# Sea Surface Temperature (AVHRR, MODIS) and Ocean Colour (MODIS) seasonal and interannual variability in the Macaronesian islands of Azores, Madeira, and Canaries

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# Sea Surface Temperature (AVHRR, MODIS) and Ocean Colour (MODIS) seasonal and interannual variability in the Macaronesian islands of Azores, Madeira, and Canaries

Martins, A. M. *[a], A. S. B. Amorim[b], M. P. Figueiredo[c], R. J. Sousa[b], A. P. Mendonça[a], I. L. Bashmachnikov[b], and D. S. Carvalho[b]

[a]Dept. Oceanography and Fisheries, Univ. Azores, Cais de Santa Cruz, 9901-862 Horta, Faial, Azores, Portugal;

[b]Regional Directorate of Fisheries of Madeira, Estrada da Pontinha, 9004-562 Funchal, Portugal;

[c]Centre of IMAR, Dept. Oceanography and Fisheries, Univ. Azores, Cais de Santa Cruz, 9901-862 Horta, Faial, Azores, Portugal

## ABSTRACT

Within the framework of ORPAM (03/MAC/4.2/A2) project, five years of AVHRR Sea Surface Temperature (SST) (in °C) (2001-2006) (HAZO station, Azores) and of MODIS Ocean Colour (OC) (chlorophyll *a* in mg $m^{-3}$) and SST (2002-2007) data (NASA/GSFC), allowed the establishment and comparison of the mean surface temporal variability among the Azores, Madeira, and Canaries regions. Results show strong and similar seasonal SST variability patterns with average values ranging between 15°C (winter) and 27°C (summer). Largest SST differences are observed during wintertime (Azores/Canaries-lowest/highest values, respectively). Interannual SST variability shows no defined patterns among the three regions. Ocean Colour seasonal variability varies inversely with SST. In the Azores, spring blooms dominate, followed sometimes by smaller autumn ones. In Madeira, spring blooms dominate. In Canaries, OC means are highest during February and March. Interannual OC variability shows the largest variation in Canaries (summertime). These results suggest strong latitudinal gradient effects. Canaries waters are generally warmest, followed by Madeira, and Azores. Highest OC averages are found in the Azores and Canaries regions. In the latter case, this most likely reflects e.g.: the contribution of the African coastal upwelling; OC algorithms failure in Case 2 waters; and winter mixing processes in the region.

**Keywords:** Macaronesia islands, temporal variability, ocean colour, sea surface temperature

## 1. INTRODUCTION

The region of the Azores is dominated by eastwards flows, which represent southern branches of the North Atlantic Current (NAC) crossing the Mid Atlantic Region (MAR) approximately at 42°-48°N, and to a less extent the Azores current (Fig. 1). The Madeira region is dominated by the Azores Front-Current system (AzFC), following the latitude of 34°-36°N, whereas the Canaries islands are strongly affected by the Canary upwelling-current system. This is characterised by intense mesoscale structure in the transition zone between the cool, nutrient-rich waters of the coastal upwelling regime and the warmer, oligotrophic waters of the open ocean ([4]). The Canary Island archipelago, which straddles the transition, introduces a second source of variability by perturbing the general southwestward flow of both ocean currents and Trade winds. The combined effects of the flow disturbance and the eddying and meandering of the boundary between upwelled and oceanic waters produce a complex pattern of regional variability ([4]).

The southern branch of the NAC and the Azores current are most pronounced in the eastern part of the Eastern subtropical *Atlantic basin and have a slight tendency to converge towards the Iberian Peninsula.

* *anamartins@notes.horta.uac.pt; phone +351 292 200 408; fax: +351 292 200 411; www.horta.uac.p*

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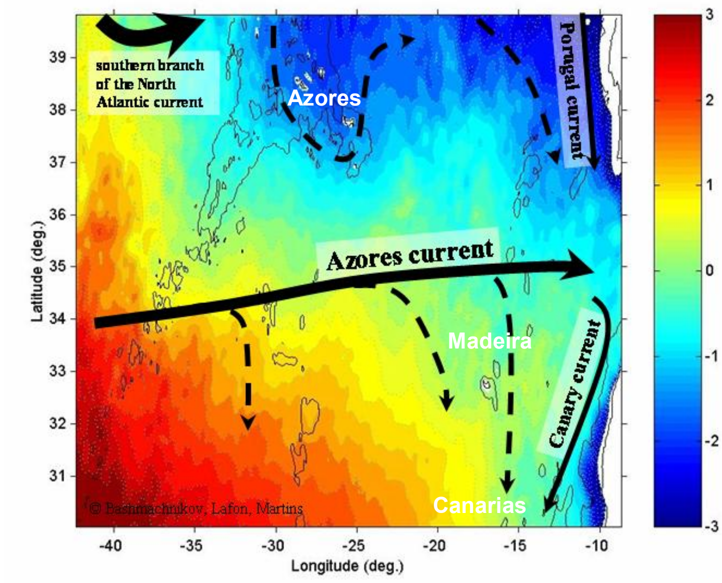



Fig. 1. HAZO ([1]) AVHRR derived Sea Surface Temperature (SST) (°C) anomalies for 2001-2004. Black thin lines represent the 2000m bathymetric. Arrow lines are schematic representations of surface currents obtained by AVISO altimetry (http://las.aviso.oceanobs.com/las/servlets/dataset). Mainland Portugal and Africa continent are observed on the right side. Location of the Azores, Madeira and Canarias archipelago is also specified (adapted from [2]).

The position of the Azores front and 60-km wide jet-like AzC exhibits seasonal migrations of about 3° latitude ([18]), performing (in the region south of the Azores) a retreat towards the south in summer and progress northward in winter ([20,21]). The Azores Current transport reaches its maximum in spring and stays quite high in summer, whereas in winter minimum transport was observed ([19]). It is interesting to note, that the Gulf Stream exhibits a similar seasonal pattern, shifting southward and reaching its maximum transport in spring-early summer ([24,25]). The North Equatorial current exhibits analogous seasonal variability and all of these reflect in fact, the seasonal meridional migrations and transport variability of the North Atlantic subtropical gyre ([29]). Those large-scale changes should have an effect on seasonal SST variability in the Azores archipelago.

Due to seasonal ocean surface warming, the isotherms (in the Azores region) start moving north in late spring and get its northernmost position in August. The backwards retreat starts in November. This upper layer warming forms the shallow (100m or less) seasonal thermocline and bar the internal water structure ([26,23]). Still significant zonal isotherm tilt, observed for the two summer months for 2001 and 2002, possibly reflects a strong influence of the advection pattern, forcing the isotherms to deviate from the zonal position. SST maximum gradients perform seasonal meridional migrations, in which enhanced SST advection during spring-summer seasons seems to play the most important role. We tend to attribute this feature to seasonal Subtropical Gyre expansion (see also [28])

In addition to seasonal variability, the study of the NAO related variability was found to be extremely important for the SST distribution in the region. Positive trends in NAOI during 2001-2002 correspond to a general increase in SST around the Azores associated with an increased tendency of the mean meridional gradients to shift north. We interpret this as the Subtropical Gyre intensification response to a NAO forcing. During a high NAOI, advection of the heat by the mean currents seems to dominate while, during a low NAOI, a substantial part of the northward heat transfer is accomplished by westward moving cyclones and anticyclones. This may result from an increase in the Azores front instability while the NAO forcing weakens. NAO monthly variability shows an opposite tendency. A sharp decrease in the NAO forcing produces simultaneous increase in the average SST, with its maximum observed in the southern region. We relate this to the Gyre surface waters northward excursions during the periods of sharply reduced atmospheric forcing. It is questionable whether the Azores front also exhibits NAO related meridional migrations.

