



# Extent of the oxygen minimum zone in the eastern tropical North Pacific

Erika A. Fee<sup>1</sup>

<sup>1</sup>*University of Washington, School of Oceanography,  
Box 355351, Seattle, Washington 98195*

*\*erikafee@uw.edu*

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## NONTECHNICAL SUMMARY

Off the west coast Mexico, in the Eastern Tropical North Pacific, there is a vast layer of water with extremely low oxygen content. This low-oxygen layer, commonly referred to as an oxygen minimum zone (OMZ), has been surveyed numerous times since the 1960s. According to a theory proposed in 1999, a rise in global temperatures will cause the volume of the OMZ to increase, becoming both shallower and deeper in the water column. To determine whether or not there has been a change in the vertical extent of the OMZ in the ETNP, I made oxygen concentration profiles along a transect from San Diego, CA to Manzanillo, MX, and made a cross-sectional profile of oxygen concentrations along 110°W to compare with past studies. The primary data presented in this paper was gathered during *R/V Thomas G. Thompson* cruise TN278 which took place 16 March to 23 April 2012. I found that the OMZ is encroaching on coastal areas and has increased in size and intensity over the past forty years. It is important to understand the extent and changes with time of the OMZ, as OMZs have a strong impact on the carbon and nitrogen cycles through carbon sequestration and denitrification. The feedback effects that change these cycles make OMZs important areas to study so that we may better predict future climatic and oceanic conditions.

## ABSTRACT

Off the west coast Mexico, in the Eastern Tropical North Pacific, there is a vast Oxygen Minimum Zone (OMZ). An analysis of O<sub>2</sub> concentration measurements in the ETNP made in 1972 identified a 600m thick layer of water with almost no detectable oxygen (Cline and Richards 1972). According to a theory proposed in 1999, a rise in global temperatures will cause the volume of the OMZ to increase, becoming both shallower and deeper in the water column (Cannariato and Kennett 1999). The primary data used for this paper was gathered during *R/V Thomas G. Thompson* cruise TN278 which took place 16 March to 23 April 2012. To determine whether or not there has been a change in the vertical extent of the OMZ, I collected water samples with Niskin bottles at ten stations along a transect from San Diego, CA to Manzanillo, MX and gathered oxygen concentration data using a CTD sensor while on board the *R/V Thomas G. Thompson*. Titrations were performed on the water samples using the Winkler method (Winkler 1888) as modified by Carpenter (1965). The results of the titration were used to calibrate the sensor readings, and corrected sensor profiles were compared to observations made during past cruises. It is important to understand the extent and changes with time of the OMZ, as OMZs have a strong impact on the carbon and nitrogen cycles (Devol and Hartnett 2001, Paulmier and Ruiz-Pino 2009) through carbon sequestration and denitrification. The feedback effects that changes to these cycles may have makes OMZs important areas to study so that we may better predict future climatic and oceanic conditions.

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The oxygen minimum zone of the Eastern Tropical North Pacific is one of the better studied OMZ in the ocean. This zone has been surveyed numerous times since the 1960s, with oxygen concentration measurements taken as far down as 1500m (Richards 1965). When this OMZ was observed during PONCHO cruise TT-026 in March 1968 and PISCO cruises TT-035 and -037 in February and April 1969 aboard the RV *Thomas G. Thompson*, the OMZ was defined as a layer extending from 200 m to 800 m where O<sub>2</sub> concentrations fell below 1 µg L<sup>-1</sup> (Cline and Richards 1972). A later study of oxygen minimum zones in the Atlantic and Pacific oceans showed that the ETNP is part of a layer of oxygen-depleted water spanning the coast of Central and South America from approximately 20°N to 15°S (Karstensen et al 2008). This same study defined the OMZ as a layer extending from 100m to 900m where O<sub>2</sub> concentrations were less than 0.1 ml L<sup>-1</sup>.

