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The Mediterranean is getting saltier

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Abstract

The deep waters of the Mediterranean Sea have been getting saltier and warmer for at least the past 40 yr at rates of about 0.015 and 0.04 °C per decade. Here we show that two processes contribute to these increases in temperature and salinity. On interannual time scales, deep water formation events in severe winters transmit increasingly salty intermediate waters into the deep water. The second process is a steady downward flux of heat and salt through the halocline-thermocline that connects the Levantine Intermediate Water with the deep water. We illustrate these two processes with observations from repeat surveys of the western Mediterranean basin we have made over the past 10 yr.

1 Introduction

The Mediterranean Sea is an evaporative basin with a net evaporation (Evaporation – Precipitation – River Runoff) estimated to amount to 50 to 100 $\mathrm{cm\,yr^{-1}}$ (Bethoux, 1979; Bryden and Kinder, 1991). The Mediterranean also loses heat to the atmosphere at about 4 to 7 $\mathrm{W\,m^{-2}}$ (Bunker et al., 1982). Thus the Mediterranean is a concentration basin that loses buoyancy due both to freshwater loss and to heat loss. For steady state Mediterranean salinity and temperature distributions, the inflow-outflow through the Strait of Gibraltar balances these freshwater and heat losses: warmer, fresher Atlantic inflow and colder, saltier Mediterranean outflow transport freshwater and heat into the Mediterranean Sea to balance the buoyancy losses (Bryden et al., 1994; Macdonald et al., 1994).

Nof (1979) first suggested that the steady state water balance for the Mediterranean was measurably disrupted by the damming of the Nile River during the 1960's. By limiting the Nile River inflow, Nof estimated a change to the overall freshwater budget of the Mediterranean Sea equal to an increase in net evaporation of 13 $\mathrm{cm\,yr^{-1}}$. Using hydraulic control theory to model the changes in Gibraltar exchange associated with

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a 10 % increase in net evaporation, Rohling and Bryden (1992) estimated that the salinity of the outflowing Mediterranean water would need to increase by 0.13 to bring the Mediterranean back into steady state.

Lacombe et al. (1985) carefully examined historical hydrographic data in the western Mediterranean and could find no evidence for changes to the salinity and temperature of the deep water from 1910 to 1970. They did report some fascinating variability in deep water properties measured by CTD in 1973 and again in 1981 and we will show that changes to the historical deep water properties were already underway when they made these profiles. Since 1985, many authors have estimated the rate of increase of salinity and of temperature in the deep western Mediterranean: some argue that they are effects associated with global warming, heating and evaporating the surface layers around the deep convection region in the Gulf of Lion (e.g., Béthoux and Gentili, 1999; Krahmann and Schott, 1998); some argue for increasing temperature and salinity in the Atlantic water inflow through the Strait of Gibraltar (e.g., Millot, 2007); some to air–sea fluxes related to variability in the North Atlantic Oscillation (Rixen et al., 2005); but most attribute the increases to the changing water budget associated with the damming of rivers, particularly the Nile River (Rohling and Bryden, 1992).

A careful model study by Skliris and Lascaratos (2004) compared Mediterranean circulations with and without Nile River discharge. They showed that removing the Nile river discharge caused the salinity of the Mediterranean to increase by about 0.04 over a time scale of 40 yr. In the model, the increase in salinity occurred first in the surface waters of the eastern Mediterranean which resulted in an increase in the salinity of the newly formed Levantine Intermediate Water (LIW). The circulation of the saltier LIW then led to saltier deep water formation in the eastern Mediterranean and when the LIW made its way into the western Mediterranean it eventually preconditioned the upper 1000 m of the Gulf of Lion to be salty enough to form deep water in moderately severe wintertime storms. Such processes do indeed seem to occur. New, saltier Aegean Sea deep water was indeed formed in the eastern Mediterranean during 1988–1992 in what is commonly referred to as the Eastern Mediterranean transient (Roether et al.,

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1996). Saltier LIW is observed to transit the Sicily Channel (Gasparini et al., 2005) and to precondition the waters in the Gulf of Lion (Grignon et al., 2010) for large deep water formation events that result in much saltier western Mediterranean deep water (WMDW) (Schroeder et al., 2010).

