Climatology of Oceanic Zones Suitable for In-flight Calibration of Space Sensors

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ABSTRACT

One way to calibrate space sensors on the visible part of the spectrum is to use acquisitions over Rayleigh scattering for dark surface conditions. Oceanic sites are good candidates because of their behaviour in term of spatial homogeneity and temporal stability. An appropriate selection is consequently required to identify the best oceanic areas. Nevertheless, the knowledge of the surface reflectance of such sites remains a limitation while their stability (and/or homogeneity) is usually not perfect. A previous study (Fougnie et al., 2002) has defined a selection of oceanic sites using one year of SeaWiFS data and regarding their spatial homogeneity and temporal stability. A first characterization of their monthly surface reflectances was derived (seasonal cycle) and used for several years as input for in-flight calibration processes. The major oligotrophic sites are located in North/South Atlantic and Pacific oceans, in Indian ocean, and in the Mediterranean Sea while some other mesotrophic sites were also defined for example in the Gulf of Mexico or Yucatan strait. The goal of this study was to revisit the definition of these sites regarding their spatial homogeneity and to analyze the annual cycle over 9 years of L3B R-2009 SeaWiFS products. Site behaviours are accurately defined with these longer time series, hence new recommendations are drawn for all sites and an updated climatology is proposed to be used for future in-flight calibrations.

Keywords: Climatology, oceanic sites, calibration, marine reflectance

INTRODUCTION

In-flight calibration of space sensors is required, once in-orbit, in order to verify the prelaunch estimation and usually to adjust it. Several techniques are used to process this in-flight characterization. Among them, on-board calibration devices, when available, provide a good knowledge of all or any part of the calibration. Through this, temporal monitoring, interband calibration or evolution of the radiometric sensitivity inside the field-of-view are possible. Nevertheless, an absolute calibration is always required to complement the final scientific objectives. To address this, calibration methods using natural targets were developed (examples in [3] and [4]).

Calibration over Rayleigh scattering ([2], [3], [4]) is an appropriate way to perform an absolute calibration of spectral bands located on the blue part of the spectrum (in fact from the blue to the red). In such a method, space measurements are selected through various geometrical and radiometric criteria over oceanic sites. The method is based on the fact that, for clear and non turbid atmospheric conditions, the scattering by molecules (i.e. the Rayleigh scattering) represents the major part of the observed light and is in addition accurately predictable. The dark oceanic surface located under the atmospheric layer is in this approach convenient because it contributes to maximize the atmospheric contribution to the top of atmosphere signal.

Nevertheless, the oceanic surface is not black in the blue part of the spectrum and, in a statistical approach, (i.e. with no in-situ measurements) hypothesis have to be considered. Because the oceanic contribution represents a few to 10% of the top of atmosphere signal, it has to be predicted with a good accuracy.

An other calibration method, based on sunglint observations over oceanic sites, performs an interband calibration of a large set of spectral bands ([3], [4]). For bands on the visible part of the spectrum, the oceanic reflectance is non negligible and has also to be predicted as much as possible.

In order to facilitate this prediction, it is preferable to select measurements over oceanic sites that are known to be spatially homogeneous, and associated with a small or limited seasonal variation. Such oceanic conditions were identified on a previous climatologic study [1] based on one year of SeaWiFS data. The goal of this paper is to make a

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review of this first climatology, to reappraise the good quality of sites that are operationally used on calibration, to identify new candidate sites, and to optimize the recommendation for the best sites based on a inter-annual analysis.

FIRST HISTORICAL CLIMATOLOGY

We briefly remind in this section the methodology and results obtained on a first climatology build on a previous study described in Fougnie et al. [1] and from which a list of oceanic sites are operationally used for calibration.

One year of SeaWiFS data (year 1999, level-3 Version 3.0, binned data product with 9km resolution,) was used to derive a statistic over the global ocean divided by elementary spatial bins. Statistics were based on monthly absolute and relative variations of the pigment concentration. These bins were agglomerated when statistic were similar to define larger oceanic areas. Some additional sites were added to the climatology but with a more experimental goal.

The resulting selection is reported in Table 1. and Figure 1 [1]. Six main oceanic sites, corresponding to "oceanic deserts" are operationally used for calibration. These sites are divided into several sub-areas or fusion when it is necessary. This means that the homogeneity was guaranteed at the elementary fusion level, but not necessarily at the larger oceanic site level. Some interesting characteristics were identified for other experimental sites as if they are not operationally used for calibration.

Most of the operational sites were characterized by a moderated seasonal variation of marine reflectances, except for the Northern Pacific for which the seasonal effect appeared to be very limited. These seasonal variations were reported on a look-up-table including monthly marine reflectances for each fusion and oceanic site and which is used as input in the calibration processing.

After many years of calibration activities based on this climatology, some limitations were reported. If the global efficiency of this climatology is obvious ([1] and [3]), some discrepancies were observed for some period in the year, or for some fusions of a given sites. This evidenced the need to reappraise the homogeneity of sites and/or to improve the characterization of marine reflectances made using the year 1999, by enlarging the statistic to several years.

