CTD

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Introduction

A precise and comprehensive charting of the distribution and variation of water temperature, salinity, and density is essential to our understanding of how the oceans affect life on Earth. The oceans buffer the heat balance of the Earth's surface; ice, vapor, and heat fluxes strongly influence wind patterns, weather, and storms. Ocean salts, dissolved from rock and biological material, are both nutrient and environment to life. Biological, volcanic, and sedimentary processes control the chemical cycling of salt in water and its eventual removal from the ocean. The ocean's temperature variations ($-2°C$ to $+40°C$) account for three-quarters of the density variations that control ocean currents; salinity variations of just 0.15% account for most of the rest. Salinity is an effective tracer: concentrated by evaporation and sea ice formation and diluted by precipitation and glacier melt, it marks the paths of currents and accumulates the effects of mingling and mixing into a rich volume of information that helps oceanographers understand ocean processes and detect signs of climate change.

The CTD is the primary tool for determining these essential physical properties of sea water, incorporating sensors for *in situ* measurement of electrical Conductivity, Temperature, and pressure (from which Depth is calculated). Conductivity is measured not for its own sake but because salinity and density can be calculated when temperature and pressure are also known. From CTD measurements, sound speed may also be computed, and sophisticated ray-path models derived, prompting military development and application of CTD technology for submarine and mine detection and other naval purposes. The accurate measurement of small temperature and salinity signals has justly preoccupied the engineers who design, and the oceanographic scientists who use, CTD instruments.

History

Although surface temperatures were surveyed earlier using buckets and mercury thermometers, the systematic study of ocean water properties began during the nineteenth century when the development of minimum/maximum thermometers made deep measurements possible. The reversing thermometer, using a wire-dropped weight to capture a temperature reading at a known depth, became available only during the last decades of the nineteenth century; combined with water sampling bottles that could be simultaneously closed by the same weight, these instruments were the first with which the deep ocean environment was systematically studied and mapped. Initially, salinity was determined from water samples by evaporation or titration – tedious and time consuming processes – but the development about 1930 of an electronic salinity bridge by the US Coast Guard pointed toward more efficient future methods.

Although an electrical resistance thermometer was tested successfully during the HMS *Challenger* Expedition (1872), the bathythermograph (BT) introduced in the mid-1930s by Spilhaus probably represents the first practical device from which continuous temperature profiles could be obtained *in situ*. The BT used a liquid thermometer and a pressure-sensing bellows to inscribe a plot of temperature (T) vs pressure (P) on the surface of a gold-coated glass plate. The desire for more resolution of features than could be obtained with these early mechanical methods encouraged the development, begun on the *Challenger*, of electrical output sensors (transducers). These convert physical properties into corresponding electrical signals that can be recorded for future retrieval or telemetered immediately to the surface. The first prototypes using these sensors *in situ* were constructed in the late 1940s, but wide application awaited the commercial development in the 1960s of the Bissett-Berman STD by Brown (STD rather than CTD because it derived Salinity, to a reasonable approximation, using clever analog circuitry). In the 1970s, the availability of powerful computers robust enough to withstand shipboard conditions led to the development of instruments that convert the CTD signals into digital numbers; the resulting data are telemetered to the surface where sophisticated calculations and corrections are readily performed. The benefits of improved calculations based on precise algorithms, the ability to observe and correct for drift and response-time errors, and the facility with which filtering and postmeasurement validation can be achieved result from this potent combination of electrical output sensors and computer processing. Apart from subsequent improvements in memory technology and the advent of satellite telemetry, the essential configuration of the modern CTD was at this time complete.

In parallel with the development of the CTD sensors and computers, the critical work of establishing the precise mathematical relationships among salinity, conductivity, temperature, and pressure was undertaken. During the 1960s Bradshaw and Schleicher established the effect of pressure on conductivity, and Brown and Allentoft described the relationships among conductivity, temperature, and salinity. Later the work of Lewis and Fofonoff led to the refinements embodied in the practical salinity scale of 1978 (PSS-78) that expresses salinity in terms of the electrical conductivity (temperature and pressure adjusted) of natural sea water. To permit consistent comparison of oceanographic data sets, this new working standard does not expressly attempt to quantify ionic concentration, however the unit magnitude was chosen so that the typical ocean value of 35 practical salinity units (PSU) corresponds very closely to 35 ppt (parts per thousand), the 'grams of salt per kilogram of water' designation in common use until about 1980.

CTD Configurations (Figures 1 and 2)

Typically, a shipboard winch lowers the CTD on a wire to obtain a vertical profile of sea water T and S; the steel-jacketed wire contains an insulated inner electrical conductor through which power is delivered to the CTD and data returned to the ship. Where 'conductive wire' is unavailable, the CTD can be powered by internal batteries and the data recorded in semiconductor memory. Either type may be towed horizontally (often at undulating depths) when a lateral characterization of the ocean water is desired. To obtain quick results from underway vessels, an 'expendable' CTD (XCTD) uses a free-fall sensor that returns a single profile via spooled wire. Temperature and conductivity sensors ('thermosalinographs') are installed in ships to monitor near-surface water taken at keel depth. CTD instruments may be moored or otherwise mounted at fixed sites where they typically record every few minutes to obtain a time series of measurements over a year or more; the data are recorded in memory for readout after instrument recovery, or transmitted by wire or acoustic link to a surface buoy for communication to shore via satellite or direct radio. Recently developed autonomous drifters (ALACE Floats) fitted with CTD sensors can profile repeatedly to depths of 1000 or 2000 meters. When they arrive at the surface, the drifters telemeter the CTD data (and their position) to shore via satellite. CTDs may also be mounted to gliders, buoyancy-driven vehicles that can maneuver horizontally. Less sophisticated drifters remain at the surface. They obtain surface salinity and temperature needed to correct satellite measurements that are critical to weather models.