2 Data

We use stations occupied by R/V *Urania* as part of CNR repeat surveys of the western Mediterranean Sea in 2004, 2005, 2006, 2008, 2010, 2013 (stations 1 to 17 in Fig. 1) to examine changes in deep water properties over the last decade. We use selected high quality historical stations at location A in the western Mediterranean near the entrance to the Alboran Sea to examine long-term changes in the deep water properties: the 1961 station is *Atlantis* station 6010 in Miller et al. (1968); the 1975 station is *Chain* station 79 in Bryden et al. (1978); the 1995 station is *Meteor* station 2 from Roether et al. (1996); and the 2004 and 2008 stations in Table 1 are from the *Urania* surveys. We also use the monthly time series of Dyfamed profiles in the northwestern Mediterranean to examine continuous time series of changing deep water properties since 1995.

3 Magnitude of the salinity and temperature increases

Over the past 50 yr the Mediterranean Sea has been getting saltier and warmer. We choose a location, A, in the western Mediterranean near the entrance to the Alboran Sea (Fig. 1) to compare temperature and salinity profiles in 5 stations spanning 47 yr from 1961 to 2008 (Fig. 2). We specifically chose this location to represent Mediterranean waters near the end of their circuit of the basin and about to exit the Mediterranean. Both the high temperature, high salinity core of LIW and the cold relatively fresh WMDW have become notably warmer and saltier since 1961 (Fig. 2). The increases in LIW core temperature and salinity are about twice as large as the changes in the deepest waters. Averaging the salinity and potential temperature below 200 m depth

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(to minimize seasonal effects in the upper waters) shows that the salinity and temperature have increased by 0.07 and 0.19 °C respectively since 1961 (Table 1). If such changes were due to changes in the evaporation-precipitation-runoff and air sea heat exchange, they amount to an increase in evaporation or decrease in precipitation or in runoff of 12 cm yr^{-1} and to a decrease in air–sea heat loss by the ocean of 1.6 W m^{-2} over 50 yr.

Much has been made of the long-term salinification of the Mediterranean Sea with an emphasis on the role of deep water formation events occurring sporadically in severe winters that mix the salty LIW down into the deep water (Schroeder et al., 2010). In fact, one can see that process in Fig. 2 by examining the differences between the 2004 and 2008 profiles: the intervening deep water formation event of 2005 transmitted the high salinity, high temperature LIW evident in 2004 profiles down into the deep water making the 2008 deep waters appreciably warmer and saltier than the 2004 deep waters.

In addition to deep water formation events, Bryden et al. (2013) argued that double diffusive salt finger processes transfer salinity and temperature downward into the WMDW. The halocline-thermocline connecting the core of LIW at about 400 m depth and the WMDW below 1900 m depth consists of warmer, saltier waters lying above colder, fresher deep waters and such stratification is conducive to salt finger processes that transfer heat, salt and density downward. Bryden et al. (2013) estimated the downward fluxes of heat and salt through the halocline-thermocline into the deep water to amount to 5.4×10^{-8} psu m s^{-1} and 12.4×10^{-8} °C m s^{-1}. Such fluxes would make a 1000 m column of deep water 0.0017 saltier and 0.019 °C warmer over the course of a year. Thus, there is evidence that Mediterranean deep water salinity and temperature can increase even in the absence of deep water formation events.

Here we examine observations from a remarkable set of repeated surveys of the deep western Mediterranean Sea over the past decade to compare the effects of sporadic deep water formation events with the effects of steady downward fluxes of salt and heat into the deep waters on causing the long-term increases in salinity and temperature of the WMDW. We concentrate on the observations at station 9 (Fig. 1) in the

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open ocean region of the southern western Mediterranean. We have sampled station 9 in 2004, 2005, 2006, 2008, 2010 and 2013 on board R/V *Urania* and a station at this location was sampled by R/V *Meteor* in 2011 (Tanhua et al., 2013). Vertical profiles of salinity and potential temperature and a Potential Temperature-Salinity diagram for these stations show the evolution of deep water properties over the past decade (Fig. 3).