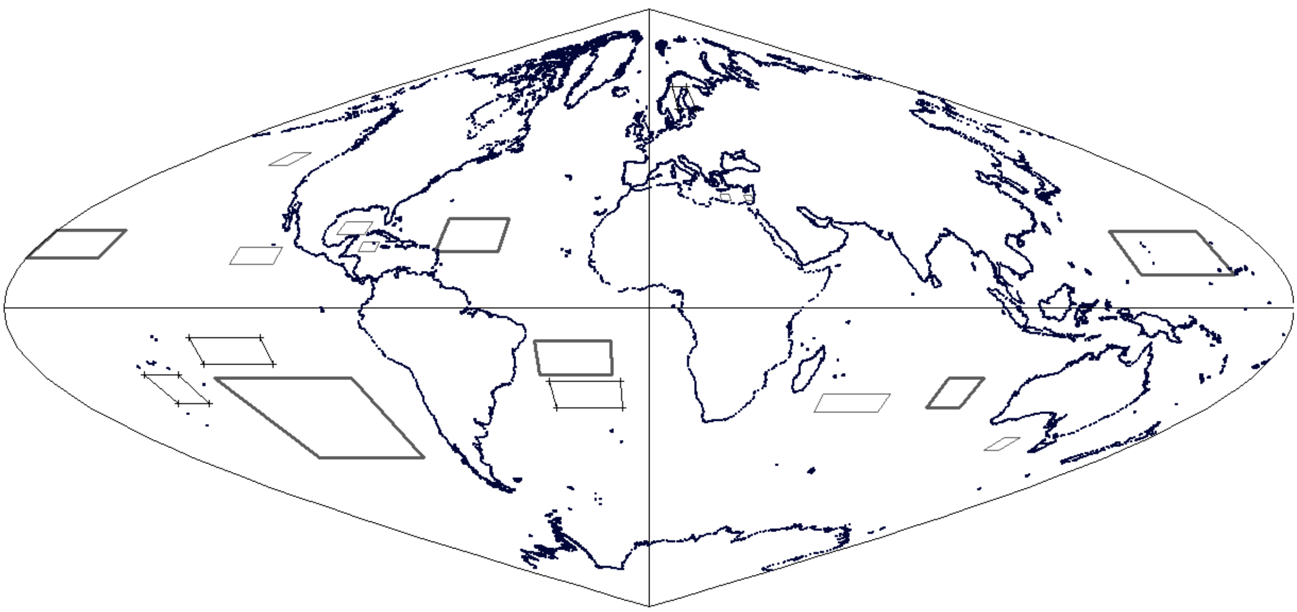

Figure 1. Location of oceanic sites : operational sites (bold line), experimental sites (plain line) both from Fougnie et al. [1], and 4 new sites proposed in this study (+ symbols and plain line)

n°	Name	Location	Sub-areas	Latitude min	Latitude max	Longitude min	Longitude max
	Operationally used oceanic sites						
0	PacSE	South-East of Pacific	8	-44.9	-20.7	-130.2	-89.0
1	PacNW	North-West of Pacific	4	10.0	22.7	139.5	165.6
2	PacN	North of Pacific	3	15.0	23.5	179.4	200.6
3	AtlN	North of Atlantic	3	17.0	27.0	-62.5	-44.2
4	AtlS	South of Atlantic	5	-19.9	-9.9	-32.3	-11.0
5	IndS	South of Indian	1	-29.9	-21.2	89.5	100.1
	Experimental oceanic sites						
6	GuMex	Gulf of Mexico	1	22.0	25.9	-94.1	-85.9
7	GuYuc	Yucatan Strait	1	17.0	19.9	-85.0	-80.0
8	DoCoRi	Costa Rica Dome	1	13.0	18.3	-120.2	-107.8
9	MedCr	Mediterranean South Crete	1	32.5	34.4	23.9	26.9
10	MedCy	Mediterranean South Cyprus	1	32.5	33.9	31.9	34.3
11	GuAlas	Gulf of Alaska	1	43.0	46.9	-145.2	-137.9
12	Hawaii	Hawaii near MOBY	1	18.0	19.9	-158.5	-156.5
13	AustS	South Australia	1	-42.9	-39.0	127.3	133.0
14	MadE	East of Madagascar	4	-31.4	-25.8	53.9	74.7
	New tested oceanic sites						
15	BothS	Bothnia Sea	2	60.0	66.5	16.0	26.0
16	PacTropS	South Tropical Pacific	2	-28.8	-20.0	-150.0	-140.0
17	PacEqS	South Equatorial Pacific	3	-17.0	-9.0	-130.0	-110.0
18	AtlSE	South-East of Atlantic	5	-30.0	-22.0	-30.0	-8.5

Table 1. Definition of operational and experimental oceanic sites, from n° 0 to 14, fully described in Fougnie et al. [1], including the number of sub-areas (or fusion) for each site. The 4 new candidate sites analyzed in this study are reported as "new tested oceanic sites", n° 15 to 18.

METHODOLOGY

In this revision of the climatology, the basic idea is to extend the analysis to several seasonal cycles in order to evaluate the inter-annual fluctuations that may cause biases on the calibration processing. The analysis is extended to years 1999 to 2007, i.e. a 9-years archive. It was not planned to re-evaluate the spatial homogeneity of all fusions and oceanic sites defined in [1]. Consequently, sites were considered as reported in Table 1.

