

1 **Contrasting impact of different Mediterranean cyclones on the** 2 **hydrological cycle and ocean heat content**

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11
12 **Abstract.** Mediterranean cyclones (MCs) play a crucial role in the Mediterranean hydrological cycle (MHC),
13 driving up to 70% of precipitation and 50% of evaporation totals, and larger fractions of their extremes. Therefore,
14 regional sensitivity to warming is often associated with long-term changes of MCs. These may lead to regional
15 climate feedback through pathways linked directly or indirectly to the MHC: from decreasing cloud cover and
16 precipitation to increased water-vapor uptake. However, the ability of MCs to generate coherent climate feedback
17 is under ongoing debate. Moreover, given the large diversity of processes driving MCs, the role of each in the
18 MHC and their variability remains unexplored. Our recent process-based MC classification allows the breakdown
19 of MC's contribution to the MHC under different dominant cyclogenetic processes. Based on 1-hourly ECMWF
20 ERA5 reanalysis data (1979-2020), 3190 MC tracks are analyzed. We first quantify the total contribution of MCs
21 to the MHC following the cyclone tracks. We analyze the spatial and temporal patterns of the annually
22 accumulated cyclone-induced precipitation (P) and surface evaporation (E). The process-based classification
23 allows the quantification of independent contributions from various cyclone drivers to cyclone-induced P and E
24 and their long-term trends. The results show that the overall annual P-E residual associated with MCs is positive
25 but decreases over time, losing ~0.5 mm/yr per year. The classification reveals opposing roles and long-term
26 trends in the annual contributions of each cyclone driver, shifting the balance between cyclone-induced P and E
27 from P-dominated towards E-dominated MCs. These changes are primarily due to reduced precipitation associated
28 with double-jet MCs and daughter cyclones and increased evaporation associated with thermal lows (-0.2
29 mm/year, each), alternately driven by changes in frequency and/or flux intensities of specific cyclone drivers.
30 Mainly, a sharp rise in frequency affects heat lows, while double-jet cyclones are mostly affected by decreasing
31 precipitation rates. The downward impact of MCs on the Mediterranean Sea heat content also varies sharply
32 between MC types: while MCs generally draw heat from the Mediterranean, certain MC types have the opposing
33 effect, adding further heat. Beyond providing a framework for follow-up analysis of MC impact on the MHC in
34 future climate simulations, the results highlight the independent and opposing contributions of different MC
35 drivers to the Mediterranean heat content, enhancing our understanding of their dynamic response to warming and
36 its impact on society.

38 **1. Introduction:**

39 Extratropical cyclones are prominent low pressure weather systems that strongly influence the hydrological cycle,
40 as they drive heavy precipitation (P) and evaporation (E). While the link between cyclones and P is well defined
41 through their forced uplifting, E involves more complex relationships with cyclone-induced perturbations via
42 wind speed, humidity and temperature.

43 The Mediterranean Sea hosts a unique subset of cyclones in the transition zone between the sub- and extra-tropics.
44 Mediterranean cyclones (MCs) differ from other open-ocean cyclones primarily in their compact spatial structure
45 and the diverse influences of orography, strong land-sea contrast, and relatively warm sea surface temperatures
46 (Flaounas et al., 2022). As a result, MCs are considered challenging to predict and represent in models on both
47 weather and climate scales (Lionello et al., 2007; Hatzaki et al., 2023), with their transient manifestation as extra-
48 tropical cyclones, subtropical heat lows, and rare tropical-like cyclones (Flaounas et al., 2015).

49 Beyond their socio-economic impacts, reviewed recently by Khodayar et al., (2025), MCs have a significant
50 influence on the Mediterranean hydrological cycle (MHC), driving extreme E and P rates and accounting for
51 considerable portions of the overall air-sea exchange of freshwater fluxes (Raveh-Rubin and Wernli 2015;
52 Lebeaupin Brossier et al., 2014; Flaounas et al., 2016). Due to their dominance on the MHC, long-term variations
53 in features of MCs are often used to explain the regional sensitivity to climate change (Lionello et al., 2007;
54 Hochman et al., 2020; Reale et al., 2022; Zittis et al., 2022). Specifically, regions prone to moistening are expected
55 to get moister, and vice versa for regions prone to drying. This phenomenon is often referred to as the “wet gets
56 wetter - dry gets drier” mechanism, or the “Mediterranean precipitation paradox”, often explained by a rise in
57 MC-associated P due to increased water-vapor uptake caused by the rise in temperatures under global warming,
58 and a drying effect as MCs become less frequent in the southern and eastern Mediterranean due to the poleward
59 shift of the Atlantic storm track (Chericoni et al., 2025).

60 However, the direct link to cyclone properties is usually implied rather than shown, and it remains unclear how
61 MCs respond to and affect the regional climate changes through their contribution to P (Zappa et al., 2015; Zittis
62 et al., 2019; Scoccimarro et al., 2025) and E (Flaounas et al., 2019; Reale et al., 2021). While in the tropics
63 enhanced E rates are deemed necessary to sustain cyclones and generate P, in the extra-tropics, extreme
64 evaporation rates may arise preferentially in their cold sector. In the cold sector, under the wake of cyclone and
65 frontal passage, E typically peaks under cold air outbreaks (Papritz et al., 2015; Thurnherr et al., 2020; Aemisegger
66 and Papritz 2021) and dry intrusions, namely, large-scale descending air streams of extratropical cyclones, that
67 amplify surface evaporation through the penetration of dry air masses with strong wind speeds from upper levels
68 to the surface boundary layer (Raveh-Rubin 2017; Ilotoviz et al., 2021; Rai and Raveh Rubin 2023; Klaider and
69 Raveh-Rubin 2023; Givon et al., 2024b). While the frequency of MCs is expected to decrease (Nissen et al., 2014),
70 uncertainty exists regarding their projected intensification under global warming, changing their overall
71 contribution to the MHC and being inconsistent among climate models (Gaertner et al., 2007). Lionello et al.,
72 (2007) investigated projected changes in cyclone activity over Europe, including the Mediterranean basin, and
73 emphasized the importance of regional characterization of changes in cyclonic activity, due to the large variability
74 among MCs.

75 Changes in water availability are often measured using the difference between E and P, with recent work
76 (Tootoonchi et al., 2025) indicating MCs (transient eddies) as the major driver of humidity convergence from the
77 ocean sources to adjacent land sinks, pointing out their importance for the atmospheric branch of the MHC.
78 Flaounas et al., (2016) used an intensity-dependent cyclone impact area to analyze the climatological contribution
79 of MCs to the atmospheric MHC in coupled, high-resolution WRF (atmosphere) and NEMO (ocean) simulations.
80 Their results show that up to 90% of P extremes (95th percentile) and up to 70% of extreme E rates are associated
81 with MCs. The study further evaluates the annual contribution of MCs to the MHC, suggesting a small residual
82 (E-P). They conclude that MCs sustain a balance between their induced E and P on longer time scales, suggesting
83 that changes in their contributions are unlikely to substantially alter the future MHC.

84 Nevertheless, considering the various manifestations of MCs, it is important to know whether their role in the
85 MHC differs by driving mechanism, as each may pose a different direction of response to climate change. Givon
86 et al., (2024a) revealed the potential of classifying MC tracks by their dominant large-scale driver to enhance the
87 dynamical understanding of MCs and their long-term variability. This classification was adopted by Rousseau-
88 Rizzi et al., (2024), Portal et al., (2024), and Portal et al., (2025) to analyze MC-related compound hazards and
89 extremes (including P) and investigate their convective features. By separating MC tracks into 9 distinct groups
90 indicative of different dominant cyclogenetic processes, the fundamentally different life cycles and weather
91 impacts of each MC driver are revealed, allowing the decomposition of the hydrological contribution of MCs into
92 a spectrum of MC drivers.

