CHAPTER 2

Data Processing and Presentation

2.1 INTRODUCTION

Most instruments do not measure oceanographic properties directly nor do they store the related engineering or geophysical parameters that the investigator eventually wants from the recorded data. Added to this is the fact that all measurement systems alter their characteristics with time and therefore require repeated calibration to define the relationship between the measured and/or stored values and the geophysical quantities of interest. The usefulness of any observations depends strongly on the care with which the calibration and subsequent data processing are carried out. Data processing consists of using calibration information to convert instrument values to engineering units and then using specific formulae to produce the geophysical data. For example, calibration coefficients are used to convert voltages collected in the different channels of a CTD to temperature, pressure, and salinity (a function mainly of conductivity, temperature, and pressure). These can then be used to derive such quantities as potential temperature (the compression-corrected temperature) and steric height (the vertically integrated specific volume anomaly derived from the density structure).

Once the data are collected, further processing is required to check for errors and to remove erroneous values. In the case of temporal measurements, for example, a necessary first step is to check for timing errors. Such errors arise because of problems with the recorder's clock which cause changes in the sampling interval (Δt), or because digital samples are missed during the recording stage. If N is the number of samples collected, then $N\Delta t$ should equal the total length of the record, T. This points to the obvious need to keep accurate records of the exact start and end times of the data record. When $T \neq N\Delta t$, the investigator needs to conduct an initial search for possible missing records. Simultaneous, abrupt changes in recorded values on all channels often point to times of missing data. Changes in the clock sampling rate (clock "speed") are more of a problem and one has often to assume some sort of linear change in Δt over the recording period. When either the start or end time is in doubt, the investigator must rely on other techniques to determine the reliability of the sampling clock and sampling rate. For example, in regions with reasonable tidal motions, one can check that the amplitude ratios among the normally dominant K_1, O_1 (diurnal) and M_2, S_2 (semidiurnal) tidal constituents (Table 2.1) are consistent with previous observations. If they aren't, there may be problems with the clock (or calibration of amplitude). If the phases of the constituents are known from previous observations in the region, these can be compared with phases from the suspect instrument. For diurnal motions, each one hour error in timing corresponds to a phase

Table 2.1. Frequencies (cycles per hour) for the major diurnal (O_1, K_1) and semidiurnal (M_2, S_2) tidal constitutents

Tidal constituent	O_1	K_1	M_2	S_2
Frequency (cph)	0.03873065	0.04178075	0.08051140	0.08333333

change of 15°; for semidiurnal motions, the change is 30° per hour. Large discrepancies suggest timing problems with the data.

Two types of errors must be considered in the editing stage: (1) large "accidental" errors or "spikes" that result from equipment failure, power surges, or other major data flow disruptions (including some planktors such as salps and small jellyfish which squeeze through the conductivity cell of a CTD); and (2) small random errors or "noise" that arise from changes in the sensor configuration, electrical and environmental noise, and unresolved environmental variability. The noise can be treated using statistical methods while elimination of the larger errors generally requires the use of some subjective evaluation procedure. Data summary diagrams or distributions are useful in identifying the large errors as sharp deviations from the general population, while the treatment of the smaller random errors requires a knowledge of the population density function for the data. It is often assumed that random errors are statistically independent and have a normal (Gaussian) probability distribution. A summary diagram can help the investigator evaluate editing programs that "automatically" remove data points whose magnitudes exceed the record mean value by some integer multiple of the record standard deviation. For example, the editing procedure might be asked to eliminate data values $|x - X| > 3\sigma$, where X and σ are the mean and standard deviation of x, respectively. This is wrought with pitfalls, especially if one is dealing with highly variable or episodic systems. By not directly examining the data points in conjunction with adjacent values, one can never be certain that he/she is not throwing away reliable values. For example, during the strong 1983–1984 El Niño, water temperatures at intermediate depths along Line P in the northeast Pacific exceeded the mean temperature by 10 standard deviations (10σ). Had there not been other evidence for basin-wide oceanic heating during this period, there would have been a tendency to dispense with these "abnormal" values.

2.2 CALIBRATION

Before data records can be examined for errors and further reduced for analysis, they must first be converted to meaningful physical units. The integer format generally used to save storage space and to conduct onboard instrument data processing is not amenable to simple visual examination. Binary and ASCII formats are the two most common ways to store the raw data, with the storage space required for the more basic Binary format about 20% of that for the integer values of ASCII format. Conversion of the raw data requires the appropriate calibration coefficients for each sensor. These constants relate recorded values to known values of the measurement parameter. The accuracy of the data then depends on the reliability of the calibration procedure as well as on the performance of the instrument itself. Very precise instruments with poor calibrations will produce incorrect, error-prone data. Common practice is to fit the set of calibration values by least-squares quadratic expressions, yielding either functional (mathematical) or empirical relations between the recorded values and the appropriate physical values. This simplifies the post-processing since the raw data can readily be passed through the calibration formula to yield observations in the correct units. We emphasize that the editing and calibration work should always be performed on *copies* of the original data; never work directly on the raw, unedited data.

In some cases the calibration data do not lend themselves to description in terms of polynomial expressions. An example is the direction channel in Aanderaa current meter data for which the calibration data consists of a table relating the recorded direction in raw 10-byte integer format (0–1024) to the corresponding direction in degrees from the compass calibration (Pillsbury *et al.*, 1974). Some thought should be given to producing calibration "functions" that best represent the calibration data. With the availability of modern computing facilities, it is no more burdensome to build the calibration into a table than it is to convert it to a mathematical expression. Most important, however, is the need to ensure that the calibration accurately represents the performance range and characteristics of the instrument. Unquestioned acceptance of the manufacturer's calibration values is not recommended for the processing of newly collected data. Instead, individual laboratory and/or field calibration may be needed for each instrument. In some cases this is not possible (for example, in the case of XBT probes which come prepackaged and ready for deployment) and some overall average calibration relation must be developed for the measurement system regardless of individual sensor.

Some instruments are individually calibrated before and after each experiment to determine if changes in the sensor unit had occurred during its operation. The conversion to geophysical units must take both pre- and postcalibrations into account. Often the pre- and postcalibration are averaged together or used to define a calibration trend-line which can then be used to transform the instrument engineering units to the appropriate geophysical units. Sometimes a postcalibration reveals a serious instrument malfunction and the data record must be examined to find the place where the failure occurred. Data after this point are eliminated (or modified to account for the instrumental problems) and the postcalibration information is not used in the conversion to geophysical values. Even if the instrument continues to function in a reasonable manner, the calibration history of the instrument is important to producing accurate geophysical measurements from the instrument.

Since each instrument may use a somewhat different procedure to encode and record data it is not possible to discuss all of the techniques employed. We therefore have outlined a general procedure only. Appendix A provides a list of the many physical units used today in physical oceanography. Although there have been many efforts to standardize these units one must still be prepared to work with data in nonstandard units. This may be particularly true in the case of older historical data collected before the introduction of acceptable international units. These standard units also are included in Appendix A.

2.3 INTERPOLATION

Data gaps or "holes" are a problem fundamental to many geophysical data records. Gappy data are frequently the consequence of uneven or irregular sampling (in time and/or space), or they may result from the removal of erroneous values during editing and from sporadic recording system failures. Infrequent data gaps, having limited duration relative to strongly energetic periods of interest, are generally of minor concern, unless one is interested in short-term episodic events rather than stationary periodic phenomena. Major difficulties arise if the length of the holes exceeds a significant fraction (1/3–1/2) of the signal of interest and the overall data loss rises beyond 20–30% (Sturges, 1983). Gaps have a greater effect on weak signals than on strong signals and the adverse effects of the gaps increases most rapidly for the smallest percentages of data lost. While some useful computational techniques have been developed for unevenly spaced data (Meisel, 1978, 1979) and even some advantages to having a range of Nyquist frequencies within a given data set (Press *et al.*, 1992), most analysis methods require data values that are regularly spaced in time or space. As a consequence, it is generally necessary to use an interpolation procedure to create the required regular set of data values as part of the data processing. The problem of interpolation and smoothing is discussed in more detail in Chapter 3.

2.4 DATA PRESENTATION

2.4.1 Introduction

The analysis of most oceanographic records necessitates some form of "first-look" visual display. Even the editing and processing of data typically requires a display stage, as for example in the exact determination of the start and end of a time series, or in the interactive removal and interpolation of data spikes and other erroneous values. A useful axiom is, "when in doubt, look at the data". In order to look at the data, we need specific display procedures. A single set of display procedures for all applications is not possible since different oceanographic data sets require different displays. Often, the development of a new display method may be the substance of a particular research project. For instance, the advent of satellite oceanography has greatly increased the need for interactive graphics display and digital image analysis.

Our discussion begins with traditional types of data and analysis product presentations. These have been developed as oceanographers sought ways to depict the ocean they were observing. The earliest shipboard measurements consisted of temperatures taken at the sea surface and soundings of the ocean bottom. These data were most appropriately plotted on maps to represent their geographical variability. The data were then contoured by hand to provide a smooth picture of the variable's distribution over the survey region. Examples of historical interest are the meridional sections of salinity from the eastern and western basins of the North Atlantic based on data collected during the German *Meteor* Expedition of 1925–1927 (Figure 2.1; Spiess, 1928). The water property maps from this expedition were among the first to indicate the north–south movements of water masses in the Atlantic basin.

As long as measurements were limited to the sea surface or sea floor, the question of horizontal level for display was never raised. As oceanographic sampling became more sophisticated and the vertical profiling of water properties became possible, new data displays were required. Of immediate interest were simple vertical profiles of temperature and salinity such as those shown in Figure 2.2. These property profiles, based on a limited number of sample bottles suspended from the hydrographic wire at

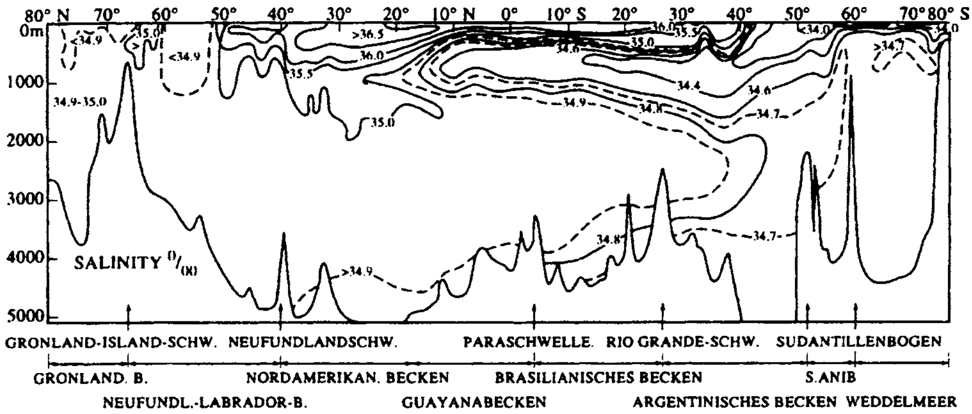

Figure 2.1. Longitudinal section of salinity in the western basin of the Atlantic Ocean (after Spiess, 1928).

standard hydrographic depths, originally served to both depict the vertical stratification of the measured parameter and to detect any sampling bottles that had not functioned properly. The data points could then either be corrected or discarded from the data set. Leakage of the watertight seals, failure of the bottle to trip, and damage against the side of the ship are the major causes of sample loss. Leakage problems can be especially difficult to detect.

The data collected from a research vessel at a series of hydrographic stations may be represented as vertical section plots. Here, the discretely sampled data are entered into a two-dimensional vertical section at the sample depths and then contoured to produce the vertical structure along the section (Figure 2.3). Two things need to be considered in this presentation. First, the depth of the ocean, relative to the horizontal distances, is very small and vertical exaggeration is required to form readable sections. Second, the stratification can be separated roughly into two near-uniform layers with a strong density-gradient layer (the pycnocline) sandwiched between. This two-layer system led early German oceanographers to introduce the terms "troposphere" and "stratosphere" (Wüst, 1935; Defant, 1936) which they described as the warm and cold water spheres of the ocean. Introduced by analogy to the atmospheric vertical structure, this nomenclature has not been widely used in oceanography. The consequence of this natural vertical stratification, however, is that vertical sections are often best displayed in two parts, a shallow upper layer, with an expanded scale, and a deep layer with a much more compressed vertical resolution.

Vertical profiling capability makes it possible to map quantities on different types of horizontal surface. Usually, specific depth levels are chosen to characterize spatial variability within certain layers. The near-vertical homogeneity of the deeper layers means that fewer surfaces need to be mapped to describe the lower part of the water column. Closer to the ocean surface, additional layers may be required to properly represent the strong horizontal gradients.

The realization by oceanographers of the importance of both along- and cross-isopycnal processes has led to the practice of displaying water properties on specific isopycnal surfaces. Since these surfaces do not usually coincide with constant depth levels, the depth of the isopycnal (equal density) surface also is sometimes plotted.

