015, the salinity and density had its largest range, varying from 10 gkg^{-1} to 35 gkg^{-1} for salinity and from 10 kgm^{-3} to 30 kgm^{-3} for density. The pattern found here is similar to the ones found in 2010, but in a much bigger scale. During this period, which lasted for almost 5 months, there was no clear separation between 2 water masses, since the bay was still adjusting from the river discharge. After reaching its maximum during the flood event, the horizontal and vertical stratification gradually decreased showing an effort of the bay to go back to a mixed, non-stratified state. The last three months of 2015 show one water mass in the bay, with salinity around 25 gkg^{-1} and density around 22 kgm^{-3} . The perturbations in density followed the perturbations in temperature.

The comparison between the 3 different periods highlight the differences between each year, depending on the amount of river discharge and precipitation. During 'wet years', the stratification and changes in salinity are limited to the river discharge, since after an event the bay would have two different water masses and would only recover with a lower density and salinity. The horizontal stratification would increase due to the fresh water and would stay in a level higher than before, since now part of the bay, specially the west side, is filled with fresher water. The vertical stratification, which had a higher range when compared to other years, practically followed the tides, mostly because the exchange between the east side of the bay and Aransas Bay. The peaks on vertical stratification are associated to the river discharge. The 'dry years', however, have an opposite pattern. Since the west side is saltier than the east side, the presence of two water masses are due to the hypersaline state, and not due to river or precipitation. During the spring and summer seasons, the precipitation and some river discharge may drop the salin-

ity on the west side, reducing the horizontal and vertical stratification. However, since the salinity in the bay is already high, the low river discharge doesn't have the strength to overcome evaporation, causing the west side to become saltier than the east side after a few months. This pattern is seen after the rainy seasons, where density is split again in two water masses. For a 'wet year' the river discharge increases stratification, and for a 'dry year' the river discharge reduces the stratification.

Based on equation 4.3, the black line on the first row of Figure 4.15 shows the calculation of horizontal stratification only considering the two points that we used as being close to Copano East and West stations. Since they are just two points and they are very close to the river discharge and the south channel, the values for horizontal stratification may differ from the bay. The terms for Equation 4.3 are: $g = 9.8 \text{ ms}^{-2}$ as gravity, $\Delta\rho$ is the difference in density between the two points, here considering only the surface, L is the distance between the two points, which is approximately 16 km, and $\rho_0 = 1025 \text{ kg/m}^{-3}$ is the reference density.

$$M^2 = (g * \Delta\rho)/(L/\rho_0) \quad (4.3)$$

First, the values of horizontal stratification are lower than in the bay because here we consider only the two points, but not the processes in between them. The horizontal stratification between only these points only confirmed what we found for the bay. As we can see, the years we considered 'dry years' and 'transition year' had well defined pattern of high vertical stratification during fall and winter, and a drop during summer and spring. For 2010 and 2015, considered 'wet years', what controlled the vertical stratification between these two points was the input of fresh water in the bay. The values reached it maximum with the fresh water and dropped after flooding events, indicating an attempt of salinity to adjust to the fresh water income. the river discharge events.

5. CONCLUSION

Copano Bay is a very particular environment, with a shallow interior, narrow mouth and sporadic river discharge. The system is influenced by winds, tides and two main rivers: Aransas River and Mission River. This configuration is common in many bays in the Gulf of Mexico, but due to the small size (approximately 200 km²), the scale of processes that affect the bay are in an order of hours to days.

The proposed division in three different classes ('wet year', 'dry year' and 'transition year') to show the salinity patterns in the bay showed satisfactory results when trying to understand how the inter annual precipitation and river discharge regime would affect the salinity throughout the years.

The first analysis of the time series of salinity at the east and west side of the bay, compared to the precipitation and river discharge levels, showed that in years where the precipitation and river discharge are high, such as 2010 and 2015, the salinity of the bay would stay in a range between 10 gkg⁻¹ to 25 gkg⁻¹, with sporadic drops in salinity due to river discharge events. The results also showed that, during these years, the difference between the surface and the bottom salinity can go as high as 20 gkg⁻¹ on the west side and as high as 10 gkg⁻¹ on the east side. This difference is because the west side is more influenced by the river discharge and the east side by the salty water coming from Aransas Bay. The difference between the east and west side was also evidenced, showing an increase in horizontal stratification during flooding events.

The transition between the 'wet years' and 'dry years' was 2011. During this year, the river discharge and precipitation was very low, causing the loss of fresh water (evaporation) to overcome the input of fresh water from precipitation and river discharge. Because of that, salinity in the bay increased at almost a constant rate, which cause a decrease in vertical stratification and horizontal stratification. After 9 months, the salinity stabilized on the east side, while it kept increasing on

the west side. This caused the west side to be saltier than the east side, resulting on an inverse estuary.

During the period between January/2012 and December/2014, the salinity was kept in a range 25 gkg^{-1} and 40 gkg^{-1} , characterizing a hypersaline state when compared to the salinity at Aransas Bay. Almost no river discharge happened in 3 years and the precipitation was also low when compared to 2010 and 2015. This pattern led to the maintenance of the inverse estuary state, indicated by the negative values in Figure 4.5, third row.