Because the preponderance of oceanographic observations need CTD measurements to portray the background environment, and because the CTD contains signal acquisition, recording, and telemetry circuits, the CTD is often used as a vehicle for support of a variety of sensors for related measurements (dissolved oxygen, fluorescence, turbidity, pH, ambient light, etc.).

CTD Sensors

Sensors for temperature and pressure to meet wide industrial and scientific needs were developed outside the ocean community, however no suitable technique for direct measurement of dissolved salt concentration has been found. Of various properties influenced by salinity, the tightest correlation offering high resolution is to electrical conductivity. Temperature, and to a lesser extent pressure, strongly affect the relationship between conductivity and salinity, so the accurate determination of salinity depends on making three measurements (C, T, P) on the same piece of water at the same time. The evolution of CTD design is profoundly constrained by this requirement.

High resolution and accuracy are needed. Characterization of ocean circulation and global heat fluxes require that temperature variations of 0.001°C and salinity variations of 0.001 PSU be resolved, i.e., about 1/40 000 of the normal ocean range in temperature and salinity. The World Ocean Circulation Experiment (WOCE) conducted in the 1990s appropriately set a data accuracy goal of 0.002°C and 0.002 PSU.

Fast response to time-varying signals is also important. It is difficult to make accurate sensors that respond quickly. Wire-lowered instruments typically profile at $1\,m\,s^{-1}$; at these speeds, important salinity and temperature detail is blurred by slow sensors. Important work is performed using horizontal CTD profilers that are towed at even higher speeds, where fast response is even more essential.

Differences in the inherent mechanical properties of the conductivity and temperature sensors challenge the ability of the CTD to coordinate their responses. The need for coordinated measurements means that the choice of individual sensors must be

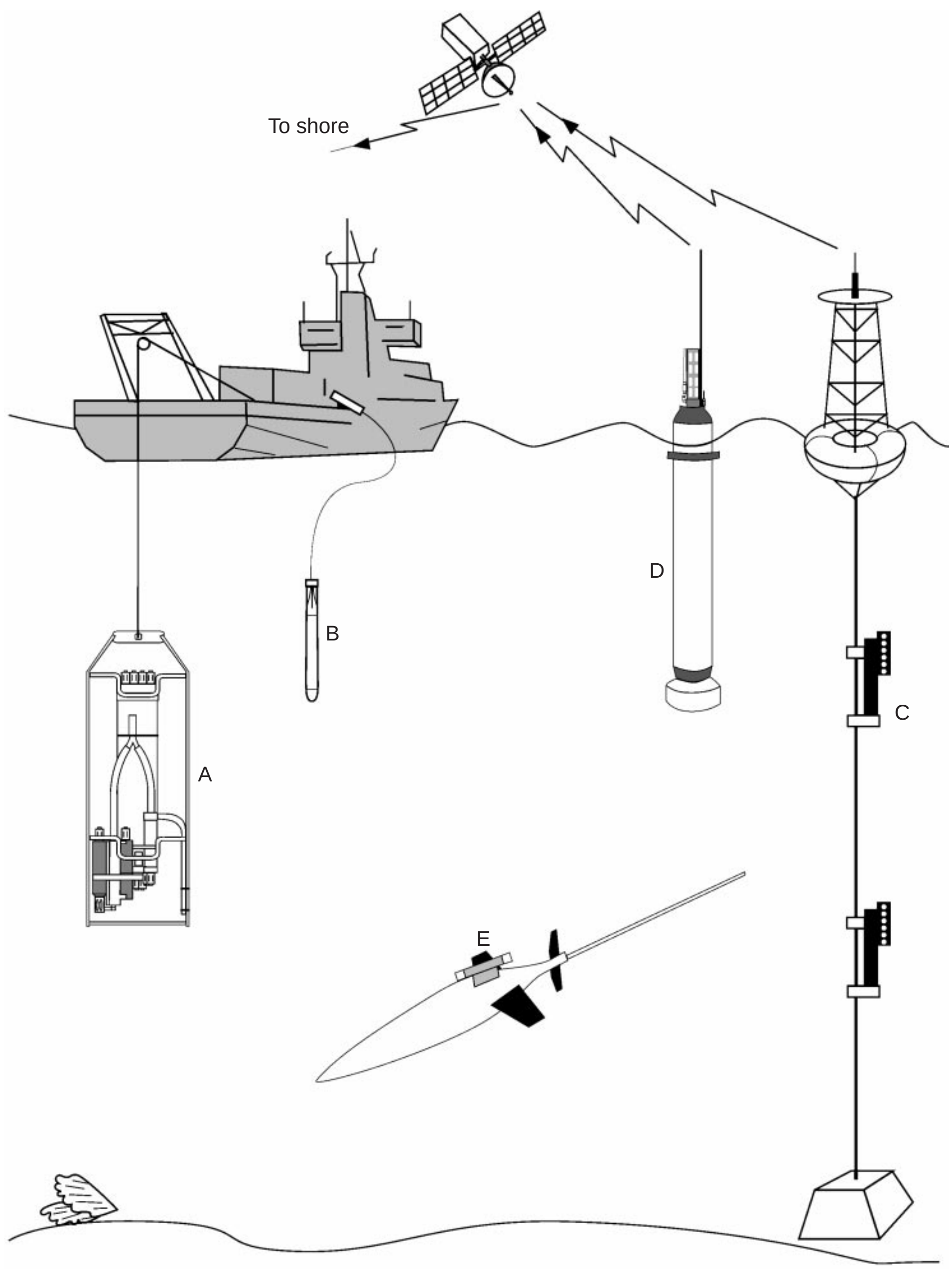
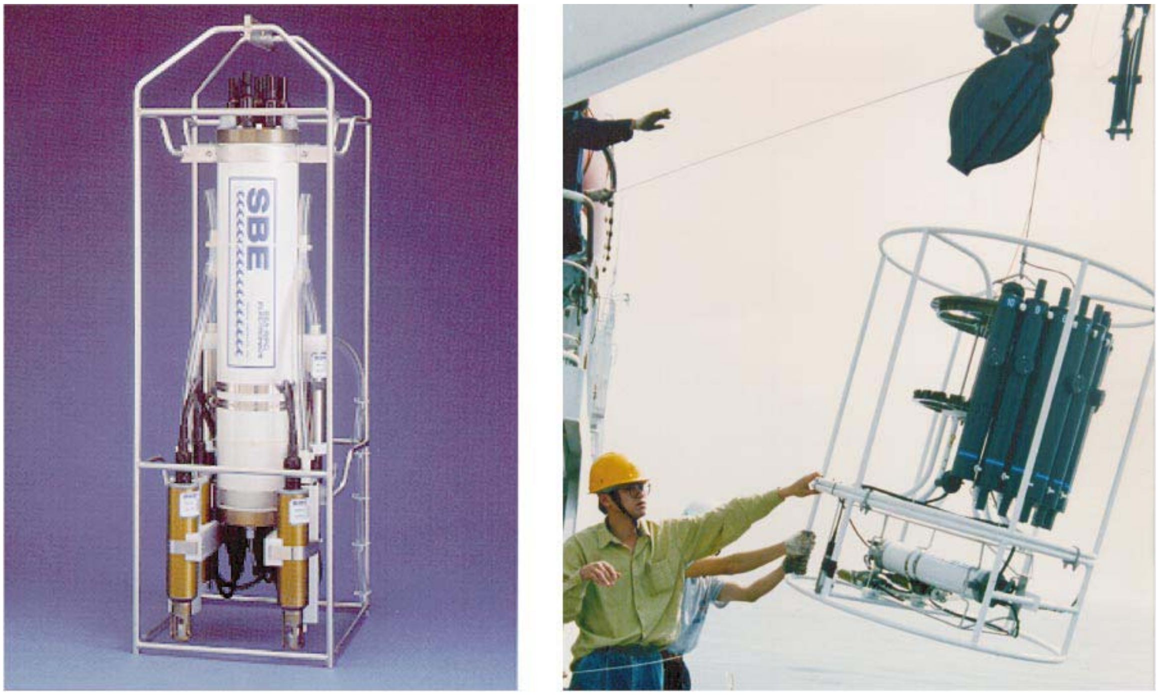


