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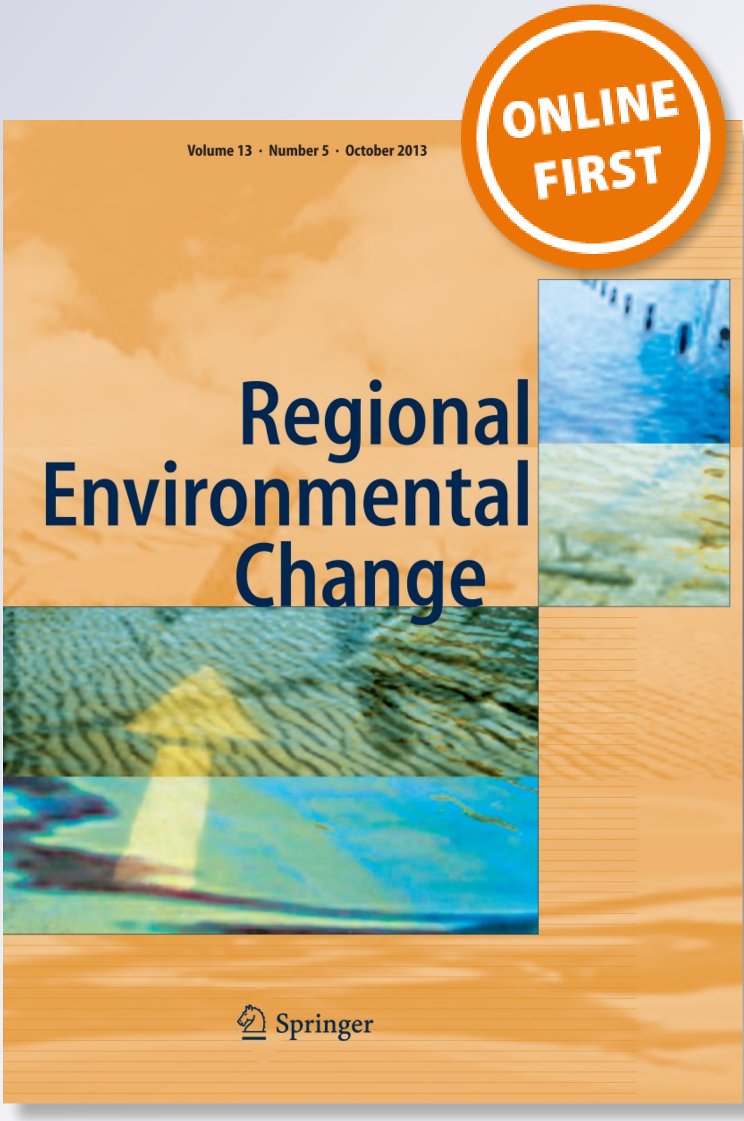

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ORIGINAL ARTICLE

Teleconnections, midlatitude cyclones and Aegean Sea turbulent heat flux variability on daily through decadal time scales

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Abstract We analyze daily wintertime cyclone variability in the central and eastern Mediterranean during 1958–2001 and identify four distinct "cyclone states," corresponding to the presence or absence of cyclones in each basin. Each cyclone state is associated with wind flows that induce characteristic patterns of cooling via turbulent (sensible and latent) heat fluxes in the eastern Mediterranean basin and Aegean Sea. The relative frequency of occurrence of each state determines the heat loss from the Aegean Sea during that winter, with largest heat losses occurring when there is a storm in the eastern but not central Mediterranean (eNOTc) and the smallest occurring when there is a storm in the central but not eastern Mediterranean (cNOTe). Time series of daily cyclone states for each winter allow us to infer Aegean Sea cooling for winters prior to 1985, the earliest year for which we have daily heat flux observations. We show that cyclone states conducive to Aegean Sea convection occurred in 1991/1992 and 1992/1993, the winters during which deepwater formation was observed in the Aegean Sea, and also during the mid-1970s and the winters of 1963/1964 and 1968/1969. We find that the eNOTc cyclone state is anticorrelated with the North Atlantic Oscillation (NAO) prior to 1977/1978. After 1977/1978, the cNOTe state is anticorrelated with both the NAO and the North Caspian Pattern, showing that the area of influence of large-scale atmospheric teleconnections on regional cyclone activity shifted from the eastern to the central Mediterranean during the late 1970s. A trend toward more frequent occurrence of the positive phase of the NAO produced less frequent cNOTe states since the late 1970s, increasing the number of days with strong cooling of the Aegean Sea surface waters.

Keywords Aegean · Turbulent flux · Cyclone frequency · Deepwater formation · Teleconnections

Electronic supplementary material The online version of this article (doi:10.1007/s10113-013-0545-0) contains supplementary material, which is available to authorized users.

J. Romanski (✉)
Center for Climate Systems Research, Columbia University, 2880 Broadway, New York, NY 10025, USA
e-mail: jromanski99@gmail.com; jr988@columbia.edu

A. Romanou · M. Bauer
Department of Applied Physics and Applied Mathematics, Columbia University, 2880 Broadway, New York, NY 10025, USA

G. Tselioudis
NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA

Introduction

Most of the world's oceans are stably stratified, with a steep pycnocline confining mixing to the upper 100 m. However, in a few places, deep water is produced. Deepwater production requires three conditions—first, there must be a cyclonic gyre, which causes doming of the isopycnals and shoaling of the pycnocline; second, there must be a weakly stratified layer beneath the mixed layer; and third, there must be strong buoyancy loss from the surface (Schott et al. 1994; Marshall and Schott 1999). These conditions are most often found in the Labrador Sea (e.g., Clarke and Gascard 1983; Lab Sea Group 1998), the Greenland Sea (e.g., Schott et al. 1994) and the northwest Mediterranean Sea (e.g., MEDOC 1970; Leaman and Schott 1991; Schott et al. 1996). At the onset of winter, large buoyancy losses caused by cold air outbreaks

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associated with intense storms erode the stratified surface layer (the preconditioning phase), setting the stage for deep convection to occur later in the winter in response to extreme heat loss events. These events are short-lived—convection occurs on the time scale of hours (Leaman and Schott 1991; Marshall and Schott 1999). Deep convection is intermittent and shows large interannual variability (Marshall and Schott 1999).

