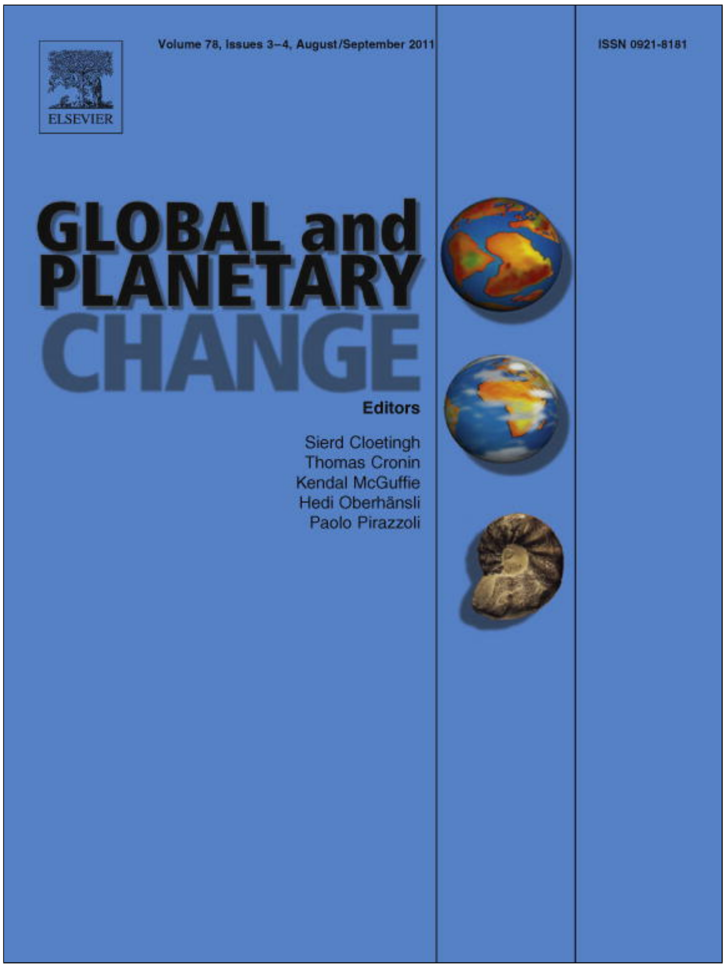
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Recent trends of SST in the Western Mediterranean basins from AVHRR Pathfinder data (1985–2007)

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ABSTRACT

Climate change in the Mediterranean region cannot be understood without taking into account changes in the Mediterranean Sea, which is an important source of moisture and heat for the Mediterranean climate system. Many research papers have been published in the last two decades increasing our knowledge about long-term trends and inter-annual variability of temperature and salinity in the Western Mediterranean. Although recent changes have been better documented, there remain uncertainties because different results are obtained depending on the period of time analyzed or the geographic region selected. This paper analyses the regional, seasonal and decadal variability of sea surface temperature in the Western Mediterranean basins (Northern (Ligurian Sea and Gulf of Lions), Balearic, Algerian and Alboran) by means of thermal satellite images. Monthly data from the PO.DAAC (Physical Oceanography Distributed Active Archive Center) have been processed for the period 1985–2007. Results show an averaged warming linear trend of 0.03 °C/yr. This rate is higher during the spring (0.06 °C/yr) in all the basins and the highest values were registered in the Northern basin in June. The study suggests that an early warming of the Sea is occurring in all the basins during the spring, with an increment of 0.5–1 °C in the mean SST of April, May and June over the two decades studied. The analysis of thermal anomalies confirms the warming trend with a dominance of negative anomalies during 1985–1996 and a dominance of positive anomalies during the last decade (1997–2007). Intense anomalies are more frequent in the Northern basin.

1. Introduction

In the context of global warming, there is apparent agreement in literature on the increase of temperature and salinity of deep, intermediate and upper layer waters in the Western Mediterranean especially during the latter half of the twentieth century. Many works can be cited (Bethoux et al., 1990; Rholing and Bryden, 1992; Bethoux et al., 1998; Tsimplis and Baker, 2000; Vargas-Yáñez et al., 2005; Salat and Pascual, 2006, Lionello et al., 2006, among others) which give different figures depending on the period of time considered and on the geographical area where data have been collected. Methodological differences make it difficult to distinguish long-term changes from decadal and multi-decadal variability. Recent reviews (Vargas-Yáñez et al., 2009, 2010) have pointed out the difficulties assessing the mean trends of temperature and salinity because the scarcity of data makes trend estimations very sensitive to instrumental biases and data processing methods. Nevertheless, much effort is being made to integrate data from different sources and regions contributing to a better understanding of the variability of temperature and salinity in the Mediterranean.

In this context, infrared satellite images can be a complementary method to in situ records for studying SST variability. Although they only register the temperature of the surface layer, they provide a complete synoptic picture of a wide area and the availability of long series of data (more than 20 years) now make them suitable for the study of longer term temporal trends.

Infrared images, mostly from the Advanced Very High Resolution Radiometer (AVHRR) of the NOAA satellite, were successfully employed early on to detect thermal fronts and their evolution in the Western Mediterranean (Champagne-Phillippe and Harang, 1982; Le Vourch et al., 1992) as well as for studying mesoscale surface circulation as a complement to hydrographic data (Millot, 1985; La Violette et al., 1990; López García et al., 1994; Millot et al., 1994). However, there are few studies about SST variability in the Mediterranean using infrared images, perhaps because, till now, the time series available were not long enough to allow statistical analysis. Santoreli et al. (1994) made a study of the seasonal and inter-annual variability in the Western Mediterranean from AVHRR for the period from 1981 to 1990 which showed a general SST increase of 0.15 °C/yr; Marullo et al., 1999a, b presented a complete analysis of the seasonal and inter-annual variability of SST in the Eastern Mediterranean using AVHRR images for the period 1983–1992; Ginzburg et al. (2004) analyzed SST in the Black Sea from 1981 to 2000 and also found a positive trend of 0.09 °C/yr. More recently

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Nykjaer (2009) quantified the SST trend in the Mediterranean Sea from AVHRR Pathfinder data from 1985 to 2006, obtaining an increase of 0.03 °C/yr for the western basin and 0.05 °C/yr for the eastern basin.

