To: Dennis McGillicuddy
From: Larry Anderson
Date: September 23, 2005

EDDIES Report #4:
Watermass Analysis of OC415 Eddies A4 and A5

1. Origin of Eddy A5

Anticyclone A5 contained highly-oxygenated (approximately) 16.5-degree Mode Water between 500-800 m at σ_θ=26.7, very similar to Eddy A1 during OC404 (Figs. 1 and 2).

- Check the monthly World Ocean Atlas 2001 for potential source regions for the A5 16.5-degree water. Note it is slightly saltier than the A1 water (Fig. 1b), and appears less diluted (Figs. 1d, 2a).
- T, S and O_2 suggested A1 probably came from Maidera, though tracking of the SSH anomaly indicated 40°N 40°W. What do the He and silicate data suggest?

2. Phosphocline versus Nitracline Depth

It is often observed in the Sargasso that the phosphocline is deeper than the nitracline. How widespread is this phenomenon? Fig. 3 maps the locations were, in World Ocean Atlas 2001, the nitracline (defined as the depth at which NO_3=1.0 μM, calculated by linearly interpolating the vertical NO_3 profiles) is more shallow than the phosphocline (defined as the depth at which PO_4 is 1/16th the molar concentration used to define the nitracline, in accord with Redfield stoichiometry.) In the annual mean climatology, the only location where the phosphocline is deeper than the nitracline is in the subtropical North Atlantic and the Caribbean (Fig. 3a). (Points are also found in the Mediterranean and Black Seas, but there NO_3=1.0 μM is not a good definition for the nitracline, because of very low nutrients throughout the water column.) However as surface nutrients typically vary seasonally (even at BATS and the equatorial Atlantic), the annual mean climatology may be misleading, so the seasonal climatologies were also examined (Fig. 3b-e). These confirm that the phosphocline is deeper than the nitracline in the Sargasso and Caribbean in every season; a few points are also found in other locations in some seasons, which may be real (seasonal [interesting!]), or may be an artifact of mapping (suggested by the small size of the zones) or data coverage (i.e. appearing or disappearing in some seasons due to lack of data). Note few points are found in the subtropical South Atlantic because there surface PO_4 generally exceeds 0.1 μM (i.e. is replete).

Fig. 4 examines the sensitivity of our estimate in Fig. 3 by decreasing the nitracline definition to 0.5 μM (and consequently the phosphocline definition by 2 also). The locations found are essentially a subset of those in Fig. 3, because there are relatively few locations with PO_4 lower than 0.04 μM (according to WOA01). Figs. 4b-e confirm that a deep phosphocline is regularly found in the Sargasso and Caribbean, and irregularly at a few locations elsewhere. Nitracline definitions of 0.2 μM or 2.0 μM are probably not appropriate.

Fig. 5 relaxes the assumption of Redfield stoichiometry, and uses a phosphocline definition which is 1/8th the nitracline molar concentration. Here the annual and seasonal climatologies regularly pick up almost the entire subtropical North Atlantic, as well as a smaller region of the western subtropical North Pacific off China. It is unclear however if relaxing the Redfield constraint is appropriate when using these concentration-based definitions of the nutriclines.

In conclusion, the phosphocline is deeper than the nitracline generally only in the western subtropical North Atlantic and Caribbean (though possibly also off of China).

- Why? Is it related to the distribution of N_2 fixers? Is it related to (Saharan) dust input, which may supply N_2 fixers with Fe or the dust particles scavange PO_4? Or is it the result of physical advection, i.e. the "conveyor belt" subducting low-nutrient (but N-fixed) water from the equatorial Atlantic? Is it related to Gruber and Sarmiento's N*? Does N_2 fixation in the subtropical North Atlantic mean Redfield stoichiometry does not apply there i.e. that a ratio of e.g. 1/18th should be used for the computation in this region? (Can then Redfield ratios be determined by computing PO_4 at the 1.0 μM nitracline? No; the nutrient distributions are due to a combination of physical and biological processes, and this would be an insufficient way to deconvolute them. It would be better to put the nutrient distributions in a physical model, and compute the biological sinks/sources required to maintain the distributions. This would address whether the phosphocline/nitracline discrepancy can be explained by physics, and what distibution of biological uptake would be required to explain it.)

- Alternatively the nutriclines could be estimated as e.g. the depth where dPO_4/dz is maximum (or reaches a certain value). For example in some locations, even though surface PO_4 is replete (> 0.2 μM), there is still a sharp dPO_4/dz at depth. In this instance, is it proper to consider the "phosphocline" as 0 m or the depth of high dPO_4/dz? In this instance the high dPO_4/dz may be related to isopycnal advection rather than the biological PO_4 uptake threshold, in which case one would expect high dNO_3/dz at the same depth (isopycnal); is this what is observed? Where surface nutrients are replete (e.g. Equatorial Pacific) dPO_4/dz may have little biological meaning. Make maps based on this alternative definition?

- WOA01 sometimes overestimates surface nutrients (e.g. if spuriously- or anomalously-high values were included in the averaging.) Check the raw data (e.g. WODB01, GEOSECS, TTO/SAVE, WOCE or Reid) to see if it is true that PO_4 is replete over most of the surface ocean. (I believe it is.)

3. Origin of Eddy A4 Low-Oxygen Water

Eddy A4 contained very low-oxygen water between 779 and 943 decibars (Fig. 6c, red box). Where could this water have come from? Based on the properties between these depths (red boxes in Fig. 6a,b,c), the World Ocean Atlas 2001 annual climatology was searched (using linear interpolation of vertical profiles, and no horizontal interpolation). Water with these properties was found in the Caribbean, Gulf of Mexico and the southern edge of the subtropical gyre at depths of 184-632 m (Fig. 6c).

The low oxygen water appears to be associated with a T-S anomaly (Fig. 6d, cyan box), although the T-S anomaly is slightly deeper and has slightly higher oxygen (Figs. 6a,b,c, cyan boxes) viz. it is at the base of the low-oxygen layer. Searching for this T-S anomaly with $O_2 < 2.8$ ml/l similarly yields points in the Gulf of Mexico and southern edge of the subtropical gyre (Fig. 7a). Interestingly, removing the oxygen constraint (which may be due to local remineralization) also yields points on the northern edge of the gyre (Fig. 7b).

While the extremes of the S ($S<35.22$) and oxygen ($O_2 <2.77$) anomalies are mutually exclusive (Fig. 8a), there is a common region (cyan and red boxes in Fig. 6a-d), which also is the location of maximum AOU (Fig. 8d,e). This suggests the most likely properties of the source water is the intersection of the red and cyan boxes in Fig. 6a-d. When these properties are searched for, again points are found along the southern edge of the subtropical gyre (including a point in the Florida Straits); when the oxygen constraint is removed points are also found along the northern edge (Fig. 9). (If horizontal interpolation were used, probably the line of points would be continuous around the southern, western and northern edge of the gyre, like Bill Jenkins' map of $35 < S < 35.2$ on the σ=27.15 isopycnal.)

The AOU maximum indicates that oxygen is vertically uniform between 779-943 m even though T and S are not because the slightly warmer water left the sea surface with slightly less oxygen. The correspondence of maximum AOU with the T-S anomaly suggests a physical source of the low oxygen over local remineralization. The high AOU anomaly associated with the T-S anomaly results in the O_2 minimum occurring slightly more shallow than the T-S anomaly. However the T-S anomaly is centered on σ_θ=27.16 while the AOU max is centered on σ_θ=27.14; this inexact agreement suggests some local remineralization occurring.

- OC415-3 Station 56 has the most extreme T-S anomaly; stations 43, 61 and 62 are very similar to 56, and stations 44, 60 and 67 less so. Stations 56 and 61 have the most extreme O_2 and AOU anomalies. Thus Sta. 56 is used for analysis.

- The O_2 concentration is the result of both physical conditions (saturation value) and biological uptake, while AOU (with surface values near zero) is a clearer indicator of only biological uptake. However, because of nonlinearity in the oxygen saturation as a function of T and S, O_2 is conserved during mixing while AOU is not. But this is only an issue when mixing water of very different T; as mixing water is typically close in T, AOU should mix nearly linearly (conservatively).

- Fig. 8b-e indicate: The O_2 minimum ($O_2 <2.8$) is on σ_θ=27.025-27.154. The S minimum ($S<35.22$) is on σ_θ=27.137-27.22, though the T-S plot (Fig. 6d) indicates the T-S anomaly is centered at σ_θ=27.16, with a range of 27.14-27.18 or 27.13-27.19. The AOU maximum (>3.5) is on σ_θ=27.095-27.173 at a depth of 880-969 m.

- AOU>3.54 ml/l corresponds with σ_θ=27.12-27.16, in close agreement with the overlap of $S<35.22$ with $O_2 <2.8$ (σ_θ=27.137-27.154). Use a broader definition of the intersection region as e.g. AOU>3.5 ml/l? Or widen the intersection region by using $S<35.23$ or $O_2 <2.9$? $S<35.23$ increases the σ_θ range to 27.13-27.23, not alot. What does $O_2 <2.9$ increase the range to? Would need to redo Figs. 6-9+. It should result in more hits in the climatological atlas.

The climatological data (Figs. 6-9) indicates two possibilities:

1. The low-oxygen water came from the southern edge of the subtropical gyre (or Caribbean or Gulf of Mexico). This would mean the *in situ* remineralization is negligible. The question is how it could have got under the 18-degree Mode Water which came from the north. One possibility is that it was entrained i.e. the 18-degree Mode Water anticyclone cannibalized or ran on top of another anticyclone which came from the south carrying the low oxygen water. But it is unclear how it could do this without mixing with southern water above 779 m. Another possibility is that the low-oxygen water was carried through the Florida Straits by the Gulf Stream to beyond Cape Hatteras, where it subducted below 18° Mode Water (see below).

2. The water came from the northern edge of the subtropical gyre. This would easily explain why it lies below 18-degree Mode Water. The question then is why the oxygen is so low, and not high like the 18-degree Mode Water. It must be because of remineralization; yet a high amount of oxygen consumption between 779-943 m with very little oxygen consumption between 100-779 m seems very unlikely, given that particle concentrations and fluxes, bacterial and zooplankton abundances, and temperatures (which govern metabolic rates) all decrease with depth. Possibly most of the oxygen consumption occurred at shallow depths, prior to the water being overlain by/subducted below the 18-degree Mode Water. In this case, one would expect to see low oxygen water on this isopycnal to the north at least seasonally.

To see whether low oxygen occurs seasonally on the northern edge, the monthly WOA01 climatology was searched. Using the low-oxygen criteria, a couple matches were found near the Gulf Stream in June (Fig. 10a) viz. at 76.5°W 32.5°N and 75.5°W 33.5°N. However, using the T-S anomaly criteria (with $O_2 < 2.8$ ml/l) resulted in no matches on the northern edge (Fig. 10b). To explore the original data which gave rise to the June matches, as well as search for any other data that may have been "lost" in the climatological objective analysis, the World Ocean DataBase 2001 high-resolution CTDs was searched from 77-40°W 32-40°N for profiles that contained $9.74 \leq \theta \leq 11.45$, $35.2 \leq S \leq 35.43$, oxygen ≤ 2.8 ml/l. Eighteen matching profiles were found (Figs. 11-14). The first profile in Figs. 11-12 is from late-winter (4/9/1989) and is found near the Gulf Stream 8 degrees north of EDDIES Station 56 (dark blue dot in Fig. 13a); the qualifying water is at 306-315 m depth, with 18° water between 50-62 m and 20° water at the sea surface. The next two profiles are very similar to EDDIES Station 56 (Fig. 11,12) are are also found straight north (magenta and cyan dots in Fig. 13a). Their similarity with Eddy A4 suggest the low oxygen water in A4 came from the north, but does not clarify the origin of the low oxygen. The final 15 profiles in Figs. 11 and 12 are all similar and from the same cruise (6-7/1990) in the Gulf Stream off of Cape Hatteras (black dots in Fig. 13a), with the qualifying water between 181-266 m. Their inclusion here is actually spurious, as they are on σ_θ=26.9 instead of σ_θ=27.0-27.2 (Fig. 13b), but they do give abundant evidence of very low oxygen values in this nearby region in a layer hundreds of meters thick (Fig. 12a), which includes the σ_θ=27.0-27.2 layer (Fig. 14) though for a different T and S range. It is unclear if this low oxygen water (a) was advected in by the Gulf Stream from the south, (b) is due to high rates of *in situ* remineralization extending from the base of the euphotic zone to 800 m depth, or (c) has a partial source in low oxygen water coming from the sediment-water interface of the continental shelf. This last possibility is intriguing, because the oxygen minima in the Indian Ocean (viz. Arabian Sea) and (northeastern) Pacific also show isopycnal linkage to the continental shelves, suggesting that the oxygen minima in the open ocean may be more closely related to the margins than previously recognized. As far as I know this is the first time such a linkage is indicated in the Atlantic.