The stationary anomaly SST field also showed persistent upwellings at the coasts of Portugal and Africa. At the coast of Africa a cold SST anomaly of 3°C was observed, while near Portugal it was only 2°C. In spring and summer both upwelling events were stronger than during winter. In winter Portugal upwelling strength decreased 3 times, whereas the North African one - less than 2 times. Spring-summer upwelling enhancement could be attributed to seasonal enhancement of southerly winds near the coast of Portugal and North Africa in summer ([30]).

In this study, Ocean Colour (OC) data and Sea Surface Temperature (SST) is used to derive near-surface pigment distributions (Chl *a* in mg $m^{-3}$) and surface temperature values (in °C) around the Azores, Madeira and Canaries archipelagos Previous studies have contributed to the understanding of ocean physical and biological dynamics in the eastern and subtropical North Atlantic. The present investigation is based on a comparative analysis of six years of MODIS/AQUA and NOAA/AVHRR monthly and seasonal satellite imagery for the three regions

## 2. DATA

### 2.1 AVHRR data

A total of 21,604 NOAA/AVHRR (-12, -14, -16, and -17) 1.1 km resolution satellite images were recorded at station HAZO([1]) for the period April 2001 to July 2007 (Fig. 2). The images are routinely processed at the Department of Oceanography and Fisheries at the University of the Azores (IMAR-DOP/UAç) using semi-automated imagery processes to compute the SST data ([3]). This is obtained using the interactive satellite data analysis software package TeraScan® 3.1 (developed by Seaspace Corporation). The total range of AVHRR-SST imagery available up to October 2006 (excluding), performing a total of sixty four months, was used in this study.

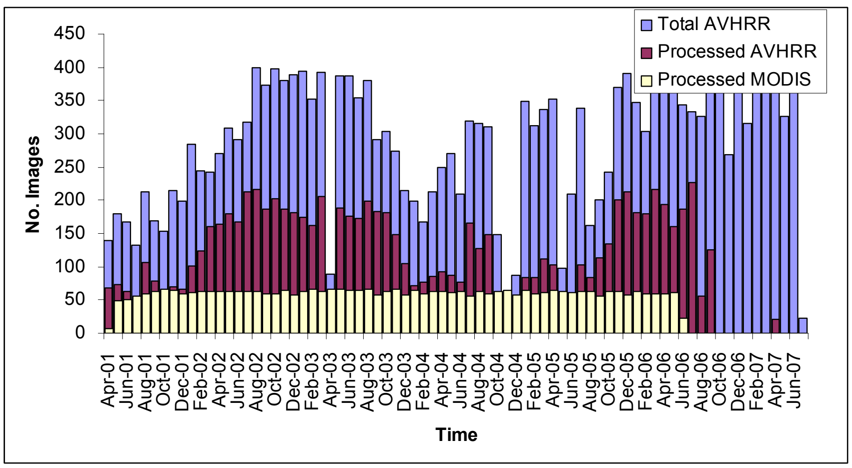



Fig. 2. Total number of HAZO satellite received AVHRR images from April 2001 (beginning of station operation) up to present time. The total number of processed AVHRR (HAZO) and MODIS (NASA/GSFC) imagery processed for this study is also indicated.

From the initial AVHRR raw imagery a total of 8499 (641, 2081, 1928, 987, 1314, and 1527 for years April 2001 to September 2006, respectively) were considered valid and processed up to obtain the geophysical SST parameter. The remaining images were rejected mainly due to bad recording and/or coverage, and navigation problems. The resultant AVHRR imagery were remapped to a Mercator projection occupying three different regions (Table 1, Fig. 3).

Table 1. Master files specifications for the Azores, Madeira, and Canaries study regions.

| Region | Latitude range | Longitude range | Pixel No. (image height) | Pixel No. (image width) |
|---|---|---|---|---|
| Azores | 34.6525 N - 42.6717 N | 33.7347 W - 23.5053 W | 800 | 1000 |
| Madeira | 30.4326 N - 35.0923 N | 19.3479 W - 14.4561 W | 464 | 469 |
| Canaries | 24.9006 N - 32.1478 N | 20.5584 W - 10.6953 W | 806 | 965 |

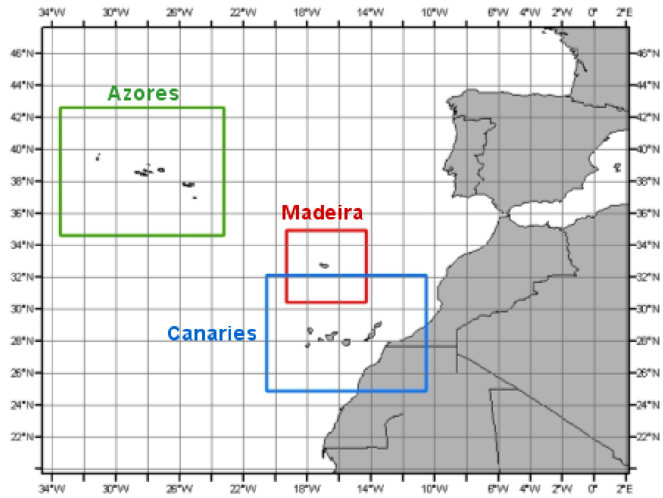



Fig. 3. The three AVHRR and MODIS regions of study in the NE Atlantic: Azores (green square), Madeira (red square) and Canaries (blue square) (adapted figure courtesy from [5]).

### 2.2 MODIS data

MODIS daily imagery is regularly obtained from the Ocean Colour Level 1/2 browser ([6]). These images are mapped (Level2-map) with SeaDAS, by creating a master file specifically for the three regions of study (cf. Fig. 3). The download and mapping process is automated within the HAZO system developed by [3]. A total of 3,767 MODIS/AQUA 1.1 km resolution satellite images were obtained from June 2002 to August 2007, performing 63 months of data used in this study (cf. Figs. 2 and 3, and Table 1).

## 3. METHODS

MODIS derived derived near-surface chlorophyll a (Chl *a* in mg $m^{-3}$) and SST (in °C) values were obtained using the OC3M ([7]) and the NLSST algorithms ([8]), respectively. NOAA/AVHRR derived SST values (in °C) were obtained implementing the MCSST algorithm ([9]).

Prior to the calculation of any statistical parameters, and as part of all imagery post-processing methodology, atmospheric noise removal was improved by inputting threshold values to each satellite each image. These values were defined after analysis of surface temperature and Chl *a* in situ data available for each region. Ocean Colour threshold values were 0.01 and 7 mg $m^{-3}$, i.e. all OC pixel values below or above these thresholds were considered “non valid” and therefore excluded from further statistical analyses. The threshold values for SST imagery were 10° and 30°C. Statistical parameters (e.g. 8-day, 15-day, monthly, and seasonal average, median, standard deviation, and coefficient of variation) were calculated from the daily images and obtained for the Azores, Madeira and Canaries regions. Only the monthly and seasonal statistical values are presented in this study.

In this study, four oceanographic annual seasons were defined. Although not exactly coincident among the three regions, neither among the two different parameters (OC and SST), seasons were standardized among all regions and parameters as: <u>spring</u> (represented by March-April-May); <u>summer</u> (as June-July-August); <u>autumn</u> (as September-October-November); and <u>winter</u> (as December-January-February).