Since becoming areas of particular interest, there have been many different units and values used to define OMZs. In a recent paper by Jody Wright, the OMZ was described as a region of suboxic and anoxic waters where oxygen concentrations fell below the threshold at which alternative electron acceptors begin to replace the use of oxygen, < 20 µmol kg<sup>-1</sup> (Wright et al 2012). Therefore, for this paper, the OMZ will be defined as the region of the water column where oxygen concentrations are ≤ 20 µmol kg<sup>-1</sup>. Hydrographic surveys of this region suggest that the low oxygen concentration results from a combination of high primary production at the surface, strong thermal stratification that inhibits, and poor ventilation (Fiedler and Talley 2006). These same hydrographic surveys also found that the OMZ is the thickest off the coast of Baja California in the eastern tropical North Pacific.

It has been theorized that OMZs fluctuate in size in response to global climate change. Global temperature changes cause the strength and location of Pacific Intermediate Water ventilation and surface productivity to fluctuate, resulting in an increase in the thickness of low oxygen layers during warmer periods and a decrease in thickness when the climate is colder (Cannariato and

Kennett 1999). Heating of surface waters reduces the solubility of oxygen and increases the strength of the thermocline, further contributing to OMZ expansion (Helm et al 2011).

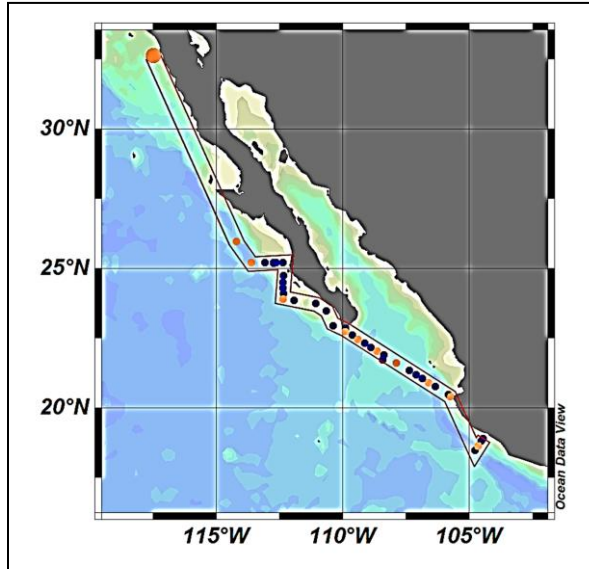
The OMZ may also have a feedback effect on global climate change through its effects on the carbon and nitrogen cycles. Reduced decomposition of sinking organic matter in OMZs causes an increased amount of atmospheric CO<sub>2</sub>, a greenhouse gas, fixed by primary productivity to be sequestered in the sediment underlying OMZs (Devol and Hartnett 2001). Expansion in OMZs also causes an increase in heterotrophic denitrification and anammox reactions, which are responsible for fixed nitrogen loss and have a negative feedback effect on oceanic primary productivity (Paulmier and Ruiz-Pino 2009), reducing the amount of atmospheric CO<sub>2</sub> sequestered by the ocean. OMZs are responsible for a significant fraction of global emissions of trace greenhouse gases N<sub>2</sub>O and CH<sub>4</sub>, which have more powerful positive radiative forcing effects than CO<sub>2</sub> (Wright et al 2012). Because of the impact OMZs have the cycling of carbon and nitrogen, it is important to have a better picture of the current extent of the OMZ and determine whether it has increased in size, and if it has, by how much.

## METHODS

The research cruise, TN278, took place 16 March to 23 April 2012 on board the *R/V Thomas G. Thompson*. Oxygen samples were taken at ten stations along the first leg of the cruise transect where depths exceeded 1000m (Fig. 1). Only the sensor data was used for the second leg of the cruise. Oxygen concentration measurements were made at each station using a SBE 43 electrode attached to the CTD, and water samples were taken using Niskin bottles fired off at eight to ten depths on the return trip. My colleague Miles Carl and I used about one liter of water from each Niskin bottle for duplicate and triplicate O<sub>2</sub> samples. We used Winkler titration (Winkler 1888) as modified by the Carpenter method (Carpenter 1965) with the shipboard Metrohm 765

Dosimat manual titrator in order to find the oxygen concentration of the samples.

Figure 1: TN278 cruise path from San Diego to Manzanillo. The orange stations are where bottle samples were taken in addition to O<sub>2</sub> sensor data.