Let us attempt to discern whether the low oxygen in the Gulf Stream water off Hatteras (Fig. 13a) came up from the south, from the continental shelf, or was due to local remineralization. The lowest O_2 is in the σ_θ=27.0-27.2 range (black dots in Fig. 14), which corresponds with $S < 35$ (Fig. 13b), suggesting a continental shelf source over a (presumably saltier) southern source. Local remineralization appears an even better contender, because the low oxygen extends to σ_θ=27.4 (Fig. 14) i.e. 700 m (Fig. 12), much deeper than the continental shelf. So most likely the low oxygen in the Hatteras water is due to local remineralization. This suggests the low oxygen between 800-900 m in Eddy A4 may have been preconditioned with low O_2 due to shallow (100-300 m) winter/spring remineralization at the gyre edge. Subsequently this water (σ_θ=27.0-27.2) would have subducted below 18-degree Mode Water.

- Confirm whether $S<35$ excludes a southern source, and determine the depth of the 27.4 surface in winter (viz. if it reaches the shelf, if that is the appropriate isopycnal).
- See if there were any articles published on the 6-7/1990 cruise, explaining the source of the low oxygen.

The WODB01 search was then extended to 77-40°W 40-50°N, where 7 matching profiles were found (Figs. 15-18). One of the profiles had very low oxygen (dark blue in Figs. 17 and 18); technically this profile was spurious, as it did not lie on the same density surface (Fig. 17b), though like the Hatteras data it did show low oxygen on σ_θ=27.0-27.2 for a different T-S range (Fig. 18). The 3/1991 profile was also technically spurious (Fig. 17b). All the other profiles have oxygen minima of about 2.8 ml/l near 300 m depth (Fig. 16a). They are clustered near 64°W 41°N, north of the Gulf Stream (Fig. 17a), which makes then less likely candidates than the data in Fig. 13a for source water. Interestingly no data matches were found in the region 62-40°W 32-50°N, at least for oxygen < 2.8 ml/l.

The close proximity of the Fig. 13a profiles to Eddy A4 suggest the low oxygen water in Eddy A4 probably came from near the Gulf Stream rather than e.g. the southeastern edge of the subtropical gyre; this would explain how it became topped with 18-degree Mode Water, which forms between Bermuda and the Gulf Stream (Michaels and Knap, 1996, DSR II, p 157). It does not however clarify whether the low oxygen water in the Gulf Stream was advected up from the south, from the continental shelf, or is due to high remineralization rates there. It also does not exclude the possibility that some of the oxygen deficit in Eddy A4 is due to *in situ* remineralization, i.e. that the source water started with $O_2 > 2.8$ ml/l. The inexact colocation of the AOU and T-S anomalies suggest *some* local remineralization, as would be expected. In order to compute the oxygen deficit that is due to *in situ* remineralization, the question is, what was the original oxygen content of the water in the oxygen minimum layer?

Fig. 19a shows that the watermass's original O_2 concentration depends strongly on its original location. If it originated near the Gulf Stream between 32-38°N 80-60°W (as suggested by

Fig. 13a), its original O_2 was probably 3.5-4.2 ml/l. (The lack of points between 32-38°N suggest this is an unlikely source region, if it were not for its close proximity to Eddy A4.) If it originated farther north, its original O_2 could have been considerably higher, with the exception of the broad range of 3-5 ml/l found at 40°N. Interestingly some points were found due east of Eddy A4 at 29-33°N 60-39°W (Fig. 19b), which have O_2 of 3.6-4.3 ml/l; as these points are at 768-812 m depth, they must have formed elsewhere, presumably to the north. (Due East or Northeast are likely directions for Eddy A4 to have come from.) The water east of Florida (25-32°N 80-70°W) has oxygen 3.0-4.2 ml/l, still in excess of that found in Eddy A4. (The data points in Fig. 19a between 25-29°N with O_2 <3.0 ml/l are actually in the Gulf of Mexico, which could only reach the Sargasso by passing through the Florida Strait at 24.5°N.) However if the water came from south of 25°N or the Gulf of Mexico, it may have originated with an O_2 of 2.8 ml/l, and consequently local reminerlization in Eddy A4 may be negligible. (Much water south of 20°N could be ruled out for having O_2 less than that of Eddy A4.) So the next step is to try to reduce this set of possible source regions by considering other tracers (see below), once the other tracer data is completed.

- Do low oxygen gouges in the oxygen profile occur in the Sargasso generally, i.e. at other T-S ranges and densities? Search WODB01 for this.
- Also search WODB01 from 40-0°W 30-70°N.
- Search for just the T-S anomaly in the WODB profiles?
- The WODB01 has alot of errors. It also may not contain all datasets. Check other datasets as well (Reid, WOCE, TTO-NAS, etc.).
- The WODB01 bottle data was also searched, and matches were found, but generally only 1 bottle per profile, due to the low vertical resolution. The low vertical resolution made quality control and trend analysis somewhat ambiguous. Though perhaps revisit the bottle data.
- Can we track SSH back to see where Eddy A4 came from? This may help narrow the source water region.
- Silicate and H/He data will help, when available; also maybe sediment trap data. In particular, if silicate is lower than the Southern water, it cannot be the source; but if it is equal or higher, the conclusion is inconclusive. How about "NO" or "PO", or TOC?

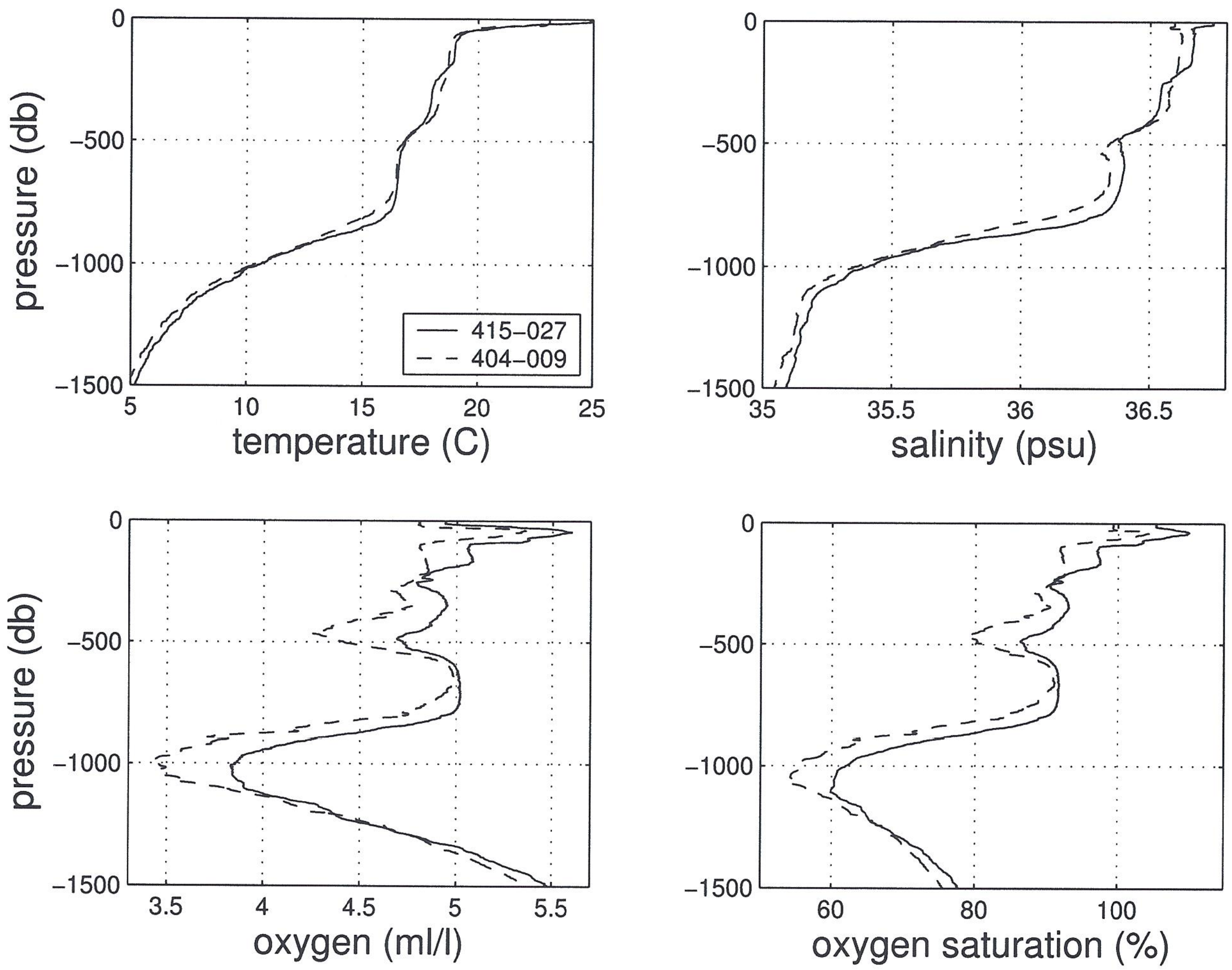


Fig. 1. Eddy A5 (OC415 Station 27) compared with A1 (OC404 Station 9).

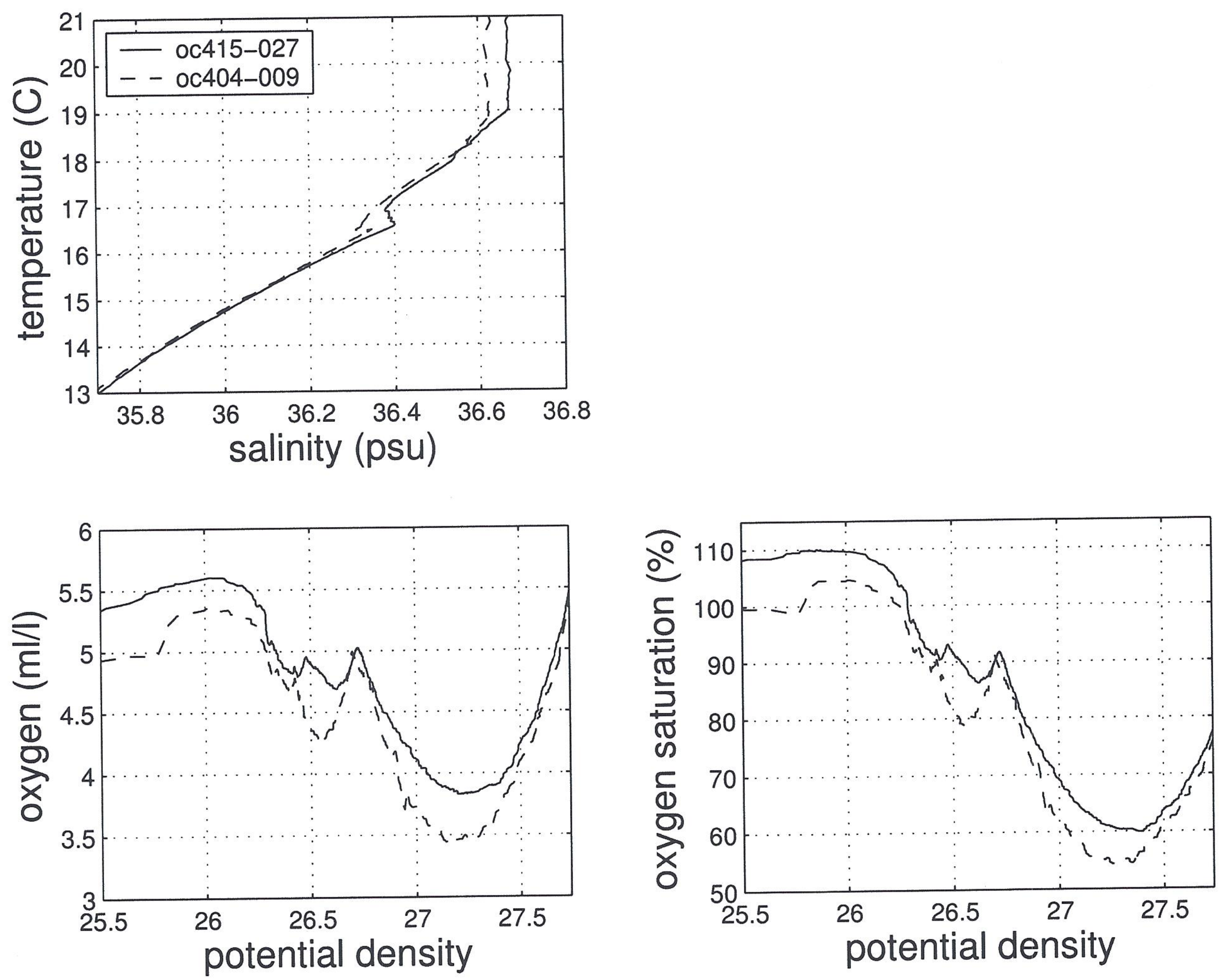


Fig. 2. Eddy A5 (OC415 Station 27) compared with A1 (OC404 Station 9).