# 4. RESULTS AND DISCUSSION

## 4.1 Inverse relationship

Among the two satellites derived parameters (SST and OC) an inverse relationship was observed not only in daily imagery (and whenever cloud coverage was not enough to disguise this relationship) but also, and mostly, in statistical imagery. In particular, in the Azores region zonal bands of increasing and decreasing chlorophyll a concentration values are observed towards the north and south, respectively ([10]), while SST values are warmer to the south and colder to the north of the Azores archipelago (Fig. 4). Three main chlorophyll a transition regions are identified in the image. These were previously reported as a ([10]): 1) "southern transition region" with Chl *a* values below 0.1 mg $m^{-3}$, in darker blue colours; 2) "central transition region" with Chl *a* values between 0.1 mg $m^{-3}$ and 0.2 mg $m^{-3}$, in lighter blue colours; and 3) "northern transition region" with Chl *a* values above 0.2 mg $m^{-3}$, in yellowish colours. The southern transition region was shown as a frontal interface rich in filaments, meanders and eddy-like structures, which was identified as the Azores Current and associated frontal zone ([10]). This is visible in the imagery approximately between 32º and 36º N (Madeira archipelago is located within this region).

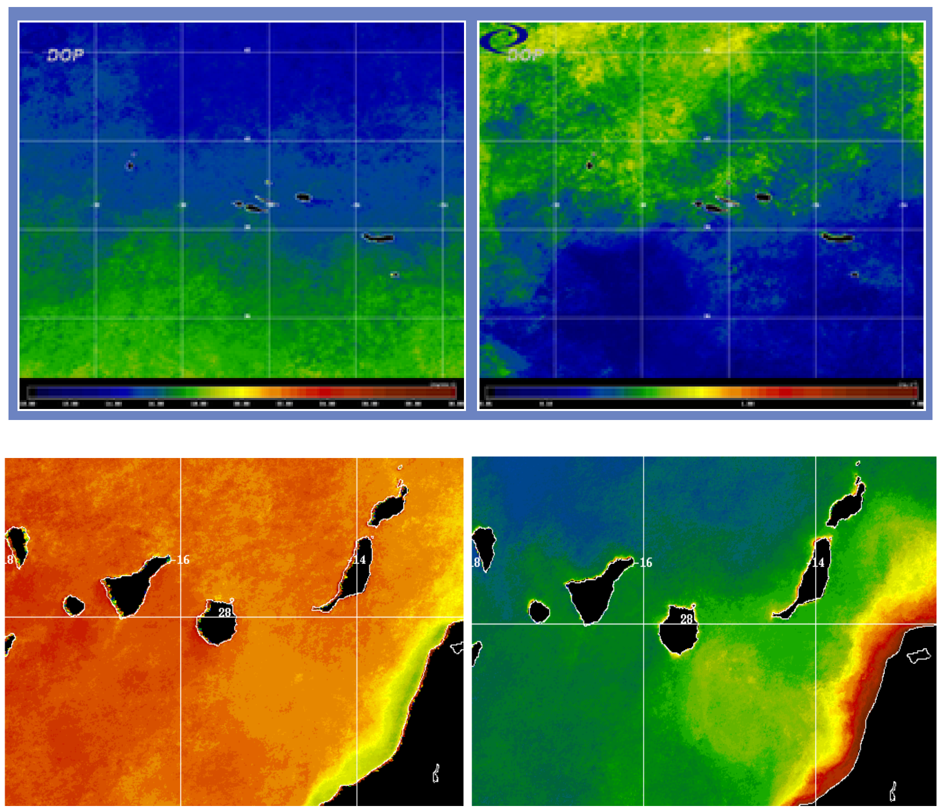


Fig. 4. MODIS-calculated SST (left) and -OC (right) top: spring (March to May 2007) seasonal median images and bottom: autumn (September to November 2002), showing clearly the *quasi* inverse relationship between Chl *a* (in mg m3) and SST (in °C) values for the Azores (top) and Canaries (bottom) regions (see http://oceano.horta.uac.pt/detra/modis/modis_pesquisar.php for more imagery data).

These OC transition regions are also observed in SST imagery (cf. Fig. 4), although in most imagery, SST patterns are not as well observed as OC ones, particularly during summertime, most probably due to the "skin effect" ([11]) and "diurnal warming" ([12]). Thermal sensors measure only the temperature of the skin (less than 1 mm thick) of the ocean, where most heat flux processes between the ocean and the atmosphere occur. Because the net fluxes are generally towards the atmosphere the skin layer is generally cooler than the bulk temperature ([13]). The second process expresses the warming of the sea surface due to solar insulation ([13]). Nevertheless, our results show evident general tendency of the SST patterns to behave inversely to the OC ones at the three study regions (Fig. 5), e.g. in the Azores, warmer waters (yellowish colours in left image in Fig. 4) are observed to the south (lower Chl *a* values reflected by the bluish colours in right image in Fig. 4), while to the north of the islands, waters are colder (SST image: bluish colours) and Chl *a* values are higher (OC image: yellowish colours).

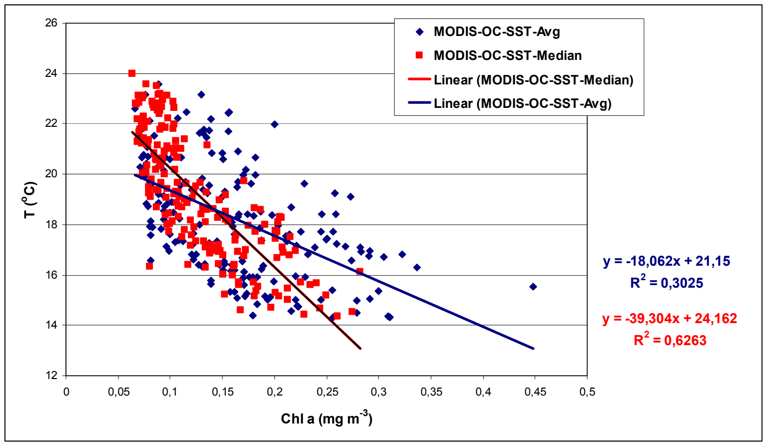
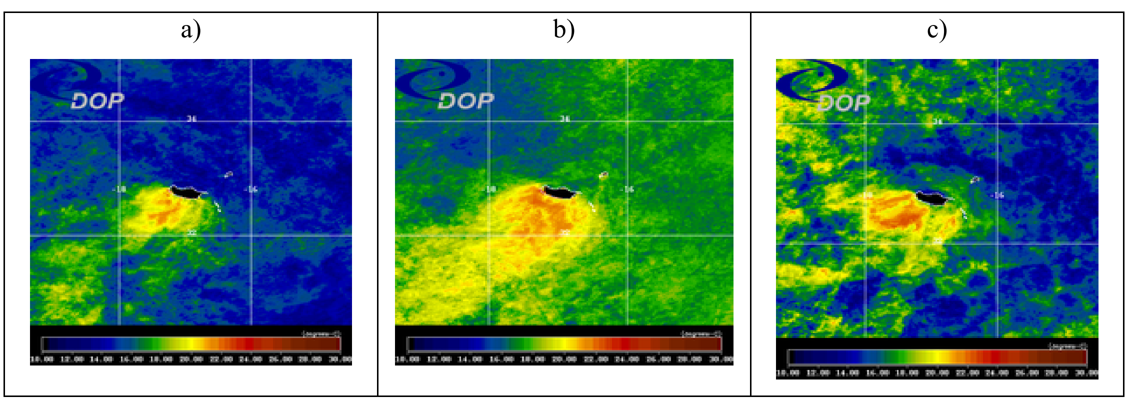



**Fig. 5.** Relationship between MODIS-calculated SST and OC monthly means (blue colours) and between MODIS-calculated SST and OC monthly medians (red colours) showing clearly in both cases, the inverse relationship between Chl *a* (in mg m$^{-3}$) and SST (in °C) values for all regions all together. For each case, a trend line (with the $R^2$ value in chart and respective equation) is also incorporated.