Deepwater formation in the eastern Mediterranean usually takes place in the Adriatic Sea. During the late 1980s and early 1990s, hydrographic observations indicated that deepwater production occurred in the Aegean Sea, replacing the original bottom water with warmer, saltier and denser bottom waters (the "Eastern Mediterranean Transient," or "EMT") (Rubino and Hainbucher 2007; Roether et al. 1996). Both hydrologic and atmospheric factors combined to produce this event—Aegean surface and subsurface waters were saltier due to reduced freshwater input from rivers, reduced low-salinity inflow from the Black Sea, and circulation changes which reduced advection of fresher Atlantic water into the Aegean while enhancing advection of saltier Levantine intermediate water (Beuvier et al. 2010; Sayin and Besiktepe 2010; Velaoras and Lascaratos 2005; Malanotte-Rizzoli et al. 1999; Samuel et al. 1999; Civitarese et al. 2010). Unusually intense atmospheric forcing associated with very cold and windy conditions acted on the saltier Aegean waters, triggering deep convection intermittently during the late 1980s and strongly during the winters of 1991/1992 and 1992/1993 (Beuvier et al. 2010; Bozec et al. 2006; Josey 2003; Theocharis et al. 1999; Samuel et al. 1999).

Recent work has attributed the enhanced atmospheric forcing during those two winters to an anomalous pattern of cyclone activity in the central and eastern Mediterranean basins (Romanski et al. 2012). During those winters, there were fewer storms than usual in the central Mediterranean, and more storms than usual in the eastern Mediterranean, especially in 1991/1992. Romanski et al. (2012) demonstrated that the atmospheric circulation pattern associated with storms in the central Mediterranean brings warm, moist air northward over the Aegean Sea, suppressing heat loss, which depends on the temperature and humidity gradient between the sea surface and the air above. The atmospheric circulation pattern associated with eastern Mediterranean storms has the opposite effect on the Aegean, advecting cold, dry air from the north, and enhancing turbulent heat loss. The combined effects of the reduction in central Mediterranean storminess and the increase in eastern Mediterranean storminess suppressed the number of warm advection events, and augmented the number of cold advection events, resulting in large turbulent heat losses during the winters of 91/92 and 92/93.

Deepwater formation has been documented in the Aegean Sea since 1912, but the lack of high spatial and temporal resolution measurements of water properties throughout the column has prevented a consensus as to the frequency and intensity of Aegean deep convection (Zervakis et al. 2004). Model analyses using a high-resolution ocean model forced with realistic high-resolution atmospheric fields from reanalyses, and a study based on seasonal mean air–sea fluxes from atmospheric reanalyses, suggest that convection may have occurred in the Aegean Sea in the mid-1970s, but at a lower rate than during the EMT (Beuvier et al. 2010; Josey 2003).

The change in the location and rates of formation of deep waters in the Mediterranean during the EMT affected not just the hydrography and circulation of the eastern Mediterranean, but the entire Mediterranean. Additionally, the EMT produced changes in nutrient and phytoplankton distributions in the eastern Mediterranean. These and other EMT-related changes are described in the Electronic Supplement.

There has been a recent focus on relationships between large-scale atmospheric teleconnections such as the NAO, East Atlantic–West Russia (EAWR), the NCP, which is similar to the EAWR, and East Atlantic (EA) patterns and various climate parameters in the Mediterranean region. The western and central Mediterranean tends to vary out of phase with the eastern Mediterranean, sometimes in addition to a full-basin Mediterranean mode that relates to the EA. The NAO generally modulates the western and central node of variability, either directly or indirectly via another oscillation, while the eastern Mediterranean is more frequently associated with the EAWR/NCP patterns, although the findings are not consistent for this region. Please see the Supplementary Online Material for a detailed discussion of the relevant literature.

While it is true that all of the components of the surface heat balance contribute to the buoyancy loss that promotes deep convection, Josey (2003) showed that in the case of the EMT, turbulent heat flux dominated the Aegean cooling. This work will focus on the turbulent fluxes, as they are the primary cooling term (Josey 2003), keeping the phasing of different components of the surface heat budget and their effect on Aegean Sea convection as a topic for future work. Moreover, in focusing on the flux-driven sea surface cooling as the main mechanism by which cyclones affect deep convection, we are neglecting other effects of intensified wind speed on the sea surface. Additional background on the relative importance of turbulent flux compared to radiative fluxes and wind-driven mixed layer and buoyancy advection is provided in the Supplementary Online Material.