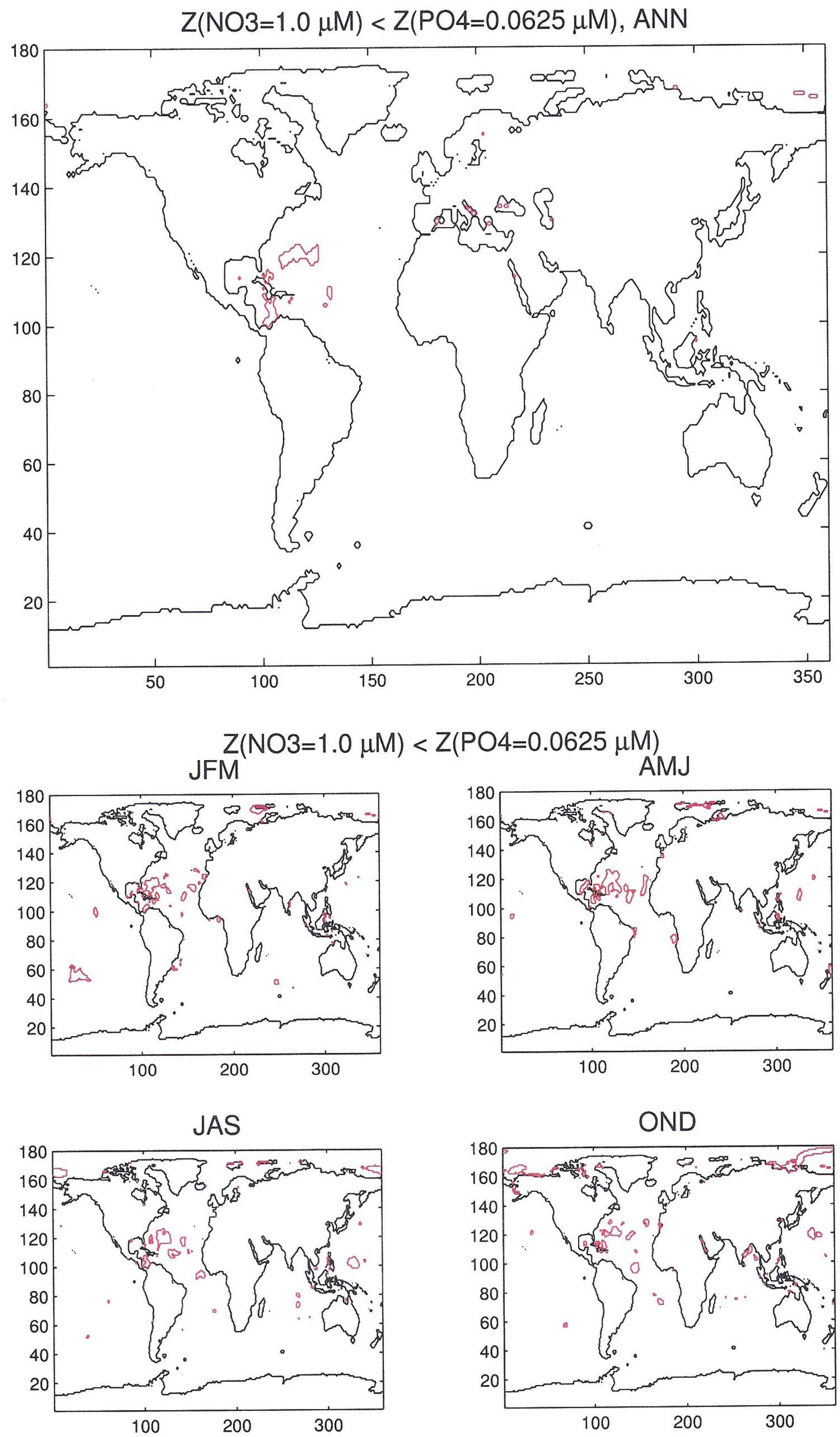
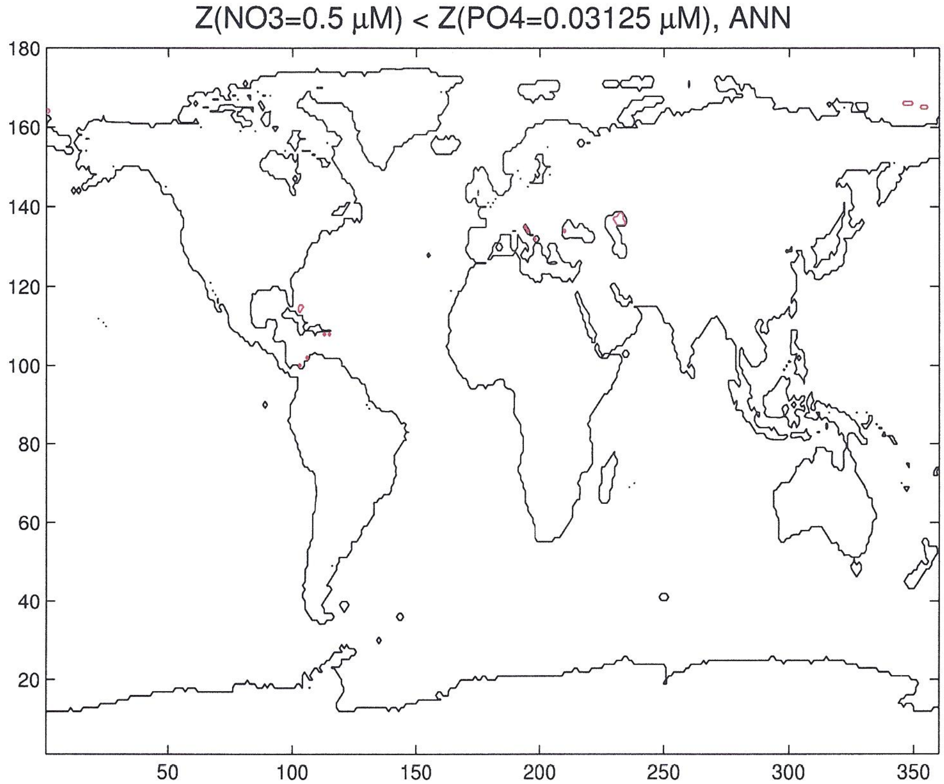


Fig. 3. Locations (red) where phosphocline is deeper than nitracline.



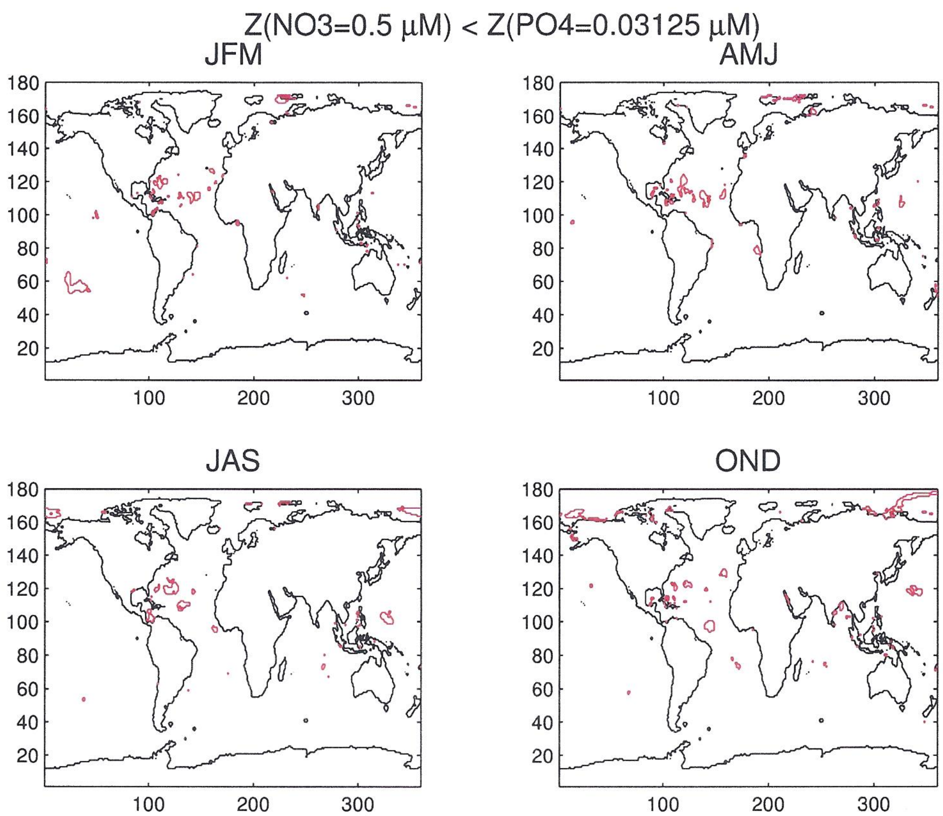


Fig. 4. Locations (red) where phosphocline is deeper than nitracline.