In Madeira and Canaries the same relationship is observed with e.g. cyclonic/anticyclonic cold/warm eddy structures observed frequently downstream of these islands ([4,14,15]) (having higher/lower Chl *a* in their centre, respectively than in surrounding waters ([10])or with evident association between colder and phytoplankton richer waters in the west coast of Africa, as a result of coastal upwelling ([14]) (cf. Fig. 4, bottom). In particular, a disturbance effect by the islands of Madeira and Canaries is frequently evident in medium term mean surface temperature images in which regions of higher temperature form wake-like patterns southwest of the Funchal island (Madeira) ([15]) and on five outer islands of the Canaries and to a lesser extent the inner two ([14,4]) (Fig. 6).



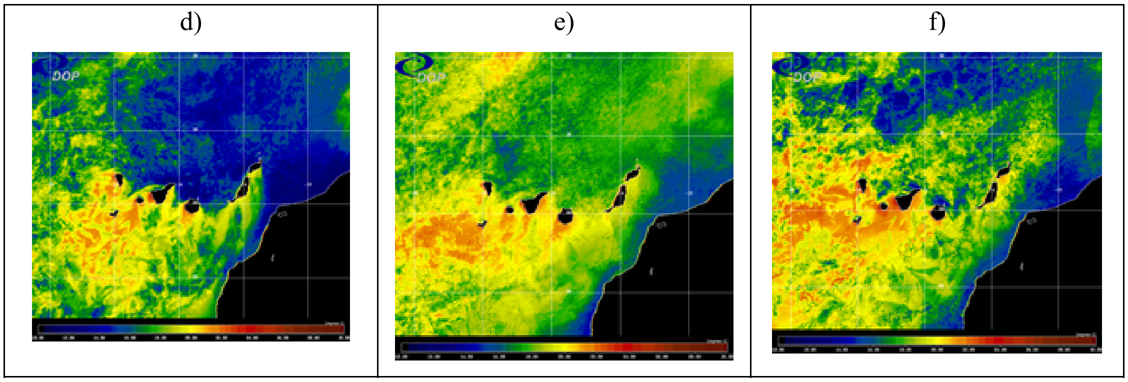



**Fig. 6.** MODIS-calculated SST 15-day averages (in °C) showing examples of island effects: a) and d) Madeira and Canaries, respectively (30 June to 14 July 2002); b) and e) Madeira and Canaries, respectively (15 July to 29 July 2007); Madeira and Canaries, respectively (30 J2002).

## 4.2 Inter-annual variability

### 4.2.1. Sea Surface Temperature

Mean (not shown) and median (Fig. 7) monthly SST values derived from MODIS and AVHRR imagery show distinct inter-annual seasonal cycles with seasonal warming clearly evidenced in all regions initiating during winter-spring and cooling during summer-autumn months. In some years (particularly, August 2001 and 2003) Azores monthly mean SST values are highest than in the other two regions, whilst monthly median values for the same years, show highest values in Madeira and Canaries generally, during the months of September and October. For that reason, it is interesting to observe that calculation of monthly mean SST values is skewed upwards by the Azores region, with maximum SST values that can reach almost 27°C (August 2003), while the highest monthly median values reach only 24.7 °C in Madeira (August 2004), suggesting that some intermittent events are contributing to these higher means in the Azores region.

Azores generally reaches maximum SST values in August, faster than Madeira and Canaries (i.e. with a time lag of about one month from the first to the latter regions, with the exception of year 2004. There is no clear similar tendency for minimum SST monthly median values.

Comparison between different satellites (cf. Fig. 7) clearly shows a tendency for MODIS to underestimate about 1 °C the SST monthly medians when compared with the AVHRR ones (i.e. MODIS values are 1.64 °C, 1.12 °C , and 1.06 °C lower for the Azores, Madeira, and Canaries regions) although, SST monthly curve patterns are quite similar among the two satellites. Both satellites results show the lowest SST monthly mean values in the Azores region (15.5 °C, AVHRR-March 2002 and 14.4 °C, MODIS-March 2003). Nevertheless, the general trend in time for the MODIS-derived median SST values is a decreasing one for the Azores, and a stable trend in time for Madeira and Canaries. However, similar trends are not observed for the MODIS-derived SST mean values, with increasing trends in time for the Azores and Canaries and a stable trend for Madeira during the whole period of data.

Inter-annual comparison among a same region shows the years 2004/2002 to represent the lowest/highest SST median amplitudes in the Azores region, respectively, while in Madeira these are observed during years 2002/2005 and in Canaries during years 2002/2004.

The existence of these SST inter-annual cycles with intensity varying with space and time implies that the three regions of study display some characteristic behaviours.

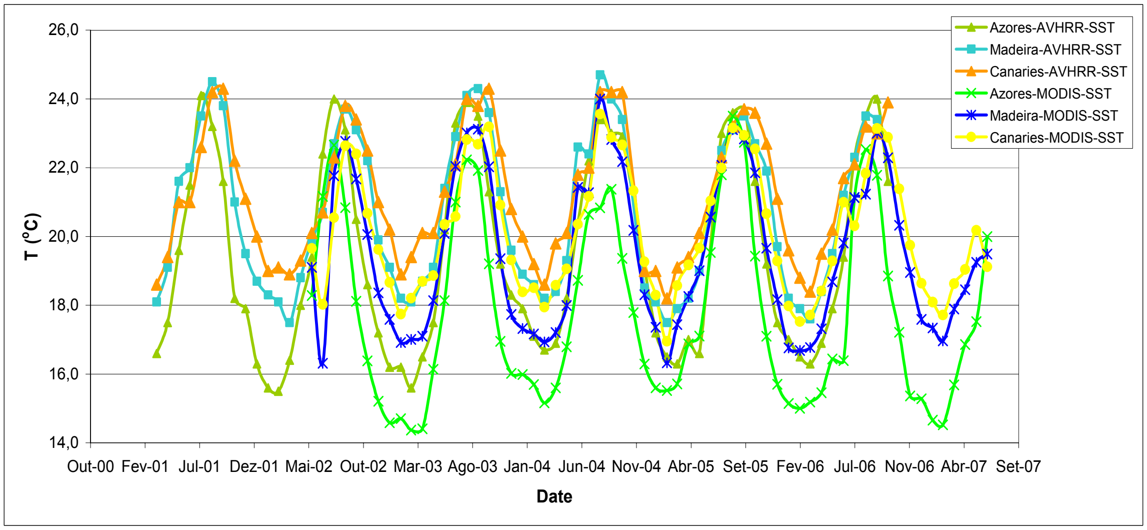



**Fig. 7.** AVHRR (2001-2006) and MODIS (2002-2007) SST monthly medians for the Azores (green colours), Madeira (blue colours), and Canaries (orange colours) regions.