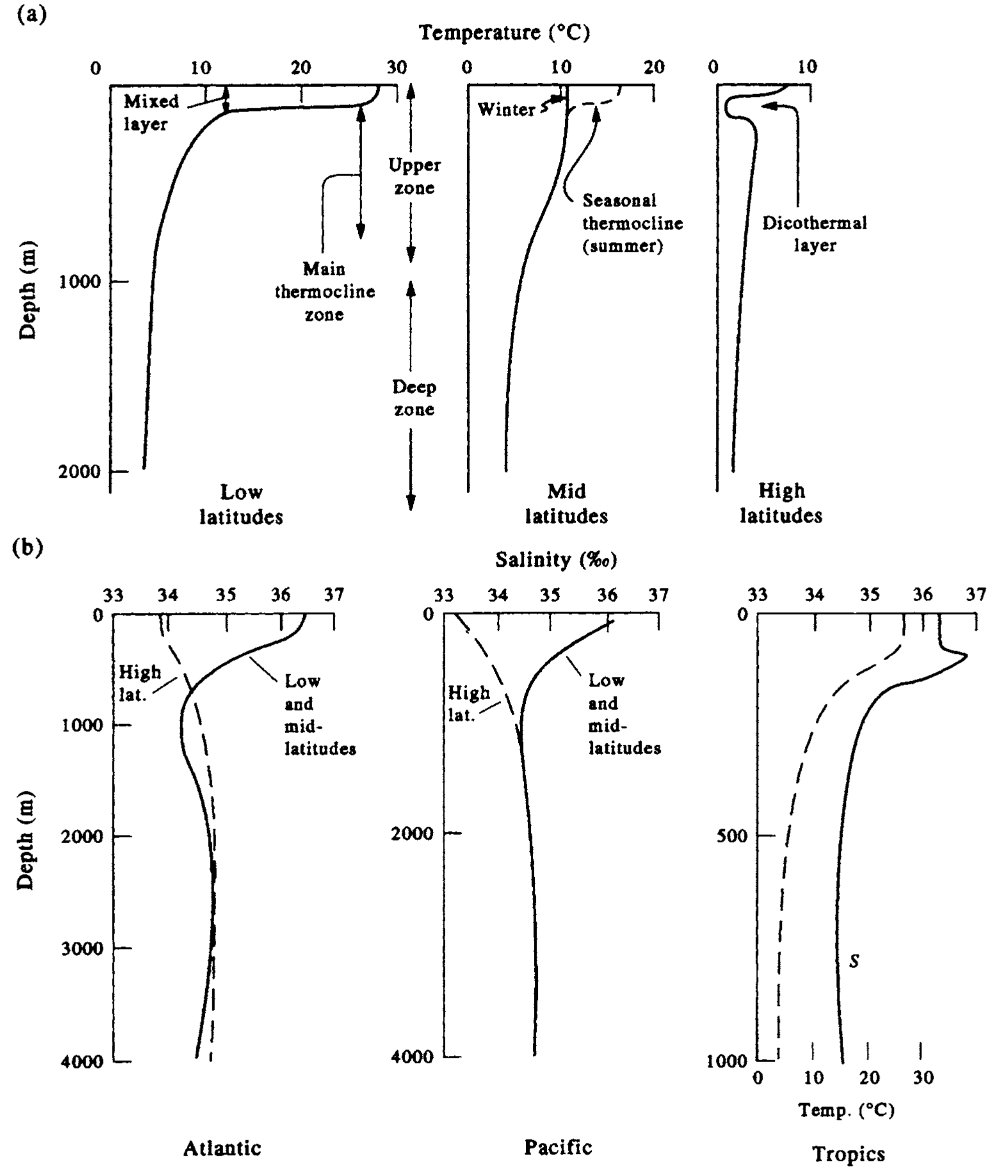

Figure 2.2. Vertical profiles. (a) Temperature profiles for tropical (low) latitudes, mid-latitudes, and polar (high) latitudes in the Pacific Ocean. (b) Salinity profiles for the Atlantic, Pacific and tropical oceans for different latitudes. The dicothermal layer in (a) is formed from intense winter cooling followed by summer warming to shallower depths. Both salinity (solid line) and temperature (dashed line) are plotted for the tropics in (b). (From Pickard and Emery, 1992.)

Isopycnal surfaces are chosen to characterize the upper and lower layers separately. Often, processes not obvious in a horizontal depth plot are clearly shown on selected isopycnal (sigma) surfaces. This practice is especially useful in tracking the lateral distribution of tracer properties such as the deep and intermediate depth silicate maxima in the North Pacific (Talley and Joyce, 1992) or the spreading of hydrothermal plumes that have risen to a density surface corresponding to their level of neutral buoyancy (Feely *et al.*, 1994).

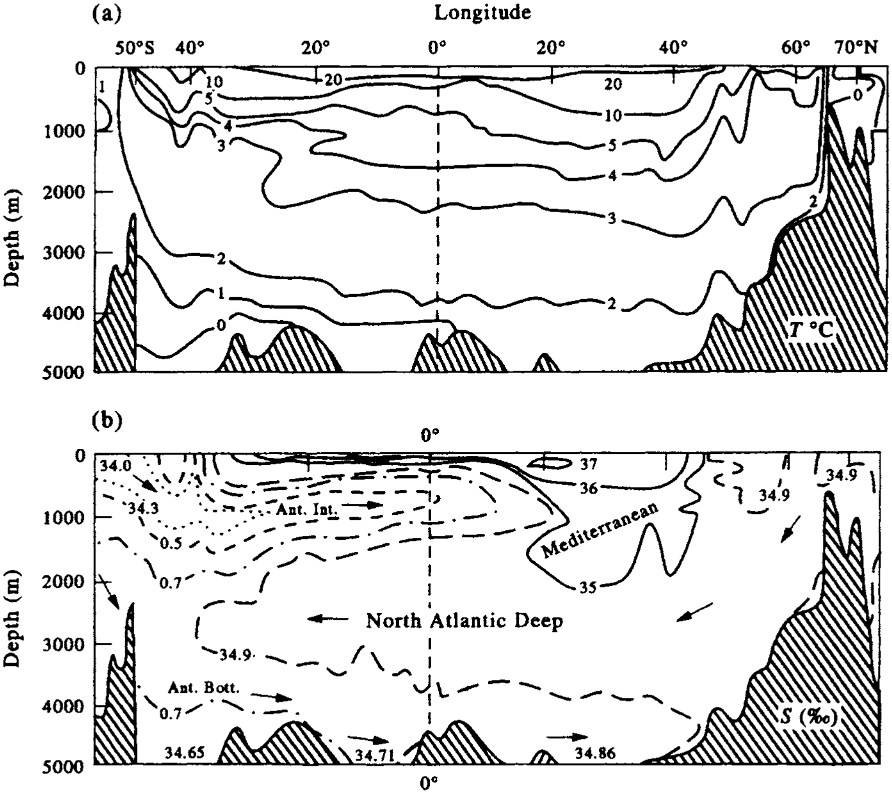

Figure 2.3. Longitudinal cross-sections of (a) in situ temperature and (b) salinity for the Atlantic Ocean. Arrows denote direction of water mass movement based on the distribution of properties. Ant. Bott. = Atlantic Bottom Water; Ant. Int. = Antarctic Intermediate Water. (From Pickard and Emery, 1992.)

Another challenge to the graphical presentation of oceanographic data is the generation of time series at specific locations. Initially, measured scalar quantities were simply displayed as time-series plots. Vector quantities, however, require a plot of two parameters against time. A common solution is the use of the "stick plot" (Figure 2.4) where each stick (vector) corresponds to a measured speed and direction at the specified time. The only caution here is that current vectors are plotted as the direction the current is toward (oceanographic convention) whereas winds are sometimes plotted as the direction the wind is from (meteorological convention). The progressive vector diagram (PVD) also is used to plot vector velocity time series (Figure 2.5). In this case, the time-integrated displacements along each of two orthogonal directions (x,y) are calculated from the corresponding velocity components $(x, y) = (x_o, y_o) + \sum(u_i, v_i)\Delta t_i$, $(i = 1, 2, ...)$ to give "pseudo" downstream displacements of a parcel of water from its origin (x_o, y_o).

A plot relating one property to another is of considerable value in oceanography. Known as a "characteristic diagram" the most common is that relating temperature and salinity called the *TS* diagram. Originally defined with temperature and salinity values obtained from the same sample bottles, the *TS* relationship was used to detect incorrect bottle samples and to define oceanic water masses. *TS* plots have been shown

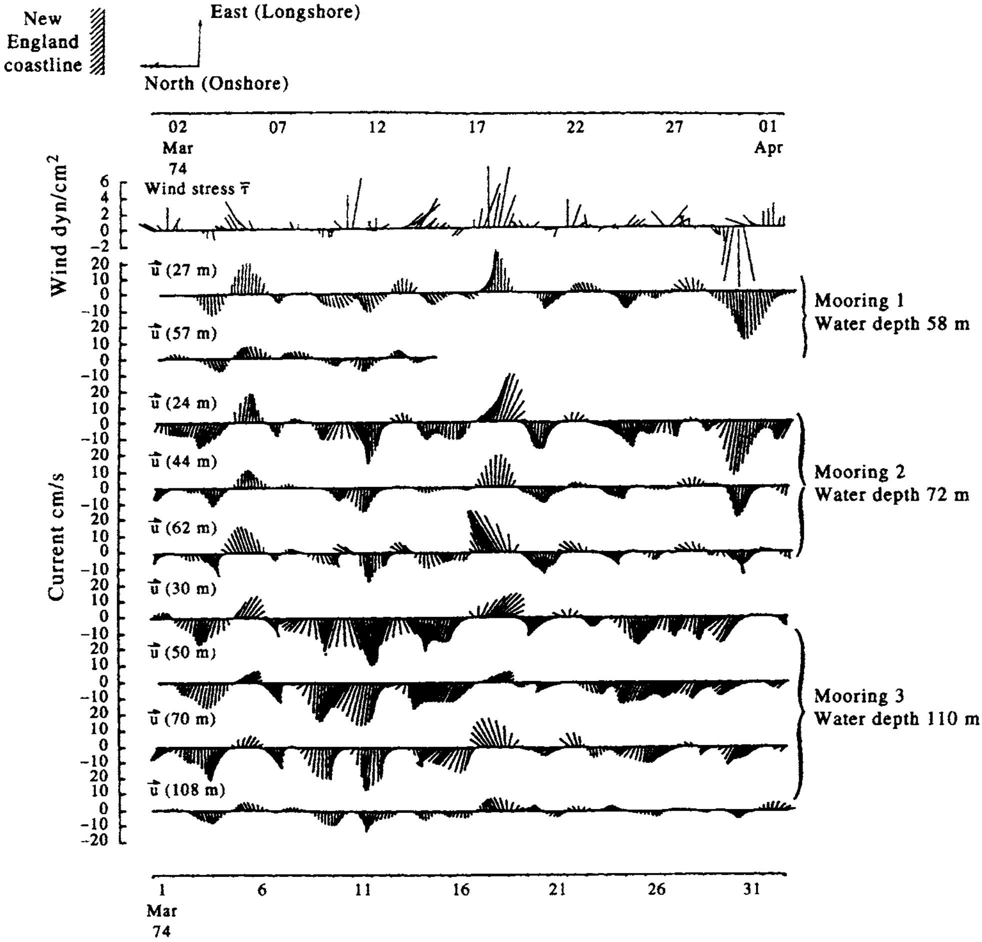

Figure 2.4. Vector (stick) plots of low-pass filtered wind stress and subtidal currents at different depths measured along the East Coast of the United States about 100 km west of Nantucket Shoals. East (up) is alongshore and north is cross-shore. Brackets give the current meter depth (m). (Figure 7.11 from Beardsley and Boicourt, 1981.)

to provide consistent relationships over large horizontal areas (Helland-Hansen, 1918) and have recently been the focus of studies into the formation of water masses (McDougal, 1985a, b). Plots of potential temperature versus salinity (the θ–S relationship) or versus potential density (the θ–σ_θ relationship) have proven particularly useful in defining the maximum height of rise of hydrothermal plumes formed over venting sites along mid-ocean ridges (Figure 2.6; Thomson *et al.*, 1992).

Except for some minor changes, vertical profiles, vertical sections, horizontal maps, and time series continue to serve as the primary display techniques for physical oceanographers. The development of electronic instruments, with their rapid sampling capabilities and the growing use of high-volume satellite data, may have changed how we display certain data but most of the basic display formats remain the same. Today, a computer is programmed to carry out both the required computations and to plot the results. Image formats, which are common with satellite data, require further sophisticated interactive processing to produce images with accurate geographical corres-

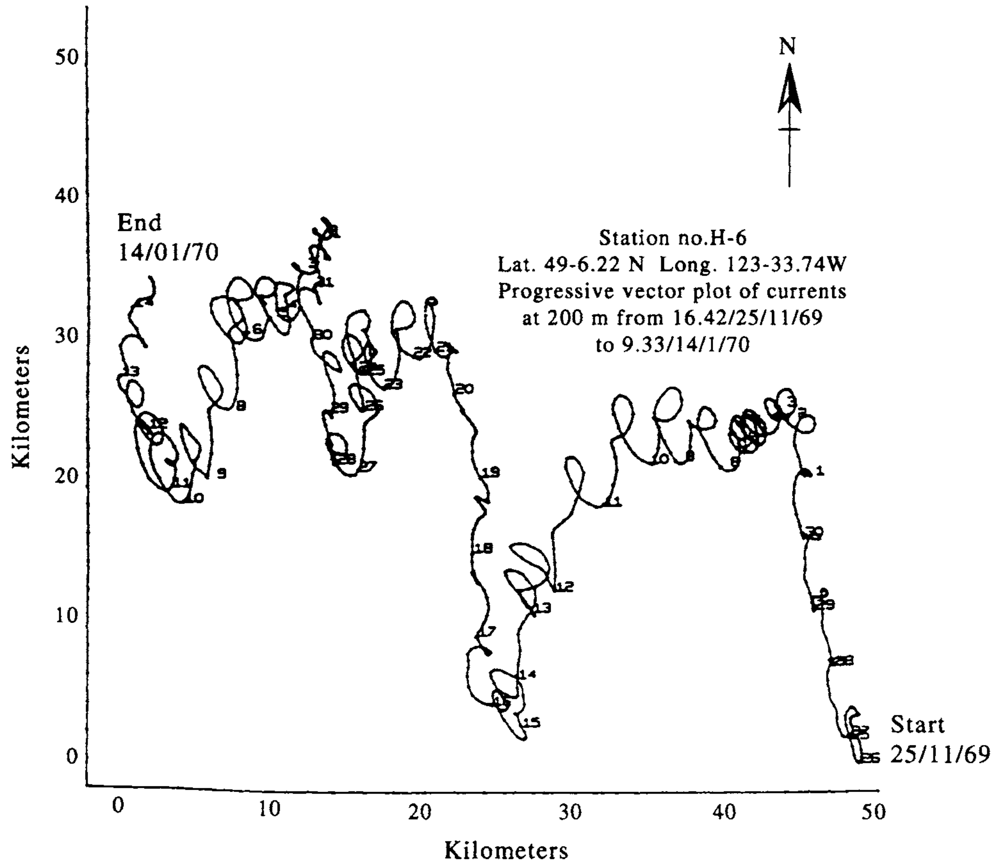

Figure 2.5. Progressive vector diagram (PVD) constructed from the east–west and north–south components of velocity for currents measured every 10 min for a period of 50 days at a depth of 200 m in the Strait of Georgia, British Columbia. Plotted positions correspond to horizontal displacements of the water that would occur if the flow near the mooring location was the same as that at this location. (From Tabata and Stickland, 1972.)

pondence. Despite this, the combination of vertical sections and horizontal maps continues to provide most investigators with the requisite geometrical display capability.

