In search of long-term trends in the ocean colour record

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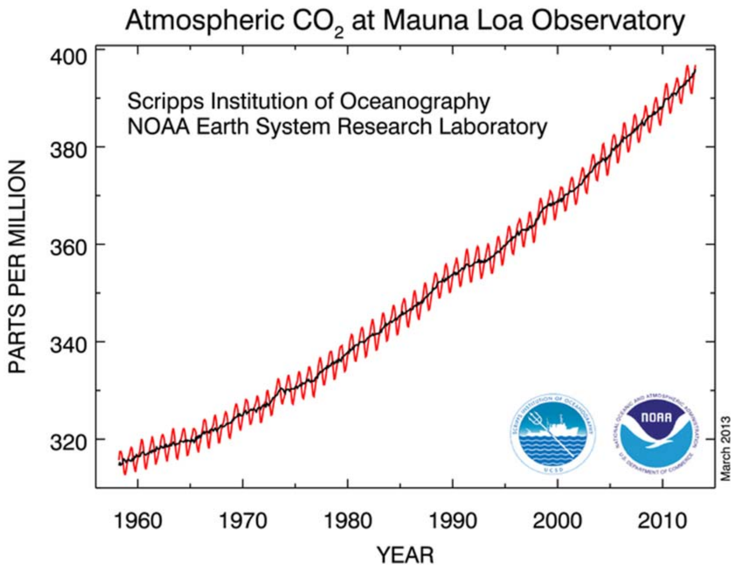
Change is the air…



www.esrl.noaa.gov/gmd/ccgg/trends

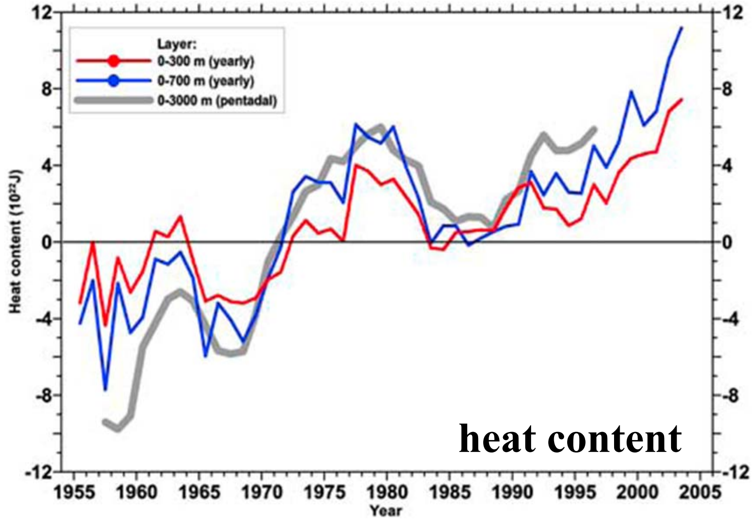
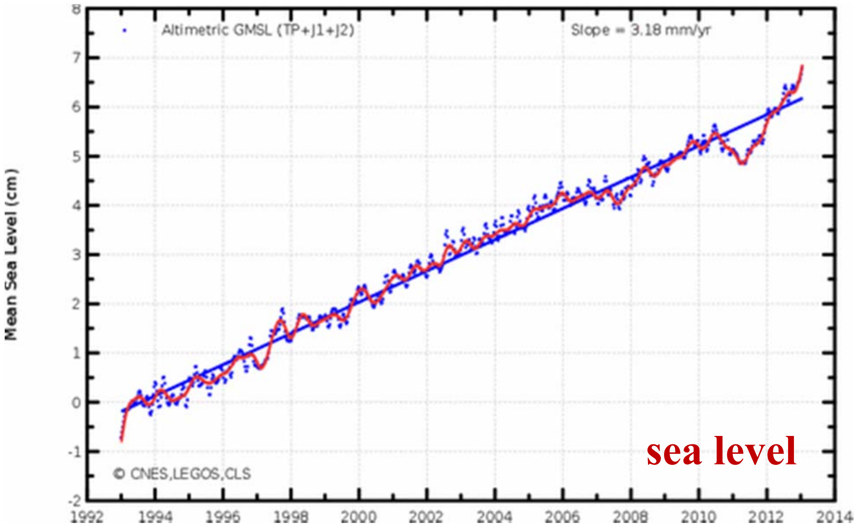
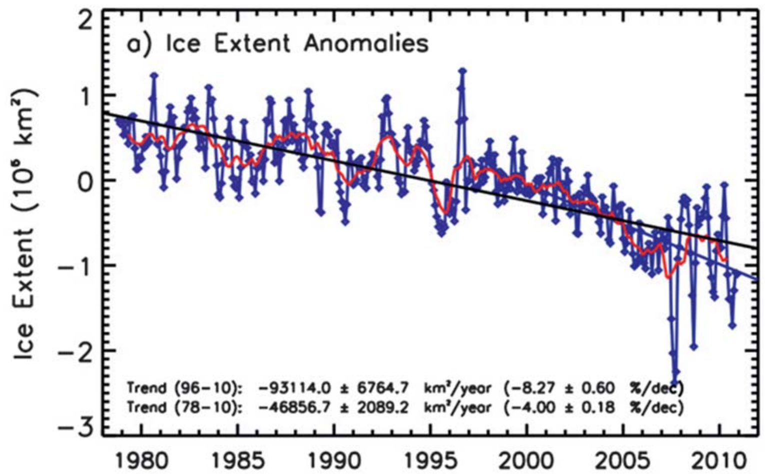


Figure 1. Time series of yearly ocean heat content (10^{22} J) for the 0 300 and 0 700 m layers and pentadal (5-year running composites for 1955 59 through 1994 98) ocean heat content (10^{22} J) for the 0 3000 m layer. Each yearly estimate is plotted at the midpoint of the year; each pentadal estimate is plotted at the midpoint of the 5-year period.

Levitus et al., *GRL* 2005





http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/

Comiso, *J. Clim.* 2012

Ocean Color Essential Climate Variables (ECVs): GCOS 2011

- Water leaving radiance / Remote sensing reflectance (R_{RS})
- Chlorophyll-a concentration (Chl*a*)

Objective:
for these ECVs, creation of Climate Data Records (CDRs) possessing "a sufficient length, consistency, and continuity to determine climate variability and change". NRC, 2004

Length: relevant for climate time scales (referred to as "long-term") need for multiple decades of data (>~50 years) Bopp et al., *GBC* 2001; Henson et al., *BGS* 2010; Yoder et al., *AOS* 2010

→ ensuring a continuous suite of satellite missions (5-10 years) while achieving a shift from a mission-centric to a variable-centric view

→ implies a high level of consistency in the different series associated with various missions

Products from different satellite missions should:
- have similar levels of uncertainties
- represent similar phenomena / processes (e.g., spatial & temporal variability)
- be quantitatively close to each other

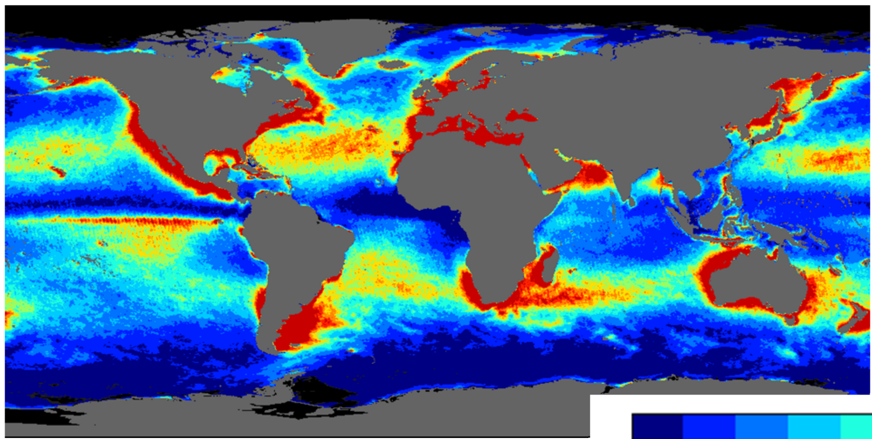
Remote Sensing Reflectance

SeaWiFS, MERIS and MODIS-A
Remote Sensing Reflectance $R_{RS}(\lambda)$ binned data (SeaDAS 6)
band-shifted (SeaWiFS bands)

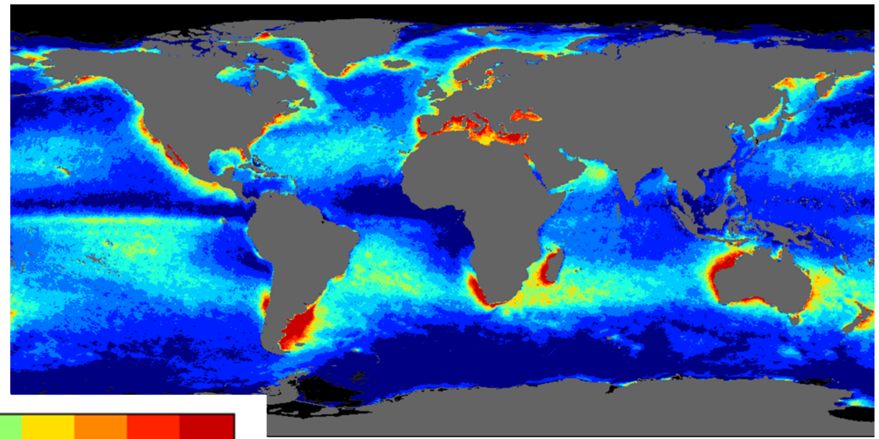
Sclep & Mélin, in prep.

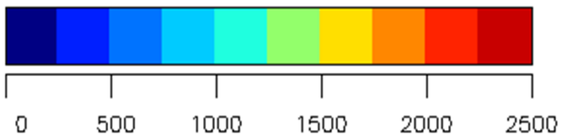
accumulates daily common R_{RS} ($1/12^{th}$ deg.)

SeaWiFS / MODIS-A



SeaWiFS / MERIS





Total number of match-ups

$1/3^{rd}$ deg. res
2003-2007

Inter-Comparison Analysis

SeaWiFS $(y_i)_{i=1,N}$ versus MODIS-A $(x_i)_{i=1,N}$ / MERIS $(x_i)_{i=1,N}$

mean relative difference
(relative bias)

$$\psi = \sum_{i=1}^{N} \frac{2(y_i - x_i)}{x_i + y_i}$$

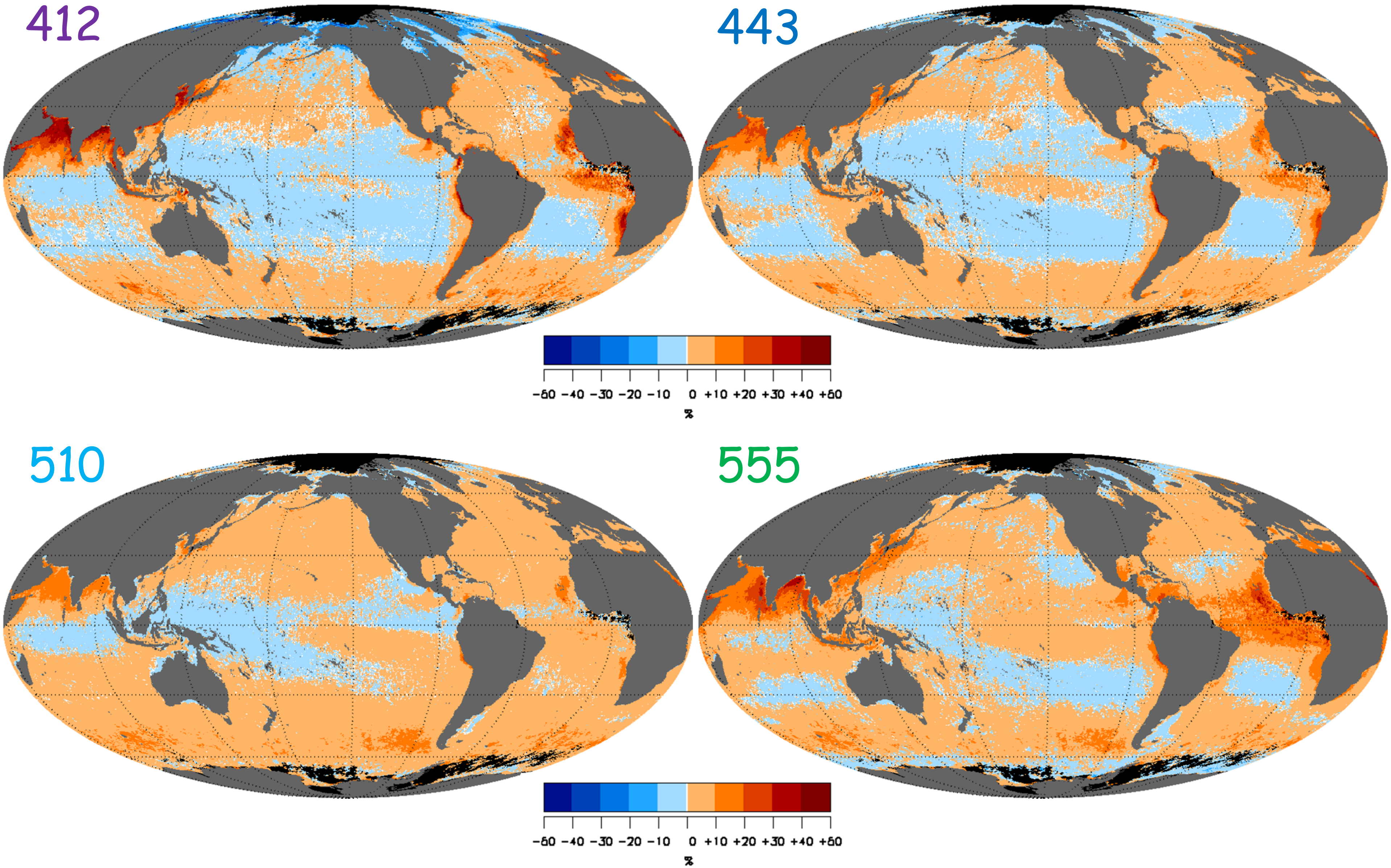
[%]

