Chapter 4
Physical Properties and Experiments in Estuaries

The investigation of processes and how estuarine systems function, presents distinct aspects, being conducted with various purposes and objectives. The experimental procedure may include sampling to perform the analysis of spatial and temporal variations of physical measurements of hydrographical properties (salinity, temperature and pressure), currents, sea level oscillations (waves and mainly tides) are of fundamental importance in Physical Oceanography. The experimental procedure may include sampling to perform the analysis of spatial and temporal variations of chemical substances (natural and anthropogenic), sediments in suspension, dissolved gases and marine organisms in the water column and at the bottom.

The physical processes common to all estuaries are their cyclical motions and the mixing of the water masses with contrasting origins: the fresh water discharged by rivers and the seawater from the ocean. As result of this process, associated with generating forces of the motions, the estuaries are non-homogeneous water bodies and their properties may vary in wide time and spatial scales presented in Chap. 2.

Taking into account the comprehensive and systematic article of Kjerfve (1979) the basic principles of measurements, reduction and data edition of estuarine properties will be presented. These data are the result of measurements of vector and scalar physical properties, and the determination of dependent properties necessary to the estuarine knowledge to study its environmental and dynamical properties. According to the technical report of Unesco (1985), the physical properties must be expressed, whenever possible, in the Standard of International Unity System, usually abbreviate as SI unity.

4.1 Research Planning

Investigations into the behavior and estuaries characteristics take many forms and are initiated with varying purposes. Field studies could include water samples to determine concentrations of nutrients, ATP, plankton, suspended sediments, pH,

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dissolved gases, and many others properties. However, independent of the discipline, all field-oriented estuarine studies include current velocity (speed and direction), water temperature and salinity measurements, associated with river discharge, tide measurements and meteorological variables, as wind speed and direction, and echo sounder measurements. Remote sensing may also be included in the investigation.

Estuaries typically experience great spatial variations, seasonal, fortnightly, semi-diurnal and/or diurnal oscillations in water level, velocity and material concentrations. This is primarily due to a combination of tidal influence, fresh-water river discharge, meteorological forcing, and the constraints imposed by the configuration and morphology of the estuary. Thus, the representativeness of any set of estuarine measurements is highly dependent on the sampling design (choice of sampling locations, sampling rate, and study duration), as well as a rational procedure of analysis and synthesis of the data. These results are used not only for the spatial and temporal variations, but also to the estuary classification and determination of flux and transports, as well as to validate theoretical results generated by analytical and numerical models.

Before any experimental investigation, a detailed analysis of the objectives and the theoretical aspects must be accomplished; this makes it possible to decide what properties must be measured, and to establish the procedure analysis of each variable for its convenient reduction.

In the classical book of Dyer (1973), examples are presented of typical estuaries illustrating the propertie's variability under the influence of different tidal amplitude, river discharge and geomorphology characteristics. In these examples, the property descriptions (temperature, salinity and current velocity) were made based in averaged values in transversal and longitudinal sections, taking into account the local variability. Other articles (Stommel 1953a; Dyer 1977; Kjerfve and Proehl 1979 and Uncles and Kjerfve 1986) were able to show that transversal motions induced by bottom topography and channel irregularities may also be as important as the longitudinal variations. In these works it was also shown that the experiment time length, to calculate the mean circulation during tidal cycles, takes into account subtidal frequency variations due to the synoptic and the seasonal meteorological forcing, as well as the time variability of the river discharge.

The tidal currents and the mixing process generate problems in data reducing and analysis which can only be solved by calculation of time mean values. The selection of a suitable sampling duration to determine the time-averaged estuarine conditions is as critical as the spatial sampling. Elliott's (1976) study points out extreme variability in time-averaged estuarine currents from one tidal cycle to another, and shows how the time-averaged current direction frequently reverses. It is likely that in most estuaries the greatest portion of the variability, on time scales from two to 20 days, occurs in response to meteorological forcing such as wind stress and atmospheric pressure fluctuations (Kjerfve 1979).

In calculating the mean flow in the Providence river estuary (Rhode Island, USA), frequently forced by the wind, Weisberg (1976) observed that, in general, it is not enough to calculate time mean values from measurements of only a few tidal cycles. Considering wind-induce current fluctuations Weisberg derived, using spectral analysis techniques, the following equation to arrive a meaningful time interval (Δt_m), which is necessary to the calculation non-tidal circulation or flux estimates,

$$\Delta t_m = \frac{\Psi^2}{2B_e \varepsilon^2 u_m^2}. \tag{4.1}$$

In this equation both $\Psi(\Psi = 2 \times 10^{-2}\,U$ is the variance of the axial current), and B_e (effective spectral bandwidth) are primarily dependent on the local wind intensity $U(\mathrm{cm\,s^{-1}})$. The symbol ε indicates the normalized error and u_m, the mean current velocity $(\mathrm{cm\,s^{-1}})$ may be anticipated from previous estuarine measurements published data, river discharge or conservations considerations for an idealized two-layered mean flow.

Let us assume, for example, that the wind speed is $500\,\mathrm{cm\,s^{-1}}\left(\Psi^2 = 10^2\,\mathrm{cm\,s^{-2}}\right)$, $\varepsilon = 0.2$, $B_e = 0.03$ cph, and $u_m = 10\,\mathrm{cm\,s^{-1}}$. Then, in this case, $\Delta t_m = 417$ h or 33 semi-diurnal tidal cycles. The main conclusion to be drawn from Weisberg's (1976) analysis is that if a too short sampling duration is selected, the resulting time-averages may not be representative of the typical conditions for a particular estuary (Kjerfve 1979); these results must be carefully interpreted, especially if during the data sampling the estuary has been forced by strong winds or abnormal meteorological events. These difficulties may be overcome with the use of continuous record instrumentation which may be operated during great time intervals. In the absence of these abnormal meteorological events and in estuaries with relatively small surface area, experiments conducted during a few tidal cycles may give reliable results.

Another example, on the correlation of the low-frequency response of estuarine sea level to non-local forcing variability, is found in the article of Kjerfve (1978). The analysis of one-year time series records of sea level, atmospheric pressure, and wind (speed and direction), representative to the well-mixed North Inlet estuary (South Caroline, USA), indicated two important sea level variability due to the forcing from the coastal ocean: a 3.2 cm high sea level wave at 6.0 days period is highly correlated with changes in atmospheric pressure, and 6.4 cm high sea level wave at 9.2 days periods is attributed to continental shelf waves driven by the along-shore wind stress.

The formulation of a project must be preceded by a scientific hypothesis, and it is not recommended to start the field sampling without one or more hypotheses, because they are the basis of the scientific method. As an environmental project, their stages must be carefully planned taking into account the following activities:

1. Planning: before the measurements and hypothesis extracted from previous studies and from the theoretical knowledge of the problem, a decision must be taken about the measurements and what should be done after data quality control.