93 Primarily through their intense evaporation rates, MCs (and cyclones in general) are effective at extracting latent
94 and sensible heat from the ocean. While several studies have focused on the cooling effect of regional gap-wind
95 regimes such as the mistral and bora winds (Berthou et al., 2018; Flamant 2003) on sea surface temperatures,
96 literature focusing on the direct impact of MCs on the ocean heat content (OHC) is scarce. Givon et al., (2024b),
97 for example, systematically analyzed ocean evaporation fluxes associated with the mistral, emphasizing the role
98 of downward advection of upper-level momentum by dry intrusions in the generation of extreme evaporation
99 rates. Keller et al., (2022) and (2024) and Keller (2025) further consolidated the importance of the mistral wind
100 to deep water formation in the Gulf of Lion. However, how different MC drivers impact the Mediterranean OHC
101 is not well known. Since OHC is often considered as an energy source for developing MCs (Stathopoulos et al.,
102 2020; Strobach et al., 2024), especially tropical-like ones (“Medicanes”, Cavicchia et al., 2014; Jangir et al., 2024,
103 Miglietta et al., 2025), we aim to evaluate which MC types are the most influential for the OHC in different regions
104 across the Mediterranean basin. Revealing subtle changes in the heat extraction capacity of MCs is important, as
105 these changes may compromise their climatological role as cooling agents in the oceanic system. Analyzing the
106 impact of the various MC drivers on both the MHC and OHC will allow a better understanding of future changes
107 in the Mediterranean climate. Therefore, our research objectives are threefold:

- 108 1. Quantify overall cyclone contribution to the mean annual MHC (P, E and P-E), and decompose this to
109 different MC drivers (following Givon et al., 2024a)
- 110 2. Reveal historical trends in (1)
- 111 3. Evaluate the influence of (1) on the OHC

112 For this study, we use comprehensive cyclone track data, generated through a composite cyclone detection
113 algorithm (Flaounas et al., 2023) based on ECMWF ERA5 reanalysis (1979-2020) and apply the cyclone-centered
114 potential vorticity (PV) classification presented by Givon et al., (2024a). We define a cyclone impact area to
115 accumulate surface evaporation and precipitation throughout each cyclone track and obtain the cyclone-induced
116 fluxes. We then separate each MC track into the 9 classes and evaluate the long-term trends in the annually
117 accumulated precipitation and evaporation. Finally, we use a NEMO simulation forced by ERA5 to quantify the
118 impact of MCs on the OHC, examining the cyclone-induced heat loss of the Mediterranean.

119 **2. Methods:**

120 **2.1. Cyclone detection and tracking**

121 MCs are here detected and tracked based on a composite cyclone detection algorithm presented by Flaounas et
122 al., (2023) and used by Givon et al., (2024a) for the dynamic classification of MCs. With this approach, 10
123 different tracking methods are applied to 1-hourly ERA5 reanalysis of ECMWF (Hersbach et al., 2020).
124 Confidence level 5 is chosen, denoting the agreement of at least 5 detection methods on every MC track. Each
125 composite cyclone track contains the location of its center throughout its lifetime. Sea level pressure at the cyclone
126 center is also reported, and its minimum along the track is used to define MC peak time for classification. Some
127 cyclone tracks that do not cross east of longitude 5°E are removed from the analysis, see more details in Givon et
128 al., (2024a). Overall, 3190 MC tracks are captured throughout the period, with a minimum lifetime of two days.

129 **2.2. Process-based classification**

130 Here, we utilize the cluster separation presented in Givon et al., (2024a). Specifically, for each MC at peak
131 intensity, the surrounding upper-level isentropic potential vorticity field (PV, vertically averaged between the 320-
132 340K isentropic levels) is extracted around the cyclone center. The PV field is considered within a domain
133 extending 20° east and west of the MC center, 40° to the north and 20° to the south. The PV field is classified using
134 a self-organizing map algorithm (SOM), producing 9 robust clusters with distinct Rossby wave patterns, unique
135 surface impacts, and inherent characteristics. Here, we attribute the cluster number originally determined for the
136 cyclone peak time throughout the cyclone's lifetime.

137 **2.3. MC impact area**

138 We integrate the hourly P and E accumulated along each MC track to derive MC-induced freshwater fluxes. To
139 attribute the fluxes to the MC track and allow an objective comparison of the different MC types we define a
140 constant 10° radius impact area around the cyclone center, within which the fluxes are accumulated in 1-hourly
141 steps along the track. This ensures that no cluster is favored or penalized by impact area differences. While a 10°
142 radius may be considered excessive to associate to MCs (Flaounas et al., 2016), it has been adopted by recent
143 studies on MC impacts (Rousseau-Rizzi et al., 2024 and Portal et al., 2024). Results show little sensitivity to the
144 MC impact area in the present framework: with a 5° radius, the spatially accumulated cyclone-induced fluxes
145 naturally decrease, but the fundamental differences among the MC types and their temporal variability are
146 unchanged. Area-weighted averages are calculated across the MC impact area and accumulated annually to
147 quantify total MC-induced fluxes.

148 To investigate interannual trends in MC-induced evaporation and precipitation, we accumulate freshwater fluxes
 149 spatially and temporally across each year, integrating along the MC tracks. We thus obtain a Lagrangian
 150 framework used to unveil the cyclone-driven component of the MHC under a process-based prism, resulting in a
 151 novel hydrological-budget analysis of differently driven MCs.

152 **2.4. Normalization by MC frequency**

153 As noted by Zappa (2014), changes in MC-induced P are influenced by both changes in MC frequency and
 154 intensity. A similar argument can be made for MC-induced E. To address both sources of variance, we complement
 155 the accumulated MHC contributions with their normalized ones. To eliminate variations in frequency and obtain
 156 the fluxes per cyclone, normalized P and E are evaluated as follows:

$$157 \quad P_{norm} = \bar{F}_{MC} \sum_y \frac{P_y}{F_y}$$

$$158 \quad E_{norm} = \bar{F}_{MC} \sum_y \frac{E_y}{F_y}$$

159 Where P_y, E_y stands for annual cyclone-induced precipitation and evaporation, respectively, F_y denotes the
 160 corresponding annual frequency of MCs, and \bar{F}_{MC} denotes the mean MC frequency across all years. The annual
 161 frequency accounts for the co-occurrence of multiple cyclones in the domain by counting the number of MC
 162 centers at every time step. Although this approach leads to large annual frequencies (up to 80%, as also recognized
 163 by Flaounas et al., 2016), it ensures the overall conservation of mass. We similarly normalize the contributions
 164 from each cluster to reveal MC types that are more susceptible to these elusive changes in intensity.

165 **2.5. Ocean heat content**

166 Ocean heat content (OHC) in the layer 0-300 m is computed using the Euro-Mediterranean Center on Climate
 167 Change (CMCC-Foundation) eddy-permitting global ocean reanalysis, C-GLORS v7. The model data is provided
 168 at daily frequency from 1993 up to 2019 and $1/4^\circ$ horizontal resolution with 50 vertical levels. Details on the
 169 model and improvements from previous versions are presented by Storto and Masina (2016). While suffering
 170 from low temporal resolution and a shorter temporal extent, the model proves valuable for process-based research
 171 on heat exchanges, in agreement with comparable independent estimates.

172 To investigate the impact of the various MC drivers on the OHC, we use a 6-day window centered at the location
 173 of each MC at peak intensity times and map the net difference in OHC before and after an MC passage. These
 174 differences are accumulated under the impact area at MC peak time on daily resolution and separated by cluster.
 175 The OHC is a measure of stored energy. As such, temporal changes in it can be interpreted as energy fluxes and
 176 are indeed affected by atmospheric fluxes of both sensible and latent heat. However, the OHC is affected by other
 177 processes as well, such as radiative and advective fluxes. Nevertheless, since the presence of MCs potentially
 178 influences all of these, and with the presence of cyclones being the only common feature of the observed data, the
 179 OHC response is interpreted as MC-driven fluxes for consistency. We thus convert the OHC difference (originally
 180 measured in Joules) to units of virtual evaporation rates (E_v , mm/year) as follows:

$$E_v = (365 * \bar{F}_{MC_d}) \frac{(OHC_{t_0+3} - OHC_{t_0-3})}{6 [days] * L_v}$$

Where \bar{F}_{MC_d} stands for the annual-mean frequency of MCs on daily scale (either as a whole or per cluster) considering only the peak-time (t_0) of each track, and L_v is the latent heat of evaporation. This way, the MC impact on the OHC is comparable to the atmospheric freshwater fluxes.

