Abyssal Variations at the Station ALOHA OceanSITES: HOT, WHOTS and ACO:

Results from the OceanSITES Deep T-S Project Informing the Deep Ocean Observing Strategy

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Introduction

Abyssal ocean observations at the Station ALOHA Site from platforms HOT (Hawaii Ocean Time-series), ACO (ALOHA Cabled Observatory), and the WHOTS Site mooring (WHOI Hawaii Ocean Time-series Station) have revealed large and rapid potential temperature (θ), salinity (S) and dissolved oxygen (O_2) variations. These are apparently associated with Antarctic Bottom Water (AABW) overflowing from the Maui Deep to the Kauai Deep, and/or with baroclinic modes within the Kauai Deep. Near-bottom CTD vertical profiles from ~monthly HOT cruises along with high temporal resolution θ, S, O_2 and velocity observations from instruments on the ACO and WHOTS mooring complement each other. The continuous observations show that these cold events are more common than indicated from shipboard observations alone, which may be due in part to non-stationary climate processes. The Kauai Deep ventilation is strongly dynamic.

AABW flows through the Samoa Passage, across the equator in the central Pacific then eastward and northward around the east side of Hawaii Island, and turning to flow northwestward along the Hawaiian Archipelago (Lukas et al., 2001; Fig. 1). Overflows of cold, salty and oxygenated AABW from the Maui Deep to the Kauai Deep are intermittent, large amplitude and sudden (Figs. 3, 4).

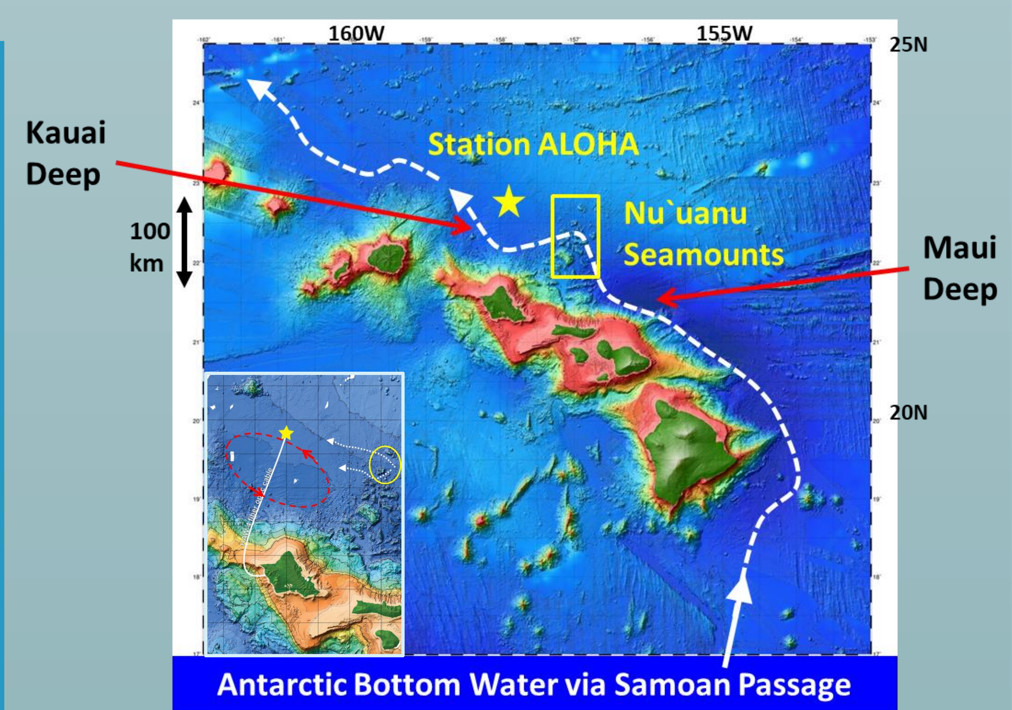


Figure 1. Station ALOHA (yellow star) and topography around the Hawaiian Islands. The pathway for AABW is indicated (dashed line). The inset shows the AABW overflow channels (yellow) through the Nu`uanu Seamounts, schematic propagation of an internal Kelvin wave (red), and the fiber optic cable connecting the ACO with Oahu (white). Bathymetry from Hawaii Mapping Research Group/SOEST/UH.