SeaWiFS data used to produce the first climatology were Version 3.0 level-3 products. This new climatology was based on updated SeaWiFS products from the recent reprocessing R2009. A first question was to verify if there is a gap between results elaborated from these 2 versions of SeaWiFS products. Some comparisons are reported in Figure 2 for year 1999, for 3 typical oceanic sites in the northern hemisphere and 3 typical sites in the southern hemisphere. The comparison is provided for marine reflectances at 443 and 555nm. For most of the cases, a small bias of a few percents appears between V4.0 and R2009. This bias is a direct consequence of a small readjustment of calibration coefficients for SeaWiFS. Nevertheless, it is noticed that for the South Pacific site (Fig. 2a), a modification of the seasonal effect is observed at 443nm in addition to the previous bias. It changes not only the month for which the marine reflectance is minimum, but also the value of the minimum.

Statistics were build for all SeaWiFS wavelengths for which the marine reflectance is provided, i.e. bands 412 to 670nm. For every months of the year and for all fusions and sites, the mean marine reflectance was computed, in addition to absolute and relative standard deviation. In addition, statistics were also computed for the surface pigment concentration.

Some new sites were added. First, based on the analysis of the marine reflectance time series over 9 years, 3 oceanic sites were defined as potential good candidates (see Table 1). An homogenous and possibly stable site, called PacTropS, was defined west to the previously defined PacSE site, at the tropic level on the south Pacific. For the same reasons, a site called AtlSE was defined south to the previously defined AtlS, on the south Atlantic. A more mesotrophic site, called PacEqS, was identified close to the equatorial Pacific and associated with an apparent very stable behavior. Finally, an experimental site was defined on the Bothnia Sea. This site, corresponding to a very high latitude of 60°N, is known to be a “dark” site on the blue part of the spectrum which could be an ideal case for calibration of blue spectral bands. The objective was to characterize such a site.

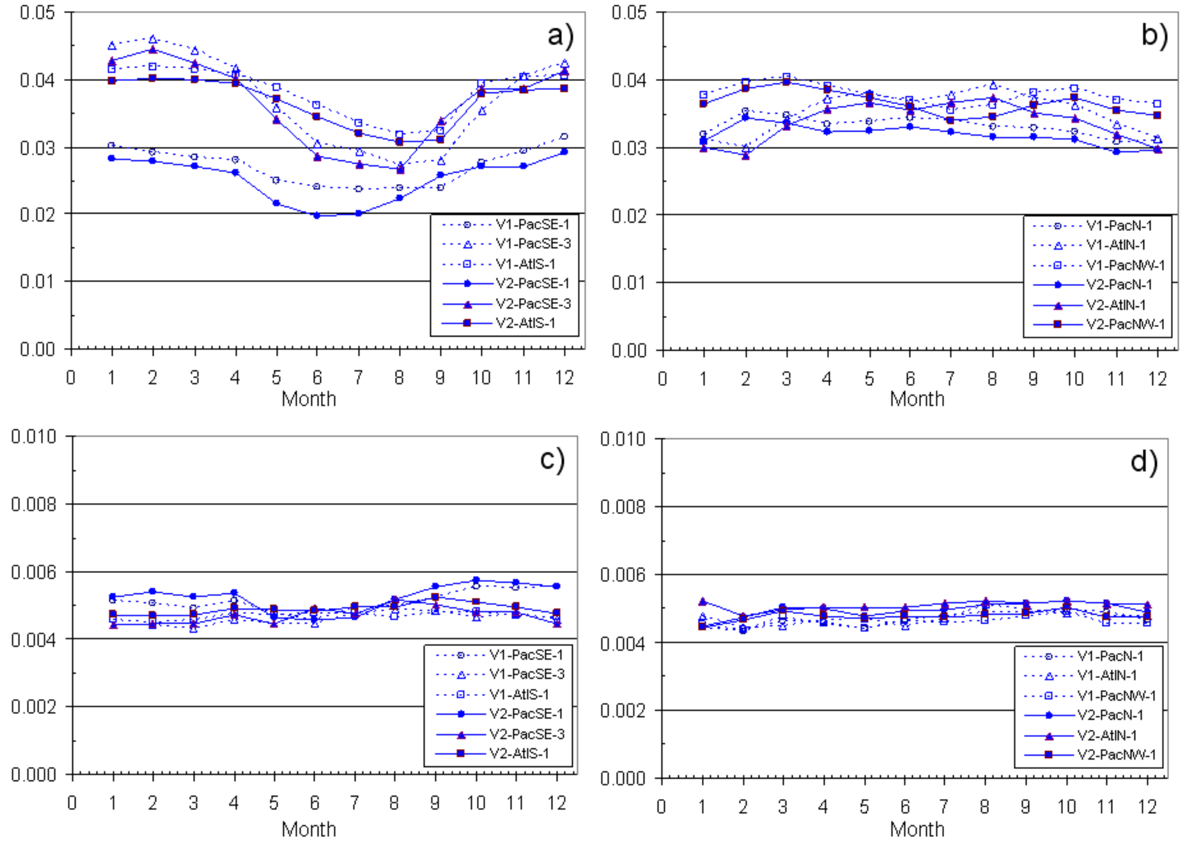

Figure 2. Comparison between the 1999 annual behavior derived from SeaWiFS reprocessing V4.0 [1] and updated in this paper using the SeaWiFS reprocessing R2009. The comparison is provided for 3 oceanic sites in the southern hemisphere ((a) and (c)), and in the northern hemisphere ((b) and (d)) and for marine reflectance at 443nm (upper figures (a) and (b)) and 555nm (bottom figures (c) and (d)).

