# Atmospheric forcing of the Eastern Mediterranean Transient by midlatitude cyclones

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[1] Hydrographic observations indicated a shift of the main deep water formation in the Mediterranean Sea from its usual location in the Adriatic Sea to the Aegean Sea during the late 1980s and early 1990s, during winters 1991/1992 and 1992/1993. This event is known as the Eastern Mediterranean Transient (EMT). We report here a connection between EMT and specific atmospheric conditions which created anomalously large buoyancy fluxes from the Aegean Sea during winters 1991/1992 and 1992/1993 (the "enhanced EMT winters"). We use newly available, state of the art datasets with high space and time resolution and show that atypical cyclonic activity in the central Mediterranean versus the eastern basin produced the enhanced atmospheric forcing which intensified the EMT. An abatement of the frequency of cyclones in the central Mediterranean during 1992/1993 drastically reduced the northward advection of warm air over the Aegean Sea compared to more typical years, while an increase in the frequency of cyclones in the eastern Mediterranean enhanced the southward advection of cold air over the Aegean Sea, especially during 1991/1992. These changes significantly increased buoyancy flux losses from the Aegean Sea during the enhanced EMT winters, intensifying deep water production. **Citation:** Romanski, J., A. Romanou, M. Bauer, and G. Tselioudis (2012), Atmospheric forcing of the Eastern Mediterranean Transient by midlatitude cyclones, *Geophys. Res. Lett.*, *39*, L03703, doi:10.1029/2011GL050298.

## 1. Introduction

[2] In the late 1980s - early 1990s, the Aegean Sea became a major source of deep water for the eastern Mediterranean, overpowering the Adriatic Sea source, and producing warmer, saltier and denser bottom waters [*Roether et al.*, 1996; *Rubino and Hainbucher*, 2007]. Hydrological changes occurred throughout this period, which preconditioned the Aegean waters for deep convection. These include a reduction in freshwater fluxes from precipitation and rivers, reduction of the fresher inflow from the Black Sea, ocean-circulation changes which enhanced inflow of salty Levantine Intermediate Water into the Aegean, and changes in the direction of flow of the Northern Ionian Gyre, which reduced inflow to the Aegean of comparatively fresh Atlantic 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]. Deep-water convection in the Aegean occurred intermittently during the late 1980s, and then strongly during the winters of 1991/1992 and 1992/1993, triggered by unusually intense atmospheric forcing in combination with the hydrological changes described earlier [*Beuvier et al.*, 2010; *Bozec et al.*, 2006; *Josey*, 2003; *Theocharis et al.*, 2002; *Samuel et al.*, 1999].

[3] Several studies [*Beuvier et al.*, 2010; *Bozec et al.*, 2006; *Josey*, 2003; *Theocharis et al.*, 2002; *Samuel et al.*, 1999] have attributed the enhanced turbulent buoyancy fluxes from the Aegean during the enhanced EMT winters to unusually cold and windy conditions, acting on unusually salty Aegean surface waters. For example, *Josey* [2003], described patterns of anomalous heat flux and flux components during the enhanced EMT winters, and associated them with Aegean deep convection. Here we expand upon the atmospheric forcing part of the event and examine the atmospheric dynamical patterns that gave rise to the winds which produced anomalously large buoyancy fluxes during those winters. We use daily observations of turbulent fluxes, their components, and a Sea Level Pressure (SLP)-based cyclone climatology for November, December, January and February ("NDJF") 1989–2009 to demonstrate the relationship between synoptic time-scale meteorology and turbulent fluxes over the Aegean. We show that a causal connection exists between those particularly severe enhanced EMT winters and the relative intensity of the cyclonic activity in the central and eastern Mediterranean basins – greater than normal cyclonic activity in the eastern Mediterranean in 1991/1992 produced unusually large advection of cold air over the Aegean, and lesser than normal cyclonic activity in the central Mediterranean during 1992/1993 produced unusually small advection of warm air over the Aegean. Both of these changes led to anomalously large turbulent heat losses from the Aegean.