2. Field work: as this stage involve data collection spatially distributed (with an oceanographic boat), and/or time series measurements of properties (fixed stations or moorings) with calibrated instruments, it is necessary to take into account the sampling details: geographic location and geometry (nautical charts), stations number and/or moorings, sample distribution in the water column, and logistic aspects related to the time interval between the measurements. It is advisable to start and finish the measurements at high or low water, mainly when estuary circulation is very low. The field work may also be associated with remote sensing (airplane or satellite) to observe the estuary in a time spot or sequentially in time.
3. Control and editing: at this stage, which may be partially accomplished on board, the experimental data must be carefully examined, to prevent observational errors and the one due to the malfunction of the equipment sensors. After that data control, the observational data are reduced and filed in a convenient format to enable its analysis.
4. Numerical treatment: analytical and numerical modeling are very useful to theoretically simulate the spatial and temporal properties, currents and transport forced by the river discharge, tidal oscillation, wind stress and density gradients. The comparison of theoretical simulations with the observational data is necessary to validate the theoretical results. This stage may also include statistical treatment of the experimental data with mathematical regressions, time series analysis (time domain) and spectral analysis (frequency domain).
5. Analysis and synthesis: this stage includes the synthesis of the experimental and theoretical results in tables and graphics, and its interpretation with known theories. This stage isn't a trivial one in a big project.
6. Reports and articles: this is the final step activity and its products are technical reports and articles submitted to specialized magazines.

Percentage estimation of these activities, in comparison to the work efforts to the financial cost and their contributions to the final product of the project are presented in Table 4.1.

Table 4.1 Project components and percentage estimation relative to the work effort, financial cost and the final product

Component	Effort (%)	Cost (%)	Product (%)
i-Planning	05	05	00
ii-Field work	20	60	05
iii-Control and editing	10	05	05
iv-Numerical treatment	40	10	05
v-Analysis and synthesis	10	05	10
vi-Report and articles	10	15	75

When there are no previous studies it is necessary to calculate theoretically the magnitudes of such variables as: current velocity, tidal height and excursion. With this information it is possible to specify correctly the equipment to be used in the measurements, in the planning and logistics to reach the objectives.

Field works, demanding lateral sampling to the knowledge of the mean vertical structure in the cross-section of a laterally non-homogeneous estuary require at least in three stations across. It also required the sampling time interval of one or half-hour ($\Delta t = 1$ h, or 0.5 h), and take care if the shallow depths near the margins are adequately sampled. To well defined vertical profiles in the water column a minimum of selected depths must be sampled from the surface down to the bottom, with intervals of $\Delta z = 1.0$ or 0.5 m. If a continuous property profiling is used in the measurements, the interpolation may be made at the same selected time intervals. When the instruments have no pressure sensors, the sampling depth (z) must be made taking into account the wire angle (ϕ, measured by a clinometer) and the wire length (L) of the hanging instruments, generally calculated by $z = L\cos(\phi)$. In longitudinal or transversal sections, the distance between the sampling stations needs to satisfy the following: (i) the difference of the property mean value between stations must be higher than the measurement error; and (ii) the property gradient must vary linearly with the distance. An analysis of the decrease in the committed error in the computation of transport or flux properties, in vertical sections with number of sampled stations, is presented in detail in the article of Boon III (1978).

The sampling time interval (Δt) during measurements of one or more tidal cycles is of crucial importance to prevent *aliasing*; if the sampling frequency is not adequately made in relation to the temporal scale of the phenomenon, it will not be sampled with the necessary detail.

The description of the motions and physical characteristics of an estuary may be obtained in two different basic methods which are related to the theoretical aspects of Fluid Dynamics, namely the Euler and Lagrange formulations. In the Eulerian description, the properties are measured in the time domain, in a fixed point of estuary, and in the Lagrangian the measurements are made in a drifting volume and in the time domain. The first description is the most used in estuarine research. For instance, in the estuary classification, using the stratification-circulation diagram, the set of measurements must be made in a fixed station and during the time, during one of more tidal cycles. Ideally, Eulerian measurements of hydrographic properties and currents should be made in a set of oceanographic stations distributed in the estuary space for its adequate sampling.

When, in the experiment, only instrumentation which needs an observer is used, it is very difficult to perform measurements during several tidal cycles. In these experiments a series of oceanographic stations may be occupied sequentially in space and time with only one equipped boat, or several stations may be simultaneously sampled with several boats aligned in the estuary cross section, as in the experiment described in the article of Kjerfve and Proehl (1979), as part of a multi-disciplinary investigation of the material transport between the cross section and the coastal ocean. In this experiment, in a the well-mixed tidally driven North Inlet estuary (South Caroline, USA), a 320 m wide cross section, with typical channel depths of 5 m, 11 stations were occupied with simultaneously sampling taken every 30 min. However, with only one instrumented boat and this sampling rate, the experimental work may cover partially the estuary and this limitation may be crucial in large estuaries. The detailed results of this investigation, related to the total material flux estimates was part of a multi-disciplinary investigation.

4.2 Current Measurements, Tide and Hydrographic Properties

4.2.1 Current Velocity

As in others branches of Physical Oceanography, among the physical properties of interest, the most difficult one to be measured is current velocity. It is a vector property which presents great spatial and time variability both in intensity (speed) and direction.

The observational procedure of current measurements in estuaries is not trivial, typically, the speed increases from zero, at slack low water, to maxima values which can be in excess of 2–3 ms^{-1} (or higher in some estuaries) at mid tide before decelerating, reversing at slack high water, and then accelerating to achieve similar or higher values in the opposite direction (Hardisty 2007).

Velocity measurements may be made using a moored boat or moored equipment in a fixed position. In the case of measurements with the sailing boat, depending on the equipment used, it is necessary to know the boat velocity and its direction, to extract the real current velocity.

In velocity measurements manual, mechanical, electronic, electromagnetic and automated techniques may be used to measure the speed and direction of the current in vertical profiles or in time series recording. Usually, current metering is made on board of a moored boat, performing velocity profiles from the surface down to the bottom at programmed depths and time intervals. Time series velocity measurements also may be made with more sophisticated electronic equipment as: autonomous moorings hanging on surface or bottom buoys, and with Acoustic Doppler Current Profiles fixed at the bottom. Mechanical devices embodying some form of rotating element which are used for water velocity measurements are called current meters, and The Proceedings of the Royal Society of London records descriptions of such devices from Newton's time (Hardisty op cit.).

The operation autonomy of this equipment in the field is determined by the time sampling rate (Δt), storage capacity (memory) and battery life duration. Although the last generation instruments are very expensive, there are less expensive versions which work at limited depths (<200 m) and can adequately be used in most estuaries.

Current meters record the current velocity (intensity and direction) by two sensors: one for intensity and other to the direction. However, others sensors may also be installed in this equipment to simultaneously measure properties as temperature, electrical conductivity, turbidity, oxygen concentration, for example. The current intensity sensors may be of three types: rotor, acoustic and electromagnetic, each one with its vantages concerning the resolution. The current direction is measured in relation to magnetic field of the Earth, with a compass (magnetic or electronic) and the equipment orientation through a steering device, or an orthogonal set of sensors which indicate its orientation with the flow. Consequently, in the data edition, it is necessary to take into account in the direction angle the magnetic declination, which depends on the geographic position and time of the measurement.

In current-meters with propellers or rotors the current intensity is measured by the time rate of the rotation, calibrated in a experimental channel with the controlled flow velocity. A type of Savonius rotor has curved plates mounted around a vertical axis. However, instruments with these types of intensity measurement respond excessively to the up and down fluctuations of the hanging cable of the instrument. This undesirable noise is known as *wave bombing*, resulting in a major intensity in all frequency energy bands. Equipments with this type of rotor must not be used hanging on board of boats due to its oscillations, mainly in the presence of moderate and high wave conditions. When hanging in moored buoys in regions which may be reached by high wind intensities, or in the proximity of the estuary mouth, which may be more strongly affected by waves, the time series record must be filtered to eliminate the undesirable fluctuations.