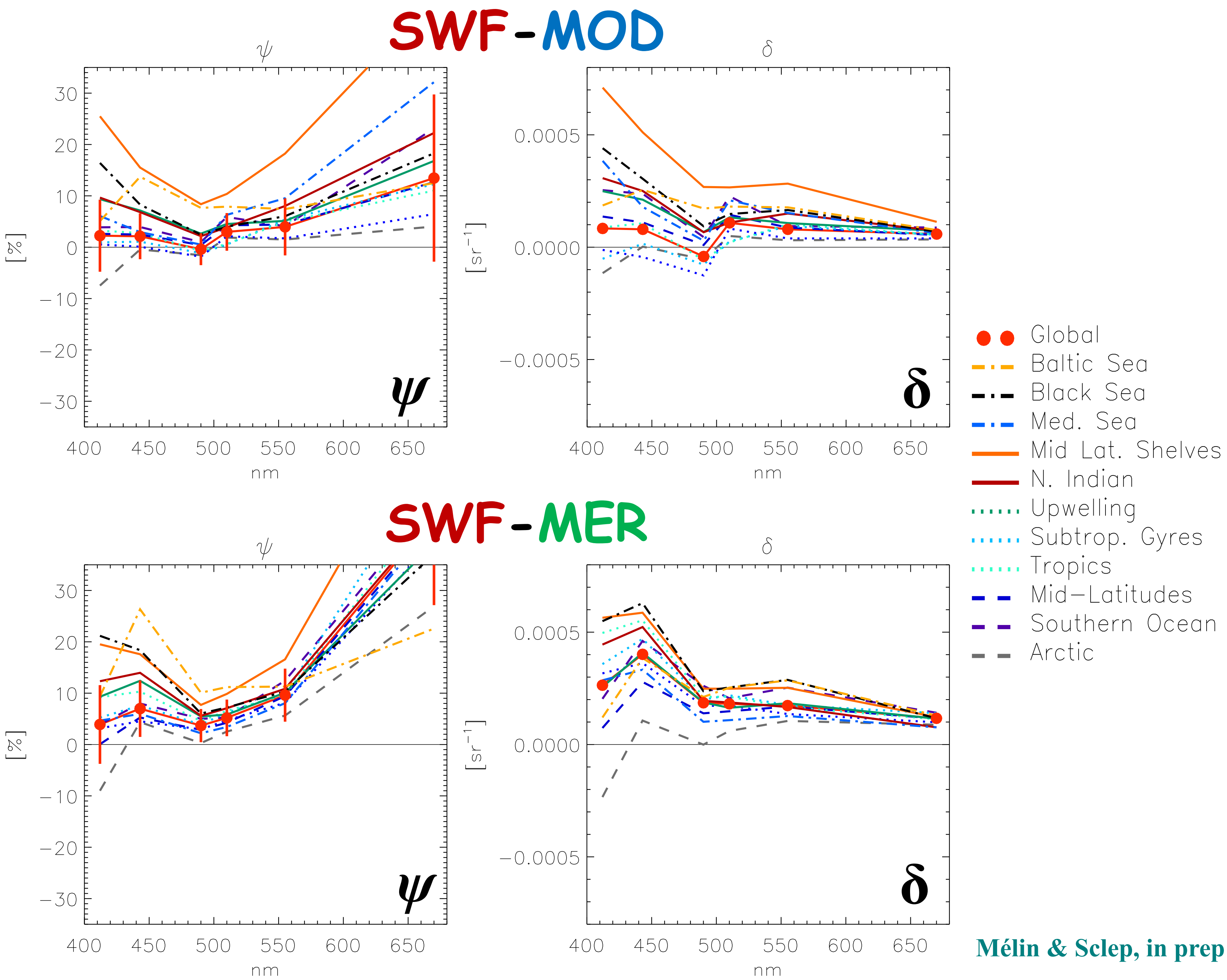
mean difference
(bias)

$$\delta = \sum_{i=1}^{N} (y_i - x_i)$$

[sr^{-1}]

relative bias: ψ (SWF-MOD)

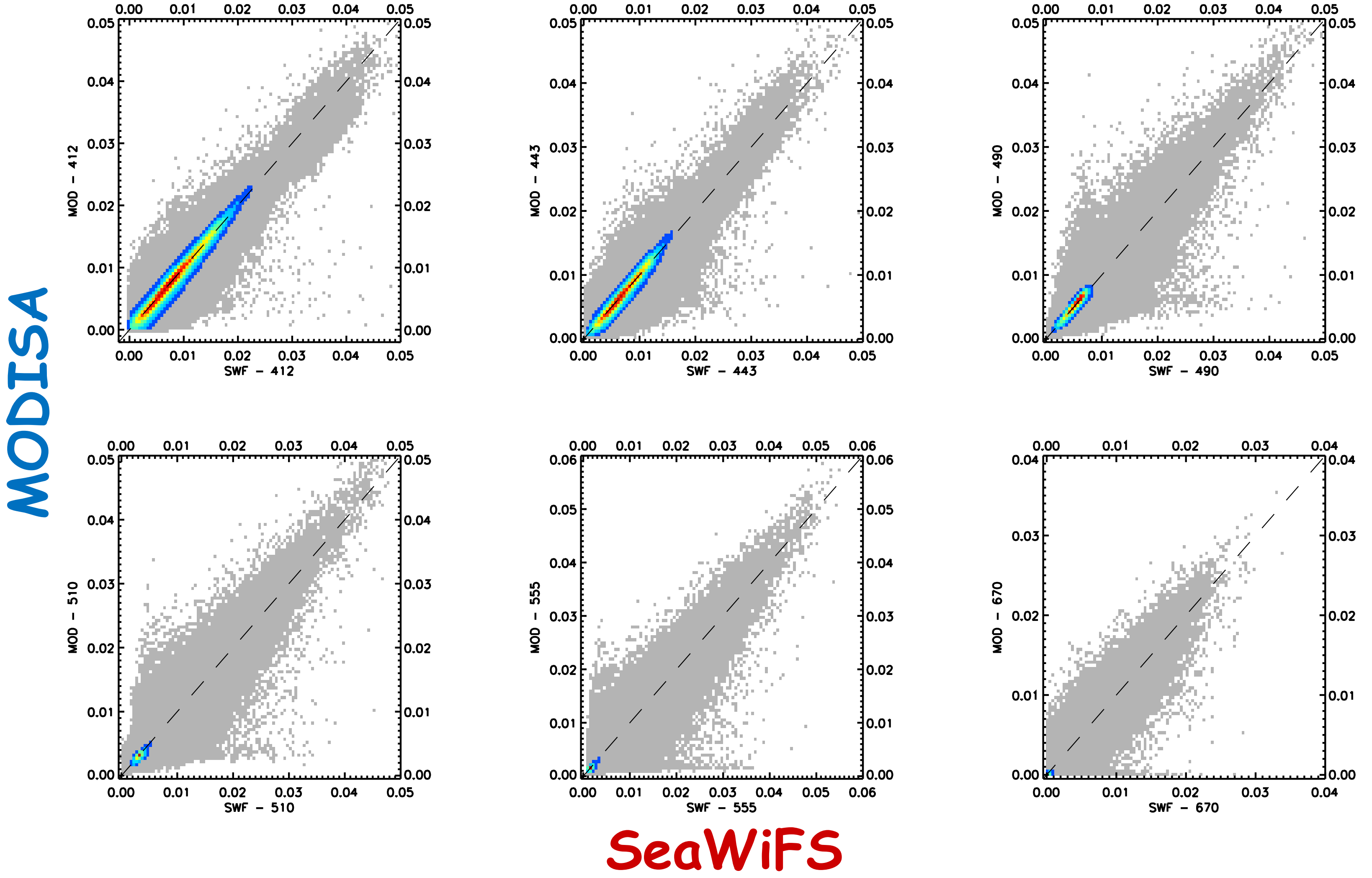




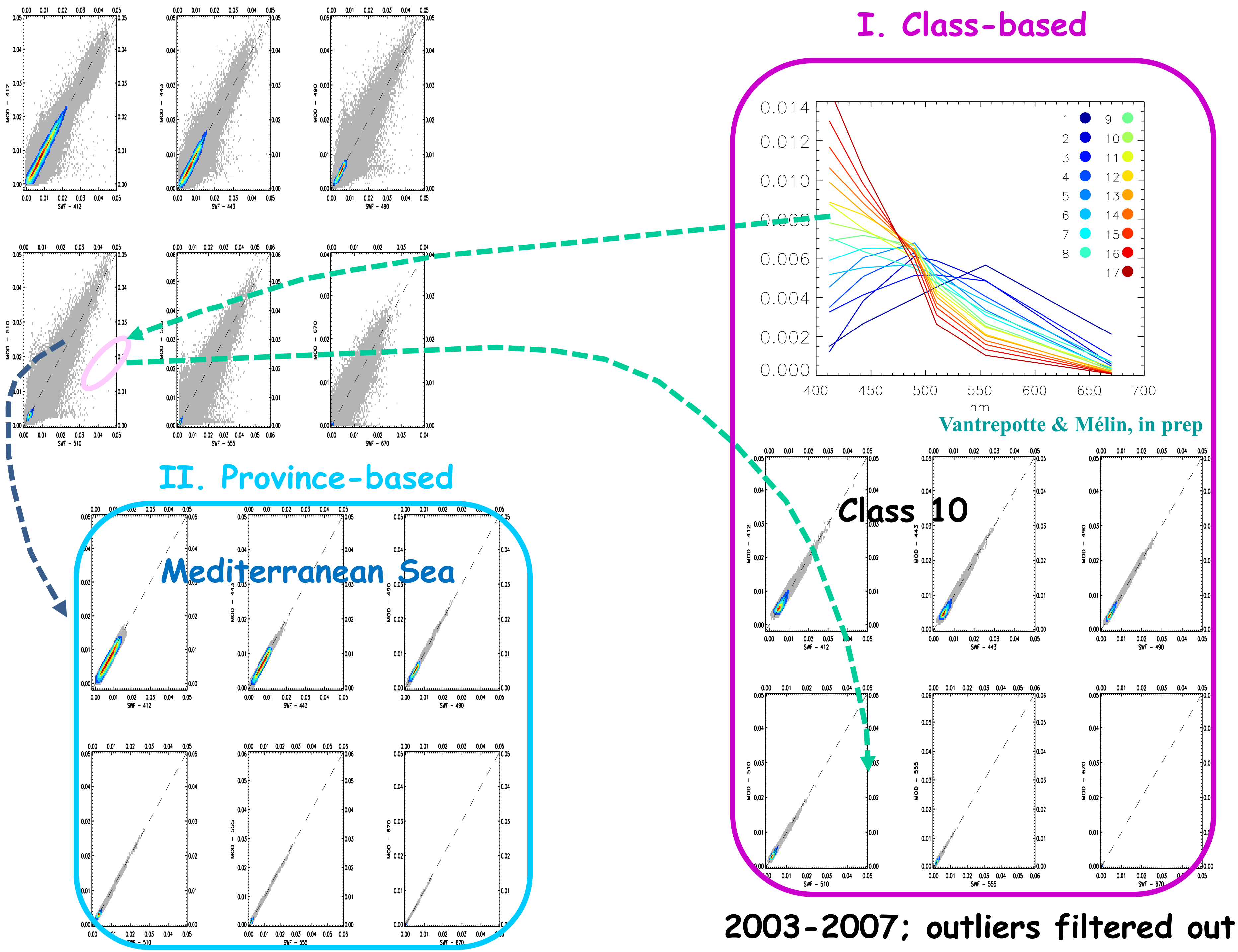
SWF-MOD
SWF-MER
ψ
δ
[%]
[sr⁻¹]
nm
30
20
10
0
−10
−20
−30
0.0005
0.0000
−0.0005
400
450
500
550
600
650
Global
Baltic Sea
Black Sea
Med. Sea
Mid Lat. Shelves
N. Indian
Upwelling
Subtrop. Gyres
Tropics
Mid−Latitudes
Southern Ocean
Arctic
Mélin & Sclep, in prep

Bias Analysis & Correction

Definition of training data set for bias model development



common R_{RS} over 2003-2007 (1 every fourth; ~64 million spectra)



I. Class-based
Vantrepotte & Mélin, in prep
Class 10
II. Province-based
Mediterranean Sea
2003-2007; outliers filtered out

Bias Analysis & Correction

Model based on multiple linear regression (MLR)

For each wavelength:

$$\delta(\lambda) = R_{RS}^{SWF}(\lambda) - R_{RS}(\lambda)$$

SeaWiFS as reference

$$<\delta(\lambda)> = a_{\lambda,0} + \sum_{i=1}^{N} a_{\lambda,i} R_{RS}(\lambda_i)$$

applied to R_{RS} with λ_i € [412-670]

D'Alimonte, Zibordi, Mélin, *RSE,* 2008

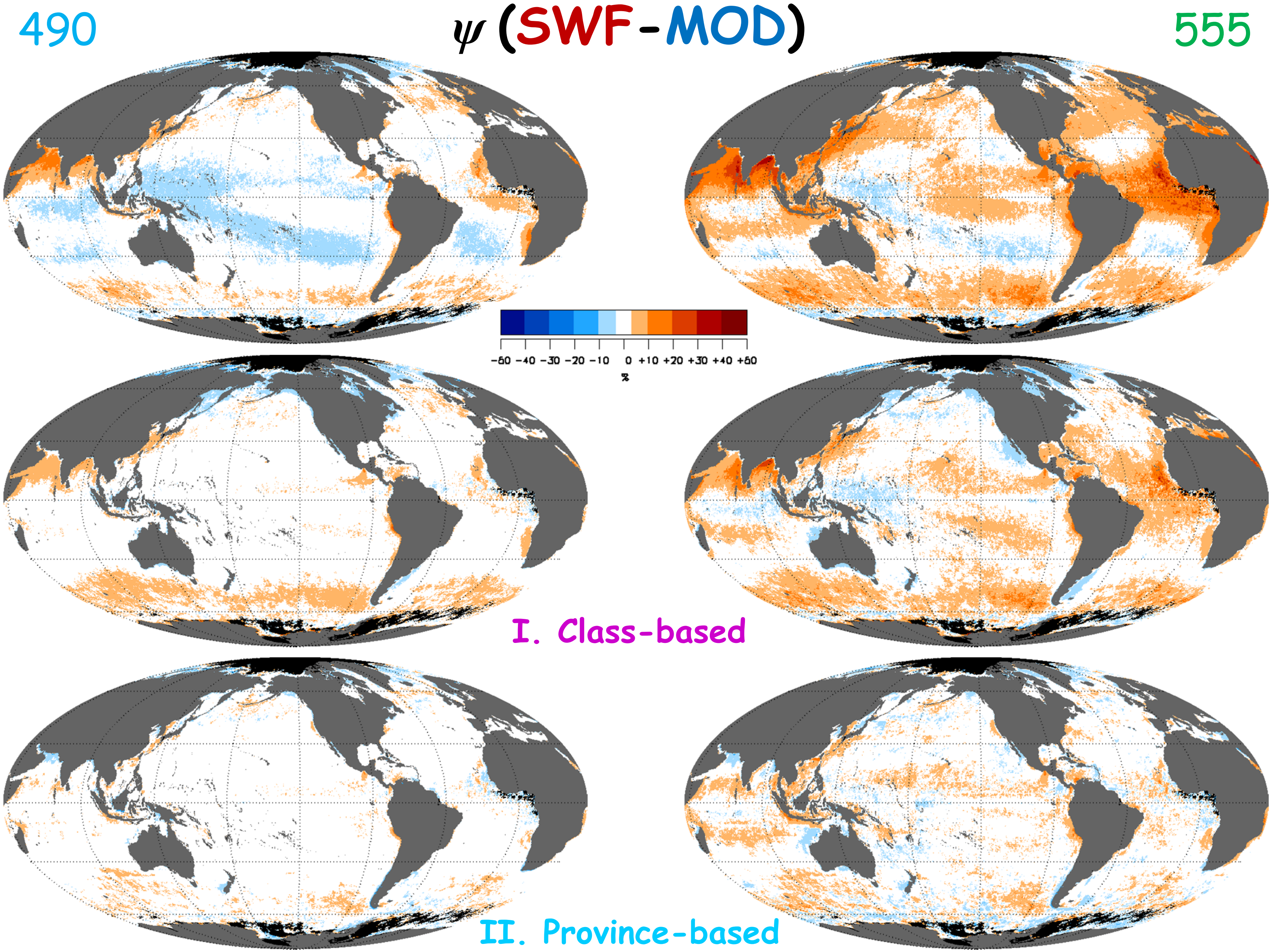
I. Class-based $<\delta_{ic}(\lambda)>$ computed with one MLR model for class ic

