Indeed, although anomalies in batrotropic circulation are very patchy to the south of 54N, which corresponds to the highly turbulent North Atlantic Current (this region is discussed below), they are overall negative to the north of 56N from 2014 to 2017. Previous studies underlined that intensifications of the subpolar gyre in the last 40 years have been associated with eastward migrations of the eastern boundary of the gyre (Flatau et al. 2003; Hátún et al. 2005; Deshayes and Frankignoul 2008), and that has actually been observed in 2016 through an eastward migration of 35.1 isohaline (Figure 4.2.3 in Gourrion et al. 2018). Hence, this suggests that the cold and fresh anomalies observed from 2014 to 2017 are the result of dynamical changes in the subpolar gyre, which drivers are discussed at length in Gourrion et al. (2018). Note that this is actually in agreement with the conclusions of Piecuch et al. (2017) although they only investigate anomalies in ocean heat content.

Figure 4.2.1 also highlights warm and salty anomalies observed to the south of the subpolar gyre during 2017. The yearly anomalies in barotropic streamfunction (Figure 4.2.5) are instrumental in speculating about their origin. Those anomalies are very patchy with alternating positive and negative patterns, which is not surprising as this is a highly turbulent region with intense mesoscale activity. Yet, there seems to be an overall intensification in the amplitude and occurrence of positive patterns from 2014 until 2017, which could reflect the interannual adjustment of the ocean to the positive North Atlantic Oscillation phase that began in 2014 (Barrier et al. 2014). Ultimately, this dynamic adjustment is expected to favour the northward penetration of warm and salty subtropical water masses, which could explain the observed warm and salty anomalies to the south of the subpolar gyre in 2017.

4.3. Anticyclonic Eddy Anomaly: impact on the boundary current and circulation in the western Mediterranean Sea

Authors: Eva Aguiar, Mélanie Juza, Baptiste Mourre, Ananda Pascual, Evan Mason, Aida Alvera-Azcárate, Joaquín Tintoré

Statement of main outcome: An intense anticyclonic eddy anomaly event was observed in fall-winter 2017 north of the island of Mallorca in the western Mediterranean Sea. Similar long-lived eddies were reported during 1998 and 2010. The eddy alters the general cyclonic circulation of the Balearic Sea and the regional water mass properties. In particular, glider data in 2017 showed an anomalous strong inflow through the Ibiza Channel of recent Atlantic Water. These changes significantly affect the heat, salt and nutrient distributions in the area with implications for climate and primary production. The monitoring of these events is thus essential for both science and society in this area.

Products used:

Ref. No.	Product name and type	Documentation
4.3.1	SEALEVEL_MED_PHY_L4_REP_OBSERVATIONS_008_051 SEALEVEL_MED_PHY_L4_NRT_OBSERVATIONS_008_050 Sea level	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-SL-PUM-008-032-051.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-SL-QUID-008-032-051.pdf
4.3.2	INSITU_MED_TS_REP_OBSERVATIONS_031_041 INSITU_MED_NRT_OBSERVATIONS_031_035 *In situ* TS data	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-INS-PUM-013.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-INS-QUID-013-041.pdf http://marine.copernicus.eu/documents/QUID/CMEMS-INS-QUID-013-030-036.pdf

Mean flows, as part of the general circulation, are responsible for heat, salt and nutrient redistribution along our coasts, affecting climate and primary production. Their interactions with eddies produces exchanges of energy and momentum that can induce changes in the general ocean circulation (e.g. Kang and Curchitser 2015). Hence, it is essential to better understand the processes that favour eddy generation and their interaction with the mean flow. Previous theoretical studies have shown that instability processes associated with mean flows can lead to eddy generation and that these eddies, in turn, play an important role driving changes in the large-scale circulation (Holland and Lin 1975; Holland 1978; Hogg and Stommel 1985; Greatbatch 1987; Dengler et al. 2004; Marshall 2006).

