The TAO Shipboard CTD Program under the National Data Buoy Center

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INTRODUCTION

Since its modest beginnings in the early 1980s, the Tropical Oceans-Atmosphere (TAO) Program in the equatorial Pacific has evolved into what has been called the "crown jewel" of the Global Climate Observation System. Along with data from the 55 surface moorings and acoustic doppler current profiler data from four subsurface equatorial moorings, the ship cruises servicing the moored arrays provide unique temperature-salinity depth (CTD) datasets. Since 2007 the TAO Program has shifted from a research program under NOAA's Pacific Marine Environmental Laboratory (PMEL) to operational status under the National Data Buoy Center (NDBC). NDBC is now responsible for at-sea operations, data quality control and processing, and data delivery of all TAO data, including the shipboard CTD data. As a result of this change in organizational responsibilities, some aspects of data processing and delivery have also changed, but NDBC is committed to ensuring continuation of the high standards of data quality and delivery as under PMEL oversight. In this paper we provide an overview of the procedures used by NDBC to provide end-users with quality controlled CTD data from the TAO servicing cruises.

TAO ARRAY AND CTD SAMPLING GUIDELINES

The TAO array of bottom-moored buoys, along with the Japanese TRITON array are shown in Figure 1. NDBC is responsible for the operation of the 55 surface buoy moorings and 4 subsurface ADCP moorings of the TAO array. TRITON moorings replaced TAO moorings at 12 sites in the western Pacific along 137°E, 147°E, and 156°E beginning in 1999. The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) is responsible for the operation of the TRITON array. Both arrays are major components of the El Niño/Southern Oscillation (ENSO) Observing System, the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS).

The TAO surface mooring array consists of 55 bottom moored buoys sited between latitudes 8˚ (or 9˚) N and 8˚ S along 8 meridional lines located every 15˚ of longitude from 95˚ W to 165˚ E, with the exception of the 170˚W and 180˚ lines. The surface buoys measure wind speed and direction, air temperature and relative humidity at 10 minute intervals. Data are stored internally for later retrieval and processing, and daily averages are telemetered back to NDBC via the Argos satellite system. Some surface buoys also measure rain rate, barometric pressure, and long wave and short wave radiation. The moorings measure subsurface temperature at 1 m depth and at 10 additional depths between the surface and 500 m, salinity (via temperature and conductivity) at 1 m near the surface and occasionally at other depths, and pressure at 300 and

500 m. Along the equator at 100˚ W, 140˚ W, 170˚ W and 165˚ E, subsurface upward-looking acoustic doppler current meter (ADCP) moorings are paired with the surface moorings to provide current measurements between about 300 m and within a few 10s of meters of the surface. The velocity data is not telemetered back and is available only in post-retrieval processed form.

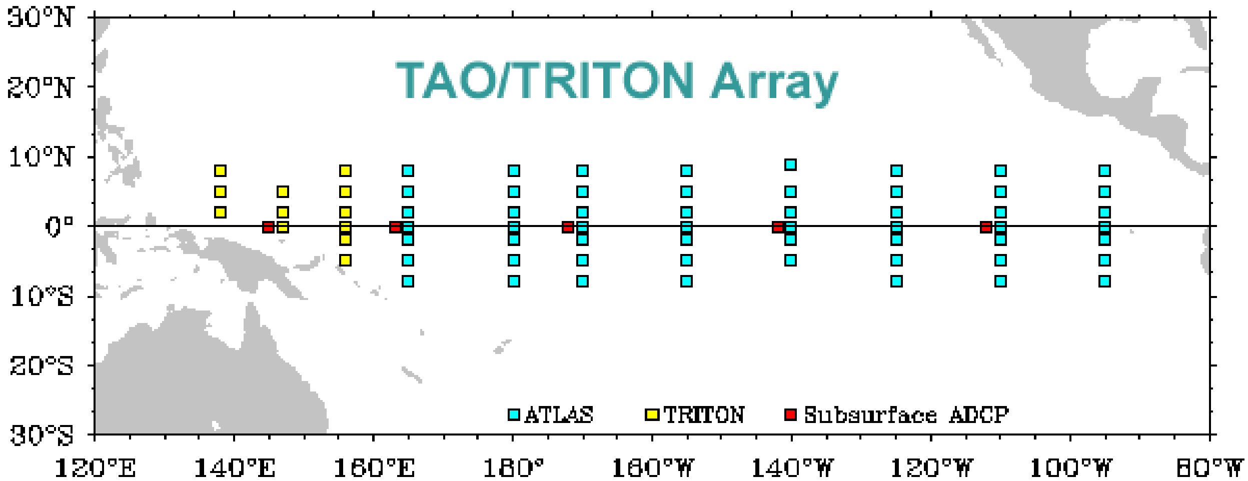

Figure 1. The TAO/TRITON array. Support for the TAO array is provided by the United States National Oceanic and Atmospheric Administration (NOAA). The Japanese Agency for Marine-Earth Science and Technology (JAMSTEC) operates the TRITON array.