Figure 1 CTD configurations. A, Wire-lowered CTD profiler (see also **Figure 2**). B, Small expendable CTD. Wire spooling from the launcher and the CTD tail section allow profiling while the ship is underway. C, CTDs on a mooring wire. Each instrument contains batteries and memory but can often transmit data on the mooring wire to the surface buoy where communication to shore is possible. D, CTD mounted on top of an autonomous drifting profiler (ALACE) after it has surfaced. These descend to 2000 m depth, drift with currents for 3–5 years and surface about once per week to send a fresh profile to shore via satellite. E, CTD mounted on (top) glider fin. Gliders maneuver during dives and climbs working their way across the ocean or maintaining their position against a current. Like ALACE they telemeter data to shore and receive instructions via satellite.

made not solely on their individual merits, but in keeping with their ability to work in concert with one another.

Conductivity Sensor (Figure 3)

Conductivity (the reciprocal of resistivity) is an intrinsic property of matter, and conductance (the reciprocal of resistance) additionally depends on geometry. For example, a kilogram of copper has the same resistivity whether it exists as a short, thick rod or is drawn into hundreds of meters of fine wire, but in the latter case its resistance is much higher. Algebraically, the geometry dependence for simple cylinders (rods or wires) of cross-sectional



(A) (B)

Figure 2 Photos of profiling CTD systems. (A) The CTD with dual temperature and conductivity sensors for redundant T and C measurements. (B) The CTD in a larger frame holding water bottles that close at various depths to bring water samples to the surface for wet chemistry analysis of salinity, oxygen, organics, nutrients, and the concentrations of various natural dissolved tracers.