In the southern part of the western Mediterranean Sea (Figure 4.3.1), the circulation in the Alboran Sea is mainly driven by the Atlantic Jet entering the basin at the Strait of Gibraltar (Parrilla and Kinder 1987; Viúdez and Haney 1997) bringing fresh Atlantic Water with salinity values around 36.5. In the northern part of the western Mediterranean, the circulation is characterised by a strong boundary current (the so-called Northern Current), which flows south-westward through the Balearic Sea, before splitting into two branches (Font et al. 1988): one deviating along the northern slope of the Balearic Islands forming the Balearic Current (Ruiz et al. 2009; Mason and Pascual 2013) and the other flowing southward through the Ibiza Channel (Pinot et al. 2002). This channel is often considered to be a choke point of meridional exchanges between the northern and southern basins (Heslop et al. 2012; Juza et al. 2013). The intense meso-scale activity

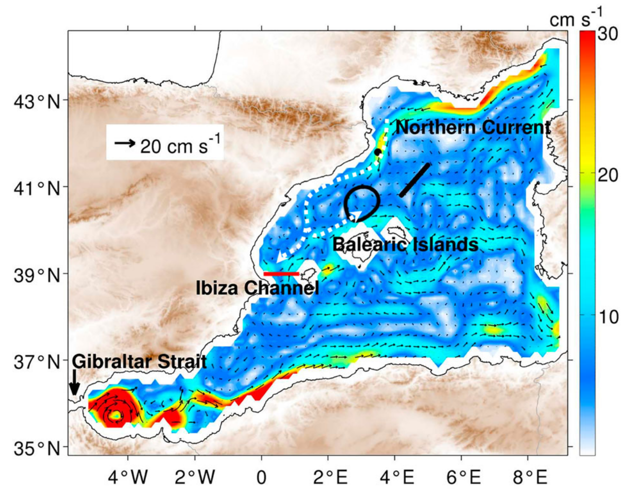

Figure 4.3.1. Mean geostrophic velocities from the product reference 4.3.1 over the period 1993–2012 in the western Mediterranean Sea. White arrows represent the main regional circulation pattern in the Balearic Sea. The black contour delimits the anticyclonic eddy anomaly influence-area where the climatological index is calculated (see text for more details). The black point denotes the deflection location of the Northern Current, the black line is the section where the transports are extracted to monitor that deviation, and the red line corresponds to the glider transect in the Ibiza Channel.

observed in the western Mediterranean Sea is associated with a small Rossby radius (approximately 10 km; Robinson et al. 2001). Moreover, the high number of available observations (Tintoré et al. 2013) converts this oceanic sub-basin into a small ocean laboratory where eddy-mean flow interactions can be monitored, detected, and studied.

In this study, we use sea level anomalies from the product reference 4.3.1 over the period 1993–2017. First, the eddy anomaly is characterised based on monthly mean sea surface height maps (adding the sea level anomaly maps to the mean dynamic topography; Rio et al. 2014) (Figure 4.3.2(a)). Then, the influence area of the anticyclonic eddy anomaly is defined (Figure 4.3.1) by calculating the mean contour of all the anticyclonic eddies detected by an eddy identification and tracking algorithm (Mason et al. 2014) north of Mallorca in 2017. A climatological index is derived from the spatially-averaged sea level over the influence area. This index is seasonal and low-pass filtered using a 30-day moving average to detect only long-lived eddy anomalies (Escudier et al. 2016) which are our focus in this study. The index enables us to define the anomalous character of the reported events (Figure 4.3.2(b)). Finally, the Northern Current is monitored at two locations as displayed in Figure 4.3.1 (Figure 4.3.2(c,d)). Geostrophic velocity time series have been computed from sea level anomalies using the equation for geostrophic equilibrium. Associated transport time series have been calculated from the perpendicular component of the velocities projected onto the defined section. High-resolution glider data in the Ibiza Channel as part of the product reference 4.3.2 are also used over their available period 2011–2017 to indicate the presence or not of anomalous Atlantic Water of recent origin south of the position of the eddy anomaly.