The coefficient of variation (CV), expressed as the standard deviation divided by the mean, allows a measure of dispersion by comparing the variation of the monthly mean SST values for the three regions and for both satellites in a standardized way (Fig. 8). Although MODIS monthly mean SST values are in general lower than AVHRR ones, their variation is highest during the whole period of study, with the exception of summer 2005 when for all three regions a sudden drop in CV is observed (i.e. variability is minimum for all three regions, indicating the highest signal-to-noise ratio (SNR) during that time). AVHRR-derived CV values do not show any particular spatial or temporal pattern, while MODIS-derived CV values, although variable with time, show some consistent patterns among the three regions of study.

Some attempts were made to relate part of the observed SST intra-annual variability with the North Atlantic Oscillation (NAO) forcing, but correlations found were, on a first sight, low.

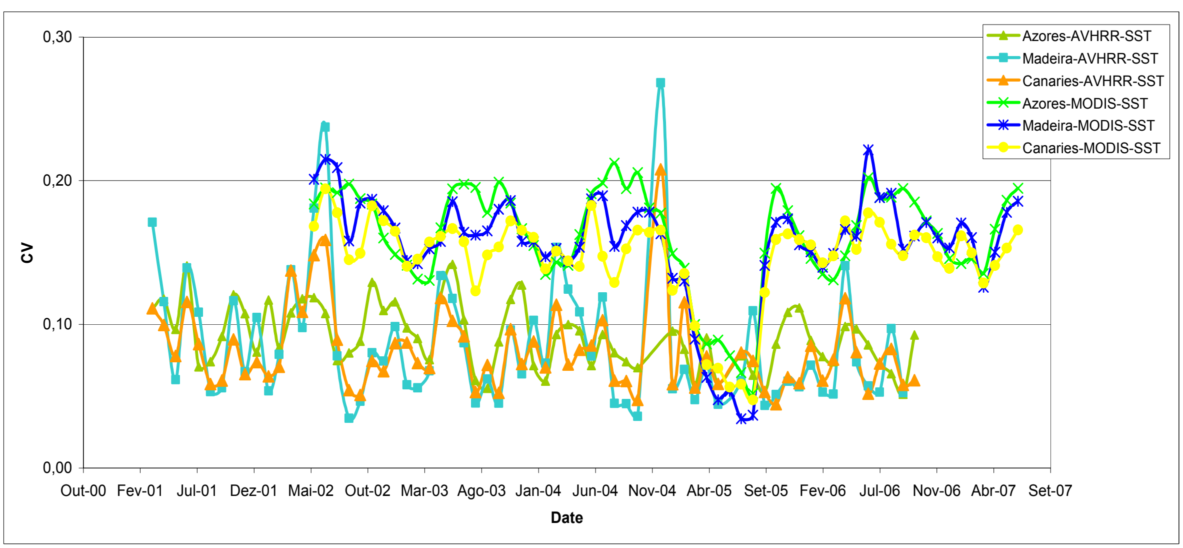



**Fig. 8.** AVHRR (2001-2006) and MODIS (2002-2007) SST monthly coefficient of variation (CV) for the Azores (green colours), Madeira (blue colours), and Canaries (orange colours) regions.

#### 4.2.2. Ocean Colour

Mean (not shown) and median (Fig. 9) monthly OC values derived from MODIS imagery show distinct inter-annual seasonal cycles with increased/decreased Chl *a* pigments clearly evidenced in all regions mostly during February-May/August-September months, respectively. In some years (particularly, during May 2003 and March 2007) Azores monthly median OC values are highest than in the other two regions, whilst monthly mean OC values (with the exception of May 2003), show in general highest values in Canaries, particularly during February 2005 and March 2006. Calculation of the monthly median OC values shows maximum values that can reach up to approximately 0.28 mg $m^{-3}$ (May 2003), while the highest monthly mean OC values reach up 0.45 °C in June 2003, suggesting that some intermittent events are contributing to variable pigment values in the Azores region. Nevertheless, both OC monthly median and mean values show the lowest biomass in Madeira region, with a general tendency for Chl *a* to increase in time in Madeira and Canaries and for the Azores to maintain a stable trend with time.

The existence of OC inter-annual cycles with intensity varying with space and time implies that the three regions of study display some characteristic behaviours.

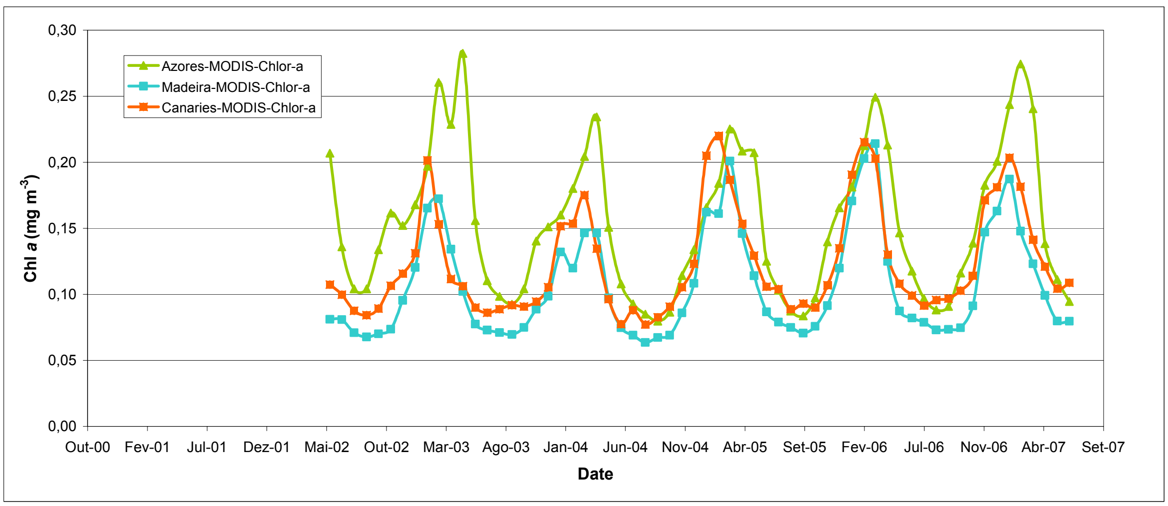



**Fig. 9.** MODIS (2002-2007) OC (in Chl *a* mg $m^{-3}$) monthly medians for the Azores (green colours), Madeira (blue colours), and Canaries (orange colours) regions.

The CV of the monthly mean OC values for the three regions (Fig. 10) shows some interesting results, with a very strong seasonal variation pattern in the Canaries region, during the whole period of study, while in Madeira and in the Azores, OC variation is much less and not as regular, particularly in the latter case where no evident patterns are observed. In Madeira, OC variation, although of smaller amplitude, seems to behave quite inversely from the Canaries case, i.e. highest/lowest variation is observed during winter/summer months, respectively.

