

**Met Office  
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# Observations of new western Mediterranean deep water formation using Argo floats 2004-2006

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## 1. Abstract

The deep convection that occurs in the western basin of the Mediterranean Sea was investigated using Argo float data over two consecutive winters in 2004-2005 and 2005-2006. The results showed deep mixed layers reaching 2000m in surprising locations, namely the eastern Catalan subbasin (39.785°N, 4.845°E) and the western Ligurian subbasin (43.392°N, 7.765°E). Subsequently, new deep water was formed in March of 2005 and 2006 with  $\theta = 12.89$ - $12.92^\circ\text{C}$ ,  $S = 38.48$ - $38.49$  and  $\sigma_\theta = 29.113 \text{ kg m}^{-3}$ . The deep water produced in the Ligurian subbasin during 2006 was more saline, warmer and denser than any historical observations of western Mediterranean deep water. The results show  $S$ ,  $\theta$  and  $\sigma_\theta$  in the western Mediterranean deep water are higher than 1990s values, with a salinity increase of  $1.5 \times 10^{-3} \text{ yr}^{-1}$ , a temperature increase of  $3.6 \times 10^{-3} \text{ }^\circ\text{C yr}^{-1}$  and a density increase of  $4.0 \times 10^{-3} \text{ kg m}^{-3} \text{ yr}^{-1}$  apparent from a dataset of western Mediterranean deep water properties spanning 1955-2006.

## 2. Introduction

- Deep convection occurs during winter in the western basin of the Mediterranean Sea<sup>1</sup>. This:
  - Involves violent mixing of surface and deep seawater, ventilating the water column.
  - Leads to formation of the Western Mediterranean Deep Water (WMDW), which drives basin-wide circulation.
- Observations of WMDW properties suggest the water mass has become warmer and saltier<sup>2</sup> over the past century.
  - Such changes are predicted to significantly alter the thermohaline circulation of the Mediterranean Sea in the coming century<sup>3</sup>.
- Profiling floats represent a new approach to studying deep convection and water mass changes within the Mediterranean Sea.

## 3. Objectives

- Determine whether deep convection took place in the western basin between 2004 and 2006.
- Understand how the deep water properties are changing with time.

Figure 1. Trajectories of 2 Argo floats in the western basin that evidenced deep convection (green – winter 2004-2005, blue – winter 2005-2006) and 3 that did not (grey). Circles indicate float locations at the start of November. The locations where deep convection was observed are marked by a star. The dashed region marks the normal extent of the deep convective regime in the Gulf of Lions and boxes 1 and 2 indicate the centre of the NCEP/NCAR re-analysis grid cells used within the study. The relevant subbasin names are also shown.

## 4. Method

- Analyse 145 temperature-salinity profiles collected between November-April 2004-2006 by 5 Argo floats deployed under the MedArgo<sup>4</sup> program (Figure 1).
- Compare water column structure in November 2004 and 2005 in the Catalan and Ligurian subbasins, by averaging all available Argo float data within two  $3^\circ \times 3^\circ$  cells, centred on the November float trajectories.
- Examine heat loss in locations proximate to Argo float trajectories using air-sea flux data from the NCEP/NCAR reanalysis<sup>5</sup>.
- Extend observational dataset of WMDW and Levantine Intermediate Water (LIW) properties<sup>2</sup> to include more recent observational evidence.

## 5. Deep convection observations

- Deep convection was observed during March 2005 in the eastern Catalan subbasin and March 2006 in the western Ligurian subbasin, by two separate Argo floats (Figure 1 and 2).