The anticyclonic eddy anomaly first occurs during September 2017 and persists until February 2018, with a radius varying between 32 and 90 km (Figure 4.3.2 (a)). The climatological index (Figure 4.3.2(b)) confirms the formation and persistence of this eddy, and also highlights the two previous events in 1998 and 2010 (Pascual et al. 2002; Mason and Pascual 2013). The maxima of the index typically occur in the fall-winter months. They are higher in 1998 and 2017 (16 and 20 cm, respectively) compared to 2010 (12 cm), and correspond to long-lived anticyclonic eddies with durations of four to five months in 1998 and 2017, and two months in 2010. Other anticyclonic eddies in the same area as reported in the literature were not persistent enough (shorter than 30 days) to be detected by the index. These include for example, the eddies in fall 2001 (Rubio et al. 2009) and in April 2008 (Bouffard et al. 2010). The anticyclonic eddy analysed by Amores et al. (2013) in 2010 occurred in a different area further south. The 2007 anticyclonic eddy studied by Garreau et al. (2011) in this area was not stationary, and was migrating along the Catalan continental slope into the Balearic Sea during a period of two months and a half.

The time series of the zonal geostrophic component of the Northern Current off Cap de Begur from 1993 to 2017 clearly indicates the eastward deviation of the current downstream from Creus Cape (black point, Figure 4.3.1) during the years associated with the anticyclonic eddy anomaly (Figure 4.3.2(c)): 1998, 2010 and 2017. During these three events, the lags between the maxima of the northern current zonal component and of the climatological index suggest that the Northern Current deviates first. The anticyclonic eddy anomaly reaches its maximum two months later in 1998 and 2017 and one month later in 2010. The maximum transport monitored further south east is produced one week after the maximum of northern current deviation in 1998, and around two months later in the case of the 2010 and 2017 events (Figure 4.3.2(d)). These delays are associated with slightly different evolutions of the eddy anomaly.

Water mass transports are computed using data from gliders in the Ibiza Channel (as in Heslop et al. 2012) (section shown in Figure 4.3.1) starting from January 2011 (product reference 4.3.2). The time series of meridional geostrophic transports show an intensification of the northward flow associated with the entrance of