RESULTS

A complete statistic was produced for all defined oceanic sites. But it is not possible to report all the results in this paper. After a description of typical temporal profiles, we decided to report results for new candidate sites and operational oceanic sites (because of possible impact on operational calibrations).

Analysis of typical temporal profiles

We first examine typical seasonal and inter-annual variations and how they can be correlated or not depending on the site. Figures 3 report the fluctuation of marine reflectance at 443nm for 6 different fusions or sites. Figures 3 illustrate both seasonal variations for one given year (so 12 months), and inter-annual fluctuations for 9 years. The following behavior are observed :

- Fig. 3a) is an example of site for which a strong seasonal effect exists, but for which this seasonal effect seems nicely reproducible year after year. Such a site is a good candidate for calibration because the climatology will be robust;
- Fig. 3b) is an example of site for which a strong seasonal effect exists, but for which this seasonal variation is sometimes strongly variable year after year. Such a site is not fully appropriate for the calibration purposes

because it is difficult to build a representative climatology, except for a few months in the year that have to be identified (here from January to May);

- Fig. 3c) is an example of site with a moderate seasonal effect, but for which 6 or 7 months in the year are very reproducible year after year while the rest of the year is strongly variable. For such a site, the recommendation will be to limit the use of the site to a restricted number of months in the year, period for which the climatology will be robust;
- Fig. 3d) is an example of site for which the seasonal effect is moderated, for which no real variability is observed year after year, but for which the standard deviation is increasing strongly for half of the year. For such a site, the conclusion is to restrict the use of the site to a limited period in the year;
- Fig. 3e) is an example of a site with no seasonal effect but for which it is observed a strong variation year after year. The use of such a site for calibration purposes seems risky;
- Fig. 3f) is an example of site for which there is no seasonal effect over the year and for which the variation year after year is very small. This site is very appropriate for calibration purposes all the year and the climatology will be robust.

Overview of profiles for operational oceanic sites

- PacSE, site n°0 in Table 1 : For the South-East Pacific site, 3 different signatures are observed which mainly depend on the latitude. The southern part of the site (fusion 0, 1, and 2) shows a moderate seasonal effect while a good consistency is observed every year (Fig. 5). For the central part of the site (fusions 3, 4, 5), the seasonal effect becomes more sensible. Consequently, the consistency between the different years is lost for several months. These fusions appear to be suitable for calibration from June to September. The northern part of the site (fusions 6 and 7, Fig. 5 and 3a)) behaves large seasonal effects which imply a degradation of the inter-annual consistency. In conclusion, this northern part is not fully suitable for calibration (or just limited to a short period, from February to May).

- PacNW, site n°1 in Table 1 : Globally, this site shows a very small seasonal effect (Fig. 3 and 4). The best part of the site is the south-east fusion 1 for which it is observed a very small seasonal effect and an inter-annual consistency (Fig. 4). If the seasonal effect remains small for fusions 0 and 2, some fluctuations are observed for the inter-annual consistency (Fig. 3f). The northern part of the site, fusion 3 in Fig. 4, shows a more pronounced seasonal effect leading to inter-annual variation the second part of the year. This northern part is recommended for calibration from January to June.

- Pac N, site n°2 in Table 1 : This site shows for each fusion a very small seasonal effect confirmed for each year. A better consistency is observed on fusion 2 (Fig. 4). This site remains a very good candidate for calibration.

- AtlN, site n°3 in Table 1 : The northern part of the site behaves better. The fusion 1 shows a moderate seasonal effect while a very good inter-annual consistency is observed (Fig. 4). Fusion 2 is more variable but remains comparable to fusion 1. Larger inter-annual fluctuations are observed for the southern part, fusion 0 in Fig. 4, limiting the interest of this fusion to the period November April.

- AtlS, site n°4 in Table 1: All fusions of the site show a similar profile. A seasonal effect is observed with inter-annual consistency from November to July, but sensible inter-annual variations for the rest of the year. The central part of the site, fusion 1, shows very good properties at least for half of the year (Fig. 5).

- IndS, site n°5 in Table 1 : the moderate seasonal effect is confirmed every year but with some small variations (Fig 5). Nevertheless, the general profiles remains acceptable for calibration purposes.

Overview of profiles for new candidate oceanic sites

- BothS, site n°15 in Table 1 : This site, extreme in term of latitude (more than 60°), is not reachable all the year. The “black” properties for the blue part of the spectrum is clear with marine reflectance less than 0.003 during several months (Fig. 6). Such values have to be considered carefully because of the extreme airmass conditions associated with the SeaWiFS observation and the corresponding atmospheric correction efficiency. Nevertheless, such a site appears to be a good candidate, for calibration of blue bands only, during April to September.

- PacTropS, site n°16 in Table 1: The northern part of the site, fusion 1, shows a small seasonal effect and a moderate inter-annual variation. The southern part of the site, fusion 0, shows a larger seasonal effect, but a better consistency for the first half of the year limiting the use of this sub-area to this period of the year.

- PacEqS, site n°17 in Table 1: The general profile of the site is the absence of seasonal effect, but a more or less sensible inter-annual fluctuation (Fig. 6). The northern part of the site, fusions 1 and 2, is more suitable for calibration because of a limited inter-annual variation while the southern part, fusion 0, is more largely fluctuant and finally feels risky for calibration.

