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Declining Winter Heat Loss Threatens Continuing Ocean Convection at a Mediterranean Dense Water Formation Site

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Abstract

A major change in winter sea surface heat loss between two key Mediterranean dense water formation sites, the North-west Mediterranean (NWMed) and the Aegean Sea, since 1950 is revealed using atmospheric reanalyses. The NWMed heat loss has weakened considerably (from -154 Wm^{-2} in 1951-1985 to -137 Wm^{-2} in 1986-2020) primarily because of reduced latent heat flux. This long-term weakening threatens continued dense water formation, and we show by evaluation of historical observations that winter-time ocean convection in the NWMed has declined by 40% from 1969 to 2018. Extension of the heat flux analysis reveals changes at other key dense water formation sites that favour an eastward shift in the locus of Mediterranean convection towards the Aegean Sea (where heat loss has remained unchanged at -172 Wm^{-2}). The contrasting behaviour is due to differing time evolution of sea-air humidity and temperature gradients. These gradients have weakened in the NWMed due to more rapid warming of the air than the sea surface but remain near-constant in the Aegean. The different time evolution reflects the combined effects of global heating and atmospheric circulation changes which tend to offset heating in the Aegean but not the NWMed. The shift in heat loss has potentially significant consequences for dense water formation at these two sites and outflow to the Atlantic. Our observation of differential changes in heat loss has implications for temporal variations in the balance of convection elsewhere e.g., the Labrador-Irminger-Nordic Seas nexus of high latitude Atlantic dense water formation sites.

1. Introduction

The Mediterranean Sea has experienced notable changes in many properties as a result of the climate crisis (MedECC, 2020). These include warming and salinification of intermediate (Schroeder et al., 2017; Margirier et al., 2020) and deep (Garcia-Lafuente, 2021) water masses. Schroeder et al. (2017) found increasing temperature and salinity of intermediate water crossing the Sicily Channel since the early 1990s while Margirier et al. (2020) identified similar trends in the North-West Mediterranean (NWMed hereafter) since 2007. Recently, Garcia-Lafuente et al. (2021) observed very strong warming of deep Mediterranean outflow to the Atlantic since 2013.

Variations in the air-sea heat and freshwater fluxes that mediate these changes are less well studied, particularly over multidecadal timescales. Here, we evaluate Mediterranean winter heat loss variability since 1950 in regions of dense water formation using the relatively high resolution ERA5 (0.25 x 0.25^{o}, Hersbach et al., 2020) reanalysis supplemented by the 20CRv3 reanalysis (0.7 x 0.7^{o}, Slivinski et al., 2019) which enables us to check for dataset consistency. We also assess the occurrence of wintertime convection in the NWMed from 1969 to 2018 using historical observations.

Severe winter heat loss leading to dense water formation has been observed at three Mediterranean Sea sites: the NWMed, Northern Adriatic and Aegean Seas (e.g. Schroeder et al., 2022). The NWMed was the first to be recognised in the Mediterranean Ocean Convection (MEDOC) observing campaigns, undertaken from 1969-1972 (MEDOC Group, 1970) and has been the subject of many subsequent surveys. The Eastern Mediterranean (EMed) has two deep water formation areas, the Adriatic Sea (e.g. Malanotte-Rizzoli and Hecht, 1988) and the Aegean Sea which contributes less regularly (Schroeder, 2019). The Adriatic is usually described as the main deep water source for the EMed (Wüst, 1961; Schlitzer et al., 1991).

However, in the severe heat loss winters of 1991-1992 and 1992-1993 (Josey, 2003), the Aegean took over and became the main EMed deep water formation site (Roether et al., 1996). After 2002, the Adriatic gradually recovered as the main site (Ozer et al., 2020; Manca et al., 2006; Rubino and Hainbucher, 2007; Bensi et al., 2013). Knowledge of possible Aegean Sea dense water formation prior to the 1980s is severely limited by lack of observations. Since 2000, more frequent observations are available and new dense water production occurred in 2003, 2006-08, 2012, 2015 and 2017 (Androulidakis et al., 2012; Karageorgis et al., 2012; Velaoras et al., 2017, 2021; Zervakis et al., 2019).

Our analysis will show both a multidecadal reduction of about 40% in the frequency of NWMed convective winters and a major shift since 1950 in the balance of winter surface heat loss between dense water formation sites in the western and eastern Mediterranean. Specifically, NWMed heat loss weakens while Aegean heat loss remains unchanged. In addition, we will show that the Adriatic Sea heat loss also weakens but by a smaller amount than the NWMed; as the Adriatic change is smaller we do not consider it in detail. The reasons for the strong contrast between the NWMed and Aegean will be determined by analysing the heat flux components and atmospheric variables driving the heat loss. Since the NWMed is the region experiencing the strong winter heat loss change, it is the primary focus of our study and we contrast it with the Aegean but do not consider the latter region in such detail as it has not undergone a major change. Finally, we discuss the implications of our results and place them in the context of recent research which suggests that NWMed dense water formation may cease in the next 20-30 years (Parras-Berrocal et al, 2022).