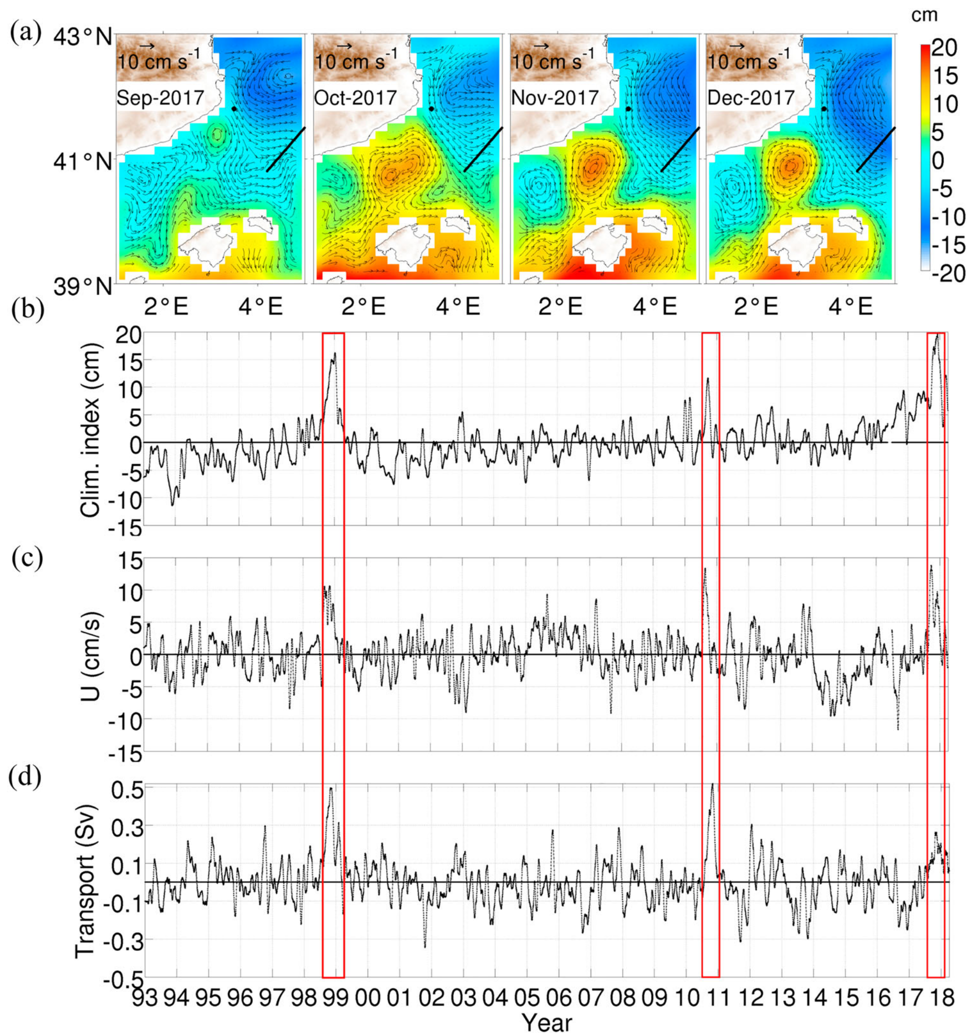

Figure 4.3.2. (a) Monthly sea surface height maps and associated geostrophic currents in September, October, November and December 2017 from the product reference 4.3.1, (b) Anticyclonic eddy anomaly climatological index, (c) Northern Current zonal component extracted at the point displayed in Figure 4.3.2(a), and (d) Geostrophic transport through the black section shown in Figure 4.3.2(a).

recent Atlantic Water into the Balearic Sea since the end of 2015 (Figure 4.3.3). Strong northward transports of this water mass are captured by the gliders, in particular in October 2016 (with values higher than 0.5 Sv) and in October 2017 when the maxima are reached (1 Sv). During these two autumnal glider missions, the inflow of recent Atlantic Water represents a large amount of the total transport (41–56% in 2016 and 48–59% in 2017) leading to an unusual and strong positive net inflow. During the anticyclonic eddy anomaly event of 1998, Pascual et al. (2002) also reported the anomalous presence of recent Atlantic Water in the Balearic Sea, which was explained by the possible weakening of the Northern Current that leads to the entrance of this water mass from the Alboran Sea through the Balearic channels.

The mechanisms involved in the process of the eddy generation are related to barotropic instabilities, due to horizontal shear perturbations of the ocean currents, and/or to baroclinic instabilities, induced by major changes in the stratification. Concretely, in this area, Pascual et al. (2002) argue that that the presence of warm water in the Balearic Sea interfered with the negative curl from the northwesterly Mistral wind shear downstream of the Pyrenees (Herbaut et al. 1997) could generate the strong eddy in fall 1998. Rubio et al. (2009) related the generation of the anticyclonic eddy in September 2001 to the separation of the coastal current downstream of Cape Creus that was induced by strong Mistral wind events. However, our empirical orthogonal function analysis of the winds in the northwestern Mediterranean Sea indicate that the zero curl-isoline on the northern edge of the eddy is a necessary but not a sufficient condition to produce the strong and long-term eddy (not shown). Consequently, we suggest a combination of several factors are responsible