- AtlSE, site n°18 in Table 1: a clear seasonal effect is present for all the sites. The western part of the site, fusions 0 and 2, are perturbed by inter-annual variation. These fusions are not suitable for calibration. The other part, fusions 1, 3, and 4, is suitable for calibration at least from November to June, while the rest of the year is more inter-annually variable.

n°	Name	Fusion	Seasonality	Typical Chl (mg.m^{3})	Water type	Best recommended period	Comment
0	PacSE	1	moderate	0.08-0.11	oligo.	year	best sub-area
		0, 2	moderate	0.05-0.12	oligo.	June to Sep.	
		3, 4, 5	sensible	0.02-0.12	ultra oligo.	June to Sep.	
		6, 7	strong	0.02-0.12	ultra oligo.	Feb. to May	
1	PacNW	0	very small	0.03	oligo.	May to Aug.	
		1, 2	very small	0.03	oligo.	year	best sub-area
		3	moderate	0.04	oligo.	Jan. to June	
2	PacN	0, 1	very small	0.05	oligo.	year	
		2	very small	0.06	oligo.	year	best sub-area
3	AtlN	0	sensible	0.05-0.30	oligo.	Nov. to Apr.	
		1, 2	sensible	0.05	oligo.	year	best sub-area
4	AtlS	0, 1, 2, 3	moderate	0.03-0.08	oligo.	Nov. to July	best sub-area
		4	sensible	0.04-0.13	oligo.	Feb. to July	
5	IndS		moderate	0.03-0.09	oligo.	year	
6	GuMex		sensible	0.10-0.20	meso.	year	
7	GuYuc		sensible	0.08-0.13	meso.	Dec. to May, Sep.	
8	DoCoRi		sensible	0.08-0.17	meso.	Oct. to Mar.	
9	MedCr		strong	0.06-0.14	oligo.	year	
10	MedCy		strong	0.05-0.18	oligo.	year	
11	GuAlas		strong	0.26-0.43	meso.	Dec. to May	
12	Hawaii		very small	0.06	oligo.	year	
13	AustE		moderate	0.16-0.43	meso.	June to Nov.	
14	MadE	0, 1, 2, 3	sensible	0.03-0.10	oligo.	July to Dec.	
15	BothS	0	moderate	5.0-10.0	eutrop.	Apr. to Sep.	best sub-area
		1	small	4.0-16.0	eutrop.	June to Sep.	
16	PacTropS	0	moderate	0.03	oligo.	Dec. to June	best sub-area
		1	small	0.03	oligo.	year	
17	PacEqS	0	very small	0.09-0.12	meso.	no	
		1, 2	very small	0.10	meso.	year	best sub-area
18	AtlSE	0, 2	sensible	0.04-0.07	oligo.	no	
		1, 3, 4	sensible	0.03-0.08	oligo.	Nov. to June	best sub-area

Table 2. Summary table reporting the re-evaluation of the suitability for calibration purposes of all operational sites, experimental sites, and new candidate sites. For each site and/or each group of similar fusions inside a site, are reported the profile of seasonality, the typical variation of pigment surface concentration (from the SeaWiFS Level-3 estimation), and the water type. The best period of the year is recommended for calibration purpose regarding inter-annual consistency of marine reflectance over the 9-years, i.e. regarding the confidence on the climatology.

CONCLUSION

Main conclusions are drawn on Table 2 where a summary of profile and typical oceanic conditions are reported. A recommendation is given in term of best sub-area for large oceanic sites, and best period to consider regarding inter-annual consistency of marine reflectance over the 9-years archive.

Look-up tables were derived from this new updated climatology and will be incorporated into operational calibration processing. Prior to this final application, a validation step has to be conducted in order to confirm the suitability and recommendation through improvement observed on large calibration matchups over various years and geographic conditions.