2. Methods

We employ monthly mean surface heat exchange, near surface meteorology and sea surface temperature fields from ERA5 and 20CRv3. Near surface variables are specified at 2 m for temperature and humidity and 10 m for wind speed. The net heat flux (Q_n) is the sum of latent (Q_e), sensible (Q_h), shortwave (Q_{sw}) and longwave (Q_{lw}) components:

$$Q_n = Q_e + Q_h + Q_{lw} + Q_{sw} \quad (1)$$

The sign convention is for ocean heat gain/loss to be positive/negative. Winter is defined to be December-February when latent and sensible heat fluxes dominate net heat flux variability.

These fluxes are dependent on near surface gradients of humidity (for latent) and temperature (for sensible) together with the wind speed through the following formulae:

$$Q_e = \rho L C_e u(q_s - q_a) \quad (2)$$

$$Q_h = \rho c_p C_h u(T_s - T_a) \quad (3)$$

Here, ρ is air density; L, latent heat of vaporisation; C_e and C_h, latent and sensible heat transfer coefficients; u, wind speed; q_s, 98% of saturation specific humidity at sea surface temperature; q_a, near surface atmospheric specific humidity; c_p, specific heat capacity of air at constant pressure; T_s, sea surface temperature (SST) ; T_a, near surface air temperature. Units employed for the variables discussed in this manuscript are heat flux (Wm^{-2}), wind speed (ms^{-1}), humidity ($g\ kg^{-1}$), temperature (^oC).

3. Results

3.1 Spatial Structure of Winter Heat Loss

We begin by exploring the structure of the mean winter heat loss and its interannual variability within the high resolution ERA5 dataset. The Mediterranean experiences ocean heat loss in winter (Fig.1a), with relatively weak loss (-50 Wm^{-2}) in the Alboran Sea, intermediate values (-100 Wm^{-2}) over most of the basin (e.g., the Ionian and Levantine Seas) and strong loss (reaching -200 Wm^{-2}) in the NWMed, Adriatic and Aegean Seas. ERA5 reveals finer scale spatial structure than was evident using earlier coarser resolution datasets (e.g., Josey, 2003). In particular, an east-west gradient of strengthening heat loss is evident in the Aegean Sea with highest values in the eastern Aegean.

Climatological winter mean values for the net heat flux and its components in the NWMed and Aegean are provided in Table 1. For each region, the largest term is the latent flux (-115 Wm^{-2} of -146 Wm^{-2} net heat loss in the NWMed and -135 Wm^{-2} of -172 Wm^{-2} in the Aegean) reinforced by the sensible flux (-30 Wm^{-2} in the NWMed, -46 Wm^{-2} in the Aegean). In the NWMed, the longwave loss is about equal and opposite in sign to the shortwave gain so these terms cancel. In the Aegean, shortwave gain exceeds longwave loss by about 10 Wm^{-2} resulting in a small net gain which reduces slightly the strong losses from Q_e and Q_h.

To provide context for the multidecadal variability which is the focus of our study, we first briefly consider the spatial structure of interannual variability of winter Q_n (Fig.1b). The variability is strongest, approaching 50 Wm^{-2}, in the NWMed and Aegean Seas. In contrast, Adriatic Sea variations are noticeably weaker, typically 30-35 Wm^{-2}, indicating it experiences steady winter heat loss. The vectors show stronger wind forcing of the Aegean and NWMed than the Adriatic. Fluctuations in these winds and the associated air mass temperature and humidity are the source of the strong interannual variability via Q_e and Q_h.

3.2 Multidecadal Variability of Heat Loss and Winter Convection

Turning to multidecadal variability, we find that winter heat loss in the NWMed exhibits a striking long-term weakening from -154±6 Wm^{-2} in 1951-1985 to -137±6 Wm^{-2} in 1986-2020 (Fig.2a). There is still notable interannual to decadal variability within this period so this weakening should not necessarily be regarded as a smooth linear change (see Supp Fig.1 and discussion). The long-term reduction in winter heat loss will in turn weaken the surface buoyancy loss and thereby threaten convection in the NWMed. With this in mind, we have assessed hydrographic survey observations from 1969 to 2018 and identified the number of convective winters in each decade in this period (Table 2). The first two decades (1969-1988) have 14 convective winters compared with 13 in the subsequent three decades (1989-2018). Thus, there has been a multidecadal reduction of about 40% in the frequency of NWMed convective winters from 7 per decade to just over 4 per decade. This is consistent with a scenario in which reduced winter heat loss has inhibited convection in recent decades (assessment of convection in the early reanalysis record from 1950-68 is not possible due to lack of observations). We have also carried out an assessment, based on available literature to date, of the four additional winters 2019 through to 2022 and find no evidence for deep convection in these winters. Thus, there are no reports of deep convection in the NWMed for the last 9 winters (2014-2022 inclusive) which suggests that cessation of deep convection in the NW Mediterranean may have already begun. The previous biggest gaps in the record going back to 1969 were 4 winters (1995-1998 and 2001-2004).