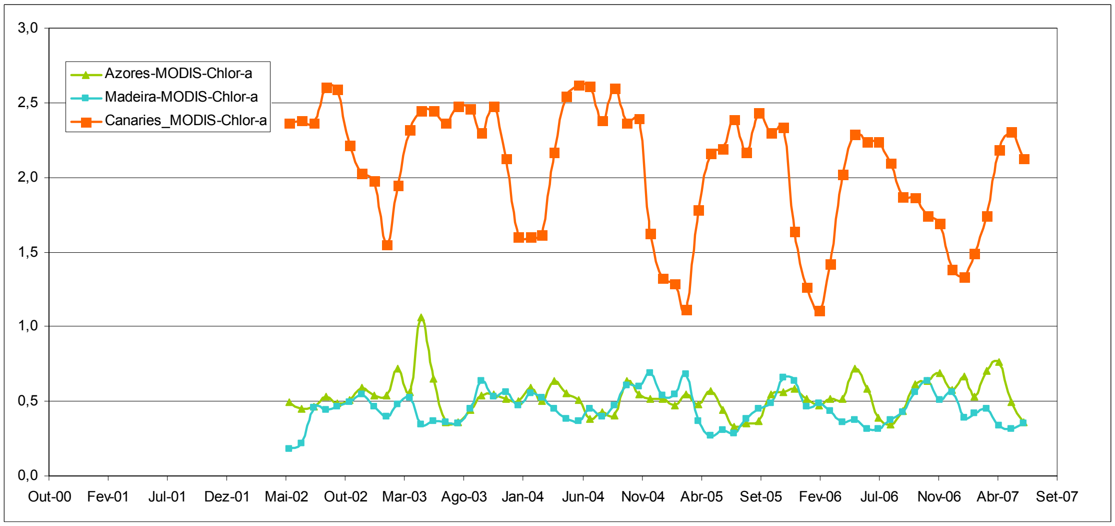



**Fig. 10.** MODIS (2002-2007) OC (in Chl *a* mg m$^{-3}$) coefficient of variation (CV) for the Azores (green colour), Madeira (blue colour), and Canaries (orange colour) regions.

### 4.3 Seasonal variability

#### 4.2.1. Sea Surface Temperature

For all three regions and satellites, strong SST seasonal patterns are evident (Fig. 11). Seasonal warming of the waters is clearly evidenced on median images, with isotherms start moving to the north during springtime and retreating during autumn and winter (Fig. 12). The upper layer water warming during spring, is often attributed to barring of the internal water structure by formation of the seasonal thermocline ([13]). The coolest waters are found to the north, although during summer time, sometimes the islands of Corvo and Flores (Azores) present the highest surface temperatures.

The general SST pattern orientation deduced from SST monthly averages is most represented by an orientation (NW-SE) but in some cases an WNW-ESE orientation is also observed mainly in winter and autumn ([13]).

Seasonal means show highest surface temperatures during summertime in Canaries, while in the Azores these are highest during summer and autumn and in Madeira, during autumn time.

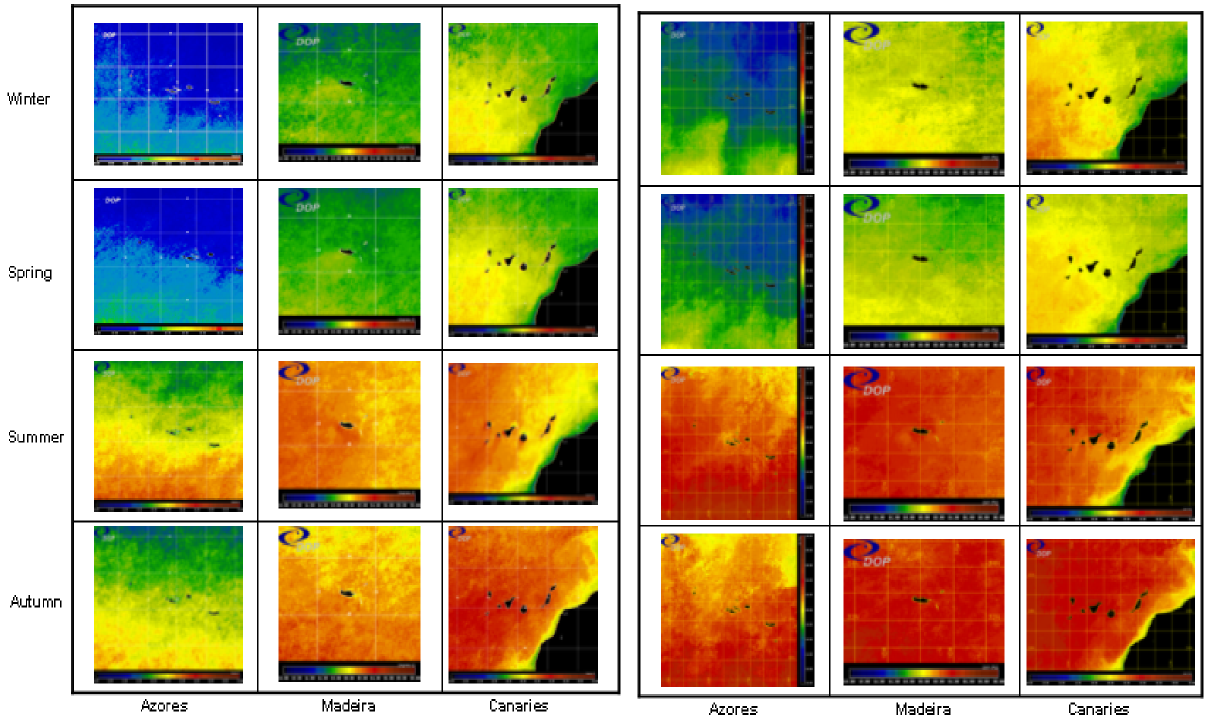



Fig. 11. MODIS SST (left panel) and AVHRR SST (right panel) calculated seasonal medians (in °C) for winter (2002-2003) and spring, summer and autumn (2003) for Azores, Madeira, and Canaries archipelagos regions (see http://oceano.horta.uac.pt/detra/modis/modis_pesquisar.php for other years SST seasonal variability). Threshold values for colour palettes are: 10 to 30 °C for all regions.

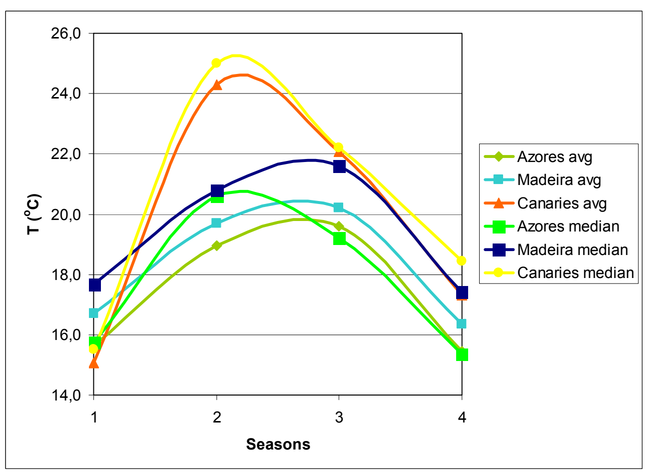



Fig. 12. MODIS SST calculated seasonal averages and medians (in °C) for: 1= spring; 2 = summer; 3= autumn; and 4= winter for the Azores, Madeira, and Canaries archipelagos regions.

### 4.2.2. Ocean Colour

For all three regions and satellites, strong MODIS-OC seasonal patterns are evident (Fig. 13). Increased Chl *a* concentration in the waters is clearly evidenced on the median images, with rich mesoscale variability patterns associated. Interestingly, with the exception of the Azores, which shows the highest seasonal means during springtime, all other regions have highest OC seasonal means during wintertime (Fig. 14). The Azores shows a typical mid-latitude behaviour with pronounced spring phytoplankton bloom patterns. These blooms are mostly trigged by increased light supply and changes in the depth of vertical mixing (i.e. warmer temperatures and increased sunlight, creates a thermocline that traps nutrients at the ocean surface, allowing phytoplankton to absorb energy and take in the nutrients they need to photosynthesize and multiply). During summertime, phytoplankton uses up the available nutrients and begin to die and drift to the bottom. As autumn begins, cooler days cause some vertical mixing that may bring nutrients up from below resulting in a relatively smaller fall bloom. Once winter begins, plummeting temperatures and frequent storms cause heavy mixing. As phytoplankton do not remain at the surface in this mix, they do not have ready access to sunlight, so blooms generally do not occur in the winter ([16]) at these latitudes.