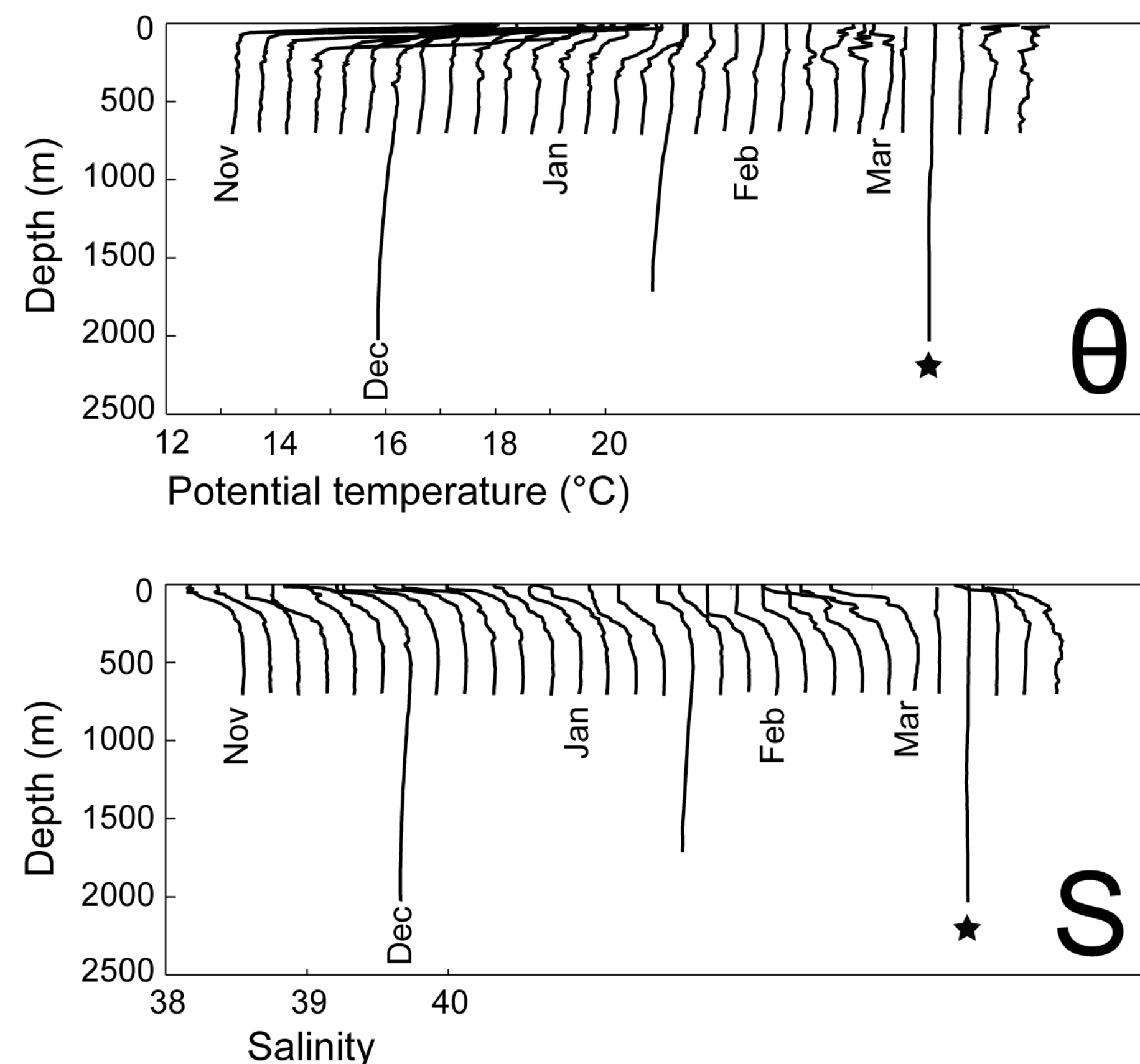


Figure 2. Potential temperature (top) and salinity (bottom) profiles from an Argo float in the Catalan subbasin (winter 2004-2005). A  $0.5^\circ\text{C}$  and  $0.2$  offset have been applied to consecutive  $\theta$  and  $S$  profiles to aid clarity. Progressive mixing of the water column in early winter is followed by a mixed layer extending to 2000m (12<sup>th</sup> March 2005 - marked by star) signalling the occurrence of deep convection. Similar evolution of vertical structures was seen the following winter in the Ligurian subbasin (results not shown).

- Argo float data recorded new WMDW produced in March 2005 and March 2006 with  $\theta = 12.89$ - $12.92^\circ\text{C}$ ,  $S = 38.48$ - $38.49$  and  $\sigma_\theta = 29.113 \text{ kg m}^{-3}$  respectively (Figure 3).