2.4.2 Vertical profiles

Vertical profiles obtained from ships, buoys, aircraft or other platforms provide a convenient way to display oceanic structure (Figure 2.2). One must be careful in selecting the appropriate scales for the vertical and the horizontal property axes. The vertical axis may change scale or vary nonlinearly to account for the marked changes in the upper ocean compared with the relative homogeneity of the lower layers. The property axis needs to have a fine enough scale so as to define the small vertical gradients in the deeper layer without the upper layer going off-scale. When considering a variety of different vertical profiles together (Figures 2.7 and 2.8), a common property scale is an advantage although consideration must be given to the strong dependence of vertical property profiles on latitude and season.

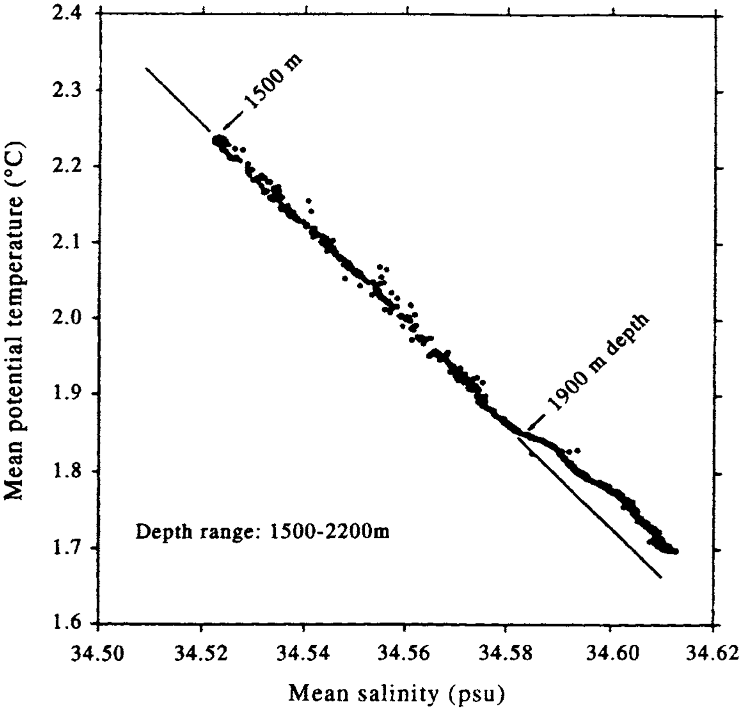

Figure 2.6. Plot of mean potential temperature (θ) versus mean salinity (S) for depths of 1500–2200 m over Endeavour Ridge in the northeast Pacific. The least squares linear fit covers the depth range 1500–1900 m, where $\bar{\theta} = -6.563\bar{S} + 228.795°C$. *The abrupt change in the θ–S relationship at a depth of 1900 m marks the maximum height of rise of the hydrothermal plume. (From Thomson et al., 1992.)*

A dramatic change has taken place recently in the detailed information contained in vertical profiles. The development and regular use of continuous, high-resolution, electronic profiling systems have provided fine-structure information previously not possible with standard hydrographic casts. Profiles from standard bottle casts required smooth interpolation between observed depths so that structures finer in scale than the smallest vertical sampling separation were missed. Vertical profiles from modern CTD systems are of such high resolution that they are generally either vertically averaged or subsampled to reduce the large volume of data to a manageable level for display. For example, with the rapid ($\approx$10 Hz) sampling rates of modern CTD systems, parameters such as temperature and salinity, which are generated approximately every 0.01 m, are not presentable in a plot of reasonable size. Thus data are either averaged or subsampled to create files with sampling increments of 1 m or larger.

Studies of fine-scale (centimeter scale) variability require the display of full CTD resolution and will generally be limited to selected portions of the vertical profile. These portions are chosen to reflect that part of the water column of greatest concern for the study. Full-resolution CTD profiles reveal fine-scale structure in both T and S, and can be used to study mixing processes such as interleaving and double-diffusion. Expressions of these processes are also apparent in full-resolution TS diagrams using CTD data. One must be careful, however, not to confuse instrument noise (e.g. those due to vibrations or "strumming" of the support cable caused by vortex shedding)

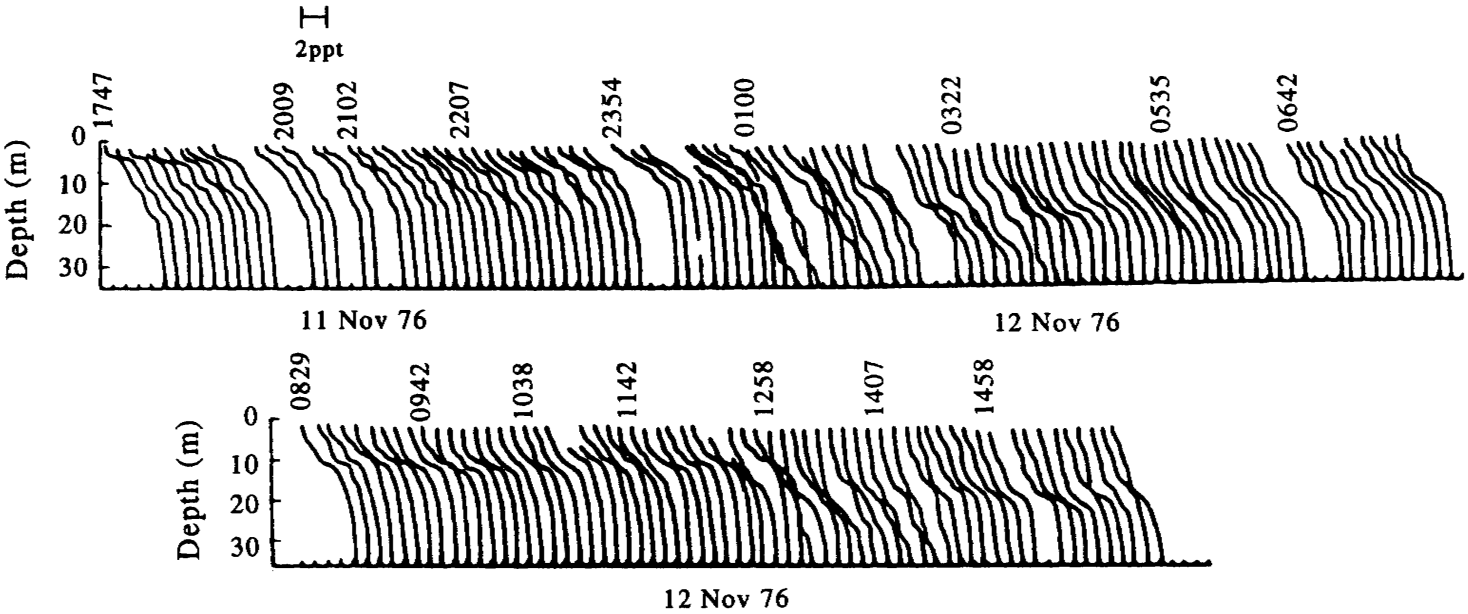

Figure 2.7. Time series of salinity profiles ("waterfall plot") taken in a highly stratified fjord. The effects of large internal waves can be seen around 0100 and 1300 on 12 November. (From Farmer and Smith, 1980.)

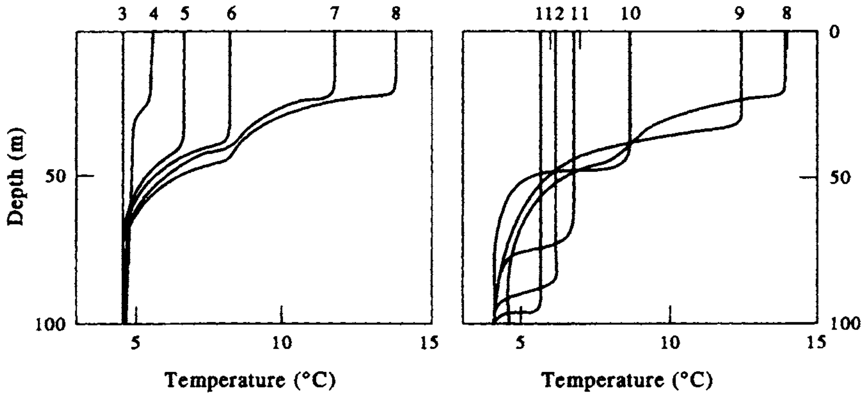

Figure 2.8. Time series of monthly mean profiles of upper ocean temperature at Ocean Weather Station "P", northeast Pacific (50°N, 145°W). Numbers denote the months of the year. (From Pickard and Emery, 1992.)

with fine-scale oceanic structure. Processing should be used where possible to separate the instrument noise from the wave number, band-limited signal of mixing processes.

Often, computer programs for processing CTD data contain a series of different display options that can be used to manipulate the stored high-resolution digital data. The abundance of raw CTD digital data, and the variety of *in situ* calibration procedures, make it difficult to interpret and analyze CTD records using a universal format. This is a fundamental problem in assembling a historical file of CTD observations. Hopefully, the statistics of CTD data that have been smoothed to a resolution comparable to that of traditional bottle casts are sufficiently homogeneous to be treated as updates to the hydrographic station data file. The increasingly wide use of combined CTD and rosette profiling systems has led to a dramatic decrease in the number of standard bottle casts. (A rosette system consists of a carrousel holding 12 or so hydro bottles that can be "tripped" from the ship by sending an electric pulse down the conducting CTD support cable. The CTD is generally placed in the center of the carrousel.)

2.4.3 Vertical sections

Vertical sections are a way to display vertically profiled data collected regionally along the track of a research vessel or taken from more extended crossings of an ocean basin (usually, meridionally or zonally). Marked vertical exaggeration is necessary to make oceanic structure visible in these sections. A basic assumption in any vertical section is that the structure being mapped has a persistence scale longer than the time required to collect the section data. Depending on the type of data collected at each station, and on the length of the section, shipboard collection times can run from a few days to a few weeks. Thus, only phenomena with time scales longer than these periods are properly resolved by the vertical sections. Recognizing this fact leads to a trade-off between spatial resolution (between-station spacing) and the time to complete the section. Sampling time decreases as the number of profiles decreases and the samples taken approach a true *synoptic* representation (samples collected at the same time). Airborne surveys using expendable probes such as AXBTs (airborne XBTs) from fixed-wing aircraft and helicopters yield much more synoptic information but are limited in the type of measurement that can be made and by the depth range of a given measurement. Although aircraft often have hourly charge-out rates that are similar to ships and generally are more cost-effective than ships on a per datum basis, operation of aircraft is usually the domain of the military or coastguard.

Fewer sample profiles means wider spacing between stations and reduced resolution of smaller, shorter-term variability. There is a real danger of short time-scale or space-scale variability aliasing quasi-synoptic, low-resolution vertical sections. Thus, the data collection scheme must be designed to either resolve or eliminate (by filtering) scales of oceanic variability shorter than those being studied. With the ever-increasing interest in ocean climate, and at a time when the importance of mesoscale oceanic circulation features has been recognized, investigators should give serious consideration to their intended sampling program to optimize the future usefulness of the data collected.

Traditional bottle hydrographic casts were intended to resolve the slowly changing background patterns of the property distributions associated with the mean "steady-state" circulation. As a result, station spacings were usually too large to adequately resolve mesoscale features. In addition, bottle casts require long station times leading to relatively long total elapsed times for each section. The fact that these data have provided a meaningful picture of the ocean suggests that there is a strong component of the oceanic property distributions related to the steady-state circulation. For these reasons, vertical sections based on traditional bottle-cast station data provide useful definitions of the meridional and zonal distributions of individual water masses (Figure 2.1).

The importance of mesoscale oceanic variability has prompted many oceanographers to decrease their sample spacing. Electronic profiling systems, such as the CTD and CTD-rosette, require less time per profile than standard bottle casts so that the total elapsed time per section has been reduced over the years despite the need for greater spatial resolution. Still, most oceanographic sections are far from being synoptic owing to the low speeds of ships and some consideration must be given to the definition of which time/space scales are actually being resolved by the measurements. For example, suppose we wish to survey a 1000 km oceanic section and collect a meagre 20 salinity–temperature profiles to 2000 m depth along the way. At an average speed of 12 knots, steaming time alone will amount to about two days. Each bottle cast would take about two hours and each CTD cast about one hour. Our survey time would range from three to four days, which is just marginally synoptic by most oceanographers' standards.