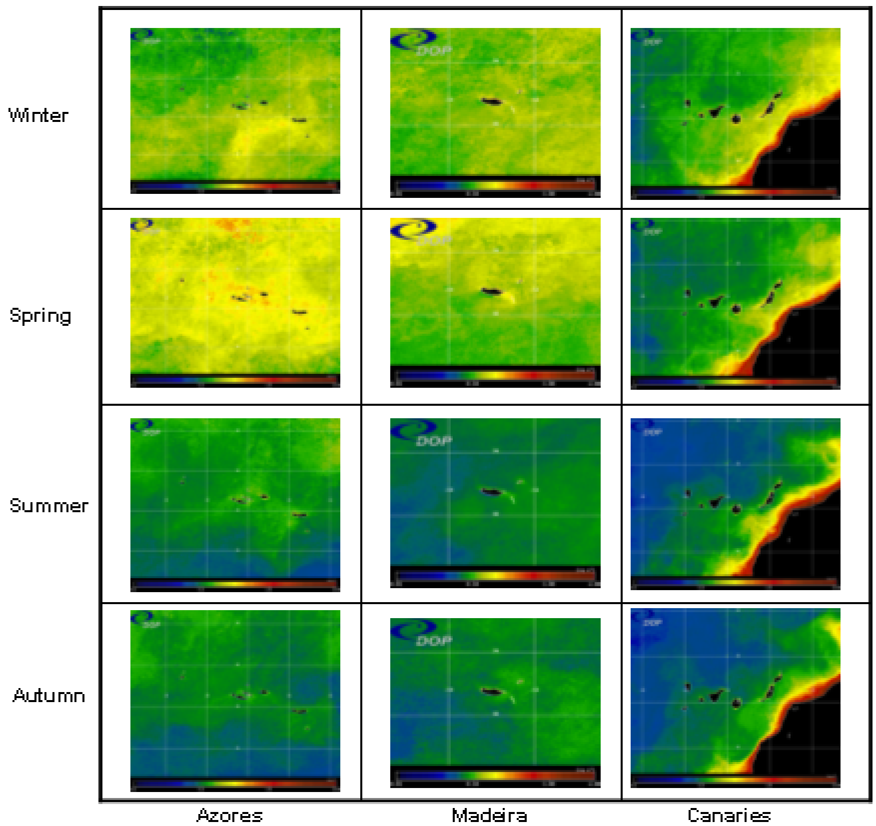



Fig. 13. MODIS OC calculated seasonal medians (in Chl *a* mg m$^{-3}$) for winter (2002-2003) and spring, summer and autumn (2003) for Azores, Madeira, and Canaries archipelagos regions (see http://oceano.horta.uac.pt/detra/modis/modis_pesquisar.php for other years of OC seasonal variability). To improve visualization threshold values for colour palettes are: 0.01 to 10.0 mg m$^{-3}$ for the Azores and Canaries, and 0.01 to 4.0 mg m$^{-3}$ for Madeira.

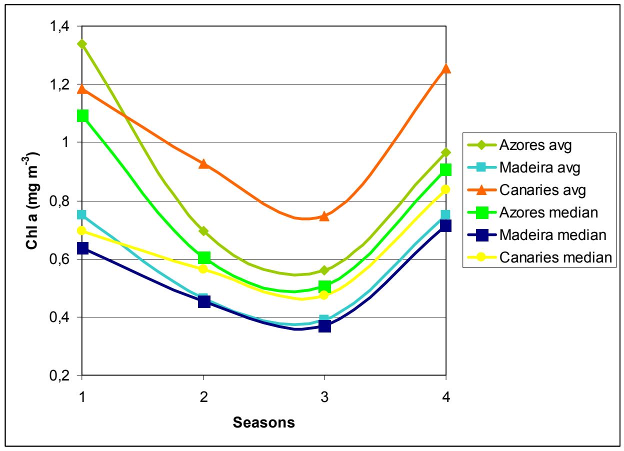



**Fig. 14.** MODIS OC calculated seasonal averages and medians (in Chl *a* mg $m^{-3}$) for: 1= spring; 2 = summer; 3= autumn; and 4= winter for the Azores, Madeira, and Canaries archipelagos regions.

## 5. CONCLUSIONS

Extensive daily analysis of six years of MODIS (OC and SST) and AVHRR (SST) time series monthly and seasonal data allowed, comparison of three groups of islands (Azores, Madeira, and Canarias) located in the NE Atlantic. Results suggest an inverse relationship between surface temperatures and Chl *a* distributions with lower temperature values being associated with regions of increased pigment concentration. Sea surface temperature monthly means suggest distinct inter-annual seasonal cycles with seasonal warming clearly evidenced in all regions initiating during winter-spring and cooling during summer-autumn months. Furthermore, Azores generally reaches maximum SST values faster (i.e. with a time lag of about one month) than Madeira and Canaries which should be related with increased warm water transport in spring-summer across the MAR.

Comparison between different satellites shows clear tendency of MODIS to underestimate about 1 °C the AVHRR-derived SST monthly medians although, monthly curve patterns are quite similar among the two satellites. Furthermore, SST trends in time differ also among MODIS and AVHRR. More studies are required to validate both satellites results comparing these with *in situ* surface temperature data.

The mean chlorophyll *a* general decrease towards southern latitudes results from a gradual transition from more productive colder and fresher Eastern North Atlantic waters to permanently stratified oligotrophic warmer and more saline Subtropical waters, although several exceptions to this rule were observed in the OC mean images (i.e. recurrence of cyclonic and anticyclonic eddies, together with the presence of upwelling filaments throughout the year in Canaries, [4,14]). Interesting is the clear tendency for Canaries OC variability to drop in Feb-Mar, when also have maximum peak in Chl *a* mean values (5-6 times higher during wintertime than the rest of the year, sometimes with a secondary maximum in October). This is most probably related to more stable (and strong) wind-upwelling conditions during late winter which generate high phytoplankton pigment concentration around Canaries ([17]). This high pigment content is reduced in early spring, but still remains visible around the coast of the islands. Also, according to these authors, this secondary maximum is apparently due to spreading of upwelling filaments from south of the Canary Island.

In conclusion, regional inter-annual and seasonal variability are clearly depicted in the OC and SST imagery, providing relevant information to study ocean dynamic variability within the Azores, Madeira, and Canaries regions. However, for a better understanding of regional differences among the surrounding waters of the three archipelagos, the synergistic use of data from various satellite (OC, SST, SSH) and *in situ* data is essential. With this in mind, this study is presently being extended to use all available satellite and *in situ* co-located CTD cruise data for the same regions. This study provides an important insight towards ocean mesoscale variability in the Azores, Madeira, and Canaries regions using OC and SST data.