The Carpenter-Winkler method was used because, if done correctly, this method has been shown to produce results accurate to within ±1% (Emerson et al 1999). The oxygen titration results were in mg-at L<sup>-1</sup>, while readings from the SBE 43 electrode were in μmol kg<sup>-1</sup>, so the titration results had to be converted in order to compare the two. The equation used to convert to μmol kg<sup>-1</sup> was:

$$\frac{\text{mg-at}}{L} * \frac{5 * 10^5}{\rho}$$

The equation used to get the density (ρ) was:

$$\rho = (999.83 + 5.053z - 0.048z^2) + (0.808 - 0.0085z)S - (0.0708(1 + 0.351z + 0.068(1 - 0.0683z)T))T - (0.003(1 - 0.059z - 0.012(1 - 0.064z)T))(35 - S)T$$

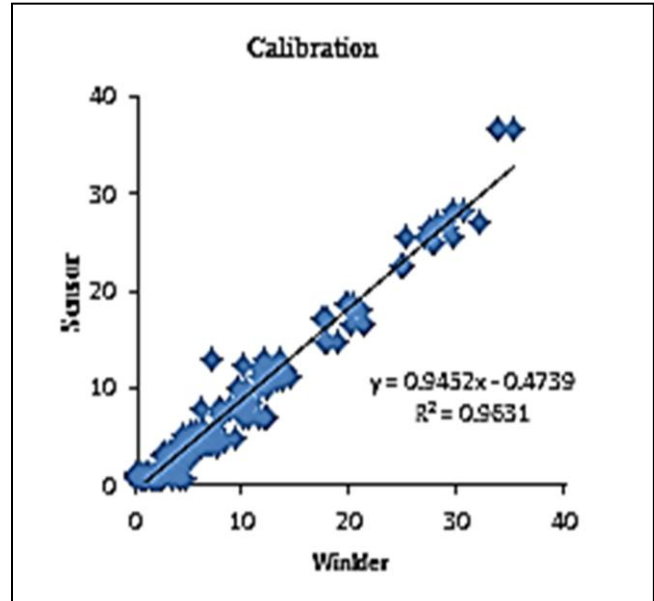
Where z is depth (km), T is temperature (K), and S is salinity (PSU).

## RESULTS

The titration results were plotted against sensor readings for every depth water samples were taken using Excel in order to produce a calibration factor for the sensor (Fig. 2). The data from Stations 2 and 26 ended up being unusable. The bottle data for the sample bottles used at

Station 2 was unavailable, while the samples for Station 26 were contaminated.

Figure 2: Sensor values plotted against titration values.



According to Figure 2, the sensor data needed to be corrected by a factor of 0.9452 in order to reflect the actual oxygen concentration values. Once corrected, the O<sub>2</sub> concentrations were plotted against depth and density (Fig. 3; Fig. 4).

Figure 3: Oxygen sensor profiles with depth for sample stations.

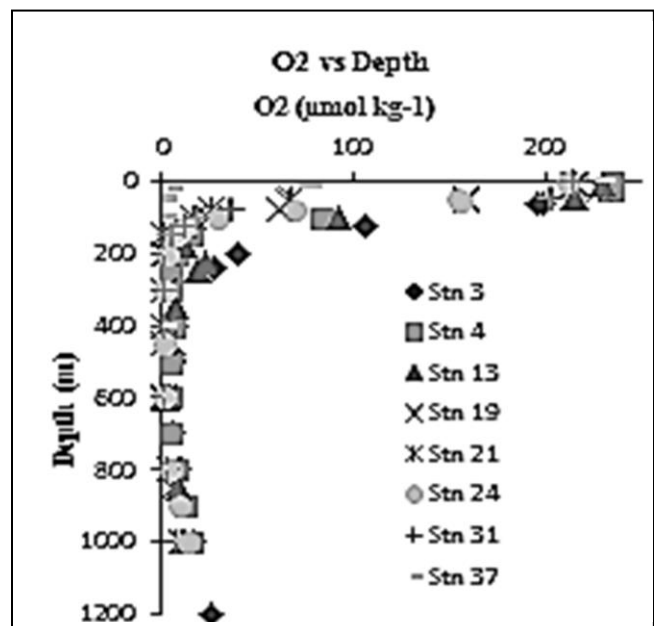
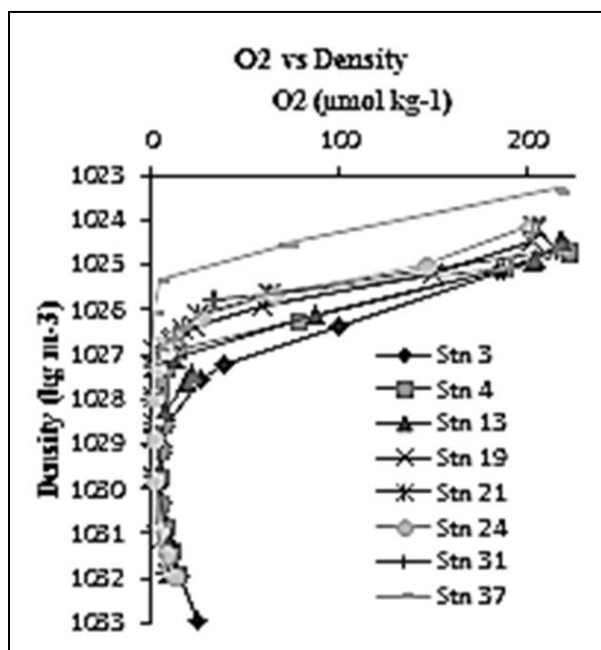