The NOAA ship Ka'imimoana is dedicated to servicing the TAO array and to collecting CTD data. At-sea, CTD casts are conducted along the eight standard meridional lines of the mooring array running from 95˚W to 165˚E about every 15˚ of longitude. Typically, each array servicing cruise will be able to cover two of the standard tracklines, with each trackline optimally traversed twice per year. Standard procedures call for CTD casts to 1,000 decibars (dbar) at one degree latitude intervals between 12°N and 8°S, with the casts extended to 3,000 dbar at the array mooring locations. Between 3˚N to 3˚S, casts are also taken to 1,000 dbar at half-degree intervals. Of course, the many challenges inherent in conducting ship-board operations mean that actual coverage each year is usually somewhat less.

DATA COLLECTION

Shipboard Equipment

The primary equipment for conducting CTD casts is provided by NDBC. Data collection and first stage processing is designed around industry-standard equipment and software provided by Sea-Bird Electronics (SBE)* of Bellevue, WA. Table 1 details the NDBC equipment suite as of 2009. Ordinarily the CTD underwater unit is deployed with a dual sensor system and values from both sensor suites (temperature and conductivity/salinity) are reported. Auxiliary sensors such as transmissometer, fluorometer, and optical backscatterance sensors are frequently connected to the underwater unit in support of ancillary projects that operate onboard during the

TAO cruises. As backup and for occasional use on other vessels, NDBC also has a secondary equipment suite (Table 2) that is usually kept at NDBC at the Stennis Space Center. The Ka'imimoana provides two Guildline* 8400B laboratory salinometers ("autosals") for high accuracy bottle salinity measurements. One is in operation in a temperature-controlled room and the other is kept stored as a spare. The Ka'imimoana also has its own complete CTD system (Table 3) as backup for the on-board projects.

Table 1. Primary NDBC TAO CTD equipment suite and calibration and maintenance intervals (as of 2009). "SBE" refers to the manufacturer, Sea-Bird Electronics of Bellevue, Washington*

Equipment	Calibration/maintenance/service intervals
SBE 9*plus* underwater unit with Paroscientific* pressure sensor	Annually
SBE 3*plus* temperature sensor (2)	Every 3 years or as needed
SBE 4C conductivity sensor (2)	Annually
SBE 5T submersible pump (2)	As needed
SBE 32 carousel w/ aluminum stand with 24 Niskin bottle capability	As needed
SBE 11*plus* V2 deck unit	As needed

*Mention of a manufacturer in no way implies endorsement by the National Data Buoy Center or the US Government

Table 2. Secondary (Backup) NDBC CTD equipment suite and calibration and maintenance intervals (as of 2009). "SBE" refers to the manufacturer, Sea-Bird Electronics of Bellevue, Washington*

Equipment	Calibration/maintenance intervals
SBE 9*plus* underwater unit with Paroscientific* pressure sensor	Annually
SBE 3*plus* temperature sensor (1)	Every 3 years or as needed
SBE 4C conductivity sensor (1)	Annually
SBE 5T submersible pump (1)	As needed
SBE 32 carousel w/ aluminum stand with 12 (5 liter) Niskin bottle capability	As needed

*Mention of the manufacturer in no way implies endorsement by the National Data Buoy Center or the US Government

Table 3. NOAA vessel Ka'imimoana CTD equipment suite and calibration and maintenance intervals (as of 2009). Available to projects as backup equipment. "SBE" refers to the manufacturer, Sea-Bird Electronics of Bellevue, Washington*

Equipment	Calibration/maintenance intervals
SBE 9*plus* underwater unit with Paroscientific* pressure sensor	Annually
SBE 3*plus* temperature sensor (2)	Annually
SBE 4C conductivity sensor (2)	Annually
SBE 5T submersible pump (2)	Annual maintenance
SBE 32C compact carousel with 12 Niskin bottle capability	As needed
SBE 11*plus* V2 deck unit	As needed
Guildline* 8400B laboratory salinometer (2)	Annually

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At-sea Data Collection Procedures

CTD deployment, retrieval, and storage procedures at sea follow generally accepted practices. Shortly prior to arriving on-station, Niskin bottles in the carousel are prepared and cocked, the protective detergent solution is removed from the sensors and plumbing of the CTD underwater unit, and the CTD and carousel are moved into position for deployment. Operation of the deck unit and other parts of the data acquisition system, including the operation of SBE's Seasave v7 data acquisition software, are checked out.