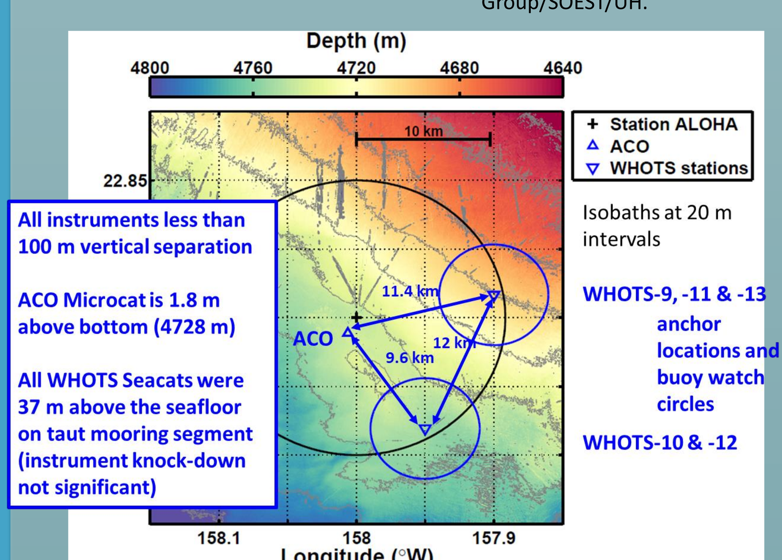
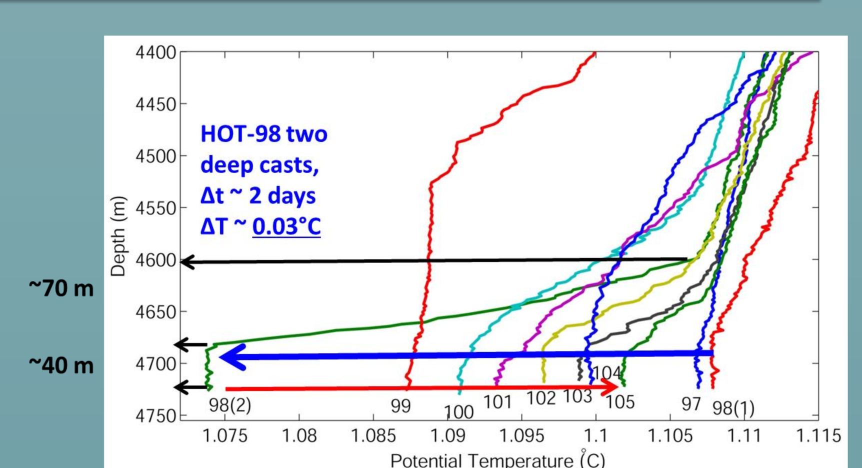


Figure 2 . Station ALOHA is defined as a 6 nm radius circle centered on 22° 45'N, 158°W.The locations of ACO and WHOTS instruments are indicated. ACO includes one unpumped SBE-37 MicroCAT (ACO/OBS), one pumped SBE-37SM (ACO/BSP-1) , one pumped SBE-52MP (ACO/BSP-2), and one Sontek Acoustic Doppler Current Profiler. Recent WHOTS deployments have included near-bottom pairs of SBE-16 Seacats and SBE-37 MicroCATs. Note alternating WHOTS anchor sites allow in-water overlap of moorings during mooring cruises.