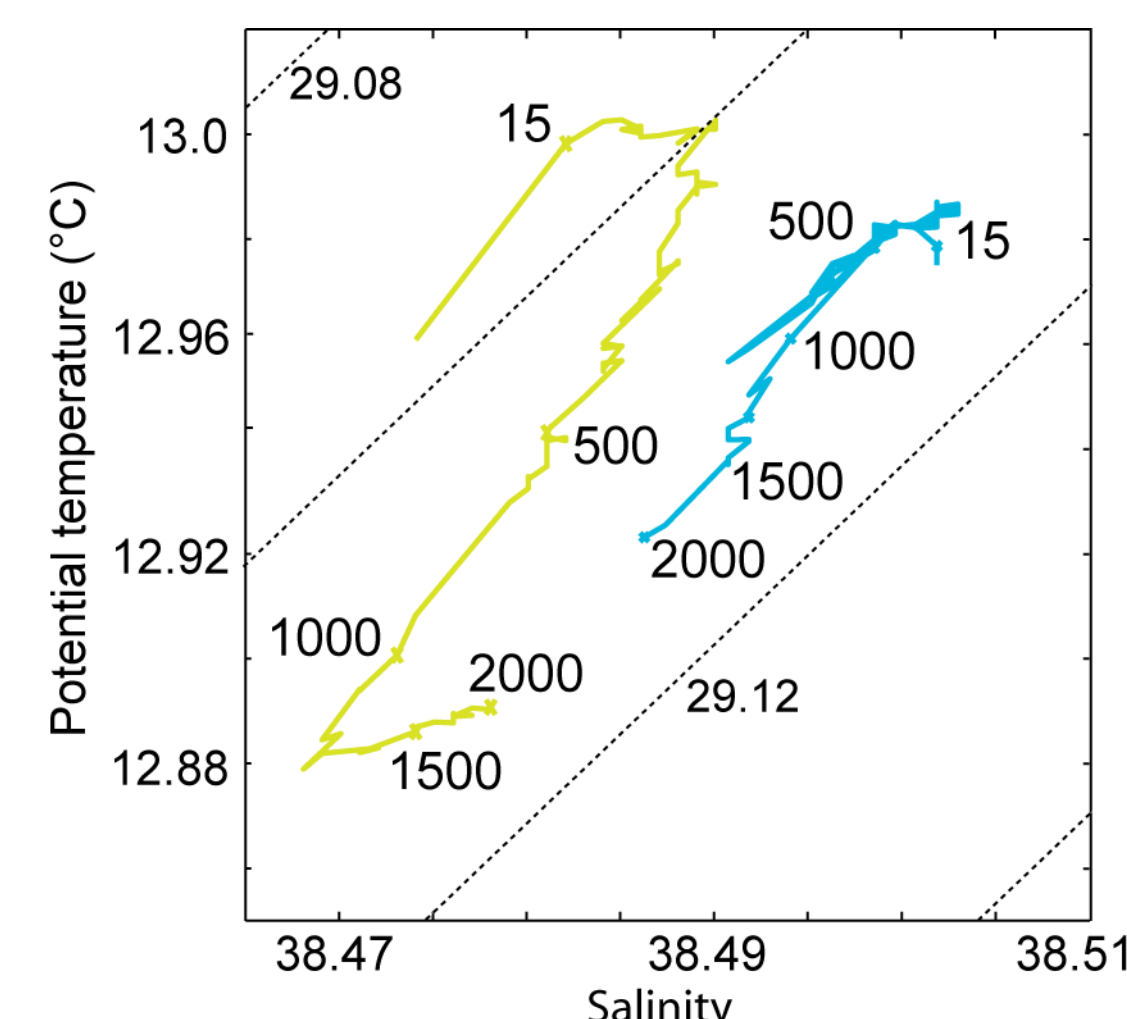


Figure 3.  $\theta/S$  diagram (with  $\sigma_\theta$  anomaly contours) from 2 separate Argo float profiles which detected new deep water production, one from the Catalan subbasin (green - March 2005) and one from the Ligurian subbasin (blue - March 2006). Tick marks denote depth of observation with new WMDW present at  $\sim 2000\text{m}$  in both cases.

- Winter 2005-2006 was characterised by an unusual water column structure (Figure 4) that facilitated deep convection in the Ligurian subbasin despite relatively low heat fluxes and heat loss (Figure 5).

