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Mediterranean Sea surface warming 1985–2006

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ABSTRACT: Satellite observations from 1985–2006 indicate that in the last 2 decades the temperature in the upper layer of the Mediterranean Sea has been increasing at an average (±SD) rate of 0.03 ± 0.008°C yr^{-1} for the western basin and 0.05 ± 0.009°C yr^{-1} for the eastern basin. The increases in temperature are not constant throughout the year but occur primarily during May, June and July. Maximum increases of 0.16°C yr^{-1} are found in June in the Tyrrhenian, Ligurian and Adriatic Seas and close to the African coast. The Aegean Sea shows maximum change in sea surface temperature during August. Only the statistically significant results are presented.

KEY WORDS: Sea surface temperature · Seasonal and temporal variability · Mediterranean Sea

1. INTRODUCTION

The Mediterranean Sea is the largest of the semi-enclosed European seas, bordering the continents of Europe, Africa and Asia. It consists of 2 major basins, the western and the eastern (Western Mediterranean, Eastern Mediterranean), separated by the Strait of Sicily and further subdivided into smaller regional seas such as the Alboran, Ligurian, Tyrrhenian, Adriatic, Ionian and Aegean Seas (Fig. 1). The Mediterranean Sea is linked to the Atlantic Ocean through the Strait of Gibraltar, to the Black Sea through the Dardanelles and to the Red Sea through the Suez Canal. Water exchange with these exterior seas is small; nevertheless the exchange with the Atlantic Ocean is of specific scientific interest as the dense, saline water that exits through the Strait of Gibraltar influences the thermohaline circulation in the northern Atlantic Ocean (e.g. Candela 2001).

The Mediterranean Sea has often been compared to a scale model of the world's oceans in terms of thermohaline circulation and deep water formation, and substantial knowledge on these topics has been built up over the last decades (POEM Group 1992, Robinson & Golnaraghi 1993, Lascaratos et al. 1999). Additionally, the Mediterranean Sea was possibly the first of the world's oceans where changes in temperature were attributed to global warming (Béthoux et al. 1990).

Several studies have shown that the temperature of the Mediterranean Sea surface water has increased during the last 2 decades. For instance, Lelieveld et al. (2002), in a study covering the period 1930–2000, noticed that sea surface temperature (SST) variability remained low for several decades after 1930. Cooling took place during the early 1970s followed by an extensive warming period that began in approximately 1980. A similar pattern was observed by Rixen et al. (2005) in a more detailed study of the Mediterranean temperature fields from 1950–2000. They noticed that cooling took place in the upper 150 m layer of the Western Mediterranean until the mid-1980s, when warming started. The Eastern Mediterranean cooled between mid-1970 and the mid-1980s, then warmed slowly. Both Lelieveld et al. (2002) and Rixen et al. (2005) reported an increase in temperature between 1980–2000 to the order of 0.5°C. Both studies were based on SST from *in situ* measurements.

Several other studies have utilised spaceborne instruments for inferring characteristic patterns of SST distribution of the Mediterranean Sea. Santoleri et al. (1994) used a 9 yr (September 1981 to December 1990, weekly intervals) satellite dataset of daytime SST derived from advanced very high resolution radiometer (AVHRR) data at 18 km resolution in a study of the seasonal and interannual variability of the Western Mediterranean.

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Fig. 1. Study area. The Mediterranean Sea is separated into western and eastern basins (Western Mediterranean, Eastern Mediterranean) by the Strait of Sicily

They found a general SST increase of 0.15°C yr^{-1} but with a noticeable seasonal variability in the trend: the summer months showed the biggest increase (0.25°C yr^{-1}) followed by winter (0.16°C yr^{-1}), autumn (0.13°C yr^{-1}) and spring (0.08°C yr^{-1}). D'Ortenzio et al. (2000) used a 12 yr (1985–1996, daily intervals) time series of nighttime SST derived from AVHRR data, at 9 km resolution and covering the entire Mediterranean Sea. In their analysis, they pooled all data together to, firstly, validate the satellite SST by comparison with independent SST measurements and secondly, to understand the variability of mean SST of the Mediterranean basin. However, their analysis did not suggest any particular trends in SST over the period considered.

In a study of the adjacent Black Sea, Ginzburg et al. (2004) used a 19 yr dataset of nighttime SST from AVHRR data, collected weekly, from November 1981 to December 2000 with 18 km resolution, to investigate seasonal and interannual variability of SST. They found a positive trend in Black Sea mean SST of ~0.09°C yr^{-1} over the period considered.