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## REFERENCES

1. A. M. Martins, P. O. Castellanos, M. Figueiredo, A. Mendonça and L. Macedo, "Implementation of Remote Sensing Techniques in the Azores (DETRA) – Study of Mesoscale Variability and Fisheries Support", *1st Interim Scientific and Financial Progress Report*, IMAR-DOP/UAç, submitted to SRAPA/DRP, Horta, Azores, Portugal, 47 pp., 2001.
2. I. Bashmachnikov, V. Lafon, and A. Martins Sea Surface Temperature Variability in the Subtropical North-East Atlantic, POSTER, *31st International Symposium on Remote Sensing of Environment (ISRSE)*, St.Petersburg, 19-24 June 2005.
3. M. Figueiredo, A. Martins, P. Castellanos, A. Mendonça, L. Macedo, M. Rodrigues, V. Lafon, & N. Goulart, HAZO: a software package for automated AVHRR and SeaWiFS aquisition and processing: Version 1. Interim progress report. Arquivos do DOP, Série Relatórios Internos, 3/2004, 91p, 2004.
4. E.D.1. Barton, J. Aristegui, P. Tett, M. Canton, J. Garca-Braun, S. Hernandez-Leon, L. Nykjaer, C. Almeida, J. Almunia, S. Ballesteros, G. Basterretxea, J. Escanez, L. Garca-Weill, A. Hernandez-Guerra, F. Lopez-Laatzen, R. Molina, M.F. Montero, E. Navarro-Perez, J.M. Rodriguez, K. van Lenning, H. Velez and K. Wild, "The transition zone of the Canary Current upwelling region", *Progress in Oceanography*, Volume 41, Number 4, pp. 455-504(50), 1998.
5. P. Amorim (2007, unpublished)
6. OceanColor Web. 2006. OceanColor level 1/2 browser (http:// oceancolor.gsfc.nasa.gov/cgi/browse.pl) (Daily accessed)
7. JE. O'Reilly, S. Maritorena , D. Siegel, MC. O'Brien, D. Toole, BG. Mitchell, M. Kahru, FP. Chavez, P. Strutton, G. Cota, SB. Hooker, CR. McClain, KL. Carder, F. Muller-Karger, L. Harding, A. Magnuson, D. Phinney, GF. Moore, J. Aiken, KR. Arrigo, R. Letelier and M. Culver M , *Ocean color chlorophyll a algorithms for SeaWiFS, OC2, and OC4: Version 4*. In: Hooker SB Firestone ER (eds) SeaWiFS Postlaunch Technical Report Series, Volume 11, SeaWiFS Postlaunch Calibration and Validation Analyses, Part 3. NASA, Goddard Space Flight Center, Greenbelt, Maryland,p 9-23, 2000.
8. http://oceancolor.gsfc.nasa.gov/PRODUCTS/SST.html
9. E. P. McClain, W. G. Pichel and C. C. Walton, "Comparative performance AVHRR-based multichannel sea sur-face temperatures", *Journal of Geophysical Research*, 90, 11,587-11,601, 1985.
10. A. Martins, I. Bashmachnikov, V. Lafon, A. Mendonça, F. Jose and M. Figueiredo, "Discovering the Azores Current/Front System with SeaWiFS imagery". *In Remote Sensing of the Ocean and Sea Ice*, Proceedings of SPIE Vol. 5569, 156-167, 2004
11. P. Schuessel, H.-Y. Shin, W. Emery and H. Grassl, "Comparison of satellite derived sea suface temperature with in situ skin measurements", *Journal of Geophysical Research*, 92, 2859-2874, 1987.
12. L. Stramma, P. Cornillon, R. A. Weller, J. F. Price and M. G. Briscoe, "Large diurnal sea surface temperature variability : Satellite and in situ measurements", *Journal of Physical Oceanography*, 16, 827-837, 1986.
13. V. Lafon, A. Martins, I. Bashmachnikov, F. José, M. Melo-Rodrigues, M. Figueiredo, A. Mendonça and L. Macedo, "SST variability in the Azores region using AVHRR imagery: regional to local scale study", In *Remote Sensing of the Ocean and Sea Ice,* Proceedings of SPIE vol.5569, p.130-139, 2004.

14. J. Aristegui, P. Tett, A. Hernandez-Guerra, G. Basterretxea, M. F. Montero, K. Wild, P. Sangra, S. Hernandez-Leon, M. Canton, J. A. Garcia-Braun, M. Pacheco and E. D. Barton, "The influence of island-generated eddies on chlorophyll distribution: a study of mesoscale variation around Gran Canaria", *Deep-Sea Research* I, Vol. 44, No. I, pp. 71-96, 1997.
15. R.M.A. Caldeira, S. Groomb, P. Millerb, D. Pilgrim and N.P. Nezlin, "Sea-surface signatures of the island mass effect phenomena around Madeira Island, Northeast Atlantic", Remote Sensing of Environment 80 (2002) 336– 360, 2001.
16. http://serc.carleton.edu/eet/phytoplankton/primer.html
17. M. M. Pacheco A. Hernandez-Guerra, "Seasonal Variability of Recurrent Phytoplankton Pigment Pattern in the Canary Islands Área". *Int. J. Remote Sensing*, vol.20, no. 7, 1405-1418, 1999.
18. R. H. Kase, and G. Siedler, "Meandering of the subtropical front south-east of the Azores". *Nature* 300 (5889): 245-246, 1982.
19. M. L. G. R. Alves and A. C. de Verdière, "Instability dynamics of a subtropical jet and applications to the azores front current system: Eddy-driven mean plow", *Journal of Physical Oceanography*, 29, 837-864, 1999.
20. L. Stramma, P. Cornillon, R. A. Weller, J. F. Price and M. G. Briscoe, "Large diurnal sea surface temperature variability : Satellite and in situ measurements", *Journal of Physical Oceanography*, 16, 827-837, 1986.
21. Maillard and R. Kase, "The near-surface flow in the Subtropical Gyre south of Azores", *Journal of Geophysical Research*, 94, 16133-16140, 1989.
22. D. Efthymiadis, F. Hernandez and P. Y. Le Traon, "Large-scale sea-level variations and associated atmospheric forcing in the subtropical north-east Atlantic Ocean", *Deep-Sea Research Part II*, 49, 3957-3981, 2002.
23. M. Alves, F. Gaillard, M. Sparrow, M., Knoll and S. Giraud, "Circulation patterns and transport of the Azores Front-current system", *Deep Sea Research II*, 49, 3983-4002, 2002.
24. G. T. Csanady, G. T, « The thermohaline driving mechanism of oceanic jet streams. *Journal of Marine Research*, Supplement 40: 113-142, 1982.
25. C. Frankignoul, G. Coetlogon, T. M. Joyce and S. Dong, "Gulf Stream variability and ocean-atmosphere interactions", *Journal of Physical Oceanography* 31: 3516-3528, 2001.
26. W.J. Gould, "Physical oceanography of the Azores front", *Progress in Oceanography*, **14**, 167-190, 1985.
27. T. Mailly, E. Blayo and J. Verron, "Assessment of the ocean circulation in the Azores region as predicted by numerical model assimilating altimeter data from Topex/Poseidon and ERS-1 satellites", *Annales Geophysicae* 15: 1354-1368, 1987.
28. R. T. Pollard and S. Pu, "Structure and Circulation of the upper Atlantic ocean Northeast of the Azores", Pro-gress in Oceanography, 14, 443-462, 1985.
29. L. Stramma and G. Siedler, "Seasonal changes in the North Atlantic subtropical gyre", *Journal of Geophysical Research* 93 (C7): 8111-8118, 1988
30. M. Tomczack, and J. S. Godfrey, 2001. "Regional Oceanography: An introduction". Available from: http://www.es.flinders.edu.au/~mattom/regoc/pdfversion.html. Last accessed June 28, 2007.