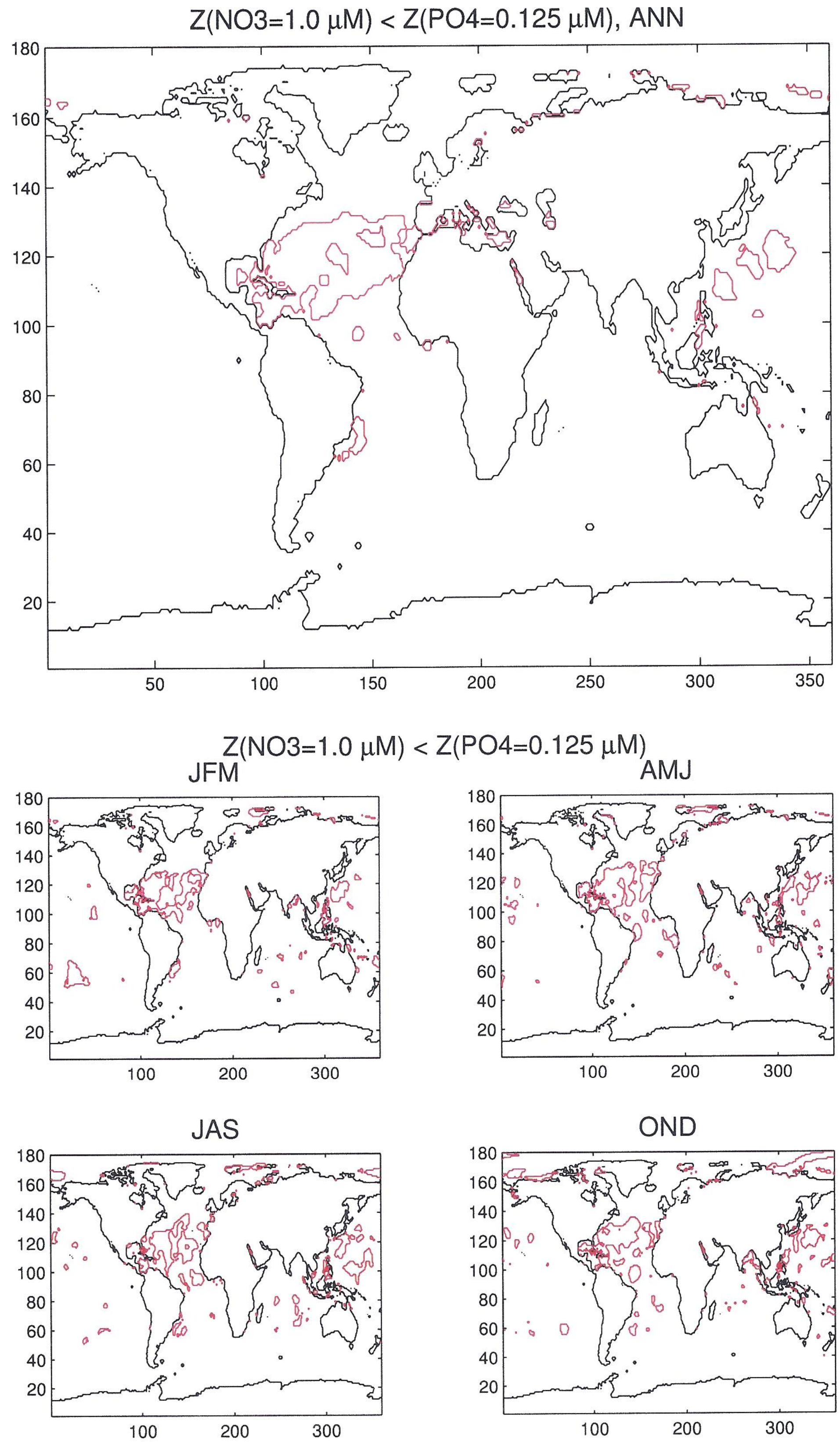
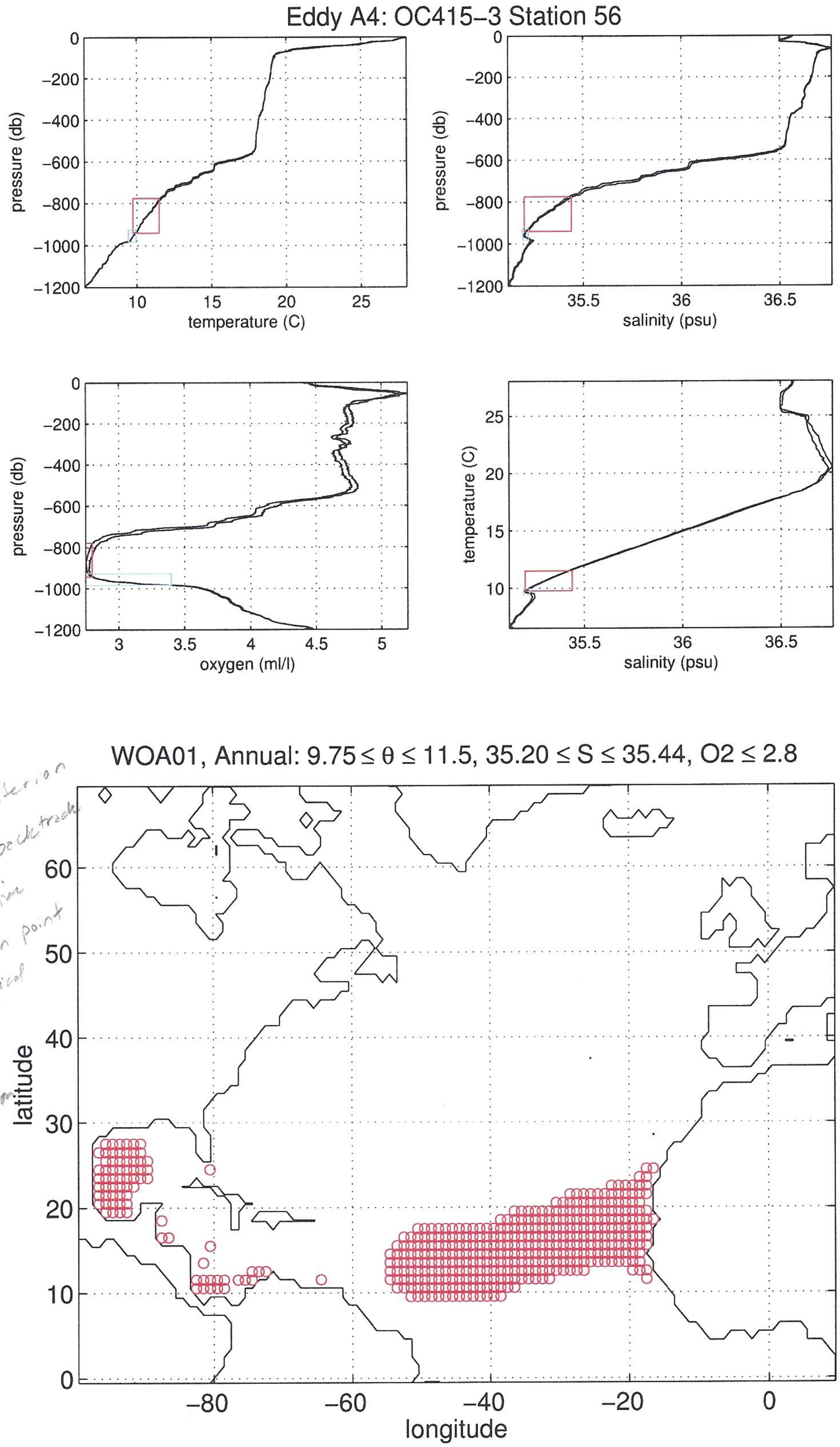
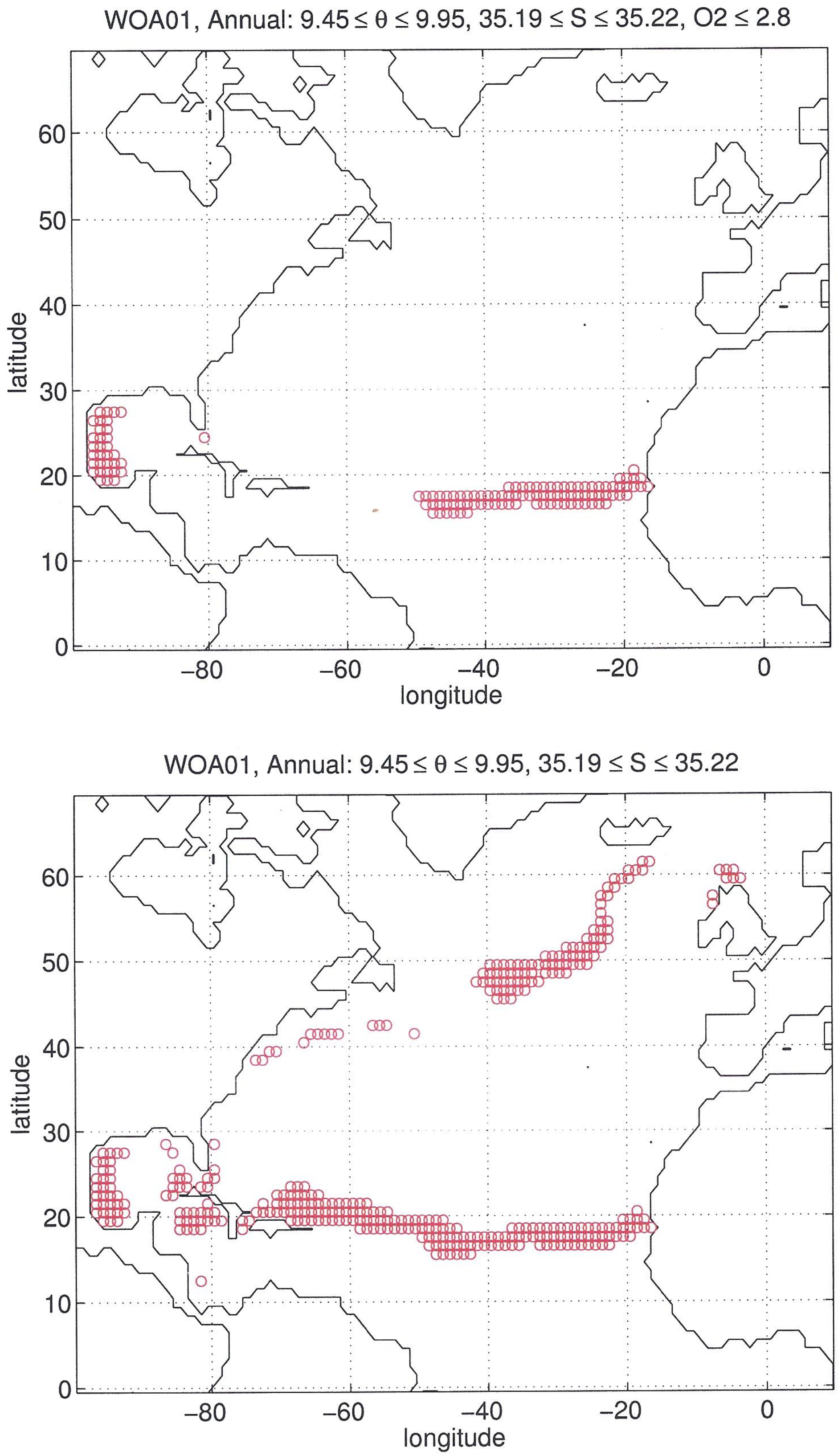


Fig. 5. Locations (red) where phosphocline is deeper than nitracline.



Larry
+ 6a search – O2 criterion
+ overlay altimetric backtrack
+ choose representative area at intersection point
+ compare climatological profiles w/ A4
+ compute remineralization

Fig. 6.



WOA01, Annual: 9.45 ≤ θ ≤ 9.95, 35.19 ≤ S ≤ 35.22, O2 ≤ 2.8
latitude
longitude
WOA01, Annual: 9.45 ≤ θ ≤ 9.95, 35.19 ≤ S ≤ 35.22
latitude
longitude

Fig. 7.