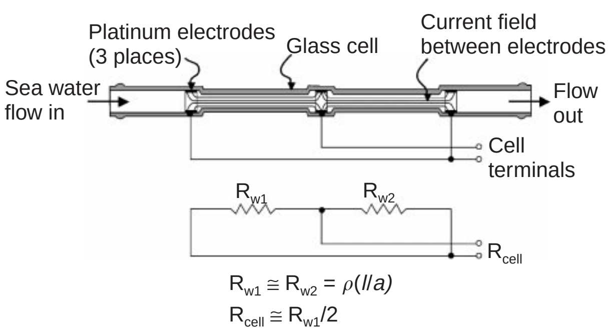


Figure 3 Glass conductivity cell. Water flows through the tube-shaped cell with internal electrodes. By connecting the outer electrodes together, electrical current flow is confined to the inner portion of the cell (diagramed) where the length, l, and crossectional area, a, are precisely controlled. There are effectively two end-to-end cells sharing a common center electrode. The electrical schematic shows how two equal cell resistances are connected in parallel and presented at the cell terminals.

area a and length l is:

$$\text{resistance} = \text{resistivity} \times (l/a)$$

or in terms of conductance,

$$\text{conductance} = \text{conductivity} \times (a/l)$$

and

$$\text{conductivity} = \text{conductance} \times (l/a)$$

As an ohmmeter determines resistance by imposing a voltage and measuring the resulting current ($R = V/I$), so conductance may be determined by forcing a current and measuring the resulting voltage ($G = I/V$). The resistivity of the copper from which a wire is made can be computed by measuring the wire's cross-sectional area and length. The conductivity of a parcel of water can similarly be found if the water is confined to a specific geometry, within the tube-like 'cell' of an electrode sensor, or in the 'hole' passing through an inductive sensor's toroidal transformer. If the sensor's dimensions ('cell constant') are fixed, variations in measured conductance may be interpreted as variations in water conductivity. Because of the dimensional complexity of cell shapes, it is not practical to measure a and l directly; the effective cell geometry is instead inferred by calibration against water of known conductivity.

The use of DC currents for measurement of the conductance of an electrolyte such as sea water is impractical with electrode cells because of galvanic action (plating) and hydrolysis. These problems can be circumvented if AC currents at sufficiently high frequencies are used, but the precise control and measurement of AC voltages and currents is difficult. Inductive sensors avoid the potential for galvanic effects and hydrolysis, but the transformers they use to couple currents directly to the water also require AC excitation.

Temperature Sensor

CTD temperature sensors make use of the predictable variation with temperature in the electrical resistance of metals such as platinum and copper, or of certain semiconductor materials (thermistors). Platinum is a noble metal with a high melt point that exhibits very stable properties, qualities that have led to its use as the interpolating thermometer for the definition of temperature itself. But although platinum sensors are essential for wide-range temperature applications, in the narrow range of the ocean environment, their low sensitivity (resistance changes about 0.4% per degree) and low initial resistance (typically 100 ohms) place heavy demands on the acquisition electronics, because the needed resolution in temperature corresponds to only a few micro-ohms in resistance. The semiconductor types ('thermistors') perform well at ocean temperatures, offer an order of magnitude higher sensitivity (4% per degree), and may be obtained at arbitrarily high initial resistances. Temperature errors introduced by comparably sophisticated acquisition electronics are accordingly lower with semiconductor types; these also have faster response times (*c.* 0.05 s compared to 0.3 s for platinum). Either sensor type must be protected from the corrosive and conductive effects of sea water, and against the crushing stress of hydrostatic pressure.

Pressure Sensor

The pressure sensor plays two roles in a CTD. Firstly, pressure must be taken into account when computing salinity and other quantities. Secondly, the pressure sensor locates the CTD so that the depth of the salinity and other measurements is known. Pressure is applied to a metal diaphragm (a drum-like plate), or in some sensors to the inside of a cylindrical Bourdon tube; the diaphragm (or Bourdon tube) is designed to deflect elastically when exposed to the stress of applied pressure. The other side of the diaphragm is typically exposed to a vacuum yielding an absolute measurement of pressure. Electrical strain gauges (wire or semiconductor types) arranged in a bridge configuration convert the diaphragm deflection into a pressure-dependent voltage that the CTD measures. Certain very high accuracy sensors transfer the force of pressure on the diaphragm to an oscillating quartz resonator whose frequency changes with pressure. The changing frequency is then measured ('counted') by the CTD circuits.

Sensor Response Times

There is inevitably a delay between the occurrence of a change in the physical environment and a sensor's response to it. Apart from the magnitude of the delay, the character of the response may be different in form depending on the specific design of each sensor type. Time–response characteristics are especially important in a CTD, because salinity and density are computed from all three primary sensors. In the presence of a changing signal, differences in the dynamic responses of the conductivity and temperature sensors cause transient errors in computed salinity – commonly termed 'salinity spiking.' Most commonly, spiking results from the fundamentally different way in which conductivity and temperature sensors function. Temperature sensors track the (changing) local environment by means of heat flow into or out of the sensing element, a process that yields an essentially exponential $(1 - \varepsilon^{-t/\tau})$ response. Conductivity sensors are entirely different: they report an instantaneous 'snapshot' of the conductivity of the water presently in the cell. The conductivity response time, therefore, depends simply on the rate at which new water flushes through the cell. Unless the rate of entry of water into the cell is fixed (e.g., with a controlled flow rate pump), the conductivity response time depends on profiling speed. When the CTD is lowered from a ship, surface waves roll the ship causing the CTD to profile at varying speeds. Because the temperature sensor has an essentially constant delay characteristic, the resulting variability in conductivity cell flushing leads to severe salinity spiking.

Acquisition of Sensor Outputs

Although conductivity sensors must operate using AC excitation, it is desirable that the temperature sensor also uses AC. Acquisition of the resulting AC signals may be performed in either of two ways. In the first, an implicit 'Ohm's Law' approach is taken where a known AC voltage is applied and the amplitude of the resulting AC current is measured; the conductance of the conductivity cell is I/V; the resistance of the temperature sensor is V/I. These current and voltage levels may be digitized directly by successive approximation against a digitally switched AC reference, or converted into

DC levels by rectification and acquired by conventional digitization methods.