Expendable profiling systems such as the XBT make it possible to reduce sampling time by allowing profile collection from a moving ship. Ships also can be fitted with an acoustic current profiling system which allows for the measurement of ocean currents in the upper few hundred meters of the water column while the ship is underway. The depth of measurement is determined by frequency and is about 500 m for the commonly used 150 kHz transducers. Most modern oceanographic vessels also have SAIL (Shipboard ASCII Interrogation Loop) systems for rapid ($\approx$1 min) sampling of the near-surface temperature and salinity at the intake for the ship's engine cooling system. SAIL data are typically collected a few meters below the ship's waterline. Oceanographic sensor arrays towed in a saw-tooth pattern behind the ship provide another technique for detailed sampling of the water column. This method has wide application in studying near-surface fronts, turbulent microstructure, and hydrothermal venting (Figure 1.11.6). These technological improvements have lowered the sample time and increased the vertical resolution.

As referred to earlier, it is common practice when plotting sections to divide the vertical axis into two parts, with the upper portion greatly expanded to display the larger changes of the upper layer. The contour interval used in the upper part may be larger than that used for the weaker vertical gradients of the deeper layer. It is important, however, to maintain a constant interval within each layer to faithfully represent the gradients. In regions with particularly weak vertical gradients, additional contours may be added but a change in line weight, or type, is customary to distinguish the added line from the other contours. All contours must be clearly labeled. Color is often very effective in distinguishing gradients represented by the contours. While it is common practice to use shades of red to indicate warm regions, and shades of blue for cold, there is no recommended color coding for properties such as salinity, dissolved oxygen or nutrients. The color atlas of water properties for the Pacific Ocean published by Reid (1965) provides a useful color scheme.

In sections derived from bottle samples, individual data points are usually indicated by a dot or by the actual data value. In addition, the station number is indicated in the margin above or below the profile. Stations collected with CTDs usually have the station position indicated but no longer have dots or sample values for individual data points. Because of the high vertical resolution, only the contours are plotted.

The horizontal axis usually represents distance along the section and many sections have a small inset map showing the section location. Alternatively, the reader is referred to another map which shows all section locations. Since many sections are taken along parallels of latitude or meridians of longitude, it is customary to include the appropriate latitude or longitude scale at the top or bottom of each section (Figure 2.3). Even when a section only approximates zonal or meridional lines, estimates of the latitude or longitude are frequently included in the axis label to help orient the reader. Station labels should also be added to the axis.

A unique problem encountered when plotting deep vertical sections of density is the need to have different pressure reference levels for the density determination to account for the dependence of sea-water compressibility on temperature. Since water temperature generally decreases with pressure (greater depths), artificially low densities will be calculated at the greatest depths when using the surface pressure as a reference (Lynn and Reid, 1968, Reid and Lynn, 1971). When one wants to resolve the deep density structure, and at the same time display the upper layer, different reference levels are used for different depth intervals. As shown in Figure 2.9, the resulting section has discontinuities in the density contours as the reference level changes.

A final comment about vertical sections concerns the representation of bottom topography. The required vertical exaggeration makes it necessary to represent the bottom topography on an exaggerated scale. This often produces steep-looking islands and bottom relief. There is a temptation to ignore bottom structure, but as oceanographers become more aware of the importance of bottom topography in dictating certain aspects of the circulation, it is useful to include some representation of the bottom structure in the sections.

2.4.4 Horizontal maps

In the introduction, we mentioned the early mapping of ocean surface properties and bottom depths. Following established traditions in map making, these early maps

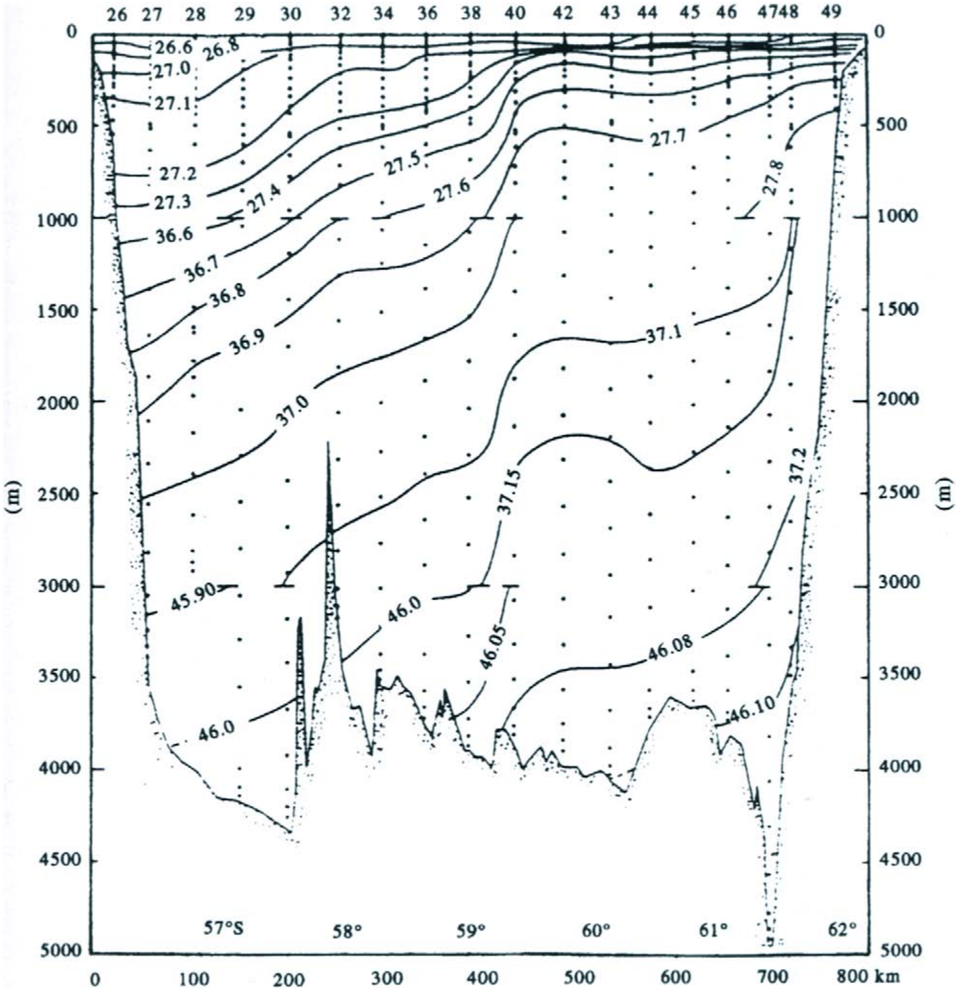

Figure 2.9. Cross-section of density (σ_t) (kg/m^3) across Drake Passage in 1976. (From Nowlin et al., 1986.)

were as much works of art as they were representations of oceanographic information. The collection of hydrographic profiles later made it possible to depict property distributions at different levels of the water column (Figure 2.10). As with vertical sections, the question of sample time versus horizontal resolution needs to be addressed, especially where maps cover large portions of an ocean basin. Instead of the days to weeks needed to collect data along a single short section, it may take weeks, months and even years to obtain the required data covering large geographical regions. Often, horizontal maps consist of a collection of sections designed to define either the zonal/meridional structure or cross-shore structure for near-coastal regions. In most cases, the data presented on a map are contoured with the assumption that the map corresponds to a stationary property distribution. For continental shelf regions, data used in a single map should cover a time period that is less than the approximately 10 day e-folding time scale of mesoscale eddies. In this context, the "e-folding time" is the time for the mesoscale currents to decay to $1/e^1 = 0.368$ of their peak values.

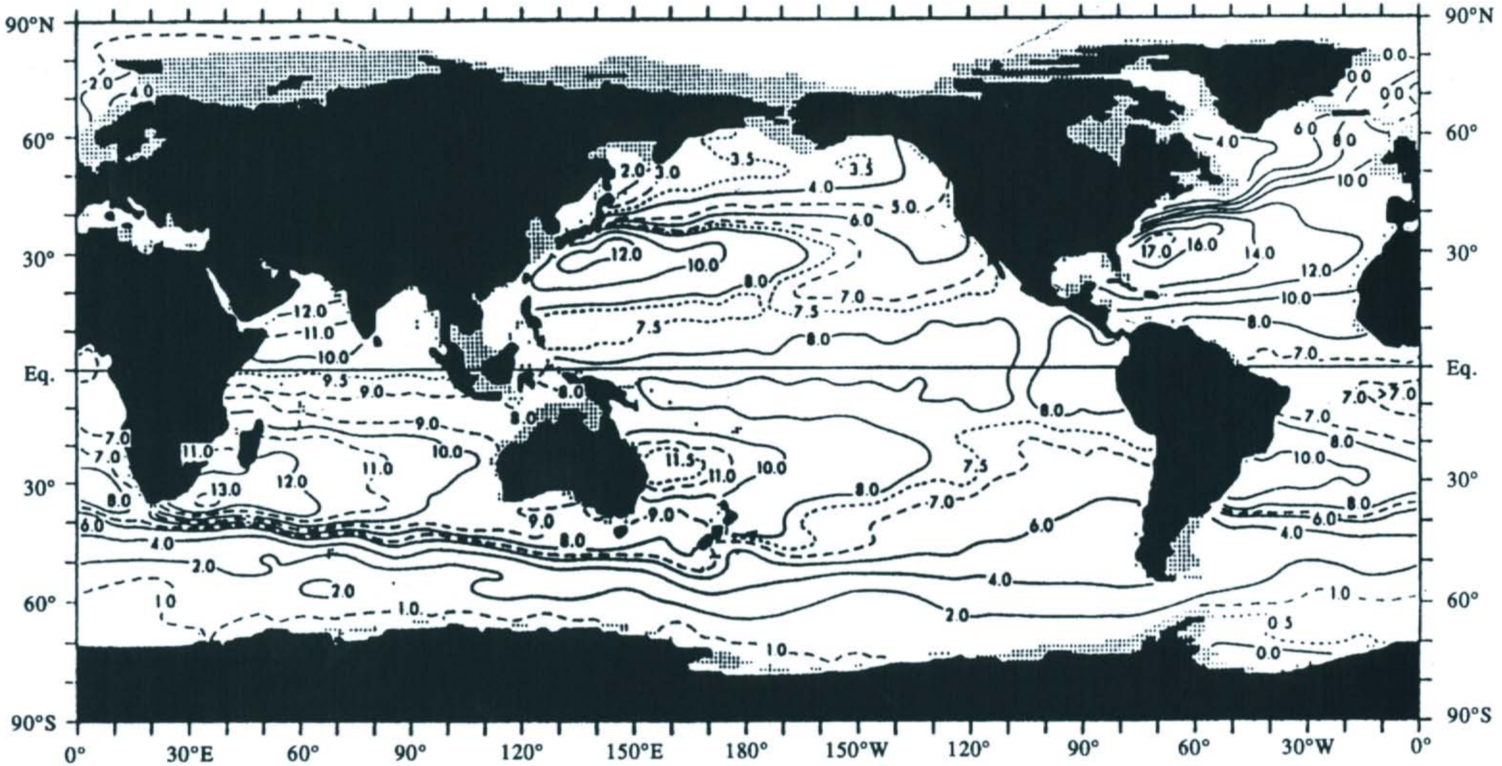

Figure 2.10. Horizontal maps of annual mean potential temperature in the world ocean at (a) 500 m. (From Levitus, 1982.)