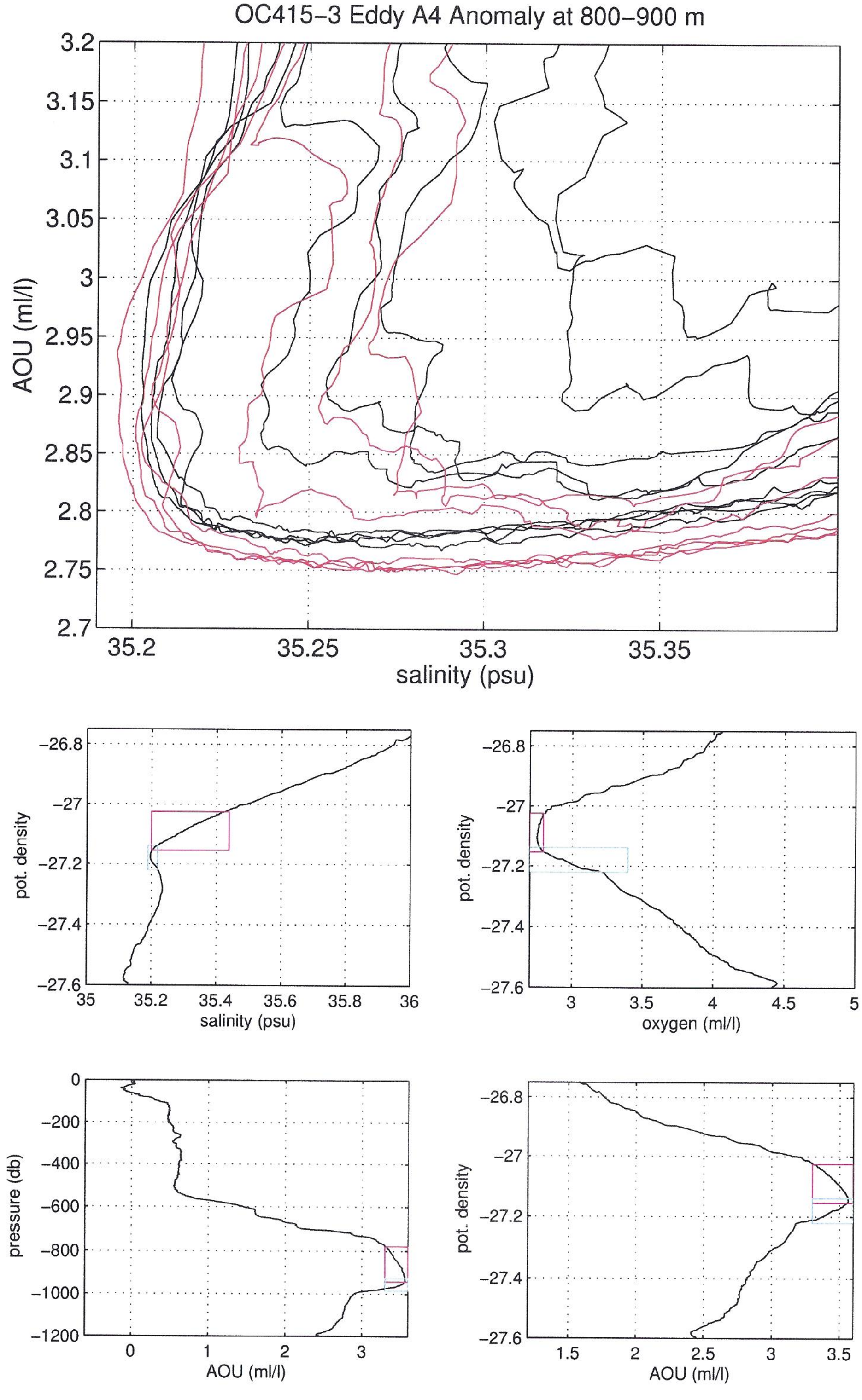


Fig. 8. (a) OC415-3 Sta. 32-68; red=upcasts. (b-e) OC415-3 Sta. 56.

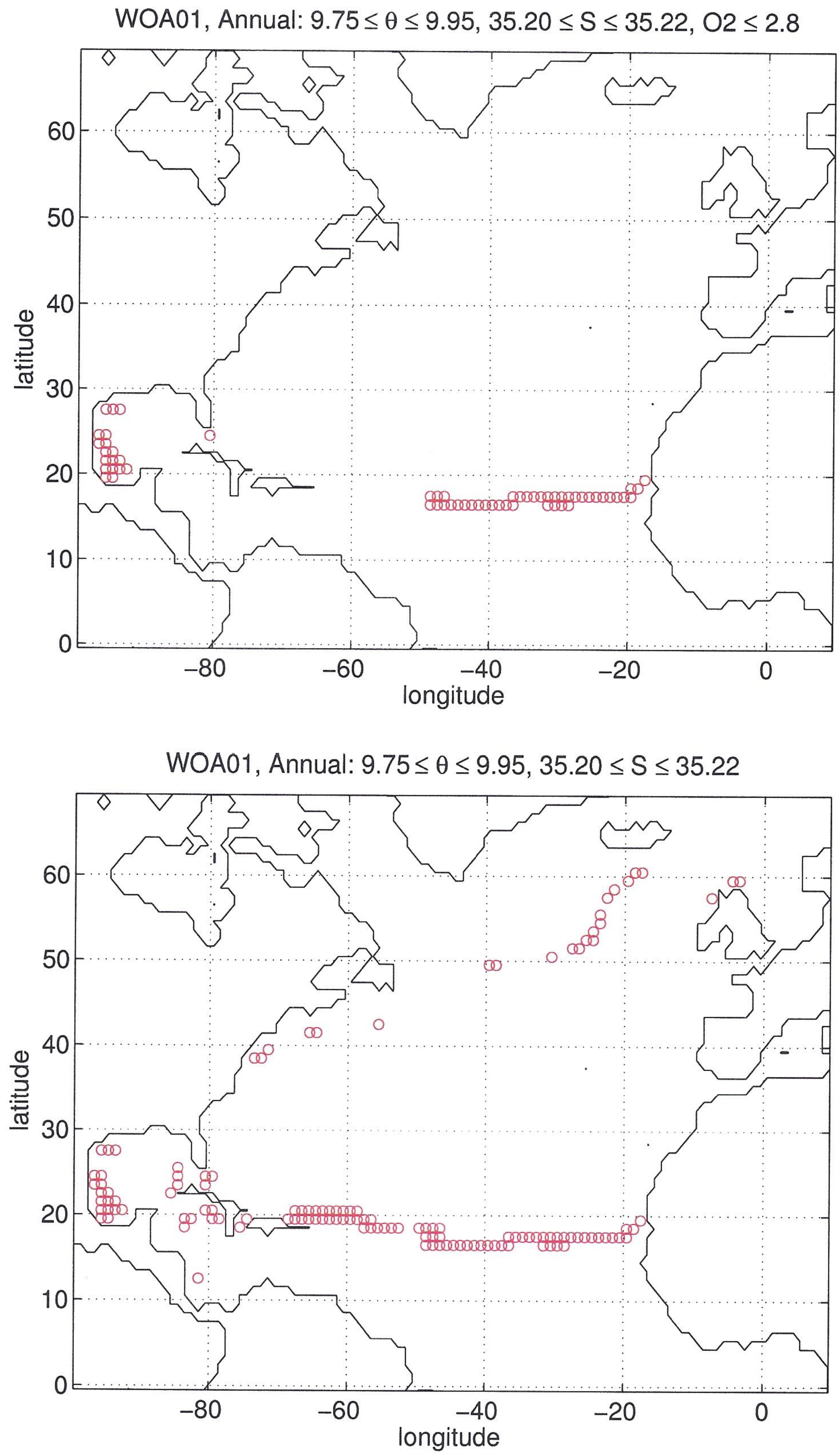

WOA01, Annual: 9.75 ≤ θ ≤ 9.95, 35.20 ≤ S ≤ 35.22, O2 ≤ 2.8
latitude
longitude
60
50
40
30
20
10
0
-80
-60
-40
-20
0
WOA01, Annual: 9.75 ≤ θ ≤ 9.95, 35.20 ≤ S ≤ 35.22
latitude
longitude

Fig. 9.

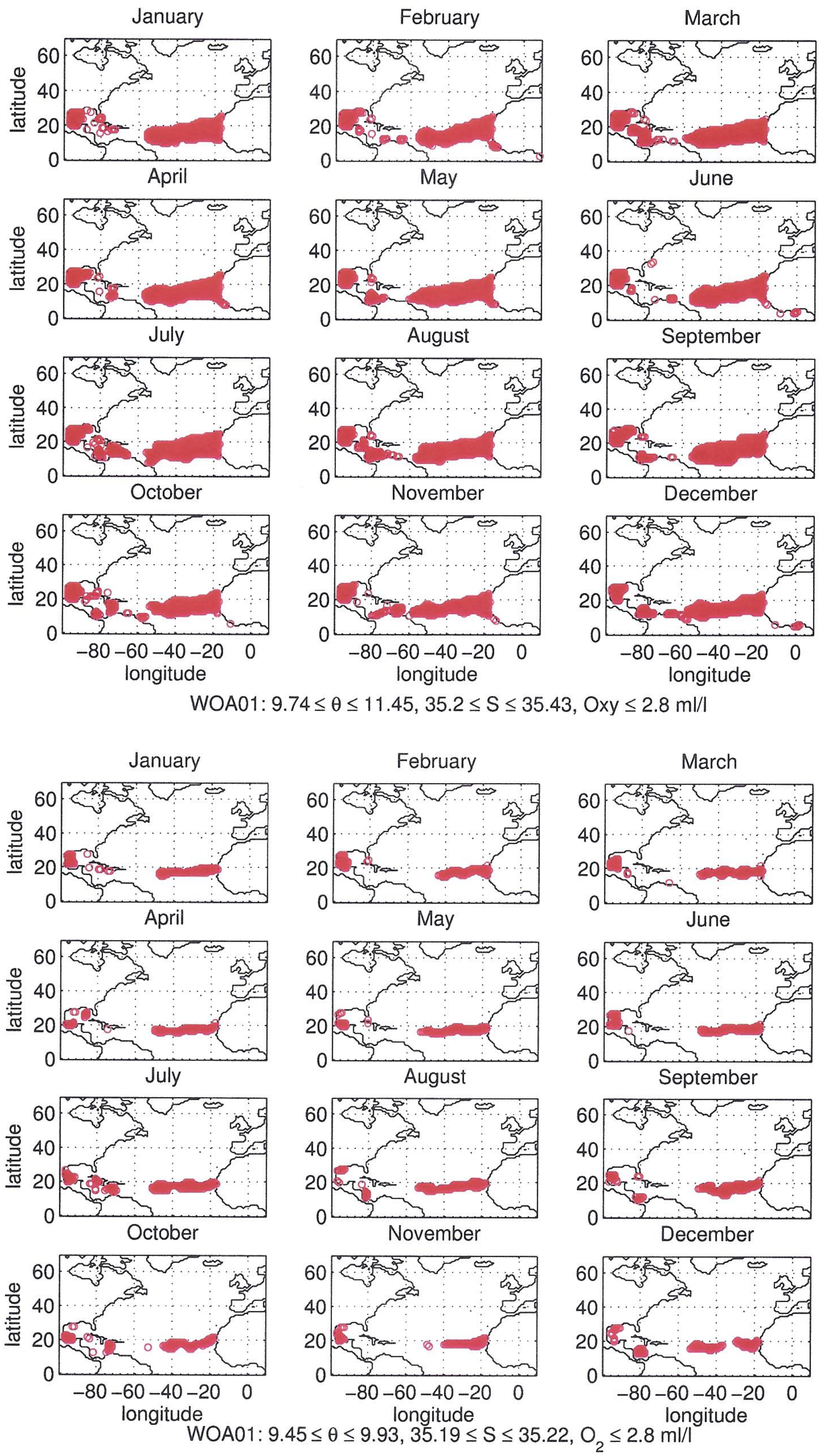

January
February
March
April
May
June
July
August
September
October
November
December
latitude
longitude
WOA01: 9.74 ≤ θ ≤ 11.45, 35.2 ≤ S ≤ 35.43, Oxy ≤ 2.8 ml/l
January
February
March
April
May
June
July
August
September
October
November
December
latitude
longitude
WOA01: 9.45 ≤ θ ≤ 9.93, 35.19 ≤ S ≤ 35.22, O_2 ≤ 2.8 ml/l

Fig. 10.