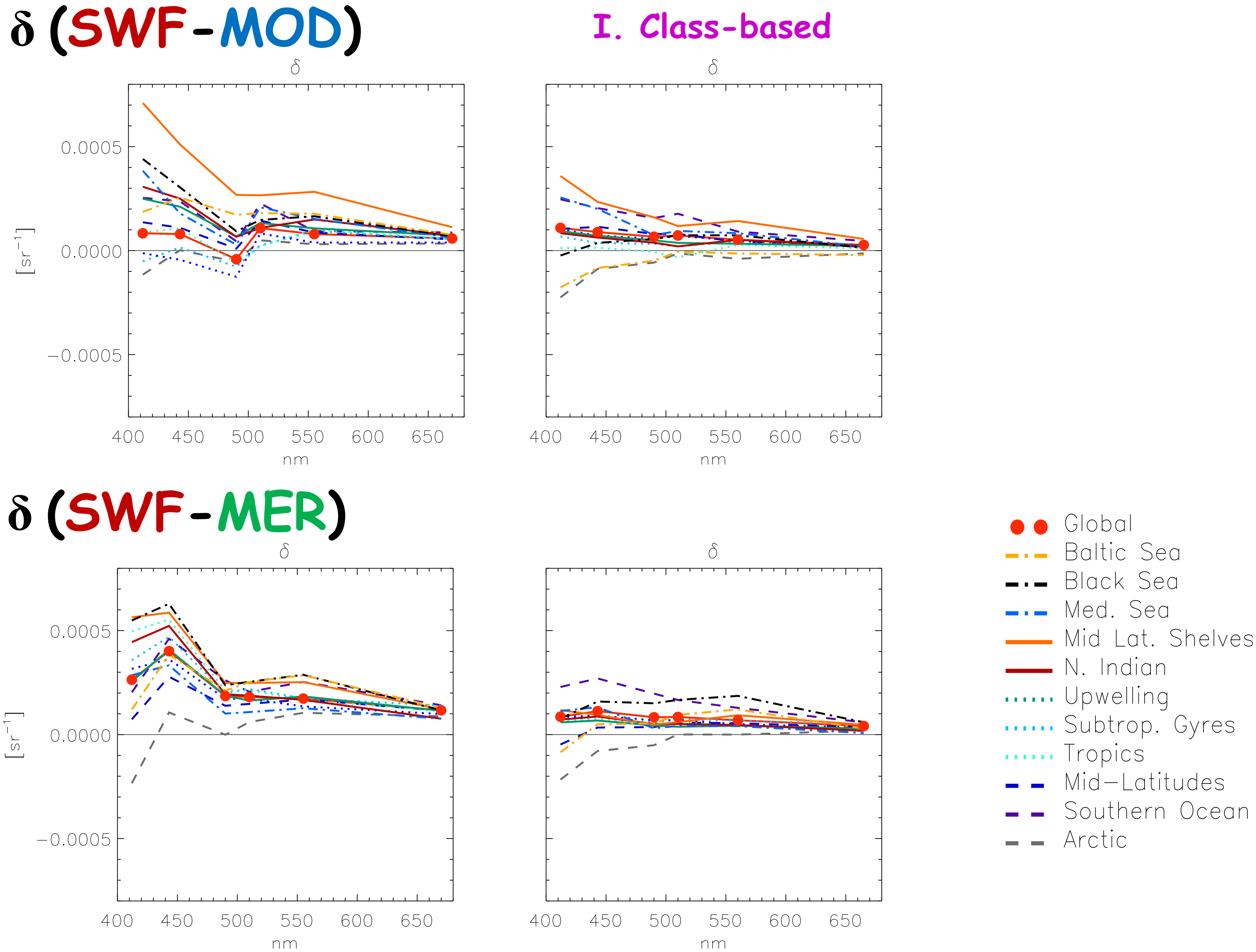
$$<\delta(\lambda)> = \sum_{ic=1}^{NC} w_{ic} . <\delta_{ic}(\lambda)>$$

w_{ic}: normalised class membership

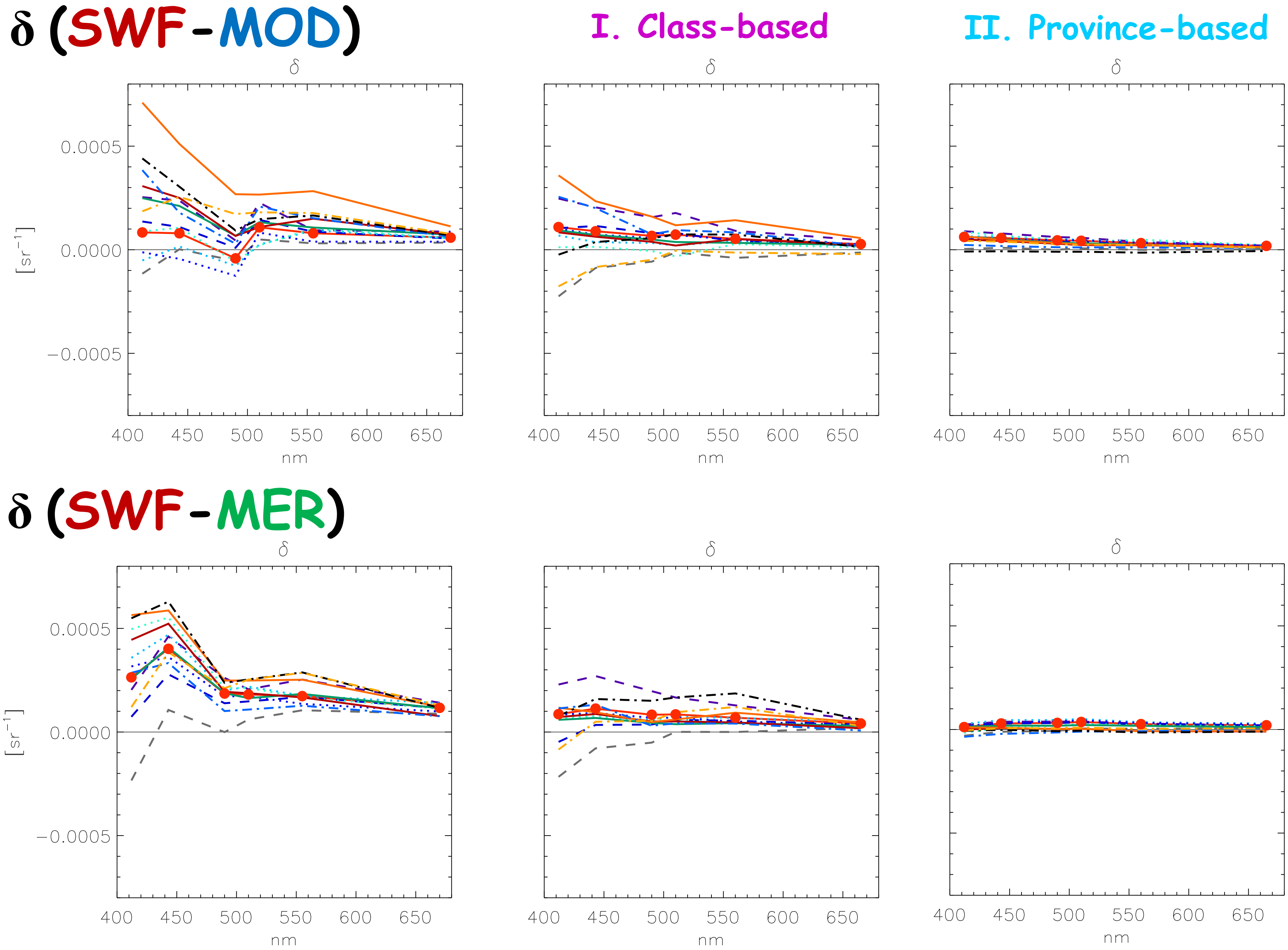
II. Province-based $<\delta(\lambda)>$ computed with one MLR model per province

Application to the daily data for MODIS & MERIS (2002-2012)

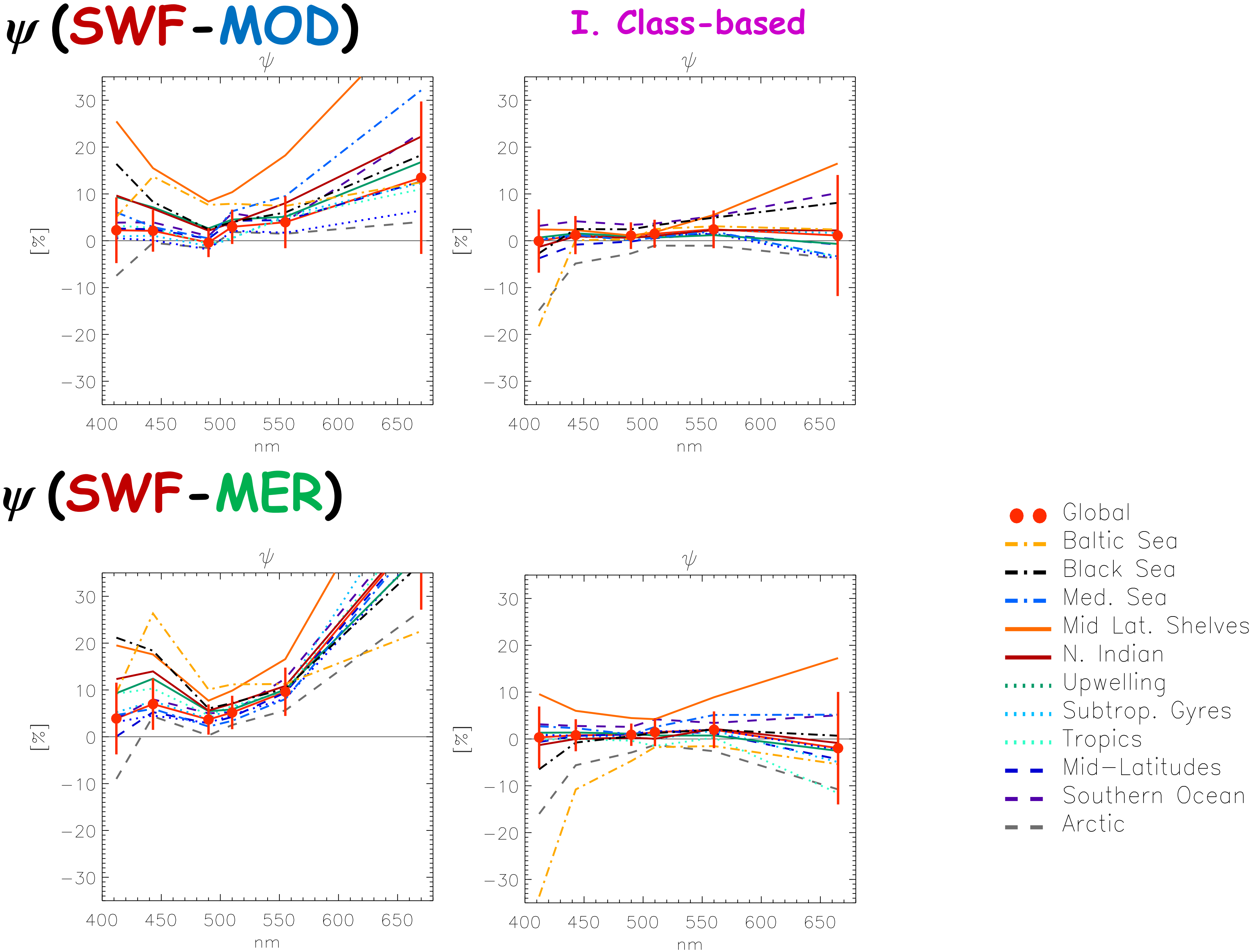

490
ψ (SWF-MOD)
555
-60 -40 -30 -20 -10 0 +10 +20 +30 +40 +60
%
I. Class-based
II. Province-based



δ (SWF-MOD)
I. Class-based
δ
[sr⁻¹]
0.0005
0.0000
−0.0005
400 450 500 550 600 650
nm
δ (SWF-MER)
Global
Baltic Sea
Black Sea
Med. Sea
Mid Lat. Shelves
N. Indian
Upwelling
Subtrop. Gyres
Tropics
Mid−Latitudes
Southern Ocean
Arctic



δ (SWF-MOD)
I. Class-based
II. Province-based
δ
0.0005
0.0000
−0.0005
[sr⁻¹]
400
450
500
550
600
650
nm
δ (SWF-MER)



ψ (SWF-MOD)
I. Class-based
ψ (SWF-MER)
ψ
[%]
nm
30
20
10
0
−10
−20
−30
400
450
500
550
600
650
Global
Baltic Sea
Black Sea
Med. Sea
Mid Lat. Shelves
N. Indian
Upwelling
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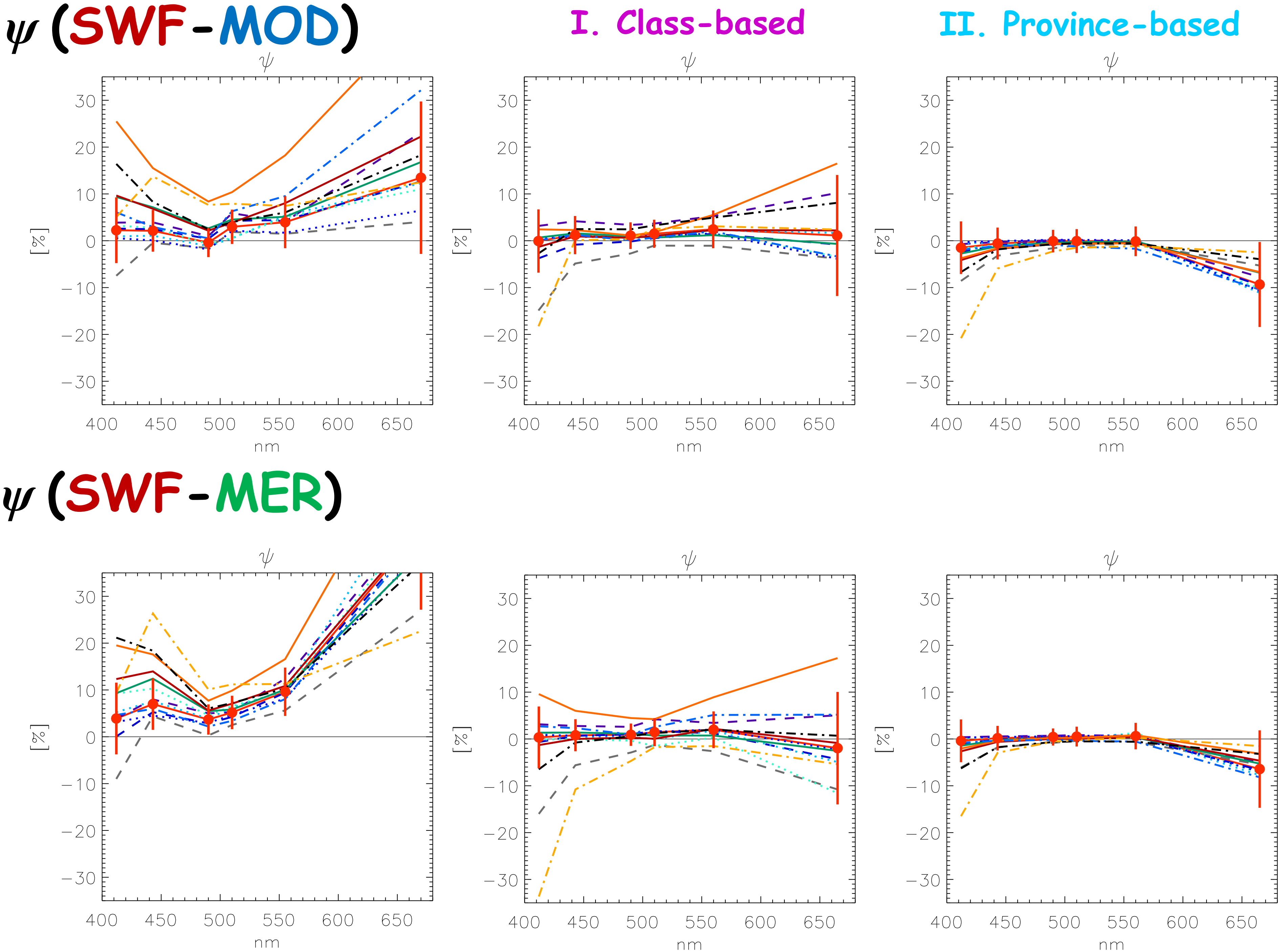
Arctic