History of Cold Bottom Water Events at Station ALOHA

Lukas et al. (2001) described the extreme HOT-98 cold event and a few subsequent events, and provided a simple heat budget model analysis. One conclusion was that turbulent mixing was enhanced around the sill depth following cold overflow events, and that this enhanced mixing brings warmer waters downward to restore the long-term heat balance. Prior to the successful installation of the ACO during May-June 2011, the only continuous near-bottom temperature measurements were from thermistor chain moorings deployed November 2008 through March 2010 (not shown). However, as seen in Fig. 4, there was an absence of strong cold events during that period.



HOT cruise # indicated below each profile

Figure 3. A very large bottom-trapped temperature decrease (~0.03°C; 30 mK) was observed between deep casts conducted ~2 days apart during HOT-98. A slow recovery occurred over several subsequent cruises. The HOT Sea-Bird 911plus CTD profiles, with dual pumped SBE-3F temperature sensors, were calibrated @ Sea-Bird to ≤ 1 mK after every cruise. See calibration history in Fig. 5.

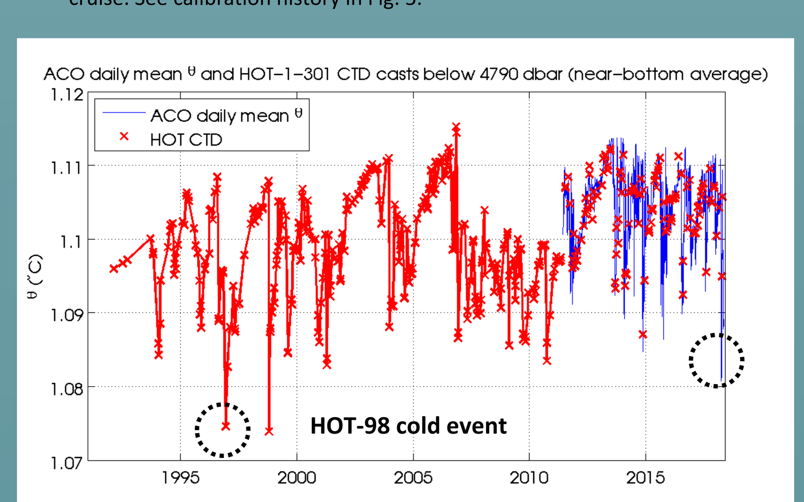


Figure 4. Time-series of near-bottom potential temperature from HOT CTD profiles (X) and from the ACO/OBS (—). While the HOT-98 event was the coldest yet observed, the recent March-April 2018 cold event was the 3rd coldest on record, and the coldest observed since the start of continuous observations from the ACO. The nonstationary nature of the time-series is apparent, as is the strong skew towards cold extremes.

Summary

- Temperature measurements accurate to better than 0.001°C across multiple Sea-Bird instruments, both in calibration lab and deployed in the abyss
- HOT 30 years; ACO 7 years; WHOTS 5 years of observations
- Large dynamic signals (cold overflow events; oscillations) in the Kauai Deep: Signal/noise ratio > 10
- Simultaneous WHOTS-ACO differences exceed 0.01 °C in 10 km over several days; one-year mean differences are much larger than measurement uncertainty
- Signals propagate along isobaths from east to west at ALOHA
- Such non-tidal dynamics are likely occurring at many other locations along abyssal circulation pathways