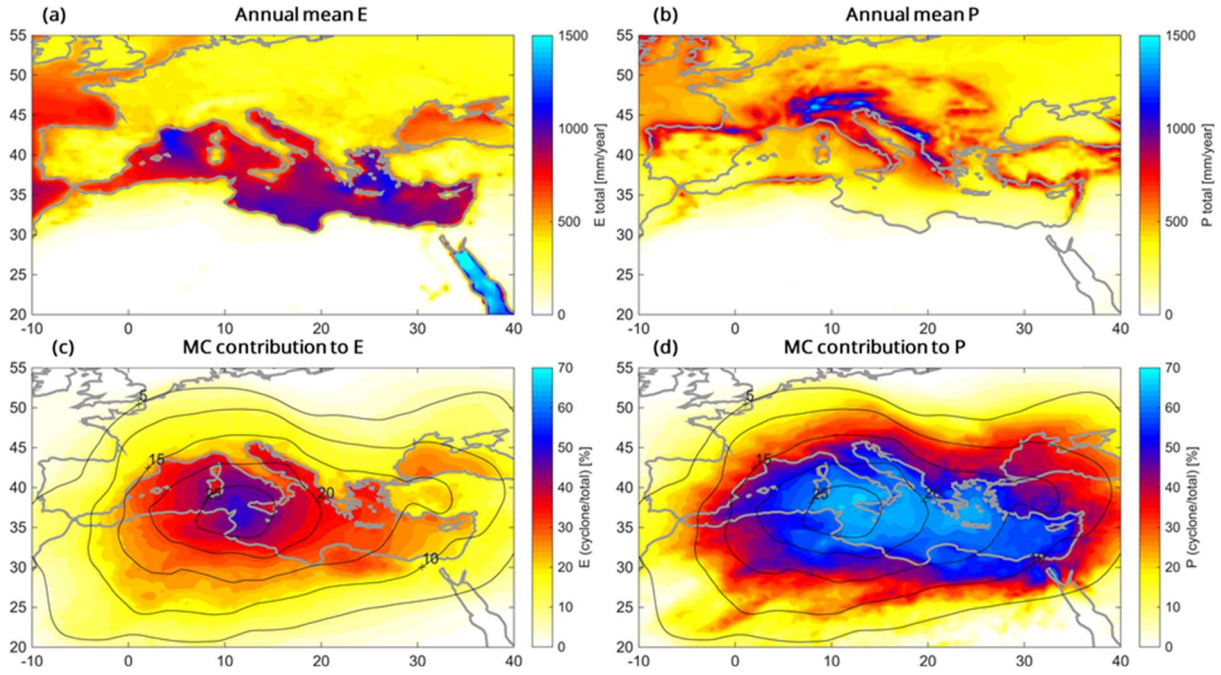
We note that this analysis does not fully disentangle the impact of the OHC on MCs, that tend to intensify with response to large OHC values. Nevertheless, the temporal evolution of the difference in OHC (not shown) suggests that the OHC response is temporally centered around the passage of MCs and provides a direct measure of the MC-related ocean-heat loss. We interpret the results as the impact of MCs on OHC, while admitting that MC intensity is partially impacted by initially high OHC values. The agreement between the MC-driven E and OHC response to MC supports this interpretation. In the future, we aim to further address this two-way coupling between MCs and the OHC in a dedicated study.

3. Results

3.1. MCs overall contribution to the MHC

We begin with a climatological overview of the MHC (Fig. 1 panels a and b), followed by the MC contribution to mean annual P and E. Overall, P is shown to mainly affect coastal areas and mountain ridges, reaching values up to 1500 mm/year, whereas E dominates over the maritime regions and is minimal over land. In agreement with previous studies (Flaounas et al., 2016; Tootoonchi et al., 2025), the results highlight the prominence of MCs on the MHC, driving up to 70% of total precipitation and up to 50% of total surface evaporation in various regions (Fig. 1 panels c and d). While the contribution of MCs to E overlaps well with cyclone density, the peaks of MC contribution to P are shifted eastwards. This is in line with the findings of Saaroni et al., (2010), highlighting the strong dependence of eastern Mediterranean rainfall on MCs. We note that the contribution of MCs to total surface evaporation is about twice their mean frequency, while their contribution to precipitation is about three times higher, indicating that MC-induced freshwater fluxes are strongly concentrated within the MC impact area rather than resulting from random spatial overlaps.

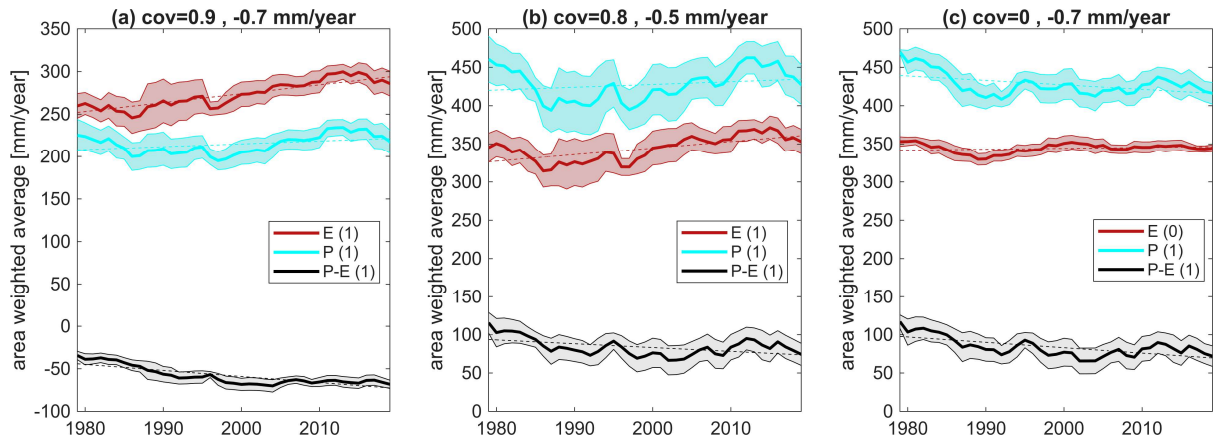
When examining the area-weighted accumulated fluxes in Fig. 2, grid points affected by MCs show higher P and E mean rates compared to the year-round average regardless of MC presence in the domain (compare panels a and b). While both P and E of MCs (Fig. 2b) are slightly increasing with time, the positive residual (P-E) associated with MCs is being gradually eroded. The normalized fluxes (Fig. 2c) reveal a decrease in P and an increase in E per cyclone. Interestingly, the covariance between MC-induced P and E is solely due to their shared MC frequencies, dropping to zero for the normalized E and P (Fig. 2c). This result suggests that instantaneous E and P rates are unconstrained when observed per cyclone, as MCs converge moisture from other sources in addition to their self-induced E to generate heavy P rates. To better understand the sources of these long-term variabilities, we examine the results under the nine dominant MC drivers.



214

215 *Figure 1: Annual-mean E (a) and P (b), and the relative contribution of MCs to E (c) and P (d) in shading, along*
 216 *with mean cyclone frequency \bar{F}_{MC} (black contours, %).*

217



218

219 *Figure 2: (a) 8-year moving mean (± 1 STD, shading) of total E (red), P (cyan), and P-E (black) within the domain*
 220 *shown in Figure 1 (10E-40W, 20N-55N). Dashed lines denote the corresponding linear best-fit. The result of a*
 221 *95% confidence level Mann-Kendall test for each component is shown in the legend (1 for a significant trend).*
 222 *(b) as in (a), but for the cyclone-induced E and P, considering only the cyclone impact area. (c) P_{norm} , E_{norm} , i.e.,*
 223 *as in (b) but normalized by annual cyclone frequency (hourly, including double counts), representing flux*
 224 *intensities. Titles denote the covariance factor between P and E followed by the slope of the linear best-fit*
 225 *(mm/year) for the P-E trends.*

226

3.2. MC contribution to the MHC by cluster

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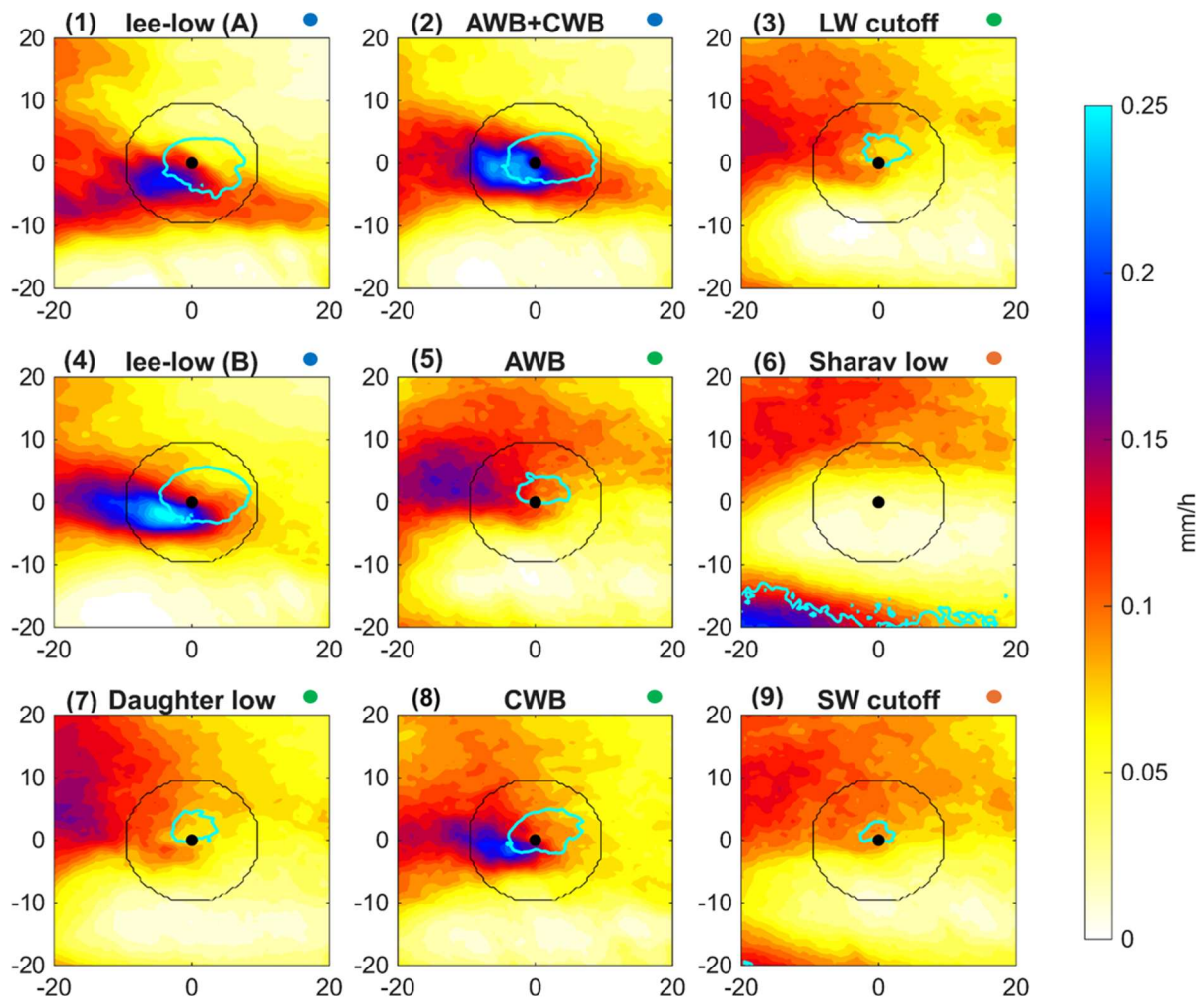
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229

