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## ENVIRONMENTAL ENGINEERING | REVIEW ARTICLE

# Practical aspects of meteorology and oceanography for mariners: A guide for the perplexed

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**Abstract:** This paper aims to review and summarize the practical aspects of meteorology and oceanography for navigation, highlighting their influence on shiphandling. It is a review for: gathering, in a summarized way, some useful information for mariners, oceanographers, coastal managers, maritime students and maritime engineers; raising important topics for discussion about the theme; and identifying shortcomings that need more research. Aspects of navigation in Brazilian waters, specifically METÁREA V, are introduced as an example, bringing to light, when applicable, the practical aspects for shallow and restricted waters navigation. The parameters analysed were: clouds, rain, smog, fog, breeze, winds, waves, tides, and coastal and tidal currents. The passage of cold fronts can change winds direction. Also, local winds can overlap the effects of breezes, depending on its intensity. Dense fog, that can reduce visibility to less than 100 m, and rain, which according to its intensity, can reduce visibility to less than 500 m, are examples of some parameters that were checked and are able to reduce visibility when navigating. In addition, were reviewed the concepts of occurrence of rain and squall, and of frontal systems and the expected changes in local weather, pressure and air temperature with their approach. The importance of waves, tides and currents is

### ABOUT THE AUTHOR

Léo Costa Aroucha is a recently graduated oceanographer, formed at Federal University of Pernambuco - UFPE, Brazil; Heitor de Oliveira Duarte is an assistant professor at the Mechanical Engineering Department, UFPE, Brazil; Enrique López Droguett is an associated professor at the Mechanical Engineering Department, Universidad de Chile, Chile; Dóris Regina Aires Veleda is an assistant professor at the Oceanography Department, UFPE, Brazil. Key research activities of the authors are mainly focused on ocean-atmospheric processes and dynamics, highlighting their influence, in particular, at Tropical Atlantic Ocean. Also, the group is also interested for topics in Risk Analysis and Navigation, especially ecological risk assessment and shallow and restricted water effect on ships manoeuvrability, respectively. This research allowed that the group research activities were brought together, since it evolves meteorology, oceanography, risk analysis and shallow and restricted water effects.

### PUBLIC INTEREST STATEMENT

Whether on a private boat, on a tanker, or on a cruise, the weather can become a serious threat when sailing. In addition, the oceanic waves and tides also influence on a ship manoeuvre, especially at shallow waters, when ships movements are restricted. This review article summarizes the main aspects of atmosphere and ocean that affect navigation, focusing at Brazilian waters and highlighting shallow waters navigation features. It contains practical hints and tips to follow when navigating in bad weather, being useful as a guide. The paper assesses weather behaviour at Brazilian coast. Also, it points that is crucial that mariners know what to do when facing adverse atmospheric conditions, in order to avoid maritime accidents, economic lost and human lives. Topics that need more research, particularly the processes already affected by climate change, are also discussed. Noticeably, new technologies would be important for the development of innovative tools that could allow a safer navigation in bad weather.

also verified, especially for shallow and restricted waters navigation. Finally, the authors conclude that the analyses and comprehension of these parameters are crucial for an efficient and safe navigation, and suggest shortcomings that need more research.

**Subjects: Climatology; Meteorology; Meteorologic Oceanography; Physical Oceanography; Environmental Studies; Environmental Management; Ship Operations; Transportation Engineering**

**Keywords: meteorology; oceanography; coastal navigation; risk analysis; Brazilian waters**

## 1. Introduction

The ocean-atmosphere interaction has a fundamental role in navigation. Winds and waves, for example, have direct influence on sea's condition and, consequently, on shiphandling (Chen, Shiotani, & Sasa, 2015; Hsu, Chen, Hsiao, & Shiau, 2013). At sea, natural phenomena can reach huge intensity (Goldenberg, Landsea, & Mestas-Nuñez, 2001), considering that the ocean reserves a great amount of energy as latent heat (i.e. the heat that an "m" mass of a substance requires for a phase change) (Halliday, Resnick, & Walker, 2012). The meteorological and oceanographic parameters are crucial for passage planning, in order to reduce time travel, fuel consumption and risk of damage or vessel's accident (Dooley, 1985). Yet, the navigation of vessels is involving higher risk since the increasing influence of global warming (Chen et al., 2015), that may cause hurricanes where and when they are not use to occur (Pezza & Simmonds, 2005) and most mariners are not aware of that.

Shallow and restricted waters navigation is defined as the navigation in ports, bays, lakes and other navigable waters, where the ship positioning is defined by landmarks and manoeuvre is restricted due to the proximity of dangers and/or reduced depths (Duarte et al., 2016; Miguens, 1996). The ability to handle large ships in shallow and restricted waters is one of the most demanding of a mariner's skills (Crenshaw, 1975; Hutchins, 1996; House, 2007; Inoue, Kubono, Miyasaka, & Hara 1998; Inoue, 2000; Macelrevey & Macelrevey, 2004). When moving ships in such waters, the ship's speed is lower so it feels greater effect of wind, sea and current. In addition, there are several different types of current acting together (i.e. wind currents, tidal currents, rip currents and storm surge), so the resulting current is heterogeneous and less predictable. In fact, approximately 90% of all marine accidents occur in shallow and restricted waters (Cockroft, 1984; Gould, Roed, Koefoed, Bridger, & Moen, 2006; Macelrevey & Macelrevey, 2004). Meteorological disturbances are more intense and have greater effect at shallow waters (Camargo & Harari, 1994). The smaller is the freedom of action of a ship, the greater is the need of setting a meteorological watch (Satow, 1952). Thus, it is very important that the mariner has the knowledge about the influence of natural phenomena on shiphandling for a safe and efficient navigation, especially in shallow and restricted waters.

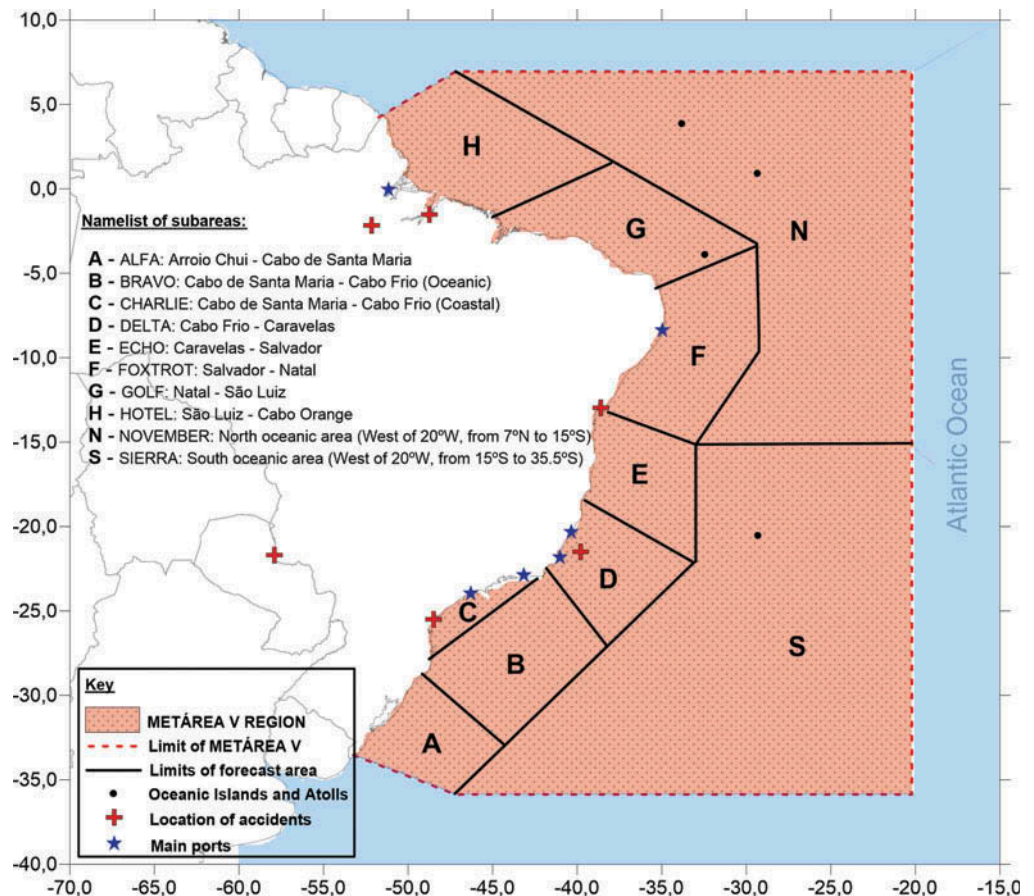
Adverse meteorological and oceanographic conditions (e.g. presence of fog or strong tidal current), when despised or misunderstood, increase the risks to the vessel, cargo, life aboard and surrounding environment, what represents losses and higher cost for any company in the long term (Calazans, 2011; Satow, 1952), especially in these days, when competition requires minimizing costs. In fact, 30% of ship accidents occur under bad weather conditions (Faulkner, 2004) and the chance of occurrence of fatal accidents is increased in 48% if the ship is submitted to adverse weather conditions (Weng & Yang, 2015). The suggestions for mariners are: to be able to understand and interpret actual weather's condition and its evolution, through bulletins and meteorological reports, satellite images, synoptic charts, as well as by feeling (sailor eye); have the knowledge of how these aspects changes ship's behaviour and manoeuvrability; and plan the passage and make necessary adjustments in the most safe and efficient way, always thinking

ahead of the ship and using wind and current to its best advantage, instead of reacting to these forces as they occur.

