The WHOI-Hawaii Ocean Time-series: Highly-Resolved Upper Ocean Trends, Variability, and Forcing

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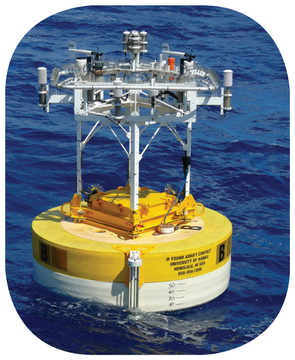
INTRODUCTION

The WHOTS (WHOI-Hawaii Ocean Time-series Site) surface mooring was first deployed at Station ALOHA in 2004, and has been maintained with annual cruises. The WHOTS mooring is a collaboration between WHOI and UH designed to quantify air-sea fluxes of heat, moisture and momentum, and their impacts on the upper ocean as part of the Hawaii Ocean Time-series (HOT), with support by NOAA and NSF. The work described here focuses on quantifying the changes of the upper ocean from the temporally-resolved moored records, and comparing those trends to the HOT shipboard time-series.



The WHOTS-10 mooring (picture, above right) is currently deployed carrying a full air-sea interaction package (ASIMET; Colbo and Weller, 2009), a pCO_2 system (NOAA/PMEL), 17 MicroCat CTDs from the surface buoy to 155 m, two Vector Measuring Current Meters, two upward-looking Acoustic Doppler Current Profilers, and two Seacats near the anchor (~4800 m). WHOTS conductivity calibrations are made using CTD yo-yo profiles near the mooring during HOT cruises and during WHOTS maintenance cruises.

Profiles of temperature and salinity have been collected at Station ALOHA with a Sea-Bird 9/11+ CTD system during near-monthly HOT cruises since 1988 (Karl and Lukas, 1996). The ~16 profiles of potential density (σ_θ), potential temperature (θ), and salinity conducted over 3 days for each cruise were averaged and fit with the MLR.

Hourly-averaged temperature, salinity, potential density and velocity records from the WHOTS mooring are shown below. The annual cycles in temperature and density are pronounced, while the salinity record is much less regular. A decrease in upper ocean temperature over time is apparent, and increases in salinity and density are visible.

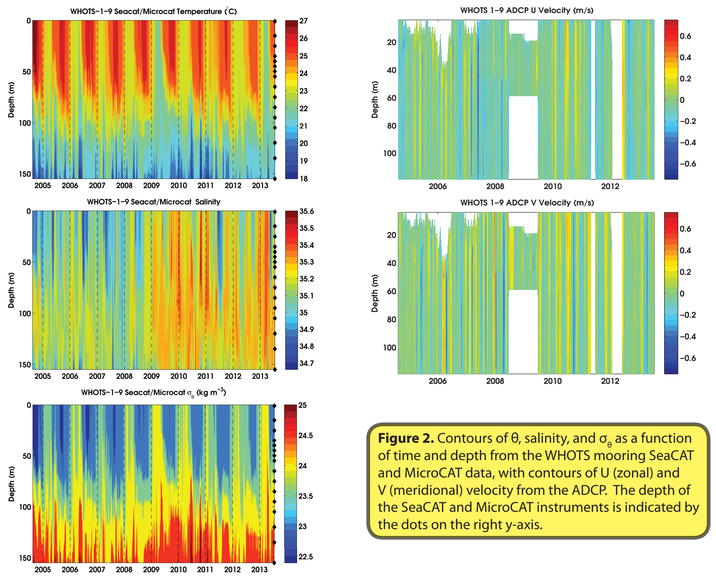


Figure 2. Contours of θ, salinity, and σ_θ as a function of time and depth from the WHOTS mooring SeaCAT and MicroCAT data, with contours of U (zonal) and V (meridional) velocity from the ADCP. The depth of the SeaCAT and MicroCAT instruments is indicated by the dots on the right y-axis.