## 2. Datasets

[4] Turbulent heat fluxes (latent and sensible heat, referred to as LHF and SHF, respectively), and their determining factors (air temperature, air humidity, wind speed and Sea Surface Temperature) are from the daily, 1° resolution Objectively Analyzed Air-Sea Heat Flux (OAFlux) merged satellite and reanalysis product [*Yu and Weller*, 2007] with biases up to 5% [*Romanou et al.*, 2010]. 10 m meridional (v) winds and 2 m temperatures are from the 6-hourly, ~0.7° resolution ECMWF Interim Reanalysis (ERA-Interim) [*Simmons et al.*, 2006] that has improved error and bias correction procedures compared to other reanalysis products

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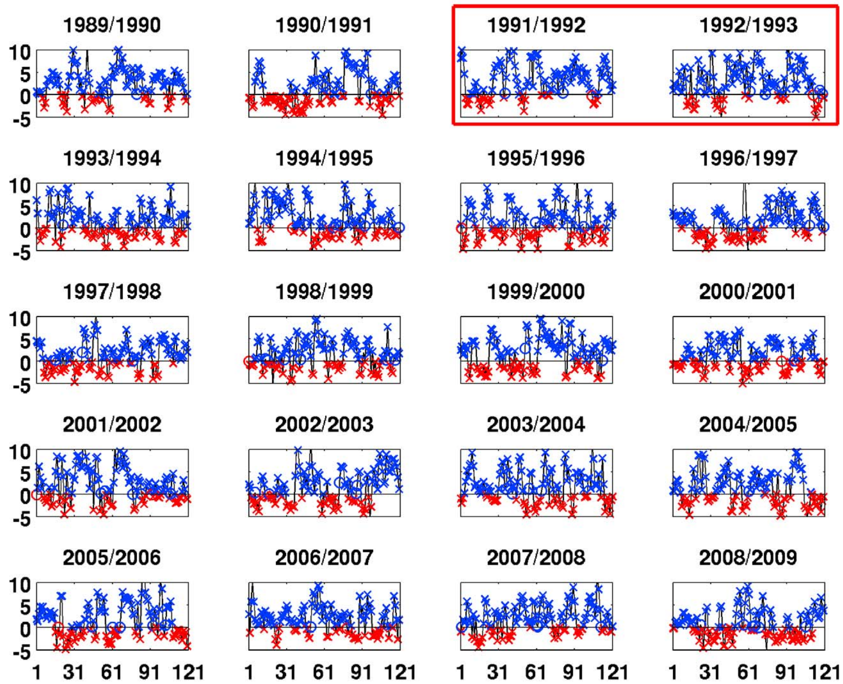


**Figure 1.** Daily mean heat advection by the meridional wind (*vdT*/*dy*, C/day) over the Aegean Sea for each NDJF from 1989/1990 to 2008/2009. Positive values in blue represent cold advection, negative values in red are warm advection. Values on the abscissa represent days since 11/1 of that NDJF season, i.e., 1 is Nov 1, 31 is Dec 1, 62 is Jan 1 and 93 is Feb. 1. The winters of 1991/1992 and 1992/1993 are delineated by the red box.

[*Romanou et al.*, 2010]. Finally, the cyclone centers and tracks are from NASA's Modeling, Analysis, and Prediction Program (MAP) Climatology of Mid-latitude Storminess (MCMS) project (M. Bauer, A New Climatology for Investigating Storminess Influences on the Extratropics, submitted to *Journal of Climate*, 2011) in which a state-of-the-art tracking algorithm is applied to a gridded SLP field derived from 6-hourly and 1.5° ERA-Interim. The study encompasses winters (defined here as NDJF) from 1989/1990 through 2008/2009. We chose these datasets because they are the current state of the art in combining observations with reanalysis products and forecast models, thus providing the most complete and accurate description at the highest resolution of the atmosphere over both open sea and coastal regions.