In a second approach, the cell conductance (or temperature sensor resistance) is a component in an oscillator. The oscillator frequency then changes with conductance (or resistance) and can be acquired by counting. This method has the advantage of being inherently integrative so that consistent timing of the acquired signal is preserved.

To obtain the desired spatial resolution at typical wire-lowered profiling speeds the measurement acquisition rate must be 20 or 30 ‘scans’ per second (each ‘scan’ is a complete suite of C, T, and P measurements). Obtaining the needed accuracy at these rates, particularly when acquiring AC signals, requires very special methods. Autonomous float CTDs and other instruments that profile more slowly acquire scans at rates of one or two per second. For instruments moored at fixed locations, samples are typically taken at intervals of several minutes, and acquisition requirements are accordingly less demanding.

Data Transmission and Archiving

Wire-lowered CTDs are suspended on cables that are mechanically strong but exhibit poor data transmission characteristics; proprietary FSK (frequency-shift-keyed) and DPSK (differential-phase-shift-keyed) modems have been developed to transmit CTD data at several thousand bits per second. At the surface, the decoded data are sent to computer for display and storage.

Moored instruments recording data in semiconductor memory must be recovered for data readout. More sophisticated instruments using inductive or acoustic modems transmit data to surface buoys in near real time. The buoy then sends the data to shore using a direct radio link or satellite relay.

Drifters and autonomous profilers that surface periodically usually report their data (and position) by satellite.

CTD Calibration

CTD temperature sensors are calibrated by comparison to a ‘Standards-grade Platinum Resistance Thermometer’ (SPRT) that has been certified to the International Temperature Scale of 1990 (ITS-90) by a primary standards laboratory, and verified against a triple-point-of-water cell (0.0100°C) and gallium melt cell (29.7646°C). As the relationship of resistance to temperature is well behaved in a properly maintained SPRT, intermediate values of temperature can be very accurately determined within this range; extrapolation errors in the slightly larger range encountered in ocean work are small. For the ocean temperature range, uncertainties in well-maintained standards are typically less than 0.0005°C.

The dependence of conductivity on temperature is influenced by the relative proportions of the ionic constituents (primarily chloride, sulfate, sodium, magnesium, and potassium) of sea water. Although the constituent mix is not perfectly uniform throughout the World Ocean, PSS-78 established clean North Atlantic water as the model for the temperature dependency. The absolute value of conductivity (and salinity) is set by a KCl standard. North Atlantic water at a temperature of 15°C and a pressure of one standard atmosphere is defined as having a salinity of 35 psu when its conductivity is equal (i.e., its conductivity ratio = 1) to the conductivity of a 32.4356 g kg^{-1} KCl solution; KCl at this concentration, temperature, and pressure has (by definition) a conductivity of 4.29140 siemens per meter (S m^{-1}). Sub-standards (IAPSO Standard Seawater) labeled for conductivity ratio and accurate to 0.001 psu are used for CTD calibration.

CTD temperature and conductivity sensors are calibrated by immersion in a well-insulated sea water bath that is vigorously stirred to minimize gradients. The bath is stabilized at each of several set-point temperatures (typically 0°C to +30°C), and the CTD-reported temperature compared to an SPRT or transfer standard; the CTD-reported conductivity is compared to water samples taken at each set point. The water samples are evaluated using a laboratory instrument (Autosal) that ratios the sample conductivity against standard seawater at a single thermostatically controlled temperature. PSS-78 is then used to infer the conductivity the sample had at each of the calibration bath set point temperatures. A calibration accuracy approaching 0.0002 S m^{-1} (approximately 0.002 PSU equivalent salinity) can be achieved.

Pressure calibration is performed against a ‘dead weight tester,’ a device allowing a known mass to bear on a piston whose area has been accurately determined in a ‘cross-float’ procedure at a primary standards laboratory. The CTD-reported pressure is compared to DWT reference pressure computed from the applied mass and its air buoyancy, piston area, local gravity, and barometric pressure. Residual errors are about 0.005% (0.3 m at a depth of 6000 m).

CTD Error Sources

Static errors are a measure of the CTD accuracy when operating in an unchanging environment to which the instrument has been thoroughly equilibrated. They reflect initial calibration uncertainties, limitations of the calibration equations, CTD design imperfections that cause nonrepeatability, unanticipated effects of temperature, and other factors. The conditions needed to quantify static errors are achieved most ideally during calibration, and are approximated when the CTD is profiling in the deep ocean where temperature and salinity gradients are small. Primarily because static errors are relatively easy to measure and quantify, they are most typically cited in the CTD manufacturer's technical brochures.

Static errors can increase with time (calibration drift) as a result of slow changes in sensor characteristics (for example, the resistance vs temperature relationship in a platinum or semiconductor thermometer). They can also be caused by errors in the electronics that convert sensor signals into digital numbers. With present best practice, an initial field accuracy of $0.0003\,\mathrm{S\,m^{-1}}$ in conductivity, 0.001°C in temperature, and 0.02% in pressure can be obtained. With careful handling of wire-lowered profilers, the uncertainty after a year's work with the instrument may be within a factor of two or three of the initial accuracy, although conductivity usually drifts by more than this as a result of petroleum or biogenic oil deposits on the sensor's cell surfaces that change its l/a ratio. Most of the conductivity drift can be corrected by using a multiplier on the l/a ratio that forces the CTD reading to agree with salinity obtained from a single bottle sample captured at depth and evaluated on a shipboard Autosal. ALACE float CTDs configured to prevent contamination by surface oils and protected from biological growth do not exhibit the drift observed with wire-lowered instruments, a fortuitous result given that sample bottle salinity corrections are not practical with autonomous free-roaming drifters.