This paper presents a study of seasonal, regional and temporal variability of SST in four basins of the Western Mediterranean (Northern, Balearic, Algerian and Alboran) from AVHRR-NOAA images covering the period 1985–2007. A total of 276 monthly images provided by the Physical Oceanography Distributed Active Archive Center (PO.DAAC) have been processed in order to assess regional variability of SST and to describe recent trends for the period 1985–2007. The objectives of this work are, firstly to contribute to understanding the recent warming trends in the Western Mediterranean basin at a regional scale and, secondly to show the possibilities and suitability of satellite images for climate analysis.

2. Data and methodology

The AVHRR Ocean Pathfinder SST data used in this study were obtained from the Physical Oceanography Distributed Active Archive Center at the NASA Jet Propulsion Laboratory, Pasadena, CA. The Pathfinder SST dataset is the longest time series of historical global datasets currently available on line (http://podaac.jpl.nasa.gov/). We have used the 4 km Pathfinder version 5 SST Project (Pathfinder V5), which is a new reanalysis of the AVHRR earlier version of the Pathfinder data set distributed since early 1990s (see Vázquez et al., 1998 and Kilpatrick et al., 2001 for more information). This reprocessing uses an improved version of the Pathfinder algorithm and processing steps to produce twice-daily global SST and related parameters at a resolution of 4 km, for temporal averages of 5-day, 7-day, 8-day, monthly and yearly. The main improvements over the Pathfinder version 4 are the more accurate land mask, higher spatial resolution of 4 km instead of the 9 km of the previous version, and the inclusion of sea ice information.

The coefficients used in the Pathfinder algorithm to estimate SST are continuously updated which make the data suitable for studying multi-year SST trends. A validation of AVHRR Pathfinder SST over the Mediterranean Sea using independent data obtained from MEDATLAS CTD and XBT casts had already been done by D'Ortenzio et al. (2000) who found a mean bias of 0.2 °C. Recently, Marullo et al. (2007) evaluated Pathfinder by comparing satellite SST to in situ data from 1985 to 2005 concluding that satellite data are able to reproduce in situ measurements with a mean bias of less than 0.1 K and RMSE of about 0.5 K. These conclusions allow us to consider that Pathfinder data are suitable for studying SST trends and anomalies at regional scale.

In this study we have analyzed 23 years of monthly data for the period 1985–2007 for a subset of the Mediterranean Sea covering the area between latitude 27-49°N and longitude 14°W–14°E. Only nighttime data were used to avoid the effect of intense diurnal heating which can be very important in the Mediterranean during the spring and summer (Deschamps and Frouin, 1984). The images have been processed in order to obtain averaged monthly temperatures for 4 zones or basins, namely Northern, Balearic, Algerian and Alboran (Fig. 1) by using the GIS software Idrisi 32. Also monthly average values have been obtained for the whole area, which will be referred in this paper as Western Mediterranean (WMED). In order to reduce the processing time, a regular sampling of 248 points (one point at every 0.5° of latitude and longitude) was designed to calculate averaged values in every zone: 51 in the Northern, 59 in the Balearic, 107 in the Algerian and 31 in the Alboran basin (Fig. 1). A comparative analysis between average values obtained from the sample points and the average values calculated from all the pixels in the areas showed no significant differences, so we proceeded to use the sample points. The pixels occasionally affected by clouds were removed from the analysis. Besides the averaged monthly temperature in every zone, standard deviations were also computed as a measure of the dispersion of the values within every zone. Thermal monthly anomalies have also been calculated for every region as the difference between monthly SST values and the monthly long term SST means between 1985 and 2007. Seasonal and inter-annual trends have been obtained for every basin.

The statistical analysis was performed by using the software PASW Statistics 17. Simple linear regressions have been applied to the time series, calculating trends for the whole area and period, but also calculating trends for every zone, season and month. The slope of the fits indicates an average trend for the period analyzed. The statistical significance at the 95% confidence level was tested by the standard *t*-test.

The four zones used in the study have been defined taking into account the geographic characteristics of the basins as well as water mass distribution and surface circulation in the Western Mediterranean (López García, 1991; Millot, 1999). The Alboran Sea is filled by Atlantic Water (AW) flowing in at surface level into the Mediterranean through the Straits of Gibraltar. This inflow of water forms a quasi permanent anticyclonic gyre in the west and a more variable current, known as the Algerian current, which progress to the east towards the Sicily Channel following the African continental platform (Bryden and Kinder, 1991; Candela, 1991, among others). The Algerian current presents a high spatial variability and, frequently, generates anticyclonic gyres that evolve and occupy the whole Algerian basin till the Balearic Islands contributing to the mixture of the recent Atlantic Water with the older

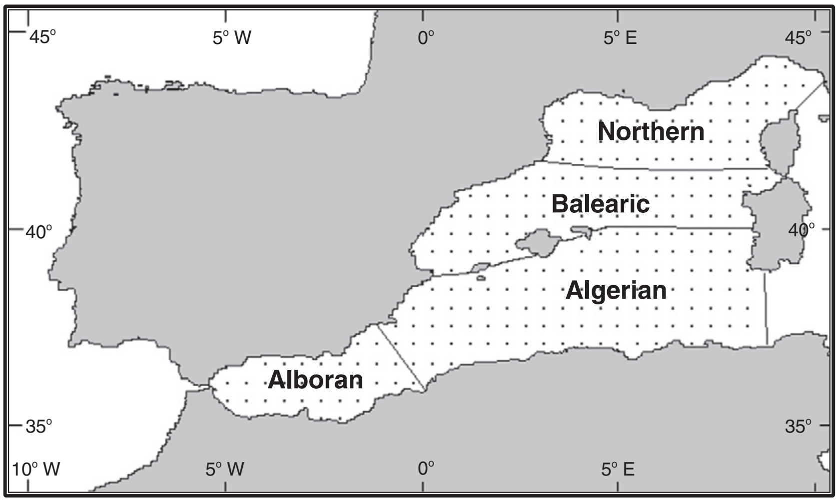

Fig. 1. Study area with the limits of the sub-basins as considered in the study and the grid points used to calculate average values.