## 3. Results

### 3.1. Anomalously Large Turbulent Fluxes During the EMT

[5] Consistent with earlier studies (e.g., *Josey*, 2003), we find large anomalous turbulent heat losses (sum of sensible and latent heat fluxes) from the Aegean Sea for NDJF 91/92 and 92/93 (see Figure S1 in the auxiliary material).[1] Daily mean variability in turbulent heat losses is attributed to wind-driven cooling and drying of the sea surface (correlations with wind = 0.89, with temperature = −0.85 and with air humidity = −0.79). All correlations are significant at the 99% significance level. In the following, we therefore focus on relationships between heat advection and turbulent flux although moisture advection behaves similarly, given the prevailing cold and dry, or warm and moist, air masses in the region during winter.

### 3.2. Heat Advection by the Meridional Wind

[6] Daily mean NDJF heat advection by the meridional wind (*vdT*/*dy*) over the Aegean Sea is shown in Figure 1. The temperature gradient is nearly always negative (i.e., temperature decreases northward), thus the sign of *vdT*/*dy* is determined by the sign of the meridional winds. It is positive when winds come from the north, transporting cold air southward ($v < 0$, $dT/dy < 0$), and it is negative when winds come from the south, transporting warm air northward ($v > 0$, $dT/dy < 0$). It is clear from examining the various time series that the two enhanced EMT winters (delineated by the red box) featured a paucity of warm advective ($vdT/dy < 0$) events compared to other years.

[7] In order to assess the relative contributions of each component to Aegean turbulent flux variability, *vdT*/*dy* is decomposed into mean and eddy components with respect to both time and space as by *Peixoto and Oort* [1992]

$$A = \overline{[A]} + [A'] + \bar{A}^* + A^{*\prime} \quad (1)$$

where [ ] and * denote the zonal mean and the deviation from it, while ¯ and ′ denote the temporal mean and the deviation from it, respectively. For the purposes of this analysis, the time averaging period is seasonal, so that all subseasonal variability appears in the transient component. The spatial averaging is zonal, so that eddies are represented by longitudinal variations. The physical interpretation of this

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL050298.

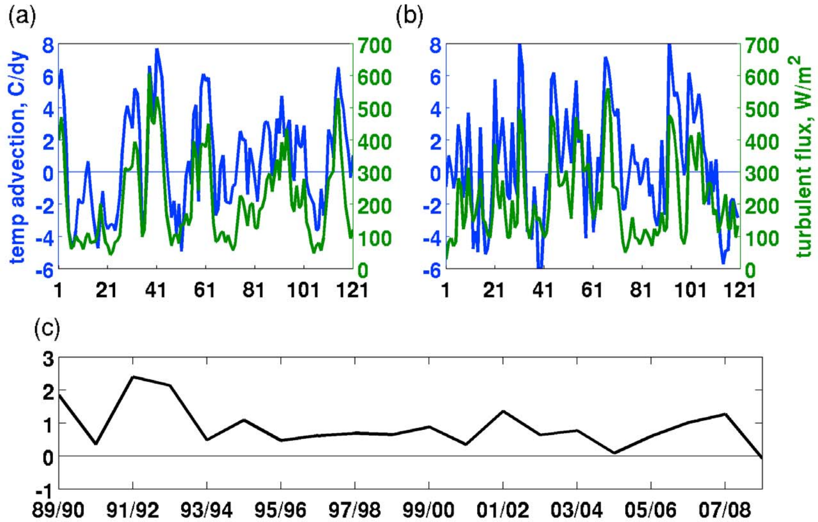


**Figure 2.** (a) Daily mean heat advection by the meridional wind associated with storms (C/day), with net turbulent heat flux (latent plus sensible heat, W/m$^2$) over the Aegean Sea for NDJF 1991/1992. Values on the abscissa represent days since 11/1 of that NDJF season, i.e., 1 is Nov 1, 31 is Dec 1, 62 is Jan 1 and 93 is Feb. 1. (b) The same as Figure 2a, but for NDJF 1992/1993. (c) NDJF mean heat advection by the seasonal mean, spatially varying component of the meridional wind.

type of decomposition is that the full field *A* comprises four parts: $\overline{[A]}$, the time mean zonal mean, which corresponds to the large scale mean pattern, e.g., the zonal mean latitudinal temperature gradient; $[A]'$, the time varying zonal mean, which corresponds to subseasonal variability of the large scale pattern, e.g., variability of the zonal mean temperature gradient; $\overline{A}*$, the time mean spatially varying component, which refers to patterns that are constant in time over the averaging period, but vary in space, e.g., standing waves; and $A*'$, which corresponds to patterns that vary in both time and space, e.g., storms.