Dynamic errors fall into three categories. The first class results from the finite time response of each sensor: sensor responses inevitably lag reality. The effect on temperature, for example, is that on the down profile temperature features are seen deeper, and on the up profile shallower, than they really are. The temperature sensor's equilibration to water temperature is delayed by its thermal inertia so that small features are blurred. The conductivity sensor response is determined by the cell's fill rate and shows a $\sin(x)/x$ characteristic. Where profiling speeds cannot be held constant, the time response of free-flushed conductivity sensors can match the temperature sensor's response at only one speed; these differences in the rate and character of sensor responses cause transient errors in salinity. A partial and imperfect solution is to heavily filter the sensor outputs until the numeric filter characteristics dominate the responses. Alternatively, the flushing of the conductivity cell may be fixed by pumping so as to approximate the temperature sensor's response.

The second class of dynamic errors results from the interaction of the CTD and the water. Vertical separation of the sensors causes them to enter new water at different times, whereas horizontal separation leads to errors when the CTD is tilted, or water surfaces are tilted by internal waves. These spatial errors can be minimized by tight clustering of the sensors, or in the case of pumped instruments, by drawing the water that will be measured by both the temperature and conductivity sensors through a single intake port (**Figure 4**).

Sensor response characteristics are also affected by motion through the water. The movement of the temperature sensor generates heat by skin friction (viscous heating) leading to an over-reporting of temperature of approximately 0.001°C at $1\,\mathrm{m\,s^{-1}}$, but varying with the square of velocity. Water in the internal boundary layer of conductivity cell is poorly exchanged resulting in a slurring of conductivity signals and hence salinity. Errors in conductivity are caused when heat is exchanged between the water passing through the conductivity cell and the cell's glass walls; the magnitude of this error is inversely proportional to the flushing rate. Errors also arise from electrical self-heating of sensor elements (0.001°C is typical in platinum temperature sensors); these errors too are modulated by velocity changes.

Especially intractable errors occur when wire-coupled ship's motion causes the profiling speed of the CTD to vary. Old water entrained in the wake of the CTD, warmed by heat dissipated by the CTD electronics or stored in the metal mass of the CTD, can mix with new water if the CTD reverses course or decelerates suddenly. Postacquisition editing-out of reversals can partly correct errors of this kind.

The third class of errors is caused by the cross-coupled effects of changing environmental temperature and pressure on sensors and their associated electronic circuits. For example, during calibration the sensing elements and acquisition circuits are at the same temperature, but when moving through a rapidly changing ocean environment the circuits, contained inside a pressure vessel, typically lag behind by several minutes. Pressure sensors report low of true on the profile downcast and high of true on the upcast, a hysteresis error correlated

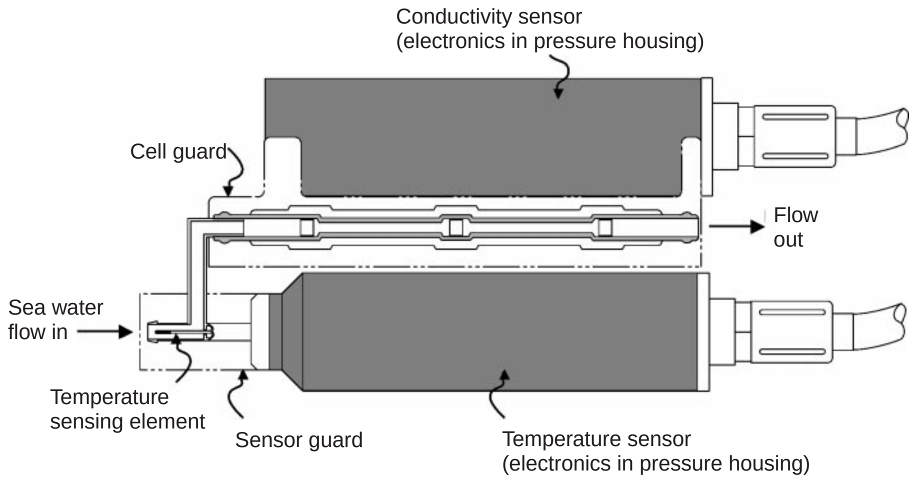


Figure 4 Conductivity (C) sensor and temperature (T) sensor mounted together. Water enters a duct connecting the temperature sensor to the conductivity cell. Flow rate is controlled by a pump that produces constant sensor response times. Coordinating the T and C measurements to the same parcel of water is accomplished by accounting for the fixed 'transit' time required for water to flow from the temperature sensor to the conductivity sensor.

to the sensor's prior exposure to pressure. And although pressure sensors are generally well compensated for fully equilibrated temperature changes, they are susceptible to the more rapid temperature changes encountered in ocean profiling. Errors of this kind can be suppressed with good engineering design work, and partly corrected numerically.