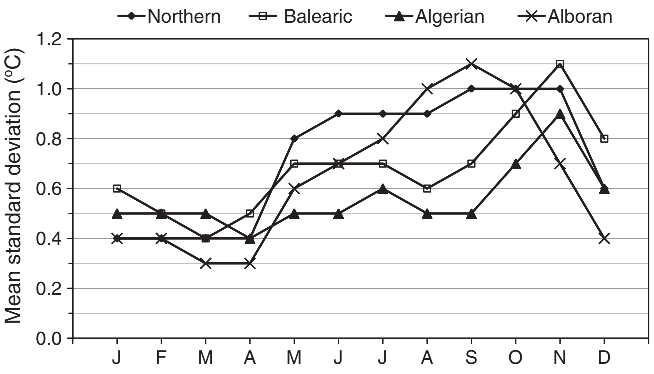

Fig. 2. SST variability within each of the sub-basins of the Western Mediterranean. The graph represents, for every month and basin, the mean value for the series 1985–2007 of the dispersion values within the zone (standard deviation calculated for the sample points in every zone).

water in the basin. This means that the Algerian basin is a reservoir of Atlantic Water (AW) (Millot, 1985, 1999; Millot et al., 1990). In the northern part of the Western Mediterranean, the Northern basin is characterized by the Liguro–Provençal–Catalan current, also known as the Northern current, formed by the junction of the northward currents along each side of Corsica (Astraldi et al., 1990). This flow, described by several authors (Font et al., 1988, 1995; Alberola et al., 1995; etc.), circulates toward the south along the Iberian peninsula continental shelf to the Ibiza Channels. The Northern basin is affected by northwestern winds which frequently flow through the Rhone corridor to the Golf of Lion, contributing to the cooling of the surface layer and to the Deep Water (DW) formation. Finally, the Balearic Sea can be considered as a transition zone between the Northern and Balearic basins where the older and modified AW at the Ligurian Sea meets the more recent AW that occupies the Algerian basin through the sills of the Balearic Islands (López García et al., 1994; Millot, 1999) forming the Balearic Front.

This zoning was also supported by a previous study on SST spatial variability in the same area, which applied cluster analysis techniques (López García, 1991). This study was based on a series of 4 years (1984–88) of weekly SST maps derived from satellite images, which was available at that time published by the Centre de Météorologie Spatiale de Lannion (France).

3. Results

In this section we present the main results obtained from the statistical analysis of SST images dealing with the seasonal and spatial variability (Section 3.1), the inter-annual trends (Section 3.2) and thermal anomalies (Section 3.3).

The study is based on SST monthly satellite images and SST averaged values calculated for the four zones described in the above section. Previous to the analysis, the spatial variability of SST within each zone has been estimated by means of the standard deviation calculated for every monthly value. Dispersions of the values vary in every zone, depending on the month and also on the year, however, monthly averages were always below 1.1 °C. Fig. 2 shows the mean values of the standard deviation within each zone calculated for the series of 23 years. We can observe that deviations are higher from May to December and lower during the winter. Also regional differences can be observed, the highest dispersions (about 1 °C) have been recorded in Alboran in late summer, in the Northern basin during the autumn and in the Balearic basin in November. Spatial variability is inherent to the SST and probably dispersions would be higher if we were dealing with weekly or daily data. Therefore, in spite of the dispersion values within each zone, we have considered that the average SST monthly values calculated for every zone can be a good parameter to assess the regional, seasonal and decadal variability of SST in the Western Mediterranean.

3.1. Seasonal and spatial variability

Table 1 shows the mean and standard deviation SST values obtained in the four basins for the series of 23 years analyzed, as well as averaged values for the whole area. In the Western Mediterranean, the minimum values (14 °C ± 0.4) are recorded in February and the maximum (25 °C ± 0.8) in August. The standard deviation shows that the inter-annual variability is higher during the summer and autumn months (σ = 0.8–0.9) and lower during the winter months (σ = 0.4). This fact agrees with the deviation values obtained within the zones and could be related to the homogenization of surface waters during winter time and to the unequal warming of the surface layer in every basin during the summer.

In order to describe the spatial variability of SST in the Western Mediterranean we, the thermal amplitude between the basins (ΔT basin), calculated as the difference between the maximum and minimum average SST obtained in each basin is included in Table 1. This amplitude varied from 1.4–1.5 °C in spring when SST in the Western Mediterranean was more homogeneous, to 2.6–2.9 °C in autumn (September–October) when the temperature distribution became more heterogeneous in all the basins. These results show that autumn is the season with the highest spatial variability as well as with a high inter-annual variability and spring is the period with the least spatial variations of SST in the Western Mediterranean. For every

Table 1
Monthly means ($\overline{x}$) and monthly standard deviations (σ) of SST in Western Mediterranean basins, for the period 1985–2007. The annual thermal amplitude (ΔT annual) and the thermal amplitude between the basins (ΔT basins) are also presented as indicators of seasonal and spatial variability. Maximum and minimum values have been marked in bold.

	Western Mediterranean		Northern basin		Balearic basin		Algerian basin		Alboran basin		Spatial variability
	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	ΔT basins
January	14.4	0.4	**13.2**	0.4	14.1	0.5	14.9	0.5	**15.3**	0.4	2.1
February	14.0	0.4	**12.9**	0.3	13.5	0.4	14.4	0.5	**15.1**	0.5	2.1
March	14.2	0.4	**13.1**	0.4	13.7	0.5	14.6	0.5	**15.3**	0.4	2.2
April	15.0	0.4	**13.8**	0.5	14.5	0.5	15.5	0.5	**16.0**	0.4	2.2
May	17.4	0.7	**16.4**	0.8	17.2	0.8	**17.9**	0.7	17.6	0.7	**1.4**
June	20.8	0.9	**19.9**	1.3	21.0	1.0	**21.4**	0.9	20.2	0.8	**1.5**
July	23.5	0.8	**22.4**	1.1	23.8	1.0	**24.2**	0.8	22.5	0.7	1.8
August	25.0	0.8	**23.7**	1.2	25.3	0.9	**25.9**	0.7	23.9	0.7	2.2
September	23.8	0.8	**21.9**	1.1	24.1	0.8	**24.8**	0.7	22.9	0.8	**2.9**
October	21.4	0.8	**19.7**	0.9	21.7	0.9	**22.3**	0.9	20.6	1.1	**2.6**
November	18.4	0.6	**16.9**	0.7	18.5	0.7	**19.2**	0.7	18.1	0.7	2.3
December	15.9	0.5	**14.4**	0.6	15.7	0.7	**16.5**	0.5	16.3	0.5	2.1
ΔT_{annual}	11.1		10.8		**11.8**		11.4		**8.9**		

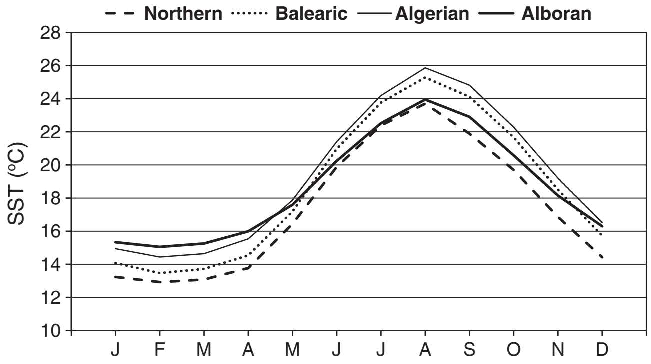

Fig. 3. Seasonal evolution of SST in the sub-basins of the Western Mediterranean described by the monthly long term means for the period 1985–2007.

month, the thermal amplitude between the basins was higher than the spatial variability obtained within each.