It is advisable to plan and suit the ship routes according to bad weather warning and to information inserted on nautical, pilot charts (i.e. meteorological navigation) (Calazans, 2011; Satow, 1952). The latter (BRASIL, 1993) gives subsidies for safe shiphandling, since they are navigation tools which contains a graphic summary of past meteorological and oceanographic data (e.g. sea surface temperature (SST), winds, air temperature, currents, isogonics lines, fog and visibility). Mariners use the pilot charts for resolution and prediction of weather and oceanographic phenomena that can occur on vessel's route (Bradarić, 2006). Satow (1952) highlighted the need of knowledge and experience by the mariner for a single-observer forecasting, and emphasized the importance of analysis and comprehension of marine forecasts provided by weather central ashore.

First, this paper aims to conduct a bibliographic review on meteorology and oceanography for navigation, for that we can gather, in a summarized way, basic information not only for mariners, but also for anyone interested in the practical aspects of meteorological navigation. Second, important topics for discussion about the subject are raised with more specific comments for: shallow and restricted waters navigation and how ocean-atmospheric aspects can affect it (clouds, rain, smog, fog, breeze, winds, waves, tides, and coastal and tidal currents); Brazilian waters; and METAREA V region (Figure 1). Third, the paper goes beyond the bibliographic review and suggests strategies to reduce the risk of navigation influenced by ocean-atmosphere activity.

**Figure 1. METÁREA V and Brazilian Coast. Red crosses and blue stars indicate location of accidents and main Brazilian ports, which will be further detailed.**

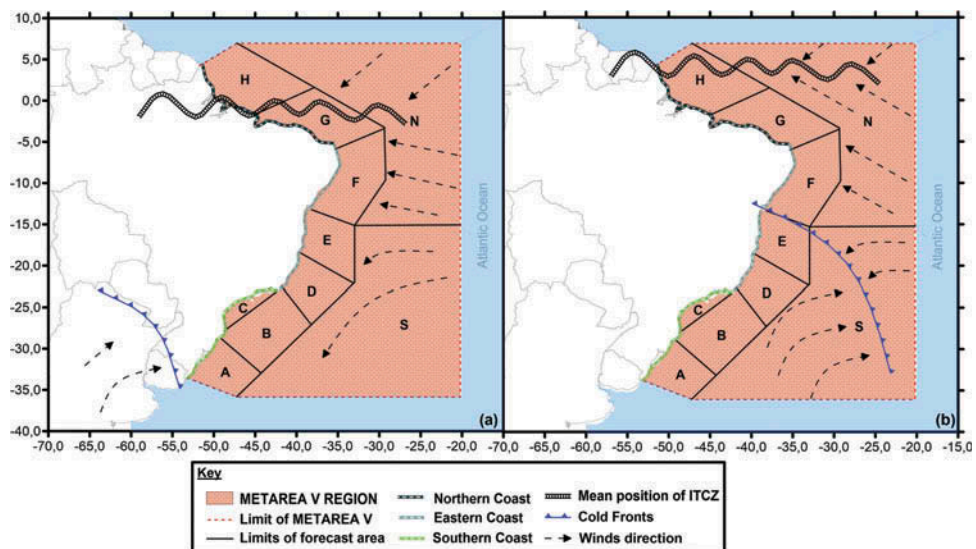


## 2. Study area

This study is focused mainly at Brazilian coastal waters and areas within METAREA V region (delimited from Brazilian coast to meridian of 20° W and latitudes from 7° N to 35.5° S) (Figure 1). METAREA V region represents the maritime area under control of Brazil, and is divided in 10 subareas: ALFA (A), BRAVO (B), CHARLIE (C), DELTA (D), ECHO (E), FOXTROT (F), GOLF (G), HOTEL (H), NOVEMBER (N), SIERRA (S). All these subareas and their forecast limits are showed in Figure 1. The Brazilian Navy, through the Directorate of Hydrography and Navigation (DHN) and the Marine Meteorological Service (SMM), is responsible for the elaboration and divulgation of meteorological forecasts and bad weather warnings for this region. METAREA V provides also a strategical and economical importance to Brazil, since the main Brazilian ports and oil basins are located within the area. Figure 1 also provides the location of reported accidents at Brazilian waters due to adverse weather conditions, and location of few of the main Brazilian ports, that will be further explained.

Here, the characteristics of Brazilian coastal waters, and general aspects of oceanic and atmospheric processes which are important for the study area are detailed, and during this paper, more information regarding some of these aspects is given. The Brazilian Coast can be divided in three portions, according to the “Roteiro” (i.e. script) of Brazilian Coast (DHN [Directorate of Hydrography and Navigation/Navy Hydrography Center], 2016): Northern Coast (from Oiapoque Bay to Calcanhar Cape); Eastern Coast (from Calcanhar Cape to Frio Cape); Southern Coast: (from Frio Cape to Chui Stream). Figure 2 highlights this division. The Roteiro publication (DHN, 2016) complements Brazilian nautical charts, providing useful information regarding the general aspects of the coast, geographical points and ports, allowing that mariners better evaluate the information in the charts. The coastal zone of Brazil extends for near 9,200 km, presenting a variety of coastal environments, which reflects the hydrodynamic regime that each part of the coast is submitted to. Regarding tidal amplitude, the Southern, Eastern and Northern parts of Brazilian coast are classified as microtidal, mesotidal and macrotidal, where maximum tidal amplitude are 2 m, between 2 and 4 m, and above 6 m for each regime, respectively (Calliari, Muehe, Hoefel, & Toldo, 2003). In addition, along the Brazilian coast, the expected wave heights are 1–2 m, and their periods 5–7 secs (Dominguez, 2006). Therefore, the Northern part of Brazilian coast is classified as tide-dominated coast, while the Southern part presents a wave-dominated coast and the Eastern part a mixed-energy coast type (Dominguez, 2006).

**Figure 2. Schematic of major climate elements affecting Brazilian coastal zone in two different moments: (a) start of cold front development at the south of South America and (b) maximum latitude reached by a cold front at Brazilian coast.**



It is known that three major components control the climate and oceanographic processes affecting Brazilian Coast: the cold fronts, the trade winds and the Intertropical Convergence Zone (ITCZ) (Dominguez, 2006), which are represented in Figure 2. Cold fronts coming from south (Figure 2a) (e.g. Argentina) reach their maximum latitude ( $10^{\circ}\text{S}$ ) at autumn and winter (Figure 2b) and are result of northward displacement of polar water masses (Dominguez, 2006; Lobo & Soares, 2007). ITCZ migrates throughout the year with associated precipitations and reduced wind speeds, moving north, away from the coast and reaching  $10^{\circ}\text{N}$  during winter. During summer and fall it approaches Brazilian Northern Coast, reaching its minimum latitude at  $5^{\circ}\text{S}$  (Dominguez, 2006; Lobo & Soares, 2007). Figure 2 demonstrates the influence of ITCZ position in trade winds direction (e.g. GOLF area). Trade winds originated from the South Atlantic high-pressure cell blow all year round, predominantly from the northeast, east and southeast in the Northern and northern part of Eastern Coast, while in the remaining Eastern and Southern Coasts they are mostly from north and northeast (Figure 2a) (Dominguez, 2006). It is important to highlight that winds' direction varies during the year according not only to the position of the ITCZ and but also the influence of the passage of a cold front (Figure 2b). Also, sea breezes can interact with trade winds along the Brazilian Coast, modifying the local wind regime. Roteiro publication (DHN, 2016) gives more detail regarding sea breezes at Brazilian coast. General climate aspects of Brazilian coastal region are: two defined climates (i.e. tropical, from Capricorn to north, average annual temperature of  $26^{\circ}\text{C}$ , and average temperature of coldest month above  $18^{\circ}\text{C}$ ; and temperate, from Capricorn to south, average annual temperature of  $22^{\circ}\text{C}$ , average temperature of coldest month below  $13^{\circ}\text{C}$ , and very distinct seasons) and relative humidity above 85% in the entire Brazilian coast (DHN, 2016). Rain regime varies for each region of the coast of Brazil (DHN, 2016). At the Northern part there are well-defined dry and rainy seasons at the first and second parts of the year, respectively. At the Eastern part, there are also one dry and one rainy season, however, the rainy season is mainly at the winter. The coast of Bahia presents the higher abundance of rain at the Eastern (DHN, 2016). At the Southern part, winter presents usually less precipitation, and rain is most frequent at São Paulo. Visibility is usually good at the Northern Coast, in exception when intense rainfall occurs. On the other hand, at Eastern and especially at the Southern Brazilian Coast fog is very frequent at autumn and winter (DHN, 2016).