The "Datasets" section describes the datasets we used in our analyses. The "Interannual variability of Aegean Sea turbulent flux distributions" section presents the interannual variability of daily mean turbulent heat fluxes over the Aegean. Characteristic spatial distributions and probability distribution functions of Aegean turbulent heat flux associated each cyclone pattern are discussed in the section titled "Midlatitude cyclones and Aegean Sea turbulent fluxes" section. The "Interannual, interdecadal midlatitude cyclone frequency variability and the NAO" section contains analyses of the time series of each cyclone state, their relationships with the NAO and NCP, and the flux variability implied by their relative frequencies as a function of time.

Datasets

Turbulent fluxes (latent and sensible heat, referred to as LHF and SHF, respectively) are from the OAFlux merged satellite and reanalysis product (Yu and Weller 2007). OAFlux data are derived by synthesizing satellite-based observations with output from several reanalyses using an objective analysis algorithm, which minimizes error with respect to independent surface-based observations. OAFlux heat fluxes agree with the ship-based National Oceanography Centre climatology (Josey et al. 1999) and are on average within 5 % of buoy–ship flux measurements (Yu and Weller 2007). They are daily means at 1° resolution. Herein, the terms "turbulent fluxes" or "turbulent heat fluxes" refer to the sum of LHF and SHF.

The 10-m meridional (v) winds and 2-m temperatures are from ERA-Interim (Simmons et al. 2006). ERA-Interim is a reanalysis product created using a state-of-the-art ECMWF operational forecast model assimilating a large number of meteorological observations (Simmons et al. 2006). It incorporates many improvements compared to ECMWF's ERA-40 product, including 4D variational analysis, improved model physics, improved formulation of background error constraint, and improved bias correction procedures. ERA-Interim also uses reprocessed Meteosat winds. This study uses the 6-hourly products at the N128 Gaussian resolution (nominally 0.703°).

Cyclones are from NASA's MAP Climatology of Midlatitude Storminess (MCMS) project (M. Bauer, A New Climatology for Investigating Storminess Influences on the Extratropics, submitted to *Journal of Climate*, 2012). The cyclone detection algorithm applies a series of filters to a gridded SLP field derived from the 2.5°, ECMWF ERA40 Reanalysis dataset. The purpose of each filter is to progressively select likely cyclones from an initial pool of candidate systems comprised of all cases where a minimum or near-minimum can be found in the local SLP field. These candidate cyclone centers are then further refined with a tracking algorithm that essentially links current and past centers via nearest neighbor and other similarity arguments.

These datasets were chosen because they provide the most complete and accurate description at the highest resolution of the atmosphere for the longest period possible over both open sea and coastal regions. We chose to use the OAFlux fluxes because Yu and Weller (2007) note that they are unbiased and have the smallest variance compared to reanalysis when evaluated against buoy- and ship-based measurements. Further, differences between OAFlux turbulent fluxes and reanalysis fluxes can be as large as 20–30 W/m^2 in subtropical oceans. While Yu and Weller (2007) did not compare OAFlux with ERA-Interim fluxes, Dee et al. (2011) specifically identify air–sea heat exchanges as a area for future ERA-Interim improvement, pointing out deficiencies in both the hydrologic cycle and ocean surface energy balance related to surface flux problems. Using different data sources for fluxes, and wind and temperature introduces some internal inconsistency in our study, however, Romanou et al. (2010) show that over the Mediterranean basin, the spread among satellite-derived and ERA40, ERA-Interim and NCEP SST and air humidity is small compared to the flux spread, and also show that in the Mediterranean region, ERA-Interim winds are quite similar to the satellite-derived winds. This study first focuses on November, December, January and February (NDJF) during the period of overlap between the OAFlux daily data and ERA40 (1985–2001) and then extends the results to the earlier portion of ERA40, which precedes OAFlux (1958–1984).

Results

Interannual variability of Aegean Sea turbulent flux distributions

Figure 1 shows the probability distribution function (PDF) of daily mean Aegean Sea turbulent fluxes for NDJF 1985/1986 through 2000/2001. The PDFs are non-Gaussian, with the distributions strongly skewed toward low-flux values, demonstrating that strong cooling events are rare. The bin sizes in Fig. 1 were chosen for clarity; however, the distribution shape remains the same at different bin sizes. There is interannual variability in both the location of the mode of the distribution, which shifts in 2 out of 16 years from the lowest flux bin (0–100 Wm^{-2}) to the second lowest bin (100–200 Wm^{-2}), as well as in the length of the high-flux tail, which extends to values above 500 W/m^2 in 6 out of 16 years. In particular, the period known for strong cooling, and deepwater production in the Aegean—the late 1980s and early 1990s—features an especially long tail, with several instances per winter of

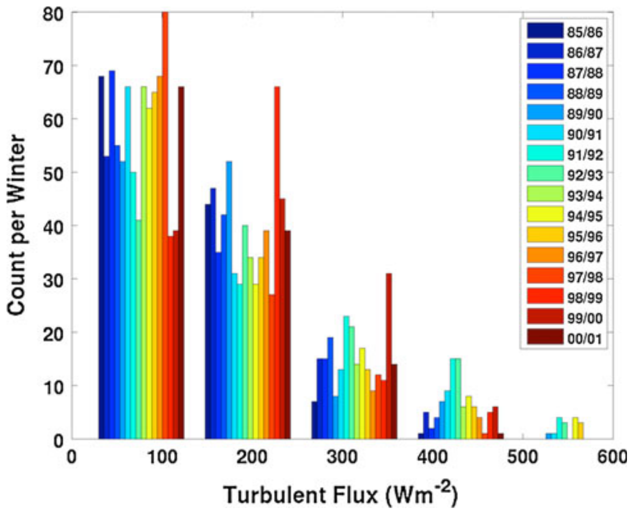

Fig. 1 Count per winter of daily mean Aegean daily mean turbulent flux values for November, December, January and February (NDJF) seasons for 1985/1986 through 2000/2001. Each color represents one NDJF season. The x-axis is turbulent flux in Wm^{-2}