Fig. 3 shows the seasonal evolution of SST for each basin. The Northern basin has the coolest waters throughout the year. During the winter and early spring there is a clear North–South latitudinal gradient, with the lowest temperatures in the Northern basin and the highest values in Alboran. These differences can be explained by the latitudinal effect of solar radiation. However, from May till December this gradient is broken: the highest values are registered in the Algerian and Balearic basins and the lowest ones in the Alboran and Northern basin which registered similar values. This is clearly related to the inflow of Atlantic Water in the Alboran basin throughout the year, which keeps its thermal characteristics more constant than the rest of the waters in the Mediterranean. The Balearic and Algerian basins are occupied by modified Atlantic Water that resides at the surface of the basin for longer and is warmed up more during the spring and summer season. Lower summer values in the Northern basin can be explained both by latitude and persistent winds. The annual thermal amplitude obtained for each basin also shows the lowest value in Alboran (8.9 °C) and the maxima (11.8 and 11.4 °C) in the Balearic and Algerian basins respectively.

Table 2
Mean annual rate of SST and Pearson correlation coefficients obtained from linear regression in the four basins. All the trends were significant at the 0.05 significance level. Although all the trends are similar, the highest rate was registered in the Northern basin and the lowest in Alboran.

Basins	Annual rate (°C/yr)	Pearson correlation coefficient (r^2)
Northern	0.033 ± 0.003	0.350
Balearic	0.031 ± 0.003	0.328
Algerian	0.031 ± 0.003	0.360
Alboran	0.030 ± 0.003	0.315
WMED	0.031 ± 0.003	0.374

3.2. Inter-annual trends

The temporal evolution of SST from the mean monthly data has been drawn in Fig. 4A for the whole study area and in Fig. 4B for the four sub-basins. A 12-month moving average has been applied to the data to remove the seasonal effect and simple linear regressions have been computed in order to obtain the rate of change. The slope of the linear regression indicates an increase trend of 0.0026 °C/month, that is, a rate of 0.031 °C/yr ± 0.003 in the Western Mediterranean. Similar trends were obtained in the four sub-basins (Table 2), with a slightly lower rate in the Alboran basin (0.030 °C/yr) and a slightly higher one in the Northern basin (0.033 °C/yr). All the regressions were significant at the 5% level.

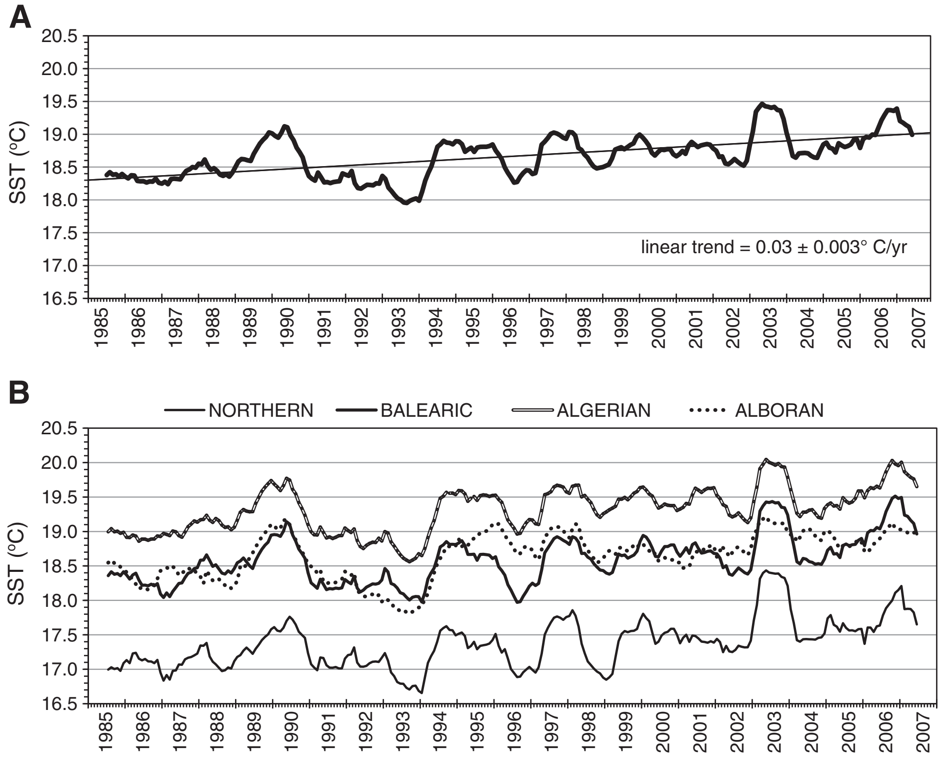

Fig. 4. (A) Inter-annual variability of SST in the Western Mediterranean from AVHRR data (1985–2007). Monthly data have been plotted and a 12 month moving average has been applied to eliminate the seasonal effect. The linear trend is also represented. (B) Inter-annual variability of SST in the Northern, Balearic, Algerian and Alboran basins from AVHRR data (1985–2007). Monthly data have been plotted and a 12 month moving average has been applied to eliminate the seasonal effect. The linear trends for each basin are presented in Table 2.