In 2004 we observe the deep water to be nearly uniform vertically below 1900 dbar with a potential temperature of 12.82 °C and salinity of 38.45. By 2005, the deep water layer 1900–2700 dbar appears to have become slightly warmer and saltier and below 2700 dbar a small bottom layer of warmer and saltier water appears. This bottom layer is the new warmer, saltier deep water formed during the extreme winter of 2005 in the northern western Mediterranean (Schroeder et al., 2008; Smith et al., 2008) that is just arriving at station 9. The major deep water formation event in the northwestern Mediterranean Sea during 2005 injected a 600 m thick layer of new deep water that is 0.024 saltier and 0.042 °C warmer than the previous bottom waters (Fig. 3a and b, Schroeder et al., 2010) that we see at station 9 in 2006. Over the succeeding 4 yr period from 2006 to 2010, the layer between the bottom of the halocline-thermocline and the top of the deep water becomes appreciably saltier and warmer. Bryden et al. (2013) attributed these changes to downward fluxes of heat and salt through the halocline-thermocline associated with salt finger processes. By 2010, the deep waters are nearly uniform vertically below 1800 dbar and have potential temperature of 12.88 °C and salinity of 38.474, nearly 0.06 °C warmer and 0.025 saltier than the old deep waters of 2004. By 2011 there has been new deep water formation raising the deep water temperature to 12.90 °C and salinity to 38.482 and by 2013 there has been additional deep water formation (Durrieu de Madron et al., 2013) raising the deepest salinity above 38.50 but with little change in potential temperature. From 2010 to 2013, the layer between the bottom of the halocline-thermocline and the top of the deep water continues to fill in with higher temperature and salinity. In the decade of our observations, deep water properties below 1900 dbar have increased in temperature by 0.08 °C and increased in salinity by 0.035 (Table 2), that is 3 times the rate of increase found from 1961 to 2008. And in the vertical depth range from 1500 to 1900 dbar above the direct influence of new deep water formation has become warmer and saltier by 0.04 °C and 0.016 respectively (Table 2).

Thus, two processes are contributing to the increases in salinity and temperature of the deep water. First, salt finger processes transport salt and heat steadily downward through the halocline-thermocline at estimated rates of 5.4×10^{-8} psu m s^{-1} and 12.4×10^{-8} °C m s^{-1}, respectively. These amount to downward salt and heat fluxes over a year of 1.7 psu m and 3.9 °C m. Secondly, sporadic deep water formation events in the northwest Mediterranean inject new warmer, saltier denser deep water that then spread beneath the older deep waters. The major deep water formation event in 2005 resulted in downward fluxes of 14.4 psu m (600 m × 0.024 psu) and 25.2 °C m (600 m × 0.042 °C), that is 6 to 8 times larger than the yearly downward flux associated with salt finger mixing. In contrast, the deep water formation event of 2012 documented by Durrieu de Madron et al. (2013) that created a large volume of new deep water had smaller downward fluxes of 2 psu m (200 m × 0.010 psu) and 2 °C m (200 m × 0.01 °C) because the salinity excess in the new deep water was not as large as in 2005 and there was nearly no potential temperature signature. Concentrating on the major 2005 event, we estimate that for a major deep water formation event occurring every 7 yr the episodic warming and salting of the deep water is the same size as the steady warming and salting associated with downward fluxes of heat and salt through the halocline-thermocline.

We can see the effects of these two processes in the time series of salinity and temperature increases at the Dyfamed site in the Ligurian Sea from 1995 to 2007 (Fig. 4). There the deep water temperature and salinity in the northwest Mediterranean increased nearly linearly from 1995 to 2005 before the large deep water formation event in 2005 occurred (Schroeder et al., 2010). We estimate an increase in 1800–2000 m temperature of 0.05 °C and an increase in salinity of 0.027 from 1995 to 2005 over 10 yr. Hence even in a decade where there is little evidence for deep water formation in the western Mediterranean, deep water salinity and temperature increase at a rate comparable to the long-term trends evidenced in Table 1. These steady changes over 10 yr are slightly smaller than the jumps we see in the Dyfamed observations in layer temperature (0.08 °C) and salinity (0.04) from 2005 to 2007 associated with the major 2005 deep water formation event.