After arriving on-station, the ship stops and the CTD underwater unit and carousel package are lowered into the water and held just below the surface while data acquisition is started and electronic creation of the cast log is begun. The package is then lowered to the pre-determined depth (generally 1000 m or 3000 m) at the generally accepted rate of 60 m/min. When at depth, meteorological information is entered into the cast log. The ascent rate is also approximately 60 m/min except for slowing as depths for each of the 8 salinity water samples are approached. The package stops at each of the pre-selected depths for a Niskin bottle water sample to be taken (see Table 4). Upon reaching 100 m the ascent rate is slowed to 45 m/min and then to 30 m/min to prevent the package from breaching the surface. These descent/ascent guidelines are modified as safety considerations and operating conditions warrant. The winch operator pauses the package slightly below the surface while the data acquisition is terminated, and then the underwater unit and carousel are brought on board. The protective detergent solution is reintroduced into the sensors and associated plumbing. Any other procedures needed for the ancillary projects then take place and the ship gets underway.

Water samples are taken from the Niskin bottles as needed. Eight samples for salinity analysis with the shipboard salinometer are taken from bottles opened at the depths listed in Table 4.

Standard procedure for taking a sample is to rinse the petcock, cap and insert, and 250 ml KIMEX[TM*] borosilicate glass sample bottle three times with water from the Niskin bottle, then fill the bottle to the shoulder from the Niskin bottle, replace the insert, and cap. The bottles are moved to the autosal room to equilibrate to the temperature in the room (22 – 24˚ C) before analysis.

When all sampling is complete, the Niskin bottles are emptied and everything is thoroughly rinsed with freshwater. The carousel and CTD underwater unit are secured and covered with a protective tarp if a long transit is anticipated before the next cast is taken. The cast log and raw data files are completed and backed up.

Table 4. Water sampling depths/pressures for salinity analysis (depths in m / decibars)

1,000 m casts: 1000, 800, 600, 400, 200, 40, 20, near surface
3,000 m casts: 3000, 2000, 1500, 500, 200, 40, 20, near surface

Salinity Water Sample Analysis

Water samples are analyzed with the high precision laboratory salinometer in order to assess the accuracy of the CTD measurements and to make corrections to these values if necessary. The Ka'imimoana has two salinometers on board, both Guildline* Autosal Model 8400. One is kept as a replacement for the active unit kept in a small temperature controlled room maintained at as constant a temperature as possible between 22 and 24˚ C. To ensure all components are at the ambient room temperature, the room and the salinometer must be maintained at the controlled room temperature for 24 hours before any salinity measurements are made. Water samples in collection bottles need to equilibrate in the room for at least 5-7 hrs.

Prior to making autosal measurements, the unit is standardized with IAPSO standard sea water. A standardization lasts 24 hours and about 40 samples can typically be processed in a reasonable day's work. Because standard sea water is fairly expensive, standard procedure is to process a minimum of about 8 stations or 40 water samples each time a batch is processed. Three salinity measurements are made for each bottle and the mean value used for comparison with the CTD data themselves. Data are recorded automatically into an Excel file.

Summary of Raw Data Collected

The raw data needed for processing of the CTD data and eventual posting on the NDBC TAO webpage are:

1.) Raw CTD data files generated by the SBE Seasave software (files with extension .con, .dat or .hex, and .bl (if water samples taken)

2.) Laboratory salinometer analyses of water samples (if taken) and information identifying cast and depth for each sample

3.) Cast logs containing the necessary metadata, including ship name, date and time, station location, weather, and identifying information that allows the cast log metadata to be associated with a particular cast.

On a few cruises not performed on the Ka'imimoana, not all these data have been returned, so we are developing procedures to minimize these problems. Unfortunately, different personnel serve on each cruise (both NDBC and ship's complement) and the ship used is not always the Ka'imimoana, so solutions for problems must evolve as they are encountered. However, one problem anticipated to be among the more common likely to occur is lack of satisfactory cast log information.

To address the problem of lack of cast log metadata if the ship does not have the same software as the Ka'imimoana for creating cast logs, NDBC created an Excel-based application that on each cast prompts the user for the minimum necessary metadata and saves them in an Excel format that can be converted to a text format readable by the processing software. A sample paper cast log form is also provided for the ultimate backup as a hardcopy; however, the level of effort in transcribing these data into an electronic form is so great that we hope this will never be necessary.