Regarding oceanographic aspects, Roteiro publication (DHN, 2016) gives the details: average density of sea water varies from a maximum at the Southern Coast ( $1026.5\text{ kg/m}^3$ ) to a minimum at Northern ( $1022.0\text{ kg/m}^3$ ); average sea surface salinity out of the coast of 35.5, and maximum at the Eastern Coast (37.2) and minimum at Southern (33.3); SST between 20 and  $25^{\circ}\text{C}$ , with minimum in August–September and maximum in march. The wave climate previously cited is controlled by atmospheric circulation, and are associated with cold fronts (especially at the Southern Coast) and trade winds. At the Northern Coast, waves can also be related to storms and hurricanes at the North Atlantic, and, therefore, the Eastern Coast is to two competing waves systems: east-northeastern and south-southeastern waves (Dominguez, 2006). Circulation patterns at the coast are mainly influenced at the surface by two major currents: North Brazil Current (NBC), that flows to north, and Brazil Current (BC), flowing to the south, which both of them are originated by the bifurcation of the central part of the South Equatorial Current (SEC) at  $8\text{--}10^{\circ}\text{N}$  (Lumpkin & Garzoli, 2005; Veeda, Araujo, Zantopp, & Montagne, 2012). The NBC, when retroflects at the Brazilian Northern Coast ( $6\text{--}8^{\circ}\text{N}$ ,  $45\text{--}48^{\circ}\text{W}$ ), is capable of generating rings moving north-westward (Johns, Zantopp, & Goni, 2003). Finally, the winds from northeast acting at the southern part of the Eastern Brazilian Coast (i.e. Frio Cape) and the Southern Brazilian Coast (i.e. Santa Marta Grande Cape) are responsible for generating upwelling processes of low salinity and temperature waters, affecting locally the weather of these regions (Lobo & Soares, 2007; Stramma, 1999).

### 3. Meteorology

#### 3.1. Major meteorological elements

The occurrence of physical phenomena requires energy, which allows the development of the physical process and their multiples transformations. This energy comes from solar radiation, and

the intensity of solar radiation that gets to the Earth surface is a function of the incident angle of the sun (Moran & Morgan, 1994; Reboita, Krusche, Ambrizzi, & Rocha, 2012). The incident angle of sun presents daily and annual variability from place to place on Earth (Chen, Busalacchi, & Rothstein, 1994; Li et al., 2013). This daily variation is the consequence of rotation movement of Earth, while the annual variation is due to the translation movement of Earth (Reboita et al., 2012). These variations are responsible for seasonality (e.g. summer in one hemisphere when sun's relative position is favourable to this hemisphere, while the other hemisphere will have winter, since the sun's relative position is not favourable). Therefore, they are also responsible for the difference between surface temperatures in different places. Besides the sun's angle of incidence, ground and vegetation features affect the total energy that Earth absorbs (Dashew & Dashew, 1998). These aspects influence directly in albedo rate (i.e. *reflected solar radiation/received solar radiation*) which is also very important for the difference between surface temperatures in different places on Earth. Same latitude places can present different temperatures. This difference is due to different rates of reflected and received solar radiation, which reflects characteristics of local ground and vegetation (Jiang, Zhang, & Lang, 2011; Swann, Fung, Levis, Bonan, & Doney, 2010). In Polar Regions, albedo rate tends to be higher (Donohoe & Battisti, 2011). Since snow surfaces have a high capacity solar radiation reflection, they are more likely to raise albedo rate. That is why, in these regions, the surface tends to be even colder. The surface temperature variation influences the surface air temperature, initiating and intensifying the physical processes of heat transport and transformation (Fraza & Elsner, 2015). The transformation and interaction of environmental aspects allow the evolution of the weather state, which can reach great intensity, affecting sea's condition, winds circulation and, consequently, any activity at sea such as navigation.

A considerable parameter for passage planning is SST. It has huge importance on ocean-atmosphere interaction, because it influences, significantly, the air-cooling. A cold SST can result in the formation of fog (i.e. clouds that are formed in the lowest atmosphere layer, next to the surface) (Koračin et al., 2014), mist (i.e. atmospheric steam that can appears like a weak fog) (Taylor, 1917) or smog (i.e. *smoke + fog*, where the carbon particles from the smoke turn impure the water contained in the atmosphere, generating air saturation quickly) (Miguens, 1996). The exact temperature to define a cold SST is dependent on air temperature, humidity and salinity of the water (Saunders, 1964). More details about fog, mist and smog possibility and probability of formation will be described further in this section. On the other hand, a high SST can intensify the convective process, the formation of Cumulonimbus clouds (i.e. clouds with big vertical development, characterized by causing storms, thunders, rain, hail and changes in local temperature and pressure) and even the development of hurricanes and storms (when SST >27°C) (Garreaud & Wallace, 1997; Holweg, 2000; Molion, 1987). Hurricanes do not occur in Brazilian waters. The reason will be explained in Section 2.4.

Variations on SST are not common, but can occur due to maritime currents with different temperatures or due to upwelling (i.e. rise of cold water from the deep to the surface, usually carrying nutrients that enhances biological productivity) (Peterson & Stramma, 1991). Cold upwelled waters can also change local weather. The weather of upwelling regions is likely to present fog (that can reduce mariner's visibility), stratified atmosphere, little convective activity and little rain (Garreaud, Barichivich, Christie, & Maldonado, 2008; Johnstone & Dawson, 2010). The significant daily and annual variations of air surface temperature, in contrast with the small variation on SST, can cause phenomena such as breeze (i.e. winds that blows on shore from the sea to the coast or from the coast to the sea) (Reboita et al., 2012) and fog, depending on seasonality (Sannino, 1989). In tropical regions (30°C > SST > 26°C) (i.e. from the Maranhense Gulf (2°S) to the Paraíba do Sul coastal plain (21.833° S) (Leão & Dominguez, 2000), the evaporation of seawater is almost instantaneous (Ponte & Vinogradova, 2016). It results in extraordinary energy transference from ocean to atmosphere, originating the formation of clouds and rain. The SST is one of the factors that explain why rainfall is so intense on tropics, seriously affecting the visibility of mariners (Kousky, 1980).

Some aspects can affect the mariner's visibility, i.e. cloudiness, rain, mist and fog. The observation of cloudiness allows the mariner to understand the conditions of atmosphere stability, that is why it is required by law to have the Clouds Frame on board for identification of clouds (COLREGS, 2005). This observation can assist mariners in the understanding of what kind of cloud is present. The most important clouds to be aware are introduced: stratus clouds, which are associated with good atmospheric conditions; Cumulonimbus (Cb) clouds, which indicate bad atmospheric conditions, air turbulence in high atmospheric layers, thunders, lightning, storms and intense rain (Garreaud & Wallace, 1997); and Cirrus clouds, which can indicate both situations. If a mariner sees stationary Cirrus clouds in the horizon, it indicates dry air and, consequently, good weather condition. On the other hand, prefrontal Cirrus (known as "Mare's Tails") moving in direction of the ship can indicate an approach of bad weather (Moran & Morgan, 1994), since this type of Cirrus occurs on the top of a Cumulonimbus cloud, which are associated with bad weather conditions (Dashew & Dashew, 1998). Cloud thickness can be estimated by observing the clarity that crosses the cloud (e.g. Cumulonimbus causes a darker sky, because it is too thick) (Dashew & Dashew, 1998). Cloud development is associated with the concept of stability. Great amount of clouds in the sky indicates a certain atmospheric instability (i.e. the situation when there are propitious conditions for air up and down movements, which is bad for navigation), that has direct influence on sea's condition for navigation; although less number of clouds in the sky can indicate an atmospheric stability (situation when there are no favourable conditions for air up and down movements, which is good for navigation) (Lobo & Soares, 2007). Knowledge of surface temperature is crucial for the forecasting of air instability and clouds development (Satow, 1952).

Regarding fog, there are two types: radiation fog and advection fog. The former occurs on the continent and it is not common on the ocean. The latter is the most important at sea. It occurs when a hot and humid air mass moves above a cold sea surface (Koračin et al., 2014). For the possibility of fog formation, SST must be smaller than the dew point temperature (DPT) (i.e. temperature when air reaches saturated conditions), and on sea fog days the DPT is 5°C greater than days without fog (Kim & Yum, 2010). The probability of fog occurrence increases when the difference between air temperature and DPT is less than 2°C for coastal and restricted waters navigation and air humidity around 95% (Lobo & Soares, 2007). The presence of fog can be very dangerous for navigation, especially in restricted waters where dangers are closer. Dense fog is responsible for 32% of all accidents at sea worldwide, 40% at the Atlantic (Tremant, 1987). Considering the fact that it occurs on the ocean surface, it difficult visual navigation, reducing mariners visibility (Koračin et al., 2014). According to Lobo and Soares (2007), atmospheric phenomena can reduce visibility to a distance of:

- Fog: less than 1 km, and in the case of a dense fog, less than 100 m;
- Rain: 1500 m, however a drizzle can reduce visibility in a larger scale. A strong drizzle, for example, can cause less than 500 m visibility;
- Mist: humid mist from 1 km to 2 km, and dry mist from 1 km to 5 km.