ψ (SWF-MOD)
I. Class-based
II. Province-based
ψ
[%]
30
20
10
0
−10
−20
−30
400
450
500
550
600
650
nm
ψ (SWF-MER)

Preliminary conclusions:

for the R_{RS} data sets studied:

e.g., for R_{RS}
Antoine et al., *JGR* 2008;
Mélin et al., *Opt. Exp.* 2011, *GRSL* 2012;
Zibordi et al., *GRL* 2006, *RSE* 2009, 2011
for aerosols:
Mélin et al., *RSE* 2010,
GRSL 2013, *Oceanologia* 2013

- ❑ good agreement of their uncertainty level
- ❑ fair consistency between products

oceancolor.gsfc.nasa.gov

- ❑ still some work to fully bring these records in line with each other

Keep up the effort at ensuring the stability of each mission

Besides inter-mission differences, spurious trends can come from:

- ❖ residual variations in the calibration equation
- ❖ artifacts in the processing ancillary data (ozone, wind, pressure, SST…)
- ❖ actual trends in variables that can impact the atmospheric correction (cloud coverage and type, aerosol, wind, …)

Chlorophyll-*a* concentration

$Chla \neq [biomass] \neq a_{ph} \neq [C]$

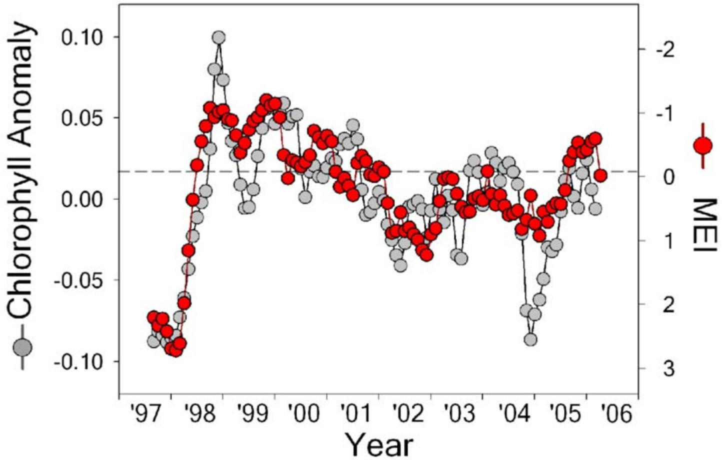
Chl*a* is affected by

- ocean physics (temperature, stratification, etc…)
- nutrient availability
- illumination regime
- carbonate system (pH, $[CO_2]_{aq}$)
- aerial deposition (dust, nutrients)
- ecological top-down pressures (*e.g.*, grazing, fishing)
- coastal inputs

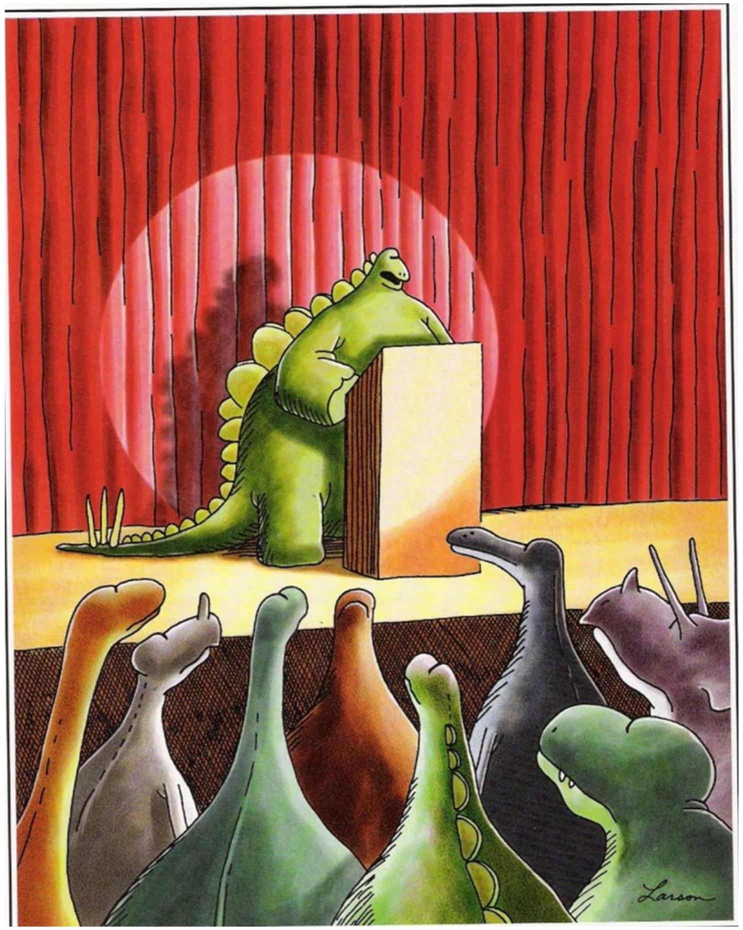
….

Phytoplankton reacts over a variety of time scales, from s to eras

- Circadian, tidal cycle, intra-annual (e.g., MJO),
- Annual cycle
- Inter-annual oscillations (NAO, SAM, ENSO/MEI, PDO, IOD …)



Behrenfeld et al., *N* 2006; Martinez et al., *S* 2009;
Chavez et al., *ARMS* 2011, Vantrepotte & Mélin *DSR* 2011



G. Larson

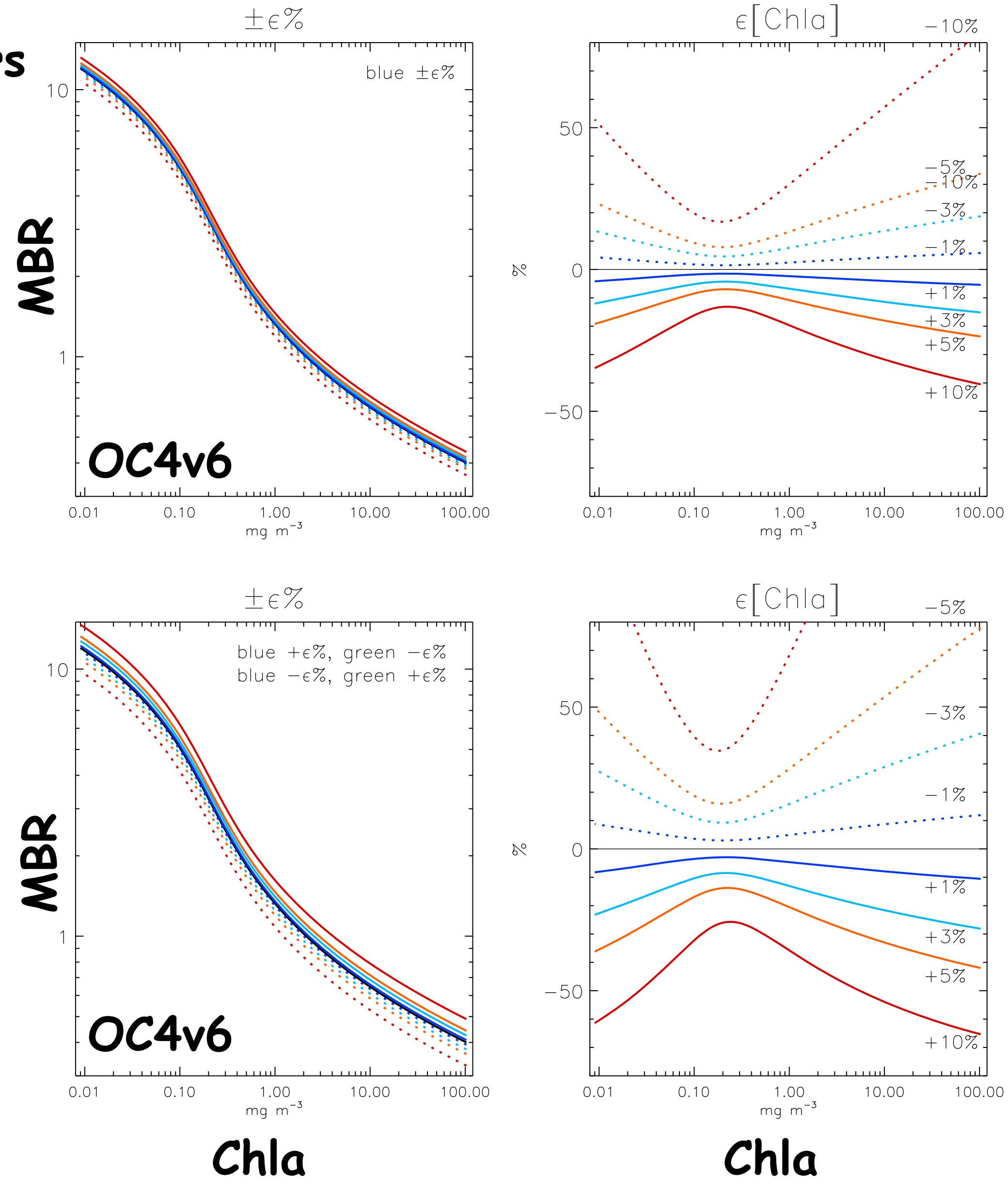
“The picture’s pretty bleak, gentlemen. … The world’s climates are changing, the mammals are taking over, and we all have a brain about the size of a walnut.”

A word on algorithms…

Sensitivity of OC4 to biases in R_{RS}

The empirical formula or parameters of today may not apply tomorrow.

Checking the sensitivity of an algorithm to biases in R_{RS} is required



Time Series Analysis

Analysis performed with monthly Chla global series
SeaWiFS: 09/1997 – 12/2007
MERIS: 05/2002 – 03/2012
MODISA: 07/2002 – 12/2012
MODIST: 03/2000 – 12/2012

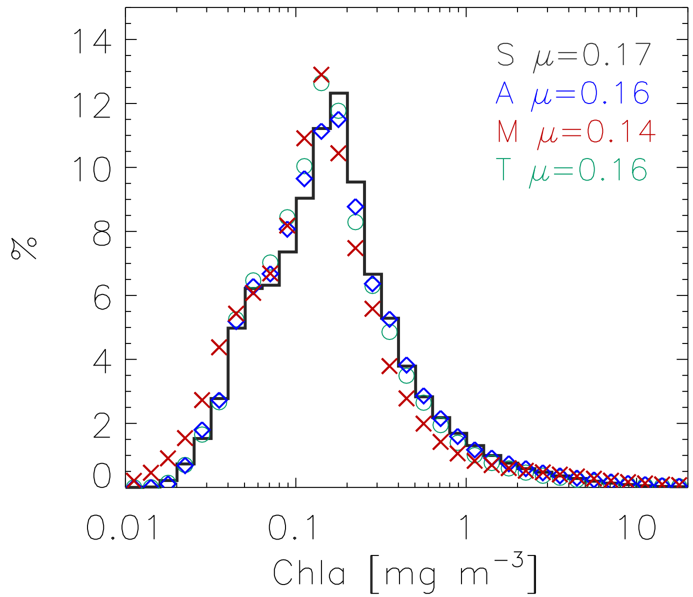
Common climatology created for the reference period: 2003-2007 (5 years)

All trends computed on sets of full years

Time Series Analysis

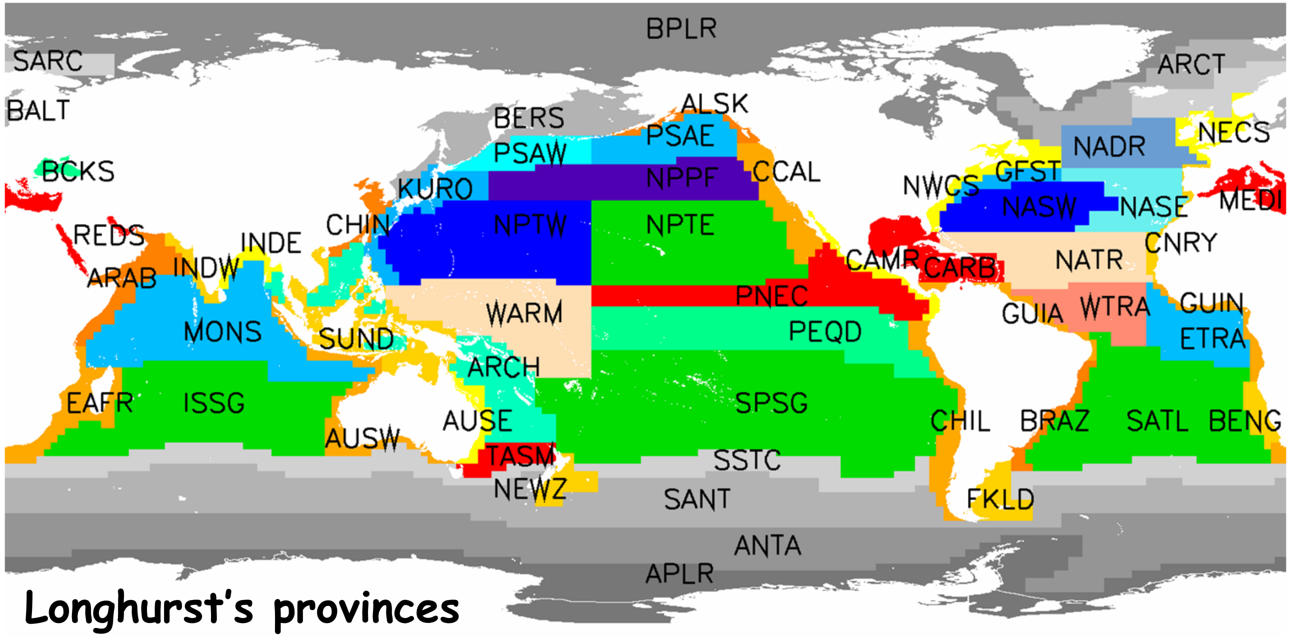
General Statistics

using yearly averaged maps 2003-2007



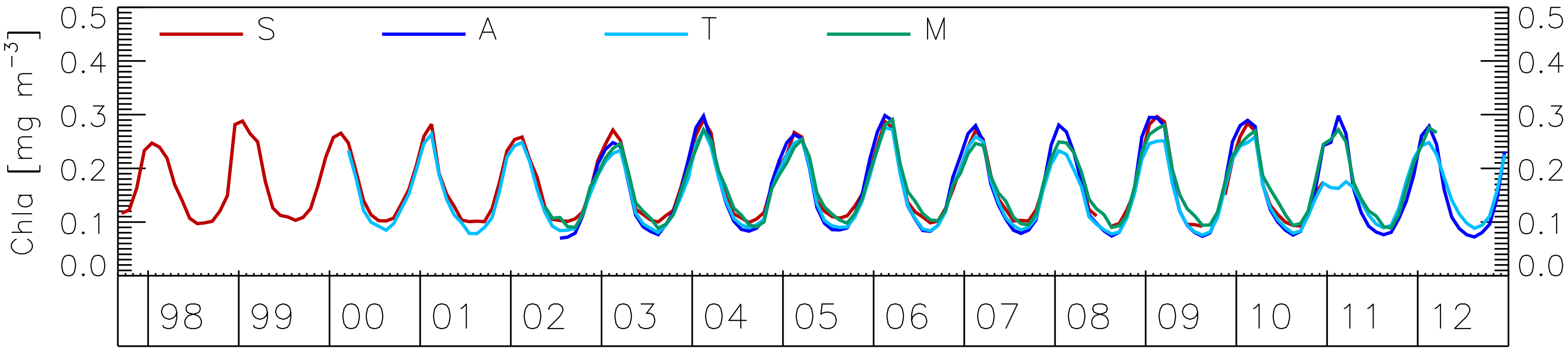
		S	M	A	T	
	avg	0.331	0.366	0.358	0.312	[mg m^{-3}]
	s.d.	0.910	1.534	1.185	1.035	[mg m^{-3}]
	median	0.157	0.132	0.151	0.145	[mg m^{-3}]
after $\log_{10}$ transform	avg	0.167	0.139	0.164	0.155	[mg m^{-3}]
after $\log_{10}$ transform	s.d.	0.432	0.467	0.442	0.418	
after $\log_{10}$ transform	median	0.157	0.132	0.151	0.145	[mg m^{-3}]