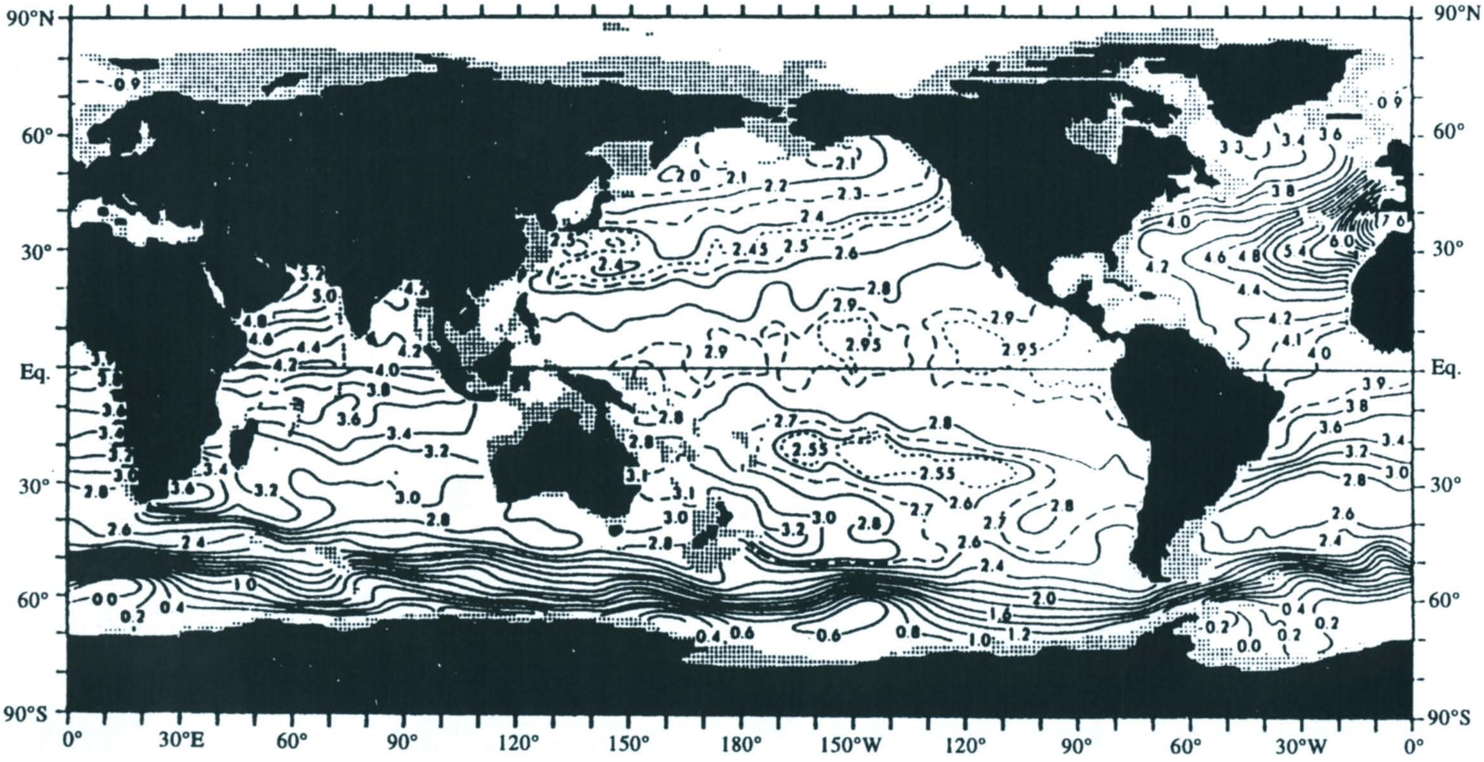

Figure 2.10. Horizontal maps of annual mean potential temperature in the world ocean at (b) 1000 m depth. (From Levitus, 1982.)

Much of what we know about the overall structure of the ocean, particularly the deep ocean, has been inferred from large-scale maps of water properties. A presentation developed by Wüst (1935) to better display the horizontal variations of particular water masses is based on the *core-layer* method. Using vertical property profiles, vertical sections, and characteristic (one property versus another property) diagrams, Wüst defined a core-layer as a property extremum and then traced the distribution of properties along the surface defined by this extremum. Since each core layer is not strictly horizontal, it is first necessary to present a map showing the depth of the core-layer in question. Properties such as temperature, salinity, oxygen, and nutrients also can be plotted along these layers in addition to the percentage of the appropriate water mass defined from the characteristic diagrams. A similar presentation is the plotting of properties on selected density surfaces. This practice originated with Montgomery (1938) who argued that advection and mixing would occur most easily along surfaces of constant entropy. Since these isentropic surfaces are difficult to determine, Montgomery suggested that surfaces of constant potential density would be close approximations in the lower layers and that sigma-t would be appropriate for the upper layers. Known as *isentropic analysis* because of its thermodynamic reasoning, this technique led to the practice of presenting horizontal maps on sigma-t or sigma-θ (potential density) surfaces. While it may be difficult to visualize the shape of the density surfaces, this type of format is often better at revealing property gradients. As with the core-layer method, preparing maps on density surfaces includes the plotting of characteristic property diagrams to identify the best set of density surfaces. Inherent in this type of presentation is the assumption that diapycnal (cross-isopycnal) mixing does not occur. Sometimes steric surfaces or surfaces of thermosteric anomaly are chosen for plotting rather than density.

The definition and construction of contour lines on horizontal maps has evolved in recent years from a subjective hand-drawn procedure to a more objective procedure carried out by a computer. Hand analyses usually appear quite smooth but it is impossible to adequately define the smoothing process applied to the data since it varies with user experience and prejudice. Only if the same person contoured all of the data, is it possible to compare map results directly. Differences produced by subjective contouring are less severe for many long-term and stationary processes, which are likely to be well represented regardless of subjective preference. Shorter-term and smaller space-scale variations, however, will be treated differently by each analyst and it will be impossible to compare results. In this regard, we note that weather maps used in six-hourly weather forecasts are still drawn by hand since this allows for needed subjective decisions based on the accumulated experience of the meteorologist.

Objective analysis and other computer-based mapping procedures have been developed to carry out the horizontal mapping and contouring. Some of these methods are presented individually in later sections of this text. Since there is such a wide selection of mapping methods, it is not possible to discuss each individually. However, the reader is cautioned in applying any specific mapping routine to ensure that any implicit assumptions are satisfied by the data being mapped. The character of the result needs to be anticipated so that the consequences of the mapping procedure can be evaluated. For example, the mapping procedure called objective analysis or optimum interpolation, is inherently a smoothing operation. As a consequence, the output gridded data may be smoothed over a horizontal length scale greater than the scale of interest in the study. One must decide how best to retain the variability of interest and still have a definable mapping procedure for irregularly spaced data.

2.4.5 Map projections

One neglected aspect of mapping oceanographic variables is the selection of an appropriate map projection. A wide variety of projections has been used in the past. The nature of the analysis, its scale and geographic region of interest dictate the type of map projection to use (Bowditch, 1977). Polar studies generally use a conic or other polar projection to avoid distortion of zonal variations near the poles. An example of a simple conic projection for the northern hemisphere is given in Figure 2.11. In this case, the cone is tangent at a single latitude (called a standard parallel) which can be selected by changing the angle of the cone (Figure 2.11a). The resulting latitude–longitude scales are different around each point and the projection is said to be nonconformal (Figure 2.11b). A conformal (=orthomorphic; conserves shape and angular relationships) conic projection is the Lambert conformal projection which cuts the earth at two latitudes. In this projection, the spacing of latitude lines is altered so that the distortion is the same as along meridians. This is the most widely used conic projection for navigation since straight lines nearly correspond to great circle routes. A variation of this mapping is called the "modified Lambert conformal projection". This projection amounts to selecting the top standard parallel very near the pole, thus closing off the top of the map. Such a conic projection is conformal over most of its domain. Mention should also be made of the "polar stereographic projection" that is favored by meteorologists. Presumably, the advantages of this projection is its ability to cover an entire hemisphere, and its low distortion at temperate latitudes.

At mid- and low-latitudes, it is common to use some form of Mercator projection which accounts for the meridional change in earth radius by a change in the length of the zonal axis. Mercator maps are conformal in the sense that distortions in latitude and longitude are similar. The most common of these is the transverse Mercator or cylindrical projection (Figure 2.12). As the name implies it amounts to projecting the earth's surface onto a cylinder which is tangent at the equator (equatorial cylindrical). This type of projection, by definition, cannot include the poles. A variant of this is called the oblique Mercator projection, corresponding to a cylinder which is tangent to the earth along a line tilted with respect to the equator. Unlike the equatorial

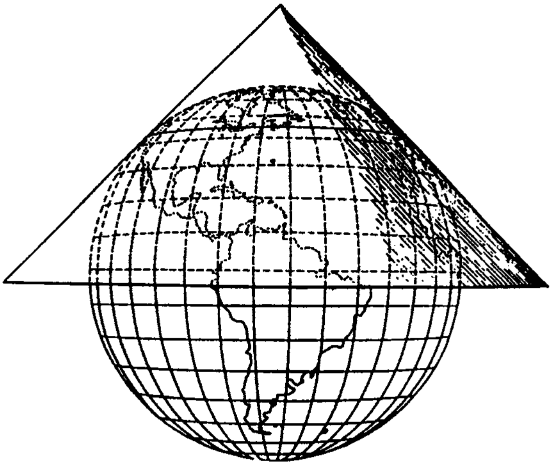

Figure 2.11. An example of a simple conic projection for the northern hemisphere. The single tangent cone in (a) is used to create the map in (b). (From Bowditch, 1977.)

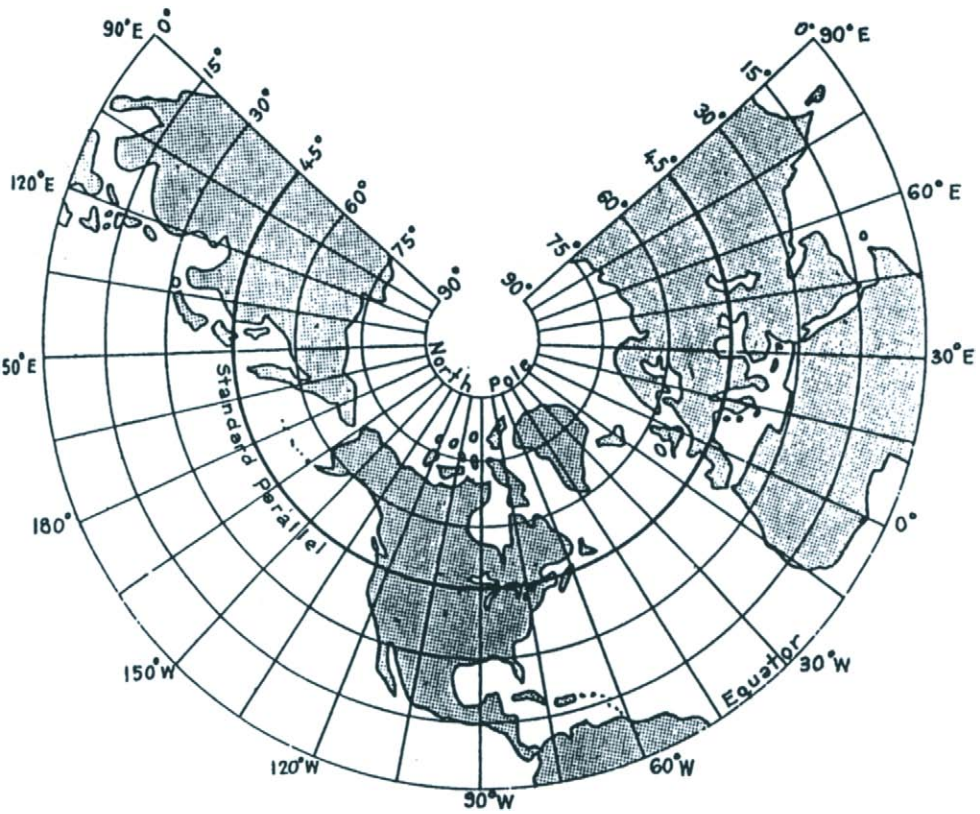

Figure 2.11. An example of a simple conic projection for the northern hemisphere. The single tangent cone in (a) is used to create the map in (b). (From Bowditch, 1977.)

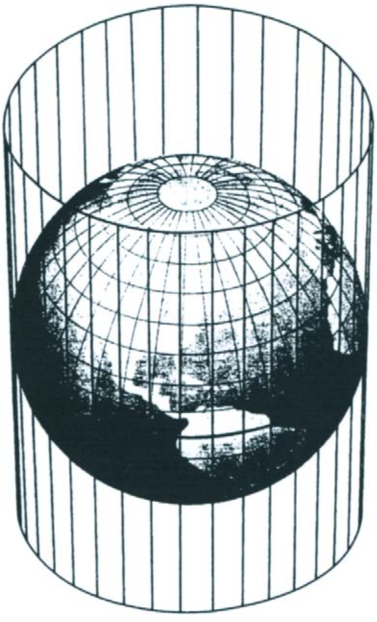

Figure 2.12. The transverse Mercator or cylindrical projection. (From Bowditch, 1977.)

(a)

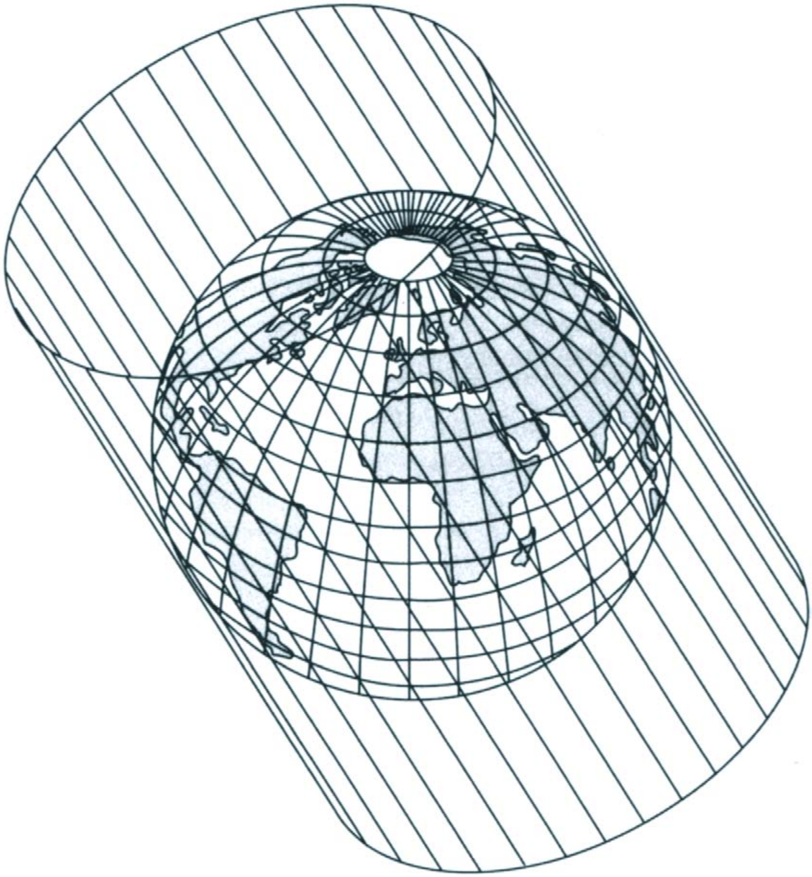

Figure 2.13. An oblique Mercator or oblique cylindrical projection that includes the poles. The cylinder in (a) is used to generate the transverse Mercator map of the western hemisphere in (b). (From Bowditch, 1977.)

cylindrical this oblique projection can represent the poles (Figure 2.13a). This form of Mercator projection also has a conformal character, with equal distortions in lines of latitude and longitude (Figure 2.13b). The most familiar Mercator mapping is the universal transverse Mercator (UTM) grid which is a military grid using the equatorial cylindrical projection. Another popular mid-latitude projection is the rectangular or equal-area projection which is a cylindrical projection with uniform spacing between lines of latitude and lines of longitude. In applications where actual earth distortion is not important, this type of equal area projection is often used. Whereas Mercator projections are useful for plotting vectors, equal-area projections are useful for representing scalar properties. For studies of limited areas, special projections may be developed such as the azimuthal projection, which consists of a projection onto a flat plane tangent to the earth at a single point. This is also called a gnomonic projection. Stereographic projects perform similar projections; however, where gnomonic projections use the center of the earth as the origin, stereographic projections use a point on the surface of the earth.