ACKNOWLEDGEMENT

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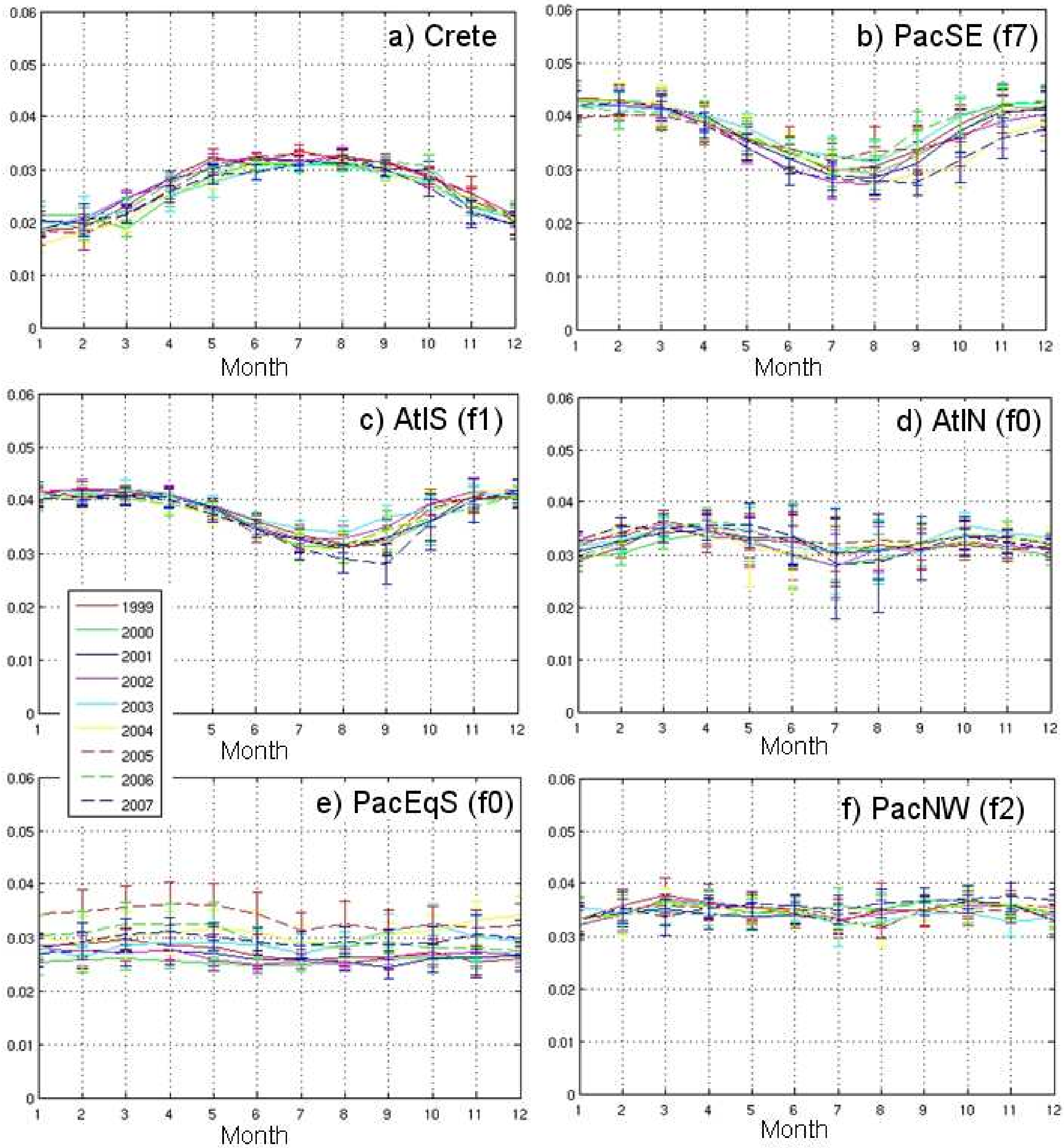

Figure 3. Typical inter-annual behavior for marine reflectance at 443nm for 6 different oceanic sites (or fusion for a given site). Each monthly mean value and its standard deviation is reported for years 1999 to 2007. Sites reported from (a) to (f) are defined in Table 1, while fusions are defined in [1].