Time Series Analysis

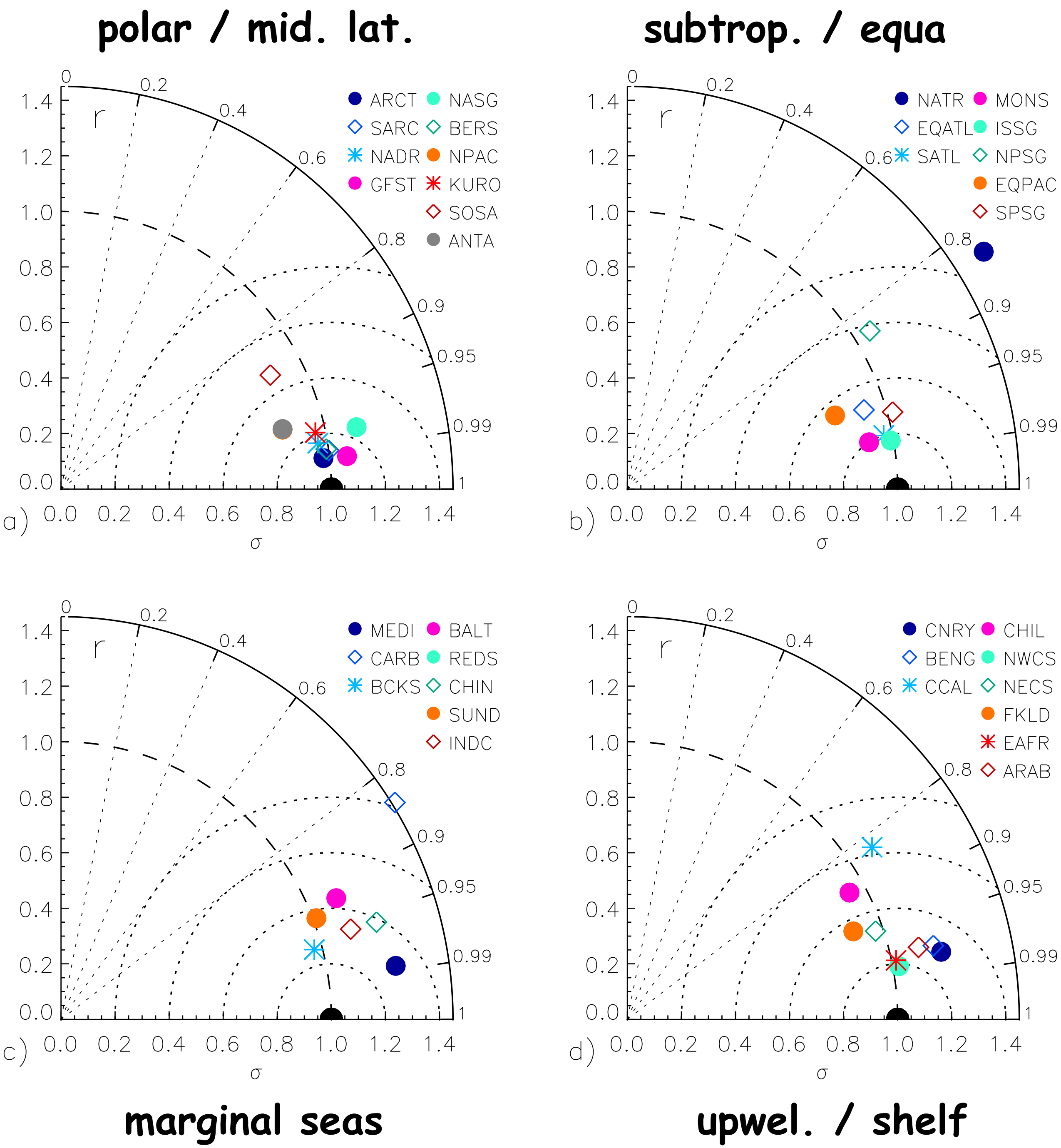


Longhurst's provinces

SeaWiFS MODISA MODIST MERIS



Mediterranean Sea

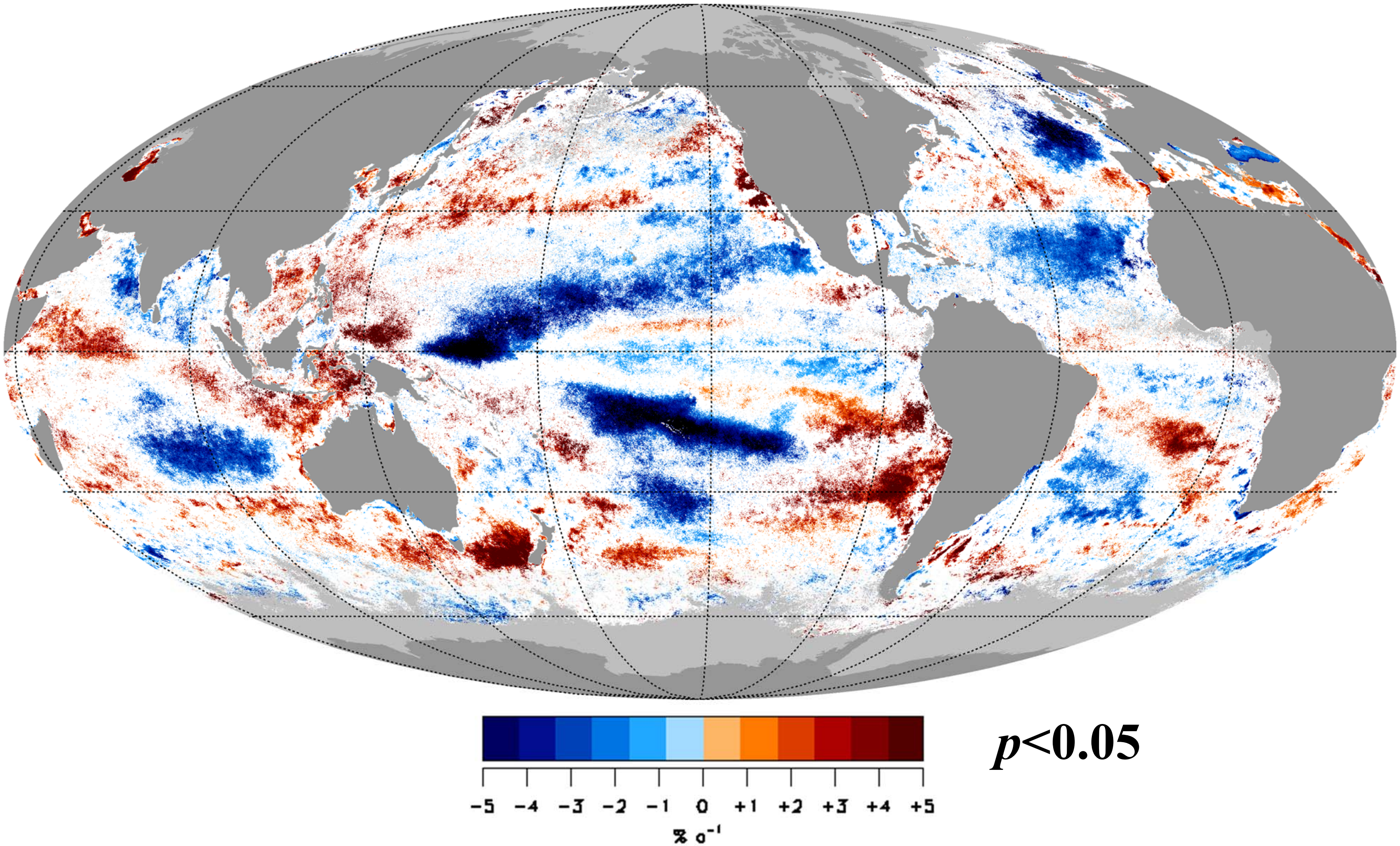


SeaWiFS vs.
MODISA
[2003-2007]

Ref.: SeaWiFS

update Djavidnia et al., *OS* 2010

Trend in the SeaWiFS Chla record [1998-2007]



$p<0.05$

non-parametric seasonal Kendall test

Vantrepotte & Mélin, *DSR* 2011

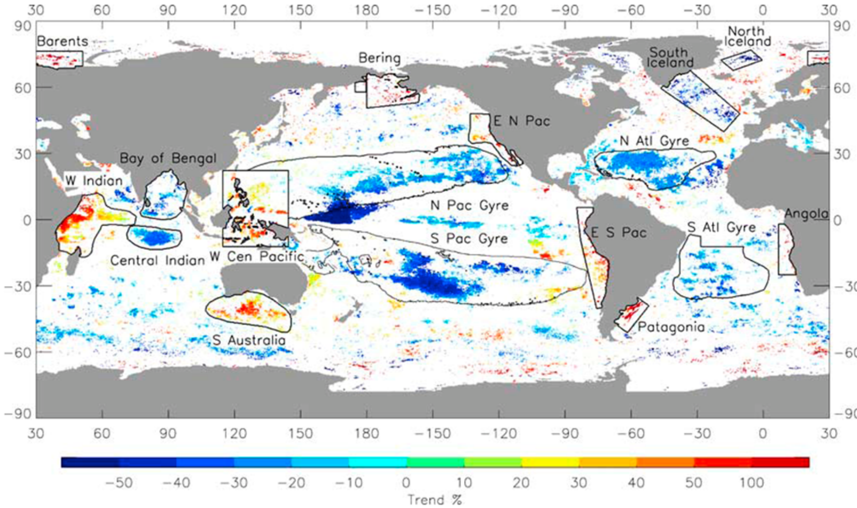
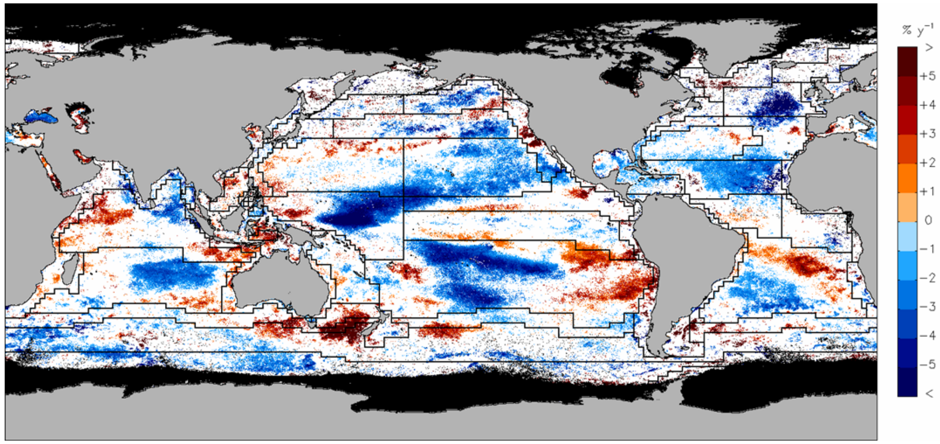
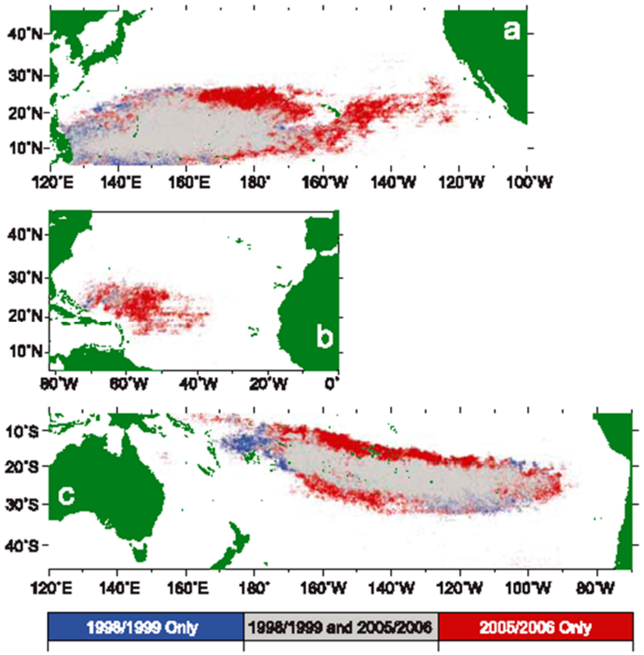


Figure 1. Regions defined by coherent distribution of 25-km grid points where chlorophyll concentrations indicated a significant trend ($P < 0.05$) over the 6-year data record of SeaWiFS. Only regions where significance was found within the region as a whole are shown here.