In contrast to the NWMed, the Aegean Sea net heat flux (Fig.2b) has remained unchanged over the past 70 years with winter mean values of -171±6 Wm^{-2} in 1951-1985 and -172±6 Wm^{-2} in 1986-2020. As noted in the Introduction, the number of available historical hydrographic surveys in the Aegean region is much lower than for the NWMed and this prevents us from undertaking a similar evaluation for the Aegean to that reported in Table 2. However, given the unchanged Aegean Sea mean winter heat loss values between the two periods reported above, we expect the potential for convection in the Aegean Sea to be unaffected by the winter heat loss regime unlike the NWMed. Note, we also examined Q_n variability in the Adriatic (using region 41-43 ^oN, 14-20 ^oE) and find weakening from -147±5 Wm^{-2} in 1951-1985 to -133±5 Wm^{-2} in 1986-2020. Thus, the Adriatic also experiences, at a slightly lower level, the reduction in heat loss found in the NWMed.

We have tested whether the reported multidecadal variability is sensitive to the choice of dataset by repeating the analysis with 20CRv3. The corresponding 20CRv3 time series are in close agreement with ERA5 (r^2=0.95/0.93 and rms difference=8.8/8.7 Wm^{-2} for NWMed/Aegean) so the observed variability is robust to the choice of reanalysis employed (Fig. 2a-b). Temporal inhomogeneity arising from assimilation of multiple data types is a potentially significant problem for reanalyses. As 20CRv3 only assimilates sea level pressure, these results indicate that inhomogeneity issues do not seriously impact the representation of variability by ERA5. We also note that we have employed a preliminary version of the ERA5 back extension for the period 1950-1978 (https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation#ERA5:datadocumentation-Dataupdatefrequency). The close agreement with 20CRv3 is indicative that the ERA5 back extension is not strongly affected by unrealistic variability but a further check using the final ERA5 back extension would be worthwhile when it becomes available. Finally, to examine whether the form of the heat loss distribution has changed, we consider distributions of NWMed and Aegean individual winter month Q_n at grid cell level which have been generated using all ERA5 grid cells within each region (Fig.2c-d). The NWMed distribution clearly shows the shift towards weaker heat loss with a reduction/increase in the number of grid cells experiencing Q_n stronger/weaker than about -130 Wm^{-2}. The corresponding Aegean distribution has remained largely unaltered with some indication of a slight narrowing.

Our focus is multidecadal variability but considering interannual variability briefly, we remark that the severe 1991-1992 and 1992-1993 Aegean heat loss winters are clearly evident in Fig.2b in both ERA5 and 20CRv3. In this context, we note that a pair of successive extreme heat loss winters was also observed in the subpolar North Atlantic in 2013-14 and 2014-15 (Josey et al., 2018, 2022). It is possible that such paired severe winters are becoming more frequent and in subsequent work it would be interesting to explore whether they have common causal processes (e.g., second severe winter triggered by ocean feedback to the atmosphere via re-emergence of first winter temperature anomalies sequestered below the mixed layer in the intervening summer).

3.3 Drivers of Multidecadal Change

Decomposition into component terms reveals that the NWMed Q_n weakening is due primarily to weaker Q_e and Q_h with an additional small contribution from stronger Q_{sw} (Fig.3). Specifically, Q_e is 8±3 Wm^{-2} weaker in 1986-2020 compared to 1951-1985, with Q_h weakening by 6±2 Wm^{-2} and Q_{sw} increasing by 4±1 Wm^{-2}. In contrast, the Aegean Sea Q_e and Q_h values are the same to within 2 Wm^{-2} in both periods and there are small compensating changes in the radiative (Q_{sw}, Q_{lw}) terms which leave Q_n essentially unchanged through the past 70 years.

Q_e (Q_h) is strongly influenced by the humidity (temperature) gradient between the sea surface and near surface atmosphere (Equations 2-3) and the wind speed. Winter mean temperature, humidity and wind speed for 1950-2020 are listed in Table 1. In each region, the sea surface is warmer than the near surface atmosphere in winter, with

ΔT = 2.1 (3.0) ^oC, in the NWMed (Aegean). Likewise, the gradient in humidity is positive with Δq = 3.5 (4.1 g kg^{-1}). Wind speed values are similar between the two regions, u=7.5 (7.1) m s^- , in the NWMed (Aegean).