DATA POST-PROCESSING AND QUALITY CONTROL

Data are brought back electronically to NDBC for processing by the Data Assembly Center, the DAC. Data files required include raw data files generated by the SBE Seasave software (files with extension .con, .dat or .hex, and .bl (if water samples taken), summaries of bottle salinity values from a laboratory salinometer and information identifying cast and depth for each sample; and cast logs containing the necessary metadata. Missing .bl or autosal analysis files are not fatal, but no adjustment of the CTD data to better agree with laboratory salinity measurements can be done before the final processed data are created and posted to the TAO website in standard form. Missing .con, .dat or .hex files or cast log files, however, result in no final salinity profiles being posted for the cast (or cruise).

Post-processing is accomplished in two phases. In the first phase the raw CTD data are processed into 1 decibar downcast profiles using the manufacturer-supplied software. In the second phase the downcast profiles are edited for spikes, noise, and other anomalies not removed by the first phase software. Next, comparisons are performed between the CTD values and laboratory salinometer water sample values. Regression equations between these two datasets are calculated and based upon evaluation of the significance levels of the coefficients and the appearance of the residuals, a decision is made for a given cruise as to whether or not to correct the CTD data using the regression equations. In the final step the fully processed data and derived quantities are written to individual standard format output files and posted on the TAO website for public access.

First Stage Post-Processing

After data files from a cruise are brought back to NDBC, the first step is to process the files collected by the SeaSave software using Sea-Bird's* SBE Data Processing package, a Windows 2000/XP program for converting, editing, processing, and plotting of oceanographic data acquired with Sea-Bird* equipment. The initial menu for the program is shown to the right. The sequence of steps used at NDBC for this first phase is given in Table 5.

The final output is a series 1 decibar resolution of ascii files of only the down cast for each cast (SBE data processing extension .cnv) and any corresponding bottle cast summary files (SBE data processing extension .btl). The second step in processing is performed with Matlab routines written specifically for this purpose.

Table 5. Processing steps with the SBE Data Processing software.

1. Data conversion	Convert raw .hex or .dat data files to engineering units, storing the converted data in a .cnv (sensor data) file and a .ros (water bottle) file (if appropriate). Both down and up casts are processed. The processed parameters are: pressure, temperature t0, t1, conductivity c0, c1, and ancillary sensor data. Ancillary sensors are converted to voltages and not further processed.
2. Mark outliers: WildEdit	Mark outliers in the data by replacing the data value with badflag. The badflag value is documented in the input .cnv header. Wild Edit's algorithm makes two passes through the data: the first pass obtains an accurate estimate of the data's true standard deviation, while the second pass replaces the appropriate data with badflag.
3. Low-pass filtering: Filter	Apply low-pass filters to smooth out high frequency variations. Two filters are possible, A and B. A is set to 0.15 sec and a low pass filter is applied to pressure with a time constant of 0.15 sec. In order to have no time shift (a zero phase shift), the filter is first run forward through the file and then backwards through the file. The B filter is set to 0, meaning no B filter.
4. LoopEdit	Mark scans where CTD is moving less than minimum velocity or traveling backwards due to ship roll. If the CTD speed is less than 0.25 m/s or the pressure is not greater than the previous scan, the scan is flagged with badflag.
5. Derive	Compute salinity s0 and s1
6. BinAvg	Average data into 1 dbar pressure bins

7. Split	Split downcast data into separate dataset. "d" placed at beginning of cast name, e.g., dka10011.cnv
8. BottleSum	Read a .ros file created by Data Conversion and write a bottle data summary to a .btl file.

Second Stage Post-Processing

This second stage of post-processing is performed using Matlab software written for this purpose. At NDBC the one-dbar resolution downcast datasets and the bottle data summary files must be transferred to a Linux system, but this step is not fundamental to the implementation of the procedures.

Graphical Editor

All downcast files (in .cnv format) are screened visually using a graphical editor. Each cast in turn is plotted in either profile or T-S form. If the CTD had two sensor suites, each suite can be screened separately.