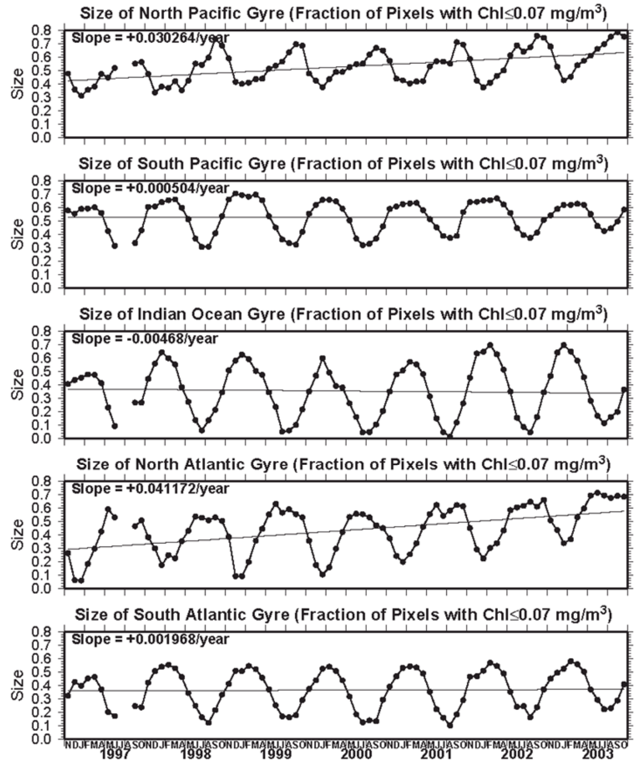
Gregg et al., *GRL* 2005



Vantrepotte & Mélin, *ICES* 2009; *DSR* 2011

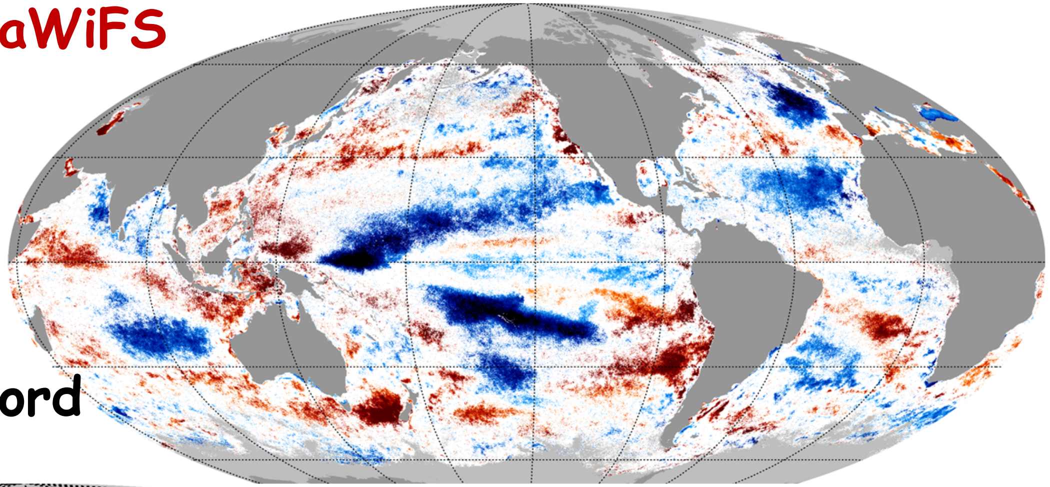


Polovina et al., *GRL* 2008

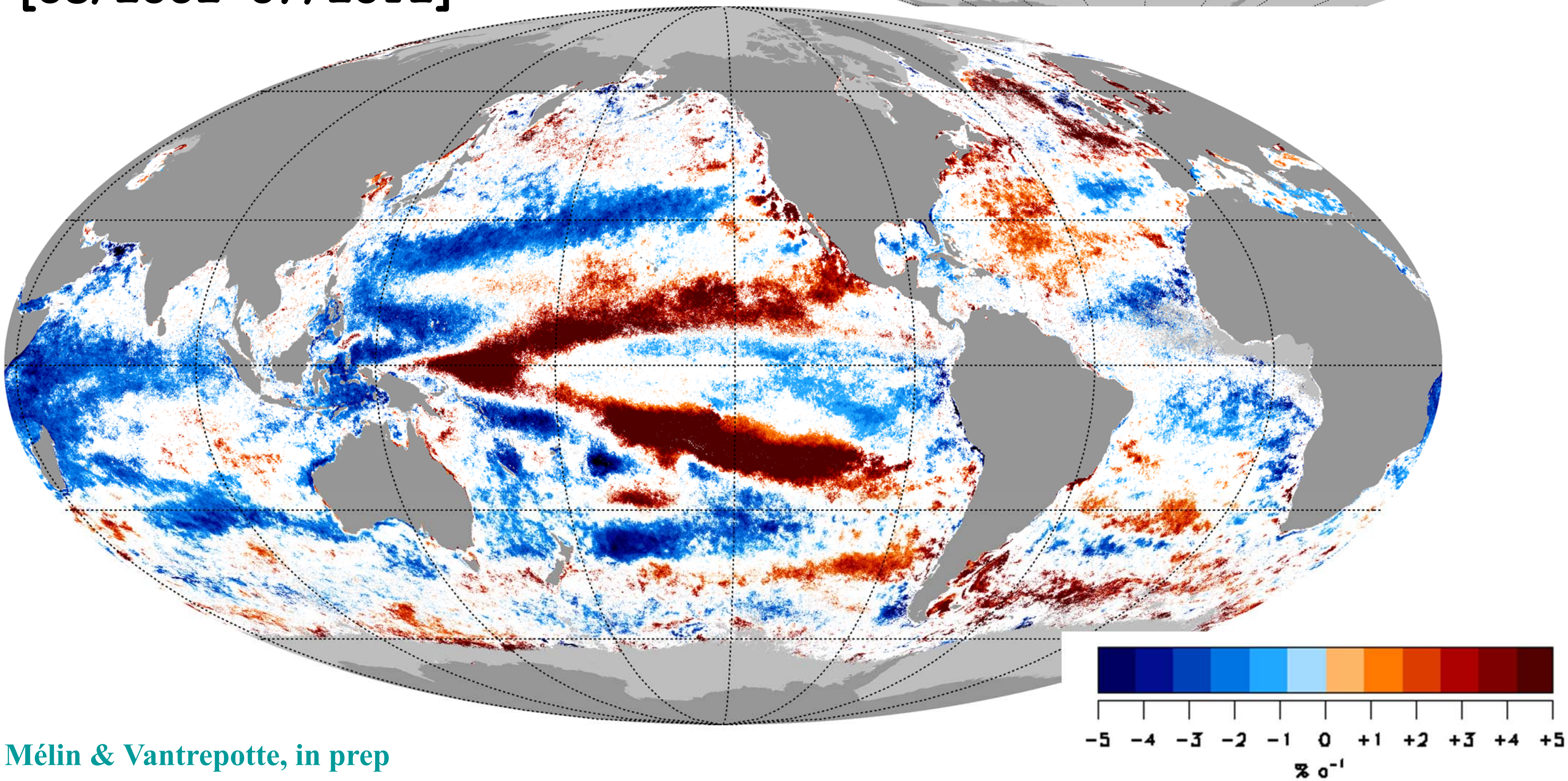


McClain et al., *DSR* 2004

SeaWiFS

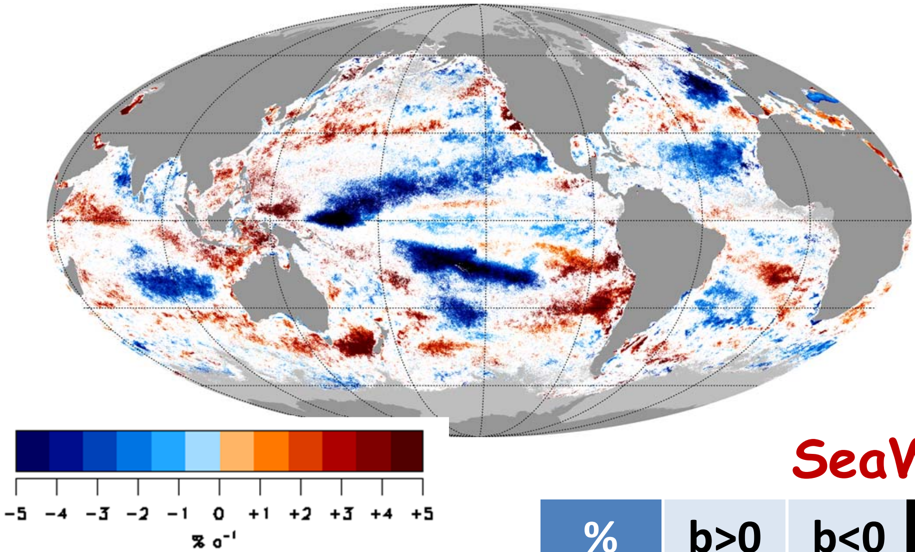


Trend in the MODISA Chla record [08/2002-07/2012]

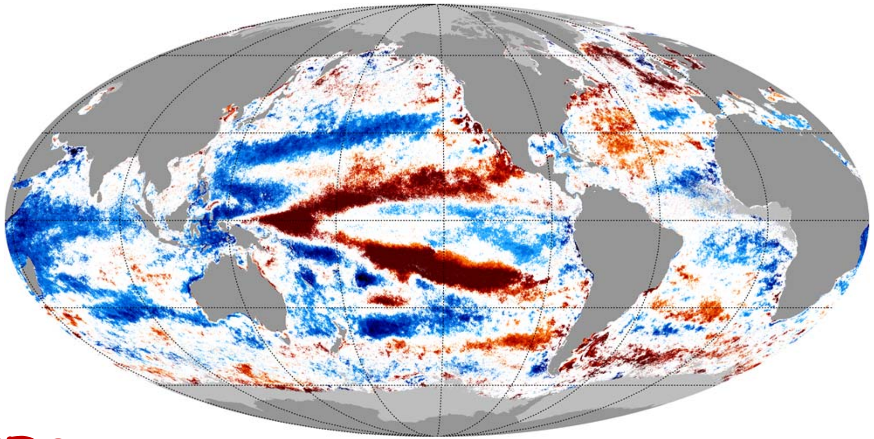


Mélin & Vantrepotte, in prep

SeaWiFS
[01/1998-12/2007]



MODISA
[08/2002-07/2012]



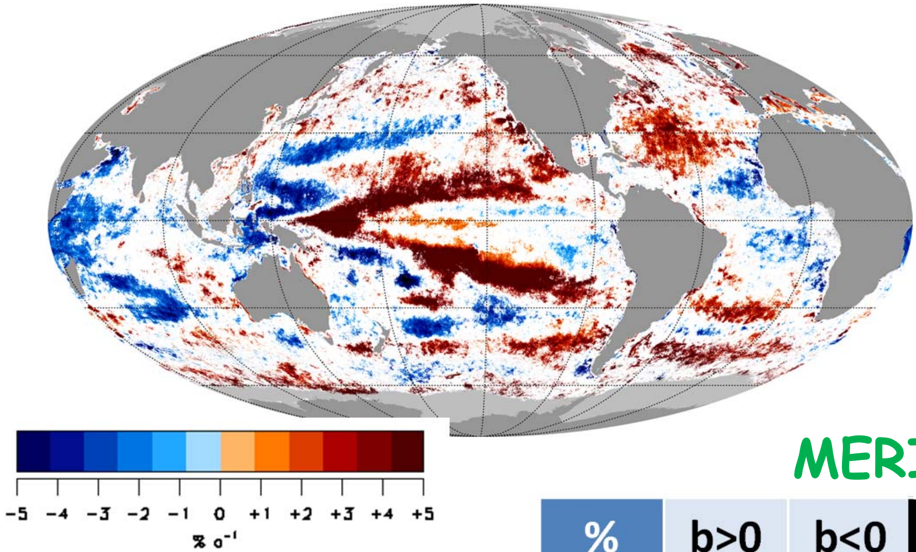
Statistics expressed as % of domain

SeaWiFS (columns) / **MODISA** (rows)

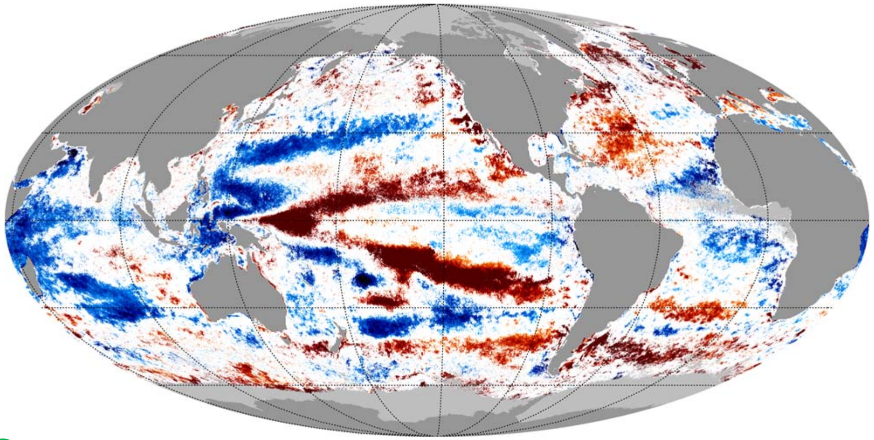
%	b>0	b<0	n.s.	b>0 *	b<0 *
b>0	18	31			
b<0	26	24	24		
n.s.		14	51		
b>0 *				1	3
b<0 *				5	1

b: slope
*: $p<0.05$
n.s.: non significant

MERIS
[08/2002-07/2011]



MODISA
[08/2002-07/2011]



Statistics expressed as % of domain

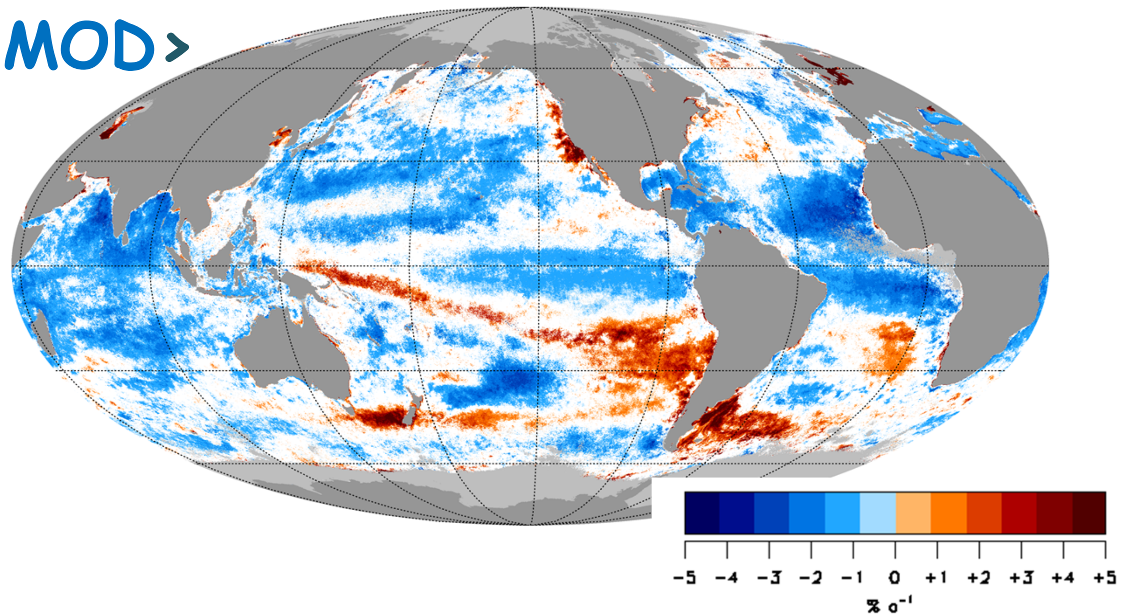
MERIS (columns) / MODISA (rows)

%	b>0	b<0	n.s.	b>0 *	b<0 *
b>0	44	6			
b<0	13	37	10		
n.s.		10	59		
b>0 *				11	0
b<0 *				0	9

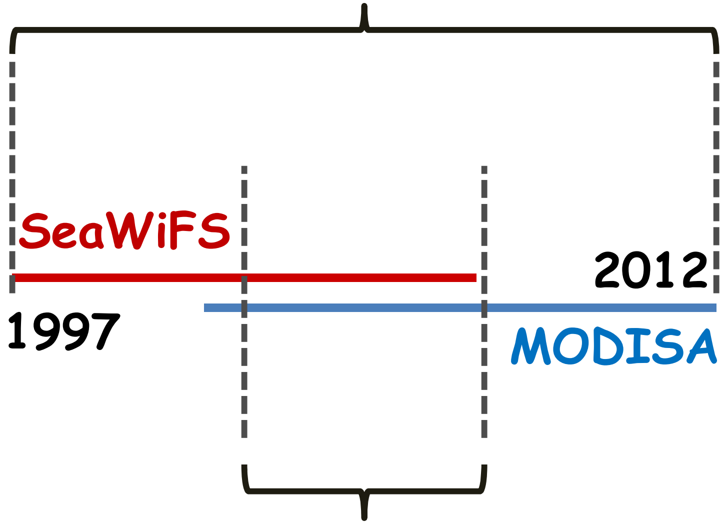
b: slope
*: $p<0.05$
n.s.: non significant

trend on averaged product [10/1997-09/2012]