The rotor with six straight blades mounted around a vertical axis, is being turned to be a standard one in oceanographic instruments. Although less sensitive to the *wave bombing* the conventional equipment which uses this rotor type are not adequate to be used on the surface layer, due to the motions induced by the gravity waves, mainly due to the delay into respond to the direction changes. Under this layer, they may be moored because are less sensitive to the cable oscillations.

There are current meters using data sampling with a system of vector means in the *burst* connection. This methodology has a high temporal resolution and alternates between short and relatively long time, with and without measurements, respectively. The time series of intensity and direction are internally processed to calculate the mean values of intensity and direction during the sampling time intervals. This equipment, even when equipped with blade rotors, may be moored near the water surface mainly because the direction sensor, which consists of a small blade fixed in the compass has a small inertia.

The acoustic current meter measure the propagation time interval of a high frequency pulse between a source and the receptor separated by a fixed distance. As much as is the water velocity in the sound direction propagation, less will be the measured time interval. These instruments may use two or three pairs of this transmitter-receptor system disposed in perpendicular axes, two measure the horizontal component or the horizontal and vertical velocity components, respectively. A compass is used to measure the earth's magnetic field, and a tilt sensor measures the instrument's angle, and with these data the direction of the instrument is determined and consequently the current direction. The current direction and speed is thus measured in relation to the equipment, and an internal compass is use to determine the true direction. These types of current sensor may be moored even near the surface layer subjected to the wave motion.

Electromagnetic current meter has its functioning principle base in the Faraday's electromagnetic law, and the seawater functions as the electric conductor in motion. Once crossing the electromagnetic field created by the instrument, the sea water induces the generation of an electromagnetic force proportional to the current intensity and perpendicular to the current direction. This equipment has a system with two axes and an internal compass which measures the velocity horizontal components. They also may be moored nearby the surface.

The Doppler Current Meter system of acoustic profiling, generally referred as ADP or ADCP, uses the principle that the sound wave propagating in the seawater is modified when reflected by an object in motion. The equipment sends pulse sounds with different intensities which propagate into the water column, and these pulses are reflected back to the equipment by the reflecting particles in the seawater. These reflectors may be materials or organisms in suspension in the water, as sediments in suspension or by planktonic organisms transported by the currents and by the Doppler effect the frequency of the reflected sound wave length is different from that originally emitted. The transducer receptor is projected to pick up these anomalous frequencies and the relative velocity between the reflector and the instrument is calculated. This equipment has three sets of transducers, each one to do the measurement of the vector velocity component (two horizontal and one vertical). As the pulse intensities are calibrated to travel different distances in the water column, Doppler current meter measures vertical velocity profiles in discrete cells in the water column. The sensitivity of these instruments is very high to oscillations, and they have sensors to measure and compensate these oscillations. They may be used fixed in the boat or in its hull, sampling velocity current during the ship's track. There are also ADP versions to be moored for an autonomous operation, being the substitute of a conventional mooring line of a set of instruments typically used.

The main difficulty for measurements of current in estuarine regions is associated with the high frequency oscillations of the free surface due to the gravity waves, intense currents and the biological fouling, accidents and vandalism. Due to the low depth of coastal plain estuaries, the wave energy usually may reach the bottom, and it is very important to choose an adequate equipment to measure the current velocity operated in boats or in equipment installed in moorings. Further, using sub-superficial moorings, with an underwater buoy in the main branch, as the classical U type shown in Fig. 4.1 must be preferred, to minimize the noise due to the waving motion in the surface in the buoy and equipment. This scheme permits also the use of warning surface flashing signals, preventing boats and fishing boats with arrested nets to catch and destroy the mooring.

The relatively high speeds which may occur during the sampling produce a drag in the boat, cables, current meters and sampling bottles. Then, when using a boat as

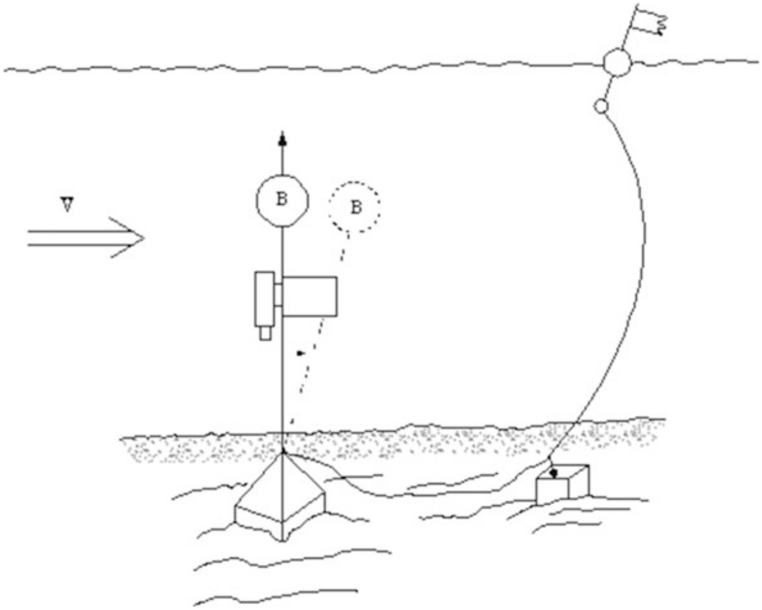

Fig. 4.1 Schematic displacement of the classical U mooring with a current meter and others sensors to measure the Eulerian variability of estuarine water mass

working platform, it must be anchored in two positions (*aft* and *fore*) to minimize its motions during the tide inversion from flood to ebb, and vice versa. Attention also must be paid in the dimension of the buoy lift that will sustain the main mooring cable. This lift drag must be strong enough for the equilibrium angle, between the vertical and the main branch inclination due to the current drag, must be less than the one specified by the current meter manufacturer. It is also desirable that the current meter has pressure sensors, so, the observed depth variations of the initial project may be established.

An instrumented mooring must receive frequent maintenance, mainly to cleaning of bio-fouling which may alter the sensors sensibility and the current meter calibration (speed and direction). The fouling may be so critical that may stop the rotor function, causing not only a gap in the time series measurement, but also money expenditure; the maintenance time interval depends on the investigated region and the season of the year. As a general rule, when measurement of current are made in a shallow water estuary and in warm season, the maintenance to clean the equipment must be more frequent, sometimes at every one or two weeks' time intervals. Recent advances in high sensors performance and anti-fouling technology is being applied to a new generation of equipment, improving the estuarine long-term data acquisition.

The equipment lost through accident with fishing nets, fault in the correct use of cable and launching procedures, inadequate chains and weights, and vandalism is relatively high in estuaries. However, using better technologies and maintenance it is possible to reaches indexes of recoveries of good measurements higher than 80–90%.

There is now underway in several estuaries around the world an up to date online measurements of velocity, meteorological, tidal height measurements and others properties. One source of these estuarine experiments is the estuarine flow data long-term acquisition PORTS (Physical Oceanographic Real Time System), operated in several USA harbors as: New York/New Jersey, Anchorage, Tampa Bay, Chesapeake Bay, Narragansett Bay, and others. These data will be very helpful for a better understanding of the Physical Oceanography of estuaries and the related components as Biological, Chemical and Geological.