Changes in the values of these terms in 1986-2020 relative to 1951-1985 are shown in Fig.3a-b (wind speed) and Fig. 3c-d (temperature and humidity terms). The NWMed weakening of Q_e (Q_h) is seen to correspond to a reduction in the driving Δq (ΔT) gradients due to q_a (T_a) increasing more than q_s (T_s) (Fig.3c). Specifically, T_a increases by 0.50 ^oC from 11.12 ^oC (1951-1985) to 11.62 ^oC (1986-2020) while T_s only increases by 0.15 ^oC from 13.41 ^oC to 13.56 ^oC and so ΔT falls by 0.35 ^oC i.e. the sea-air temperature difference weakens. Similar behaviour is observed for humidity with Δq weakening by 0.12 g kg^{-1}. In contrast, the ΔT and Δq changes in the Aegean are small (Fig.3d). Here, T_a and T_s increase by 0.16 ^oC and 0.09 ^oC respectively so the reduction in ΔT is only 0.07 ^oC i.e. the Aegean sea-air temperature difference is essentially unchanged in contrast to the 0.35 ^oC reduction in the NWMed. Likewise, Δq is virtually unchanged in the Aegean.

There is also the potential for wind speed (u) changes to influence Q_e and Q_h. However, changes in u are similar between the NWMed and Aegean so they are not responsible for the different Q_n changes over the past 70 years. In the NWMed, u falls slightly from 7.6±0.1 m s^{-1} in 1951-85 to 7.3±0.1 m s^{-1} in 1986-2020 while in the Aegean the corresponding change is also a slight reduction from 7.1±0.1 to 6.9±0.1 m s^{-1}.

We now investigate why the near surface air temperature and humidity have increased more rapidly in the NWMed than the Aegean. One possibility is that global heating is being modulated by regional changes in atmospheric circulation such that the heating is offset in the Aegean or amplified in the NW Med. The change between 1951-

1985 and 1986-2020 of ERA5 winter mean T_a and u are shown in Fig.4a. A broad pattern of warming is evident with increases over the sea typically 0.2-0.5 ^oC and larger values over land (0.5-1.0 ^oC). The T_a increase in the NWMed is greater than in the Aegean, consistent with our results noted above (note the near surface humidity shows a similar contrast between these two regions, Fig. SF2). The wind field reveals a strengthened northerly airflow over the Aegean while the NWMed experiences just a small, localised change. This difference may partly explain the East-West gradient in the strength of the warming. Specifically, the global heating signal in the Aegean may be partially offset by the increased northerly airflow which is cooler because of the climatological north-south gradient in air temperature. We propose that this combination of pervasive global heating and regional cooling due to atmospheric circulation changes has the potential to lead to the observed differential changes in the strength of winter heat loss (and thus potential for dense water formation) in the NWMed and Aegean.

4. Discussion and Conclusions

The Mediterranean Sea is one of the few regions of the global ocean that provides the opportunity to investigate winter surface heat loss in regions of dense water formation. Previous research has considered extreme winter heat loss (e.g. Josey, 2003; Schroeder et al., 2010; Velaoros et al., 2017) and recent trends which now register the impacts of the climate crisis (Garcia-Lafuente, 2021). Our focus is multidecadal variability in the NWMed and Aegean. We find a major change in winter heat loss. In the NWMed, heat loss has weakened by 17 Wm^{-2} (from -154 Wm^{-2} in 1951-1985 to -137 Wm^{-2} in 1986-2020) primarily because of latent and sensible heat reductions. A similar but slightly smaller reduction of 14 Wm^{-2} is found in the Adriatic. In contrast, the Aegean heat loss has remained unchanged. The different NWMed and Aegean variability is mainly due to changes in the sea-air humidity and temperature gradients. These gradients have weakened since 1950 in the NWMed due to more rapid warming of the near surface atmosphere than the sea surface. The corresponding gradients in the Aegean have remained near constant. This difference may reflect regional circulation cooling of Aegean air temperature that potentially offsets pervasive background global heating. Further research with Mediterranean climate models is needed to test this suggestion.

The strong reduction in NWMed heat loss will impact the buoyancy flux and thus threaten continued winter convection in this region. We have tested whether this is evident in the hydrographic record and find that number of convective winters has fallen from 18 in the first half (1969-1995) of the period since reliable hydrographic observations began to 9 in the second half (1996-2022). So, we suggest that the multidecadal decline in severity of NWMed winter heat loss is linked to a corresponding decline in convection and thus new dense water formation. We also find that there are no reports of deep convection in the NWMed for the last nine winters (2014-2022 inclusive) which suggests that cessation of deep convection in the NW Mediterranean may have already begun. We note that previous studies have produced mixed results for changes to the Mediterranean heat flux, with no consistent evidence for significant trends (Dubois et al., 2012; ,Nabat et al., 2014; Sevault et al., 2014; Somot et al., 2018) apart from Mariotti (2010). These studies have employed models as well as observation-based datasets and typically considered shorter periods than the one we have considered with a tendency to focus on basin scale budgets rather than regional variations. Of particular interest is the study of Somot et al. (2018) which does have a regional focus and explores in detail the processes controlling interannual variability of deep water formation in the NW Med. They find no trend in either the net heat flux or the number of convective winters but this may reflect the shorter period used for their analysis (1980-2013).