Since all the studies mentioned above use satellite data originating from the same sensors, i.e. the AVHRR instruments on board the NOAA series of satellites, the main reason for the different results obtained is likely to be found in the different time scales studied. The present study quantifies the SST trend in the Mediterranean Sea as observed over the last 2 decades starting from 1985, and identifies regional and local variability in the same SST trend.

2. MATERIALS AND METHODS

The data used in the present study are the AVHRR Pathfinder SST v. 5.0. Pathfinder is a joint NOAA/NASA project aimed at producing global SST maps from 1985 up to present. For a complete description of the SST dataset see Vazquez et al. (1998). The spatial resolution of the data is nominally 4 km and the temporal resolution used is 1 mo, which should be sufficient for examining seasonal and interannual variability. The Pathfinder SST data are available for daytime and nighttime separately, as different physical processes during day and night influence the observed temperatures. In the present study only nighttime images were used, thereby avoiding the potential bias that may be induced by using daytime images influenced by intense diurnal heating. The entire time series originated from 8 different satellites.

During processing of the AVHRR images, each pixel was examined to evaluate for the possibility that the SST value may be of suspect quality due to cloud contamination or other environmental influences. Up to 10 individual tests were carried out for each pixel and the various tests were combined to define 8 different quality levels (Kilpatrick et al. 2001). Only SST values flagged with the highest quality value were used. The number of highest quality observations per pixel varied depending on season and location. Fig. 2 shows the average number of highest quality observations per pixel per month for the entire Mediterranean basin and Fig. 3 shows 2 maps representing the number of highest quality observations during the worst month (January) and the best month (July). Data coverage is generally better during summer than winter (Fig. 2), which is largely attributed to less cloud cover during summer months. If all observations were perfect, i.e. no cloud cover or any other environmental influences, the maximum number of SST observations per month would be approximately 100. There were no substantial differences between the spatial data coverage in the western and the eastern basins during winter (Fig. 3a), but summer months tend to be better observed in the eastern than in the western basin (Fig. 3b).

Pathfinder SST is derived from fitting satellite brightness temperatures to *in situ* buoy temperatures. However, space instruments measure the skin temperature originating from the upper mm of the water surface while the buoy temperatures are bulk temperatures measured some meters below the sea surface. Hence the regression involved in deriving Pathfinder SST takes into account, statistically, the difference between ocean bulk and skin temperature, but whenever abnormal conditions occur in either atmosphere or ocean, Pathfinder SST may differ from the actual bulk temperature. The accuracy of the satellite-derived SST has been the subject of several papers (Kearns et al. 2000, Kumar et al. 2003, Minnett 2003). Recently, Marullo et al. (2007), in a very detailed validation study

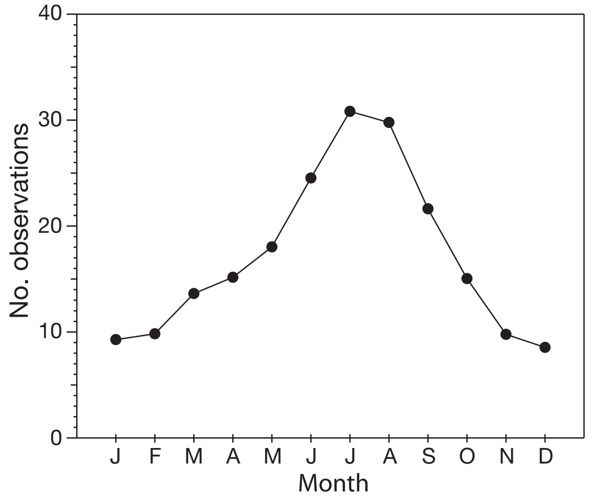

Fig. 2. Mean number of highest quality SST observations per pixel for the Mediterranean Sea, 1985–2006