Under the cyclone-centered PV classification, the complexity and competing effects of the various MC drivers on the MHC is clarified. Fig. 3 highlights the variability between the different MC drivers at peak cyclone intensity. Cluster 4, representing fully developed baroclinic MCs, shows the most intense instantaneous E and P fluxes while

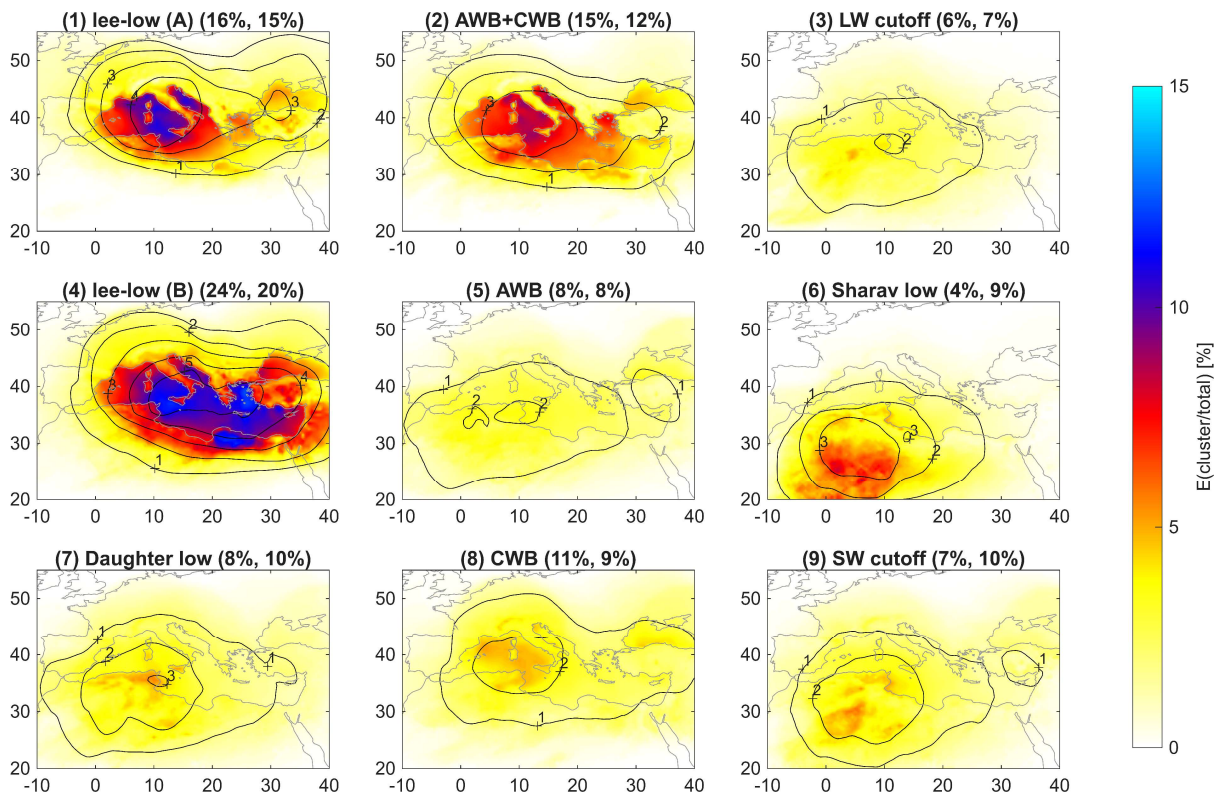
230 cluster 6, typically impacting North Africa, is associated with much weaker freshwater exchanges. However, sharp
 231 differences are also evident between clusters that share similar seasonal and geographical amplitudes, such as
 232 clusters 1, 2, and 4, and clusters 3, 5, and 7. Cluster 8, associated with narrow, cyclonically curving PV streamers,
 233 and recently found to be the most favorable for deep convection (Portal et al., 2025), notably exhibits the most
 234 intense fluxes among the off-winter clusters.

235 We note that the impact area well captures the E and P features associated with MCs. The relatively strong
 236 evaporation observed about 15° to the west of the MC centers of clusters 3, 5, and 7 (i.e., outside of the impact
 237 area) mostly occurs over the Atlantic Ocean, given their preferred locations (black contours in Figs. 4 and 5 and
 238 Fig. 7 in Givon et al., 2024a in more detail). With this MC-centered view it appears that a first-order correlation
 239 exists between instantaneous MC induced E and P. However, since some of the clusters appear more frequently
 240 on land, we next evaluate the accumulated fluxes throughout the MC duration and consider their geographical
 241 areas of influence.



242
 243 *Figure 3: cyclone-centered cluster composites of E (shading) and P (cyan contours, 0.25 mm/h) at classification*
 244 *time (minimum SLP time of each MC track). The black circles denote the 10° radius impact area considered for*
 245 *cyclone-induced fluxes. Colored circles indicate the dominant season for each cluster: blue for winter, red for*
 246 *summer, and green for spring/autumn.*

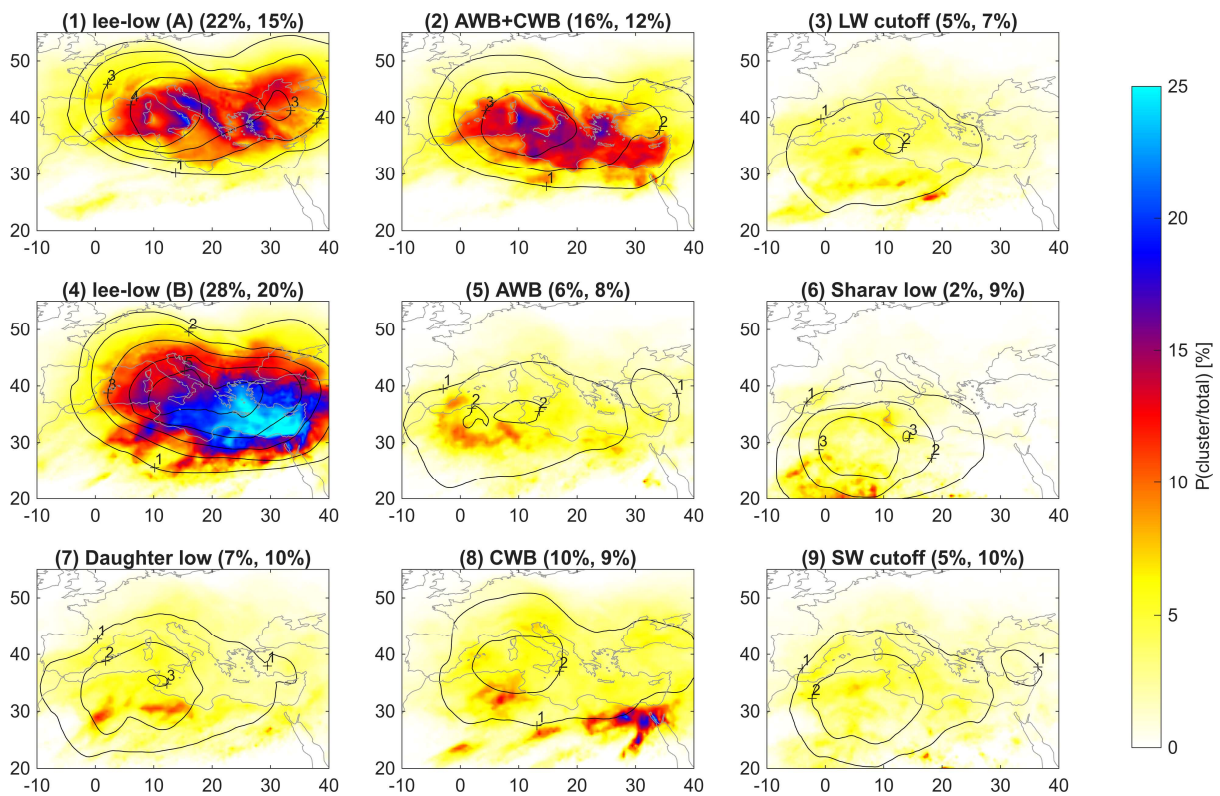
247 The independent contributions of each MC type to the overall annual E are shown in Fig. 4. Cluster 4 stands out
 248 as a major contributor, accounting for up to 24% of the MC-induced E despite forming 20% of the total MC
 249 frequency (see Fig. 4 titles). The ratio between the MC contribution and local frequency surpasses 3 in the eastern
 250 Mediterranean and along the north African coast, suggesting high conditional probability. Cluster 1, representing
 251 cold cyclones anchored to topography, shows significant E contributions especially in the Ligurian and Adriatic
 252 seas, as may be expected from the strong gap-winds regimes triggered at the early stages of Alpine lee-
 253 cyclogenesis and their link to evaporation (Buzzi et al., 2020, Givon et al., 2021, Givon et al., 2024b). On the
 254 other hand, the contributions of summer clusters 6 and 9 are weaker than their mean frequency, which is often
 255 over land, possibly due to already high evaporation rates throughout the season (Ruiz et al., 2008). Nevertheless,
 256 Sharav lows (North-African heat lows captured by cluster 6) are associated with strong evaporation hot-spots in
 257 north-western Africa, possibly affecting the great lakes and land-moisture in the region (Rieder et al., 2025).
 258 Cluster 2 MCs are denoted by a unique combination of anticyclonic and cyclonic Rossby wave breaking
 259 simultaneously deforming the same PV streamer, that extends from the anti-cyclonic shear zone of the sub-polar
 260 jet to the north the cyclonic shear zone of the sub-tropical jet to the south (Figure A1). The double-jet configuration
 261 denoted by cluster 2 notably contributes 15% to total MC-induced evaporation despite its 12% relative frequency,
 262 suggesting strong – yet apparently more local – evaporative capabilities, appearing as relatively sporadic
 263 evaporation hotspots.