Figure 4: Oxygen sensor profiles with density for sample stations.



Oxygen data from every CTD cast of 1000m or more was evaluated using Ocean Data View (Fig. 5). Each point of data was extrapolated out to produce a continuous cross-sectional profile following the cruise track. To examine the changes in the OMZ with time, a cross-sectional profile of the second leg of the cruise following 110°W was compared with cross-sections of data for the same track (Fig. 6) made by previous publications (Codispoti and Richards 1976, WOCE 2002).

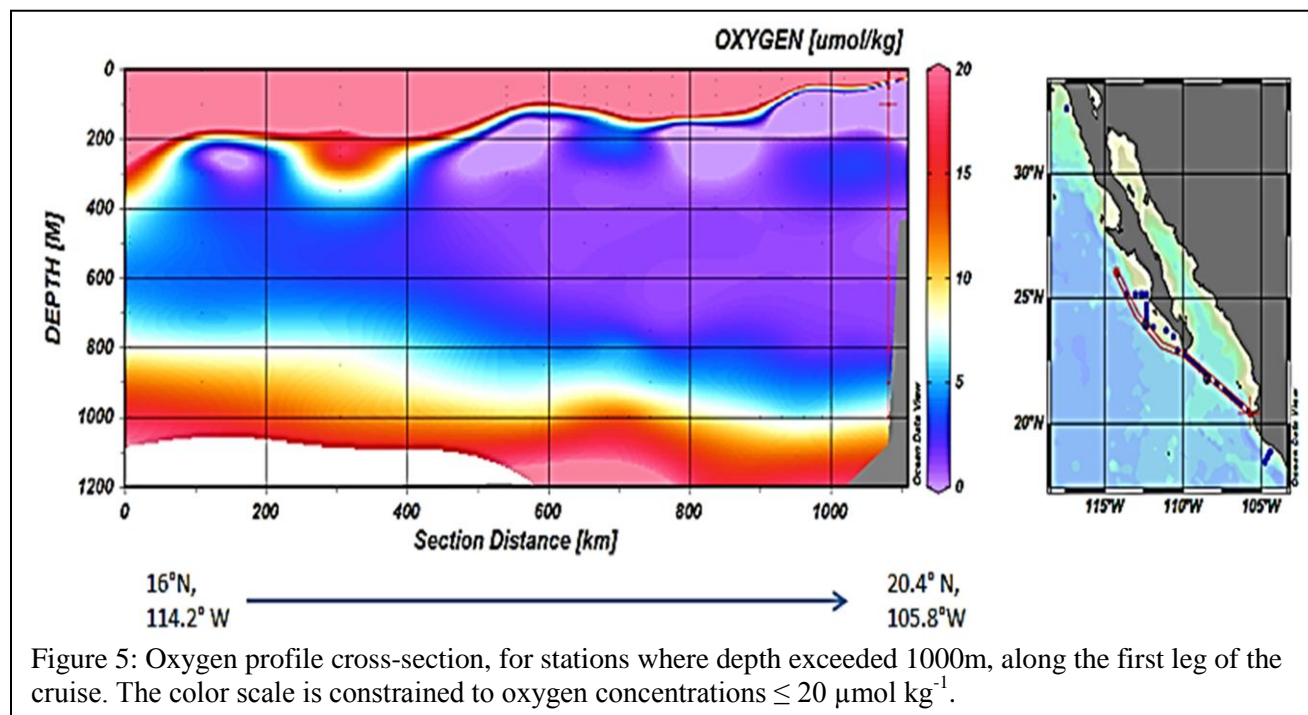
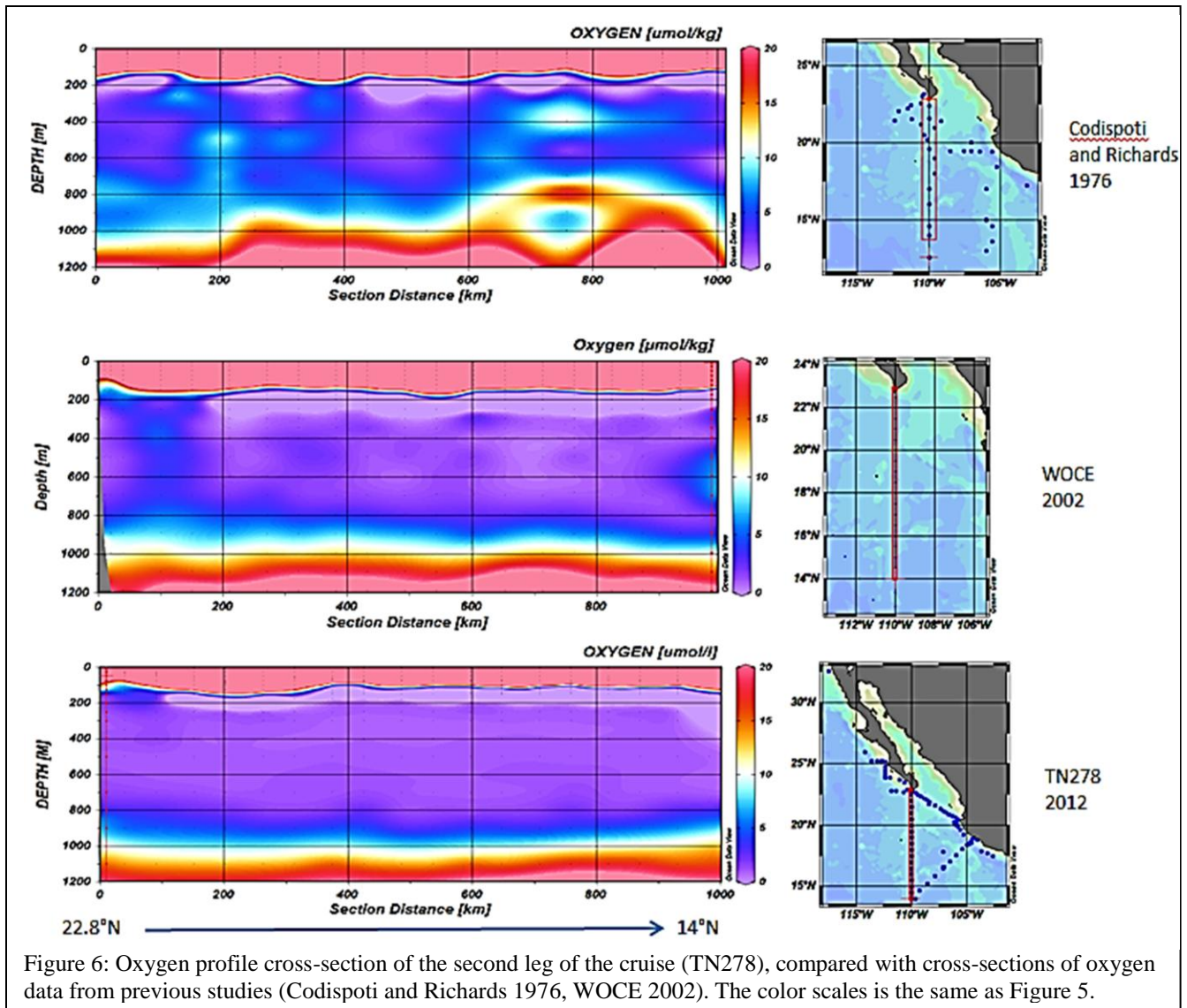