A schematic summary of our findings is shown in Fig. 4b. In the NWMed, T_a has increased by substantially more than T_s, leading to a reduction in sea-air temperature difference; similarly for the humidity variables (not shown). In turn, the reduction in ΔT and Δq weakens NWMed heat loss as these gradients are drivers of Q_e and Q_h. Consequently, we expect a multidecadal reduction in NWMed convection as observed. In contrast, the Aegean T_a increase is only slightly larger than $T_{s,}$ so the sea-air temperature difference and winter heat loss in this region are largely unchanged. The regional change in atmospheric circulation which we suggest may have brought colder air from the north to the Aegean, partially offsetting the pervasive global heating increase is also shown in Fig.4b. The background sea level pressure change field in the figure shows that the NWMed has experienced a multidecadal increase in pressure while the Aegean is positioned such that the pressure change favours an enhanced northerly flow in winter. Additional research is required to establish the consequences for Mediterranean Sea dense water formation and circulation. Such changes have the potential to impact the properties of the water outflowing to the Atlantic through the Strait of Gibraltar which is difficult to represent in climate models (Behr et al., 2022). The potential for differential changes in heat loss, driven by a combination of global warming and regional atmospheric circulation anomalies, also has implications for temporal variations in the balance of convection elsewhere. In particular, the Labrador-Irminger-Nordic Seas nexus of high latitude Atlantic dense water formation sites is known to be sensitive to changes in the regional atmospheric circulation (e.g., Josey et al., 2019; Kenigson and Timmermans, 2021) and the combination of such changes with the background effects of global heating merits investigation.

Our results are relevant to studies of future changes in Mediterranean Sea dense water formation (Somot et al., 2006; Adloff et al., 2015; Soto-Navarro et al., 2020; Amitai et al., 2021; Parras-Berrocal et al., 2022). Parras-Berrocal et al. (2022) recently found using a high-resolution regional climate model that dense water formation in the NWMed collapses by 2040-2050 primarily due to stronger vertical stratification. We have found from a multidecadal observation-based analysis that weakening NWMed heat loss is likely to have already played a role in limiting dense water formation. It is worth stressing that the relative roles of these two processes (weakening heat loss, stronger stratification) and the potential for possible mutual dependence have not yet been explored. Indeed, determining their relative contributions to declining NWMed dense water formation is likely to form a major challenge for the community in the years ahead. Further work is needed to integrate the post-1950 weakening identified here, with studies of post-2000 changes (Garcia-Lafuente et al., 2021) and projections over the 21st century (e.g. Parras-Berrocal et al., 2022). The reduction in heat loss that we have identified threatens ongoing convection in the NWMed and is a potential contributory factor to the collapse of dense water formation in this region projected to occur in the decades ahead.

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Data Availability Statement

The data that support the findings of this study are openly available. See the following sites for details:

ERA5 reanalysis - https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview

20CRv3 reanalysis - https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.html.

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Tables

	NWMed	Aegean Sea
Q_e (Wm^{-2})	-115	-135
Q_h (Wm^{-2})	-30	-46
Q_{lw} (Wm^{-2})	-85	-86
Q_{sw} (Wm^{-2})	84	95
Q_n (Wm^{-2})	-146	-172
u (ms^{-1})	7.5	7.1
T_a (^oC)	11.4	11.6
T_s (^oC)	13.5	14.6
ΔT (^oC)	2.1	3.0
q_a (g kg^{-1})	6.0	6.1
q_s (g kg^{-1})	9.5	10.2
Δq (g kg^{-1})	3.5	4.1

Table 1 Winter (DJF) net and component heat flux means for the reference period 1951-2020 averaged over the NWMed and Aegean Sea boxes regions outlined in Fig.1a. Units Wm^{-2}. Also tabulated are the corresponding wind speed, temperature and humidity means.

Decade	NCW	Convective Winters
1969-1978	6	1969[1, 2], 1970[1, 2], 1971[1], 1973[1], 1976[1], 1978[1]
1979-1988	8	1979[1], 1980[1], 1983[1], 1984[1], 1985[1], 1986[1], 1987[1, 3, 4], 1988[1, 3]
1989-1998	4	1991[3], 1992[3, 5], 1993[1], 1994[1]
1999-2008	4	1999[3, 7], 2000[3], 2005[3], 2006[3, 7]
2009-2018	5	2009[6, 7], 2010[6], 2011[6], 2012[6], 2013[6, 7]

Table 2 Individual convective winters by decade from 1969-1978 through 2009-2018 in the NW Mediterranean Sea. NCW is the number of convective winters in each decade and has been defined according to whether, for the specific winter, there are observations, numerical models or reanalyses reported in the literature that indicate deep convection events (convection to depths ≥ 1900 m or denser than 29.0 kg m^{-3}). Reference key: 1-Mertens and Schott, 1998. 2-Gascard, 1973. 3-Pinardi et al., 2015. 4-Schott et al., 1988. 5-Rhein, 1995. 6-Margirier et al., 2018. 7-Somot et al., 2018.