4.2.2 Tide

The estuarine water surface oscillates horizontally and vertically forced by several distinct processes. In temporal scales from seconds to year the main are gravity waves, tidal co-oscillation, wind shear, seasonal river discharge and atmospheric pressure, as well as the circulation due to the wind shear stress on the continental shelf.

The measurement of the sea level oscillation in the intratidal domain are made by tidal gauges, installed in coastal stations, or rigidly moored on the estuary bottom. There are two main types of tide gauges: the mechanical driven by a surface buoy, and the acoustic.

In the mechanical instruments the sensor is a fluctuating buoy installed in the interior of a tube vertically displaced. The connection between the buoy and the water is made through a small diameter hole in the lateral, or situated at its bottom. The correct relationship between the tube and the diameter acts as a filter to the oscillating non-desirable noise of the gravity waves. The buoy, through a steel cable, senses the up and down tidal motion which is transferred to a mechanical devise and a pen that records analogically the tidal motion in function of time. Once installed, it must be calibrated by leveling in relation to a known *datum level*, and a periodic maintenance by cleaning the tube and buoy due to the bio-fouling. In remote places, it is necessary to take into account the possibility of vandalism.

Electronic pressure tide gauges are usually settled at the bottom in rigid platforms to prevent undesirable motions. The majority pressure sensors use the crystal piezoelectric effect whose precision is adequate to estuarine investigations. The equipment configuration must be set previously (time, date, sampling time rate, maximum tidal height) and, if necessary, signalization surface buoys may be launched to prevent the mooring to be drag by fishing nets.

The tidal height sampled by tide gauges are used to perform tidal analysis (components determination) and prediction. The first devices for tidal prediction were the tide prediction machine invented by Lord Kelvin, who devised the method of harmonic analysis in the second half of the XIX century. Between the several

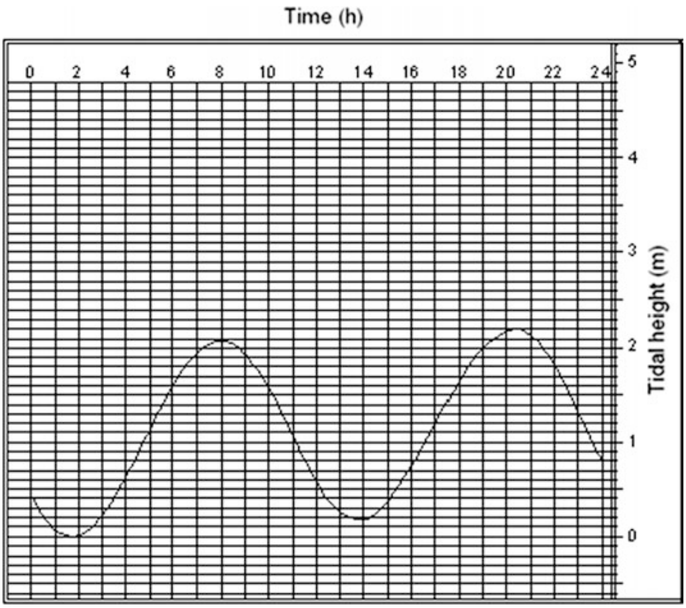

Fig. 4.2 Tide forecast for 24 h (two tidal semi-diurnal cycles) for the Natal harbor using the Pacmaré developed by Franco (2000)

methods we have already mentioned (Chap. 2) the software developed by Franco (2000), which uses the spectral analysis to tidal and current analysis and prediction (Pacmaré), using discrete tidal heights or current sampled at different time intervals (usually $\Delta t = 1.0$ or 0.5 h). The *Pacmaré* has a set of programs which compute the following correlated tasks: (i) Harmonic analysis for current, and tide and prediction, processing time series up to 3–4 years; (ii) Long time series analysis and prediction, processing up to 18.6 years. The computed results of set of harmonic tidal (current) components are used to predict the tidal heights or current speeds for any desired time and may be extracted in tables or graphic format. To exemplify one of the results which may be obtained with this software, the tide predicted to the Natal harbor (Rio Grande do Norte, Brazil) was calculated from an hourly time series of tidal heights with 1.8 years (Fig. 4.2).

4.2.3 Hydrographic Properties

The temperature and especially the salinity are hydrographic properties to be sampled in an estuary investigation. As shown in Chaps. 1 and 2, the salinity is a fundamental property, but also because its longitudinal gradient (or density gradient) is capable to generate the up-estuary longitudinal circulation due to the baroclinic pressure gradient and its vertical gradient indicates the vertical stratification (stability). Knowing the distribution of this property enables its classification according to the salinity stratification and the calculation of the Stratification-circulation Diagram, however, for that the longitudinal steady-state motion also must be known.

The density of the seawater is dependent on the temperature (T), salinity (S) and pressure (p), usually known as independent variables, and the density as function of these properties, $\rho = \rho(S, T, p)$, is calculated by the Equation of State of Sea Water. The pressure influence on the density is important to be considered only in type fjord estuaries, because of the great depth, which may reach 1000 m. As the most common are coastal plain and shallow estuaries, the pressure influence on the density is of minor importance, and the density may be considered only as function of salinity and temperature, $\rho = \rho(S, T)$, it may be determined by the equation state of seawater at atmospheric pressure ($p = 0$), or with simplified equations. As studied in the Chap. 2, the density is the physical property necessary to the determination the baroclinic component of the gradient pressure force (Eq. 2.10a); this component, associated with the river discharge and the vertical mixing processes, generates the *gravitational circulation*.

Temperature is the thermodynamic property to indicate if two physical bodies are or are not in thermodynamic equilibrium, or it may be taken as a measure of the heat content of a volume element. This property has variation in space and time, $T = T(x, y, z, t)$, due to the advective and diffusive processes and the exchange of sensible and latent heat with the atmosphere. The temperature may be measured at different depths in the water column with the classical protected *reversing thermometer*, having as sensor the differential coefficient of cubic expansion mercury in glass, was first manufactured in Italy by Negretti and Zambra, in 1874. This instrument was improved in Germany and, in about ten years, reached the high precision (±0.02 °C and ±0.005 °C). The detailed description of this thermometer may be found in classical books of Oceanography (Sverdrup et al. 1942; Defant 1961; Neumann and Pierson 1966, among and others). Nowadays, these classical thermometers are being replaced by the high precision *electronic reversing thermometer* with platinum temperature sensors. These thermometers were specially projected to be installed in bottles of Nansen, Ninskin or Van-Dorn bottles, to enable water sampling simultaneously to determination of salinity, and others chemical components and micro-biological micro-specimens of estuarine water mass.

The temperature (T’) registered in a thermometer of the mercury in glass type is read in the boat laboratory or on the deck and, at a different temperature measured in situ (T). Then, it is necessary to apply a correction (ΔT), due to the volumetric expansion, because the temperature difference of the water in situ and the one in the boat (t_a), at the reading time of the reversing thermometer. The temperature (t_a) is measured by a thermometer named auxiliary, located at the same protecting glass of the reversing thermometer. Besides this influence, it is necessary to algebraically add to the reading T’ (made with a magnifying glass) an experimental correction (I), named *index error* obtained in laboratory during the thermometer calibration against a standard thermometer, furnished by the manufacturer. Then, the in situ temperature is determined by:

$$T = T' + \Delta T + I. \qquad (4.2)$$

A detailed revision on the published equations to calculate the volumetric expansion error (ΔT) was published in the article of Keyte (1965). To calculate this error it is necessary the following physical quantities furnished by the manufacturer: (i) V_0—volume of mercury in the capillary tube of the reversing thermometer, at the temperature 0 °C; (ii) K_T the coefficient of volumetric expansion of the thermometric system. For the water mass of the coastal plain estuaries it is enough to use the simplest correction formula, as the one deduced by G. Ferruglio in 1912:

$$\Delta T = (T' + V_0)(T' - t_a)/K_T. \qquad (4.3)$$

This ΔT value combined with the Eq. (4.2), is the accurate value of the in situ temperature (T).