### 3.2. Air circulation

This understanding allows mariners to predict what they might expect when shiphandling (Calazans, 2011). For example, when the weather report or synoptic chart mentions the presence of instability line, it means that in this region the mariner will find bad weather condition, with the possibility of intense rain and strong winds due to convective activities from direct circulation originated from instability (Lobo & Soares, 2007). In fact, the observation of surface meteorological charts that indicate horizontal gradients of pressure (i.e. synoptic charts) is very important for navigation. The wind tends to blow almost parallel to isobars (i.e. lines of constant pressure with 4hPa spacing between them) and the closer the isobars the stronger the wind. However, near surface, in the friction layer, the turbulent friction that the Earth exerts on the air slows the wind down (Chiang & Zebiak, 2000). This slowing wind reduces the Coriolis force, and the pressure gradient force becomes more dominant, so the total wind deflects slightly towards lower pressure.

High- and low-pressure centres in atmosphere cause direct influence on navigation. Low-pressure centre is an area characterized by the pressure decrease from the periphery to the centre of the area, which is limited by nearly circular isobars (Ahrens, 2015). The air circulation in a low-pressure centre is convergent, associated with vertical ascendant movement of air, and clockwise direction on Southern Hemisphere (SH). Centre of high pressure is an area characterized by the pressure increase from the periphery to the centre of the area, which is also limited by nearly circular isobars (Ahrens, 2015). The air circulation in a high-pressure centre is divergent, associated with vertical descendent movement of air, and counter-clockwise direction on SH. When these pressure systems move, change on weather conditions occurs in the region (Carvalho, Jones, & Liebmann, 2004; Kousky, 1979). Therefore, is extremely important that the mariner follows the position and displacements of high- and low-pressure centres when consulting synoptic charts, and be always verifying the meteorological report. The pressure variation should be verified on board through a barometric tendency plot in an attempt of predicting the weather's condition (Calazans, 2011). Through local observation of wind direction, the mariner could identify his position related with these high- and low-pressure centres. For that, there is a practical rule in navigation based on air circulation patterns: the mariner must always position backwards the winds direction (i.e. in a position where the wind is striking his back) and he will have the low-pressure centres on his right and the high-pressure centres on his left in Southern Hemisphere; while the opposite is true for the Northern Hemisphere (Holweg, 2000).

Regarding air circulation, there are a several types of winds. The most important ones for mariner's understanding are detached:

A. General atmosphere circulation: the general atmosphere circulation generates winds that blow in different directions, transporting heat and contributing to thermal balance of Earth (Moran & Morgan, 1994). It can be observed in two different directions (i.e. meridional and zonal circulation). In meridional circulation are observed three cells in each hemisphere: the Hadley cell in the tropics, with surface trade winds converging from tropics to equator, forming the ITCZ, a Ferrel cell with westerly winds of middle latitudes flowing from tropics to 60 degrees latitude and, a Polar cell with easterly winds from 60 to 90 degrees latitude (Ahrens, 2015). This circulation is affected by the earth's rotation expressed by the Coriolis Force, and allows the occurrence of Zonal circulation, with East winds on the Equatorial Belt, trade winds from NE (in Northern Hemisphere—NH) and SE (in SH) on Tropics and West winds on midlatitudes (Reboita et al., 2012). The Coriolis Effect on circulation is to deflect the circulation towards the right in the NH and towards the left in the SH (Lobo & Soares, 2007);

B. Gradient winds: large-scale horizontal winds, without friction and that blow parallel to isobars through a curve way (Lobo & Soares, 2007). It is a result from the interaction between three forces: pressure gradient, Coriolis and centripetal;

C. Surface winds: They are the resulting wind from the interaction between four forces: pressure gradient, Coriolis, centripetal and friction (Lobo & Soares, 2007). When analysing the synoptic charts, it is important the perception of isobars layout and regions with high-pressure gradient, since winds moves parallel to isobars and pressure gradient indicates winds force (Dashew & Dashew, 1998).

D. Breeze: Land and sea breeze are meteorological processes well known by mariners (Lobo & Soares, 2007). Breezes are originated from the difference between air temperature on the land and on the sea surface, generating a pressure gradient (Crosman & Horel, 2010). The sea breeze results in a horizontal wind from the sea to the land in low levels (i.e. onshore wind) (Reboita et al., 2012) acting in the afternoon, when the land temperature is higher than SST, allowing air ascendant above the continent. Therefore, it requires special attention from the mariner that demands access to ports in the afternoon (Lobo & Soares, 2007). The land breeze results in a wind on the opposite direction, from the land to the sea (i.e. offshore wind), acting in the dawn and morning, when SST is higher than land temperature, allowing air ascendant above the sea (Reboita et al., 2012). These processes can be very significant in some regions,



especially for navigation in shallow and restricted waters, because it occurs on the coast. However, it also is important to observe the influence of large scale winds that can blow in an opposite direction to the breeze. For example, in Brazilian coast, in FOXTROT area (i.e. from Salvador to Natal) (Lobo & Soares, 2007), the offshore breezes do not occur in many mornings of the year due to the influence of trade winds that are frequently stronger than the influence of offshore breezes. The breeze intensity is sensitive to large-scale wind speeds, changing significantly when the speed of large-scale wind changes (Zhong & Takle, 1993). Thus, the resulting wind (e.g. in a port) will be the sum of vectors between the breeze and the larger scale winds. The resulting wind will only blow offshore when the land breeze is stronger than the trade winds. Local winds can also overlap the effects of breezes, depending on its intensity (Truccolo, 2011). An offshore wind is usually favourable to navigation because it makes the water smooth.

The atmospheric circulation can also affect sea-level variability, which is important for harbour; buildings close coastal waters; as well for navigation security (Dailidienė, Davulienė, Tilickis, Stankevičius, & Myrberg, 2006). The influence occurs, for example, along the southeast Brazilian coast, in the Cabo Frio region, from September to April, when the atmospheric circulation is strongly influenced by the large-scale South Atlantic high-pressure centre, which makes the prevailing winds blow from the northeast with a large component parallel to the coast. This favours the occurrence of coastal upwelling in the region (Franchito, Brahmananda Rao, Oda, & Conforte, 2007; Mazzini & Barth, 2013).

### 3.3. Development of convective activities

Tropical cyclones are synoptic-scale low-pressure centres that are generated in tropical and subtropical regions, and that can develop and become a hurricane, if it finds favourable conditions to it (Holland & Lander, 1993). According to winds force, they can be classified and graduated in ascending order: low-pressure centres, tropical depression, tropical storm, hurricane. A tropical cyclone must present winds greater than  $33 \text{ ms}^{-1}$  to be classified as a hurricane (Pezza & Simmonds, 2005). The low-pressure centres cause variations around 1 cm per 1 hPa, i.e. a 10 hPa surface pressure drop results in an increase of 10 cm into the sea level, a phenomenon known as “Inverted Barometer Effect” (Campos, De Camargo, & Hararu, 2010).

Tropical cyclones are a threat for safety navigation (Wu, Wen, Peng, Zhang, & Xiao, 2013), and coastal areas are usually the most affected by the passage of a cyclone (e.g. coastal flooding, strong waves and winds that may cause damage). However, it can also cause devastating effects offshore: big waves and strong winds causing sea turmoil, disturbing oceanic navigation; and shipwreck, leaving a cold water trail behind it, turning the region less suitable for posterior tropical cyclones (Calazans, 2011). Therefore, mariners should understand the favourable conditions for tropical cyclones formation and development, as well as its average trajectory and behaviour, as an attempt to avoid the cyclone. The favourable conditions for its formation are: SST > 27°C, liberation of latent heat through condensation, absence of wind shear (i.e. vertical gradient of horizontal wind) (Houchi, Stoffelen, Marseille, & De Kloe, 2010), and atmospheric disturbance associated with air convergence circulation in low layers (Holweg, 2000). The region limited by 0° and 20°N, for example, has high SST and Easterly Waves coming from Africa, that are responsible for the absence of wind shear and for disturbance necessary to initiates the cyclone formation (Leão & Dominguez, 2000; Coutinho & Fisch, 2007). Tropical Waves (i.e. Easterly Waves) are indeed important for hurricanes formation, since 75% of hurricanes and 85% of intense tropical cyclones in the Atlantic are originated from them (Calazans, 2011; Holweg, 2000).

Hurricanes average trajectory tends to follow winds direction and the general air circulation, according to its magnitude (Holweg, 2000). In North Atlantic Ocean, it is formed between 0° and 20°N and is taken to West by East Waves and east trade winds until 30°N latitude. In this latitude, the hurricane changes his course (that was in NW direction) to NE direction, following the general air circulation. Hurricanes also tend to dissipate when: they get to the continent, because the

latent heat from the ocean no longer exists; they are subjected to vertical wind shear, that can arrest the tropical cyclone development by separation of convective areas (Emanuel, 1988, 2007). In the hurricane intermediary region, next to hurricane's "eye", wind reach its maximum intensity, with wind speed exceeding  $50 \text{ ms}^{-1}$  (Goldenberg et al., 2001; Landsea, 1993). The "eye" of a hurricane is a calm region in the centre of the cyclone characterized by very low pressure (Dashew & Dashew, 1998). However, it is practically impossible for a vessel to pass through this region, since, before it reaches the hurricane centre of low pressure, the ship will face the region of maximum wind intensity, which would probably cause an accident. It is advisable for potentially exposed ships the avoidance of the storm-force winds entirely or, if not possible, the minimization of the wind and sea state which the ship is exposed (Dashew & Dashew, 1998; Holweg, 2000). There are strategies to avoid hurricane's trajectory for the development of a safe navigation. The cyclonic wind from the hurricane affects a circular area that can be divided in: navigable semicircle and dangerous semicircle (Holweg, 2000; Lobo & Soares, 2007). This area is divided according to the vector sum of winds, where the dangerous semicircle has the stronger winds, taking the ship towards hurricane's direction. In SH, the dangerous semicircle is on the left of hurricane's trajectory, while in the NH it is on the right of hurricane's trajectory. Consequently, the navigable semicircle is on the right of hurricane's trajectory in SH and in the left on NH (Dashew & Dashew, 1998; Holweg, 2000).