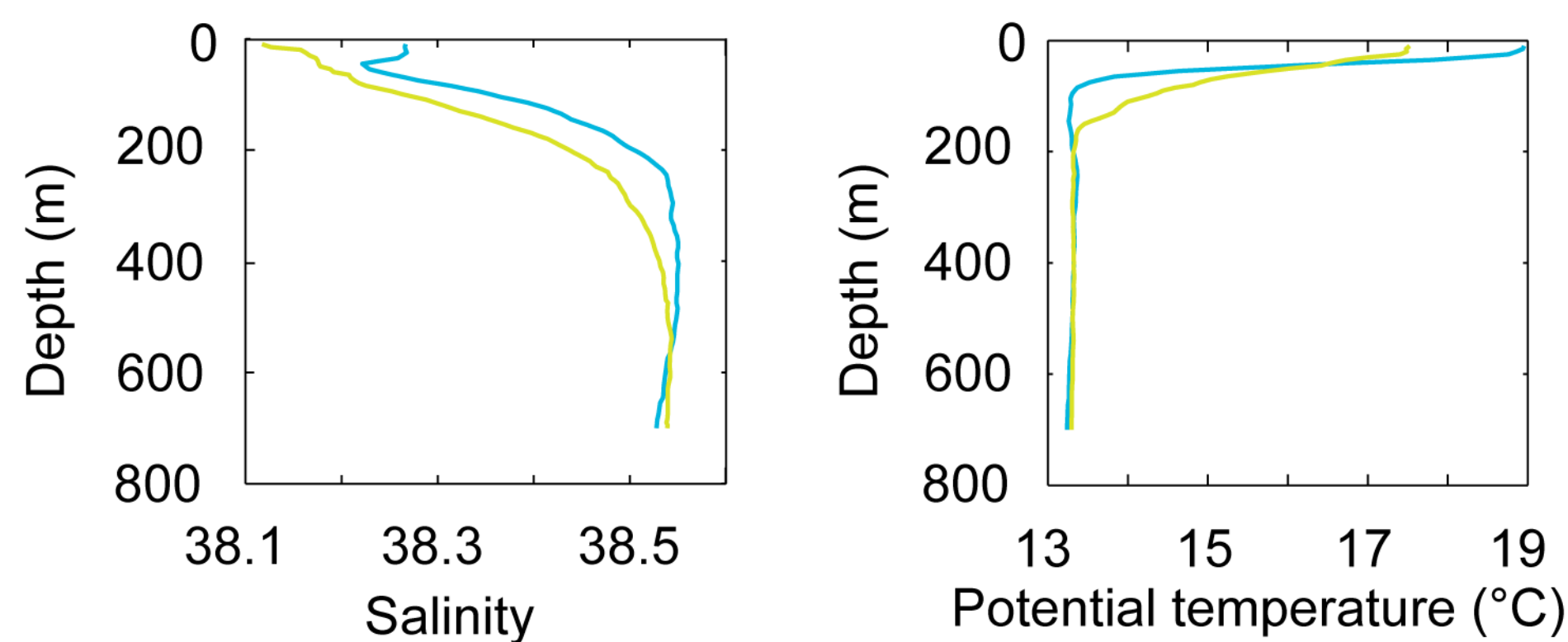


Figure 4. Comparison of vertical salinity and potential temperature profiles. These represent an average of all available Argo float data within the Catalan (green) and Ligurian (blue) subbasins during November 2004 and 2005 respectively. The Ligurian subbasin is characterised by a shallower, saltier and warmer intermediate water at  $\sim 400\text{m}$  (LIW), along with a colder and more saline surface water, during November 2005.

- Water column heat loss during both winters is attributed to persistent surface forcing from Mistral and Tramontane winds.
  - Winter 2004-2005 experienced unusually strong heat fluxes and a larger (cumulative) heat loss (Figure 5). As such, the deep convective regime was larger than normal<sup>6</sup>.