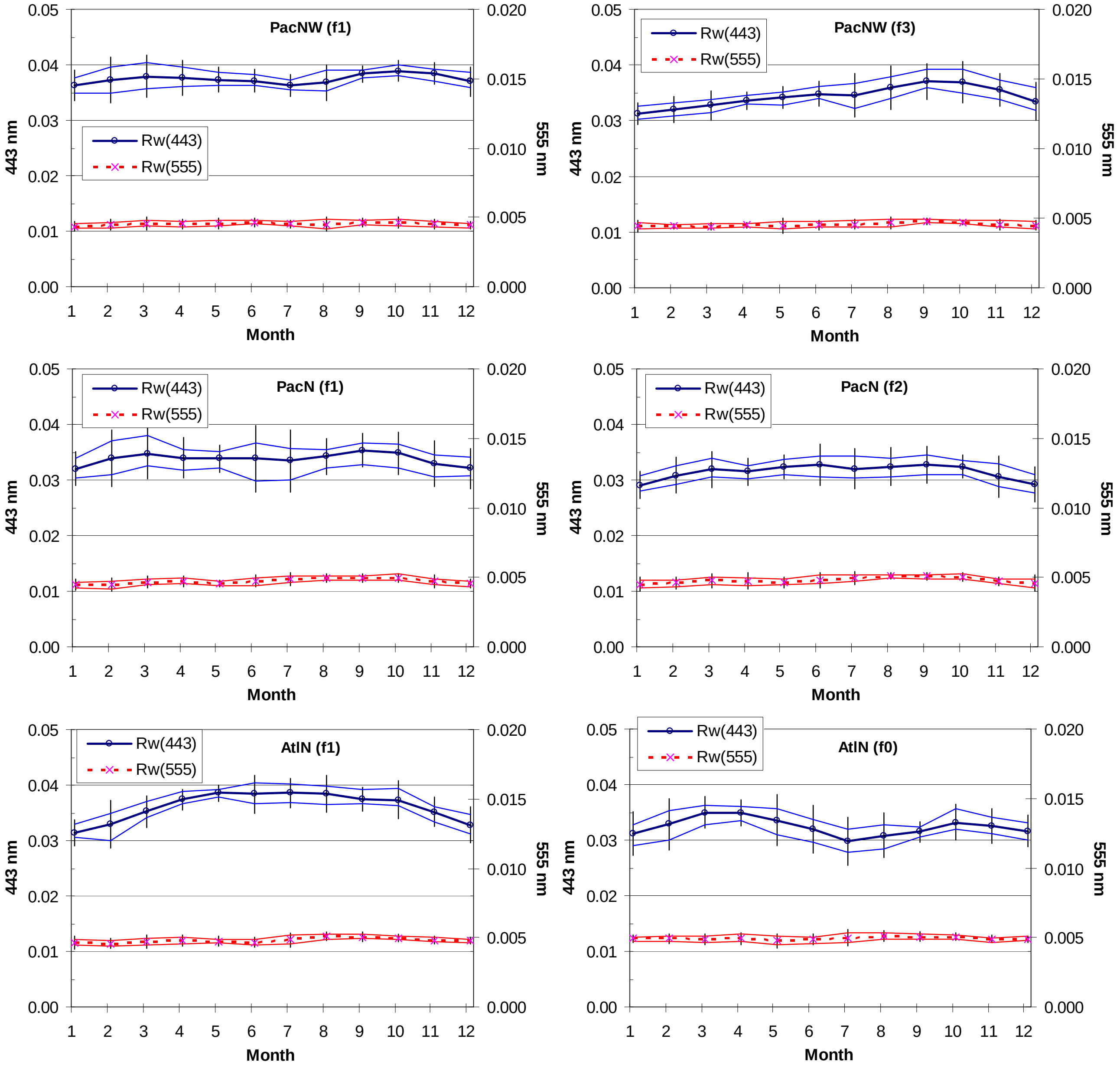

Figure 4. Seasonal effect of marine reflectances at 443nm (left axis) and 555nm (right axis) for 6 fusions or sites of the northern hemisphere among operationally used sites defined in Table 1. Bold plain line (443) and bold dashed line (555) are mean value computed over the 9 years archive (from 1999 to 2007) for the considered month. Error bars are 3 times the associated standard deviation (equivalent to 99% of the samples for a Gaussian distribution). Plain lines above and under the bold plain line are the minimum and maximum of monthly means computed for each of the 9 years.