Other aspect that also requires attention from mariners is the development of convective activities. The ocean and the ITCZ intensify this process, because the latent heat from water provides the necessary energy for it (Garreaud & Wallace, 1997). Intensified convective activities can originate Cb clouds, initiating storms (Carvalho et al., 2004), which affects visibility and requires more attention for shiphandling. Cumulonimbus clouds are the only clouds that normally present thunders and lightning, for so, mariners use this observation to identify the approach of storms (Petterssen, 1968). Wind gusts over 30 knots precede storms in Cb (Lobo & Soares, 2007).

### **3.4. Tropical and synoptic systems**

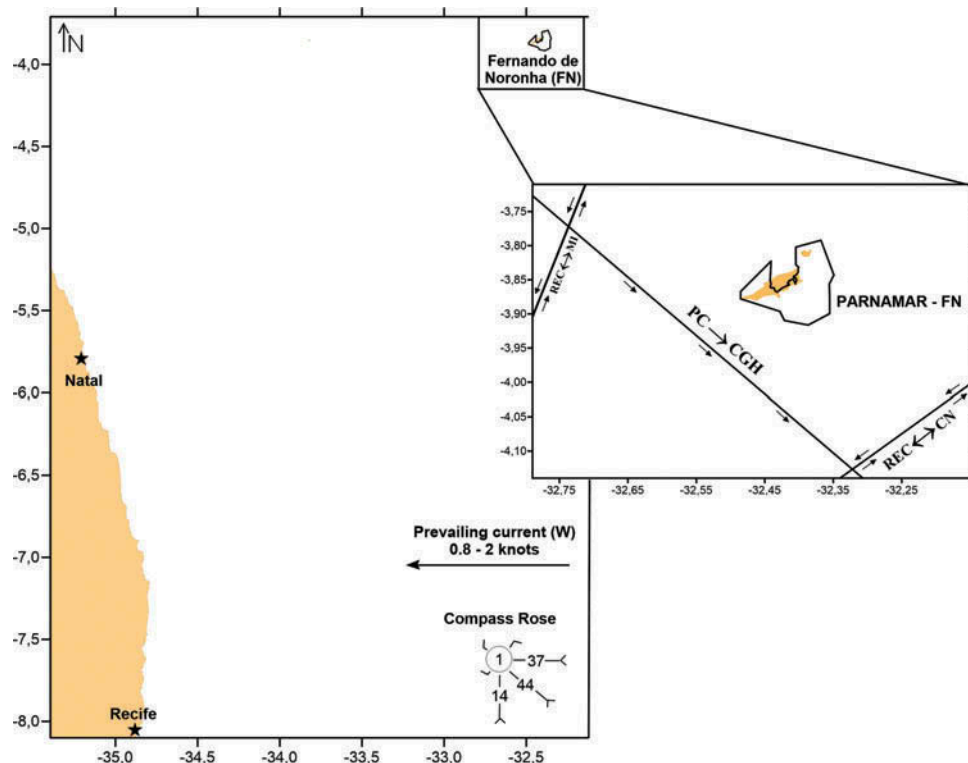
The location of ITCZ varies seasonally, following the thermal equator. The meridional shift on Atlantic is located near  $15^{\circ}\text{N}$ , when is summer in NH—and near  $5^{\circ}\text{S}$  when summer in SH (Schneider, Bischoff, & Haug, 2014). The movement of ITCZ disturbs the air circulation, promoting, in Brazil, a variation of winds direction and cloudiness according to the months during the year (Hastenrath, 1985). In Brazilian north-eastern coast, SE trade winds prevail from September to November, while from December to March the predominance is of NE trade winds (Silva, Façanha, Bezerra, Araújo, & Pitombeira, 2011). The position of ITCZ affects the Northern and North-eastern Brazilian coast, from March to April, time when cloudiness and rain associated with ITCZ are observed in this part of Brazil (Carvalho et al., 2004; Kousky, 1980). This means unfavourable conditions in terms of visibility, but cloudiness and rainfall associated with ITCZ does not mean necessarily strong winds. Through the analysis of pilot and synoptic charts, is concluded that in North and Northeast Brazilian coast the winds are stronger in August and September from SE direction.

Hurricanes do not affect Brazilian coast directly. This fact is due to the non-occurrence of hurricanes in South Atlantic Ocean (Leão & Dominguez, 2000). The favourable conditions for this activity (i.e.  $\text{SST} > 27^{\circ}\text{C}$ , liberation of latent heat through condensation, absence of wind shear, and atmospheric disturbance associated with air convergence circulation in low layers) (De Maria, Knaff, & Connell, 2001; Gray, 1968; Zehr, 1992) are not common to act all together in this region. This fact is good for navigation, since the effects of tropical cyclones are strong winds, high waves and reduced visibility. However, Pezza and Simmonds (2005) reported the occurrence in March 2004 at Brazilian Southern coast of the first South Atlantic hurricane (i.e. hurricane Catarina) ever documented, generated by the weakening of wind shear as a global warming effect. They also suggested the increase in probability of occurrence of South Atlantic tropical cyclones for the next years (Pezza & Simmonds, 2005).

Despite the practically non-occurrence of hurricanes and tropical cyclones in South Atlantic Ocean, the swell (i.e. waves that were generated in a different time and in a different area from where they were observed) (Silva et al., 2011) generated by cyclones in North Atlantic Ocean can move for great distances and reach the Brazilian Northeast coast (north of FOXTROT and GOLF area) generating big waves breaking ashore (Silva et al., 2016). Fernando de Noronha Archipelago (FN), which has landmarks frequently used by mariners in international routes for location at sea, is affected by swells from North Atlantic hurricanes, with long wave period (i.e. 18–20 s) (Teixeira, Cordani, Menor, Teixeira, & Linsker, 2003), forming breaking waves that can get to the height of 5 m. Figure 3 shows three international routes in which mariners should pay attention to such swells (Duarte & Droguett, 2015): Ponce and Colón—Cape of Good Hope (PC—CGH—going); Recife—Madeira Island (REC—MI—going and return); Recife—Cape Nouadhibou (REC—CN—going and return).

Synoptic systems (i.e. term employed to designate an agglomerate of clouds that interact between themselves and that can be associated with high rainfall rate) (Kousky, 1980) are responsible for abrupt variations on sea's conditions, winds direction and intensity, rainfall and visibility, sea and air's temperatures (Yarnal, Comrie, Frakes, & Brown, 2001). It is important to know how to handle the ship and how to interpret the information provided by the Brazilian meteorological report in these situations. Cold fronts move until 64 km/h towards the equator (Kousky, 1980). In Brazil, cold fronts occur more often on the south coast, however they can move up to 13°S of latitude, region of Salvador city (Figure 1) (Leão & Dominguez, 2000). The occurrence of cold fronts is expected in intervals from 5 to 7 days on the Brazilian coast, especially in winter (Lobo & Soares, 2007). In other words, if a cold front passes by a given location today and causes its adverse effects, it is probable that a new cold front will pass by the same location 5–7 days later. During almost the entire year, the cold fronts take 48 h to move from Rio Grande do Sul to Rio de Janeiro (Figure 1) (Lobo & Soares, 2007). In the SH, the cold fronts trajectory is usually to E/NE. Awareness is recommended in the case of changes in physical parameters due to the passage of a

**Figure 3. International routes in Brazilian waters exposed to big swells caused by hurricanes in the NH: Ponce and Colón—Cape of Good Hope (PC—CGH, going); Recife—Madeira Island (REC—MI, going and return); Recife—Cape Nouadhibou (REC—CN, going and return). Prevailing current between 0.8 and 2 knots to W. Prevailing winds from direction SE (44%) and E (37%), force Beaufort 2.**



**Table 1. Change in physical parameters due to the passage of a cold front**

Scenario	Air Pressure	Air Temperature	Wind direction (SH)	Cloudiness
Cold Front approaching	Drops	Raises	Blows from NW or N	Raises (appearance of “Mare’s Tails” Cirrus
After the passage of Cold Front	Raises	Drops	Blows from SW	Rain (reduced visibility) and thunderstorms

cold front (Table 1). Before the approaching of a cold front, when the hot air mass is too dry, the bad weather is only related to strong winds, and cloudiness is not observed in the region. In addition, in Brazilian South and Southeast we observe winds and waves from the sea to the coast, after the passage of a cold front, and winds from the coast to the sea during the approach of the cold front, which the latter is usually favourable to navigation because it smoothes the sea.