The effects of map projection on mapped oceanographic properties should always be considered. Often the distortion is unimportant since only the distribution relative

(b)

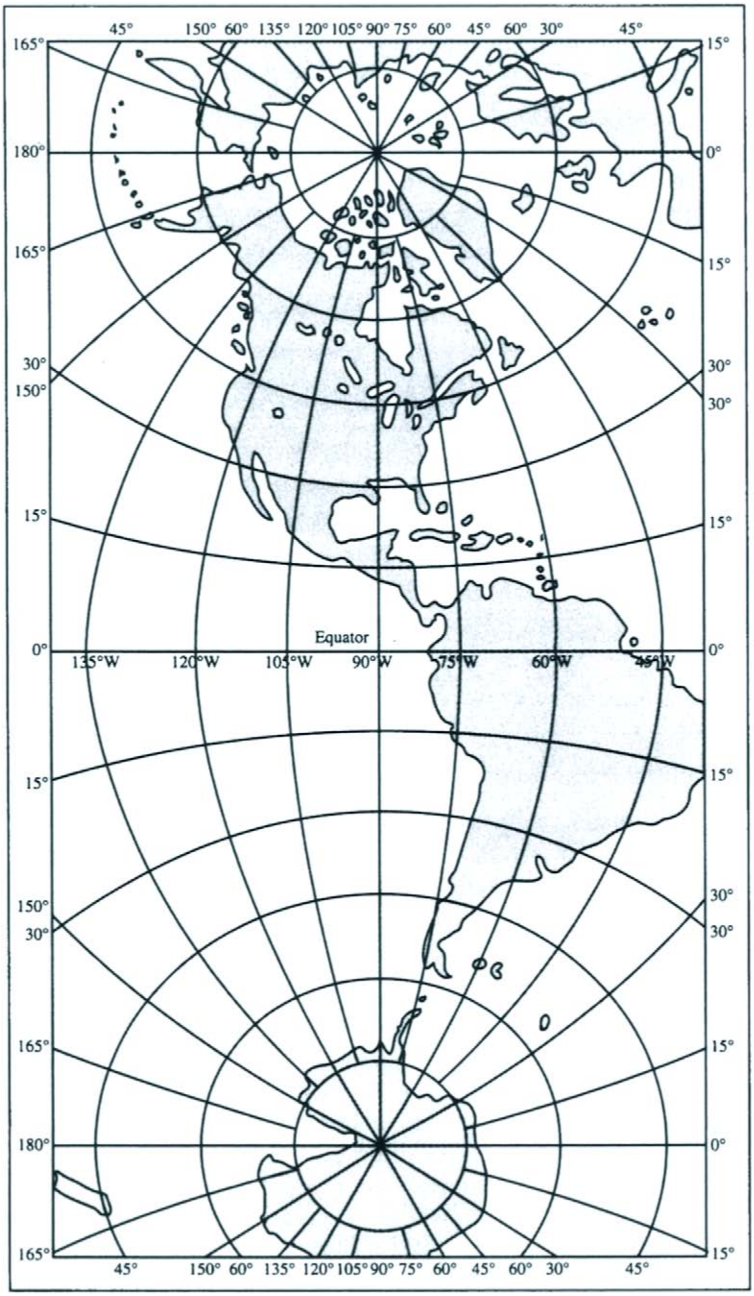

Figure 2.13. An oblique Mercator or oblique cylindrical projection that includes the poles. The cylinder in (a) is used to generate the transverse Mercator map of the western hemisphere in (b). (From Bowditch, 1977.)

to the provided geography (land boundaries) is important. In other cases, such as plots of Lagrangian trajectories, it is important to compare maps using the same projection from which it should be possible to roughly estimate velocities along the trajectories. Variations in map projections can also introduce unwanted variations in the displays of properties.

2.4.6 Characteristic or property versus property diagrams

In many oceanographic applications, it is useful to relate two simultaneously observed variables. Helland-Hansen (1918) first suggested the utility of plotting temperature (T) against salinity (S). He found that TS diagrams were similar over large areas of the ocean and remained constant in time at many locations. An early application of the TS diagram was the testing and editing of newly acquired hydrographic bottle data. When compared with existing TS curves for a particular region, TS curves from newly collected data quickly highlighted erroneous samples which could then be corrected or eliminated. Similar characteristic diagrams were developed for other ocean properties. Many of these, however, were not conservative and could not be expected to exhibit the constancy of the TS relationship (we will use TS as representative of all characteristic diagrams.)

As originally conceived, characteristic diagrams such as the TS plots were straightforward to construct. Pairs of property values from the same water bottle sample constituted a point on the characteristic plot. The connected points formed the TS curve for the station (Figure 2.14). Each TS curve represented an individual oceanographic station and similarities between stations were judged by comparing their TS curves. These traditional TS curves exhibit a unique relationship between T, S, and Z (the depth of the sample). What stays constant is the TS relationship, not its correspondence with Z. As internal waves, eddies, and other unresolved dynamical

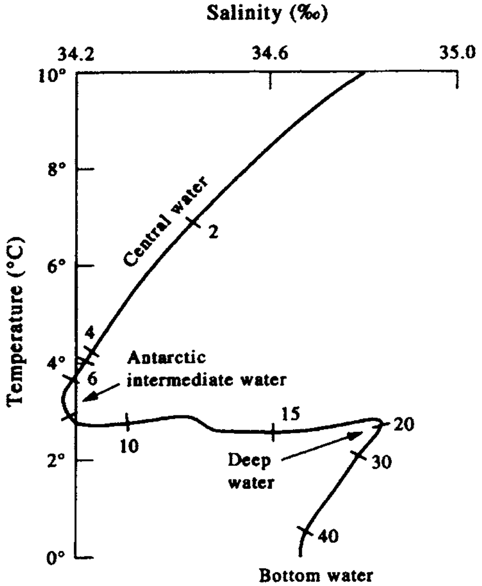

Figure 2.14. Temperature-salinity curve for the western basin of the South Atlantic at 41°S latitude. Depths are marked in hundreds of meters. (Adapted from Tchernia, 1980.)

features move through a region, the depth of the density structure changes. In response, the paired *TS* value moves up and down along the *TS* curve, thus maintaining the water mass structure. This argument does not hold in frontal zones where the water mass itself is being modified by mixing and interleaving.

Temporal oceanic variability has important consequences for the calculation of mean *TS* diagrams where *TS* pairs, from a number of different bottle or CTD casts, are averaged together to define the *TS* relationship for a given area or lapsed time interval. Perhaps the easiest way to present this information is in the form of a scatter plot (Figure 2.15) where the dots represent individual *TS* pairs. The mean *TS* relationship is formulated as the average of S over intervals of T. Depth values have been included in Figure 2.15 and represent a range of Z values spanning the many possible depths at which a single *TS* pair is observed. Thus, it is not possible to define a unique mean T, S, Z relationship for a collection of different hydrographic profiles.

The traditional *TS* curve presented in Figure 2.15 is part of a family of curves relating measured variables such as temperature and salinity to density (sigma-*t*) or thermosteric anomaly ($\Delta_{S,T}$). The curvature of these lines is due to the nonlinear nature of the ocean's equation of state. In a traditional single-cast *TS* diagram, the stability of the water column, represented by the *TS* curve, can be easily evaluated. Unless one is in an unstable region, density should always increase with depth along the *TS* curve. Furthermore the analysis of *TS* curves can shed important light on the advective and mixing processes generating these characteristic diagrams. We note that the thermosteric anomaly, $\Delta_{S,T}$, is used for *TS* curves rather than specific volume

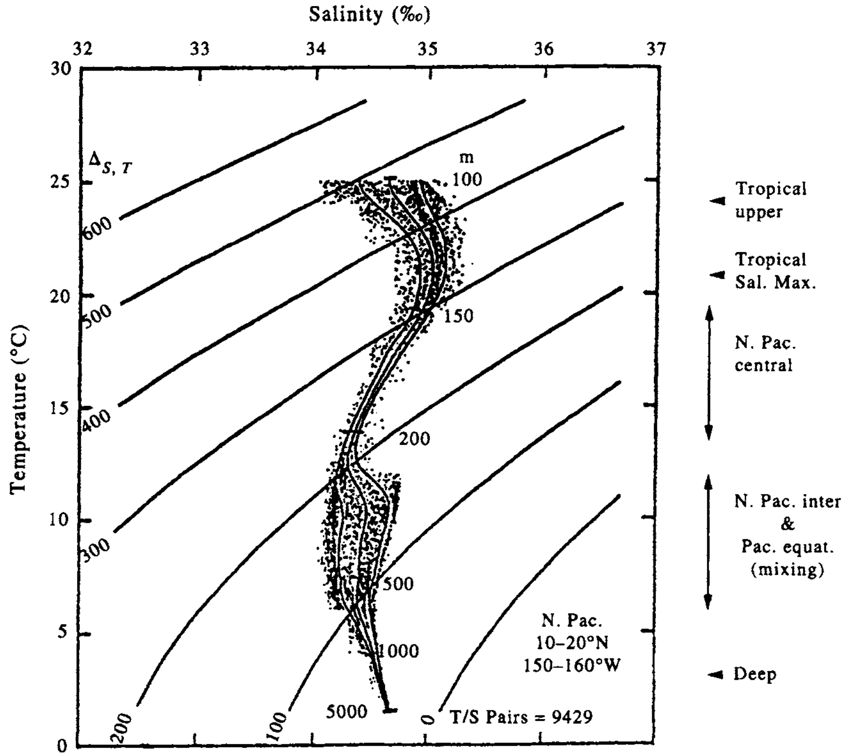

Figure 2.15. Mean temperature-salinity curves for the North Pacific (10–20°N; 150–160°W). Also shown is the density anomaly $\Delta_{S,T}$. (From Pickard and Emery, 1992.)

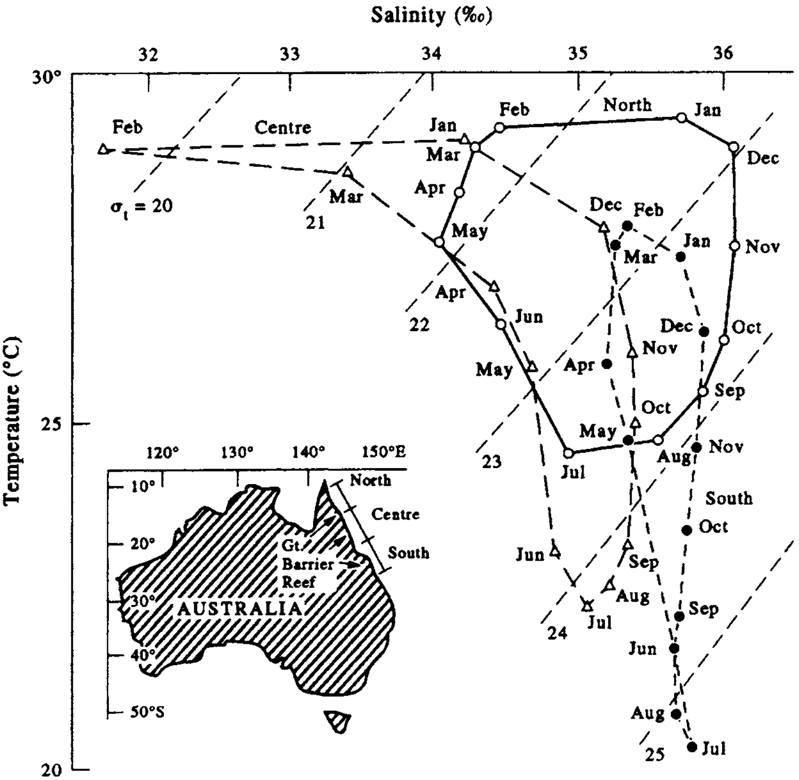

Figure 2.16. Monthly mean temperature–salinity pairs for surface water samples over a year in the lagoon waters of the Great Barrier Reef. (From Pickard and Emery, 1992.)

anomaly, $\delta_{S,T}$, since the pressure term in included in $\delta_{S,T}$ has been found to be negligible for hydrostatic computation and can be approximated by $\Delta_{S,T}$, which lacks the pressure term.

The time variability of the *TS* relation is also a useful quantity. A simple extension of this characteristic diagram shown in Figure 2.16 reveals the monthly mean *TS* pairs for surface water samples over a year in the vicinity of the Great Barrier Reef. The dominant seasonal cycle of the physical system is clearly displayed with this format.