Figure 5: Oxygen profile cross-section, for stations where depth exceeded 1000m, along the first leg of the cruise. The color scale is constrained to oxygen concentrations  $\leq 20 \mu\text{mol kg}^{-1}$ .



## DISCUSSION

The sensor readings were more precise than the titrations, but were unable to provide accurate oxygen readings below a concentration of  $1 \mu\text{mol kg}^{-1}$  (Fig. 2). It was also found that the sensor tended to underestimate  $\text{O}_2$  values in the mixed layer, returning values that were about 90% saturation. Despite these two discrepancies, the general trend of  $\text{O}_2$  concentrations along the first leg of the cruise transect was a progressively shallower and deeper OMZ the further south and east one travels along the transect (Fig. 3).

Comparisons of oxygen with density show a similar trend of decreasing oxygen.

Looking at the cross-sectional, the northern most boundary of the OMZ is somewhere above  $16^\circ\text{N}$ , and it gets shallower at an average rate of  $\sim 0.2 \text{ m km}^{-1}$  and deeper at an average rate of  $\sim 0.16 \text{ m km}^{-1}$  (Fig. 5). Of particular concern is that the OMZ is encroaching upon the continental slope and coastal waters at the south-east end of the transect. This area is experiencing an extremely shallow ( $\sim 40\text{m}$ ) OMZ where oxygen concentrations are  $< 5 \mu\text{mol kg}^{-1}$  throughout much

of the water column with an especially thick anoxic layer close to the surface. As 50% of coastal marine animals cannot survive in waters where the oxygen concentrations are  $< 70 \mu\text{mol kg}^{-1}$ , this “shoaling” of the OMZ, coupled with increasing ocean acidification, can have an extremely negative impact on marine animal populations and local fishing (Seibel 2010). Determining the horizontal extent of the OMZ would provide a better understanding of how coastal areas are being affected.

Station 13 is an exception to the overall trend of a progressively shallower OMZ. The

oxygen profile for Station 13 shows an inversion between  $\sim 175 \text{ m}$  ( $1027 \text{ kg m}^{-3}$ ) and  $\sim 350 \text{ m}$  ( $1029 \text{ kg m}^{-3}$ ), and the  $\text{O}_2$  concentration values are greater than those of the previous station over the same range (Fig. 3, Fig. 4). Given Station 13’s close proximity to the continental shelf break, it is possible that this inversion represents upwelling of oxygenated water at this location. Comparing the oxygen profile with a salinity profile appears to support the possibility of upwelling (Fig. 7). ADCP data did not go deep enough to provide current directions over the depth range of the inversion that would confirm upwelling.