Other system that it is advisable to consider for Brazilian coast is the SACZ (South Atlantic Convergence Zone). The SACZ is a band of maximum of cloudiness, rainfall and low layer humidity convergence, occurring from Northwestern Brazil towards Southeastern Brazil, crossing the country (Kodama, 1992). The system is characterized by enhanced convective activity, cloudiness from Amazonia to South Atlantic, and is generated from a combination of factors (Carvalho et al., 2004; De Almeida, Nobre, Haarsma, & Campos, 2007), i.e. a cold front from Brazilian South that stagnate and become stationary for days at Brazilian Southeast, a humidity flux in low layers that comes from Amazonia (Kousky, 1988), and a high-pressure centre in high layers generating an ascendant air movement (Bolivian High). Other factor to be considered is the high-level tropospheric cyclonic vortices (HLTCVs), that are related to the Bolivian High, and that does not allow the development of cloudiness in its centre (Reboita et al., 2012). On the other hand, arc-shaped cloudiness occurs on HLTCVs periphery in surface, generating rainfall in Brazilian Northeast (Kousky & Gan, 1981). All these factors combined allow the development of cloudiness in NW/SE direction over Brazilian continent, generating a high rainfall rate, from 5 to 7 days, especially from Rio de Janeiro to Espírito Santo (Lobo & Soares, 2007). Cold fronts from the South Atlantic Ocean linked to the SACZ can contribute to increased precipitation also over de Brazilian Northeast (Houson-Gbo, Araujo, Boulès, Veleda, & Servain, 2014). Mariners should always be aware of conditions for SACZ formation, since rainfall can drastically reduce mariner’s visibility.

The mariners have access to a great amount of information provided through meteorological satellite images, meteorological reports, synoptic and pilot charts. This information helps them to understand the weather’s condition, what raises the chance of safe navigation. It is very important to know how to interpret these data. Introducing the most significant aspects to be born in mind when looking at such data:

- In infrared images, provided by the National Institute of Spatial Research (INPE/DGI), and which are based on air column temperature information: from the intensity of white in the image, from the lightest to the darkest, Cb clouds are firstly identified, followed by Cirrus, low Stratus, little Cumulus and ocean or continent surface (Lobo & Soares, 2007);
- In synoptic charts, the formation and evolution of low- and high-pressure centres, synoptic systems, and the ITCZ are observed (Calazans, 2011). The trough’s axis are associated with front’s position, and indicates an instable area (Lobo & Soares, 2007), while ITCZ indicates intense convective activity. These charts are provided by DHN/SMM and can be consulted in their website;
- For shallow and restricted waters navigation the weather report for port areas is provided by Meteoromarinha Report (DHN/SMM). The purpose of meteorological reports is to provide the

information for navigation in safe places, with better weather and sea's condition (Calazans, 2011). It provides information about bad weather warning, weather forecast, sky's condition forecast, predominant winds forecast, waves forecast, visibility forecast and temperature tendency forecast.

Some meteorological parameters can indicate significant changes in weather. Air temperature, pressure and humidity indicate the properties of the air mass, and an abrupt change in one of these aspects point out the approach of other air mass. The relative humidity in low temperatures can also indicate the possibility of fog. Observing the winds can show the position of surface pressure systems and horizontal gradient of temperature and pressure. In addition, the observation of the sky by the mariner is very important. Clouds can indicate the weather's condition, according to the type of cloud that is appearing in the sky.

#### 4. Oceanography

In this chapter, the influence of oceanographic aspects in navigation, such as tides, currents and waves is analysed. Sea's condition varies seasonally due to oceanic-atmosphere interaction (Holweg, 2000). SH presents softer climate changes than NH, because SH presents a smaller continental shelf (Flato & Boer, 2001). Oceanic-atmosphere interaction exercises great influence on the Earth's thermal balance, reflecting on climate and weather's condition (De Almeida et al., 2007; Fraza & Elsner, 2015; Peterson & Stramma, 1991). Alfredini, Arasaki, Pezzoli, and Fournier (2013) detached the effects of climate change on shallow waters maritime navigation, since it could change the conditions of bathymetry, tides, winds, currents and waves. The knowledge of main maritime hydrodynamics provides conditions to avoid the sea extreme events hazards influencing in vessel operations (Alfredini, Pezzoli, Cristofori, Dovetta, & Arasaki, 2012).

Water depth is extremely important to be considered, especially in the case of shallow and restricted waters navigation. The effect of depth restrictions is very significant in shallow water, and dominates the ship's behaviour in very shallow water (Barrass, 1995; Duarte et al., 2016; Macelrevey & Macelrevey, 2004; Vantorre, 2003). Sea level varies according to the tides, i.e. regular upward and downward movements of sea level that normally are repeated twice a day (semi-diurnal tides) (Pugh, 1987). In shallow waters, the tidal heights are higher (Tierney, Kantha, & Born, 2000). The semi-diurnal tides exist in Brazilian coast, from the Port of Santana (Amapá) (0.061° S, 51.167° W) to the Port of Vitória (Espírito Santo) (20.322°S, 40.336°W) (Figure 1) allowing the prediction of futures tides height through interpolation method (Lobo & Soares, 2007; Pugh, 1987). From Cabo Frio (Rio de Janeiro) (22°58'21.59" S, 42.014°W) to Brazilian southern coast, inequality diurnal tides occurs (Lobo & Soares, 2007). At Ubatuba (23.300° S, 45.700° W) and Cananéia (25° S, 47.500° W) (i.e. litoral of São Paulo), the sea level may vary hourly 2 m, due to the variability of winds force and direction and to the passage of cold fronts, as long as the daily variability values are about 70 cm at the border of those cities (De Mesquita, 2003).

The real depth is calculated by adding the tides height to the value indicated on Nautical Charts (Lobo & Soares, 2007). Nautical charts provide depths, according to a reference level (i.e. tidal datum, specific sea level used for calculation of tidal depth, guaranteeing that even at low tides in syzygy days, the sea level is higher than the reference level) (Pugh, 1987). This method aims to ensure that water depth presented at nautical chart is always shallower than real depth. However, there are negative tides some days of the year and is advisable that mariners check local tide tables. Moreover, meteorological parameters, such as winds and cold fronts, are able to affect sea-level variation and time of occurrence of minimum and maximum tides (De Mesquita, 2003). For safe navigation it is recommended a calculated depth (depth given by nautical chart + tide given by tide table) of at least the ship's draft plus 2 m (or plus 15% of the ship's draft, whichever is greater) (Miguens, 1996). The Tidal Table, provided by DHN, includes the forecast for the 47 main Brazilian ports, terminals and oceanic islands, and eight ports of Latin America, containing a Correction Table that allows tidal prediction at any time (Miguens, 1996). Other tools that could be used for tidal prediction are tidal prediction softwares, such as: Tidal Analysis Software Kit

(TASK) (Bell, Vassie, & Woodworth, 2000); T\_Tide Harmonic Analysis Toolbox (Pawlowicz, Beardsley, & Lentz, 2002); and ATLANTIDA3.1\_2014 software (Spiridonov, 2014).

Tidal sea-level change at shore is mainly associated with tidal currents along the coast, i.e. currents generated by the tidal movement and are divided in: ebb currents, when water move out of a bay or river with an approach of low tide; and flood currents, when water goes into a bay or river with an approach of high tide (Garrett, 2003; Trujillo & Thurman, 2014). Tidal currents can be a threat for mariners especially when shiphandling in shallow and restricted waters, where they have an amplified effect (Erofeeva, Egbert, & Kosro, 2003). The geography of the region influences tidal currents (Pugh, 1987), resulting in a different behaviour of speed and direction in different points of ports access waterway, cove or bay (Thomson, 1981). Regarding geographic features, some can modify water movements in flood tides or ebb tides, such as: bay's depth, waterway's length and width, presence of shoals, islands, etc. All this information is available on tidal currents reports. Tidal currents in syzygy days are the most worrying situations for shiphandling, especially when combined with other currents at the same direction. Tidal Currents Charts are very useful tools for the identification of those kinds of currents when approaching to ports (Miguens, 1996).

Ocean currents can seriously affect navigation (Chen et al., 2015); therefore, mariners should consult pilot charts and observe current directions and velocity in the present region. For shallow and restricted waters, be aware of storm surge and wind currents (i.e. currents generated by the wind stress due to the friction with the ocean surface, that are among the strongest currents in the sea surface layer) (Tomczak & Godfrey, 1994). Storm surges are unusual variations in sea level mainly driven by atmospheric forcing, such as storms and tropical cyclones (Flather, 2001). This situation is common from Delta to North of Charles areas (Lobo & Soares, 2007), in Brazilian Southeast, due to winds and waves directions (SW, S, SE), after passage of cold fronts (Reboita et al., 2012). Mariners should be alert of this event, especially if coinciding with high-tide periods. Other aspects to mariners pay attention are wind currents, because they influence the vessel, according to the winds direction, when approaching or getting away from the coast. It is also very important to ponder the effects of Ekman drift current (Arnault, 1987). The Ekman drift current is a current generated by the interaction between the wind and the sea surface, influenced by the Coriolis Effect, that moves within an angle to the wind stress and becomes weaker with depth (Tomczak & Godfrey, 1994). This deflection is usually 45° to the left (right) in the SH (NH) (Trujillo & Thurman, 2014). These effects on Brazilian coast, especially in East and Northeast are often observed (Peterson & Stramma, 1991).