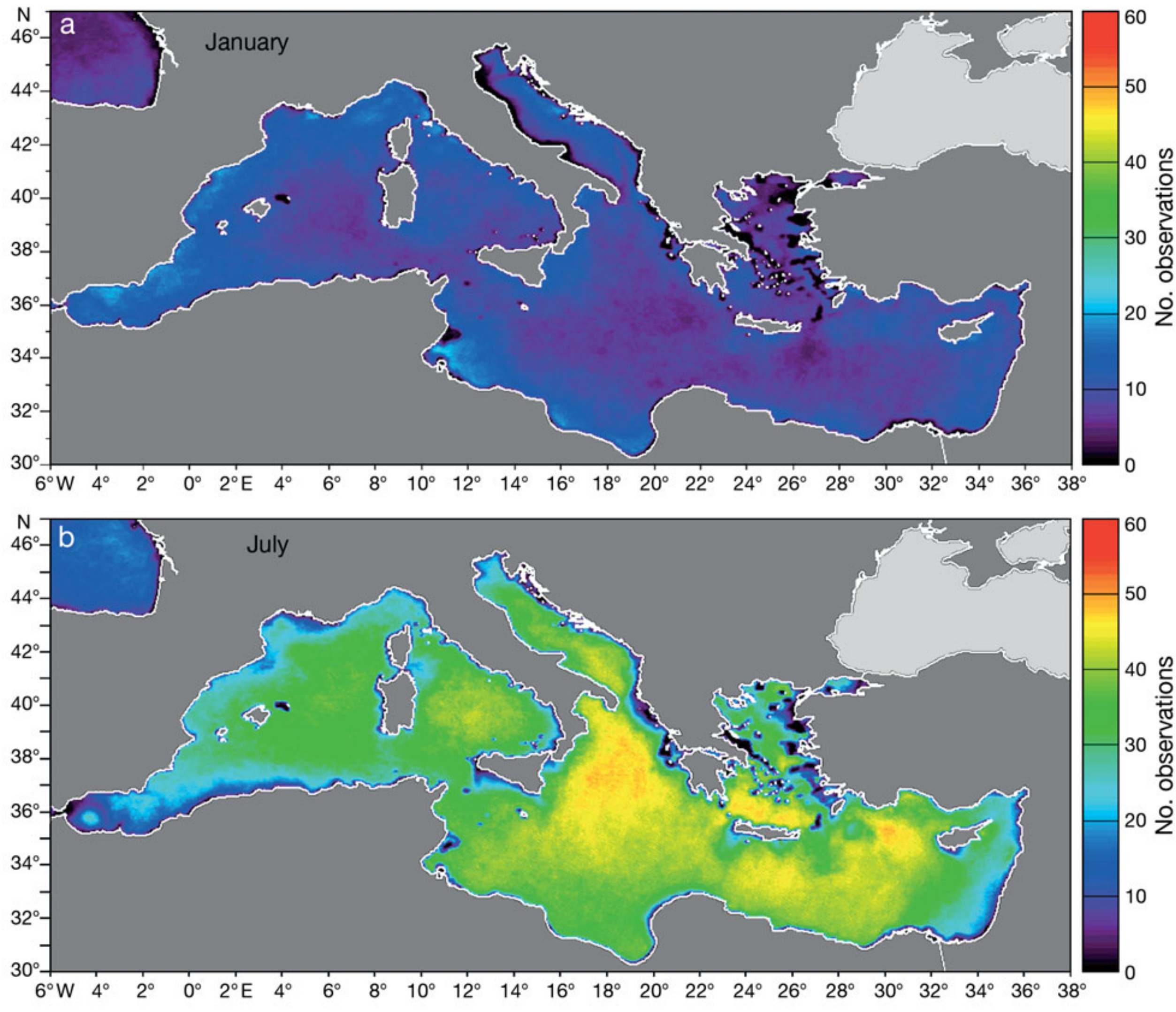

Fig. 3. Spatial distribution of the average of highest quality SST observations during (a) January (worst month) and (b) July (best month) in the Mediterranean Sea, 1985–2006

of Pathfinder data for the Mediterranean Sea, compared satellite SST to *in situ* data from 1985 to 2005 and found a mean bias of less than 0.1 K with a root mean square error of 0.5 K. The best fit of satellite SST occurred using *in situ* data at 4 m depth. They also concluded that the error was weakly dependent upon season and did not drift with time, a fact that renders the Pathfinder SST a valuable dataset for studying trends and anomalies.

The Pathfinder SST dataset is the longest time series of historical global datasets currently available. Although not originally designed for studying climatic changes, with careful selection the data can be used for examining SST over a longer time period against which any future changes in SST can be assessed. For future studies, it should be mentioned that in recent years an international effort named The Global Ocean Data Assimilation Experiment (GODAE) has initiated the Global High Resolution Sea Surface Temperature Pilot Project (GHRSST-PP) to address an emerging need for more accurate high resolution global SST products. GHRSST-PP now provides the best possible SST data fields, derived from a multitude of sensors and instruments, which are continuously subject to proper quality control and validation (Donlon et al. 2007).