Data Quality

A careful tracking of CTD calibration drift permits field data to be corrected, and, if unusual trends are observed, faulty sensors repaired. In the past, an independent measure of *in situ* temperature was often obtained with mercury reversing thermometers, however these are not accurate enough to evaluate modern CTDs. Certain electronic sensors are available that can play this role, and fully redundant sensors are sometimes mounted.

Several well-tested assumptions about the nature of ocean water masses (that gradients are smooth, layers are gravitationally stable, and T-S relationships are historically stable) provide criteria by which CTD data may be judged. For example, 'wild point' editing is performed to reject individual samples that depart significantly from mean gradients, large density inversions are interpreted as likely indicators of salinity errors (usually attributed to the conductivity sensor), and the predictability of deep ocean T-S relationships serves as a sensitive check on CTD accuracy.

Data Units and Presentation (Figures 5–7)

Although oceanography employs SI units for temperature, SI does not address salinity; oceanographers use the practical salinity scale (PSS-78) described earlier. Because PSS-78 was derived before the revision of the temperature definition to ITS-90, temperature used to compute salinity must be converted into the former IPTS-68 definition.

Because water density is around 1000 kg m^{-3} and ocean variations are comparatively small, 1000 is subtracted yielding what oceanographers call 'sigma'; for a typical sea water density of 1026, sigma = 26. Sigma-theta is the density the water would have if the effects of compression were removed. This is a measure of the relative density water parcels would have, if moved to a common pressure, that usefully characterizes gravitational stability.

Oceanographers typically express pressure in 'decibar' (dbar) units that correspond within a few percent to a meter of depth. The dbar is exactly 10^4 Pascals and approximately a tenth of a standard atmosphere. Although the pressure exerted at any depth results from the weight of the water and atmosphere above, it is conventional within oceanography to define sea surface pressure as zero. Accordingly, PSS-78 and other established relationships assume that one standard atmosphere will be subtracted from the *in situ* absolute pressure as measured by a CTD.

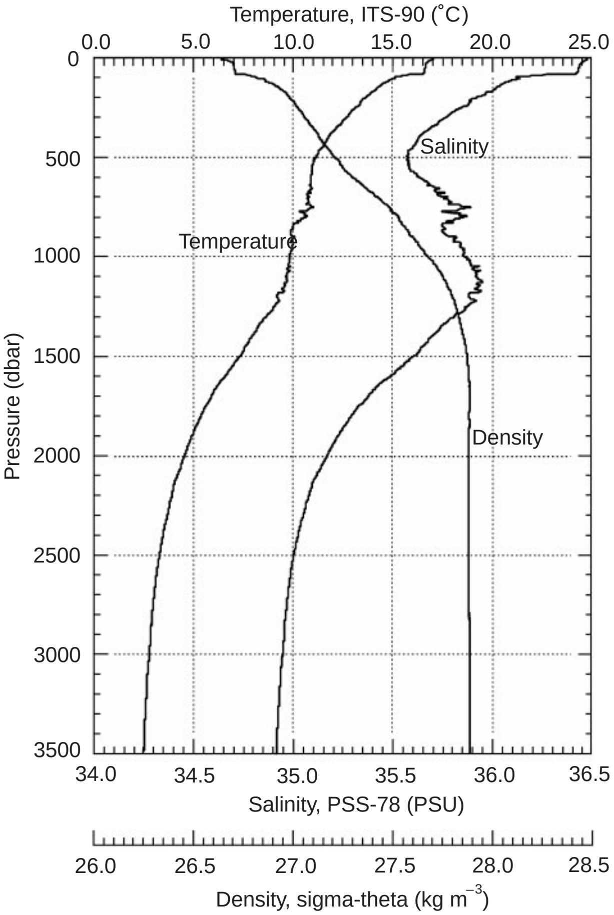


Figure 5 Temperature, salinity, and density profile data from the North Atlantic Ocean (35°N 12°W) showing typical features. The depth is approximately 3500 m, and density increases smoothly with depth. A wind-mixed surface layer (~ 100 m), a thermocline in the top 2000 m, and the characteristic cold deep ocean water of about 34.9 psu salinity are in evidence. At this location abnormally warm and salty water from the Mediterranean Sea are intruding into the North Atlantic at about 1200 dbar pressure.

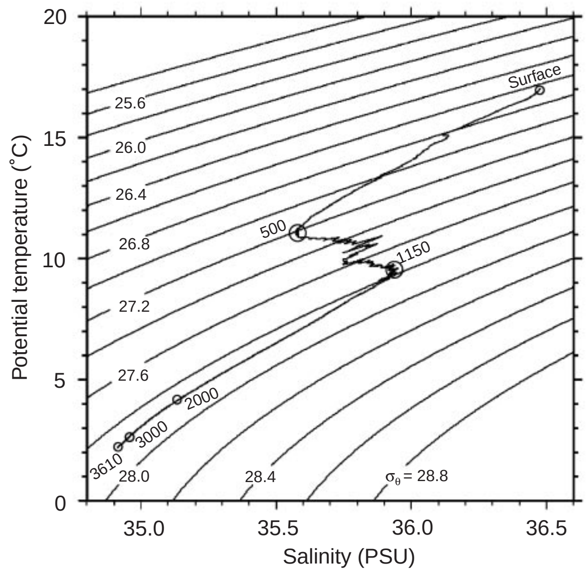


Figure 6 T-S diagram. A method used by oceanographers to identify various source waters that are present in CTD profile data. Here data from **Figure 5** are plotted as temperature against salinity. Depths are marked near open circles. Variations in temperature and salinity are predominantly parallel to contours of constant density (sigma-theta) indicating that currents stir and mingle water on a constant density surface in the ocean. The saltiest water found on the sigma-theta = 27.8 density surface originates from the Mediterranean Sea, whereas less salty water on the 27.9 density surface originates in the Greenland and Norwegian Seas.