High period waves from deep waters can double or even triple in height when they approach shallow waters (Sannino, 1989). Rip currents (i.e. rapid flux of water towards offshore and originated in the surf zone) (Dalrymple, Macmahan, Reniers, & Nelko, 2011) from waves are more dangerous with big wave-length waves (Thomson, 1981). The deep-water waves (i.e. waves occurring when depth >0.5 wavelength) (Trujillo & Thurman, 2014) are responsible for serious damages to ships and coastal installations (Lobo & Soares, 2007). The process of formation of waves initiates on ocean-atmosphere interaction and on transfer of energy from atmosphere to the ocean. When cold winds blow over warm waters and there is an unstable atmospheric layer, a stronger growth of waves is noted (Calkoen, 1992; Kahma, 1981; Young, 1998). The largest the wave height is, larger is the energy dissipation and the impact on the coast. For so, due to the shoaling that increases wave height, mariners should observe more agitated sea condition when approaching to the coast. Besides depth, other aspects can influence wave's behaviour and affect navigation in shallow waters. These aspects are: incidence angle of wave-front; and presence of high background that can promote the occurrence of ripples in the sea (Jimenez, 1981). To identify a wave generating area mariners should analyse synoptic charts, looking for isobars spacing and curvature, as well as area extension where isobars are rectilinear and parallel (Dashew & Dashew, 1998). These parameters give information about wind's intensity and direction, extension of generating area, and persistence (time that the wind keeps its intensity and direction). The small waves will increase in size as long as the wind blows. The stronger the wind tends to blow in the

region, more energy is transferred from the atmosphere to water, which in turn affects the sea's condition (Glejin, Kumar, Balakrishnan Nair, & Singh, 2013). The analysis of synoptic charts is also very important to predict the occurrence of swell, their direction and intensity (Lobo & Soares, 2007), since they represent serious threats to sailing vessels (Zhang & Li, 2017). Those charts warn mariners to avoid locals of severe sea's condition.

## 5. Pilot charts and coastal navigation

### 5.1. Pilot charts

A pilot chart is a navigation tool used for solving some navigation problems (Bradarić, 2006). They are not appropriated for isolated use, but together with other devices that support navigation (Calazans, 2011). They include location of fronts and isobars that allows the prediction of acting synoptic systems and mean sea level (Satow, 1952). The information inserted in pilot charts helps mariners to avoid certain dangers and to choose the most recommended route. Shiphandler should analyse elements that can affect navigation (intensity and direction of winds, for example). Overall, mariners will find some important parameters for navigation in pilot charts, such as: winds, currents, isotherms, routes, isogonics, fog, surface pressure, visibility, air temperature. Pilot charts indicate the most frequent phenomena, based on decades of analysis, month by month, during multidisciplinary researches in the sea (Bradarić, 2006; Lobo & Soares, 2007). However, to develop a safe navigation, the ship handle should be conscious of the monitoring provided by Brazilian Navy.

It is important the habit of consulting pilot charts every month. This consult allows mariners to interpret which parameter vary during the year, and understand how these changes could affect shiphandling. Holweg (2000) suggests even daily risk analysis using pilot charts, depending on the season and on the proximity of a storm. In general, it is the biggest importance that shiphandler know how to interpret pilot charts, as soon as the development of a safety navigation depends not only on the shiphandler skills, but also the information that is given to them, and how they use this information for navigation. However, is a mariner responsibility to evaluate how the weather is developing in its own vicinity (Satow, 1952). Climate charts, which detect significantly changes on weather's state and sea's condition for every ocean, are as well recommended to be used (Lobo & Soares, 2007).

### 5.2. Brazilian coastal navigation

For coastal navigation, Satow (1952) recommended a previous study of the coastal topography and propagation conditions when making the land, also working the course and speed of approach according to the prevailing weather. In fact, adverse weather in ship accidents is known for the increased per cent of losses (40–50%), especially due to foundering (i.e. sinking, leaking or breaking in two caused by rough weather) (Primorac & Parunov, 2016). Ship accidents that occurred from 1998 to 2017 at Brazilian coastal, inland waters and METÁREA V region were investigated through the analysis of the Safety of Accidents and Maritime Incidents Investigation Reports from Brazilian Navy. According to these Reports, adverse weather conditions added to the non-compliance of safety procedures and indications in these situations contributed or were the main cause of six accidents at Brazilian waters at that period. The locations of these accidents are indicated in Figure 1. Two non-fatal accidents pointed for the contribution of the weather conditions due to no consideration of them by the mariner, both happening in October, the first in 2009 at Paranaguá Port (25.491° S, 48.489° W) with a pusher-tug ship, and the latter in 2015, with a cattle vessel, at Vila do Conde Port (1.537° S, 48.751°W). In both cases, foundering was observed, and, while in 2009 the distraction was regarding the tide current velocity and direction, that caused an entrance of water into the ship, in 2015 the agitated sea condition due to storm surge was not considered. Fatal accidents, unfortunately, were the majority in the case of bad weather. One of these accidents was described as the fall into the water of a crew member due to non-compliance of safety procedures and guidelines, including the using of personal protective equipment, when standing at the main deck in bad weather. This Platform Supply Vessel (PSV) accident occurred in

June 2014, at Campos Basin, Rio de Janeiro (21.494° S, 39.795° W). Three major fatal foundering accidents with passenger vessels were also reported. The first occurred in Paraguay River (21.698° S, 57.893° W) which was actually in Paraguay waters, at the Brazilian frontier, in September 2014, and happened due to the persistence of the mariner on keep the sailing even in a rough weather and bad sea state conditions. When approaching the port, a waterspout, formed during the storm, hit the vessel, and was followed by the occurrence of strong wind bursts (93 km/h), and increased wave heights of 1.6 m. This caused the foundering of the vessel and the death of 14 from the 26 people on board. A similar fatal accident was observed at Xingu River (2.167° S, 52.167° W) in August 2017, where the ship was also hit by a waterspout. Added to this was the rain, the crew fatigue, since they were sailing for longer period than allowed, and the persistence of the commander in proceeding, even with the opportunity of overturn when observing the weather state. 23 deaths and 30 survivors were registered at this accident. Finally, the occurrence of a quasi-stationary frontal system could be responsible for generating anomalous atmospheric and oceanic conditions, such as winds, waves, rain and visibility, while those atypical conditions could have caused the foundering of another passenger vessel also in August 2017. This accident occurred at the city of Vera Cruz, Bahia (12.959° S, 38.593° W), and was responsible for 19 fatal and 59 hurt victims.

In addition to adverse weather conditions, sailing in shallow and restricted water can also make ships vulnerable to accidents. The greatest vulnerability at coastal navigation occurs when vessels are approaching the pilot holding point in a pilotage zone. Waters become shallower and, if the ship speed does not decrease, it may cause vibration to the ship and difficulties when manoeuvring. Beyond that, many vessels are converging to this same point, what increases the chances of accidents. Furthermore, isolated dangers might be present for mariners to be aware of when approaching some ports. Here are highlighted these dangers for four of the Brazilian main ports, based on Roteiro publication (DHN, 2016): Açu Port (21.821° S, 41.020° W); Rio de Janeiro Port (22.900° S, 43.167° W); Suape Port (8.383° S, 34.967° W); and Santos Port (23.982° S, 46.293° W). Those ports are indicated in Figure 1. For the Açu Port are highlighted the presence of two sunken hulls: one at 24 m depth, located at 21.800° S, 40.500° W; and other with a visible structure located at 21.731° S, 40.766° W. Rio de Janeiro Port is located at Guanabara Bay. Roteiro (DHN, 2016) indicates the dangers for the entire Guanabara Bay. The great concentration of rocks makes manoeuvre in that region very dangerous. Therefore, it is indicated that only maritime pilots with increased knowledge and experience in sailing in that region are able navigating in depths under 5 m at Guanabara Bay. At Suape Port there are a lot of submerged rocks until 1.5 nm from the coast, and close to the maritime pilot boarding point the only known danger is the Sitiba Shoal, which is 11.5 m depth, marking 116° and with a distance of 0.43 nm from the jetty head lighthouse Suape. Also, berthing manoeuvre at this Port can also be influenced by currents from the Ipojuca river discharge, especially at an ebb tide. Finally, at Santos Port the main danger is regarding the shallow depth close to the margins of the dredged channel along the Piaçaguera channel, which is under 2 m. More detailed information regarding every danger when approaching Brazilian ports and terminals are given in Roteiro publication. Also, Brazilian navy make raster and vector digital nautical charts available, and can be obtained at DHN website, and at the International Centre for Electronic Navigational Charts (IC-ENC) website, respectively.