Figure Captions

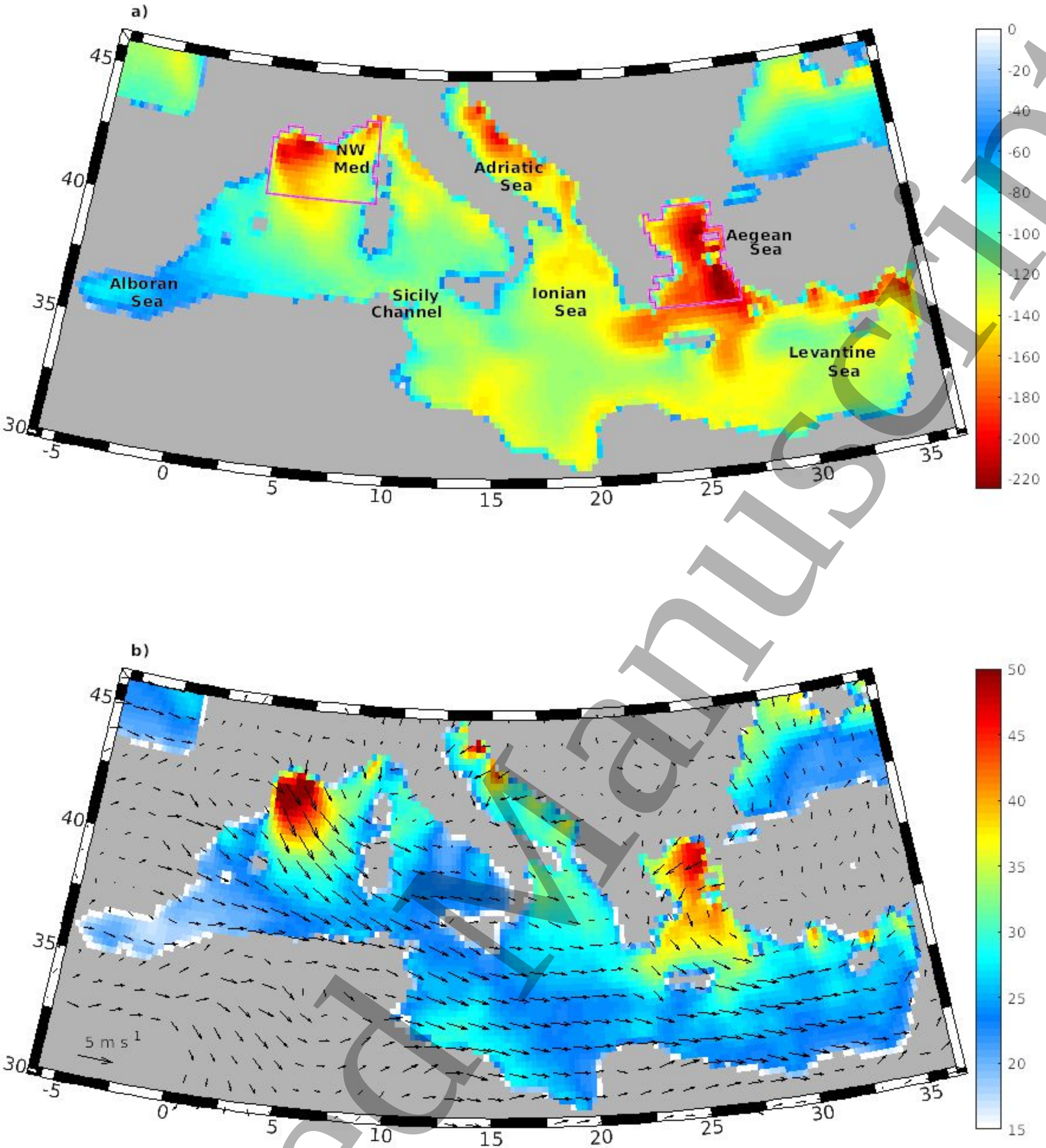
Figure 1 a.) ERA5 1950-2020 winter mean net air-sea heat flux, Q_n, units Wm^{-2}. Regions referred to in the text are labelled. Magenta outlines show the NW Med and Aegean Sea boxes used for Table 1. b.) Standard deviation of individual winter mean Q_n. Vectors show winter mean wind speed.

Figure 2 a-b) Time series of ERA5 (black) and 20CRv3 (green) winter Q_n for a) the NWMed and b) the Aegean. The 20CRv3 time series has been offset by the difference in ERA5 and 20CRv3 winter mean Qn for 1951-2020 in order to facilitate comparison (offset value: NWMed, -13.5 Wm^{-2}; Aegean, 1.9 Wm^{-2}). c-d) Distributions of individual winter month Q_n using all ERA5 0.25x0.25^o grid cells within each Fg.1a box for 1951-1985 (blue) and 1986-2020 (red) for c.) the NWMed and d.) the Aegean.