[8] Decomposing both the meridional wind field and the meridional temperature gradient field and multiplying the two, we find (see Figures S2–S5) that the largest components are the advection of the: (1) mean temperature gradient field by transient eddy meridional winds ($v*'\overline{[dT/dy]}$); (2) stationary eddy temperature gradient field by transient eddy meridional winds ($v*'\overline{dT/dy*}$); (3) transient eddy temperature gradient field by transient eddy meridional winds ($v*'\ dT/dy*'$); (4) mean temperature gradient field by stationary eddy meridional winds ($\bar{v}*\overline{[dT/dy]}$); and (5) stationary eddy temperature gradient field by stationary eddy meridional winds ($\bar{v}*\overline{dT/dy*}$).

[9] The day-to-day winter mean flux variability is controlled by advection of the temperature field by meridional winds associated with storms on daily time scales (Figures 2a and 2b). Correlations between the sum of the first three components of *vdT*/*dy* (as enumerated in the previous paragraph), which vary on daily timescales, and turbulent fluxes are higher for the two enhanced EMT winters than the rest of the winters (0.9 compared to 0.7, significant at 99%), further demonstrating that daily turbulent flux variability is tightly linked to heat advection by storms, especially during the EMT. On longer (inter-annual) timescales, mean *vdT*/*dy* is tightly correlated (0.97, significant at 99%) with heat advection by the seasonal-mean regional-scale meridional wind patterns (the sum of (4) and (5) above, Figure 2c), which is higher during the two enhanced EMT winters. In conclusion, during the two enhanced EMT winters, cold advection by the mean local-scale meridional winds was nearly twice as large as in other years (the inter-annual portion of the variability), and there were fewer warm advection events (the daily portion of the variability, Figure 1). The winter of 1989/1990 also featured large cold advection by the mean meridional winds, as well as relatively few warm advection events, compared to post-1992/1993 winters. During that winter, convection did occur in the Aegean, although it was not as strong as in the enhanced EMT winters [*Beuvier et al.*, 2010].

### 3.3. Midlatitude Cyclones During the EMT

[10] Cyclone frequency anomaly plots for the two enhanced EMT winters (Figure 3) reveal that the enhanced EMT winters were much stormier than usual in the eastern Mediterranean in the 1991/1992 winter, and less stormy than usual in the central Mediterranean in both winters, but especially in 1992/1993. Analysis of the MCMS dataset (results not shown here) shows that wintertime central Mediterranean cyclones have an average radius of about 800 km, implying that cyclonic flow from such storms would affect wind patterns over the Aegean. Eastern Mediterranean cyclones are smaller, with an average radius of 700 km, but occur in the immediate vicinity of the Aegean Sea, clearly affecting local wind conditions. First order examination of the anomalous storm patterns in Figure 3 suggests that reduced cyclonic activity over the central Mediterranean and enhanced activity over the eastern Mediterranean would both act to enhance the southward advection of cold air over the Aegean, thus leading to large turbulent heat losses.