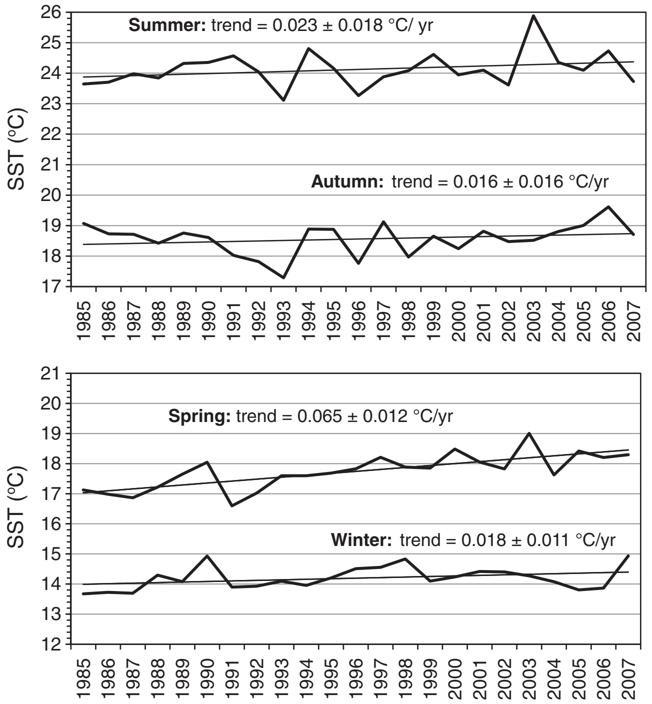

Fig. 5. Inter-annual variability of seasonal SST in the Western Mediterranean, above in summer (JAS) and autumn (OND), and below in spring (AJJ) and winter (JFM). The linear trend for every season has been depicted.

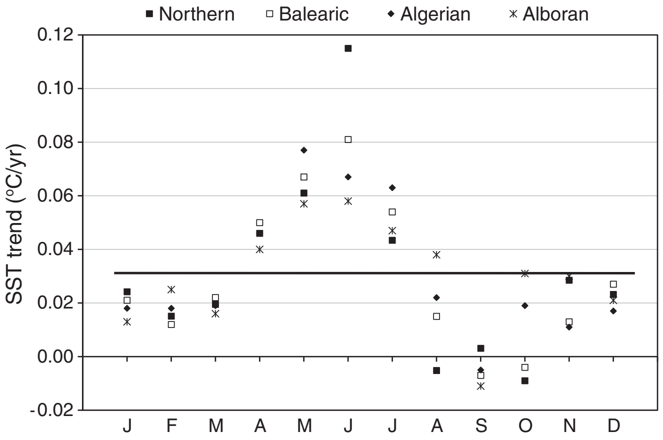

Fig. 6. Linear SST trends for each month in the four basins of the Western Mediterranean. The line represents the averaged annual SST trend. The highest warming trends are registered in spring and early summer. August, September and October show a small negative trend in some basins. The trends were significant at the 5% level of confidence only for April, May and June in all the basins and July in the Algerian and Alboran basin.

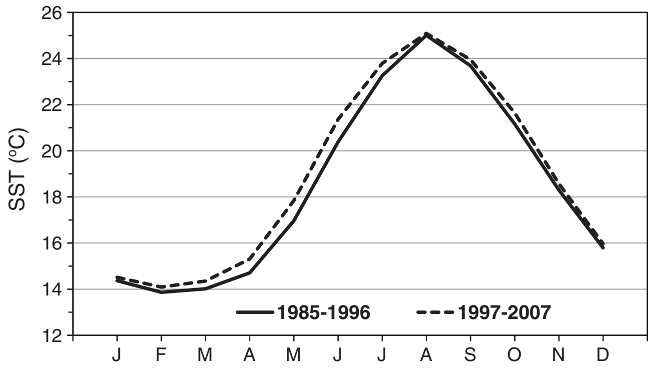

Fig. 7. Seasonal cycle of SST in the Western Mediterranean in terms of monthly means of the two different decades: 1985–1996 (solid line) and 1997–2007 (dashed line).

Seasonal trends have been calculated for each basin by grouping the monthly data in the four seasons defined as: winter (January, February, March), spring (May, June, June), summer (July, August, September) and autumn (October, November, December). This grouping has been adopted instead of the standard meteorological seasons considering that water bodies heat and cool more slowly than land areas and consequently maximum and minimum SST are reached in oceans about one month later (Strahler and Strahler, 2003), consequently season groupings have been delayed by one month. Fig. 5 shows the linear regressions and the trends obtained for each season in the whole Western Mediterranean. Of all the regressions, only the spring one, which shows the steepest slope, was significant at the 5% level. These results suggest that the warming of the Western Mediterranean is mainly occurring during the spring season, at an average trend of 0.065 °C/yr ± 0.012 for the whole basin. For the rest of the seasons, although positive trends were obtained, the rate of change is much lower, about 0.02 °C/yr, and the regressions were not statistically significant.

A more detailed analysis was performed by calculating the trends separately for each month and in each basin. Table 3 shows the annual linear trends obtained in these regressions. Although the trends are significant at the 5% level of confidence only for April, May and June (spring season) in all the basins, as well as July in the Algerian and Alboran basin, we have represented all the trends for every month and basin in Fig. 6. This graph shows the variability of the SST rate of change during the year. The highest warming trends were registered during the spring and early summer, especially in the month of June and in the Northern basin where rates of 0.115 °C/yr ± 0.032 have been obtained. Even considering that this high rate could be affected by some local anomaly, high rates (between 0.06 and 0.08 °C/yr) were registered in May and June in all the basins. Winter and autumn, however, showed lower rates (which were not statistically significant) with values around 0.02 °C/yr, and at the end of the summer (August, September, October) even a negative trend appeared in some of the basins.

These data highlight the importance of monthly and seasonal analysis in the studies of global warming. Annual trends alone smooth over seasonal differences which may have far reaching implications for understanding and dealing with the consequences of change. In the Western Mediterranean our results indicate that seasonal variations in the warming rate contribute more significantly to the annual trend than the variations registered between the different basins.

In order to complete our analysis we split the time series of data in two sets: one set from 1985 to1996 when we found a predominance of

Table 3
Linear trends for each month in the four sub-basins. Significant trends at the 0.05 significance level are in bold.

	J	F	M	A	M	J	J	A	S	O	N	D
Northern	0.024	0.015	0.020	**0.046**	**0.061**	**0.115**	0.043	−0.005	0.003	−0.009	0.029	0.023
Balearic	0.021	0.012	0.022	**0.050**	**0.067**	**0.081**	0.054	0.015	−0.007	−0.004	0.013	0.027
Algerian	0.018	0.018	0.019	**0.046**	**0.077**	**0.067**	**0.063**	0.022	−0.005	0.019	0.011	0.017
Alboran	0.013	0.025	0.016	**0.040**	**0.057**	**0.058**	**0.047**	0.038	−0.011	0.031	0.030	0.021

negative anomalies (see below), and a second set from 1997 to 2007 when the frequency of positive anomalies was higher. For each period the averaged monthly data have been computed in all the basins. Fig. 7 shows the monthly distribution of SST in both decades for the whole Western Mediterranean. We can observe that an increment of temperature of nearly 1 °C was registered from April to July over the two decades. This can be interpreted as the shortening of the spring and the earlier inception of a longer summer during the decade 1997–2007. Similar results were obtained when computing the monthly evolution of SST in both decades in the four sub-basins separately. This regional analysis shows that the highest warming was recorded in the Northern basin where an increment of temperature over the two decades of 1.4 °C was detected in June. It will be interesting to observe whether this trend continues in the coming years and, if so, the likely affects on the biological activity of the waters would be worth further study.