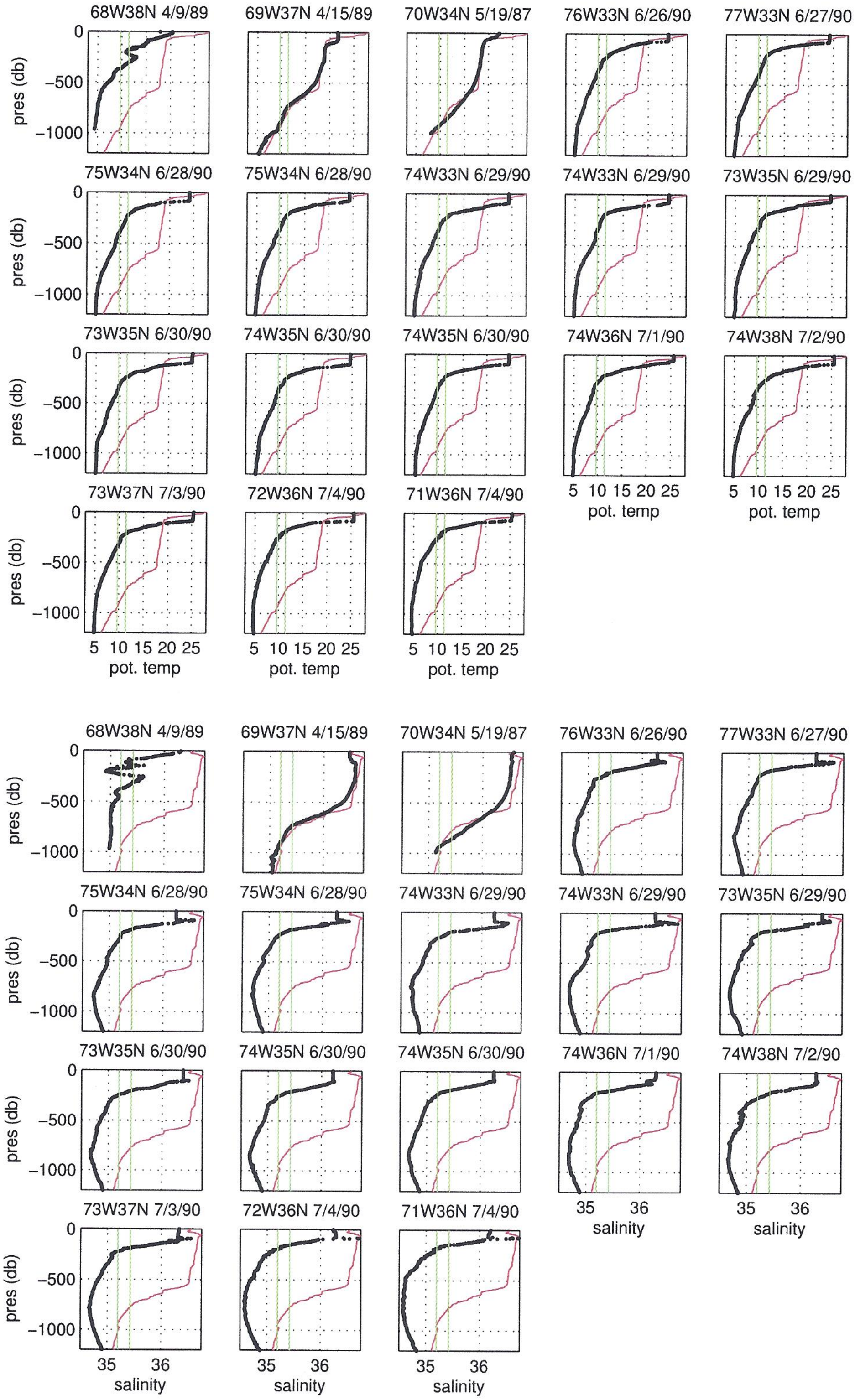


Fig. 11. World Ocean DataBase 2001: 32-40°N 77-40°W profiles.
red = OC415-3 Station 56; green = search limits.

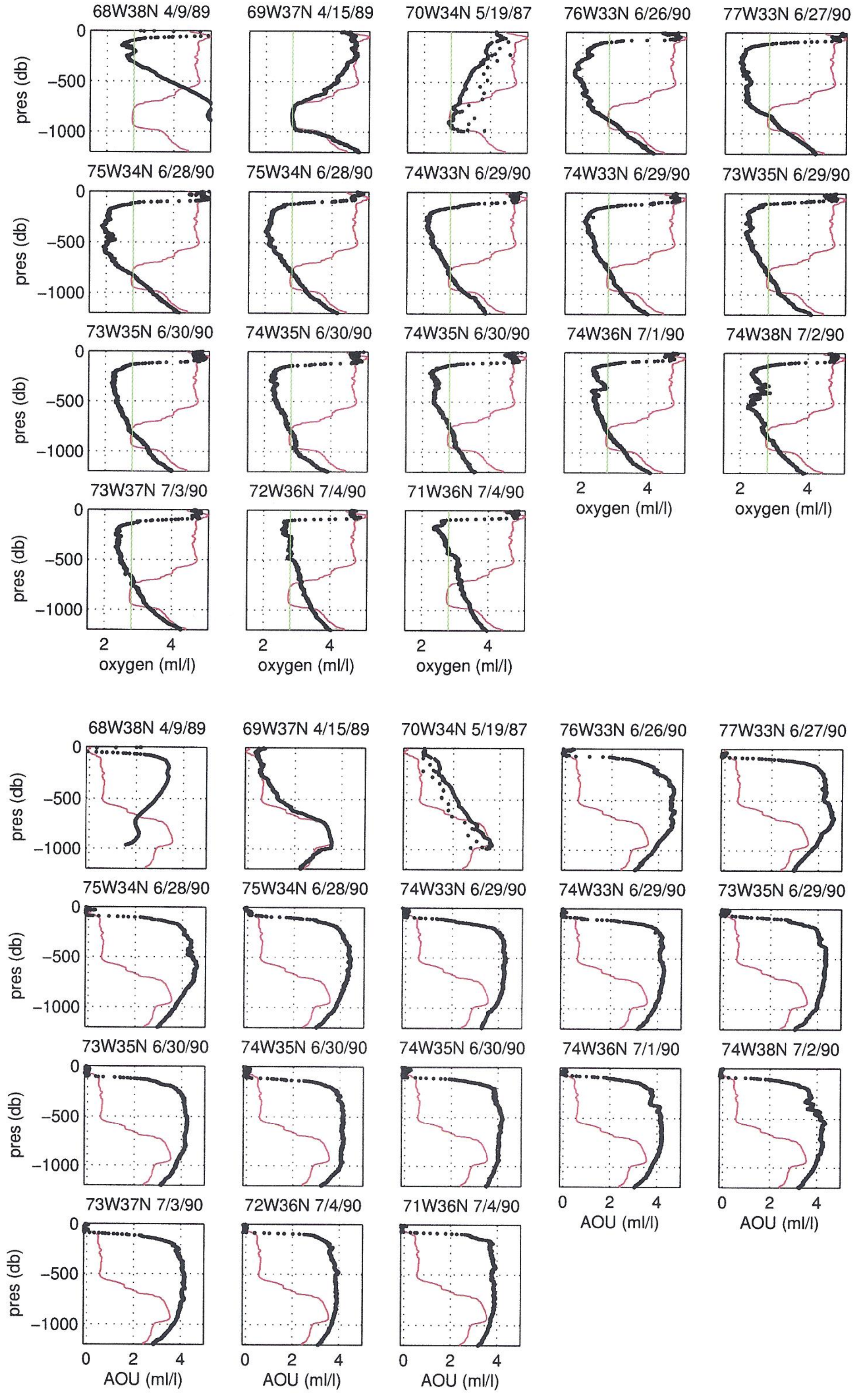


Fig. 12. World Ocean DataBase 2001: 32-40°N 77-40°W profiles.
red = OC415-3 Station 56; green = search limits.

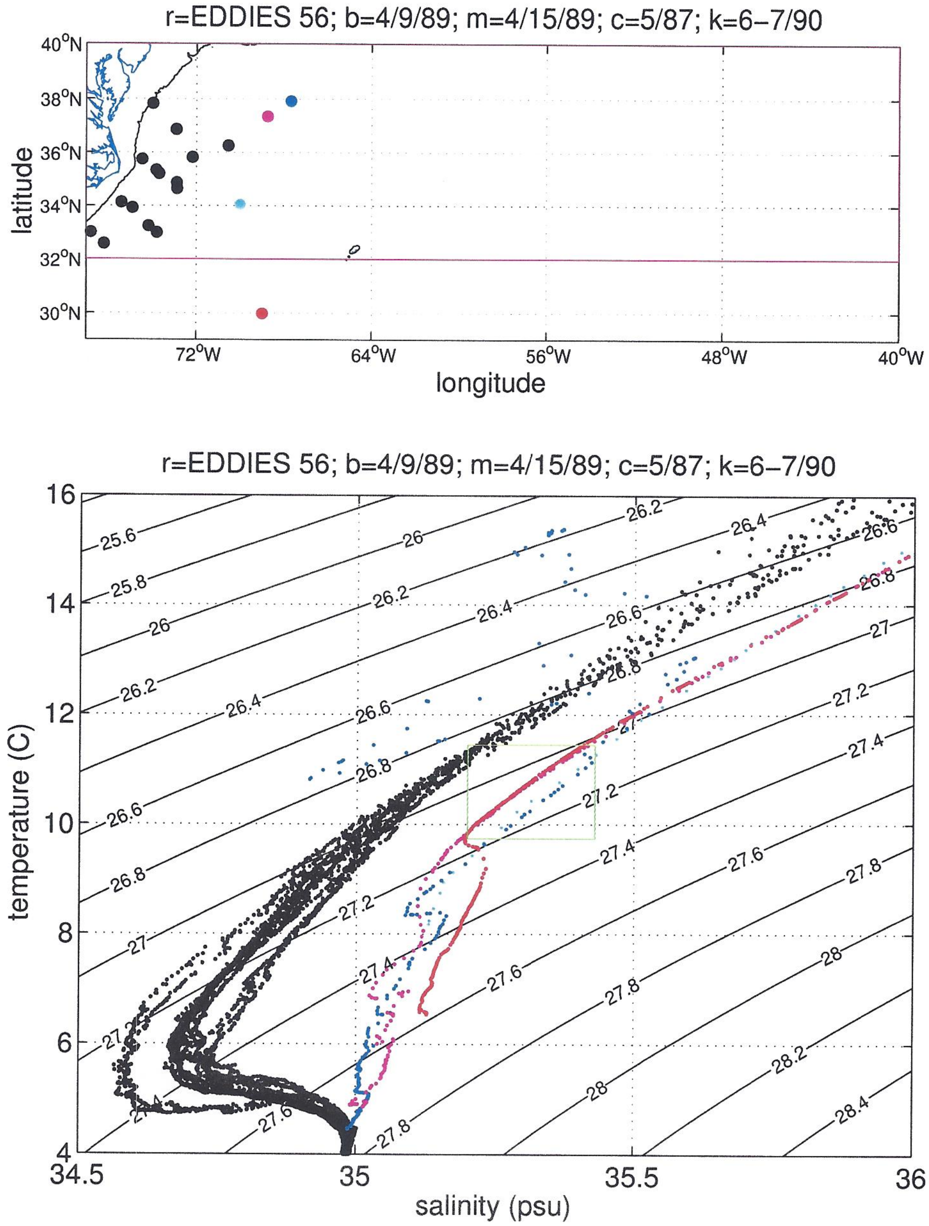
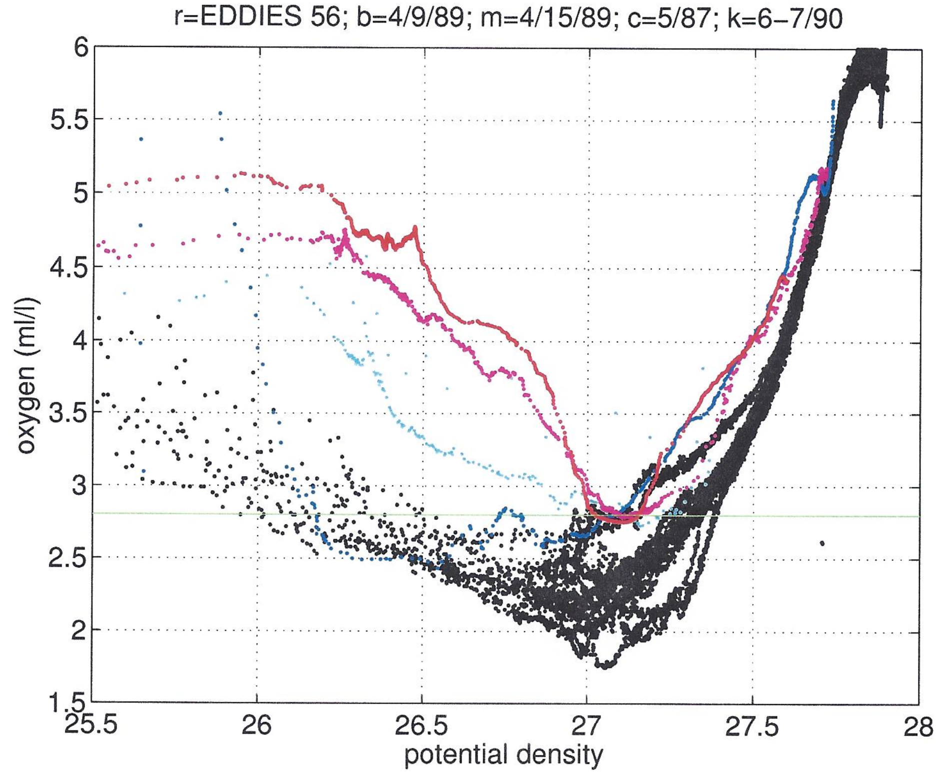


Fig. 13. World Ocean DataBase 2001: 32-40°N 77-40°W profiles. (a) 200 m contour in black.