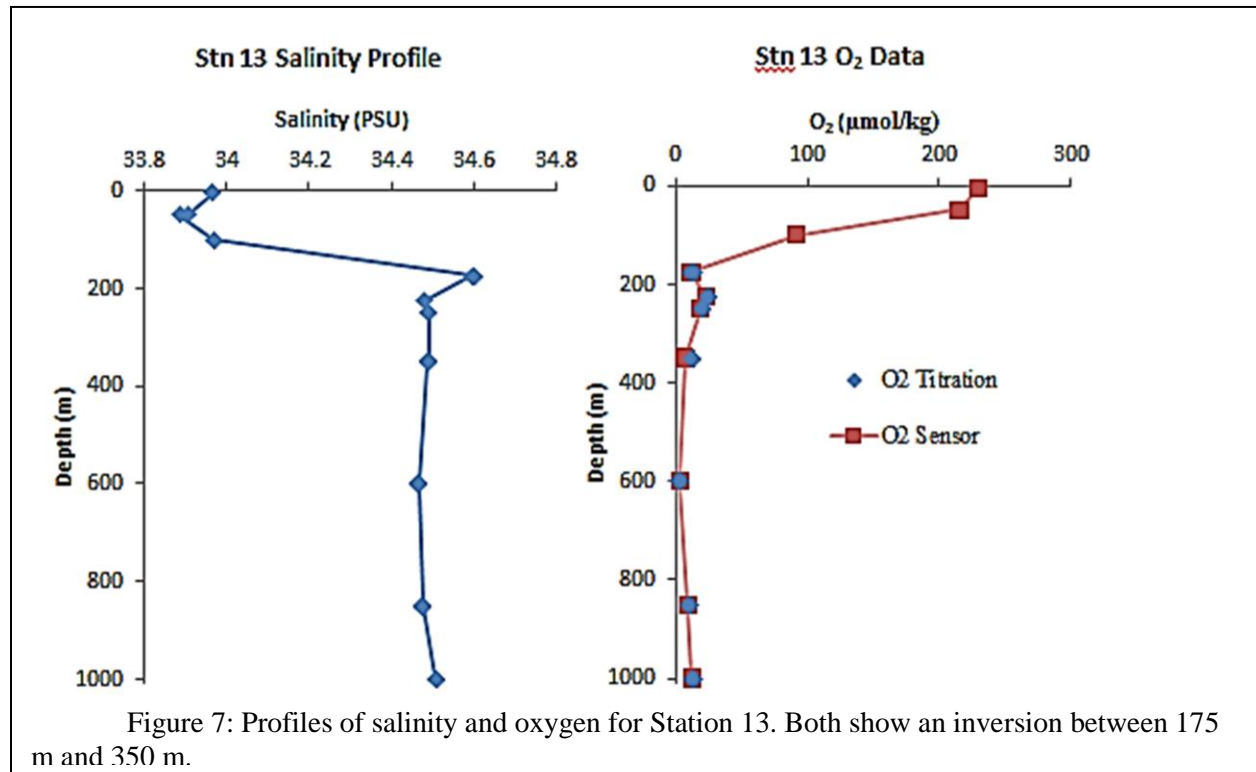


Figure 7: Profiles of salinity and oxygen for Station 13. Both show an inversion between 175 m and 350 m.

Comparing the cross-section of the second leg of the cruise following  $110^\circ\text{W}$  to observations of the OMZ along the same transect made by Codispoti and Richards (1972) and WOCE Global Data (WOCE 2002), there have been some significant changes in the OMZ with time. Over the past forty years, the OMZ has gotten shallower, deeper, and more oxygen deficient. In 2009, an estimated 8% of the ocean’s volume contained less than  $20 \mu\text{mol O}_2 \text{ kg}^{-1}$  (Seibel 2010).

The changes in the OMZ in the ETNP suggest that this percentage has likely increased and will continue to increase. The oxygenated surface layer has been compressed, decreasing habitat available to marine life, especially high-performance species like tuna, and increasing the distance organisms have to travel during diel vertical migration in order to reach oxygenated waters (Stramma et al 2012, Wright et al 2012).

## CONCLUSIONS

These findings of an increase in size and intensity of the OMZ in the ETNP are consistent with past studies of OMZs. Assuming the increasing size of the OMZ in the ETNP is representative of expansion of OMZs worldwide, the ocean is becoming increasingly oxygen deficient as global temperatures increase. The positive and negative feedback effects carbon and nitrogen cycling in the OMZs have on global climate are complex and proportional to the size of the OMZ (Devol and Hartnett 2001, Paulmier and Ruiz-Pino 2009, Wright et al 2012). In order to understand the overall feedback effect OMZs have on global climate, a better understanding of these processes as well as the current and potential future extent of global OMZs is crucial.

Increasing oxygen stress and vulnerability to overfishing resulting from the increase in the size of OMZs will have negative consequences for the populations of marine organisms. This is especially true for species such as tuna which have a high oxygen demand and are the targets of commercial fishing (Stramma et al 2012). Compression of the oxygenated surface layer and shoaling of the OMZ greatly reduce the amount of habitat available to marine life and will negatively impact population sizes and biodiversity. Identification and careful management of particularly severe OMZs is necessary to maintain sustainable populations of marine animals and avoid future food shortages.

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