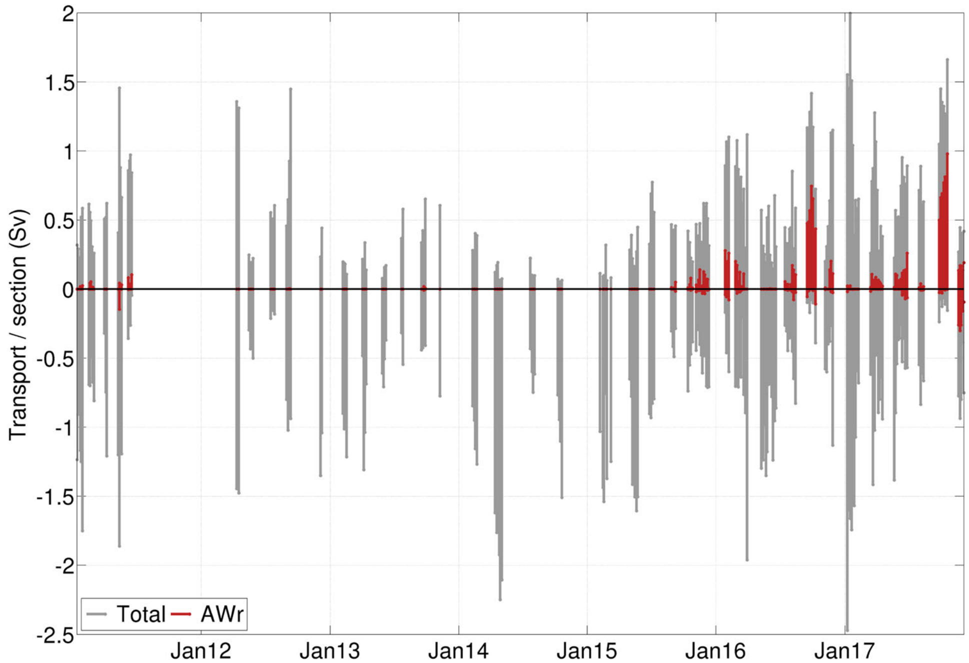

Figure 4.3.3. Northward (positive) and southward (negative) geostrophic transports in the Ibiza Channel integrated over the full water column (grey) and only considering recent Atlantic Water (red) obtained from product reference 4.3.2 during the glider missions from 2011 to 2017.

for the formation of the eddy event in 2017. These include the intense Mistral wind jets which could be responsible for the coastal detachment of the Northern Current. This in turn would favour the recent Atlantic Water coastal intrusion, and which would then gain negative vorticity due to the negative curl caused by wind in this area. High-resolution numerical model simulations will be used in the future to analyse this hypothesis and to improve our knowledge of the generation and permanence of these mesoscale eddies and their interaction with the mean flow.

Acknowledgements

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4.4. Insights on 2017 Marine Heat Waves in the Mediterranean Sea

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Statement of main outcomes: Overall, 99.6% of Mediterranean Sea surface experienced at least one Marine Heat Wave event during year 2017. Strong Marine Heat Wave events occurred at regional scale, in June, July and August. Analysis of sea surface temperature from CMEMS revealed unprecedented Marine Heat Wave total duration in the north-western sub-region (up to 225 days locally in the north Catalan Sea) and exceptionally long single event (entire summer) in the Eastern Levantine Sea. In all sub-regions examined, a long-term increasing trend in annual Marine Heat Wave duration is obvious over the 1982–2017 period. As for previous significant Marine Heat Wave events (e.g. summer 2003), mass mortality events affected the benthic biota in the north-western Mediterranean Sea in 2017. Unprecedented large-scale and long-lasting benthic mucilaginous bloom also occurred in the north Catalan Sea. Analysis of *in situ* temperature time series in Scandola Marine Protected Area showed sub-surface intensification of Marine Heat Wave events (both in intensity and duration) which could not be inferred from surface data only. Enhancing the monitoring framework on physical and biological indicators is thus required for good evaluation of Marine Heat Wave and their impacts on Marine Coastal Biodiversity at local and regional scale.

Products used:

Ref. No.	Product name and type	Documentation
4.4.1	SST_MED_SST_L4_REP_ OBSERVATIONS_010_021 Sea surface temperature data	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OSI-PUM-010-021-022.pdf QUID: http://marine.copernicus.eu/documents/QUID/

(Continued)