3.3. Thermal anomalies

Monthly anomalies have been obtained in each basin as the difference between the monthly temperature and the average monthly value in the period. Global values for the whole study area (WMED) have also been computed. Considering that the standard deviation for monthly temperature calculated over the series 1985–2007 ranges from 0.4 °C in winter to 0.8–0.9 °C in summer/autumn (see Table 1), thresholds of 0.5 and 1 °C were defined. The 0.5 °C threshold gave a total of 98 anomalous months when applied to global values for the Western Mediterranean: 48 months when monthly temperatures were 0.5 °C above the monthly average (positive anomalies) and 50 months when monthly temperatures were 0.5 °C below the monthly average (negative anomalies). Intense anomalies with monthly averages differing by more than 1 °C from the twenty year mean showed 30 months: 17 positives and 13 negatives in the whole Western Mediterranean. Analysis of the distribution of these anomalies, both positive and negative, over the study period, the variations between the four basins, and their monthly distribution all reinforce the results obtained from looking at the inter-annual trends.

Fig. 8 shows the series of anomalies calculated for the whole study area. The maximum positive anomalies were registered during the summer of 2003 with temperatures of 2.6 °C above the monthly average, July 2006 (>2.1 °C) and September 1991 (>1.9 °C). The maximum negative anomalies were registered in September 1996 with values 1.8 °C below the monthly average, November 1993 and May 1991 with values <1.6 °C. However, higher anomalies are found when we analyze the four basins separately. Thus, the maximum positive anomalies were registered in the Northern basin in June of 2003 (3.8 °C) and July 2006 (3.3 °C), and the maximum negative anomaly was registered in the Alboran Sea in October 1993 (2.3 °C).

Fig. 9A1–D1 shows the frequency of monthly anomalies (positive and negative) registered over the series in the four basins. We can observe that, in all the regions, the number of months with negative anomalies is higher during the first half of the period (1985–1996) and the number of months with positive anomalies increases during the second half (1997–2007). This can be clearly observed in Fig. 9A2–D2 where the percentage of positive and negative anomalies has been represented for every period in every basin. Negative anomalies are about 60–70% of the total number of anomalies during the period 1985–1996 and positive anomalies are 60–70% of the total number during the decade 1997–2007.

Some common features can be observed in the four basins, but there are also differences. With respect to negative anomalies, two periods of predominance can be detected: 1991–1993 and 1985–1987. The first period 1991–93 shows a high number of negative anomalies in all the basins, especially in Alboran where there were 7 months with temperatures 0.5 °C below the average in the three years. Although in September of 1991 a maximum on the positive anomalies was registered in all the basins, this was a cool period in the series analyzed. The second period 1985 to 1987 can be clearly observed in the Algerian, Northern and Balearic basin, but it is not so evident in the Alboran where only 1986 had a clear dominance of negative anomalies. Also, during 1996 a high number of negative anomalies were registered in the Northern and Balearic basin but not in the Algerian or Alboran, the latter with a dominance of positive anomalies.

With respect to positive anomalies, the Alboran Sea registered the highest number of months with temperatures of 0.5 °C above the average of all the basins, especially from 1994 to 2007. Some periods with a dominance of positive anomalies in the four basin can be observed: 1990, 1997, 2003 and 2006–2007 with 4 or more months of positive anomalies. However, some years have registered a number of positive anomalies only in some basins, like 2004 with 5 months of positive anomalies in Alboran, or 1989 with 4–5 months of positive anomalies in the Algerian and Alboran basins.

The monthly distribution of positive and negative anomalies for each basin is represented in Fig. 10. The Alboran basin registered the highest number of anomalies (123) and the Northern basin the lowest (108). In all the basins, anomalies are more frequent from May to December (74% of the anomalies in the WMED), with October as the month with the highest number of records, especially in the Alboran and Balearic. When considering the monthly distribution of the intense anomalies, that is, when temperatures are 1 °C above or below the average monthly temperature (Fig. 11), we can observe that the Northern basin is the region where the intense anomalies were most frequent (53 in total) with the highest occurrence during the spring and summer. The Alboran and Algerian basins had the lowest number of intense anomalies (30) with the highest occurrence in October. During the winter there were rarely any intense anomalies in any of the basins.

4. Discussion and conclusions

This paper describes the regional, seasonal and decadal variability of SST in four basins of the Western Mediterranean during the period 1985–2007 from the analysis of monthly data obtained from nighttime satellite thermal images. Although the series of data are not very long,

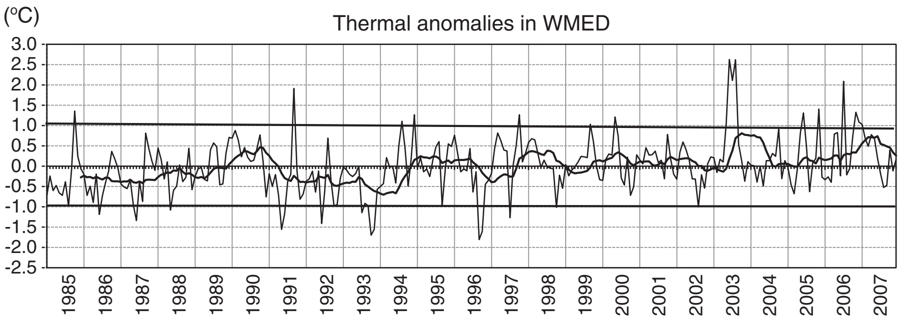

Fig. 8. Monthly thermal anomalies in the Western Mediterranean. The data has been calculated as the difference between monthly SST and the mean monthly value for the period 1985–2007. The smooth line in the graph represents the 12 month moving average. The straight lines point out intense anomalies above and below 1 °C.