[11] To further examine the relationship between central and eastern Mediterranean storminess and temperature advection over the Aegean, Figure 4 shows composites of

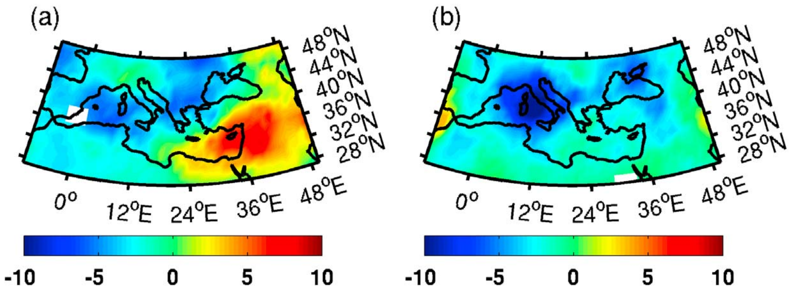


**Figure 3.** (a) Anomalous cyclone frequency, the number of storms (i.e., cyclone centers) which occur within a 5 degree latitude radius (1000/deg. lat.$^2$), for NDJF 1991/1992. Anomaly is computed relative to the average of NDJF 1989/1990 to 2008/2009. (b) The same as Figure 3a, but for NDJF 1992/1993.

anomalous *vdTdy* on days where there is a storm in the central Mediterranean (defined here as the regions 10–15E, 38–40N and 15–20E, 30–40N) (Figure 4a) and the eastern Mediterranean (defined here as 25–37E, 32–37N) (Figure 4b) from 1989 through 2009 (results are not sensitive to the exact choice of boundaries). Figure 4a shows that the wind field associated with storms in the central Mediterranean advects warm air northward over the Aegean. Intense anomalous warm advection associated with central Mediterranean storms occurs in the central Aegean Sea, in the location where oceanographic cruise observations indicate deep convection during the EMT period [*Sayin and Besiktepe*, 2010]. The reduction in storminess in this region which occurred in 1991/1992, and especially during 1992/1993, decreased the incidence of warm, southerly winds which inhibit Aegean turbulent fluxes. Figure 4b reveals that winds associated with cyclonic circulation around low pressure systems over the eastern Mediterranean, which were especially numerous during 1991/1992, advect cold air southward. Both anomalous storm patterns – the reduction in central Mediterranean storminess present in 1992/1993 and to a smaller extent in 1991/1992, and the increase in eastern Mediterranean storminess present in 1991/1992 – served to enhance turbulent flux losses over the Aegean Sea during the enhanced EMT winters. The opposite pattern – stormy central Mediterranean and calm eastern Mediterranean – results in small turbulent heat flux losses over the Aegean. (Anomalous cyclone densities for a low Aegean Sea flux winter (2004/2005) are shown in Figure S6. Note the pronounced dominance of the central Mediterranean compared to the eastern Mediterranean during 2004/2005, corresponding to the low turbulent heat losses during that winter.)

## 4. Discussion and Conclusions

[12] Wintertime cyclones in the northwestern Mediterranean region form when North Atlantic synoptic systems interact with the local topography and the land/sea temperature contrast [*Maheras et al.*, 2001; *Trigo et al.*, 1999], leading to the formation of sub-synoptic systems in the Gulf of Genoa, which then may propagate to the Aegean and Black Seas, or travel southeastward along the Italian coast. By contrast, storms in the eastern Mediterranean more often form in place [*Flocas et al.*, 2010], although their cyclogenesis is related to the large-scale flow [*Shay-El and Alpert*, 1991] as well. Storms are generally deeper and occur more often in the central than in the eastern Mediterranean [e.g., *Trigo et al.*, 1999]. Furthermore, storm frequency and location are influenced by large-scale teleconnection patterns such as the North Atlantic Oscillation (NAO) and the North Caspian Pattern (NCP) /East Atlantic West Russia (EAWR) patterns [*Kutiel and Benaroch*, 2002]. Recent decades have seen a decline in the frequency and intensity of cyclones in the western and central Mediterranean related to the northward shift of the storm track associated with more frequent occurrence of the positive phase of the NAO, while NAO-related changes in the eastern Mediterranean tend to be smaller [*Nissen et al.*, 2010; *Flocas et al.*, 2010; *Trigo*, 2006; *Alpert et al.*, 2004; *Maheras et al.*, 2001]. The relationship