fluxes above 500 Wm^{-2}. The peak deepwater production winters of 1991/1992 and 1992/1993 show not only a long tail, but more flux values at 400–500 Wm^{-2} than other years. Daily LHF and SHF anomalies are strongly correlated ($r = 0.93$ for NDJF 1985–2001, $r = 0.95$ for the two EMT winters), reflecting the prevalence of cold, dry or warm, moist air masses. In general, LHF anomalies are larger than SHF anomalies—the maximum LHF anomaly during NDJF 1985–2001 was 273 $\mathrm{W/m^2}$, compared to a maximum SHF anomaly of 195 $\mathrm{W/m^2}$. Mean LHF is also larger than mean SHF: 121 $\mathrm{W/m^2}$, compared to 45 $\mathrm{W/m^2}$. LHF is positive definite, while SHF may attain negative values. Because wintertime synoptic meteorology produces highly correlated variations in both LHF and SHF, Romanski et al. (2012), and this study as well, treat LHF and SHF together, as turbulent heat fluxes. As we have demonstrated (Romanski et al. 2012) in our paper on the EMT, the combination of the unusually large number of storms in the eastern Mediterranean basin and the unusual paucity of storms in the central Mediterranean, produced an anomalous atmospheric wind field. The anomalous wind field enhanced cold advection events while suppressing warm advection events, leading to unusually large heat loss from the Aegean (Romanski et al. 2012). We will show later in this paper that the long flux tail in the PDF occurs when there are cyclones in the eastern but not central Mediterranean, a situation where the storm-induced advection of cold air is most extreme, producing the most extreme turbulent fluxes.

The PDFs of turbulent flux are decisively non-Gaussian, and the strongest heat losses are comparatively rare and episodic. The relationship between storm patterns and extreme heat loss events that promote deep convection may be more clearly revealed by examining the low frequency, i.e., interannual variability of the PDFs, than the seasonal or even monthly mean flux. Although we do not have direct observations of Aegean Sea convection, Marshall and Schott (1999) state that the timing of buoyancy loss is important as well as the total loss for the major ocean convection sites. Large buoyancy losses induced by a few extreme winter storms are more likely to produce deep convection than the same total buoyancy loss spread out over the entire winter. Without intense buoyancy loss, lateral advection of stratified water into the potential convection site may restabilize the water column and inhibit convection (Marshall and Schott, 1999). This restratification, or “capping,” was observed in the northwestern Mediterranean by Leaman and Schott (1991). Våge et al. (2008) made a similar argument regarding convection in the Irminger Sea, and a modeling study of the North Atlantic by Bigg et al. (2005) found reduced volume of overturning water produced in response to climatological mean heat loss compared to time-varying heat loss. Monthly or seasonal mean fluxes describe the overall cooling during a winter, while the PDFs provide complementary information, which permits us to discriminate the short but intense cooling events, which may be critical to deepwater production.

Midlatitude cyclones and Aegean Sea turbulent fluxes

There are large temperature and moisture gradients over the Aegean Sea region during winter, with warm Mediterranean waters to the south and cold land masses to the north. Cyclonic wind flow around cyclone centers transports cold air southward on the western side of the storm and warm air northward on the eastern side. Thus, the location of the cyclone determines whether cold or warm air is transported over the Aegean—if the cyclone is in the central Mediterranean, warm air is advected over the Aegean, whereas if the cyclone is in the eastern Mediterranean, cold air is advected over the Aegean. Analysis of the spatial distribution of cyclones during the winters of 1991/1992 (Romanski et al. 2012) demonstrated that there were unusually few central Mediterranean cyclones and unusually frequent eastern Mediterranean cyclones during that time. This anomalous storm pattern was then shown to alter heat transport over the Aegean Sea by reducing the frequency of warm advection events associated with central Mediterranean cyclones and increasing the frequency of cold advection events associated with eastern Mediterranean cyclones. This altered the turbulent flux over the Aegean and led to strong buoyancy losses during those winters. A detailed description of the role of heat advection by the meridional wind in determining Aegean Sea surface cooling is presented in the Electronic Supplement.

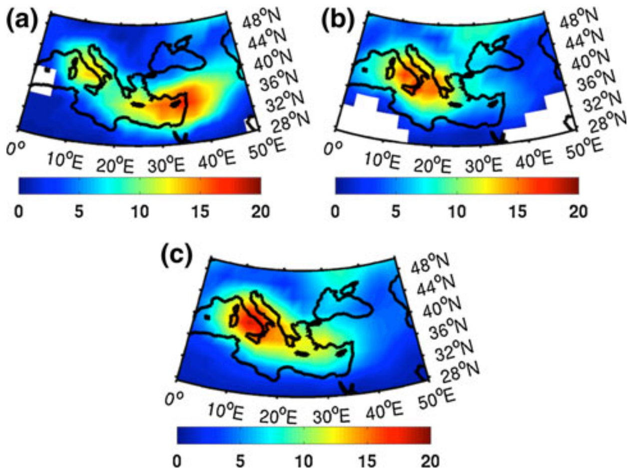

Fig. 2 **a** Cyclone density, number of storms (i.e., cyclone centers) which occur within a 5° latitude radius (1,000/deg lat^2), for November, December, January and February 1991/1992. **b** The same as Fig. 3a, but for November, December, January and February 1997/1998. **c** The same as Fig. 3a, but for November, December, January and February 1958/1959–2000/2001