The great advantage of the electronic thermometers, in relation to the mercury in glass, is that the reading is made in a display digital and there is no volumetric expansion of the system. These thermometers have the same characteristics as the classic ones (they may be fitted to any sampling bottle) and have the following advantages:

- They are programmed in three operation modes (wait, continuous and sampling), which are selected by a magnetic key;
- There is no correction in the reading and its precision is ±0.015 °C;
- The display electronic can't be erased by mistake.

The salinity (S) is a physical-chemical property calculated as the ratio of the salt concentration mass (m, in grams) dissolved in a given mass of seawater (M, in kilograms): then, it is a non-dimensional property, $[S] = [MM^{-1}]$. Besides its importance to the ecologic characterization of the estuary this property it is used to calculate the density of the seawater. In the estuary the salinity presents great variability in time and space, $S = S(x, y, z, t)$, mainly due to the process of mixing (advection and diffusion) and the of river discharge; with some exceptions, the direct exchanges of the estuarine water mass with the atmosphere (through the processes of precipitation-evaporation) generally do not have an important contribution to the salinity variations, with exception to the hypersaline estuaries which may be formed in regions of arid climate.

The history of the salinity definitions and the methodology to its determinations dates back to 1693, thanks the early work of Robert Boyle, on measuring the saltiness of the seawater, evaporating the water, and weighing the solid residue (Hardisty 2007). Without going into the details, several definitions of this property evolved, and are from the dominion of the physical-chemistry, it follows that the main results are internationally known.

(a) *Classical definition of Martin Knudsen*

The traditional parameter used for estimate salinity is the chlorinity (Cl) concentration chemically determined in g/Kg (symbolically ‰), which measures chloride and bromide concentrations in the seawater usually by a volumetric procedure using a standard sea water as reference (*normal seawater*). The conversion of Cl concentration in salinity is made with the equation $S = 0.03 + 1.805 \times Cl$, named Knudsen equation, and may be used to in the range from 2.0 to 42.0‰, with an accuracy of ±0.03‰. This procedure was published in the Hydrographic Table of Knudsen et al. (1902), where the salinity has been defined as: "The total amount of solid material in grams contained in 1 kg of sea water when all carbonate has been converted to oxide, the bromine and iodine replaced by chlorine, and all organic matter completely oxidized". In the above equation the constant 0.03 represent approximately the solid content of river water flowing into the Baltic Sea, being the dominant influence in determining the ratio of ions in the solution of low salinity water.

(b) *Inductive scale*

With the advent of the electronic instruments to measure accurately the *conductivity ratio* (R_t), defined as the conductivity in situ in relation to that of a standard, in the 1960 decade, the salinity was redefined and the oceanographic community has started to use this accurate method to obtain this property of seawater more quickly and with higher precision.

To maintain the continuity of Knudsen scale and redefine the salinity as an addictive property, the conversion of chlorinity in salinity was made with the following equation: $S = 1.80655 \times Cl$. For $Cl = 19.374$ it follows, from these equations and the one of Knudsen, the same salinity $S = 35.0‰$. Using a set of 135 samples of seawater collected in the oceans which were carefully and precisely analyzed of its chlorinity content (Cl) and conductivity ratio (R_t) values, which were correlated with multiple correlation techniques, and a 5th° polynomial equation was fitted to determine salinity as variables R_t and the T, as independent variables, $S = S(R_t, T)$, with $T \geq 10$ °C. This equation was used to calculate the salinity in the inductive scale, in the same salinity interval of the Knudsen scale, and the algorithms for its determination were published in the Unesco Technical Papers in Marine Sciences (UNESC0 1966), enabling the salinity precision of ±0.003‰. The conductive ratio (R_t) and the simultaneous temperature of the sample (T) to be converted in salinity are measured with an equipment named Salinometer.

Until 1979, the salinity was reported in the same unity as in the classical unity (grams per kilogram or ‰). In the General Assembly of the International Association for the Physical Sciences of the Sea (IAPSO), held in December, it was made the recommendation that the symbol ‰, should be replaced by 10^{-3}; thus, for example, a salinity value of 35.120‰ should be expressed as 35.120×10^{-3} and, in non-dimensional formulation (kg/kg). However, due to the inconvenience of the unity change this recommendation has not been used by the oceanographic community.

(c) *Practical Salinity Scale*

As pointed out by Lewis (1980) the *conductivity ratio* (R_t) defines the salinity scale better than *chlorinity* scale for density determinations, and the new Practical Salinity Scale (1978) has been defined to eliminate the following difficulties of the former definitions: (i) The *standard seawater* may the reproduced in laboratory, independent on the ionic composition of seawater; (ii) The same algorithm approved by the Joint Panel on Oceanographic Tables and Standard (JPOTS) may be used for the calculation of the practical salinity from conductivity at all temperature and pressure over the ranges of oceanographic interest, in laboratory equipment or *in* with Conductivity-Temperature-Depth instruments; (iii) It turns to be a conservative property (Unesco 1981a).

Independent of the measured property (chlorinity or electrical conductivity) the Practical Salinity Scale and the former scales reproduces the same value corresponding to the value S = 35‰. And this value of S = 35‰ has by definition the conductivity ratio of unity ($R_t = 1.0$) at 15 °C, with a potassium chloride solution with concentration of 32.4356 g KCl/Kg. For conductivity ratio measurements in laboratory (at atmospheric pressure), and the salinometer has been standardize with a sub-standard of the KCl solution, the determination of the salinity is also made with a 5th° polynomial equation, but having as independent variable the square root of the conductivity ratio and the temperature, $S = S(R_t^{1/2}, T)$ with an accuracy of ±0.003‰. This polynomial expression may also be used to the determination salinity values at the atmospheric pressure, which may be accomplished using the algorithms published in the Technical Reports of Unesco (Unesco 1981a).

As in those former scales, accurate values may be calculated in the range of 2 and 42‰. Further details on the polynomials fitting may found in Perkin and Lewis (1980), and the algorithms for the salinity determination as function of R_t and T have been programmed in the MatLab® computational environment by Morgan (1994). It should be pointed out that it is possible to apply this new salinity definition to hyper-saline seas, estuaries and coastal lagoons, because the upper limit of the Practical Salinity Scale (42‰) was increased up to (50‰) by Poisson et al. (1991).

The described salinity definitions have as fundamental hypothesis the constant composition of the seawater. However, due to the river and runoff discharges into estuarine waters, other ions may be found discharged, and this hypothesis may not be true, and the accuracy of the methods (±0.03‰ Knudsen) and (± 0.003‰ Inductive and Practical scales) are only for oceanic waters. For coastal and estuarine waters there is no yet detailed information on its correct ionic composition and errors of ±0.04‰ in salinity and $\pm 5.0 \times 10^{-5}$ g cm^{-3} = $\pm\ 5.0 \times 10^{-2}$ kg m^{-3} in density may be tolerated. Thus, the Practical Salinity Scale and the International Equation of State of Seawater can be used for estuarine systems even without the detailed knowledge of their ionic composition (Millero 1984).