Another more widely used variation of the *TS* diagram is known as the volumetric *TS* curve. Introduced by Montgomery (1958), this diagram presents a volumetric census of the water mass with the corresponding *TS* properties. The analyst must decide the vertical and horizontal extent of a given water mass and assign to it certain *TS* properties. From this information, the volume of the water mass can be estimated and entered on the *TS* diagram (Figure 2.17). The border values correspond to sums across *T* and *S* values. Worthington (1981) used this procedure, and a three-dimensional plotting routine, to produce a volumetric *TS* diagram for the deep waters of the world ocean (Figure 2.18). The distinct peak in Figure 2.18 corresponds to a common deep water which fills most of the deeper parts of the Pacific. Sayles *et al.* (1979) used the method to produce a good descriptive analysis of Bering Sea water. This type of diagram has been made possible with the development of computer graphics techniques which greatly enhance our ability to display and visualize data.

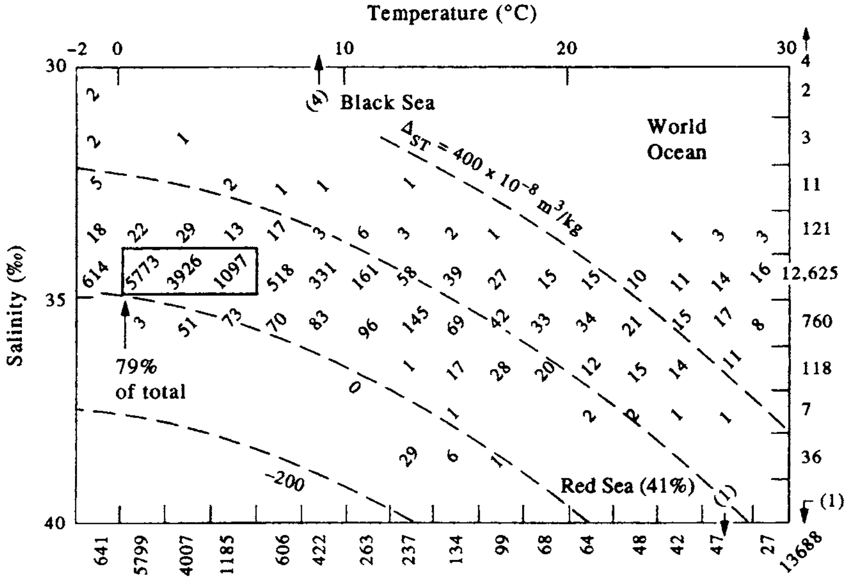

Figure 2.17. Volumetric temperature-salinity (T–S) curve in which the number of T–S pairs in each segment of the plot can be calculated. (From Pickard and Emery, 1992.)

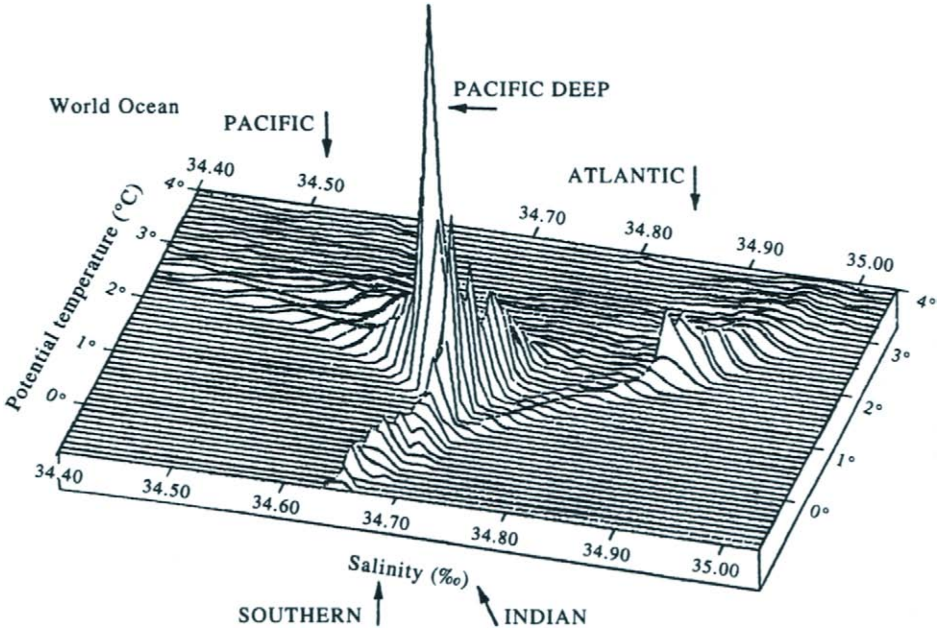

Figure 2.18. Three-dimensional volumetric TS diagram for the deep waters of the world ocean. The distinct peak corresponds to common deep water which fills most of the deeper parts of the Pacific. (From Pickard and Emery, 1992.)

In a highly site-specific application of *TS* curves, McDuff (1988) has examined the effects of different source salinities on the thermal anomalies produced by buoyant hydrothermal plumes rising from mid-ocean ridges. In potential temperature–salinity ($\theta - S$) space, the shapes of the $\theta - S$ curves are strongly dependent on the salinity of the source waters and lead to markedly different thermal anomalies as a function of height above the vent site.

2.4.7 Time-series presentation

In oceanography, as with other environmental sciences, there is a need to present time-series information. Early requirements were generated by shore-based measurements of sea-level heights, sea surface temperature and other relevant parameters. As ship traffic increased, the need for offshore beacons led to the establishment of light- or pilot-ships which also served as platforms for offshore data collection. Some of the early studies, made by geographers in the emerging field of physical oceanography, were carried out from light-ships. The time series of wind, waves, surface currents, and surface temperature collected from these vessels needed to be displayed as a function of time. Later, dedicated research vessels such as weather ships were used as "anchored" platforms to observe currents and water properties as time series. Today, many time-series data are collected by moored instruments which record internally or telemeter data back to a shore station. The need for real-time data acquisition for operational oceanography and meteorology has created an increased interest in new methods of telemetering data. The development of bottom-mounted acoustical modem systems and satellite data collection systems such as Service Argos have opened new

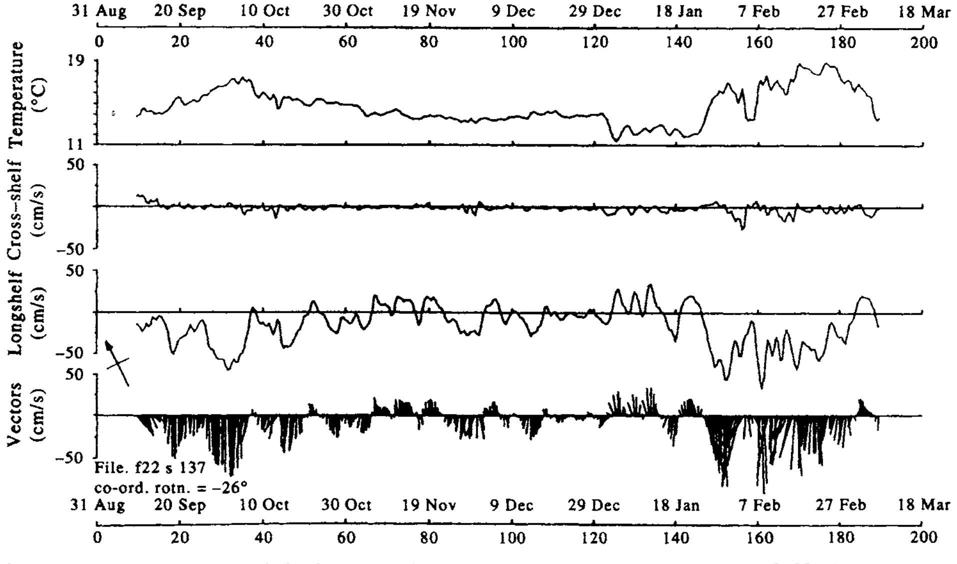

Figure 2.19. Time series of the low-pass filtered u (cross-shelf, x) and v (longshelf, y) components of velocity together with the simultaneously collected values of temperature (T) for the east coast of Australia immediately south of Sydney, 31 August, 1983 to 18 March, 1984. The axes for the stick vectors are rotated by −26° from North so that "up" is in the alongshore direction. The current meter was at 137 m depth in a total water depth of 212 m. Time in Julian days as well as calendar days. (Freeland et al., 1985.)

possibilities for the transmission of oceanographic data to shore stations and for the transmission of operational commands back to the offshore modules.

The simplest way to present time-series information is to plot a scalar variable (or scalar components of a vector series) against time. The time scale depends on the data series to be plotted and may range in intervals from seconds to years. Scalar time series of the u (cross-shore, x) and v (alongshore, y) components of velocity are presented in Figure 2.19 along with the simultaneously collected values of temperature. Note that it is common practice in oceanography to rotate the x, y velocity axes to align them with the dominant geographic or topographic orientation of the study region. The horizontal orthogonal axes can be along- and cross-shore or along- and across-isobath. Sometimes the terms cross-shelf and long-shelf are used in place of cross-shore and longshore. Since current meters and anemometers actually measure speed and direction, it is also customary to display time series of speed and direction as well as components of velocity. Keep in mind that oceanographic convention has vectors of current (and wind) pointing in the direction that the flow is *toward* whereas meteorological convention has wind vectors pointing in the direction the wind is *from*.

As noted in section 2.4.1, two common methods of displaying the actual vector character of velocity as a function of time are stick-plots and progressive vector diagrams (PVDs). A stick-plot (Figures 2.4 and 2.19) represents the current vector for a specific time interval with the length of the stick (or "vector") scaled to the current speed and the stick orientation representing the direction. Direction may be relative to true north (pointed upward on the page) or the coordinate system may be rotated to align the axes with the dominant geographic or topographic boundaries. The stick-plot presentation is ideal for displaying directional variations of the measured currents. Rotational oscillations, due to the tides and inertial currents, are clearly represented. The PVD (Figure 2.5) presents the vector sum of the individual current vectors plotting them head to tail for the period of interest. Residual or long-term vector-mean currents are readily apparent in the PVD and rotational behavior also is well represented. The signature of inertial and tidal currents can be easily distinguished in this type of diagram. The main problem with PVDs is that they have the appearance of a Lagrangian drift with time, as if measurements at one location could tell us the downstream trajectory of water parcels once they had crossed the recording location. Only if the flow is uniform in space and constant in time does the PVD give a true representation of the Lagrangian motion downstream. In that regard, we note that Lagrangian data are presented either as trajectories, in which the position of the drifting object is traced out on a chart or as time series of latitude $x(t)$ and longitude $y(t)$. Distance in kilometers may be used in place of earth coordinates although there are distinct advantages to sticking with Mercator projections.

Another type of time series plot consists of a series of vertical profiles at the same locations as functions of time (Figure 2.20a). The vertical time-series plot has a vertical axis much like a vertical section with time replacing the horizontal distance axis. Similarly, a time series of horizontal transects along a repeated survey line is like a horizontal map but with time replacing one of the spatial axes. Property values from different depth–time (z, t) or distance–time (x, t) pairs are then contoured to produce time-series plots (Figure 2.20b) which look very similar to vertical sections and horizontal maps, respectively. This type of presentation is useful in depicting temporal signals that have a pronounced vertical structure such as seasonal heating

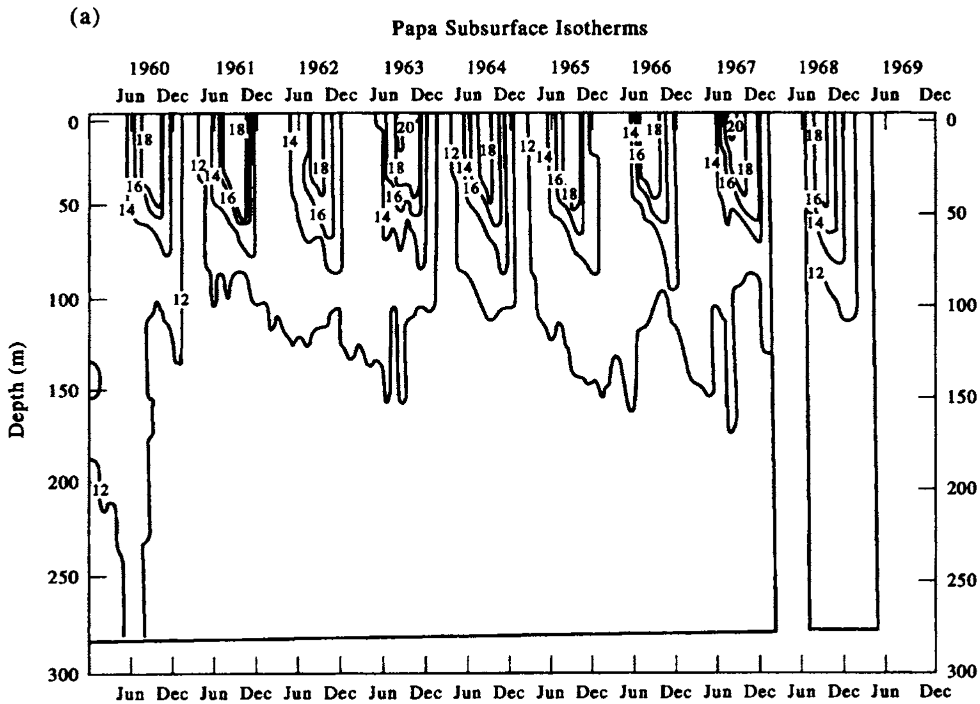

Figure 2.20. Time-series plots for: (a) Repeated vertical profiles at Ocean Weather Station "P" (50°N, 145°W in the northeast Pacific) for the period 1960–69. (From Fofonoff and Tabata, 1966.)

and cooling. Other temporal changes due to vertical layering (e.g. from river a plume) are well represented by this type of plot.