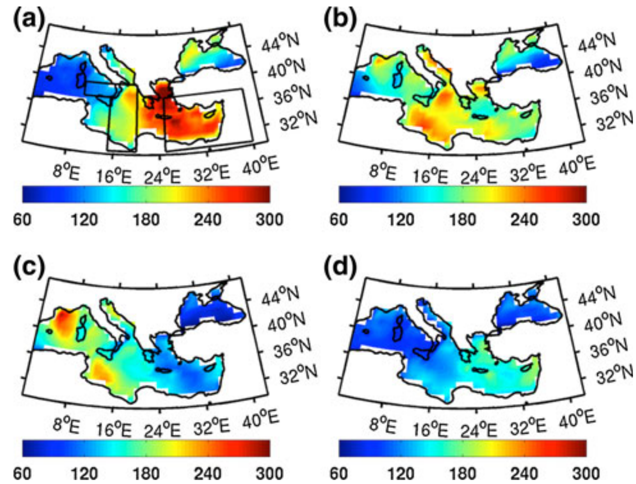

Fig. 3 **a** Composite of daily mean turbulent flux (Wm^{-2}) when there is a storm in the eastern Mediterranean, but not the central Mediterranean (eastern and central Mediterranean regions are outlined in black; see text for definition) eNOTc. **b** Composite of daily mean turbulent flux when there is a storm in both the central and eastern Mediterranean eANDc. **c** Composition of daily mean turbulent flux when there is a storm in the central Mediterranean, but not the eastern Mediterranean cNOTe. **d** Composite of daily mean turbulent fluxes when there is a storm in neither location NOTeNOTc. All are for November, December, January and February 1985/1986–2000/2001

Here, we examine the climatological pattern of cyclone frequency during NDJF 1958/1959–2000/2001 and consider two unusual seasons. Figure 2a shows the cyclone center density for NDJF 1991/1992, Fig. 2b shows cyclone center density for NDJF 1997/1998, and Fig. 2c portrays the climatological mean cyclone center density. The cyclone patterns are very different. In 1991/1992, cyclones occurred mainly in the eastern Mediterranean, while in 1997/1998, they occurred primarily in the central Mediterranean. The climatology reveals that the central Mediterranean is the preferred location for cyclones, in agreement with Trigo et al. (1999). We expect, based on the findings of Romanski et al. (2012), that the different storm locations in each season will produce different flux distributions. As can be seen in Fig. 1, 1991/1992 and 1997/1998 have very different flux PDFs. The NDJF season 1991/1992 has fewer values at the low end of the distribution, more values at the high end, and a longer tail than 1997/1998, which has a large number of low-flux values, and few high values.[1] The climatological pattern resembles that of 1997/1998, favoring lower fluxes from the Aegean.

Figure 3 shows turbulent flux composites for each of the four possible cyclone states in the central and eastern Mediterranean [here, central Mediterranean is defined as 10–15E, 38–40N and 15–20E, 30–40N and eastern Mediterranean is defined as 25–40E, 30–38N] for NDJF 1985/1985–2000/2001. Figure 3a depicts turbulent flux when there is a storm in the eastern Mediterranean, but not in the central Mediterranean (eNOTc, occurs 14.7 % of the time from 1958/1959–2000/2001), Fig. 3b shows turbulent flux when there are storms in both the central and eastern Mediterranean (cANDe, occurs 6.3 % of the time from 1958/1959–2000/20001), Fig. 3c illustrates turbulent flux when there is a storm in the central but not eastern Mediterranean (cNOTe, occurs 25.5 % of the time from 1958/1959–2000/2001), and Fig. 3d presents turbulent flux when there is a storm in neither location (NOTcNOTe, occurs 54.1 % of the time from 1958/1959–2000/2001). Each cyclone state has a characteristic flux pattern. Storms in the eastern Mediterranean (eNOTc) produce large turbulent fluxes over the eastern Mediterranean and especially over the Aegean Sea; storms in the central Mediterranean (cNOTe) produce large fluxes in the central and western Mediterranean, especially the Gulf of Lion; and storms in both locations produce moderate fluxes in the central Mediterranean and Aegean Sea. We expected the NOTcNOTe cyclone pattern to produce low fluxes over the Aegean, but instead we see the same pattern as in eNOTc, but with much smaller magnitude. The NOTcNOTe pattern is not sensitive to the choice of boundaries for the eastern Mediterranean. There are small, short-lived storms and open lows that do not pass the MCMS cyclone tracking algorithm's criteria, but nevertheless may influence turbulent fluxes. This situation occurs more often in the eastern

[1] Please note that Romanski et al. (2012) incorrectly states that 1997/1998 was an average flux year, and 2004/2005 was a low-flux year. That is incorrect—1997/1998 was a low-flux year, and 2004/2005 was a high-flux year. We apologize for the error.