The second analysis, based on local events, showed how the change in wind direction would affect the salinity of the bay in a scale of hours and/or days. The first case showed that during January/2010, a high precipitation and river discharge event caused the salinity to drop on the west side by 8 gkg^{-1} and to recover after 2 days. This event did not cause much difference on the east side. The second event, during February/2013, showed how a hypersaline state would be affected by the input of fresh water into the system. After the wind changed, the salinity at the surface dropped from 41 gkg^{-1} to 10 gkg^{-1} , and it took 3 days to recover to the previous state. The reason why the salinity took one extra day to recover is probably due to gradient between the fresh water and the water in the bay. The bay would take longer to go from 10 gkg^{-1} to 41 gkg^{-1} than from 7 gkg^{-1} to 15 gkg^{-1} . The last case, during May/2015, the maximum river discharge episode within 5 years, caused the estuary to go from inverse to normal. The estuary took now a week to adjust to the river discharge and the final salinity was lower than before, indicating a change in the entire bay. For all three cases the salinity on the east side did not change much.

Based on the point where the salinity in the bay reached its lowest value and started to adjust, we estimated approximately how long the bay would take to go from vertically stratified to mixed again. Equation 4.2 shows that the half life for the salinity to start adjusting is approximately 10 hours, which is a very short

time. This is probably due to the small size of the bay. As mentioned before, this is just an estimate, since it depends on many other factors such as the amount of fresh water, the salinity before the event, the wind and the dynamics.

The plots on the model's output on Section 4.3.1 shows the evolution of the river plume for all the three cases. The results showed that regardless of the amount of fresh water, the river plume doesn't reach the mouth of the bay, which is controlled by the tide. This shows that the difference between the east and west side is very well marked. Without any river discharge, the west side will be mostly mixed, while the east side will be weakly stratified due to the constant water exchange with Aransas Bay. As the fresh water enters the system, the west side becomes stratified and the horizontal stratification along the bay is induced. However, since the volume of fresh water is small compared to the total volume of the bay, the plume stays trapped by the north and northwest sides of the bay.

The last analysis showed how the density changed over time in the bay, and how it was affected by temperature and salinity. Also, the results showed the response of vertical and horizontal stratification to changes in density and salinity. Considering first a normal condition, without any river discharge, for a 'wet year', the horizontal stratification is due to the salty water coming from Aransas Bay, which affects mostly the east side. The vertical stratification follows the tides and the density range shows one main water mass. After a flooding event, the vertical stratification is maximum, coinciding with an increase in the horizontal stratification. The input of fresh water causes a larger range of salinity and the density to split in two different water masses, one with lower salinity corresponding to the west side of the bay, and one with a higher salinity, corresponding to the east side of the bay. In this case, the input of fresh water increases the horizontal stratification.

The second case, where the levels of river discharge and precipitation are low, and the bay is in a hypersaline state, the year starts with two water masses with

different density and salinity. The upper limit of density corresponds to the west side, considering the fact that this side is saltier than the east side, while the lower limit corresponds to the side closer to the mouth of the bay. As the rainy seasons approach, followed by some river discharge, the salinity on the west side decreases, causing a decrease on horizontal stratification. In this case, the input of fresh water contributes to west side and east side to be more similar.

For both cases, the temperature changed as expected, i.e. higher temperatures during summer and lower during winter. However, due to extreme events, subtle drops on temperature would cause small perturbations on density, although not enough to change the trend, which followed the salinity pattern.

One other thing that should be mentioned is that, according to Valle-Levinson (2010), inverse estuaries have a more sluggish flux than normal estuaries, which can affect the dynamics of the bay, specially on the west side. Considering that Copano Bay is a source of fish and oyster farming, during the dry season, when the upper bay is saltier than the mouth, the system is more susceptible to water quality problems and to pollutants. Understanding the dynamics under these extreme conditions is also important for the economy and a matter of public health.

Overall, the model validation showed that the three-dimensional model was good at representing the trends in salinity and temperature. Even though we only had data at the surface, the results give a good insight on how the salinity changes in a vertical scale.

As a final conclusion, one can see that even though the mouth of Copano Bay is dominated by the tides, the changes in salinity of the bay is mainly controlled by the river discharge located away from the mouth, at the west side. The variations of the salinity volume due to tides have little effect on the bay, but the input of river discharge can cause a decrease in the overall salinity depending on the amount of fresh water. Still, considering the fact that the adjustment time of the bay is greater than forcing time scale, such as the river discharge, tides and

changes in the wind direction, Copano Bay can be considered an unsteady estuary, where the shallow depths will cause the bay to be mostly mixed with the possibility of having stratification depending on the river input. There is a clear difference in the behavior of the bay regarding the east and west sides, and the 'wet years' and 'dry years' that should be taken in account for the next studies.

6. FUTURE WORKS

As mentioned before in the first section, the monitoring system for Copano Bay only uses a 2D model to describe the salinity pattern in the bay. By neglecting the vertical stratification, the previous works have been applying the models to oil spills, to ecology studies, in a way that the small changes in density are now well represented.

In the future, this work will be sent to the scientific committee of the Mission Aransas National Estuarine Research Reserve, in order to contribute to their research on Copano Bay and Mission-Aransas estuary.

Also, more data is needed to better understand the dynamics of Copano Bay. Since the system is so complex, small changes at the surface can and will cause perturbations in density and stratification. By measuring the salinity, temperature and velocities not only at the surface, but also at the bottom, the models can better estimate horizontal and/or vertical stratification, which will have influence on oyster farming, on the economy, and how the bay responds to pollution and hypersaline conditions.

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