264
 265 *Figure 4: Relative contribution of each cluster to total E (shading, %) and cluster mask frequency (black contours,*
 266 *% , in 1% intervals). Titles denote cluster numbers and the dominant driving mechanism as reported in Givon et*
 267 *al., (2024a). Numbers in brackets indicate the mean contribution of each cluster to total MC-induced surface*
 268 *evaporation (left) and the mean cluster frequency out of all MCs (right).*

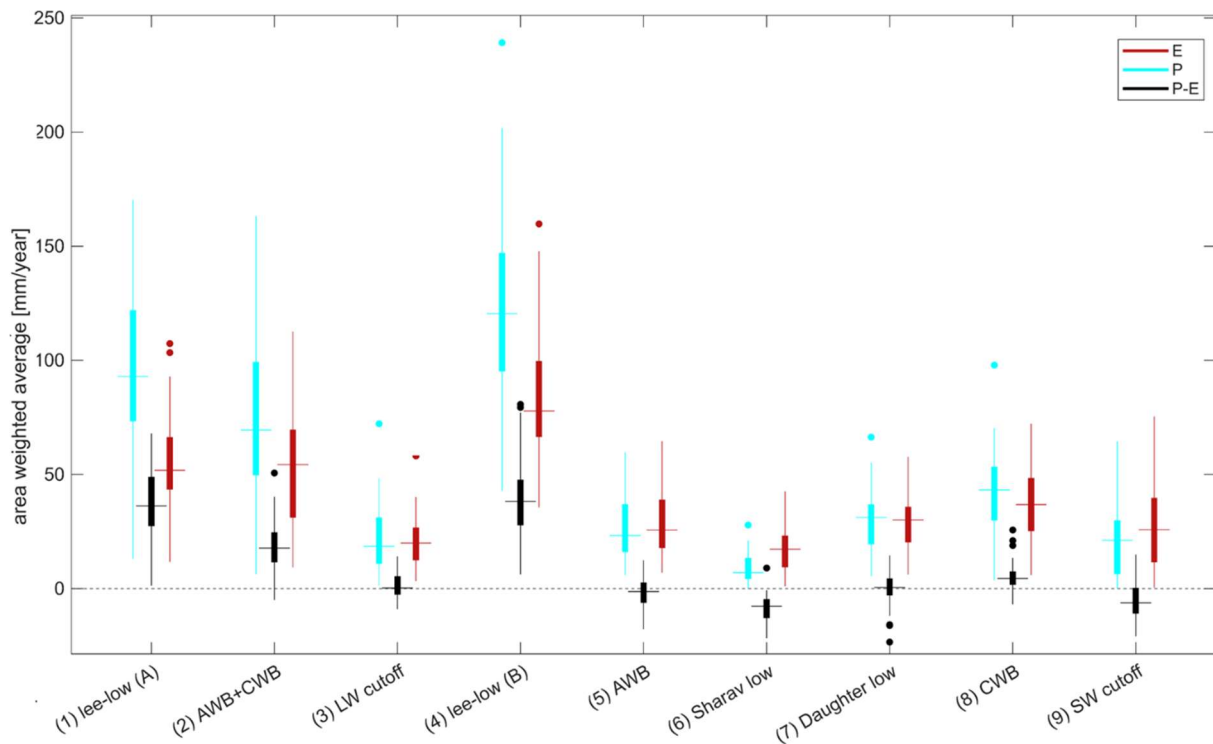
269 The cluster-separation of contributions to P is even more pronounced (Fig. 5). Cluster 4 dominates in the central
 270 and eastern Mediterranean, overall contributing 28% of total MC induced P, and cluster 1 in the western coasts of
 271 Italy, Greece and Turkey, and along the Adriatic, providing 22% of total MC induced P. The precipitation induced
 272 by cluster 2 again exhibits more localized hot spots, while the contributions of the other clusters are significantly
 273 weaker. Intriguingly, precipitation along the Egyptian coast shows a tight link to cyclonic wave breaking (CWB)
 274 MCs captured in cluster 8, with ~20% of annual precipitation delivered in a mere 1% regional cluster frequency.
 275 Moreover, this region is hardly responsive to other MC clusters. The tight connection between RWB patterns and
 276 extreme precipitation were recently highlighted by de Vries (2021), especially for semi-arid areas such as the
 277 eastern-Mediterranean.

278 These results illustrate well the robustness of the PV clustering even beyond the classification time, with profound
 279 implications on geographical, seasonal, and dynamical variability. Each MC driver thus plays a fundamentally
 280 different role in shaping the MHC.



281
 282 *Figure 5: As Figure 4 but for P.*

283 To evaluate the total contribution of MCs and their drivers to the MHC, we accumulate the fluxes spatially and
 284 temporally across the years, analyzing both annual P and E distributions as well as their difference, P-E, per
 285 cluster. Fig. 6 shows that the overall slightly positive P-E contribution of MCs is the result of a delicate balance
 286 between inherently imbalanced MC contributions: while winter clusters 1, 2, and 4 act as moisture sources, each
 287 adding about 30 mm/year per grid-point within a 10° radius impact area, these inputs are partly offset by a
 288 consistent drying effect imposed by the summer-prone clusters 5, 6, and 9. Seeing as the relative frequencies of
 289 each cluster are changing in recent decades (Givon et al., 2024a), we further analyze the long-term variability of
 290 each cluster, accounting for both variations in frequency and intensity.