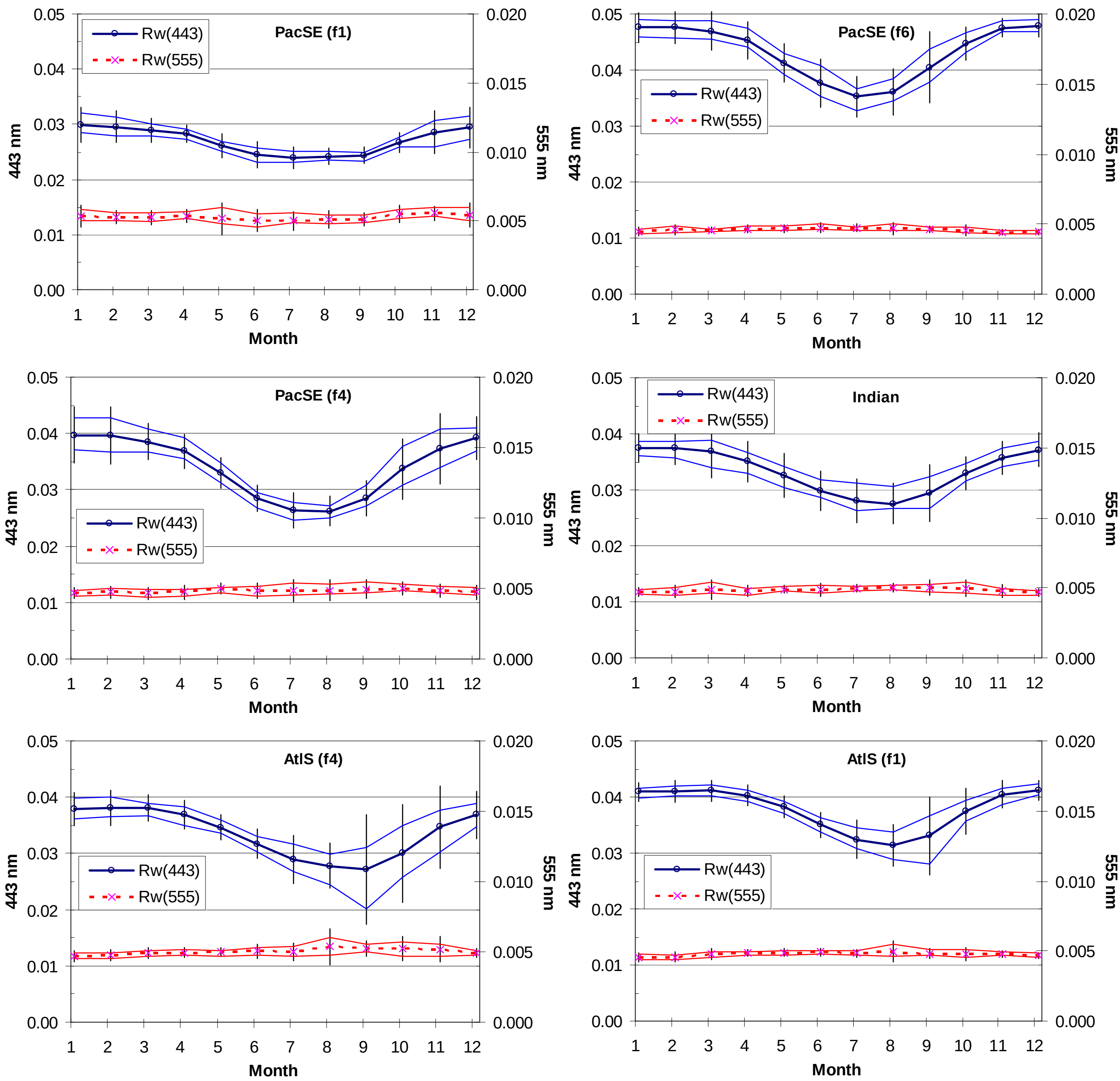

Figure 5. Seasonal effect of marine reflectances at 443nm (left axis) and 555nm (right axis) for 6 fusions or sites of the southern hemisphere among operationally used sites defined in Table1. Bold plain line (443) and bold dashed line (555) are mean value computed over the 9 years archive (from 1999 to 2007) for the considered month. Error bars are 3 times the associated standard deviation (equivalent to 99% of the samples for a Gaussian distribution). Plain lines above and under the bold plain line are the minimum and maximum of monthly means computed for each of the 9 years.

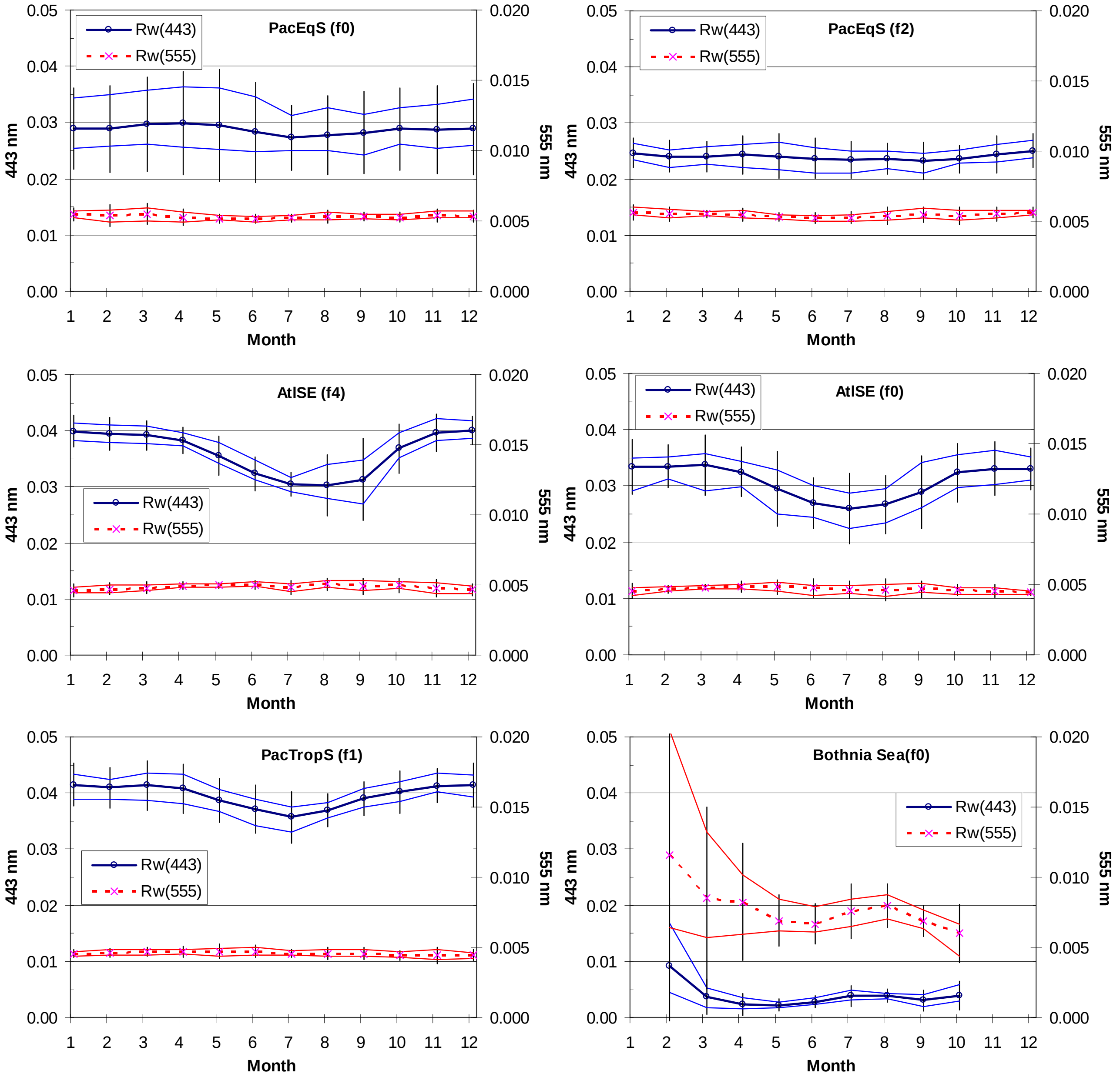

Figure 6. Seasonal effect of marine reflectances at 443nm (left axis) and 555nm (right axis) for 6 fusions or sites among new candidate sites defined in Table1. Bold plain line (443) and bold dashed line (555) are mean value computed over the 9 years archive (from 1999 to 2007) for the considered month. Error bars are 3 times the associated standard deviation (equivalent to 99% of the samples for a Gaussian distribution). Plain lines above and under the bold plain line are the minimum and maximum of monthly means computed for each of the 9 years.