3. RESULTS AND DISCUSSION

For comparison with previous studies, a first analysis was carried out at basin level, dividing the Mediterranean Sea into western and eastern basins separated at the Strait of Sicily. The average monthly SST obtained for both the Western and Eastern Mediterranean is shown in Fig. 4. The slope of the linear regression, which indicates the trend of the mean (±SD) annual SST, is 0.03 ± 0.008°C yr^{-1} in the western basin and 0.05 ± 0.009°C yr^{-1} in the eastern basin. Over the entire time series these trends translate into a total increase of 0.66 and 1.1°C, respectively. Although the slopes are small, classical Student's *t*-tests revealed that the slopes are significantly different from 0 at the 1% level. The increase in SST is higher than that derived from hydrographic data by Rixen et al. (2005), who reported total increases to the order of 0.5°C over the same period. It should be mentioned that Rixen et al. (2005) used a fixed vertical depth of 150 m for their upper layer temperature evaluation; however, the mixed layer depth is usually not constant throughout the year. Recently, the structure of the mixed layer in the Mediterranean Sea was addressed by D'Ortenzio et al. (2005), who used more than 250 000 *in situ* vertical profiles of temperature, collected from 1940 to 2004, to construct a monthly climatology of the mixed layer depth. The mixed layer depth from each vertical profile was defined as the depth where the water was 0.2°C colder than the near-surface value at 10 m depth. Using this criterion, they found that, from November to February or March, the mixed layer deepens and exceeds 100 m, while an abrupt stratification starts in April and maintains a shallower mixed layer which hardly exceeds 30 m during the summer months. Therefore, it may be reasonable to assume that the increases in the SST average annual value derived from Fig. 4 reflect only the increase of temperature in the mixed layer, which is the layer where heat is accumulated in particular during summer, as opposed to the 0.5°C heating in the upper 150 m as presented in Rixen et al. (2005).

Compared to other studies conducted using AVHRR-derived SST, the trends of Fig. 4 are lower than what was found by Santoleri et al. (1994) in the Western Mediterranean and different from the results of D'Ortenzio et al. (2000), who found no trend. However, at least for the Eastern Mediterranean, SST trends are approaching those found in the adjacent Black Sea by Ginzburg et al. (2004). Santoleri et al. (1994) and D'Ortenzio et al. (2000) used datasets generated in the

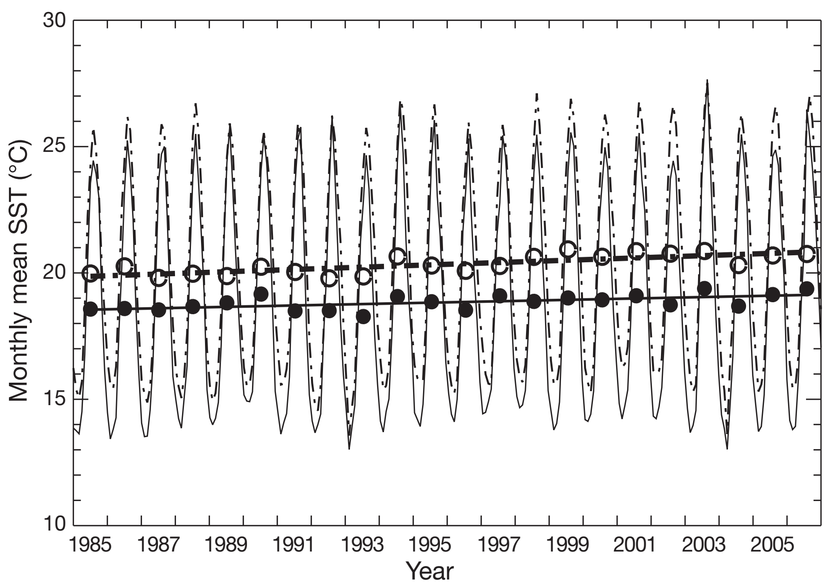

Fig. 4. Time series of monthly mean SST of the Western (—) and Eastern Mediterranean (–·–) from 1985 to 2006, and annual means for the Western (●) and Eastern Mediterranean (○). Least squares fit through the annual means for the Western (——) and Eastern Mediterranean (– · –) are also shown

1981–1990 and 1985–1996 timeframe, respectively, while the Ginzburg et al. (2004) study was conducted over approximately the same period and using the same data source as the present study. Therefore, it is suggested that the discrepancies found between the present study and others based on AVHRR-derived SST are mainly due to the different periods over which the trend is calculated.