With the advance of the Electronic Engineering applied to Physical Oceanography, small equipment from the type of Conductivity-Temperature-Depth (CTD) were developed to operate in estuarine waters. With these instruments it is possible to sample continuous vertical salinity profiles, and concentration of others properties. The electrical conductivity or the conductivity ratio measured with these instruments, are automatically converted in salinity with the algorithms of the Practical Salinity (PSS-1978).

Salinity determination in hyper-saline estuaries and coastal lagoons presents difficulties when values to be sampled are higher than 50‰. These difficulties may be overcome under the hypothesis that it has the same ionic compositions as seawater. If so, to reduce the salinity to a determinable value, the sample may be dissolved with a certain amount of distilled non-ionic water, and the analysis of the new sample may be made with the methodologies already known, and the salinity of the original sample may be calculated by applying a correction factor.

Although less precise, the hyper-saline waters (S > 50‰) may have its salinity determined indirectly using measurements with refractive instruments and an hydrometer, both graduated with known high salinity samples. The hydrometer, in the Baumé scale, has the measurements in Be degrees; a measurement value may be converted in density with the following equation (CRC 1979):

$$\rho = \left[\frac{145}{(145 - \mathrm{Be}}\right] \mathrm{x}\, 10^3, \tag{4.4}$$

with the density in SI unities. For a distilled sample water at 4 °C and Be = 0^o, it follow from this equation $\rho = 10^3$ kg m^{-3}. This method has been used to determine the salinity in a study related to the hydrology and salt balance in the hyper-saline Araruama lagoon (Rio de Janeiro, Brazil). In this study, the following linear correlation between salinity and the Be degrees was determined: $S = -2.9 + 11.0 \times \mathrm{Be}$ (Kjerfve et al. 1996).

Time series of the longitudinal velocity component (velocity decomposition will be presented in the next chapter), salinity and tidal measurements were sampled in the Cananéia-Iguape Estuarine System (Fig. 1.5). The Eulerian temperature and salinity time series were measured in a self recorder current-meter, moored at 6 m depth from the bottom and equipped with temperature and salinity sensors. The hydrographic properties were recorded, and are presented comparatively to the tidal record (Fig. 4.3). The visual analysis of the *intratidal* time variability of the current component (v) indicates the influence of the longitudinal circulation forced by the barotropic component of the gradient pressure force (tidal forcing). Visually it may be observed that there is a phase difference of approximately two hours between current and tidal oscillations, with the tide in advance of the velocity oscillation, indicating a non-progressive tidal wave. It is also possible to visualize that the ebb current (v < 0) is more intense than the flood current (v >0), which indicate the superposition of a seaward residual motion generated by the system of rivers discharges empting into the estuary. The salinity variability also presents a local variability that, although out of phase with the tidal oscillation, oscillates closely to the tidal current. Mainly due to the advective salt flux this property increases and decreases during the flood and ebb tidal oscillations, respectively. Low frequency

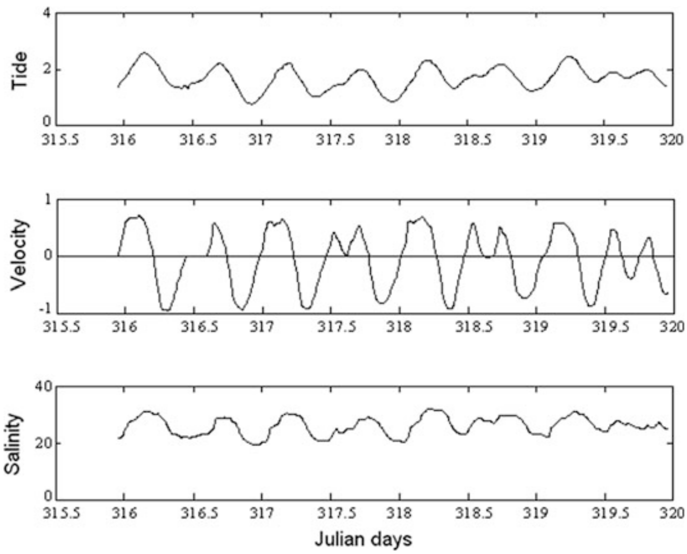

Fig. 4.3 Four day time series of tidal height, longitudinal velocity component and salinity recorded in the Cananéia-Iguape Estuarine System (São Paulo, Brazil) (November, 1996). The abscissa axis is graduated in Julian days (according to Miranda and Castro 1998)

variations, superimposed to the tidal, current and salinity oscillations may also be seen in this four day time series.

The accuracy of temperature and salinity measurements in estuarine waters are not so critic as in the open ocean, mainly due to the strong advective and diffusive influence of the tidal oscillation, and the occurrence of strong horizontal gradients (mainly salinity) in comparison to the open ocean. However, it should be pointed out that the longitudinal density gradient, necessary to calculate the baroclinic component of the gradient pressure force has a great time variability, turning it to be a very difficult physical quantity to be determined in the estuary. Then, although every measurement must be made as accurate as possible, and the high accuracy as in oceanic sea water may not be reached, it is very important in the estuarine research that measurements should be made as fast as possible to minimize the error induced by its relative high variability.

(d) *Pressure*

Around the year 287 (BC), Archimedes formulated the laws of hydrostatics. He also combined numbers and experiments and gave the principle of the surface level. These historical facts, which were of fundamental importance to the development of the Fluid Dynamics and Oceanography, were cited in the von Arx (1962) book relying on secondary sources of the Mc-Grow Hill series of history books.

Under ideal hydrostatic conditions, the pressure at every level of a water column is assumed to be equal to the weight of the fluid per unit area $[ML^{-1}T^{-2}]$.

Departures from hydrodynamic balance along the estuary and under normal conditions, it is mainly a consequence of the combined effects of the non-uniform density distribution and tidal oscillations. The analytical expressions of these components were presented in Chap. 2 (Eq. 2.10a, b).

The units of pressure usually employed in Oceanography are generally derived from the c.g.s. (centimeter, gram, second) system of units. In this system the force is expressed in dyne and, because the average atmospheric pressure (p_a) is $\approx 1.01 \times 10^6$ dynes cm^{-2}, it become a commonplace to consider pressure in terms of the *bar* (1.0 bar = 1.0×10^6 dynes cm^{-2}). The bar unity and its decimal parts as the decibar (1.0 decibar = 10^{-1}bar = 1.0×10^5 dynes cm^{-2}) is a very convenient unity of pressure, because the depth in meters in a seawater column may be numerically approximate to the pressure in decibars. This may be easily understood by the hydrostatic law written as $\Delta p = \rho g \Delta z = 1.03 \times 9.8 \times 10^2 \times 1.0 \times 10^2$ which is $\approx 1.0 \times 10^5$ dines cm^2 = 1.0 decibar; then, for an increase in the depth of 1 m (1.0×10^2 cm) the increase in pressure is 1.0 decibar, with an error less than 2%. This numerical equality is very useful and pressure sensors in CTD's usually have a piezoelectric as pressure sensor calibrated in decibar's.