Figure 3 a-b) Change in winter heat flux (1986-2020 minus 1951-1985) and wind speed for a) the NWMed and b) the Aegean. Heat flux values (green), wind speed (black). c-d) Corresponding change in temperature (red) and humidity (blue) variables for c) the NWMed and d) the Aegean.

Figure 4 a.) Difference (1986-2020 minus 1951-1985) of ERA5 winter 2 m air temperature (coloured field, ^{o}C) and 10 m wind speed (vectors). b.) Schematic of the main changes in winter SST (orange arrows), air temperature (red arrows), sea-air temperature difference (dark blue arrows) for the NWMed and Aegean. Numerical values are the temperature difference (1986-2020 minus 1951-1985). Purple ellipses indicate main dense water formation regions. Black arrows indicate whether winter heat has loss weakened or remained unchanged in 1986-2020 relative to 1951-1985. Light blue arrow shows increased cold air advection over the Aegean. Background colour field is the difference sea level pressure (1986-2020 minus 1951-1985, units mb).

Figures



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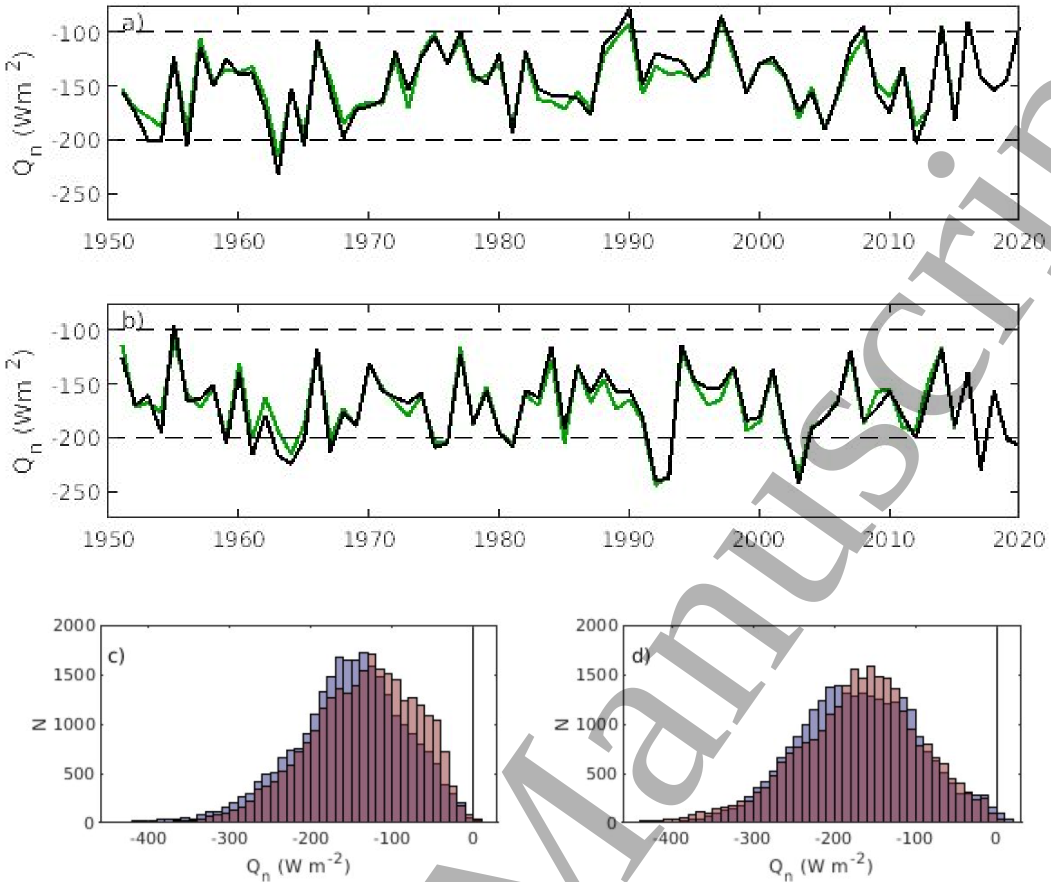