Integral time scales were calculated for the residuals from MLR model fits to each variable and depth as described in Methods (poster center section). These are shown on the right, and they fall within the range of 20-60 days, indicative of eddy timescales. The largest values are for temperature in the mixed layer and the smallest values are in the upper thermocline where internal gravity waves are most energetic. The residuals using the sub-model without the decadal cycle have longer integral time scales for salinity and density in the upper thermocline.

The decadal cycle amplitude is smallest in the mixed layer for temperature and density, increasing with depth in the upper thermocline. Decadal salinity variation is comparable across the mixed layer and upper thermocline. The phase structure for all three variables shows variations in the upper thermocline leading the mixed layer.

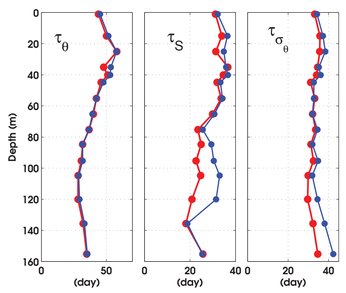


Figure 3. Integral time scales for θ (left), salinity (center), and σ_θ (right), from the WHOTS mooring data multiple linear regression models (MLR-F:red and MLR-D:blue) from Figure 5.

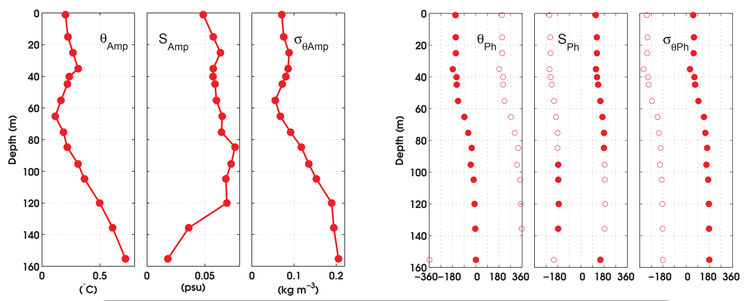


Figure 4. Amplitude (left panel), and phase (right panel) of the decadal cycle for θ (left), salinity (center), and σ_θ (right) for the WHOTS mooring data from the MLR-F model from Figure 5.

RESULTS

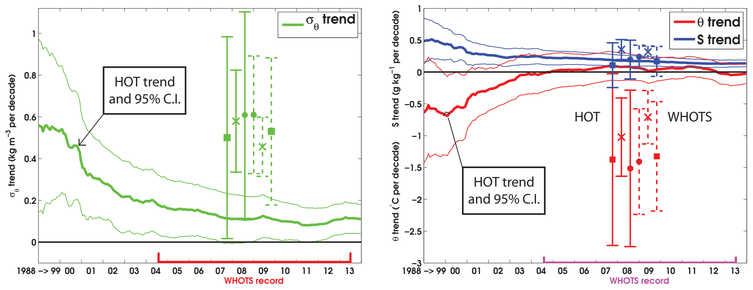


Figure 1. Time-varying linear trends (heavy lines) of potential temperature (θ), potential density (σ_θ), and salinity in the mixed layer (30 m) at Station ALOHA with 95% confidence intervals (CI, light lines). The first trend value in the plot includes data from the first ten years of HOT; consecutive values are after adding one cruise at a time. Symbols and error bars show the trend estimates and 95% CI during the WHOTS mooring record near 30 m; solid are from HOT data, and dashed are from mooring data; circles are from a MLR-F regression, crosses are without decadal cycle, and squares are without interannual cycle in the regression. See Methods below.