Moreover, increased vulnerability is likewise observed from the pilot holding point until the berthing, and vice-versa, when the maritime pilot is conducting the pilotage manoeuvre. This specific moment amplifies the probability of accident occurrence due to few aspects: at this point is when ships are most exposed to dangers, such as fixed objects and other vessels sailing nearby; the manoeuvre area is limited; the hull speed is lower, which makes the ship more suitable to be affected by winds and currents, also reducing rudder effectiveness; several currents (induced by wind, tidal currents and rip currents) acting together in shallow waters, what results in less predictable and more heterogeneous prevailing current; ships behaviour and manoeuvrability, in particular, are altered due to the narrowing and shallowing of water in channel and ports. The presence of the maritime pilot, therefore, is crucial to diminish the accident risk. However, ships are



becoming bigger, day by day, presenting greater length, draft and beam, while ports infrastructure is static. As an example, Tannuri, Rateiro, Fucatu, and Ferreira (2014) assessed, using a low-speed manoeuvring simulator, the manoeuvres with an oil tanker of 170.000 gross tonnage, at Suape Port (Figure 1), after the dredging and operations of Abreu e Lima refinery. They have agreed that this manoeuvre has an unacceptable risk with 1 knot of transversal current and 25 knots of SE winds (Tannuri et al., 2014). In practice, many maritime pilots make the manoeuvre. In fact, maritime pilots usually manoeuvre the ships even if the risk is increased, since the economical aspect play the major role at this question.

Another considerable risk and vulnerability of accidents occurs when vessels are approaching oil platforms, at Campos Basin where, many kinds of PSVs converge to the same point. The berthing at the platform is nearly impracticable when facing bad weather conditions, therefore some vessels stay hovering with less power facing current direction, attempting to remain at the same point, while other vessels keep moving along a zigzag course, which helps them to be maintained near the platform. However, adverse conditions can last for weeks, and, due to restricted visibility, high concentration of ships, and fatigue of the crew, this waiting time became a serious threat for the accident occurrence between vessels, especially ships collision.

Lobo and Soares (2007) commented some aspects on routes for navigation on Brazilian coast. Fernando de Noronha and Rocas Atoll region: good weather's condition, weak wind and calm waters. Currents in this region flow to N/NW and to S/SW. For so, is recommended to leave the islands from starboard. On the other hand, mariners that demand Abrolhos Archipelago on north course should leave it from port, due to currents flowing to SW (Castro, Dottori, & Pereira, 2013). Close to Recife, currents are stronger near the coast (Arnault, 1987). Therefore, to avoid the counter-current, is necessary open 10–15 nautical miles (nm), especially who is coming from the South. On Brazilian coast, significant occurrences of bad weather's state and severe sea's condition is observed from Santos to Santa Marta Cape (Charlie and Bravo areas) (Lobo & Soares, 2007), especially from July to October (Arnault, 1987). On July, there is a frequency of 10% of waves higher than 12 ft in areas until 10°S, including areas A, B, D, E, F of Meteoromarinha Report (Lobo & Soares, 2007). Moreover, storm surges in Aracajú and Maceió are observed, especially in August, when cold fronts get to the ocean by latitude of Salvador (Kousky, 1979).

The impossibility of occurrence of hurricane events at the coast of Brazil might now be changing. As pointed by Pezza and Simmonds (2005), the probability of occurrence of South Atlantic tropical cyclones for the future is increasing. Climate change is probably affecting and enhancing this chance. In addition, climate change might also be interfering the occurrence and development of other ocean/atmosphere phenomena. Therefore, since climate change is affecting what is known, an update of basic bibliography on meteorology and oceanography for mariners, and more future research on climate change topic is necessary. Is also recommended an updated mapping of routes used by ships at Brazilian waters and which ocean/atmosphere events have local impacts on these routes and Brazilian ports.

It is suggested for future works the possibility of development of a numerical model that could provide the safest ship route during adverse weather conditions. Currently, this decision is made subjectively by human mind, and the efficiency in the choice of best ship route depends on the mariners' skill and experience. However, this model, which could be built from an input of information contained in nautical and pilot charts, and from data of synoptic systems forecasted for the next few days (e.g. 48 h), would already provide as output the safest route, reducing the risk of accident by the sum of adverse weather conditions and human error. The model could also be very useful if integrated to the Electronic Chart Display Information Systems (ECDIS). The development of possible criteria for ship manoeuvrability under adverse weather conditions and the practical assessment procedures were proposed by Shigunov (2018). In fact, a model combining the safest route output with these manoeuvrability criteria could provide sufficient information for the mariner know exactly how to act in bad weather conditions.

## 6. Conclusion

This work reviewed the practical aspects about meteorology and oceanography for mariners, detaching how they influence the shiphandling. The focus was on Brazilian coast (METÁREA V) and when applicable specific comments for shallow and restricted waters navigation are made, which is responsible for 90% of all marine accidents. The paper allowed the gathering of useful information for mariners, oceanographers, meteorologists and maritime engineers, and can also be helpful as a basic review on oceanographic and meteorological phenomena in Brazil. As follows, the most important aspects for mariners to be aware are raised.

- High SST at the Tropical region is responsible for a large release of latent heat flux to the atmosphere, reason that can contribute to intense rainfall in Brazilian Coast;
- Hurricanes do not occur in the Brazilian coast due to the non-occurrence, at the same time, of the favourable condition for this event (i.e. SST >27°C, absence of wind shear, latent heat liberation to atmosphere, air convergence circulation in low layers). Still, climate change might be changing this scenario;
- Mariners should also be alert with the swell generated by hurricanes at North Atlantic Ocean. These waves can affect Brazilian Coastal Navigation at the Northeastern coast and Brazilian archipelagos (e.g. Fernando de Noronha). The consult of synoptic charts is recommended, not only for the South Atlantic, but also for the North Atlantic;
- Clouds observation indicates the atmospheric condition. High concentration of clouds in the sky represent atmospheric instability, affecting sea's condition and consequently navigation; while clear sky stands for stability of atmosphere;
- Cumulonimbus clouds are associated with storms and intense rainfall (wind gusts over 30 knots precede storms in Cb);
- Prefrontal Cirrus indicate approach of bad weather; and stationary Cirrus point to good weather condition;
- Fog formation is only possible when DPT > SST. When this difference is less than 2°C, and air humidity around 95%, the possibility of fog formation increases for shallow and restricted waters;
- Weak fog reduces visibility to less than 1 km, while this reduction in the case of a dense fog is 100 m. Dense fog is responsible for 40% of all marine accidents at the Atlantic;
- In Brazilian South and Southeast, winds from the coast to the sea can be observed when a cold front approaches, what can smooth the sea. After the passage of a cold front winds from the sea to the coast are observed;
- When the ITCZ is further north (i.e. winter at SH), trade winds prevail from SE direction, while at summer in SH the predominance is of NE trade winds; mainly in North/Northeast Brazilian coast.
- The position of ITCZ further south (i.e. March to April) also difficults the visibility at sea in Northern and North-eastern Brazilian Coast, since clouds and rainfall are associated with this zone;
- The development of cloudiness in NW/SW direction related to the SACZ, HLTCVs and Bolivian High over the Brazilian continent generates a rainfall rate from 5 to 7 days, especially from Rio de Janeiro to Espírito Santo;
- Cold fronts can move up, with E/NE trajectory, to 13°S of latitude at Brazilian coast with a velocity of 64 km/h. They take 48 h to move from Rio Grande do Sul to Rio de Janeiro, and in winter, they usually take 5–7 days to pass by the same location in this region;
- The approach of a cold front is associated with: drop of air pressure, raise of air temperature, winds blowing from NW to N and “Mare’s Tails” Cirrus;
- After the passage of the cold front there is: raise in air pressure, drop in air temperature, winds blowing from SW, reduced visibility during rain, and thunderstorms;

- The knowledge of water depth is crucial especially in shallow and restricted water navigation, where the effect of depth restriction is very significant. The consult of Tidal Tables or use of software, such as TASK, T\_tide and ATLANTIDA3.1\_2014 are suggested;
- The effects of tidal currents, wind currents, rip currents and storm surges are crucial for shallow and restricted waters since they have amplified effect at these waters;
- The geography of the region has influence in tidal currents, resulting in an unexpected behaviour of their direction and velocity;
- Storms surges are common from Delta to Charles areas (i.e. Brazilian Southeast) due to the passage of cold fronts;
- The use of meteorological reports, satellite images, synoptic charts, pilot charts, and tidal currents charts is strongly recommended for safe navigation;
- It is also of great importance that the mariner has a previous knowledge to be able to interpret all of this data available;

It is necessary to anticipate natural forces and be ready for them. These forces are uncontrollable and it is better for mariners to handle and plan navigation in a proactive way, using these natural forces to their benefit and not in a reactive way, fighting against nature, consuming lots of fuel and putting vessel, crew and environment in risk. The best to be done when navigating in bad weather conditions is a good planning, which requires knowledge of the geography, the weather and especially the meteorological phenomena that usually occurs in the region. This planning can be sometimes tedious and time consuming, however the time spent conducting it will be worth it to avoid a storm threat to the vessel and its crew. In shallow and restricted waters the mariner's knowledge and ability have to be even higher, due to closer dangers and higher risk of accident. Some shortcomings need more research:

- The impossibility of hurricane events in Brazilian Coast and how does climate change affect and enhance this chance;
- The development of a model that could predict the probability of fog occurrence in ports, based on parameters such as SST, DPT and humidity;
- Mapping of routes used for ships in Brazilian waters and which ocean-atmospheric events could locally have a significant impact on these routes and on Brazilian ports;
- Update of basic bibliography on meteorology and oceanography for mariners, since climate change is affecting what is known;

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