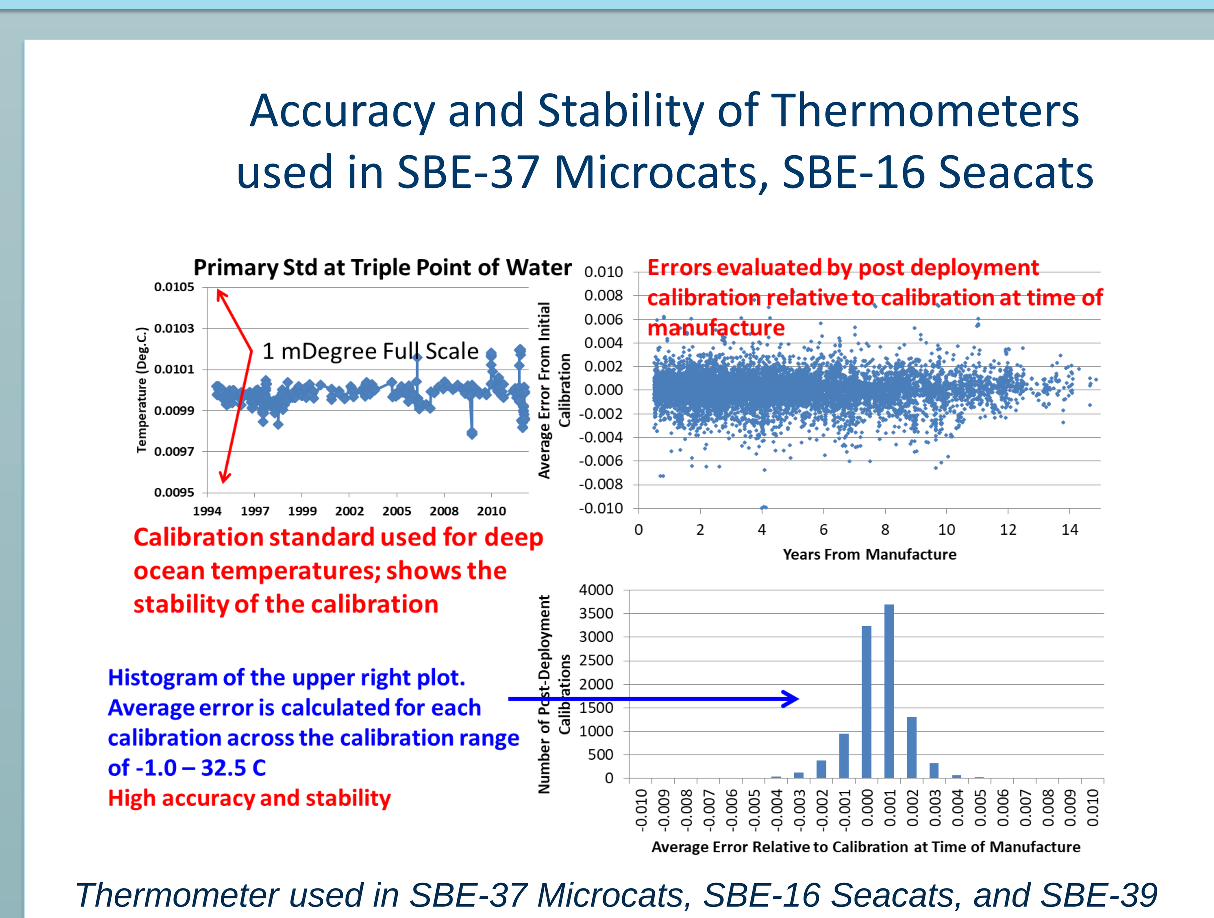


Figure 5 . History of calibration standard used at Sea-Bird shows the stability of their calibrations (left). Errors in sensors' calibrations relative to their initial calibration as a function of years of manufacture (upper right), and its corresponding histogram (bottom right) show their stability and accuracy.

Temporal character of temperature variations. ACO

Not long after the ACO was deployed in mid-2011, a cold event began (Fig. 6). From mid-2013 onward, nine distinct cold events were observed. Six of these events saw drops in temperature > 20 mK over only a few days, followed by large oscillations (10-60 days) of about 10 mK. The recovery phase of these events was characterized by small variations around distinct trends, consistent with turbulent diffusion of heat downward as modeled by Lukas et al. (2001).

The measurements from the ACO, along with measurements from the test of the ALOHA Profiling Mooring nearby, were used by Alford et al. (2011) to study the prolonged cold event that occurred during the fall of 2011, and to infer turbulent diffusion of heat.