Depth ranges over which salinity alone or temperature-salinity together are problematic are identified and deleted (example in Fig. 2). Values within the deleted depth ranges are replaced with the missing value code. To aid in editing over small depth ranges, a zoom capability is available. The edited cast is saved and the data analyst moves on to the next cast until all casts in the cruise have been processed

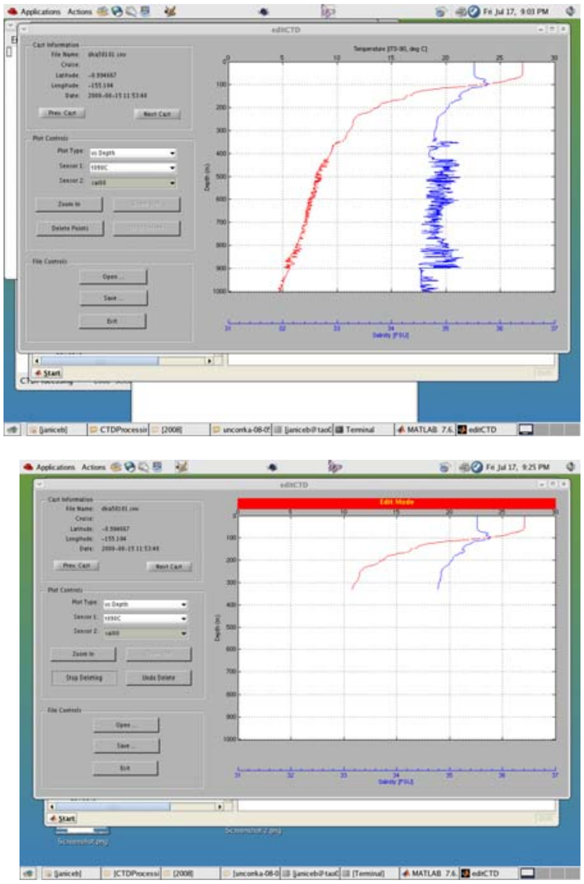

Figure 2. Screen shots illustrating use of the CTD graphical editor to remove portions of noisy data.

Correction of CTD Salinity Values

Because temperature is a much easier and robust measurement than conductivity, CTD temperatures are assumed to be correct. Because we are not interested in conductivity *per-se*, we do not attempt to correct conductivity but compute salinity and examine the necessity of correcting the derived value of salinity for each sensor suite.

Regressions of CTD salinity measurements against bottle salinities and against bottle salinity and a quadratic in normalized pressure are performed for each sensor suite's salinity values for all of the edited casts taken during a cruise. Regressions have a linear correction in salinity (offset and slope) and may also have a quadratic correction in pressure. If statistically warranted, the regression equations are used to correct the CTD salinity values. Specifically, regressions are computed for each sensor suite individually for the relationships

$$Salinity_{CTD} = a + b \cdot Salinity_{bottle}$$

and

$$Salinity_{CTD} = a + b \cdot Salinity_{bottle} + c \cdot P + d \cdot P^2$$

where P is normalized pressure, defined as pressure in decibars divided by 1000. The statistical significance of both forms of the regression equations are checked as is any pattern of the residuals plotted against depth and the best equation, if any, is chosen for each sensor suite. Then, if needed, the CTD salinities are recomputed. For most of the cruises we have found that applying a small linear correction (not the same for the two sensor suites) is statistically desirable and improves the data from the standpoint of making the two salinity profiles more similar. Temperature is assumed correct, and then derived quantities are computed for output into a standardized ASCII format. All casts are made available to the public on the TAO website. The full set of parameters made available in each cast file (with extension .cor for "corrected") is:

Pressure (decibars)
Temperature, 1st sensor suite (˚C)
Temperature, 2nd sensor suite (˚C)
Salinity, 1st sensor suite (psu)
Salinity, 2nd sensor suite (psu)
Sigma-t, 1st sensor suite
Sigma-t, 2nd sensor suite
Potential temperature, 1st sensor suite (˚C)
Potential temperature, 2nd sensor suite (˚C)
Sigma-theta, 1st sensor suite
Sigma-theta, 2nd sensor suite
Transmissometer voltage
Fluorometer voltage
Backscatterance voltage

To maintain a consistent format, all 14 parameters are always given, even if a sensor is not present, with the missing-data code (99.999) inserted for any missing or bad data. All parameters are reported to 3 significant figures.

DATA DELIVERY TO THE USER COMMUNITY

Each final CTD cast dataset contains metadata documenting where and when the data were collected, weather at time of the cast, variables presented, and what if any regression equations were used to adjust the CTD salinity according to autosal measurements. Only the downcast data are provided, since upcast data are contaminated by the motion of the CTD package. Data from both sensor suites are given at a 1 decibar resolution, as well as data from ancillary sensors attached by other projects to the CTD such as transmissometer, fluorometer or backscatterance voltage, if present. Final datatsets are made available by site in the TAO CTD Data section of the TAO website, http://tao.noaa.gov.

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