<SWF+MOD>



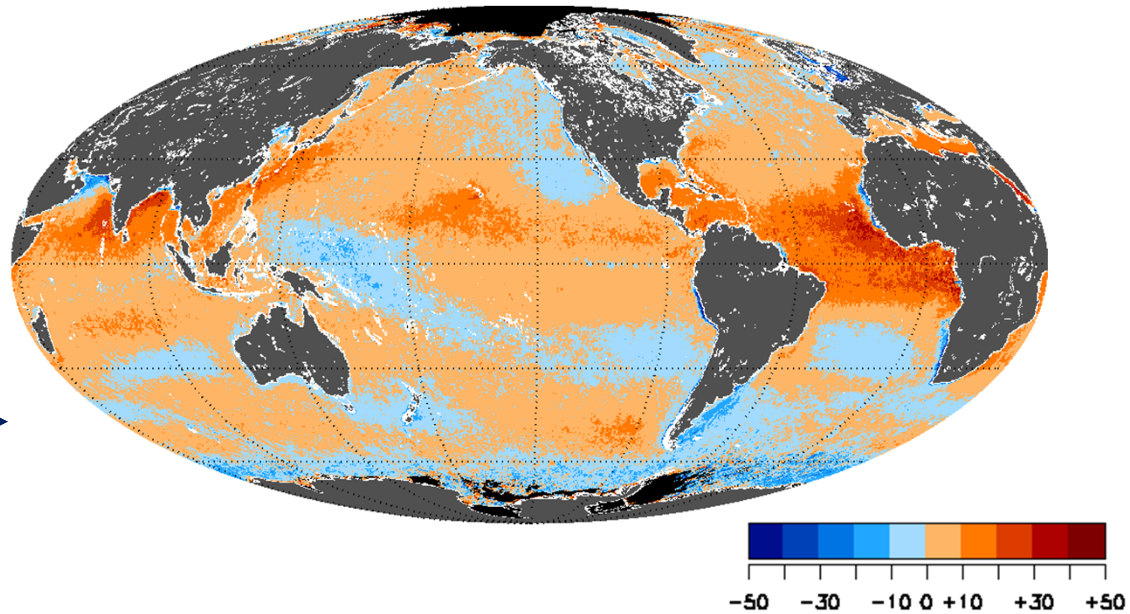
average series

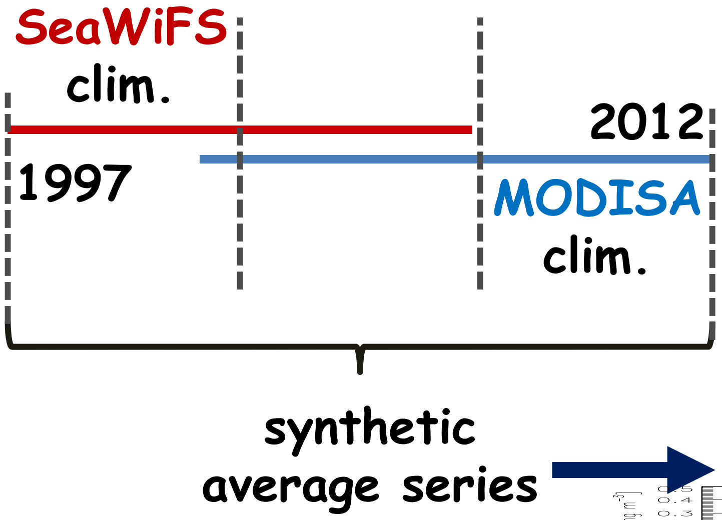


overlap:
2003-2007

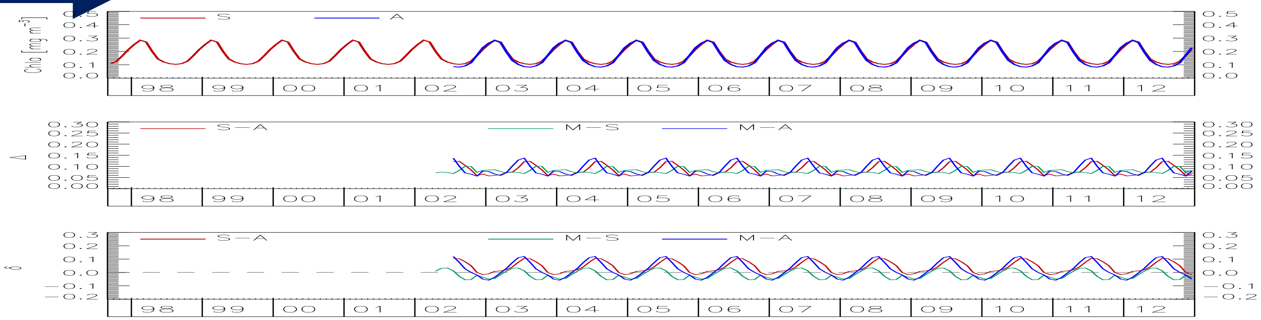
used to compute bias
(1/4° res.)

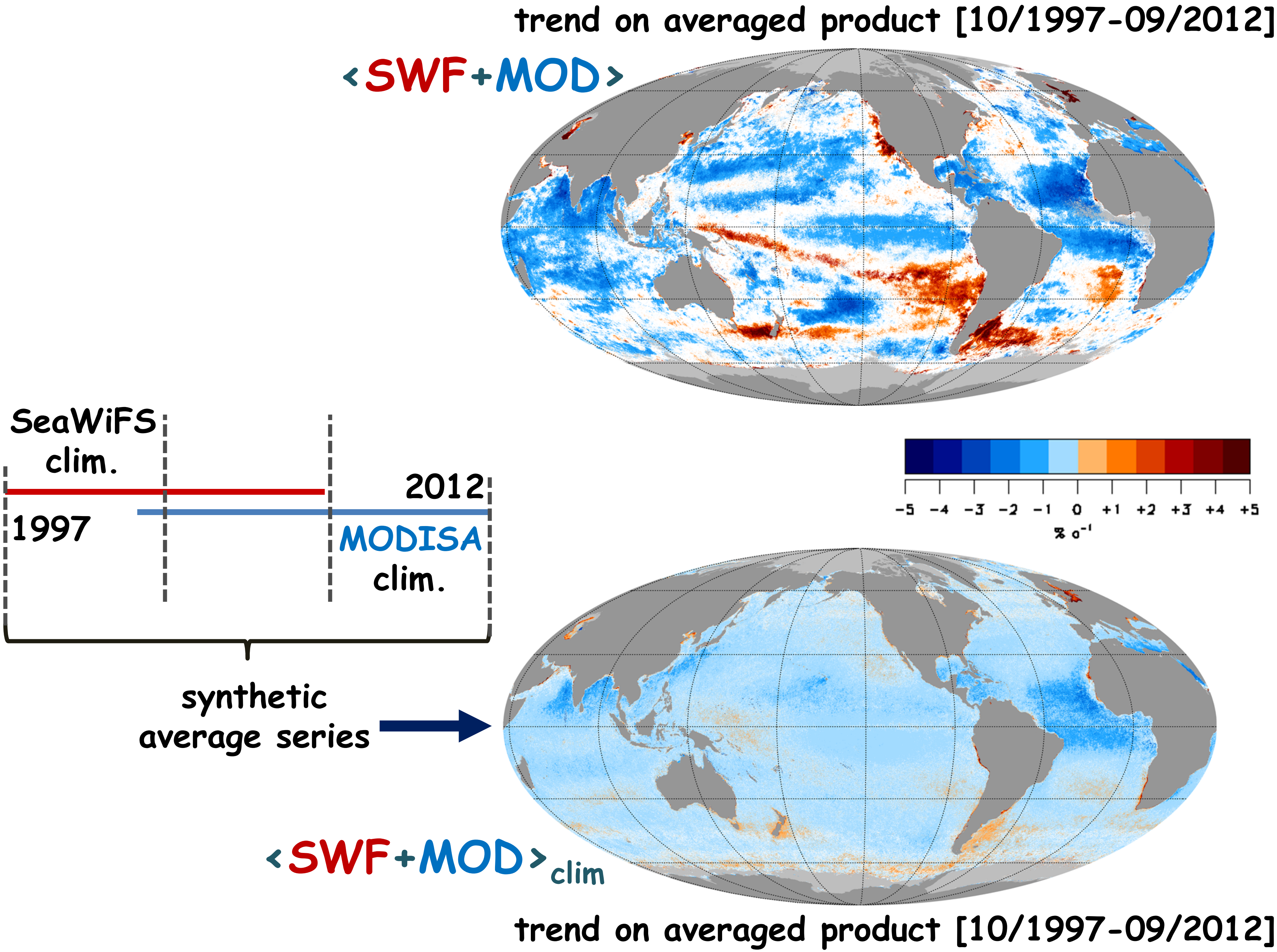
relative bias (SWF-MOD) [%]



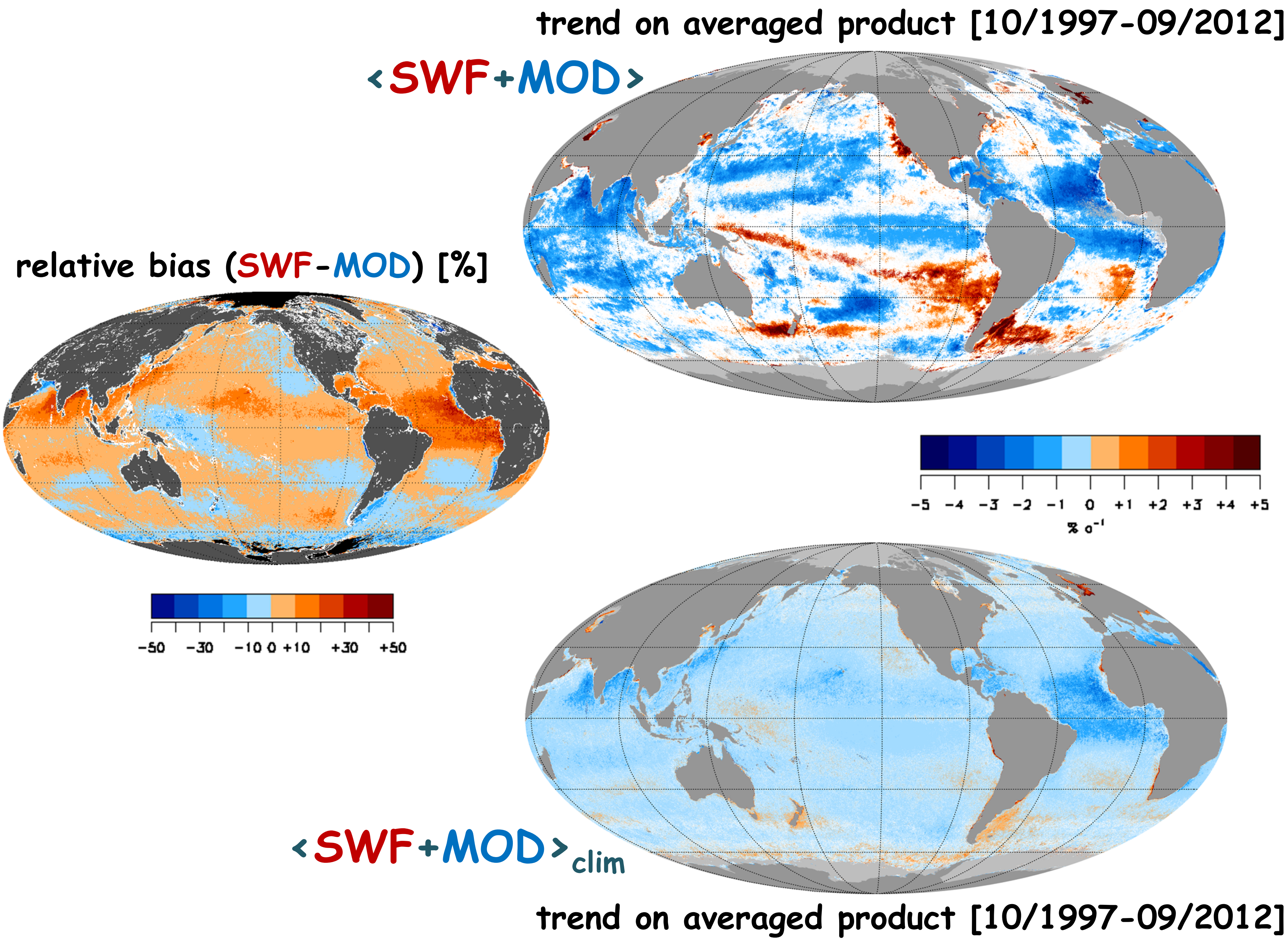


Ex.:Mediterranean Sea





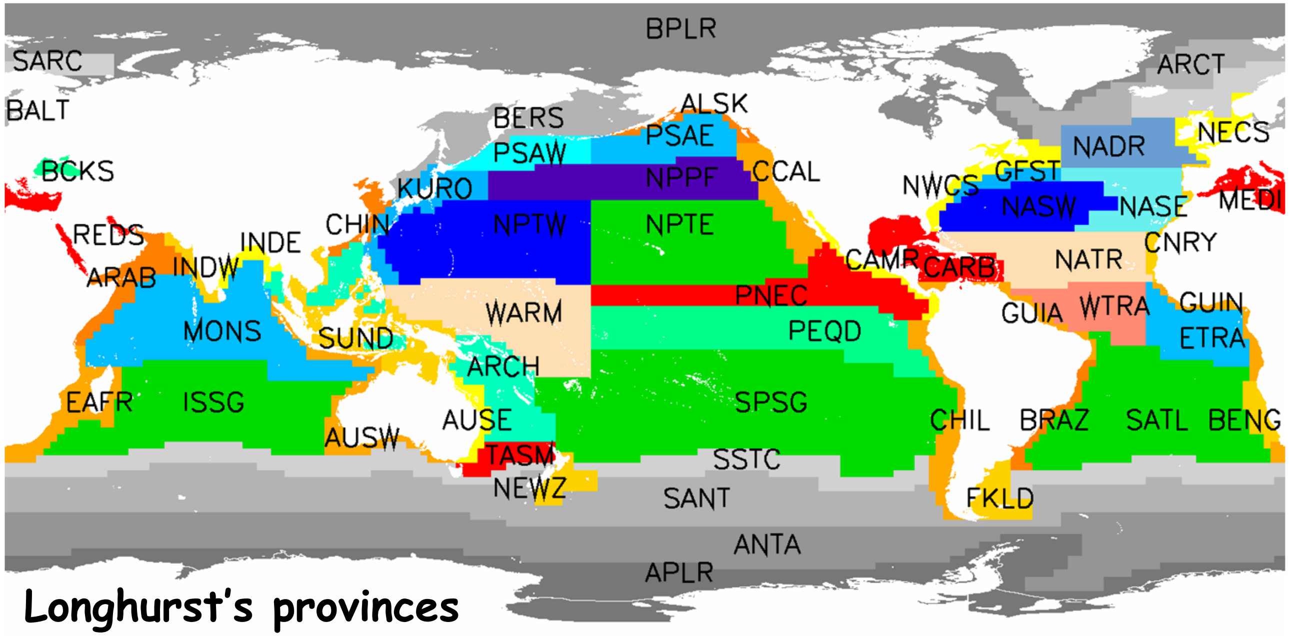
trend on averaged product [10/1997-09/2012]
<SWF+MOD>
SeaWiFS clim.
2012
1997
MODISA clim.
synthetic average series
-5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
% a^-1
<SWF+MOD>clim
trend on averaged product [10/1997-09/2012]


trend on averaged product [10/1997-09/2012]
<SWF+MOD>
relative bias (SWF-MOD) [%]
-50 -30 -10 0 +10 +30 +50
-5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
% a⁻¹
<SWF+MOD>clim
trend on averaged product [10/1997-09/2012]

Inter-mission biases, if not properly accounted for, generate spurious trends

How much inter-mission bias can we afford in the context of trend detection?