4 Discussion

In a steady state Mediterranean, the temperature of the deep water would represent a competition between the warming resulting from salt finger processes down through the halocline-thermocline and the intermittent cooling associated with the formation of new deep water during particularly severe winters. New deep waters are naturally colder and fresher than the maximum temperature and maximum salinity LIW so we expect downward salt finger mixing to be a constant source of heat and salinity to the deep water. The deep water formed in the western Mediterranean must have a salinity equal to the column average salinity in the formation region because the wintertime formation events do not have long enough duration to appreciably change the salinity over a water column 2500 m thick (Smith et al., 2008). At the onset of deep convection, the temperature of the new deep water must be that temperature that combines with the water-column average salinity to equal or just exceed the density of the existing deep water. As severe winter heat loss (mostly due to evaporation) continues, the new deep water can become colder and slightly saltier and denser, but mostly colder.

In terms of deep salinity, salt finger processes would make the deep water saltier over time while deep water formation would lead to new deep salinities just slightly above the depth average salinity in the formation region. Vertical mixing of the deep water with saltier water above would also make the deep waters saltier. To maintain a steady state salinity in the deep waters, the depth average salinity in the wintertime formation region must be lower than that in the older deep waters so the newly formed deep water is slightly fresher than the older deep waters.

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In terms of deep density, salt finger processes make the deep water denser; deep water formation also makes the new deep water slightly denser than the older deep waters. In a steady state these two processes making the deep water denser are balanced by vertical mechanical mixing processes that decrease the density of the deep water.

While becoming warmer and saltier over the past 50 yr, the deep water in the western Mediterranean has not appreciably changed its density (Fig. 2c): deep water potential density has remained about 29.11 since the 1960's, with perhaps a small change in deep density to 29.12 in the 2005 deep water formation and maybe to 29.13 in the 2012 deep water formation event (Durrieu de Madron et al., 2013). A conundrum is how the deep water can maintain constant density when salt finger mixing transfers density downward as part of the instability process. Both the episodic injection of new deep water and salt finger mixing would seem to lead to increasing density of the deep water. The answer seems to be that the density increase associated with salt finger mixing is very small, amounting to only 0.0004 $kg\,m^{-3}\,yr^{-1}$ according to Bryden et al. (2013). Thus, increases in deep water density can only occur in measurable amount when there is an extended deep water formation event, when prolonged buoyancy loss increases the density of the new deep water, such as that in 2005 when the deep water density appeared to increase by 0.01 $kg\,m^{-3}$ (Schroeder et al., 2010).

It is notable that the density of the Mediterreanean intermediate and deep waters at the entrance to the Alboran Sea have not changed much over time (Fig. 2c). Rohling and Bryden's (1992) argument for the adjustment of Mediterranean salinity after the reduction in Nile run-off was based on hydraulic exchange theory that concludes that the Mediterranean salinity is ultimately set by the maximum exchange between the Atlantic and Mediterranean through the Strait of Gibraltar. Their hypothesis was that increasing net evaporation (due to reduced river run-off) leads to an increase in Mediterranean salinity and density that allows a stronger exchange flow through the Strait. Rohling and Bryden were actually arguing for an increase in density of the Mediterranean deep water by about 0.2 $kg\,m^{-3}$ to enable a stronger exchange flow to balance the increased

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net evaporation. No such sizeable increase in density has been observed. Without the hydraulic control argument, application of Knudsen relationships for the exchange flow through the Strait of Gibraltar would suggest that the salinity difference would increase linearly with the increasing net evaporation: a 10 % increase in net evaporation would lead to a 10 % increase in the Mediterranean – Atlantic salinity difference, from 2 to 2.2 so the Mediterranean salinity would increase by 0.2, providing the Atlantic water salinity, inflow and outflow remain constant. Since the 1960's, the Mediterranean deep water salinity has increased by half that amount.