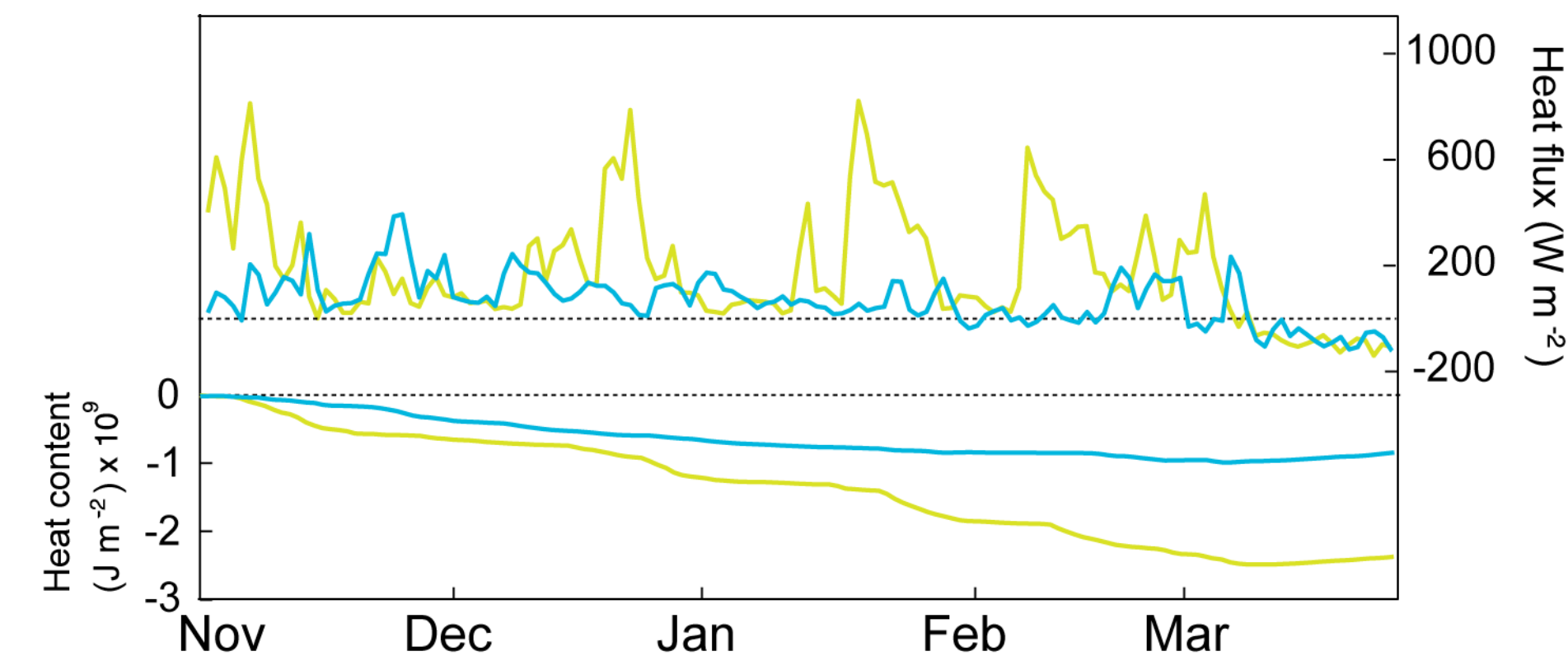


Figure 5. Air-sea heat fluxes (top - positive out of water column) and cumulative heat loss (bottom) from NCEP/NCAR re-analysis locations 1 (green, winter 2004-2005) and 2 (blue, winter 2005-2006). Of note are the large heat fluxes and heat loss in the Catalan subbasin, winter 2004-2005.

## 6. Is the deep water warming?

- Updated dataset of WMDW and LIW properties indicates the new WMDW formed during March 2006 in Ligurian subbasin is likely the warmest and saltiest in past century (Figure 6).
- WMDW has warmed on average by  $3.6 \times 10^{-3} \text{ }^\circ\text{C yr}^{-1}$ , with accompanying increases in salinity of  $1.5 \times 10^{-3} \text{ yr}^{-1}$  and in density of  $4.0 \times 10^{-4} \text{ kg m}^{-3} \text{ yr}^{-1}$  between 1955-2006.
- Similarly, the LIW has experienced a salinity increase of  $9.17 \times 10^{-4} \text{ yr}^{-1}$  over the same period