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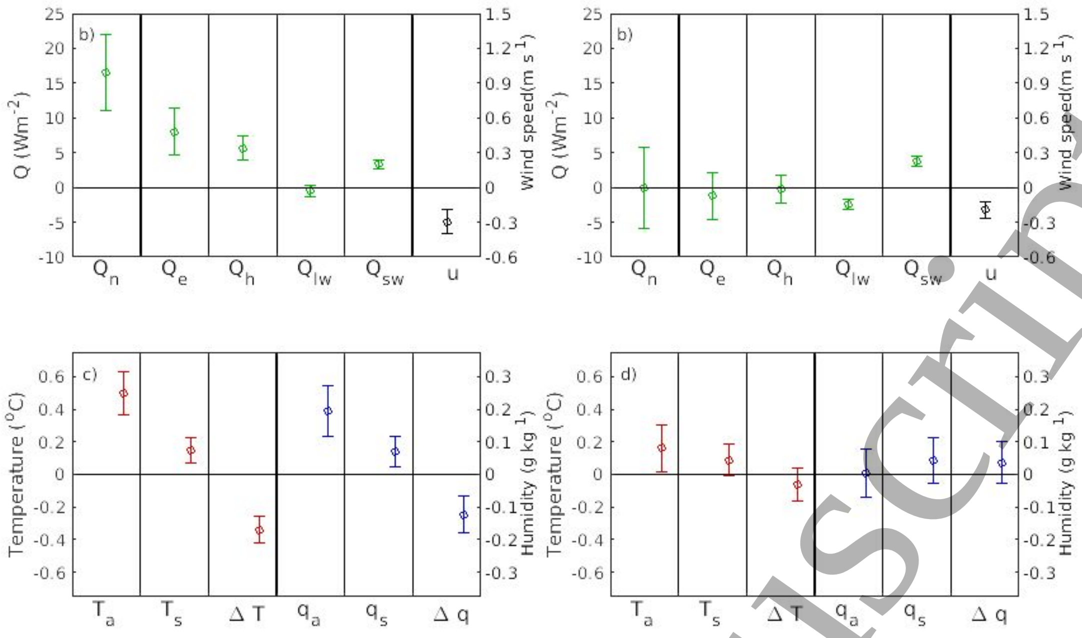

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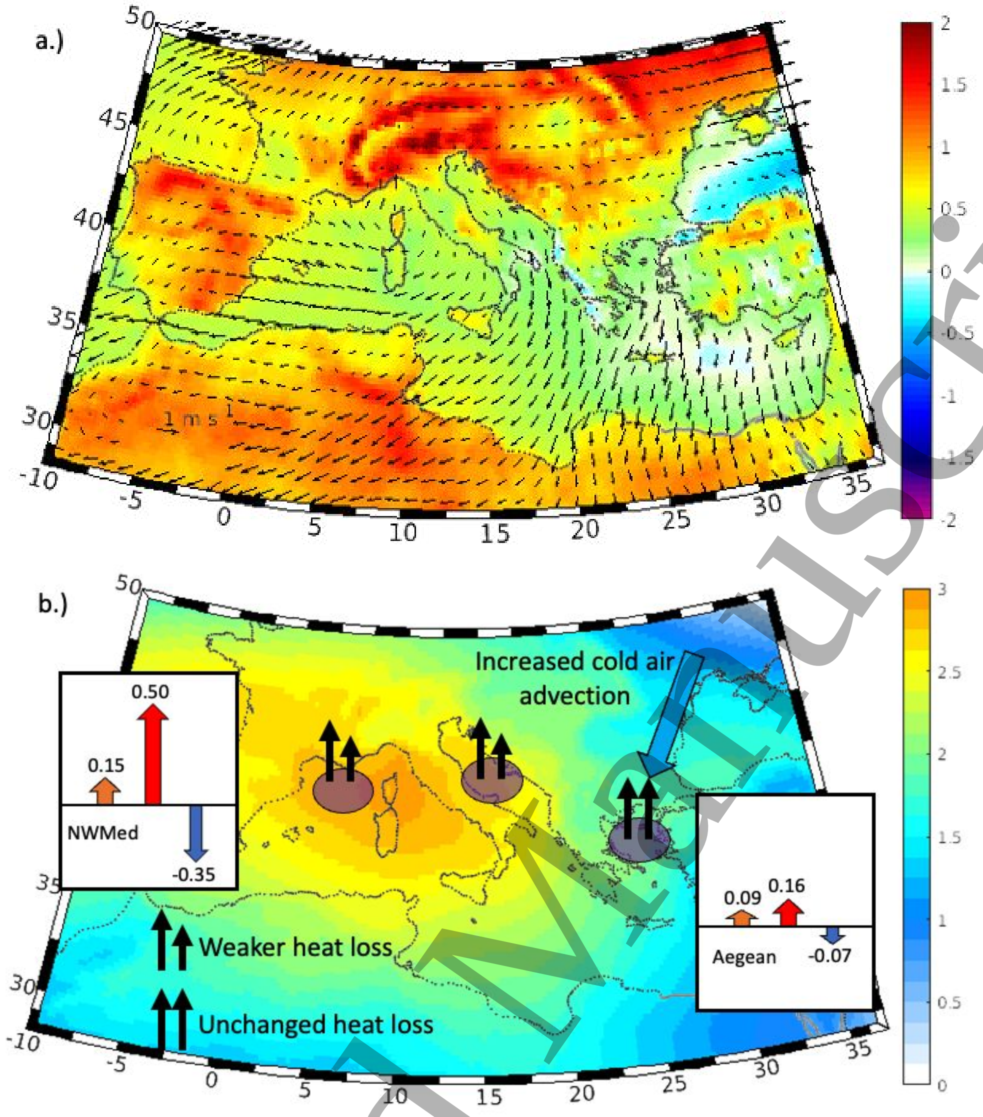

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