For profiling instruments, a plot of temperature, salinity, and density as a function of pressure is the most common presentation (**Figure 5**). These plots typically show a wind-mixed surface layer with a thermocline at its base and the mid-depth decrease of temperature to low values in all deep ocean waters. Salinity variability in the near-surface is large as a result of evaporation and freshwater inflows, and density normally displays the smooth progression toward higher values reflecting the basic gravitational stability of the water column.

TS plots (**Figure 6**) are based on potential temperature (*in situ* temperature with the effect of pressure removed). Plot features can often identify unique water masses thereby giving important clues to ocean circulation patterns.

Contour plots of salinity, temperature, and density (**Figure 7**) provide an overview of large-scale ocean characteristics that illuminates patterns of ocean circulation and the workings of processes that shape and alter climate.

Conclusion

Recognition of the rich variability of ocean water has been remarkably linked to our ability to detect it. Ironically, the surprisingly complex temperature and salinity structure reported by early CTD instruments was attributed by many to sensor malfunction. The refinement and growing sophistication of these instruments has enormously expanded our ability to portray the complexity of the world ocean, but it is a picture assembled painstakingly from thousands of widespread glimpses and obtained with much labor and cost over long and interrupted intervals. A fuller understanding of the workings of Earth's oceans awaits the more nearly synoptic and universal perspective inherent in the emerging technologies that permit autonomous observations of planet-wide extent and enduring persistence.

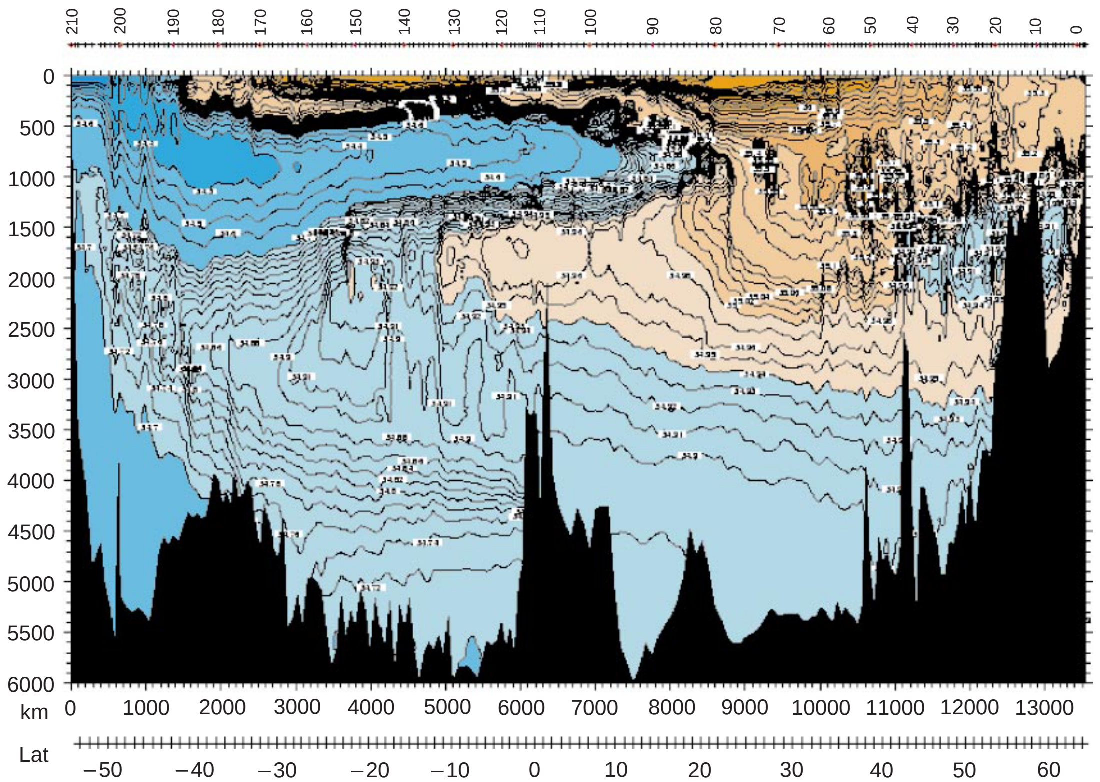


Figure 7 Color-flooded contours of salinity on a vertical slice through the middle of the Atlantic Ocean extending from South Georgia Island (54° South) to Iceland (63° North) exhibit intricate patterns that help to identify the origins and movement of water within the ocean. The deep-orange hues of the tropical ocean surface identify high salinity that is concentrated by evaporation. A dark-blue tongue of lower salinity water traces the northward movement, at 1000 m depth, of a watermass called Antarctic Intermediate Water that originates near the surface in Antarctica. A thick southward moving tongue of North Atlantic Deep Water, at 2000 m depth, is identified by light-tan hues. This higher-salinity watermass is fed by the cold Labrador, Greenland and Norwegian Seas and is heavily influenced by salty water from the Mediterranean Sea. Creeping northward along the ocean bottom is Antarctic Bottom Water.

See also

Satellite Measurements of Salinity. Satellite Remote Sensing of Sea Surface Temperatures.

Further Reading

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