The March-April 2018 cold event (Figs. 6, 7), exhibited a very rapid onset. The coldest potential temperature in this recent event is only the third coldest on record, though coldest for the ACO era. It is apparent that the rapid cooling was preceded by a distinct and rapid warming (Fig. 6). Pronounced, but diminishing, oscillations around the cooling trend were observed. The close correspondence of changes in theta, S and O_2 is clear (Figs. 7, 8). Cold, salty, higher O_2 water is from the Maui Deep. There are no simple correlations between potential temperature changes and horizontal velocity; vertical motions are certainly important. Following the initial rapid cooling, each oscillation reaches progressively less cold values. This might be due to the gradual weakening of NWward along-isobath flow (and perhaps greater mixing downward of warmer waters from above.)

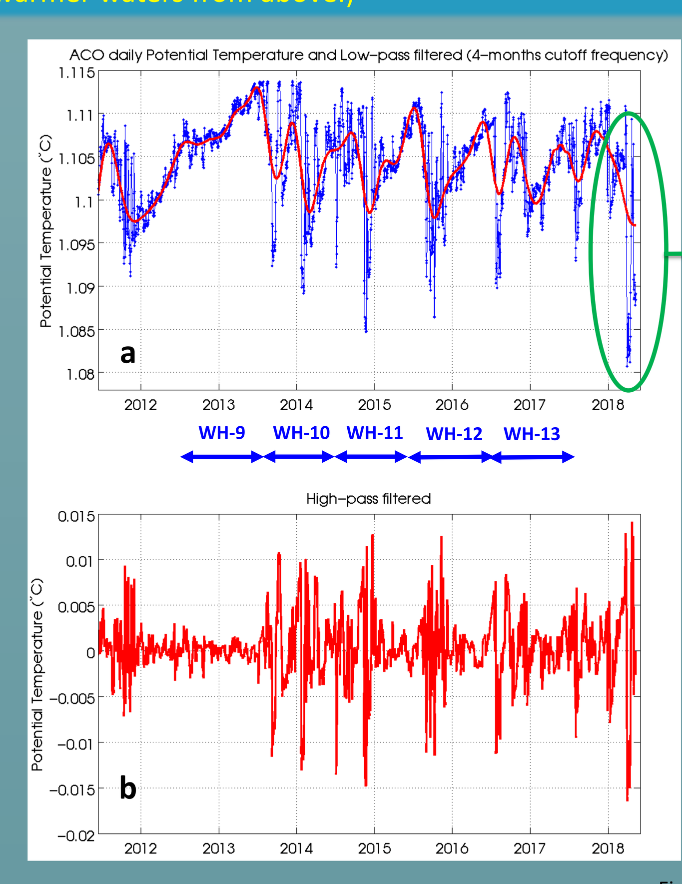


Figure 6. a: ACO potential temperature (blue), with smoothing cubic spline fit (red). Cold events show increased variance more than an order of magnitude larger than measurement uncertainty. b: High-pass filtered data, shows a 30 mK peak to peak variability for variations with periods shorter than 120 days.