291

292 *Figure 6: Distributions of area weighted annual mean MC-induced E, P, and P-E, separated by cluster. The*
 293 *medians of each distribution are denoted by the horizontal lines, the boxes mark the 25 to 75 percentiles of the*
 294 *distribution, and whiskers mark the 2.5 and 97.5 percentiles, setting the threshold for outliers, marked by the*
 295 *colored dots.*

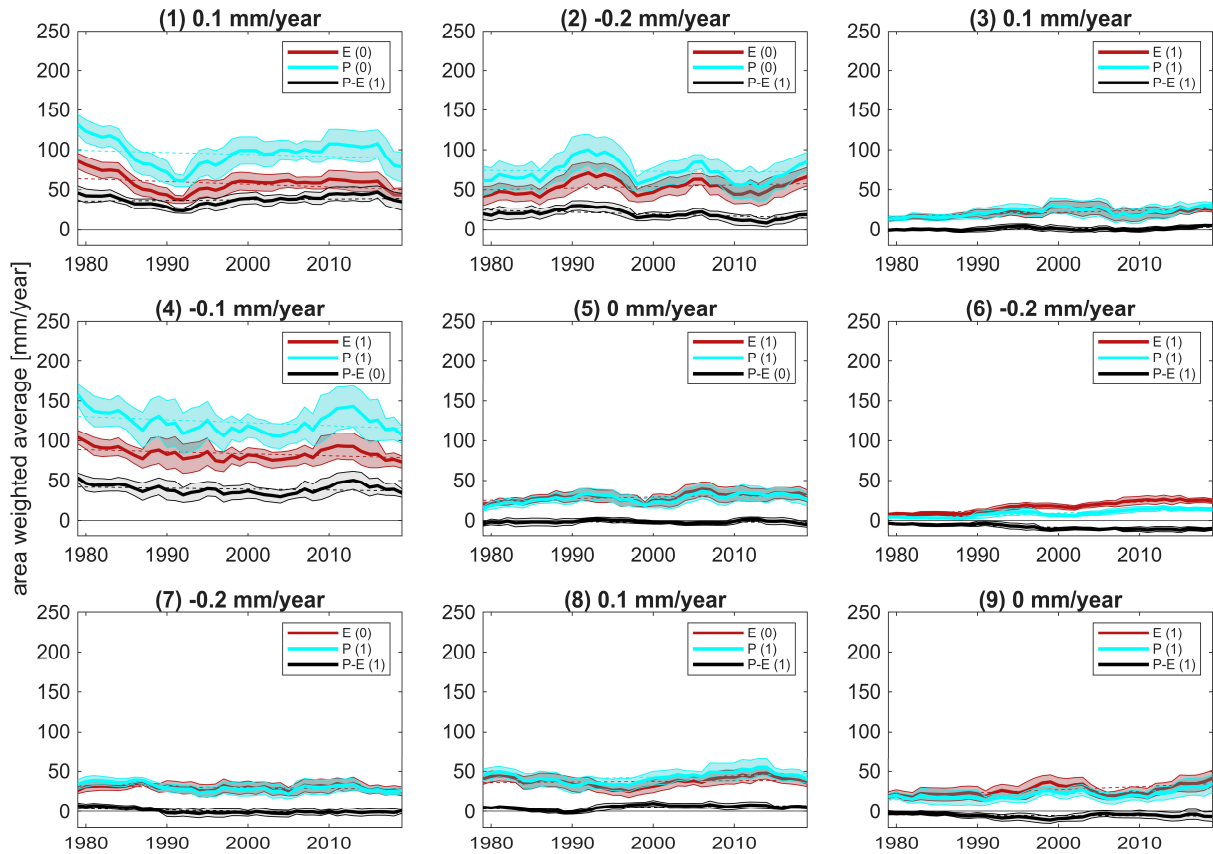
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3.3. Long-term variability by cluster

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Long term variability of MC occurrence and interaction with the MHC strongly depends also on MC cluster type. The relative importance of each MC cluster is shifting over recent decades, as shown in Fig. 7. While some clusters are well balanced and hardly contribute to the MC-induced P-E (e.g., clusters 5 and 9), P-E is growing larger for some (clusters 1, 3, and 8) and smaller for others (clusters 2, 4, 6, and 7). The strongest change is captured for the double-jet cluster 2, losing 0.2 mm/year which corresponds to ~1% erosion of its annual precipitation surplus per year, with similar trend magnitudes reported for clusters 6 and 7. The net negative contributions from clusters 2, 4, 6, and 7 differentially stem from either a reduction in precipitation (clusters 4 and 7), an increase in evaporation (6), or both (cluster 2). By contrast, cluster 8 contribution is positive and slightly increasing with time, due to enhanced P and near-constant E. As these changes can arise from either changes in frequency or intensity, we next examine the normalized fluxes and their trends, effectively eliminating frequency changes and highlighting changes in E and P intensities.

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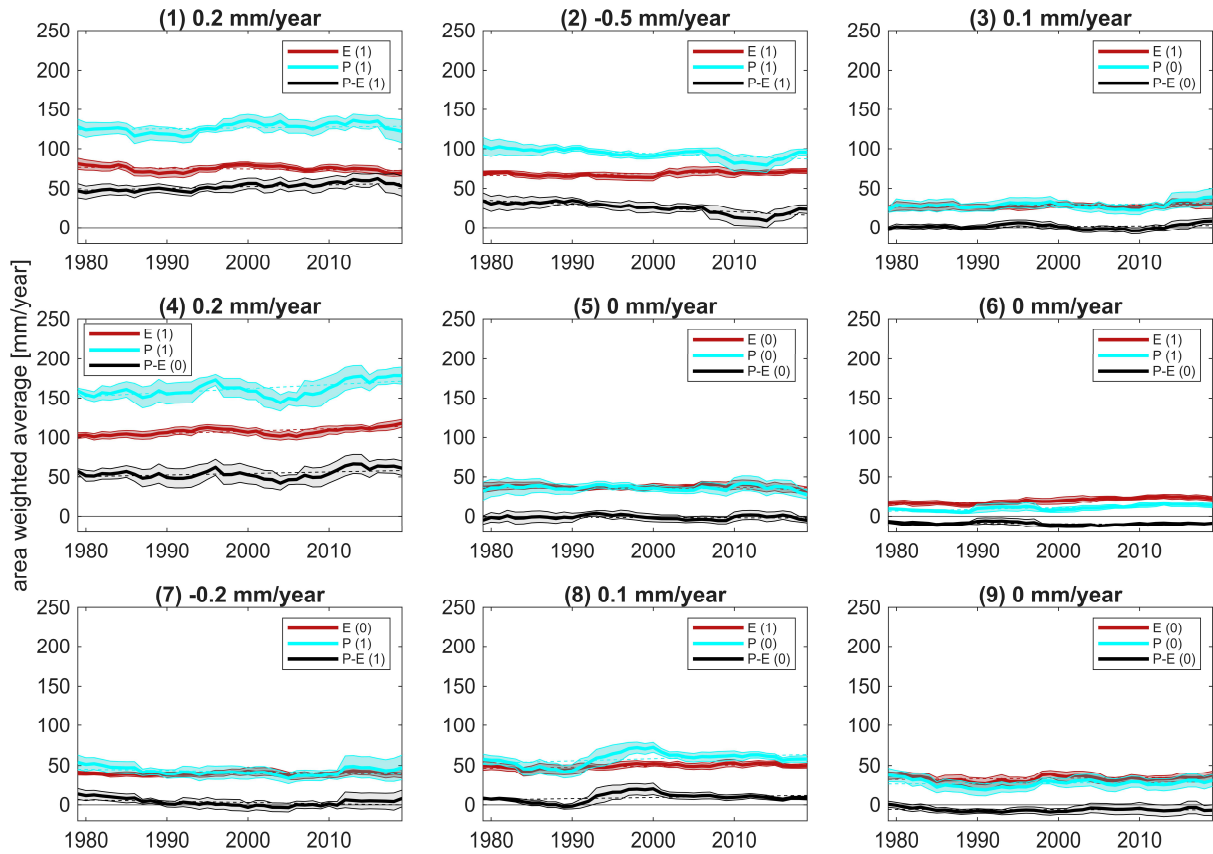


308

309 *Figure 7: As Figure 2 (b) but separated by cluster. Titles denote the cluster number followed by the slope of the*
 310 *linear best-fit (mm/year) for the P-E trend. The result of a 95% confidence level Mann-Kendall test for each*
 311 *component is shown in the legend (1 for a significant trend)*

312 Indeed, the net contributions (P-E) of each cluster vary differently when only changes of flux intensity are
 313 considered (Fig. 8). The intensity-only loss from cluster 2 is enhanced to -0.5 mm/year, indicating that its
 314 increasing frequency masks a drop in intensity. Interestingly, the E_{norm} and P_{norm} associated with cluster 2 evolve
 315 in opposite directions, with decreasing P_{norm} (and increasing E_{norm}). As suggested by previous studies, the overall
 316 drop in precipitation for cluster 4 is indeed driven solely by a reduction in frequency, while the intensity of both
 317 E_{norm} and P_{norm} steadily increase. For cluster 6, changes in intensity exist but are well balanced, suggesting changes
 318 in frequency are dominant in determining P-E for these Saharan heat lows.

319 When separated by cluster, the P-E residual shows distinct long-term trends that are affected by variations in both
 320 frequency and intensity. In agreement with previous studies, winter MCs grow in intensity and decrease in
 321 frequency, with the latter being more dominant, resulting in a long-term reduction in P-E. Summer MCs, on the
 322 other hand, are primarily affected by a rise in frequency, leading to further drying.



323

324 *Figure 8: As Figure 7 but normalized by cluster frequencies, highlighting flux-intensity variations.*

325 To derive the overall impact of MCs on the MHC, net cluster frequencies and their area weighted
 326 contributions to the MHC relative to accumulated climatological values across space and time are
 327 shown in Table 1. The net frequencies consider the temporal occurrence of each MC cluster and the
 328 ratio between the number of grid-points within the MC masks to the total number of grid points in the
 329 domain. These frequencies hence describe the fraction of MC affected areas throughout the entire
 330 analysis period and across the whole domain. The overall net climatological P-E in the Mediterranean
 331 is -52 mm/y (Fig. 2a). The overall MC-induced P-E is, however, positive, counter balancing 24% of the
 332 climatological negative P-E. The MC contribution is primarily driven by lee-cyclones (clusters 1 and
 333 4), while specific MC drivers (clusters 5, 6 and 9) act to enhance the overall excess E in the
 334 Mediterranean.