The linear trends in annual SST from Fig. 4 have been derived for the purpose of comparison with previous studies. In reality the observed SST increase is not uniformly distributed across seasons. By performing a linear fit to monthly SST, i.e. a fit through all the Januaries, Februaries, etc., the seasonal distribution of the trends for the 2 basins becomes as illustrated in Fig. 5; a Student's *t*-test has been carried out for each month and those months with trends significantly different from 0 at the 5% level are indicated. In the Western Mediterranean (Fig. 5a), significant trends are only found from April to July with peak in June of 0.08°C yr^{-1}, and the Eastern Mediterranean (Fig. 5b) shows additional positive trends during late summer and autumn. Taking advantage of the high spatial resolution of the satellite data, it is possible to map the trend of seasonal distribution at the full 4 km resolution rather than grouping the data for the 2 basins. The corresponding monthly images illustrating the spatial distribution of rate of change are shown in Fig. 6. As for the previous analysis, a Student's *t*-test was carried out, and areas where the trend is not significantly different from 0 at the 5% level have been masked out and reproduced in white in the figure. In May the rate of change is almost homogeneous throughout the Mediterranean basin, while June is heterogeneous with a maximum rate of change of 0.16°C yr^{-1}, corresponding to a total increase of 3.5°C over 22 yr in the Tyrrhenian, Ligurian and Adriatic seas and close to the African coast. July is homogenous with a pattern similar to May. During the rest of the year the rate of change in SST is only significant in the Eastern Mediterranean, with the most noticeable patterns being the peak in the Aegean Sea during August and the 2 mesoscale features of high SST change rate in the vicinity of areas with almost permanent eddy-like features (known as the Rhodes and Ierapetra Gyres) during November.

The heat that accumulates in the upper layer propagates to deeper layers most likely through deep water formation mechanisms. The questions on how this process is altered by increasing SST and how these alterations may impact ocean circulation remain to be investigated through subsequent work.

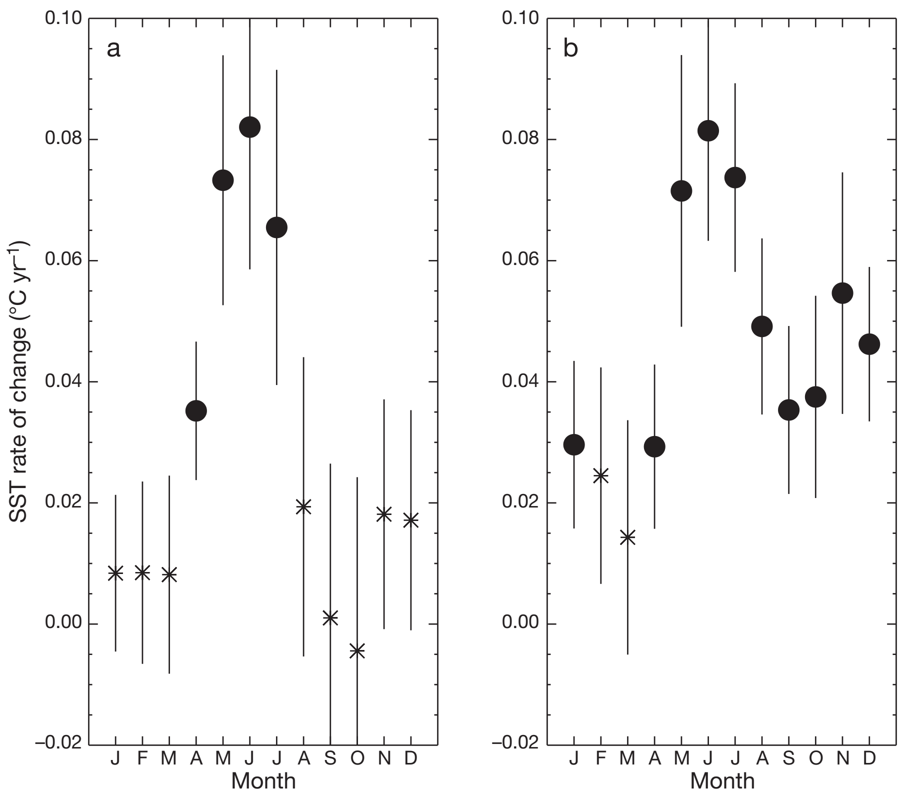

Fig. 5. SST rate of change at monthly scale for the (a) Western and (b) Eastern Mediterranean. Vertical bars are SD. Rate of change (●) is statistically significant from zero; (⚹) not significantly different from 0