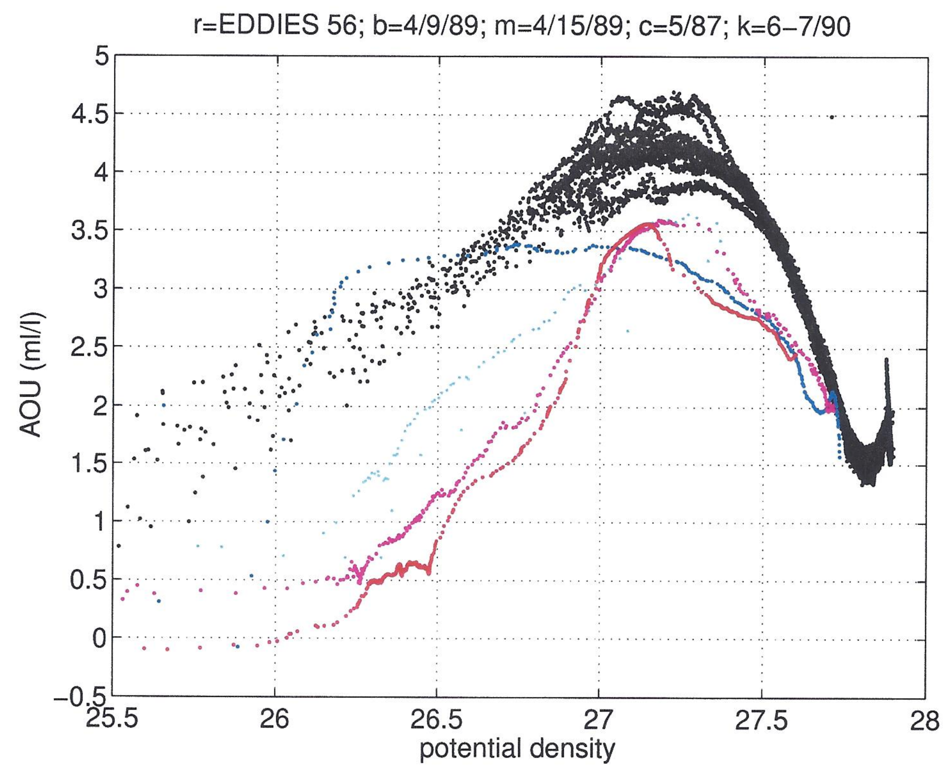


Fig. 14. World Ocean DataBase 2001: 32-40°N 77-40°W profiles.

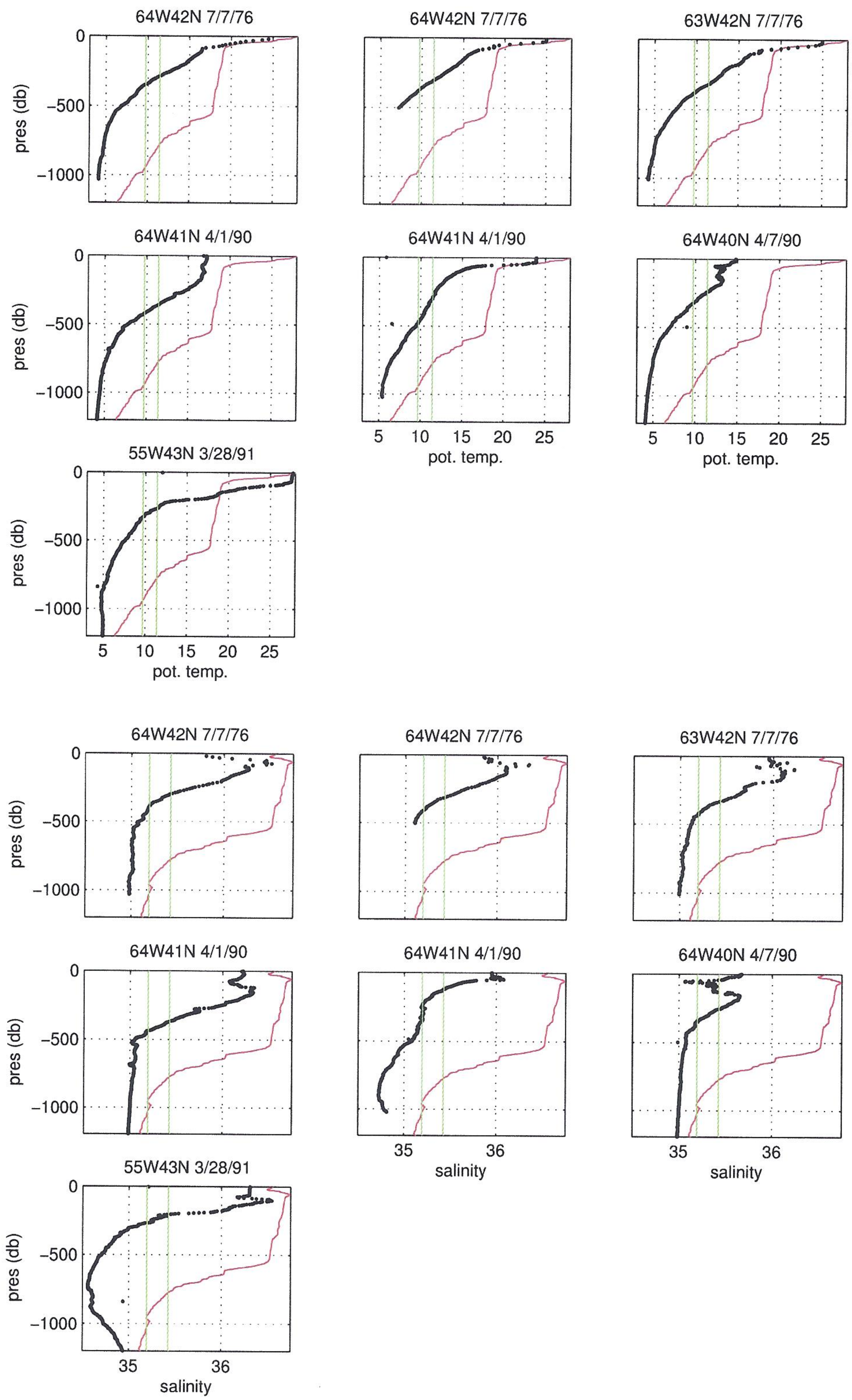


Fig. 15. World Ocean DataBase 2001: 40-50°N 77-40°W profiles.
red = OC415-3 Station 56; green = search limits.

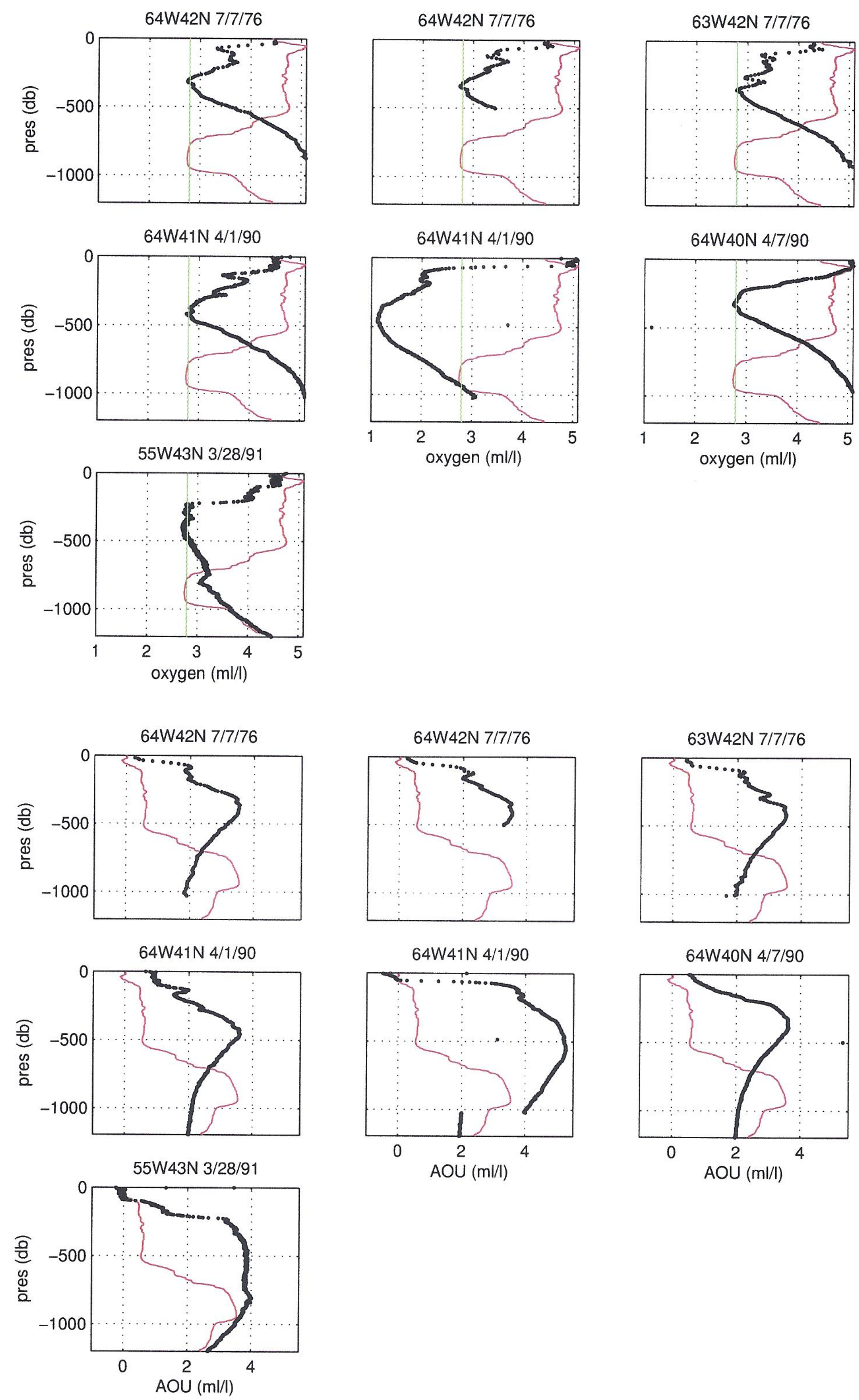


Fig. 16. World Ocean DataBase 2001: 40-50°N 77-40°W profiles.
red = OC415-3 Station 56; green = search limits.