Key aspects of estimating upper ocean climate changes are revealed by observations at Station ALOHA (Figure 1). Conditions near the start of the record, as well as the length are critical in trend estimates. The linear trends (see Methods, below) of θ, S, and σ_θ calculated in the mixed layer from the first decade of HOT observations have wide confidence intervals, and are seen to vary considerably as more data is collected. Confidence intervals narrow with time, and the trends in all three variables become smaller. The increasing density in the mixed layer is confirmed over time, but what started out as significant at 95% becomes marginally significant. The HOT and WHOTS trends computed for the WHOTS period are consistent with each other, and the CI for the HOT trends are larger due to fewer observations. Clearly, the absolute values of the HOT and WHOTS trends in temperature and density are much greater than for the complete HOT record, illustrating the sensitivity of trends computed from shorter records to their starting points. We note that the temperature trend for the HOT record is almost never significantly different from zero, and that it is negative most of the time. Both the HOT and WHOTS mixed layer temperature trends from the WHOTS period are negative, leading to increased density. The density increase is augmented by the increasing trend in salinity, which is significant at 95%.

Potential temperature (θ) and density (σ_θ) trends are significant at 95% confidence for the mixed layer and deeper than 120 m. The mixed layer cooled by more than 1°C/decade, with the thermocline warming by twice that near 150 m. Corresponding to these trends in temperature, σ_θ increased in the mixed layer and decreased below 80 m. Thus, the stratification of the upper ocean at ALOHA decreased significantly during the WHOTS record.

Salinity increased throughout the upper ocean, with a relative minimum in the trends in the range 80-120 m. Increasing salinity reinforced the density increase in the mixed layer due to cooling, and partially compensated the warming in the thermocline.

The effects of excluding the decadal cycle from the MLR model were to weaken the θ trends and increase the S trends over the entire upper ocean. The increase of σ_θ in the ML was reduced slightly, and the decrease in the thermocline was reversed. Without the decadal cycle, the salinity increase appears to be significant at 95% over the entire upper ocean. The mixed layer θ and density σ_θ trends remain significant.

Because the 9-year record length is shorter than the decadal cycle, there are some mean differences between the full MLR model and MLR-D. These are negligible except for mixed layer salinity, and those are small relative to the mean vertical variation. The MLR model is a good fit to the temperature and density variations in the mixed layer (80-90% of the variance explained), and much less so in the thermocline. The full model explains about 50% of the variance of salinity throughout the upper ocean. The MLR-D shows no change to R^2 for θ and σ_θ in the mixed layer, and some reduction in the thermocline.

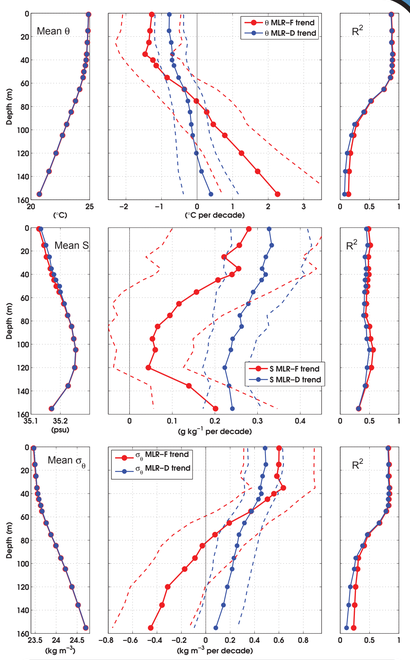


Figure 5. Mean (left), trend (middle) and correlation-squared (right) as a function of depth from multiple linear regression model fits to hourly potential temperature (θ, top panel), salinity (middle panel), potential density (σ_θ, bottom panel), and data from the WHOTS mooring between August 2004 and July 2013. The red dots (MLR-F) are for the full model; the blue dots are from a sub-model (MLR-D) that does not include the decadal cycle. The dashed lines are the 95% confidence intervals.