4.3 Density and Equations of State

The seawater density (ρ) and the volume specific ($\alpha = 1/\rho$), representing physically the ratio of the mass per volume unity and its inverse, with dimension $[ML^{-3}]$ and $[L^3M^{-1}]$, respectively, are dependent on the salinity (S), temperature (T) and pressure (p). To the majority of estuaries (coastal plain), with the exception to the fjord estuaries, the density (volume specific) may be considered as dependent only on the salinity and temperature. The salinity variation interval usually is great as compared to the temperature, and the pressure effects on low pressure variations ($p < 100$ decibars$\approx$100 m) on the density may be disregarded.

Although CTD's (equipment with conductivity, temperature and pressure sensors) have high sensitivity and their measurements have good precision, as indicated above, this precision is not adequate to the determination of the horizontal component of the pressure gradient (Chap. 2, Eq. 2.9c) which is used to the determination of the gradient pressure force per mass unit, and it is impossible to separate with this measurement, the barotropic and baroclinic components (Eq. 2.10a, b Chap. 2). Then, this problem may only be resolved if the pressure is calculated in function of the density and under the assumption of the hydrostatic equilibrium, $dp = -\rho g dz$, remembering that the signal minus indicate in this equation that the Oz axis is oriented against the gravity acceleration).

There are in some tropical regions that, according to the season of the year, the river discharge into the estuary is too low, and there are two possibilities: (i) high evaporation and the estuary turns to be hyper-saline, and (ii) the surface heating is too intense and capable to cause density gradients, and thus influencing the estuarine circulation. In this last condition, due to the diurnal cycle of the temperature variation, these effects usually are transitory. In the fjords type estuaries occurring in high latitudes, the intense cooling on the surface layer during the winter time may generate deep convection, and thus the increase in the oxygen concentration in these layers. Hence, according to the estuary characteristics the temperature influences may not be disregarded (Dyer 1973).

The equation of state of seawater at the atmospheric pressure in function of the independent variables S and T enabling the determination of the density, $\rho = \rho(S, T)$ was based in laboratory experiments. In between these equations we may detach the classical Knudsen equation and the International Equation of Seawater (IESS-1980) (Knudsen 1902; Unesco 1979, 1981b), which have non-linear dependence on the variables S and T. The classical Knudsen equation is composed of a set of relations obtained in picnometer measurements under controlled conditions of S and T, using also the well-established state equation of pure water of E. H. Amagats (1893, quoted in Mamayev (1975)), and the seawater state equation at 0 °C. Originally it was resolved in relationship to one seawater parameter (Sigma–t or σ_t) associate to the density, $\rho = \rho(S, T)$, and defined by $\sigma_t = [\rho(S, T)-1] \times 10^3]$, with the density expressed in the *c.g.s* system of unity.

The International Equation of State for Seawater, 1980 (IESS-1980) was determined with highly precision experimental data which were algebraically manipulated to result a set of equations in the polynomial format (algebraic power series in the S and T variables). The first equation of this set is the equation of pure water. The final result of this equation is the density value in units of the International System of Units (SI), and density is expressed in kg m^{-3}; due to the use of the SI system the parameter σ_t (also named density anomaly at the atmospheric pressure) is defined as $\sigma_t = \rho(S, T)-10^3$.

Due to the great variability of the ionic composition of the estuarine water mass and the expected accuracy of ±0.04‰ in the salinity determination, with the PSS (Millero 1984), the precision in the determination of the seawater density with the IES-1980 is ≈0.05 kg m^{-3}. Due to the great variability of the density in estuaries this accuracy is satisfactory to the solutions of problems related to their hydrodynamics. These equations are widely found in technical papers and oceanographic tables (Fofonoff and Millard 1983; Unesco 1987), and all algorithms have been programmed in the computational MatLab® environment by Morgan (1994).

In the theoretical and numerical treatment of the circulation and mixing processes in estuaries, it is necessary to solve a closed hydrodynamic system of equations, and the state equation, $\rho = \rho(S, T, p)$ or $\rho = \rho(S, T)$ must take part of this system. In analytical solutions, simplified linear and non-linear equations that is reasonably efficient numerically, and has a wide range of application is one developed by Mellor (1991); this is an equation to calculate density whose independent variables are salinity, potential temperature, and pressure, and cover the small range of pressure and the large range of temperature and salinity found in estuaries, as well as, the large pressure range for deep basins application.

Due to the difficulties in analytical solutions it is convenient the use of equations of state in simplified linear and non-linear formulations, so disregarding the pressure effect. For deduction of linear equations, according to Mamayv (1975), the total differential ($d\rho$) of the functional relation $\rho = \rho(S, T)$, must be obtained,

$$d\rho = \left(\frac{\partial \rho}{\partial S}\right)_{T,p} dS + \left(\frac{\partial \rho}{\partial T}\right)_{S,p} dT. \tag{4.5}$$

As the saline ($\partial \rho/\partial S$) and thermal ($\partial \rho/\partial T$) gradients, according to their definitions, are related to the coefficients contraction of salinity (β) and thermal expansion (α_e) by,

$$\beta(S,T) = \left(\frac{1}{\rho_o}\right)\left(\frac{\partial \rho}{\partial S}\right), \tag{4.6}$$

and

$$\alpha_e(S,T) = -\left(\frac{1}{\rho_o}\right)\left(\frac{\partial \rho}{\partial T}\right), \tag{4.7}$$

where ρ_o is a density reference. Then, the combinations of Eqs. (4.6) and (4.7) with Eq. (4.5), and the differential $d\rho/\rho_o$ is expressed by:

$$\frac{d\rho}{\rho_o} = \beta dS - \alpha_e dT. \tag{4.8}$$

As known from the Thermodynamic of Seawater the coefficients β and α_e are dependent on the S and T. In the assumption of a mean value for these coefficients for the estuarine water mass, the differential expression (4.8) turns to be an equation with constant coefficients, and may be easily integrated,

$$\rho(S,T) = \rho_o(\beta S - \alpha_e T) + C. \tag{4.9}$$

the integration constant (C) may be, for simplicity, taken as $\rho_o = \rho(0,0)$, equal to the density of pure water at 0 °C ($\approx 1.0 \times 10^3$ kg m^{-3}), and the linear equation of state of the estuarine water is given by:

$$\rho(S,T) = \rho_o(1 + \beta S - \alpha_e T). \tag{4.10}$$

When the temperature effects may be disregarded, it follows the linear expression of the equation of state,

$$\rho(S, T) = \rho_o(1 + \beta S). \tag{4.11}$$

or, in terms of the specific volume,

$$\alpha(S, T) = \alpha_o(1 + \beta S)^{-1}. \quad (4.12)$$

The constant values of the saline contraction and thermal expansion in the preceding equations must be mean values of the thermohaline characteristics of the estuary under investigation. These coefficients, determined with the analytical expressions have the following mean values: $\beta = 7.5 \times 10^{-4}$ and $\alpha_e = 2.0$ 10^{-4} °C^{-1}; these order of magnitudes are valid for the following variation intervals of salinity and temperature: 15 < T < 30 °C, and S > 10‰. However, the variation of β with S and T is much less than the dependency of α_e with these variables, and their values must be altered according to the problem to be studied. These values may be calculated with the Morgan's (1994) MATLAB® routines for calculating properties of seawater.