When will the Mediterranean reach a steady state in response to the changing water balance associated with increased evaporation, reduced precipitation and reduced river run-off? When will the salinity of the Mediterranean stop increasing? What value will it achieve? Answering these questions represent a challenge for the Mediterranean modelling community and validating the model predictions will require continuing observations of the deep Mediterranean Sea.

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Table 1. Depth-average salinity and potential temperature below 200 m for historical stations in the western Mediterranean near the eastern entrance to the Alboran Sea. The 1961 station is *Atlantis* station 6010 in Miller et al. (1970). The 1975 station is *Chain* station 79 in Bryden et al. (1978). The 1995 station is *Meteor* station 2 from Roether et al. (1996). The 2004 and 2008 stations are *Urania* stations made as part of CNR repeat surveys of the western Mediterranean Sea (Schroeder et al., 2010).

Year	Salinity	Potential Temperature
1961	38.406	12.766
1975	38.431	12.822
1995	38.452	12.879
2004	38.477	12.966
2008	38.478	12.954

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Table 2. Depth-average salinity and potential temperature at station 9 in the western Mediterranean over the past decade: deep water 1900–2750 dbar and above the direct influence off deep water formation 1500–1900 dbar. Stations in 2004, 2005, 2006, 2008, 2010, 2013 were occupied by RV *Urania* as part of CNR repeat surveys of the western Mediterranean Sea; the station in 2011 was occupied by R/V *Meteor* during a west-east transect of the Mediterranean (Tanhua et al., 2013). Intercalibration of salinity values between expeditions is subject to uncertainties of 0.002.

	Average 1900–2750		Average 1500–1900	
Year	Salinity	Potential Temperature	Salinity	Potential Temperature
2004	38.449	12.824	38.459	12.856
2005	38.450	12.828	38.461	12.860
2006	38.463	12.857	38.457	12.850
2008	38.470	12.873	38.458	12.835
2010	38.474	12.881	38.464	12.873
2011	38.482	12.900	38.480	12.906
2013	38.484	12.904	38.475	12.898

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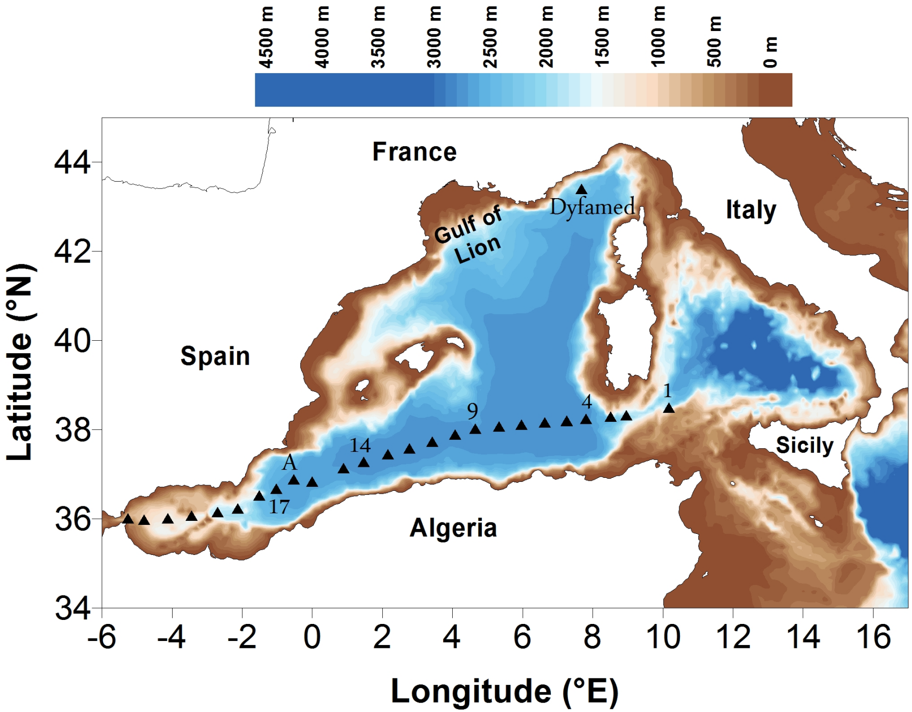