METHODS

An empirical multiple linear regression (MLR) model was fit to observations from HOT cruises and from the WHOTS mooring. The full model (MLR-Full) includes terms for the mean (a_0), trend (a_1), decadal (10 years), interannual (4 and 2 years), and annual harmonics (1, 1/2 and 1/3-years). Because the WHOTS mooring record is shorter, we use only the first two harmonics of the annual cycle, and one interannual period (4 years).

$$y(t) = a_0 + a_1 t + \sum_{i=2}^{M} (a_i \cos \omega_i t + b_i \sin \omega_i t)$$

$$A_i = \sqrt{a_i^2 + b_i^2}, \qquad \varphi_i = \tan^{-1}(b_i/a_i)$$

Where t is time, and ω_i, A_i, and φ_i are the harmonics frequency, amplitude and phase respectively.

Sub-models are also used that eliminate decadal (MLR-D) or interannual cycles (MLR-I) to determine the impact of excluding each on the other model coefficients. 95% confidence intervals in the trend are computed assuming a normal distribution. The degrees of freedom (DoF) are empirically determined for each record by calculating the integral time scale (τ) following Davis (1976).

$$\tau = 2 \sum_{i=0}^{N} (C_i^2 \Delta t), \qquad DoF = N\, \Delta t / \tau$$

Where C_i is the autocorrelation function at lag i of the residuals of the MLR, Δt is the series time interval, and N is the number of data in the series.

CONCLUSIONS

- Upper ocean stratification has weakened significantly over the recent decade, and over the entire HOT record; this is contrary to conventional wisdom in a warming world
- The mixed layer at Station ALOHA has been cooling, while the upper thermocline has warmed.
- Salinity has increased significantly in the mixed layer, and throughout the upper ocean, contributing to the density increase in the mixed layer and partially offsetting the warming in the upper thermocline.
- The salinity increase is consistent with the trend in net freshwater flux; the mixed layer temperature decrease is also consistent with the decreasing trend in net heat flux
- Trend magnitudes in HOT ML θ, S and σ_θ stabilized only after about 20 years; HOT trends during the WHOTS period are consistent with those estimated from the WHOTS mooring, but are much larger than those estimated from the beginning of HOT.
- Trend estimates are sensitive to the length of the series and the starting point. The decadal cycle is important in estimating the trends
- Long time-resolved records are required to detect statistically significant climate trends

The WHOTS mooring system consists of a surface buoy with a full suite of meteorological instruments, and subsurface instrumentation to resolve the temporal variations of shear and stratification in the upper pycnocline. The data analyzed here are from 9 consecutive annual deployments from August 2004 to July 2013 (see Santiago-Mandujano et al. (2007) for a complete description). High-quality air-sea fluxes of heat and freshwater were computed from data collected by the meteorological instruments every minute, and hourly data were used in the MLR analysis for each of the fluxes of net heat, latent heat, fresh water, evaporation and precipitation.

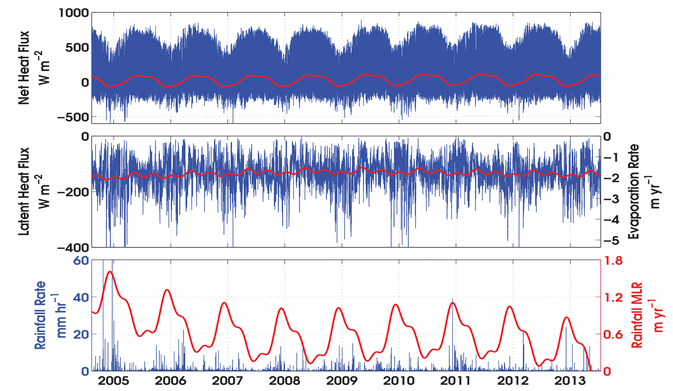


Figure 7. Hourly-averaged time series (blue lines) of net surface air-sea heat flux (top panel), latent heat flux lost from the ocean (middle panel) and rainfall rate (bottom panel) measured from the WHOTS buoy. The red line in each panel is MLR-F model fit to the data including mean, trend, decadal (10 year), interannual (4 year), and annual harmonics (1, 1/2, 1/3 year). The right y-axis in the middle panel indicates the evaporation rate.