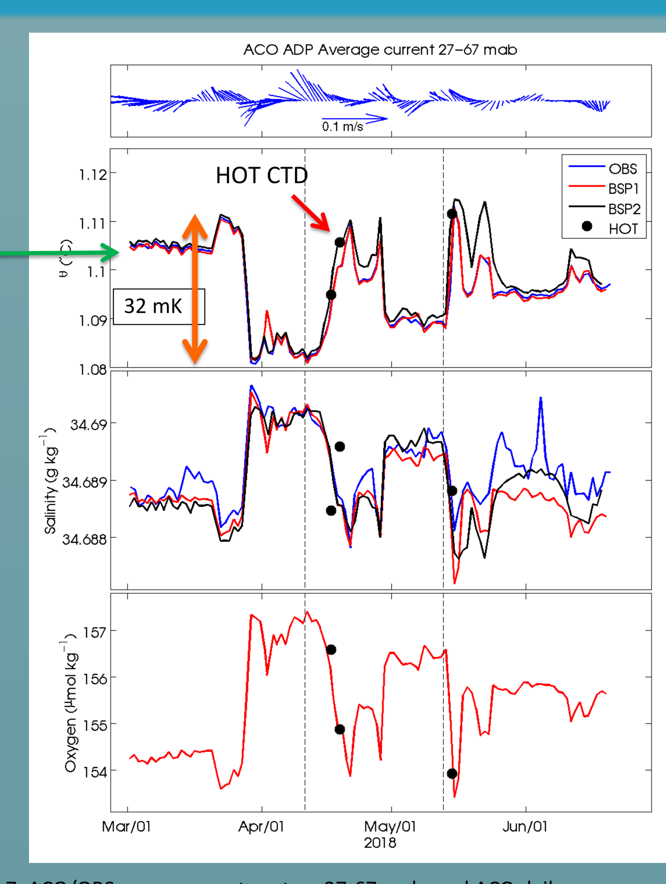


Figure 7. ACO/OBS mean current vectors 27-67 mab, and ACO daily mean potential temperature (OBS, BSP-1 and BSP-2), salinity(OBS and BSP-1 and oxygen (BSP-1) during the March-April 2018 cold event, including near-bottom values from HOT CTD profiles. BSP2 temperatures are higher than the others after the dates indicated by the dashed lines because the package detached from the bottom and moved on two occasions 25 and 50 mab respectively. HOT salinities during the April cruise seem to disagree with ACO, however hourly ACO data (not shown) show short-term variability matching the HOT data.

Discussion

- Large dynamic abyssal temperature signals in the Kauai Deep — cold overflow events and oscillations — much greater than instrumental uncertainty
- One-year mean θ differences are real and significant; WHOTS colder than ACO is consistent with bottom water source to east — the Maui Deep
- RMS ACO-WHOTS differences ~5 mK during 2014-2015 (~10 km separation)
- Simultaneous WHOTS-ACO differences exceed 1 mK/km over several days. Strong near-bottom baroclinic pressure gradients
- Signals propagate from east to west on average, faster than the daily mean near-bottom flow @ the ALOHA Cabled Observatory
- One out of 5 WHOTS deployments show little or no spatial differences from ACO: non-stationarity is important
- Internal Kelvin waves with periods of days to weeks?
  Consistent with westward propagation at ALOHA (i.e. counterclockwise propagation around Kauai Deep)
- Forcing?: May be from above (surface weather; baroclinic eddies) or by overflow gravity currents
- Issues: Internal Rossby radius of deformation depends on stratification, which depends on frequency and magnitude of cold overflows