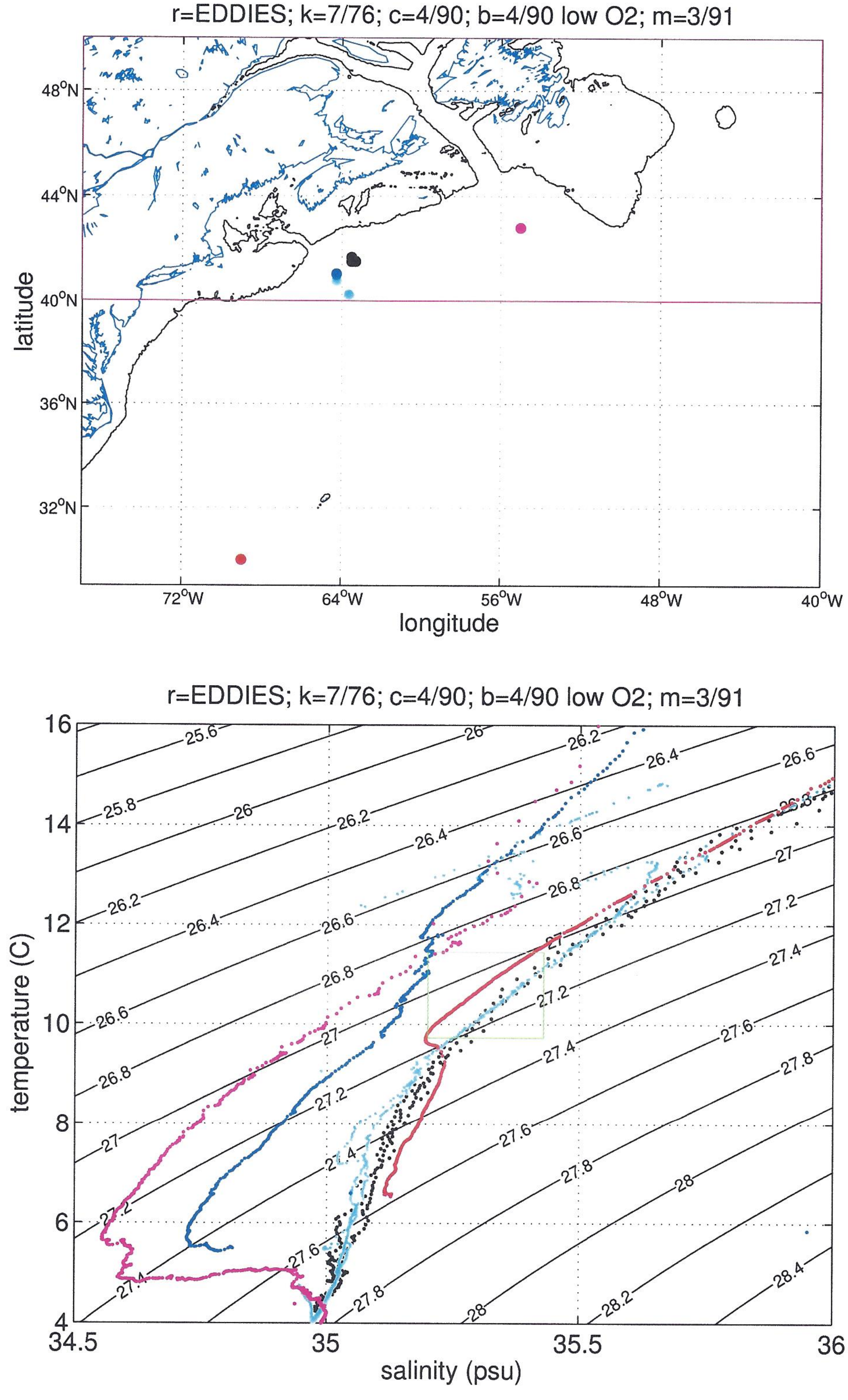
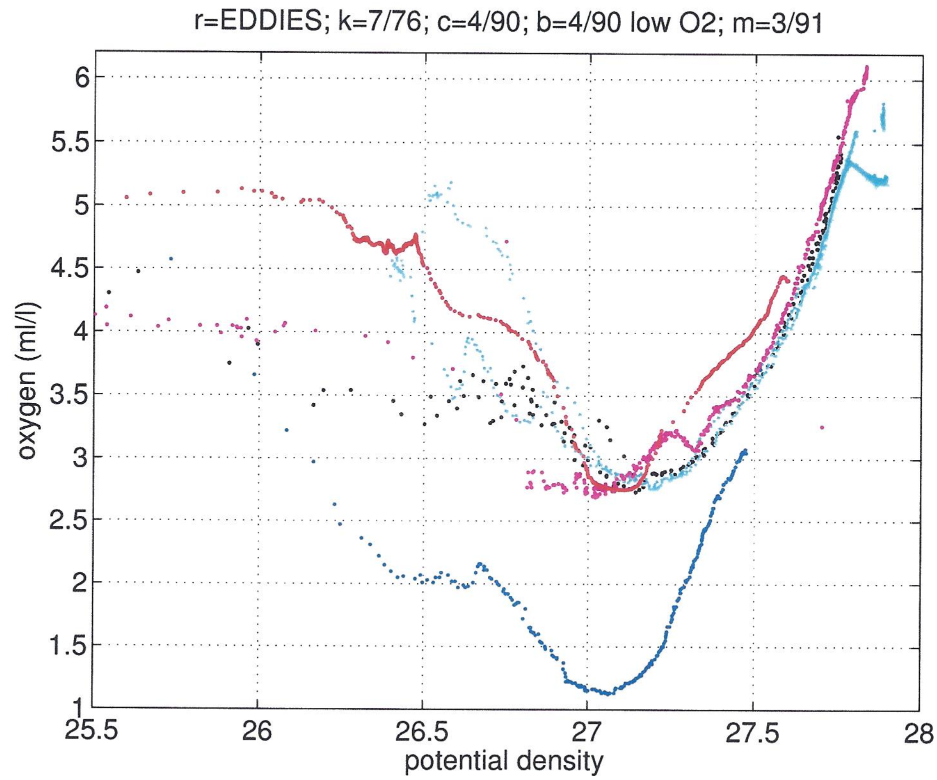


Fig. 17. World Ocean DataBase 2001: 40-50°N 77-40°W profiles.
(a) 200 m contour in black.



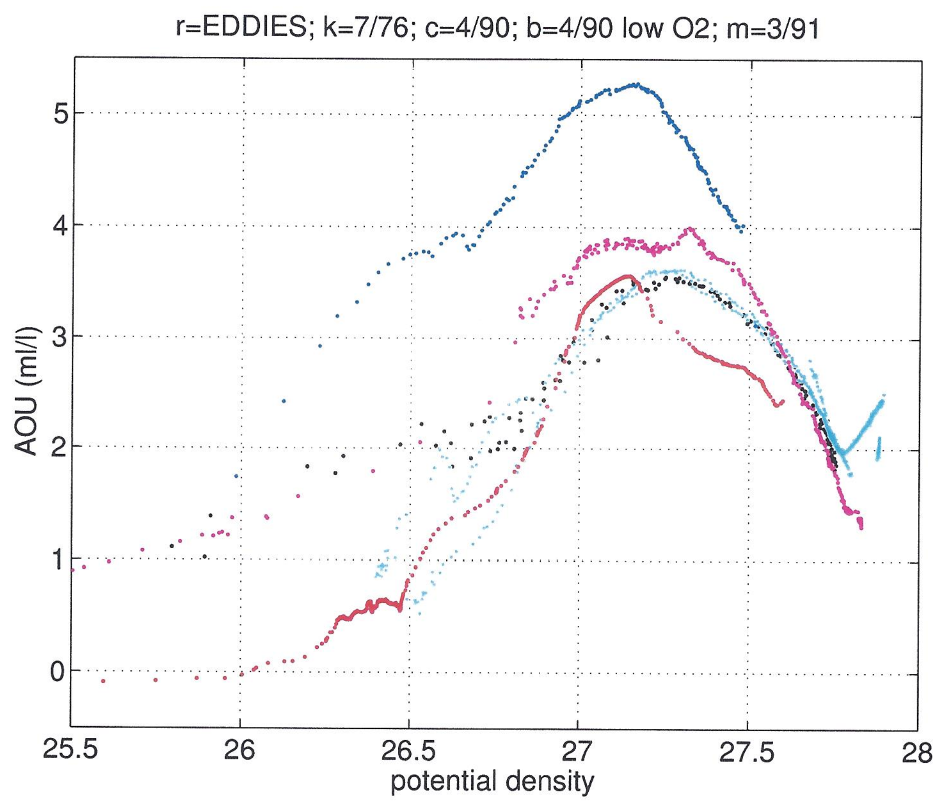


Fig. 18. World Ocean DataBase 2001: 40-50°N 77-40°W profiles.

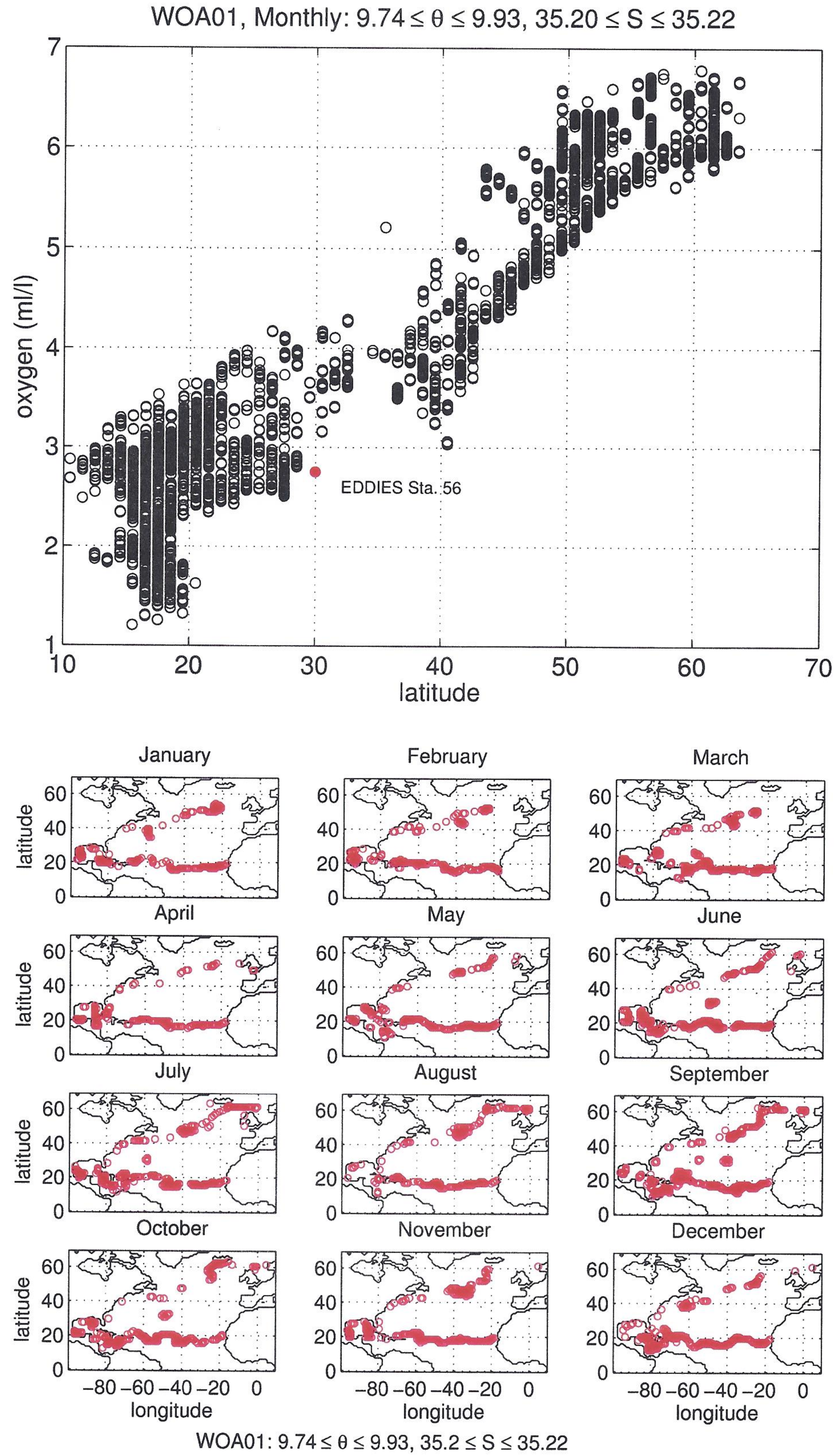

WOA01, Monthly: 9.74 ≤ θ ≤ 9.93, 35.20 ≤ S ≤ 35.22
oxygen (ml/l)
latitude
EDDIES Sta. 56
January
February
March
April
May
June
July
August
September
October
November
December
longitude
WOA01: 9.74 ≤ θ ≤ 9.93, 35.2 ≤ S ≤ 35.22

Fig. 19.