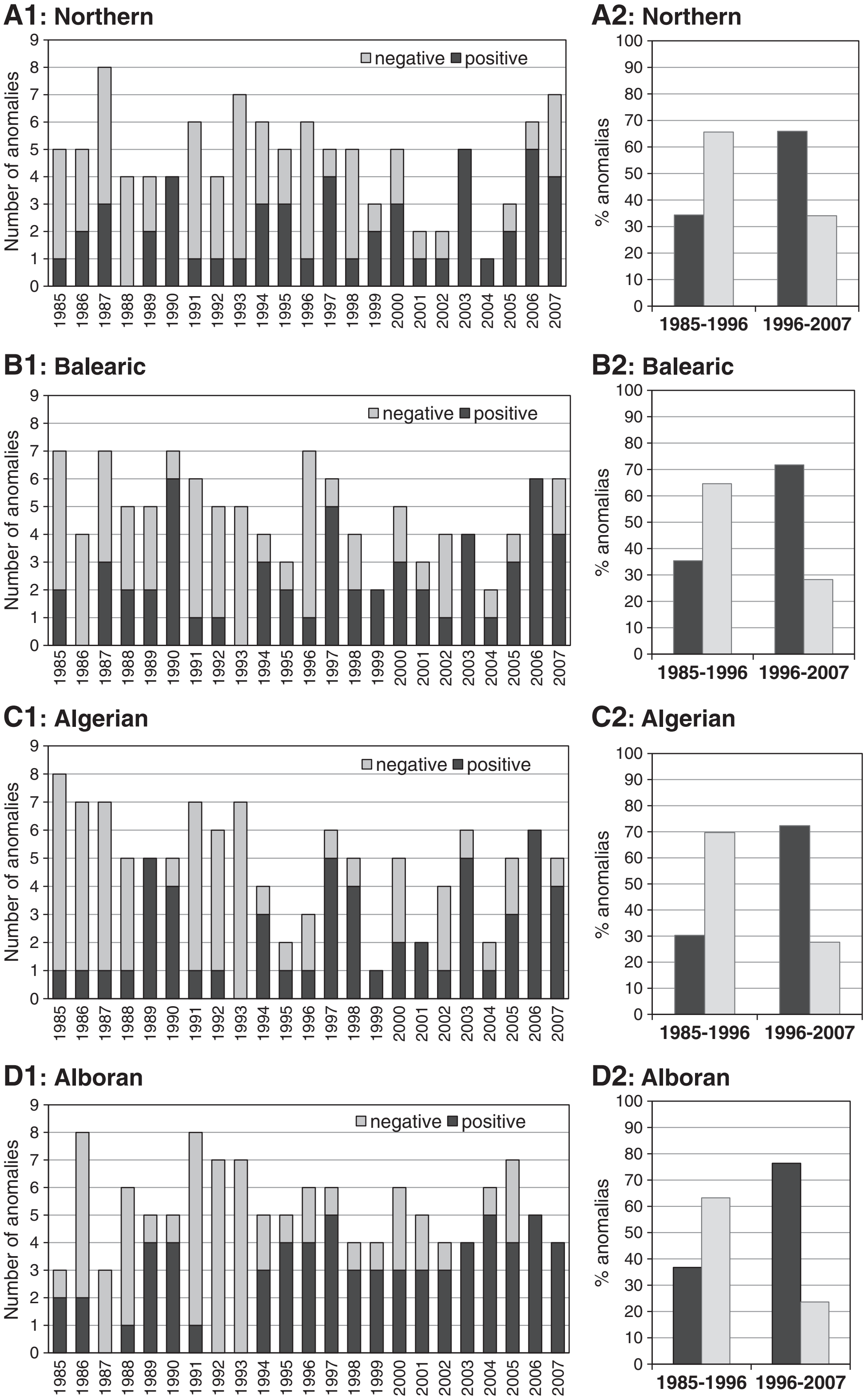

Fig. 9. (1) Number of months in each year with thermal anomalies 0.5 °C above (positive) or below (negative) the mean monthly SST of the period 1985–2007. (2) Percentage of positive and negative thermal anomalies calculated for the two decades of the study period. Figures from A to D represent the results obtained in each sub basins of the Western Mediterranean.

the availability of averaged monthly data covering the whole basin has allowed us to analyze in detail the recent trends at a regional and monthly scale. The main conclusions are summarized below.

Analysis of the SST spatial variability in the Western Mediterranean basins has revealed that the regional differences between basins are highest in autumn, with a difference of nearly 3 °C between the

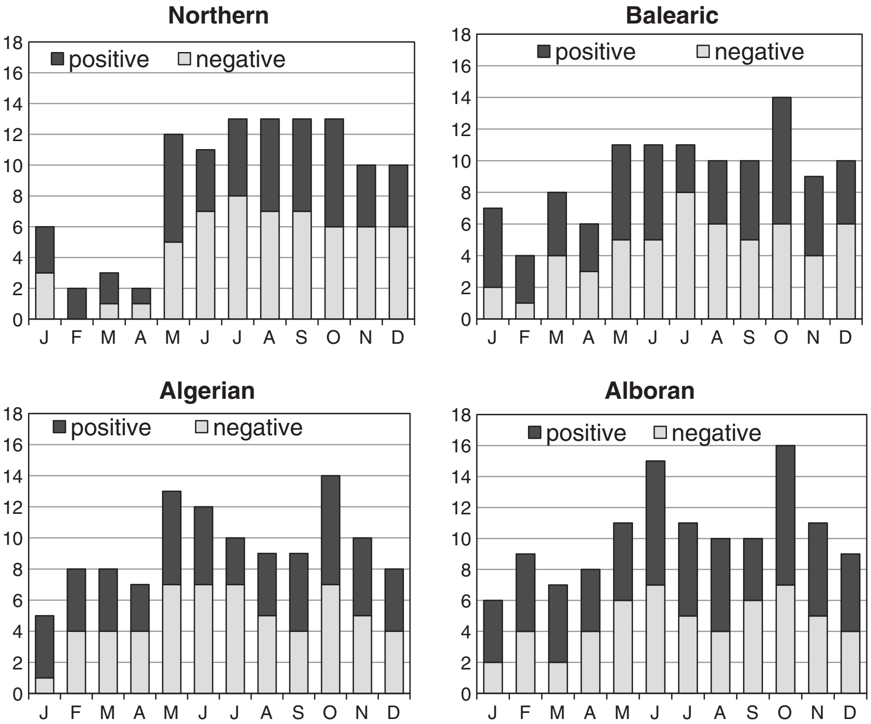

Fig. 10. Monthly distribution of thermal anomalies in Northern-, Balearic- (top), Algerian- and Alboran-basins (bottom). The figure represents the number of months in the period 1985–2007 with SST 0.5 °C above (positive) or below (negative) the monthly long term mean of the period.

warmest (Algerian) and the coolest basins (Northern) in September and October.