Cluster	Net Freq. (%)	E (%)	P (%)	P-E (%)
1	2.0	2.6	5.1	10.7
2	1.6	2.5	4.0	5.5
3	0.9	0.9	1.2	0.6
4	2.6	3.9	6.6	10.4
5	1.1	1.2	1.4	-0.2
6	1.2	0.7	0.5	-2.2
7	1.3	1.3	1.6	0.3
8	1.3	1.7	2.2	1.4
9	1.3	1.2	1.1	-1.4
All	13.4	15.5	22.9	24.1

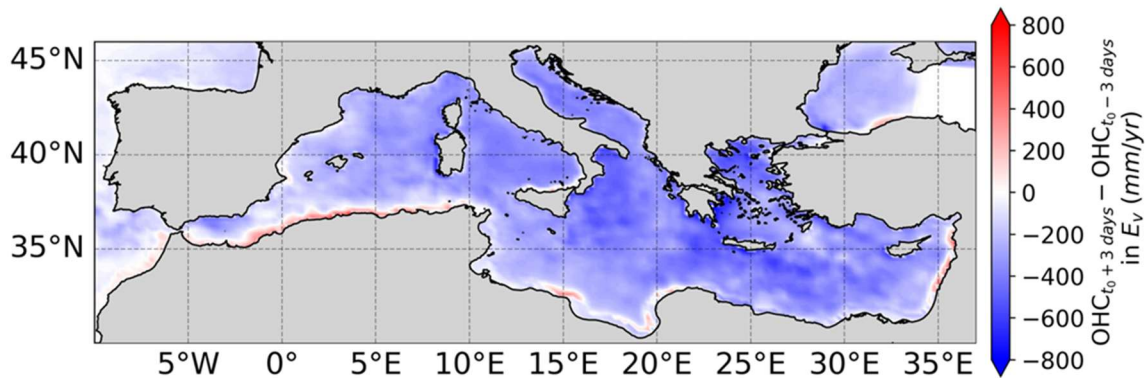
335 *Table 1: total cluster spatio-temporal frequencies and corresponding MHC contributions relative to the total*
336 *accumulation of the climatological values across the domain. Note that the spatio-temporal frequencies include*
337 *the fraction of MC-affected grid-points to all grid-points in the domain, as well as their mean temporal*
338 *frequencies. 'All' stands for all MC clusters combined.*

339 **3.4. MC-induced OHC perturbations**

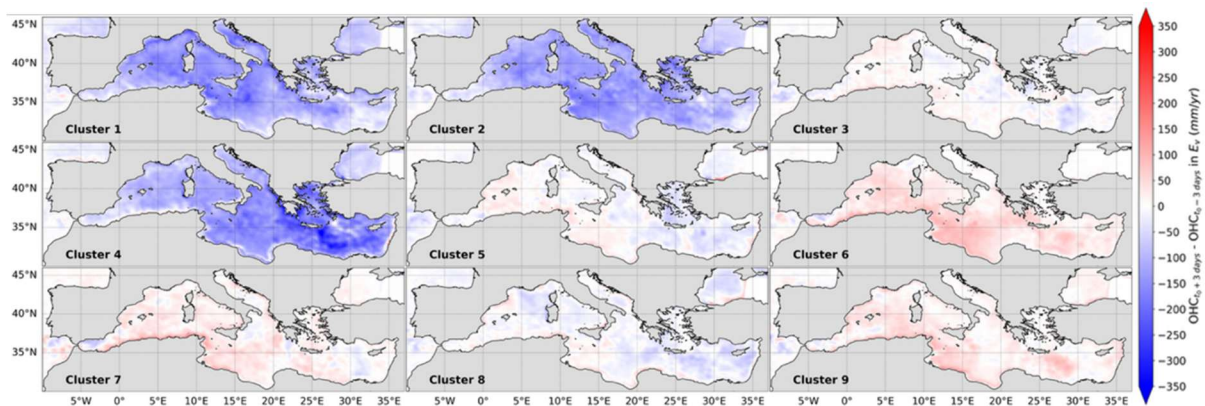
340 The overall impact of MCs on the OHC (Fig. 9) shows that on average, MCs extract heat from the Mediterranean
341 at a mean rate equivalent to 645 mm/year of E. Although other processes affect the OHC, including lateral
342 advection and radiative effects, the contribution of MC induced E alone accounts for up to ~350 mm/year (Fig.
343 2), more than 50% of the net OHC difference with response to the passage of MCs. Notably, the OHC response
344 to MCs is positive along the North-African and eastern Mediterranean coasts, suggesting MCs tend to add heat to
345 these areas. While this local reversal could be the result of sensible heat fluxes triggered by heat lows that often
346 affect these areas, further research into oceanic flows is required to definitively explain these signals.

347 Once more, the cluster breakdown provides a more detailed picture of the independent role of MC types (Fig. 10):
348 MC drivers that provide excess P also appear to drain heat from the ocean (clusters 1, 2, 4, and 8), as their E is
349 still higher than that of E-dominated MCs. The E-dominated MCs (clusters 6, 7, and 9) act as heat sources,
350 enhancing the OHC as they evolve rather than lowering it. This may be the result of their dry formation
351 environments, prohibiting precipitation and leading to convergence of dry, warm air towards the MC center,
352 generating enhanced downward sensible and possibly radiative (i.e., reduced cloud cover) fluxes. Spatial
353 variability is evident for some of the clusters, suggesting certain drivers, e.g. clusters 3 and 5, act differently in
354 different regions. Specifically, these MCs act as heat extractors when impacting the eastern Mediterranean, and
355 heat suppliers when impacting the western parts. The OHC response to the various MC drivers is in-line with the
356 atmospheric perspective, suggesting that opposing contributions of MCs to the MHC also bear the opposite impact

357 on the OHC. This highlights the importance of considering the internal variability of MCs when assessing their
 358 role in future climate.



359
 360 *Figure 9: Composites of the difference in ocean heat content ± 3 days before and after the influence of a MC,*
 361 *normalized by annual MC frequencies. Negative values indicate net heat extracted from the ocean towards the*
 362 *atmosphere.*



363
 364 *Figure 10: As Figure 9 but separated into clusters. Note that the values are normalized by annual MC cluster*
 365 *frequencies, thus representing the net heat taken from (negative values) and added to (positive values) the*
 366 *Mediterranean per cluster, per year.*

367 4. Discussion

368 This work investigates the impact of MCs on precipitation (P), evaporation (E), and the P-E residual as well as
 369 Mediterranean ocean heat content (OHC), separating between the independent contributions of 9 dominant MC
 370 'types'. MCs account for up to 70% of annual P and 50% of annual E (locally, see Fig. 2), but the contribution to
 371 each component is highly asymmetric when separated by MC type, as captured by the cyclone-centered PV-based
 372 clusters (Givon et al., 2024a). Cluster-dependent trends in cyclone-induced P, E, and P-E are revealed, controlled
 373 both by changes in MC cluster frequencies and in instantaneous flux intensities. The net annual P-E of MCs is
 374 positive and slightly decreasing due to a decrease (increase) in frequency of winter (summer) MCs. This trend is
 375 corroborated by an unbalanced reduction in precipitation intensity associated with intense and compact MCs that
 376 evolve under a double-jet configuration (Fig. A1). The results highlight the individual role and potential response
 377 of each MC type in the MHC in recent decades, and underline multiple dynamic relationships:

378 The growing negative contribution of summer MCs to P-E (clusters 6 and 9) reflects both their higher frequency
379 and the rise in sea surface temperature, which enhances E over longer timescales by amplifying air-sea temperature
380 gradients (Yu 2007). The major winter clusters 1 and 4 play different roles in the MHC despite their apparent
381 similarity. Cluster 1 consistently provides excess P and is mostly restricted to topography, exhibiting no long-term
382 trend in intensity or annual P-E contributions. Cluster 4, on the other hand, travels farther from its genesis region
383 (mostly the lee of the Alps) and delivers excess P to the central and eastern Mediterranean, at a gradually
384 decreasing rate. Cluster 8, although rare, contributes substantially to P-E and shows a distinct increase in P
385 intensity, likely reflecting enhanced convective activity in response to rising surface temperatures – consistent
386 with its high convective potential (Portal et al., 2024). Finally, cluster 2 shows the steepest trend in P-E, losing
387 ~ 0.2 mm/year per affected grid-point, due to changes in mean intensity, despite a subtle rise in frequency.