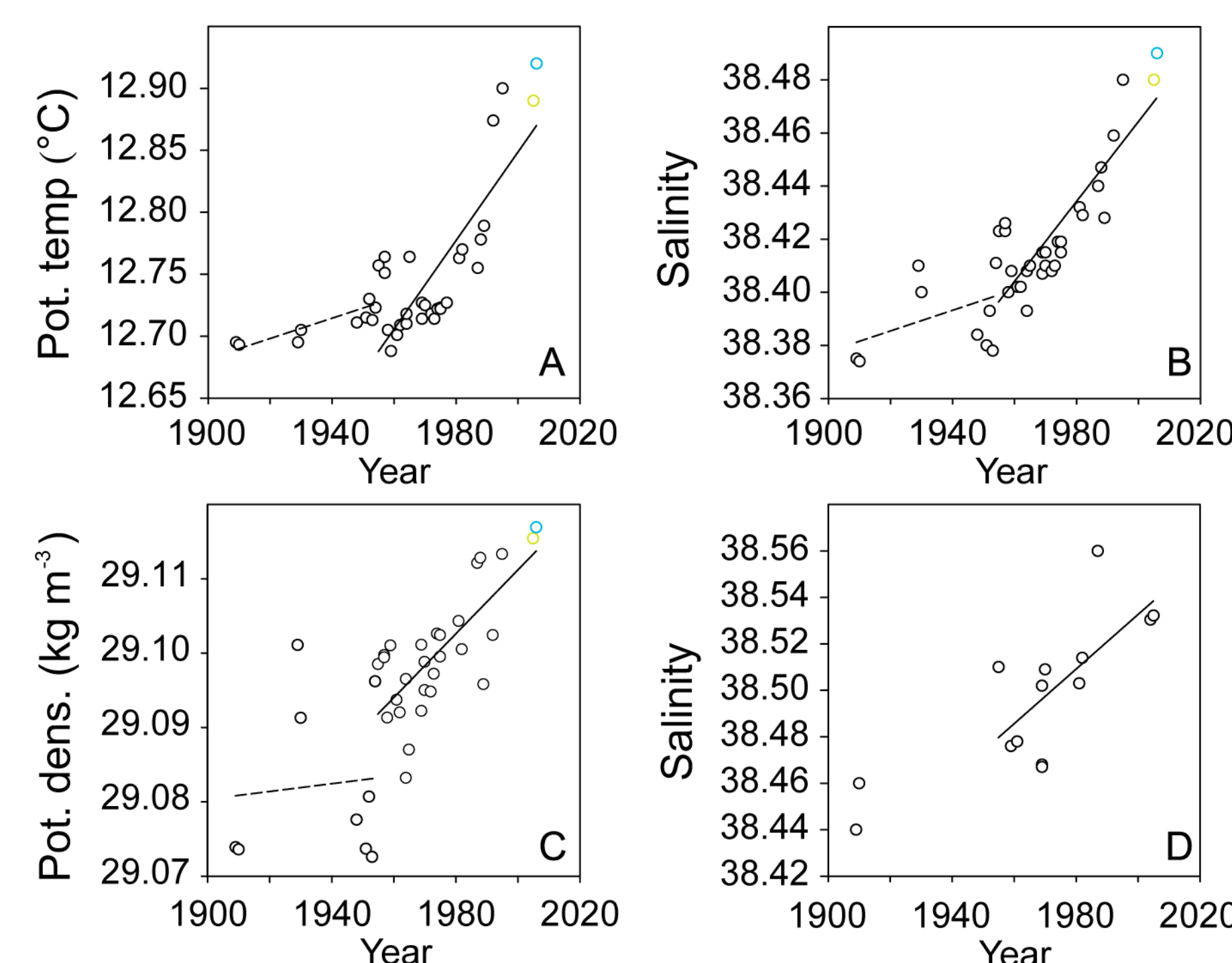


Figure 6. Observed potential temperature (A), salinity (B) and potential density (C) of the WMDW and salinity (D) of the LIW in the western basin (1909-2006). Trends were estimated from linear regressions for the periods 1909-1955 and 1955-2006 (dashed and solid lines). There are insufficient data to compute linear regressions pre-1955 in the LIW salinity. The new WMDW observed in March 2005 (green) and March 2006 (blue) is highlighted.

## 7. Discussion and conclusion

- Long-term salinity and temperature trends in the WMDW are linked to a higher salinity LIW present in the western basin. Increasing salinity in the LIW has been attributed to anthropogenic<sup>2</sup> reductions in freshwater fluxes and climatic cycle-induced<sup>7</sup> changes to heat fluxes within the eastern basin.
- There has been an enhancement of LIW salinity changes due to a shift in the location of deep water production in eastern basin<sup>8</sup>.
- Reduced rainfall inputs to the Mediterranean Sea are likely to have also increased the salinity of surface waters<sup>9</sup> in the western basin, facilitating deep water production and affecting WMDW properties.

**Deep water production between 2004-2006 occurred in 2 unusual locations within the western basin, detected using Argo floats. Production of a record WMDW in 2006 was linked to unusually saline surface waters and a shallower, higher salinity LIW present in the western basin. Salinity, temperature and density in the WMDW are higher than 1990s values, with positive trends evidenced in all three properties. For more detail please refer to Smith et al. (2008).**

8. References  
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