In winter there is a clear latitudinal gradient of about 2 °C between the cooler north (Northern) and the warmer south (Alboran). However this gradient disappears in the spring when the largest regional differences were only 1.5 °C but with almost no difference between the Algerian and the Balearic basins. This temporary uniformity in the spring occurs as the surface water that occupies the more central Balearic basin starts to warm up. By summer the highest temperatures are registered in the Balearic and Algerian Basins with the regional differences increasing through to the autumn maximum.

The analysis of thermal anomalies during the period 1985–2007 found a clear difference between the two decades. During the first half

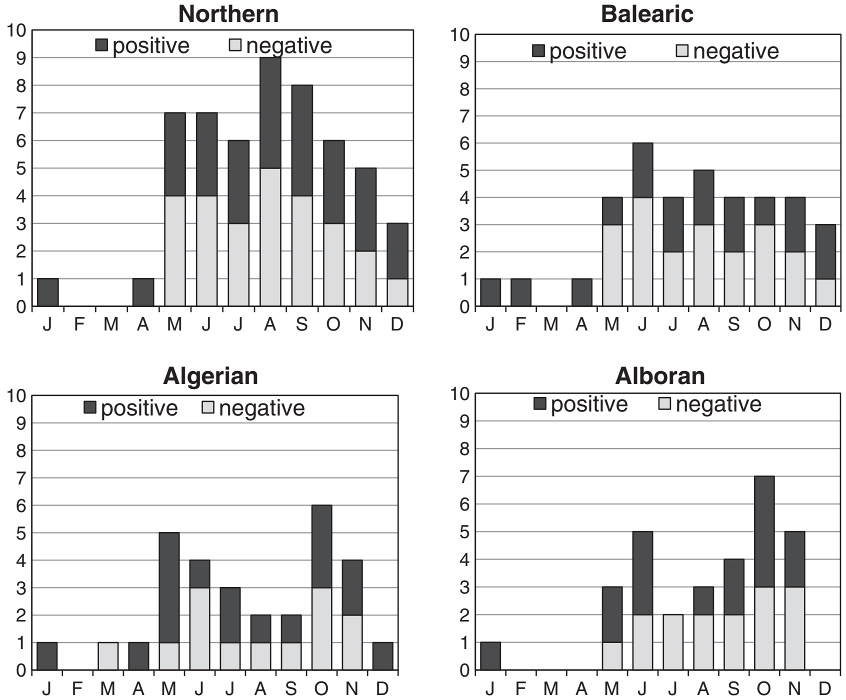

Fig. 11. Monthly distribution of intense thermal anomalies in Northern-, Balearic- (top), Algerian- and Alboran-basins (bottom). The figure represents the number of months in the period 1985–2007 with SST 1 °C above (positive) or below (negative) the monthly long term mean of the period.

of the period (1985–1996) about 70% of the anomalies are negative, and during the second half (1997–2007) about 70% of the anomalies are positive. In general, thermal anomalies (positive or negative) are more frequent from May to December in all the basins. Some regional differences have also been detected. The frequency of anomalies above or below 0.5 °C the average is higher in the Alboran basin, but the frequency of intense anomalies (1 °C above or below the average) is higher in the Northern basin. This fact is consistent with the high inter-annual variability observed in the Northern basin during the summer (see Table 1), when the largest standard deviation in all the basins (about 1 °C) was registered, and also the high dispersion of the values around the mean values observed in the analysis of spatial variability within the zones (see Fig. 2).

The study of SST temporal evolution shows an increase rate of 0.03 °C/yr in average across the basin. This rate is the same given for the whole Western Mediterranean (including the Tyrrhenian Sea) by Nykjaer (2009) from a study also with Pathfinder AVHRR data for the same period of time. It also coincides with the trend rate given by Salat and Pascual (2006) from data registered in the oceanographic station of L'Estartit for the period 1974–2005. This station, located at the continental shelf in the North Western Mediterranean (42° 03′N, 3° 15′ 15″E) is operated by the Institut de Ciencies del Mar (ICM, Spain) and is the longest hydrographic series available of weekly data. Similar warming rates have been obtained in other hydrographic stations in the Western Mediterranean during the second half of twentieth century (Vargas-Yañez et al., 2005, 2008, 2009).

The seasonal study of trends has found that the rate of change of SST in the Western Mediterranean varies depending on the season considered and that this variation is higher than the regional differences in trends observed for the four basins of the study area. Spring is the season where the highest warming rate has been registered, with 0.065 °C/yr ± 0.012 while during the rest of the seasons the trends are around 0.02 °C/yr or less. Salat and Pascual (2006) also observed a higher warming trend during the spring season at the oceanographic station of L'Estartit, with a rate of 0.043 °C/yr in surface waters, which they also interpreted as an advance of the summer conditions at this location. Our study shows a higher trend which has been registered in all the basins of the Western Mediterranean.

From the monthly analysis of trends, we can conclude that June is when the highest trends were detected, ranging from 0.058 °C/yr in Alboran to 0.115 °C/yr in the Northern Sea. In consequence, if these results are confirmed, we think that, when dealing with global warming in the Western Mediterranean, the annual rates of change should be carefully considered as the global figures of warming can miss or mask important seasonal trends.

Our study suggests that over the two decades analyzed the onset of summer has moved forward as April, May, June and July have increased their mean SST by nearly 1 °C with a consequent lengthening of the summer in the last decade. This advance of the springtime warming could affect the process of stratification of the water column, which is a key factor in marine productivity. In the Mediterranean, the development of water column stratification typically occurs from May to October, but if this period should become longer many biological processes would be affected. For instance, Coma et al. (2009) have analyzed the relationship between the enhanced stratification registered in coastal waters of the northwestern Mediterranean and some events of mass mortality of invertebrates, pointing out that positive temperature anomalies in the water column during the summer are the underlying cause of mass mortality, due to the exhaustion of dissolved surface nutrients. If the tendency of longer summers described in our study is confirmed and continues during the coming years, such impacts on the ocean circulation, primary productivity, ecosystems, and on other components of the climate system will need to be addressed.

This paper has presented a new insight into recent warming trends in the Western Mediterranean and has described regional and seasonal SST variability in four basins from satellite images data. The discussion of the physical mechanisms responsible for the decadal warming as well as the possible links and feedbacks between SST spatial variability and the variability of ocean currents has not been addressed as this would exceed the scope of objectives of this work as defined by the authors. Contributions from the expertise of other research groups will, undoubtedly, help to explain changes and their implications in the whole Mediterranean system.

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