388 The seasonal cycle is embedded in the cluster separation. To isolate the role of seasonality, the results were further
389 separated into winter and summer subgroups, specifically November through March and May through
390 September (not shown). While summer E is weaker across all clusters, the relative impact of each cluster as well
391 as the spatial patterns remain surprisingly similar in both sub-groups. Specifically, cluster 4 still shows the largest
392 instantaneous fluxes, followed by clusters 2 and 1. Winter cluster 6 cyclones are especially rare, while cluster 8
393 is more evenly distributed between the seasons and shows similar E and P patterns (not shown). We conclude that
394 a further seasonal breakdown does affect the results quantitatively, but not qualitatively with respect to the relative
395 importance of each MC type. This shows that MC types exhibit consistent features across seasons.

396 The OHC analysis further emphasizes the independent role of each MC driver, with opposing impacts of different
397 MC drivers across the basin. The overall OHC loss is proportional to MC-induced E, but is generally higher due
398 to added sensible, radiative and advective fluxes, all of which are potentially affected by the presence of MCs. We
399 show that certain MCs, primarily RWB patterns and cut-off lows, may even add heat to the Mediterranean instead
400 of extracting it, stressing the importance of non-linear PV dynamics to the OHC.

401 Overall, the study reveals that each MC driver contributes differently to the MHC and OHC, with some drivers
402 showing opposing long-term trends. These trends are in-line with the Mediterranean precipitation paradox,
403 demonstrating the different dynamical responses generating it: North-Mediterranean winter MCs are indeed
404 showing increased precipitation rates despite their drop in frequency, while off-winter MCs frequently impacting
405 the southern and eastern Mediterranean are increasing in frequency and evaporation rates at the expense of
406 precipitation intensities, contributing to the drying of these regions.

407 The impact of MCs on the MHC agrees with the trends of total regional P derived by André et al., (2024). The
408 “all quartiles increase” pattern, describing an increase in all precipitation quartiles (i.e., extreme and moderate
409 values alike, not restricted to the occurrence of MCs) suggested for the European continent can be related to the
410 increased P of clusters 1 and 4 often affecting the area. However, the decrease in clusters 2, 6, and 9 partially
411 explain the reduction in P intensity across the central, eastern, and southern parts of the domain.

412 Taken together, the results show that quantifying the climate impact of MCs requires a process-based approach
413 that resolves their internal diversity. Each cyclogenetic process responds differently to warming, leading to
414 opposing influences on both the MHC and OHC. Long-term trends imply that the warming buffer provided by
415 MCs is being eroded, with severe implications for the regional hydrological budget and heat balance. Moreover,

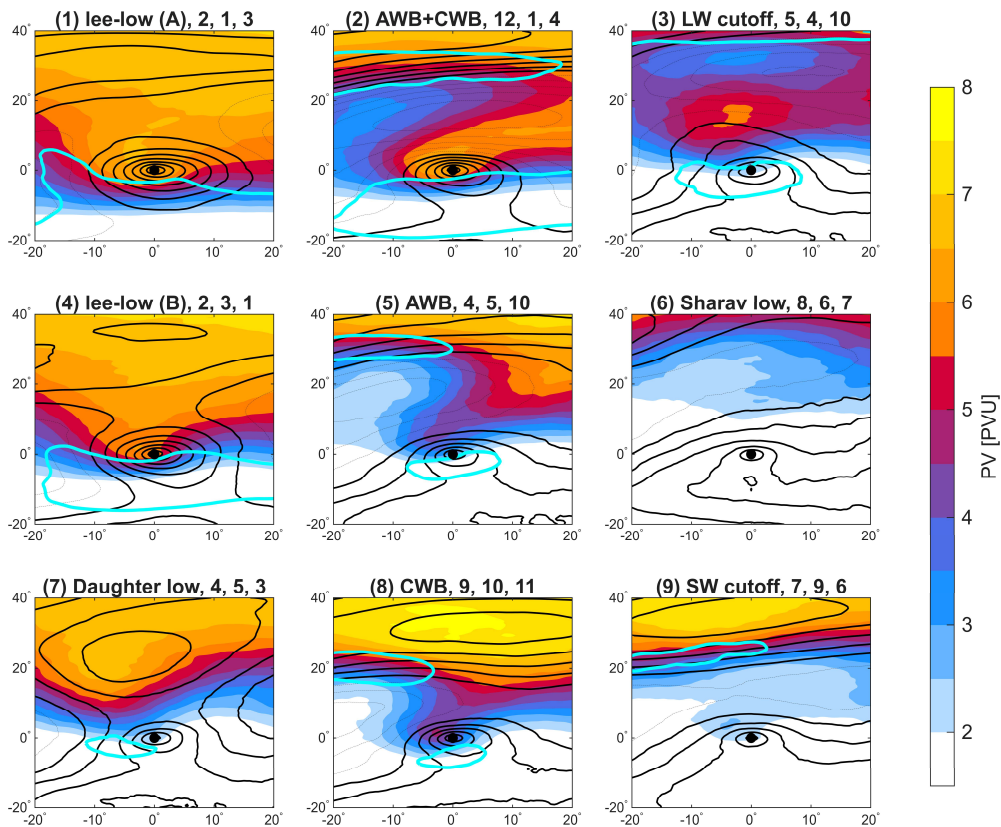
416 changes in MCs impact on the MHC could develop nonlinearly in the future, as shifts in both frequency and
417 intensity align with ongoing warming for several MC drivers. E.g., winter cyclones do not only drop in frequency
418 or intensity – they are being replaced by MCs with an opposing sign of MHC impact.

419 The presented framework for the process-based classification and impact attribution presented here is not only
420 relevant for the Mediterranean but also transferable to other regions where cyclones play a critical role in
421 regulating hydroclimate and air-sea exchanges. Applying this methodology more broadly represents a promising
422 avenue for future research.

423

424 **Appendix A: PV-based clusters of MCs**

425 To provide context for the MHC results by MC cluster, we summarize the PV-based MC cluster characteristics in
 426 Givon et al (2024a). The classified PV patterns are shown in Fig. A1 as cyclone centered composite means,
 427 depicting the different large-scale settings associated with peak time of each MC track. These include long and
 428 short-wave cut-off structures observed for clusters 3 and 9, the anticyclonic and cyclonic Rossby wave breaking
 429 patterns for cluster 5 and 8, respectively, and the daughter-cyclone highlighted by cluster 7. Intriguingly, from the
 430 cyclone-centered, upper-level PV perspective, clusters 1 and 4 differ only slightly. However, this seemingly subtle
 431 difference effectively distinguishes between two stages of lee cyclogenesis (Givon et al., 2024a). The cyclone-
 432 centered composite of 300 hPa winds (Fig. A1) visualizes the double-jet pattern associated with cluster 2 MCs,
 433 supporting anticyclonic and cyclonic Rossby wave breaking on the poleward and equatorward flanks of the PV
 434 streamer, respectively. This unique set-up leads to the extension of the PV streamer furthest equatorward with
 435 respect to the sub-polar jet hence generating maximum PV anomalies and surface winds compared to the other
 436 clusters. Based on these and other observed features explored in Givon et al (2024a), each cluster is named after
 437 its dominant cyclogenetic process. These processes are not limited to specific non-linear RWB life cycles (see
 438 panel titles) but also include thermal (Sharav) lows with weak upper-level forcing forming in a ridged environment
 439 (cluster 6) and secondary cyclones forming along the fronts of synoptic-scale cyclones (cluster 7).



440
 441 *Figure A1: Cyclone-centered cluster composites of upper-level (320–340 K averaged) PV (PVU, shading) and*
 442 *SLP (black contours at 2 hPa intervals, dashed above 1015 hPa) at minimum SLP time. Overlaid is the*
 443 *corresponding composite of the 30 m s⁻¹ isotach on the 300 hPa geopotential surface (cyan contour, roughly*
 444 *denoting the subpolar and/or subtropical jets). Titles denote cluster number, name, and the leading cluster months*
 445 *in a descending order.*

446 **Author contributions.** YG and SRR conceptualized the research. YG conducted the research, performed the
447 analysis of the atmospheric data, and wrote the underlying codes and the manuscript. DKJ performed the OHC
448 analysis and produced the corresponding figures. All coauthors took active part in reviewing and editing the
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460 **Data Availability.** The composite cyclone tracks with the resulting cluster attribution are available in the
461 supplementary assets of Givon et al., (2024a). The track labels correspond to the composite cyclone track dataset
462 at confidence level 5, made available as a Supplement by Flaounas et al. (2023) (“TRACKS_CL5.dat”). ERA5
463 data are available at: [https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-](https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?utm_source=chatgpt.com)
464 [levels?utm_source=chatgpt.com](https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?utm_source=chatgpt.com) , and details on C-GLORS v7 data availability can be found at [http://c-](http://c-glors.cmcc.it/index/index-7.html?sec=7)
465 [glors.cmcc.it/index/index-7.html?sec=7](http://c-glors.cmcc.it/index/index-7.html?sec=7).

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