These linear Eqs. (4.11 and 4.12) have been used in solutions the of analytical steady-state models on gravitational circulation as, for example, in the classical article of Hansen and Rattray (1965), which resulted in theoretical profiles of the longitudinal velocity and salinity in estuaries partially mixed. In some solutions, the longitudinal density gradient $\left(\frac{\partial\rho}{\partial x}\right)$ may e substituted by the longitudinal salinity gradient using the relationship $\left(\frac{\partial\rho}{\partial x} = \rho_0\beta\frac{\partial S}{\partial x}\right)$.

The non-linear approximations of the equation of state of seawater have been introduced in order to maintain the main non-linear dependence of the density with the properties S and T. The first simplified non-liner equation was presented by N. E. Dorsey in 1968, and later modified in the following more convenient formulation for practical applications (Mamayev, 1975):

$$\rho(S,T) = \rho_o + b(T - T_o) + c(T - T_o)^2 + [f + g(T - T_o)](S - S_o). \quad (4.13)$$

In this equation the coefficients b, c, f and g are constants to be determined. S_o and T_o are also constant values of salinity and temperature, which may be chosen according to the variation of these properties. For convenience, the first term of the equation is $\rho_o = \rho(S_o, T_o)$; with this approximation, the thermal $(\partial\rho/\partial T)$ and saline $(\partial\rho/\partial S)$ gradients, with the first calculated with $S = S_o$, turns to be linear functions of the temperature.

Starting from the generic non-linear formulation of Eq. (4.13), and with S_o = 35‰ and T_o = 0.0 °C, Mamayev (1964, quoted in Mamayev (1975)), calculated the following equation to the density determination at atmospheric pressure, using values of the classical Knudsen equation, expressed in terms of the Sigma-t (σ_t) parameter:

$$\sigma_t(S,T) = 28.152 - 7.35 \times 10^{-2}T - 4.69 \times 10^{-3}T^2 + \left(0.802 - 2.0 \times 10^{-3}T\right)(S - 35), \quad (4.14a)$$

and the density, in g cm^{-3}, is determined by;

$$\rho(S, T) = 1 + 10^{-3}\sigma_t(S, T). \tag{4.14b}$$

This equation may be applied for S and T varying in the following intervals: 0 < S < 40‰ and 0 < T < 30 °C, to calculate the density of the estuarine water mass. The comparison the results of this Eqs. (4.14a, 4.14b), with the Knudsen equation used in the determinations of its coefficients, indicate mean deviations varying from $\pm 5 \times 10^{-5}$ g cm^{-3} to $\pm 1.0 \times 10^{-4}$ g cm^{-3}.

Applying the same procedure, but using the thermal and saline gradients calculated by the IESS-1980, the following simplified non-linear state equation was obtained:

$$\begin{aligned}\rho(S,T) &= 1028,106 - 7.18575 \times 10^{-2}\,T - 4.54944\mathrm{x}10^{-3}\,T^2 \\ &+ \left(7.99667 \times 10^{-1} - 1.84981 \times 10^{-3}\,T\right)(S - 35.0).\end{aligned} \tag{4.15}$$

This equation, with the density expressed in the SI units system (kg m^{-3}), may be applied to the following intervals of S and T: 0 < S < 40.0 ‰ and 0 < T < 40.0°C, which may be used to calculate the density when the salinity is measured in the practical scale (PSS-1978). The deviation in comparison with the IESS-1980, are near the deviations calculated by Millero (1984) which may be expected due to the different ionic composition of the seawater and coastal water masses ($\pm$0.05 kg m^{-3}). This precision is adequate to the purposes of the Physical Oceanography of coastal plain estuaries.

The analytical expressions of dependent properties of seawater presented in this chapter, as the equation of state at atmospheric pressure $\sigma_t = \sigma_t(S, T)$ or $\rho = \rho(S, T)$, the coefficients of saline contraction $\beta = \beta(S, T)$, the thermal expansion $\alpha_e = \alpha_e(S, T)$ and the algorithmic of the PSS-1978, among others fundamental of sea water properties, may be easily determined with the Morgan's (1994) sub-routines.

An up to date item of information on salinity and the state equation of seawater is that, in 2010, the Intergovernmental Oceanographic Commission (IOC) and others associations, jointly adopted the new standard for the calculations of the absolute salinity (S_A), and a new standard for the calculation of the thermodynamics properties of sea water. This new standard, called Thermodynamic Equation of Ocean Seawater (TEOS-10), has been adopted in substitution the former equation of state of seawater (IESS-1980). The absolute salinity is defined in function of the currently used methodology of salinity measurements (PSS-1980), based on conductivity ratio measurements, and depends on the ionic composition of seawater at a geographical position of latitude (φ) longitude (λ) and pressure (p), expressed by Pawlowicz (2010);

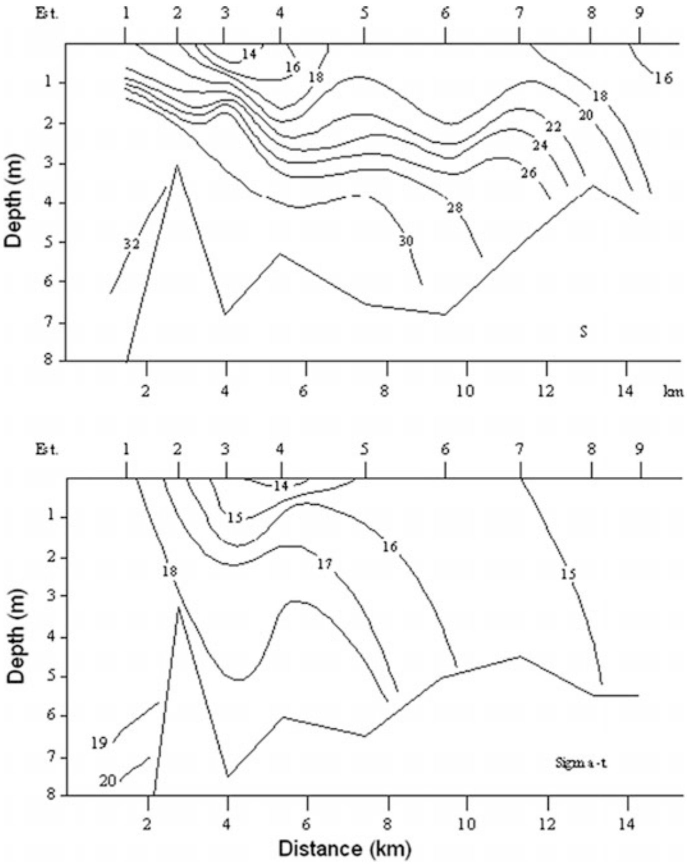

Fig. 4.4 Longitudinal salinity and density (Sigma-t) distributions in the Bertioga channel in the Santos-São Vicente Estuarine System (Fig. 1.5)

$$S_A = \left(\frac{35.16504}{35.0}\right) S_P + \delta S_A(\varphi, \lambda, p). \tag{4.16}$$

However, due to the difficulties for the accurate determination of the ionic composition of the estuarine water mass, which is necessary to know according to the S_A expression (4.16), its determination with the classical PSS-1980 salinity algorithmic will continue to be used in the estuarine research.

The longitudinal salinity and density (σ_t) distributions, in the estuarine channel of Bertioga (Fig. 1.5, Chap. 1) are presented in Fig. 4.4. The longitudinal salinity and density (σ_t) distributions in the estuarine channel are characterized by the isohalines and isopicnals with configurations with some similarities, showing that between the salinity and temperature properties, the first is the main one responsible to influence the density of the estuarine water mass in this environment.

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