Fig. 1. Map of hydrographic stations in the western Mediterranean Sea that are used here to examine the processes leading to long term changes in Mediterranean temperature and salinity. Here we focus on long-term (1961–2008) changes in temperature and salinity of the Mediterranean waters at location A at the eastern entrance to the Alboran Sea and on recent (2004–2013) changes at station 9. Stations 4 to 17 were used by Bryden et al. (2013) to estimate downward heat and salt fluxes into the deep water. Also indicated is the Dyfamed station with monthly time series temperature and salinity profiles extending back to 1995.

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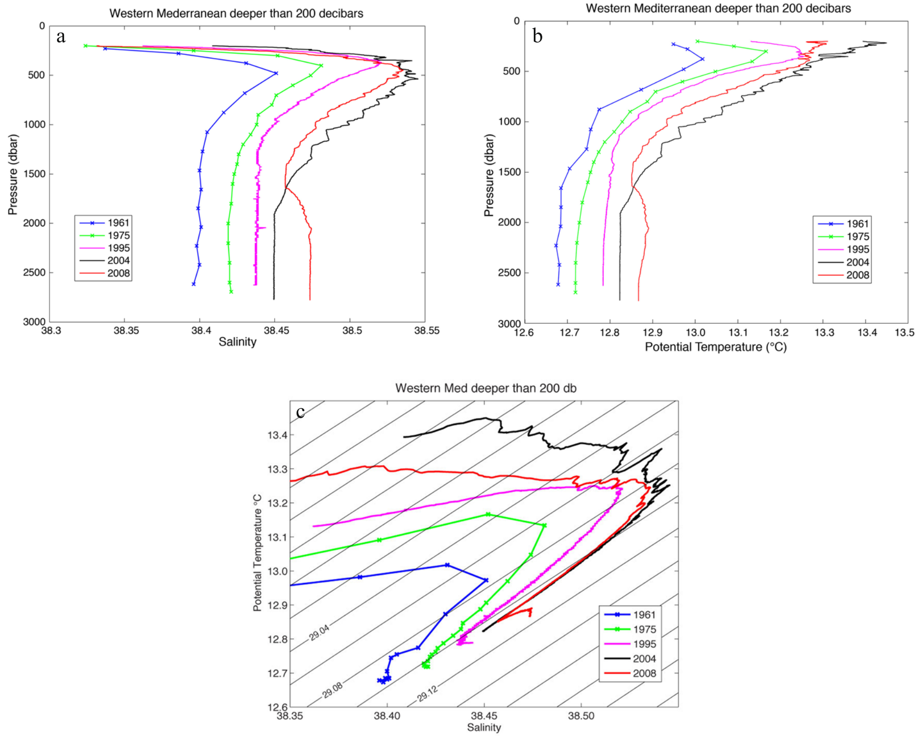

Fig. 2. Profiles of **(a)** salinity and **(b)** potential temperature vs. pressure for historical stations at location A at the eastern entrance to the Alboran Sea. **(c)** Potential temperature-salinity diagrams for the historical stations with contours of potential density relative to 2000 dbar indicated. Depth-averaged salinity and potential temperature below 200 m depth are given for each station in Table 1.