The WHOTS mooring provides a critical platform at Station ALOHA for state-of-the-art measurements of all components contributing to the surface heat and freshwater fluxes. The record-average net surface heat flux (Table 1) derived from the MLR model is ~26 Wm^{-2} into the ocean and the net surface freshwater flux is ~1.2 m yr^{-1} lost to the atmosphere. This is typical of the central tradewind regime of the subtropical gyres. The heat gain and freshwater loss are approximately balanced on long time scales by advective fluxes and turbulent mixing.

The decreasing trend in the net heat flux is consistent with the cooling of the mixed layer, but the mixed layer would cool by 6.4°C/decade — if advection and mixing were unchanging — much more than is observed (-1.3°C/decade, see Figure 5).

The surface freshwater flux trend is -1.0 m/decade, almost doubling the annual average loss after only one decade. This is solely due to the decreasing trend of rainfall; the trend in evaporation partially offsets it (Table 1). For the ~50 m average depth of the mixed layer, this results in 0.7 g Kg^{-1}/decade salinity trend. The trend estimated from the subsurface instruments (Figure 5) is 0.25 g Kg^{-1}/decade.

The loss of buoyancy from the mixed layer, and the increase below (warming and freshening), reduces the stratification and thus leads to deepening of the mixed layer. The mixed layer at ALOHA is deepening, by about 4 m/decade (not shown here.) Because the ALOHA mixed layer is underlain by the salinity maximum, this deepening enhances the turbulent salt flux upward through the base of the mixed layer. Low frequency circulation and/or eddy freshwater fluxes are required to reconcile the observed trends.

Table 1. Statistics of air-sea fluxes from MLR analysis of WHOTS observations

MLR	Full MLR			MLR - Decadal		
	Mean	Trend (per decade)	CI (95%)	Mean	Trend (per decade)	CI (95%)
Net Heat Flux (W/m²)	25.8	-3.9	± 8.2	26.1	22.9	± 3.9
Latent Heat Flux (W/m²)	-134.9	18.0	± 29.7	-133.8	11.1	± 14.2
Evaporation Rate (m/yr)	-1.81	0.24	± 0.40	-1.79	0.15	± 0.19
Rainfall Rate (m/yr)	0.63	-1.25	± 0.67	0.61	-0.53	± 0.32
Fresh Water Flux (m/yr)	-1.18	-1.00	± 0.69	-1.18	-0.39	± 0.33

A question which is asked sometimes is, "How many years more of data do you need?" That depends on the particular goal. N^+ is the number of additional years of record that is required to achieve 95% confidence in the value of the trend, assuming that the actual trend is stable and has the same value as estimated here. (See Figure 1 regarding this assumption!) Because the temperature and density trend values between 60 and 100 m are small relative to the residual variance, more than 15 years of additional measurements would be required to achieve statistical significance. With 3 more years of record, the θ trend at 105 m would become significant at 95%, and the S trend at 55 m would also.

It is important to note that improved estimates of the magnitudes and vertical structures of decadal and interannual thermohaline variability in the upper ocean at ALOHA would require much longer extension of the measurements.

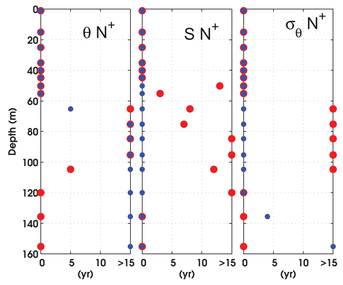


Figure 6. Number of additional years of record required to achieve 95% confidence in the value of the trend for θ (left), salinity (center), and $\sigma\theta$ (right), from the WHOTS mooring data multiple linear regression models (MLR-F:red and MLR-D:blue) from Figure 5.

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http://www.soest.hawaii.edu/whots/
http://uop.whoi.edu/projects/WHOTS/

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation

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