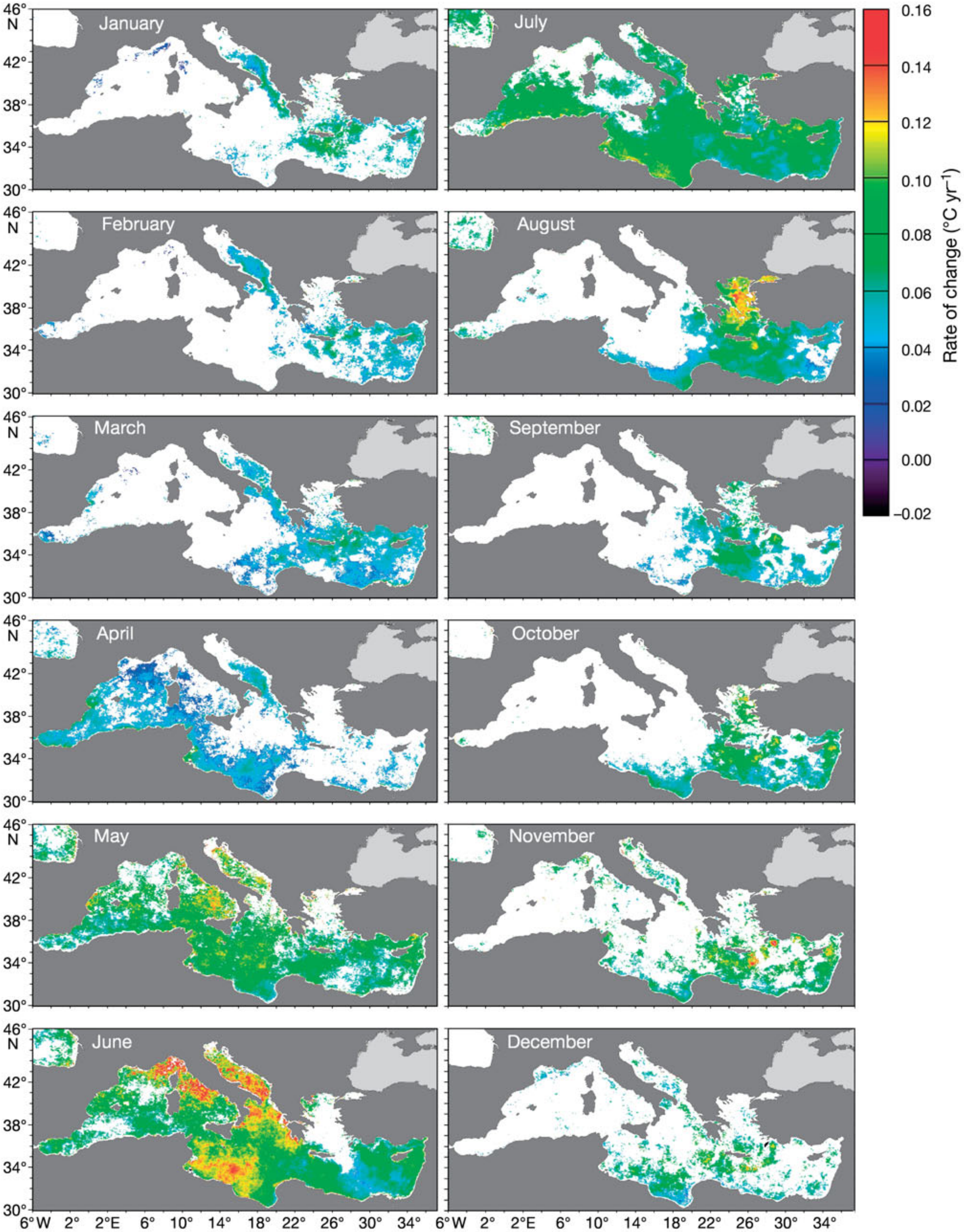

Fig. 6. Monthly SST rate of change over the preriod 1985–2006. Areas masked out in white are areas where the rate of change in SST is not statistically significant at the 5% level

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