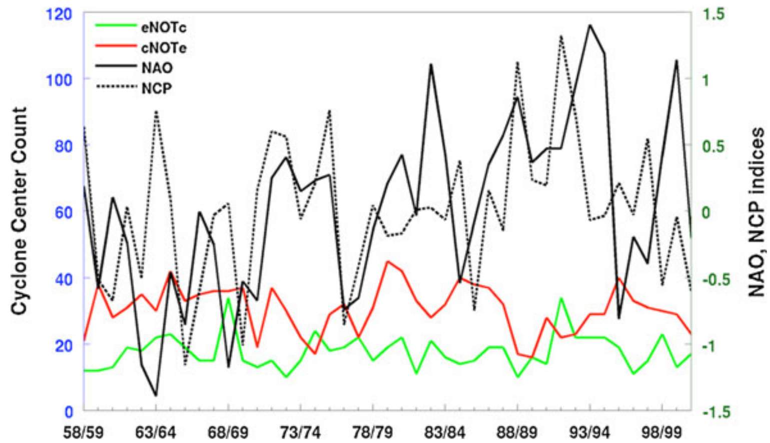

Fig. 4 NDJF mean NAO index (*solid black curve*), NCP index (*dotted black curve*), frequency of occurrence of the cNOTe cyclone state (*red curve*) and frequency of occurrence of the eNOTc cyclone state (*green curve*)

Mediterranean, in agreement with Maheras et al. (2001), who finds a tendency toward weaker, short-lived storms in the eastern Mediterranean. This would cause some flux-generating low-pressure systems to be included in the NOTcNOTe category, rather than in the eNOTc category, producing a weak echo of the eNOTc flux pattern. Aegean daily mean flux PDFs for each cyclone state are shown and described in the Electronic Supplement.

Interannual, interdecadal midlatitude cyclone frequency variability and the NAO

The large body of evidence on the influence of large-scale atmospheric teleconnection patterns on different aspects of central and eastern Mediterranean climate prompted us to investigate their role in modulating cyclone frequency. The number of days on which there were cyclones in the eastern but not central Mediterranean (eNOTc) and the central but not eastern Mediterranean (cNOTe) per NDJF winter for 1958/1959 through 2000/2001 is shown in Fig. 4, along with the NDJF mean NAO and NCP indices. There is no observable trend in the number of days in the eNOTc cyclone state. There are many more eNOTc days during 1968/1969 and 1991/1992 (34 days during each winter, compared to 17.7, the mean number of eNOTc days per winter), a prolonged series of eNOTc stormy winters in the early 1990s, and a prolonged series of calmer winters in the early 1970s. There is a downward trend of −0.1 days/winter in cANDe, which significant at the 95 % confidence level. There is also a downward trend of −0.1 days/winter in the number of days in the cNOTe state, but this trend is not significant ($p = 0.30$). There is large interannual variability in cNOTe, which may be responsible for the non-significance. The apparent trend in cNOTe is the same magnitude as the trend in cANDe, and the only commonality between the two is the number of days during, which there is a storm in the central Mediterranean. Hence, although we cannot say that there is a trend in cNOTe, we

Table 1 Number of intervals of successive winters with same-sign cNOTe and eNOTc anomalies, and successive winters with same-sign NAO and NCP indices, and mean interval lengths for NDJF 1958/1959–2000/2001, NDJF 1958/1959–1977/1978 and NDJF 1978/1979–2000/2001

	1958/1959–2000/2001	1958/1959–1977/1978	1978/1979–2000/2001
cNOTe			
Number of intervals of same-sign anomalies	8	3	6
Mean interval length	4.25	4	4.4
eNOTc			
Number of intervals of same-sign anomalies	12	5	7
Mean interval length	3.25	3.75	2.7
NAO			
Number of intervals of same-sign anomalies	9	3	6
Mean interval length	3.56	8.5	4
NCP			
Number of intervals of same-sign anomalies	11	6	5
Mean interval length	2.55	2.3	2.8

believe it is plausible that cANDe and cNOTe are both influenced by the downward trend in the frequency of central Mediterranean storms described by Nissen et al. (2010), Trigo (2006) and Alpert et al. (2004). We will show later that this trend is related to variability in the NAO, especially during the latter half of the record. Table 1 shows the number and mean length of intervals of successive winters with positive or negative anomalies for cNOTe and eNOTc, and the number and mean length of intervals of successive winters with positive or negative NAO and NCP indices. The results indicate that, unlike eNOTc, in which extended series of low- or high-frequency winters is rare (mean length of intervals of successive

Table 2 Correlation coefficients of the eNOTc and cNOTe cyclone states with the NAO and NCP indices for NDJF 1958/1959–2000/2001, NDJF 1958/1959–1977/1978 and NDJF 1978/1979–2000/2001

	1958/ 1959–2000/2001	1958/ 1959–1977/1978	1978/ 1979–2000/2001
eNOTc, NAO	−0.05	**−0.51**	0.30
eNOTc, NCP	0.11	0.03	0.19
cNOTe, NAO	**−0.30**	−0.29	**−0.42**
cNOTe, NCP	**−0.34**	−0.27	**−0.44**

Coefficients in bold are significant to the 95 % confidence level

winters = 3.25), the cNOTe cyclone state tends to persist over several winters (mean length = 4.25 winters). The tendency toward successive cNOTe winters is especially pronounced in the latter portion of the time series, where the cNOTe state persisted for a mean length of 4.4 winters, compared to only 2.7 for eNOTc. cNOTe occurred frequently during the eleven winter period from 1977/1978 to 1987/1988, skipping the winter of 1982/1983. cNOTe anomalies during 1977/1978–1987/1988 were >0 for 10 of those 11 years, with a mean frequency of 35.8 days/winter, compared to the mean over all winters of 30.7 days/winter. That period was followed by one of less frequent occurrences of cNOTe, until 1994/1995, with negative cNOTe anomalies and a mean frequency of 21.2 days/winter.