2.4.8 Histograms

As oceanographic sampling matured, the concept of a stationary ocean has given way to the notion of a highly variable system requiring repeated sampling. Data display has graduated from a purely pictorial presentation to statistical representations. A plot format, related to fundamental statistical concepts of sampling and probability, is the histogram or frequency-of-occurrence diagram. This diagram presents information on how often a certain value occurred in any set of sample values. As we discuss in the section on basic statistics, there is no set rule for the construction of histograms and the selection of a sample variable interval (called "bin size") is completely arbitrary. This choice of bin size will dictate the smoothness of the presentation but an appropriately wide enough interval must be used to generate statistically meaningful frequency-of-occurrence values.

2.4.9 New directions in graphical presentation

Plotting oceanographic data has gone from a manpower-intensive process to one primarily carried out by computers. Computer graphics have provided oceanographers with a variety of new presentation formats. For example, all of the data display formats previously discussed can now be carried out by computer systems. Much of the investigator's time is spent ensuring that computer programs are

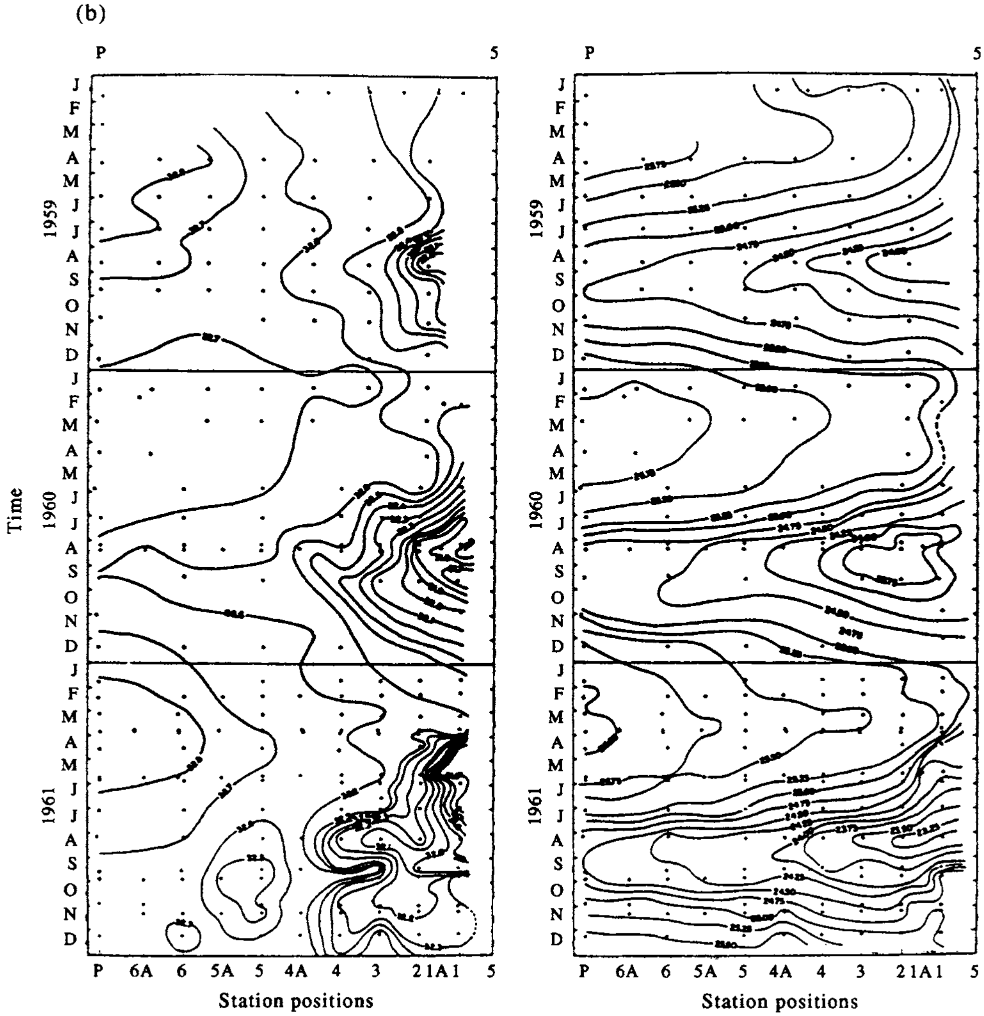

Figure 2.20. Time-series plots for: (b) salinity (psu) and density (σ_t) at 10 m depth from repeated transects along Line P between Station P and the coast of North America for the period January 1959 to December 1961. (From Fofonoff and Tabata, 1966.)

developed, not only for the analysis of the data, but also for the presentation of results. These steps are often combined, as in the case of objective mapping of irregularly spaced data. In this case, an objective interpolation scheme is used to map a horizontal flow or property field. Contouring of the output objective map is then done by the computer. Frequently, both the smoothing provided by objective analysis and the computer contouring can be performed by existing software routines. Sometimes problems with these programs arise, such as continuing to contour over land or the restriction to certain contour intervals. These problems must either be overcome in the computer routine or the data altered in some way to avoid the problems.

In addition to computer mapping, the computer makes it possible to explore other presentations not possible in hand analyses. Three-dimensional plotting is one of the more obvious examples of improved data display possible with computers. For

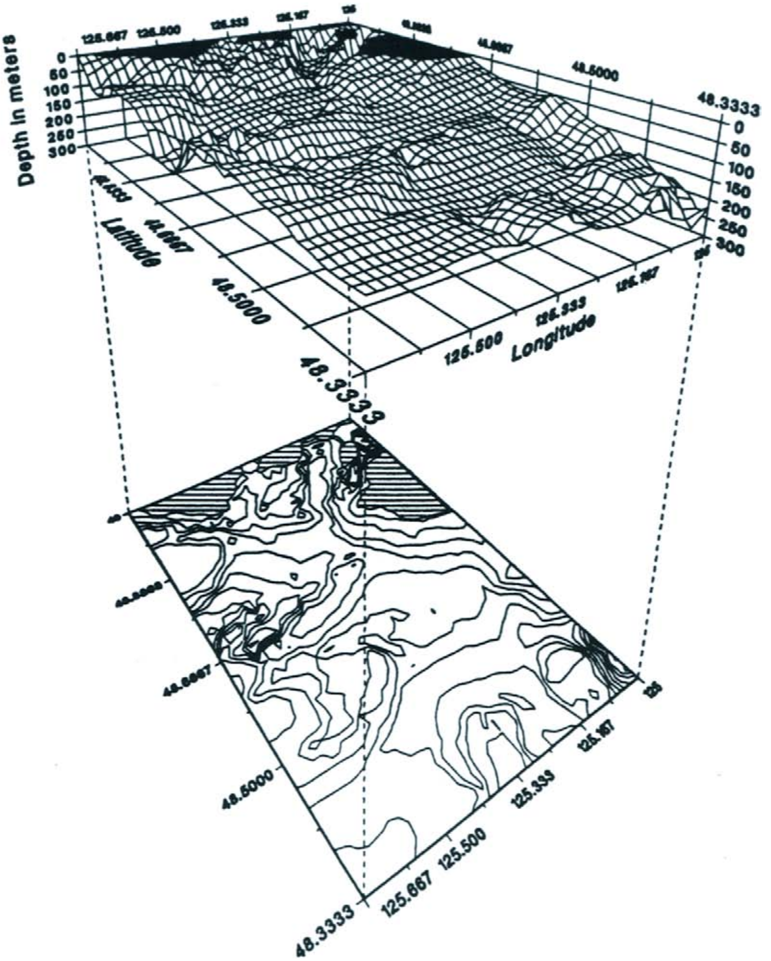

Figure 2.21. Three-dimensional plot of water depth at 20 m contour interval off the southwest coast of Vancouver Island. The bottom plot is the two-dimensional projection of the topography. (Courtesy Gary Hamilton, Intelex Research.)

example, Figure 2.21 shows a three-dimensional plot of coastal bottom topography and a two-dimensional projection (contour map) of the same field. One main advantage of the three-dimensional plot is the geometrical interpretation given to the plot. We can more clearly see both the sign and the relative magnitudes of the dominant features. A further benefit of this form of presentation is the ability to present views of the data display from different angles and perspectives. For example, the topography in Figure 2.21 can be rotated to emphasize the different canyons that cut across the continental slope. Any analysis which outputs a variable as a function of two others can benefit from a three-dimensional display. A well-known oceanic example is the Garrett-Munk spectrum for internal wave variability in the ocean (Figure 2.22) in which spectral amplitude based on observational data is plotted as a function of vertical wavenumber (m) and wave frequency (ω). The diagram tells the observer what kind of spectral shape to expect from a specific type of profiling method.

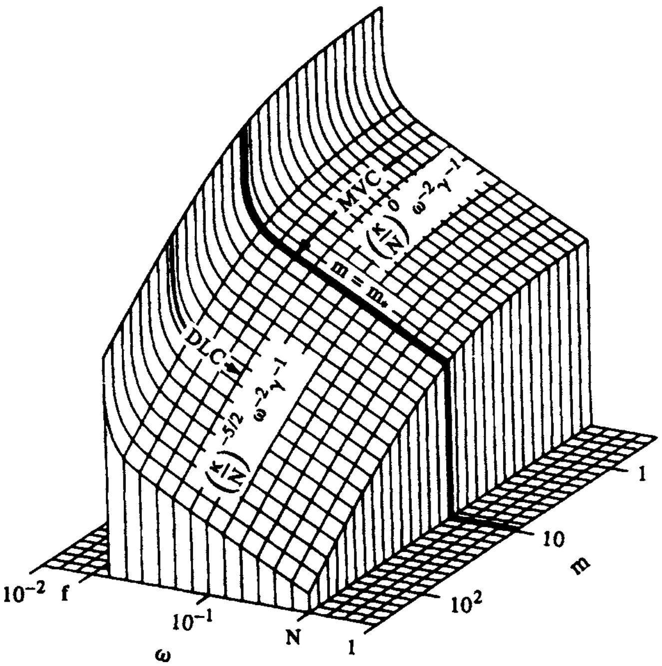

Figure 2.22. Garrett-Munk energy spectrum for oceanic internal waves based on different types of observations. Spectral amplitude (arbitrary units) is plotted against m (the vertical wavenumber in cycles per meter) and ω *(the wave frequency in cycles per hour). Here,* m^* *is the wavenumber bandwidth,* κ *is the horizontal wavenumber, N the buoyancy frequency, f the Coriolis parameter, and* $\gamma = (1 - f^2/\omega^2)^{1/2}$*. MVC = moored vertical coherence and DLC = dropped lag coherence between vertically separated measurements. (From Garrett and Munk, 1979.)*

The introduction of color into journal papers represents another important change in presentation method. As mentioned in the discussion of vertical sections, color shading has been used traditionally to better visually resolve horizontal and vertical gradients. Most of these color presentations have been restricted to atlas and report presentations and were not available in journal articles. New printing procedures have made color more affordable and much wider use is being made of color displays. One area of recent study where color display has played a major role, is in the presentation of satellite images. Here, the use of false color enables the investigator to expand the dynamic range of the usual gray shades so that they are more easily recognizable by eye. False color is also used to enhance certain features such as sea surface temperature patterns inferred from infrared satellite images. The enhancements, and pseudo-color images, may be produced using a strictly defined function or may be developed in the interactive mode in which the analyst can produce a pleasing display. One important consideration in any manipulation of satellite images is to have each image registered to a ground map which is generally called "image navigation" in oceanographic jargon. This navigation procedure (Emery *et al.*, 1989b) can be carried out using satellite ephemeris data (orbital parameters) to correct for earth curvature and rotation. Timing and spacecraft attitude errors often require the image to be "nudged" to fit the map projection exactly. An alternative method of image correction is to use a series of ground-control-points (GCPs) to navigate the image. GCPs are usually features such as bays or promontories that stand out in both the satellite image and the base map. In using GCP navigation a primary correction is made assuming a circular orbit and applying the mean satellite orbital parameters.

Access to digital image processing has greatly increased the investigator's capability to present and display data. Conventional data may be plotted in map form and overlain on a satellite image to show correspondence. This is possible since most image systems have one or more graphics overlay planes. Another form of presentation, partly motivated by satellite imagery, is the time-sequence presentation of maps or images. Called "scene animation", this format produces a movie-style output which can be conveniently recorded on video tape. With widespread home use of video recorder systems, this form of data visualization is readily accessible to most people. A problem with this type of display is the present inability to publish video tapes or film loops. This greatly restricts the communication of results which show the time evolution of a spatial field such as that shown by a series of geographically coincident satellite images.

Digital image manipulation also has changed the way oceanographers approach data display. Using an interactive system the scientist–operator can change not only the brightness scale assignment (enhancement) but can also alter the orientation, the size (zoom in, zoom out) and the overall location of the output scene using a joystick, trackball or mouse (digital tablet and cursor). With an interactive system, the three-dimensional display can be shifted and rotated to view all sides of the output. This allows the user to visualize areas hidden behind prominent features.

As more oceanographers become involved with digital image processing and pseudo-color displays, there should be an increase in the variety of data and results presentations. These will not only add new information to each plot but will also make the presentation of the information more interesting and "colorful". The old adage of a picture being worth a thousand words is often true in oceanography and the interests of the investigators are best served when their results can be displayed in some interesting graphical or image form.