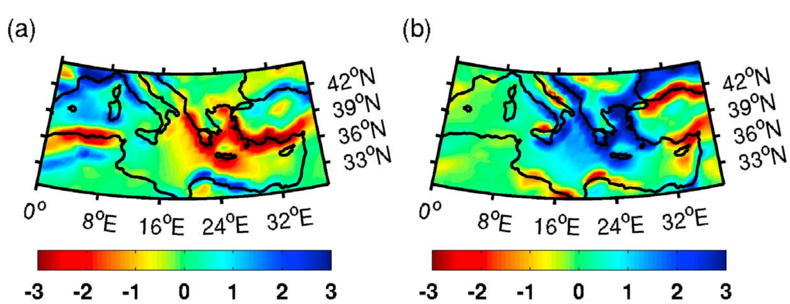


**Figure 4.** (a) Composite of daily mean *vdTdy* (C/day) when there is a storm in the central Mediterranean (see text for definition) for NDJF 1989–2009. (b) Composite of daily mean *vdTdy* (C/day) when there is a storm in the eastern Mediterranean (see text for definition) for NDJF 1989–2009.

between the NAO and storms over the western and central Mediterranean has been reported several times in the literature, however the connection between the NAO and Aegean heat fluxes has not been as clearly made, and linking the EMT to NAO variability is problematic since only one EMT has been reported. Our analyses do not show a correlation between NDJF monthly mean Aegean fluxes and the NAO index over the period 1989–2009, in agreement with *Josey* [2003]. *Nastos et al.* [2011] and *Gündüz and Özsoy* [2005] attribute some of the variability of Aegean surface temperatures, winds, and hence fluxes, to the NCP. We find that monthly mean NDJF Aegean turbulent fluxes are correlated with the monthly mean NCP index, with a correlation of 0.60 at the 99% significance level. Finally, the cyclone pattern observed in 1991/1992 closely resembles the Anticyclonic Westerly synoptic regime identified by *Black* [2012, Figure 4], which occurs most frequently when both the NAO and EAWR are positive.

[13] In conclusion, our analyses of time series of the turbulent heat fluxes, temperature advection by meridional winds and cyclonic activity changes during the enhanced EMT winters show that the atmospheric forcing during the most intense portion of the EMT was caused by the combined relative changes in the frequency of storms in the central and the eastern Mediterranean basins. There was a reduction in central Mediterranean storminess, which typically brings warmer air masses over the Aegean Sea, during both enhanced EMT winters, and an increase in eastern Mediterranean storms mostly in 1991/1992 which brought colder air-masses in this region, and resulted in anomalously large turbulent heat losses. The atmospheric forcing during the enhanced EMT winters, combined with the longer-term increased salinity due to reduced freshwater input and circulation changes, described in Section 1, intensified and maintained deep convection in the Aegean Sea during the enhanced EMT winters. The present result may imply a triggering mechanism, combined with favorable ocean conditions, or a culminating series of events, as discussed by *Beuvier et al.* [2010]. More research in this area is needed.

[14] The altered cyclone pattern during the enhanced EMT winters, particularly the decrease in central Mediterranean storminess, is consistent with changes in the storm track position related to the positive phase of the NAO while changes in the eastern Mediterranean are connected to NCP/EAWR-related variability. The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC-AR4) [*Intergovernmental Panel on Climate Change*, 2007] concluded that this poleward storm track shift is robust among climate models and has been recorded in observations. Meanwhile studies such as [*Marcos et al.*, 2011; *Raible et al.*, 2010] indicate that under different climate change scenarios the circulation pattern associated with the positive phase of the NAO will occur more often as the climate warms. Potential changes in the frequency and intensity of the EAWR with climate change are less well studied, however there is evidence that a positive NAO triggers a positive EAWR [*Krichak and Alpert*, 2005]. More frequent NAO positive events, accompanied by more frequent positive EAWR events, would increase the frequency of occurrence of the EMT-like cyclone pattern, and EMT-like atmospheric forcing conditions will become more common in the future. As climate models become more skilled in regional predictions, such connections will be more readily resolved.

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