The NAO index shows the well-known shift from predominantly negative values to predominantly positive values that occurred in the late 1970s, as well as the long term positive trend (e.g., Hurrell 1995). The NCP shows a similar positive trend. We computed correlation coefficients between the eNOTc and cNOTe cyclone states and the NAO and NCP indices, respectively, for both the full time series, and for the first half (1958/1959–1977/1978) and second half (1978/1979–2000/2001) of the time series separately. Correlation coefficients are given in Table 2. Of the correlations which are statistically significant to 95 %, we find that cNOTe is negatively correlated with both the NAO and NCP over the full period. eNOTc is negatively correlated with the NAO during the first half of the time series, but not the second half, while cNOTe is negatively correlated with the NAO during the second half, but not the first half. cNOTe is also negatively correlated with the NCP during the second half of the time series. During the first part of the record, there was a relationship between NAO and the number of stormy days in the eastern Mediterranean, but at the same time as the shift from negative to positive NAO indices occurred, the area of influence of the NAO shifted from the eastern Mediterranean to the central Mediterranean. The PDO also shifted from negative to positive in the mid-1970s, which was shown to affect Mediterranean and Black Sea storminess by Voskresenskaya and Maslova (2011), and could have altered the response of each cyclone state to interannual modes like the NAO and NCP. As can be shown in Table 1, there is a tendency in the latter half of the record toward more frequent occurrences of periods of same-sign anomalies in both the cNOTe cyclone state frequency and the NAO index, i.e., the likelihood of having 2 or more similar winters in a row is greater.

The results presented above demonstrate that the relative frequency of the four different cyclone states, eNOTc, cNOTe, cANDe and NOTcNOTe during each winter determines the distribution of Aegean Sea turbulent fluxes, and so determines whether atmospheric conditions are conducive to deepwater formation in the Aegean.

We have used the period where we have both daily flux and cyclone data (1985–2001), to determine how the relative cyclone state frequency controls the PDF of daily mean Aegean turbulent flux for a given winter, and these results are shown in the Supplementary Online Material. We can use what we have learned about the relationship between relative cyclone state frequency and turbulent flux to hypothesize which years featured atmospheric states that were conducive to deepwater production prior to 1985. Figure A3 in the Supplementary Online Material shows that eNOTc occurred more often than usual, while cNOTe was average or less frequent than usual during 1974/1975, 1975/1976 and 1977/1978 and during 1963/1964. These are roughly the same years that Josey (2003) identified as high-flux years.

Discussion

The above results show that interannual variability of wintertime Aegean Sea turbulent fluxes occurs via variation in the strength of the most frequent events (i.e., shifting the mode of the turbulent flux PDF) and also by variation in the frequency and intensity of extreme events (i.e., extending or contracting the length of the high-flux tail of the PDF). The shape of each winter's PDF depends on the relative frequencies of storms in the central and eastern Mediterranean basins, each of which induce atmospheric circulation patterns which produce characteristic heat advection and turbulent flux distributions over the Aegean Sea. The most frequent flux value (the mode of the PDF) is between 0 and 100 W/m^2 in 14 out of 16 winters and between 100 and 200 W/m^2 in 2 out of 16 winters, indicating that even during high-flux winters, fluxes are low on most days. Extreme high-flux events are rare, with daily mean fluxes over 500 W/m^2 occurring during 6 out of 16 winters, and no more than 5 days during each of those 6 winters. The extreme high-flux events which drive strong buoyancy loss and promote deepwater formation are comparatively rare and episodic. The close link between deep convection and extreme high-flux events has been observed in other primary deepwater production regions—the Labrador Sea, the Greenland Sea and the northwest Mediterranean (Marshall and Schott 1999). Vertical velocity is strongly correlated with buoyancy flux (Steffen and D'Asaro 2002), with the strongest fluxes producing vertical currents in convective plumes of as much as 9 cm/s in the northwest Mediterranean during a strong Mistral, when heat losses approached 1,000 W/m^2 (Leaman and Schott 1991). Vertical velocity reached 10 cm/s in the Labrador Sea, in response to heat losses of over 500 W/m^2 (Lavender et al. 2002). Here, we see that in Aegean Sea as well, a larger than usual number of rare, strong storms is associated with deepwater formation.

Each winter's flux comprises contributions from four distinct cyclone patterns, or states, each of which has a characteristic flux spatial distribution and PDF. The presence or absence of cyclones in the eastern and central Mediterranean results in characteristic spatial distributions of heat advection by the meridional wind, which is strongly related to turbulent flux on daily time scales. Fluxes are largest when there is a storm in the eastern Mediterranean but not in the central Mediterranean, advecting cold, dry air over the Aegean Sea. Fluxes are smallest when there is a storm in the central Mediterranean, but not in the eastern Mediterranean, advecting warm, moist air over the Aegean, and inhibiting flux (Romanski et al. 2012). Fluxes are moderate to large when there are storms in both locations, and small when there are storms in neither location.

Time series of daily cyclone states for each season allow us to infer flux PDFs for winters prior to 1985, the earliest year for which we have daily flux observations. We find that the combination of the four cyclone states was most conducive to large Aegean fluxes during the mid-1970s, in agreement with Josey's (2003) observation that there was a prolonged period of strong cooling during those years, and also during the winter of 1968/1969, which Josey (2003) did not identify as a high-flux year. The cNOTe cyclone state shows an increase in the frequency of occurrence of persistent anomalies over multiple winters, so that there is a greater likelihood of prolonged periods of cooling or warming. The eNOTc cyclone state—cyclones in the eastern but not central Mediterranean—does not have a trend over the time series. There are nearly always fewer instances of eNOTc per winter, and eNOTc usually has smaller interannual variability, with the exceptions of the winters of 1963/1964 and 1991/1992, during which there were many more eastern Mediterranean storms than usual. The two time series, cNOTe and eNOTc, are not correlated ($r = 0.02$), suggesting that at least most of the time, storms are not moving from the central to the eastern Mediterranean. This concurs with Flocas et al.'s (2010) finding that eastern Mediterranean cyclones tend to form in place, rather than arrive from upstream. A more complete description of the differences between central and eastern Mediterranean cyclogenesis is given in the Electronic Supplement.