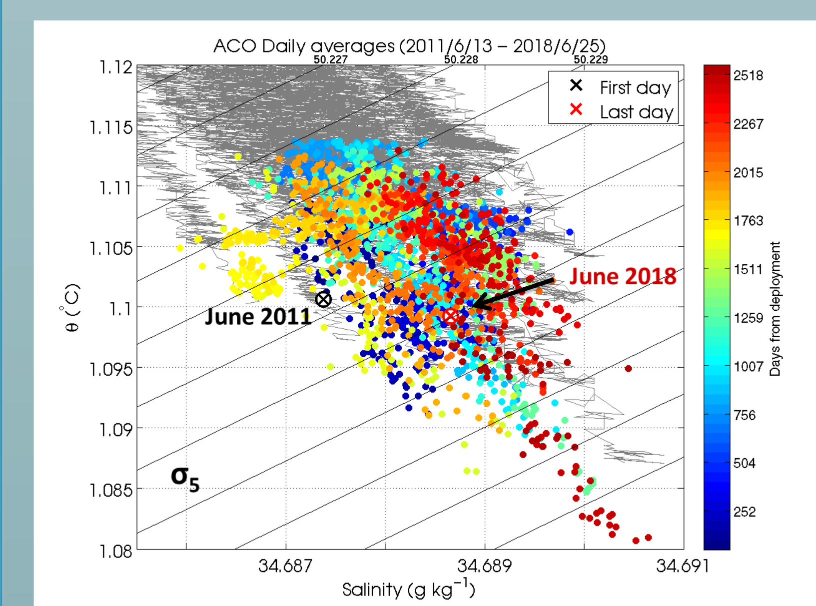


Figure 8. θS diagram of HOT CTD profiles (gray), and daily ACO/OBS MicroCAT data colored in time from blue (older) to red (recent). All measurements were made after the ACO was connected to the ALOHA Cable. The March-April 2018 cold event (Fig. 7) is apparent in the points at the bottom right corner of the plot. The diagonal black lines are sigma-5 potential isopycnals. The ~3 g/kg salinity range, and more than 0.03°C range of potential temperature for the ACO/OBS is apparent and confirmed where HOT CTD profile data are available.

Spatial character of temperature. ACO-WHOTS

Potential temperature differences between MicroCATs on the ACO and on WHOTS moorings reach more than ±0.02°C (20 mK) (Fig. 9), and the ACO current speed and direction reveal complex dynamics.

Temperature differences during overlapping periods between moorings and ACO (~10 km separation) (Fig. 10) are up to 10 mK, and numerous multi-day, very significant differences between ACO and WHOTS-11 are indicative of strong near-bottom baroclinic pressure gradients . WHOTS-10, -11, -12 and -13 differences from ACO lead ACO by 1-3 days for 10-12 km separation (Fig. 11), yielding 0.04-0.11 m/s propagation speed.

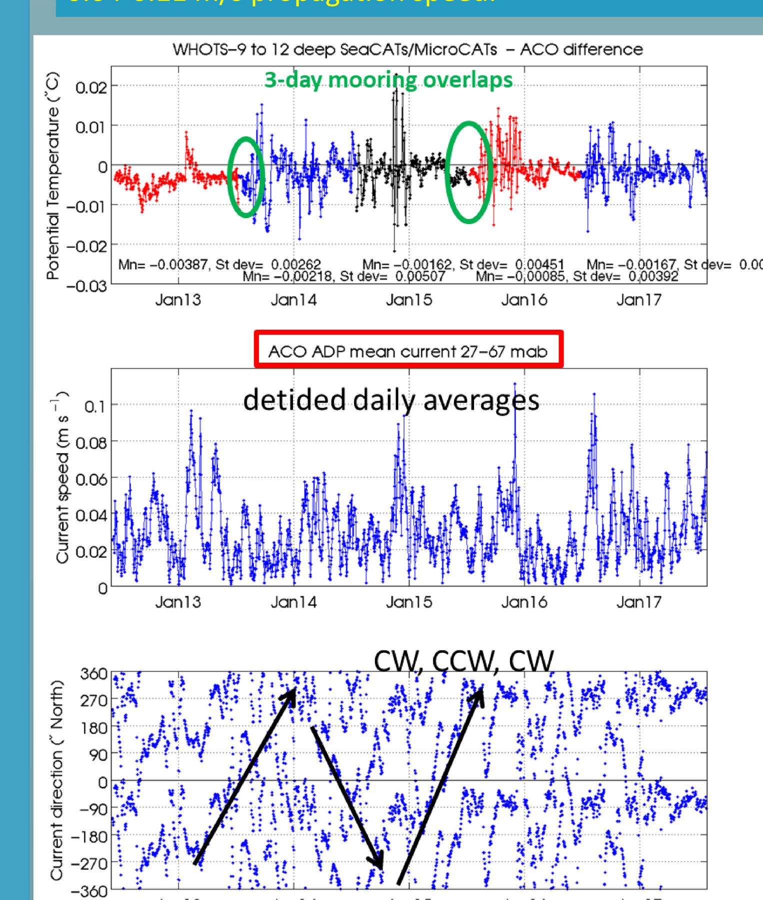


Figure 9. Potential temperature differences between the ACO/OBS and five WHOTS mooring deployments, each with dual SBE-16 Seacats or SBE-37 Microcats above anchor releases, 37 m above bottom (top). See Weller et al. (2017) for details on calibrations. ACO current speed (middle) and direction (bottom).