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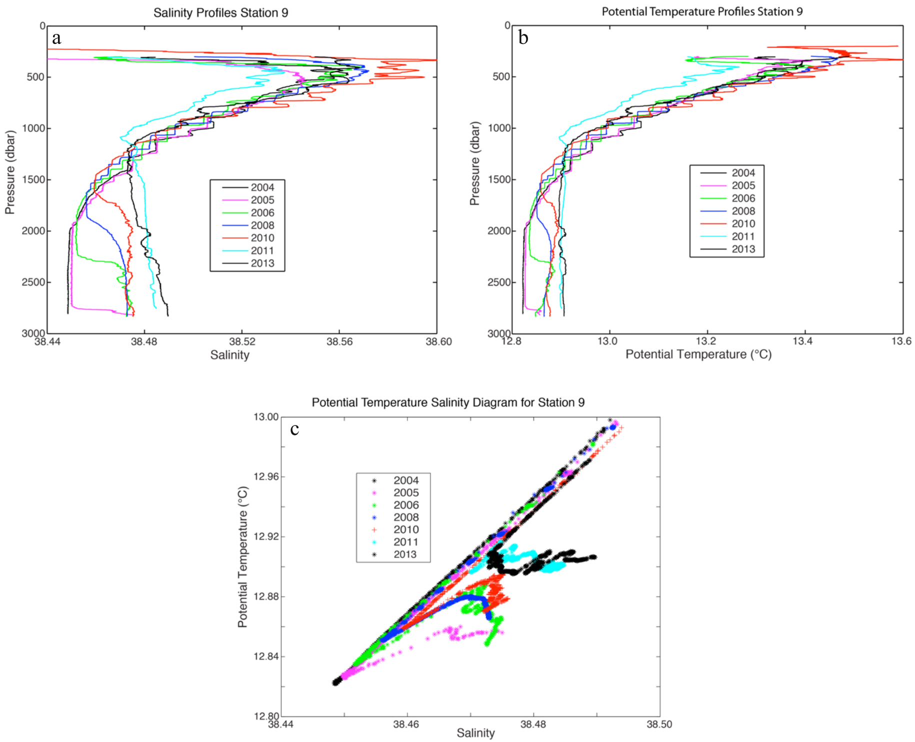

Fig. 3. Profiles of **(a)** salinity and **(b)** potential temperature vs. pressure for the repeat occupations at station 9. **(c)** Potential temperature-salinity diagrams for these recent stations below 1000 dbar. Depth-averaged salinity and potential temperature 1900–2750 dbar and 1500–1900 dbar are given for each station in Table 2.

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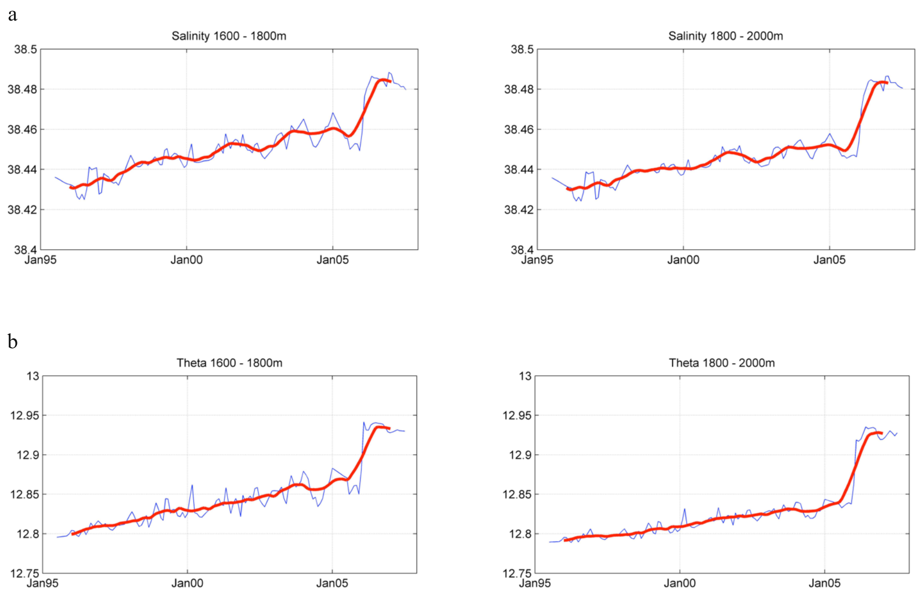

Fig. 4. Time series average **(a)** salinity and **(b)** potential temperature in the layers 1600–1800 m and 1800–2000 m at the Dyfamed station in the Ligurian Sea.

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