We find a negative correlation between the NDJF mean NAO and the number of eNOTc stormy days per winter over the first half of the time series, and a negative correlation between the NAO and NCP indices and the number of cNOTe stormy days per winter over the second half of the time series. Together, these indicate that the area of influence of the NAO shifted from the eastern to the central Mediterranean basins during the mid-1970s. The association between the increased frequency of the positive phase of the NAO in recent decades and the reduction in western/central Mediterranean cyclones has been noted several times (e.g., Nissen et al. 2010; Trigo 2006; Alpert et al. 2004). Nissen et al. (2010) also link the EAWR, a mode of variability similar to the NCP, to the decline in central Mediterranean storminess. The literature reports mixed trends for the eastern Mediterranean—some finding an increase in storminess (Nissen et al. 2010; Maheras et al. 2001) related to the NAO and EAWR (Nissen et al. 2010, Krichak et al. 2002), while others report a decrease (Alpert et al. 2004, Krichak and Alpert 2005) or no trend (Flocas et al. 2010). Additional discussion of our findings in the context of the literature on the effect of the NAO and EAWR/NCP on central and eastern Mediterranean storminess and on Aegean Sea fluxes can be found in the Supplementary Online Material.

Analyses of Mediterranean storminess in various climate change scenarios indicate that the circulation pattern associated with the positive phase of the NAO will occur more often as the climate warms (Marcos et al. 2011; Raible et al. 2010; Lionello et al. 2008; Pinto et al. 2007). The northward shift of the storm track over Europe associated with NAO positive events has been recorded in observations and is robust among climate models (Intergovernmental Panel on Climate Change 2007). Our results suggest that a tendency toward fewer central Mediterranean storms, perhaps accompanied by more eastern Mediterranean storms, would shift the PDF of Aegean Sea turbulent fluxes toward higher flux (the mode) and would increase the occurrence of extreme high fluxes (the tail). These changes, along with NAO-related changes to the freshwater budget of the Aegean, will increase the likelihood of deepwater formation in the Aegean Sea. Aegean deep convection itself may promote future deep convection, as described by Velaoras and Lascaratos (2010). The combination of these factors suggests that in the future, the Aegean could become a more consistent region of deep convection, as described by Bozec et al. (2006), affecting bottom water mass characteristics in not just the eastern

Mediterranean, but the western basin as well (Herrmann et al. 2010), and eventually the global circulation.

Conclusions

We find that variability in daily Aegean Sea turbulent fluxes is determined by contributions from each of four cyclone states corresponding to the presence or absence of storms in the central and eastern Mediterranean basins. Each cyclone pattern—storms in the central Mediterranean only, storms in the eastern Mediterranean only, storms in both basins and storms in neither basin—has a characteristic wind field and resulting spatial distribution of turbulent heat flux in the eastern Mediterranean, and each pattern produces a distinct probability distribution function of Aegean daily mean turbulent heat flux. The frequency of occurrence of each cyclone state during a particular winter determines the Aegean Sea flux for that winter. Examination of time series of daily cyclone states for winters prior to 1985 suggests that large Aegean fluxes likely occurred during the mid-1970s and during the winter of 1968/1969.

We find a non-stationary relationship between the NAO and NCP, and the relative frequency of cyclones in the different basins. Before the mid-1970s, the frequency of occurrence of the eNOTc cyclone state was anticorrelated with the NAO index. After that time, both the NAO and NCP indices are anticorrelated with the frequency of occurrence of the cNOTe cyclone state. The area of influence of the NAO and NCP shifted from the eastern to the central Mediterranean in the mid-1970s. Since then, the NAO and NCP influence Aegean fluxes via modulating the frequency of central Mediterranean storminess, not eastern Mediterranean storminess. The tendency toward more frequent periods of continuous NAO positive phase would produce successive winters with low cNOTe frequencies, and fewer low-flux days, such as was observed in the early 1990s.

There are potentially large environmental impacts to the eastern Mediterranean region of a shift toward more frequent positive NAO and NCP phases. By altering the relative frequency of central and eastern Mediterranean storms, such a shift would enhance the probability of atmospheric conditions that promote EMT-like events. Wintertime temperature, wind and precipitation are all influenced by the NAO and NCP (e.g., Josey et al. 2011; Kazmin et al. 2010; Krichak and Alpert 2005). This in turn affects vertical mixing and the thermohaline circulation of the eastern Mediterranean (Malanotte-Rizzoli et al. 1999; Klein et al. 1999) via changes to surface heat fluxes, wind forcing and salinity (Josey 2003; Romanski et al. 2012). Circulation changes then alter the biogeochemistry and biological productivity of the eastern Mediterranean (Touratier and Goyet 2010; Klein et al. 2003). Biological effects are short-lived and primarily affect the eastern Mediterranean, while the influence on the water mass characteristics extend through the entire Mediterranean and may persist for many years (Herrmann et al. 2010).

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