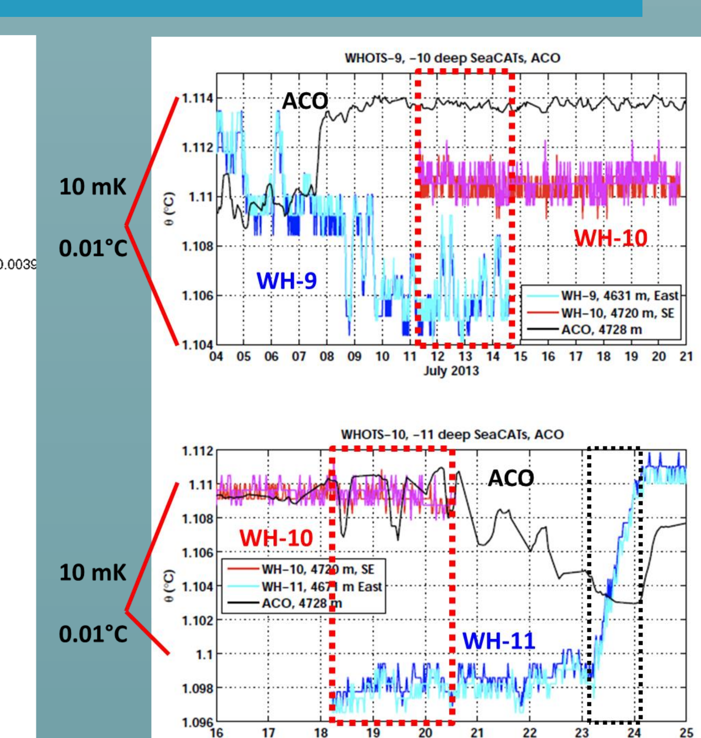


Figure 10. Potential temperatures during transitions between WHOTS-9 and -10 (top), and between -10 and -11 moorings (bottom). Moorings overlap by 3 days while moored sensors are compared and calibrated using shipboard instruments. Note the close agreement between dual instruments on each mooring. WHOTS-ACO differences are 0-11 mK (WHOTS colder), for 9.6-11.4 km separation ~along isobaths. WHOTS-WHOTS differences are 2-11 mK for 12 km separation across isobaths.

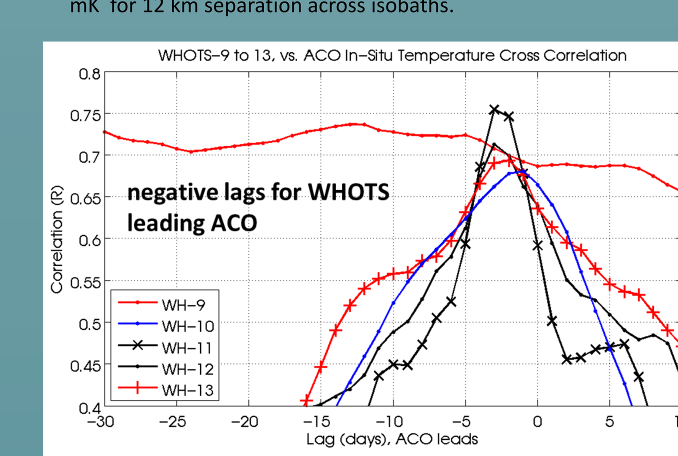


Figure 11. Lagged cross-correlation between WHOTS and ACO temperatures. WHOTS-9 tracks ACO very closely except for one month-long event. WHOTS-10, -11, -12 and -13 differences from ACO are larger and lead ACO by 1-3 days respectively for 10-12 km separation.

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Acknowledgments

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