Testing on average time series computed over a global set of provinces

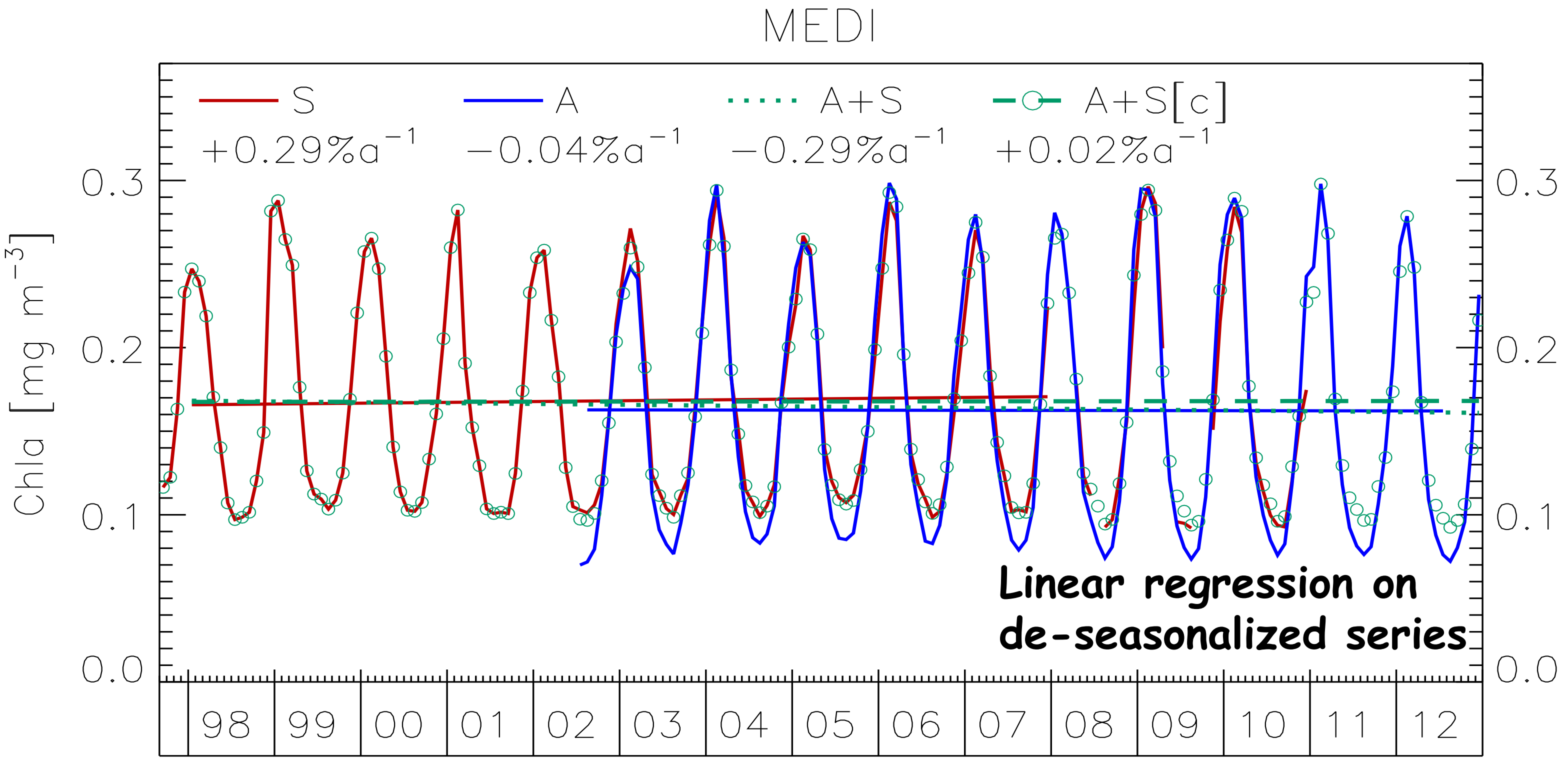


Longhurst's provinces

merged product

merged product
MODIS
clim. corrected

Mediterranean Sea



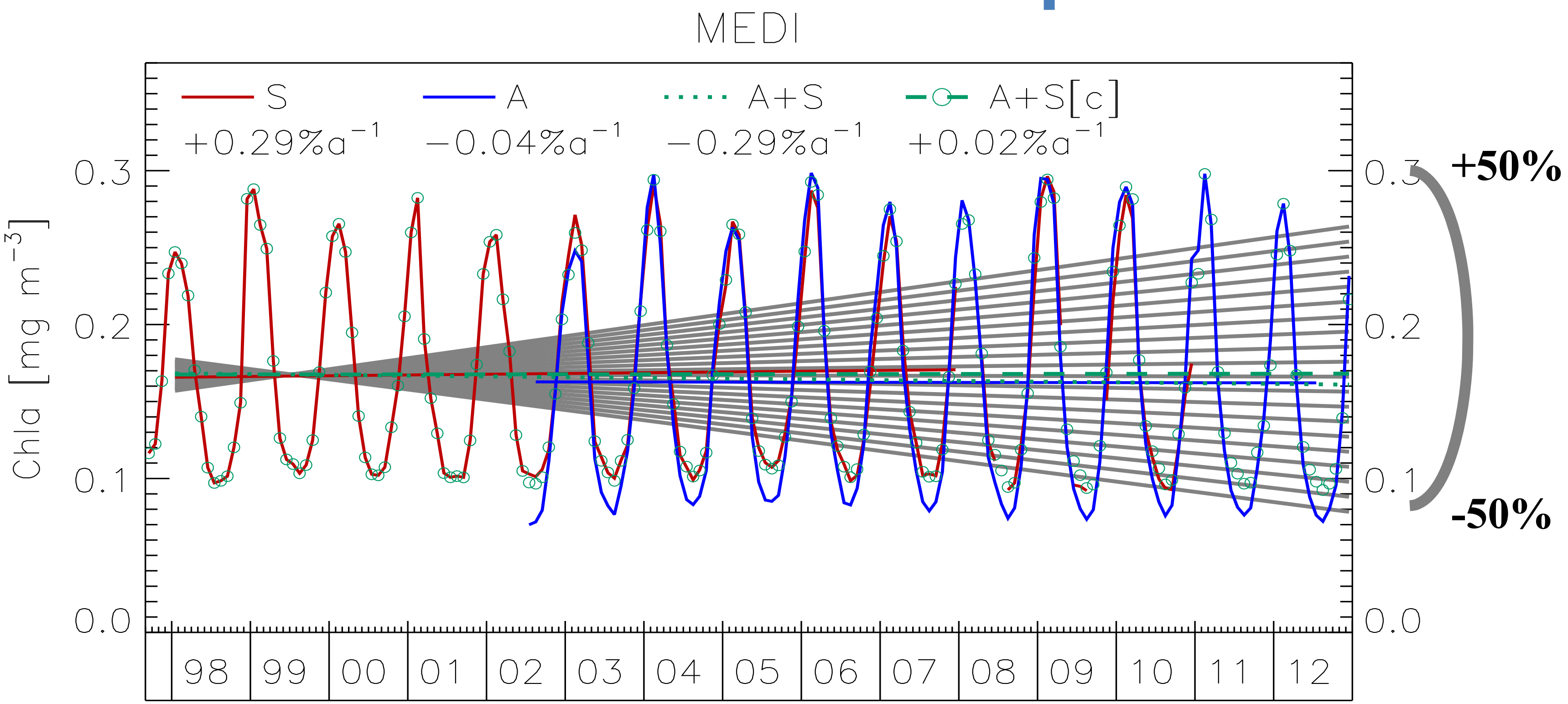
Climatological correction: $x_{A,corr}(m) = x_A(m)+(x_{S,clim}(m)-x_{A,clim}(m))$

Probability that the trends found for the reference (climatologically corrected) and the uncorrected series are significantly different

→ **matrix [province, probability]**

Mediterranean Sea

reference product

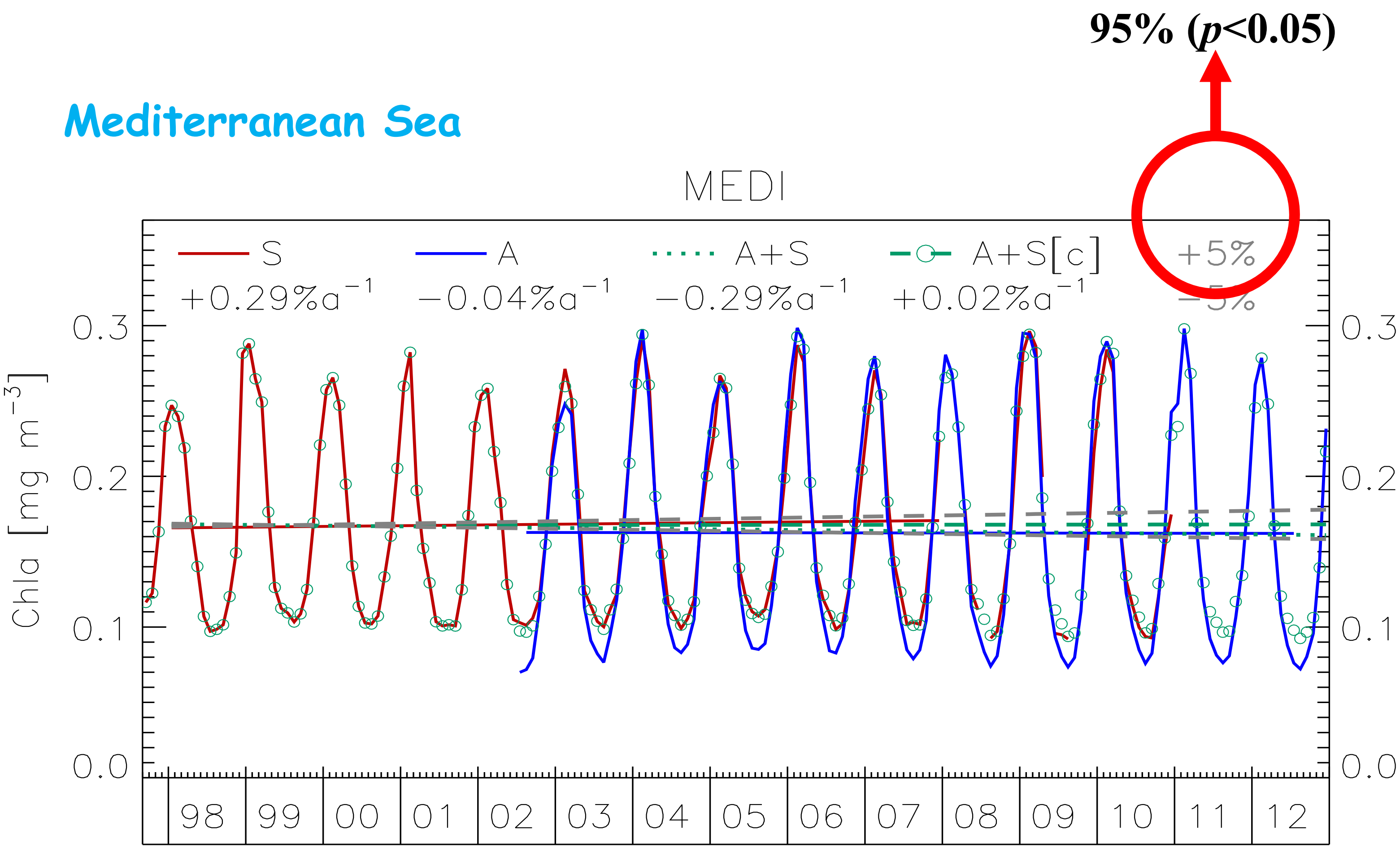


$x_{MRG}(m) = x_S(m)+(1 + \%bias/100)\ x_{A,c}(m)$ %bias: [-50% to +50%]

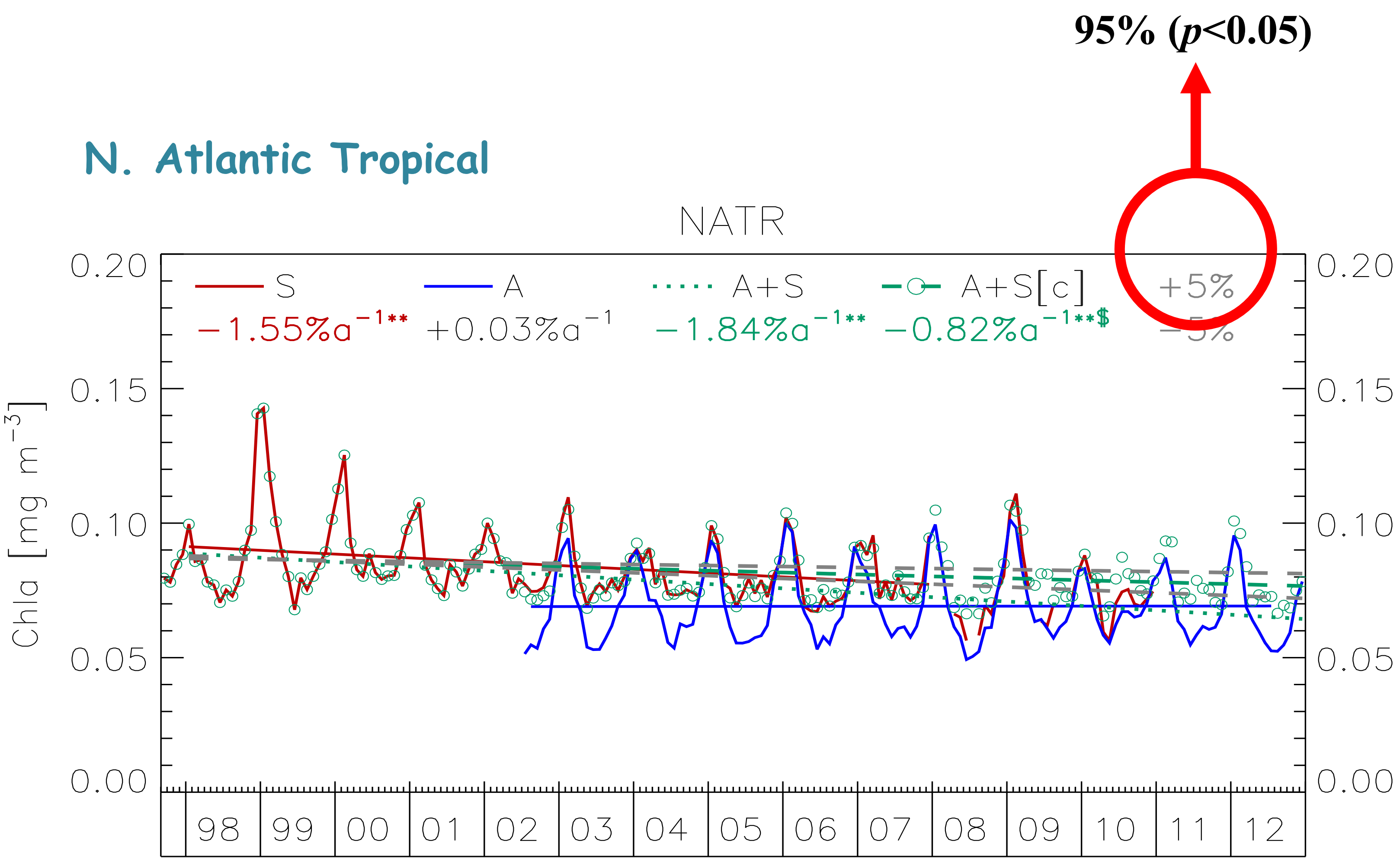
Probability that the trends found for the reference (climatologically corrected) and the “biased” series are significantly different

→ **matrix [province, bias -> probability]**

Mediterranean Sea



Probability that the trend of the "biased" series be significantly different from the reference trend

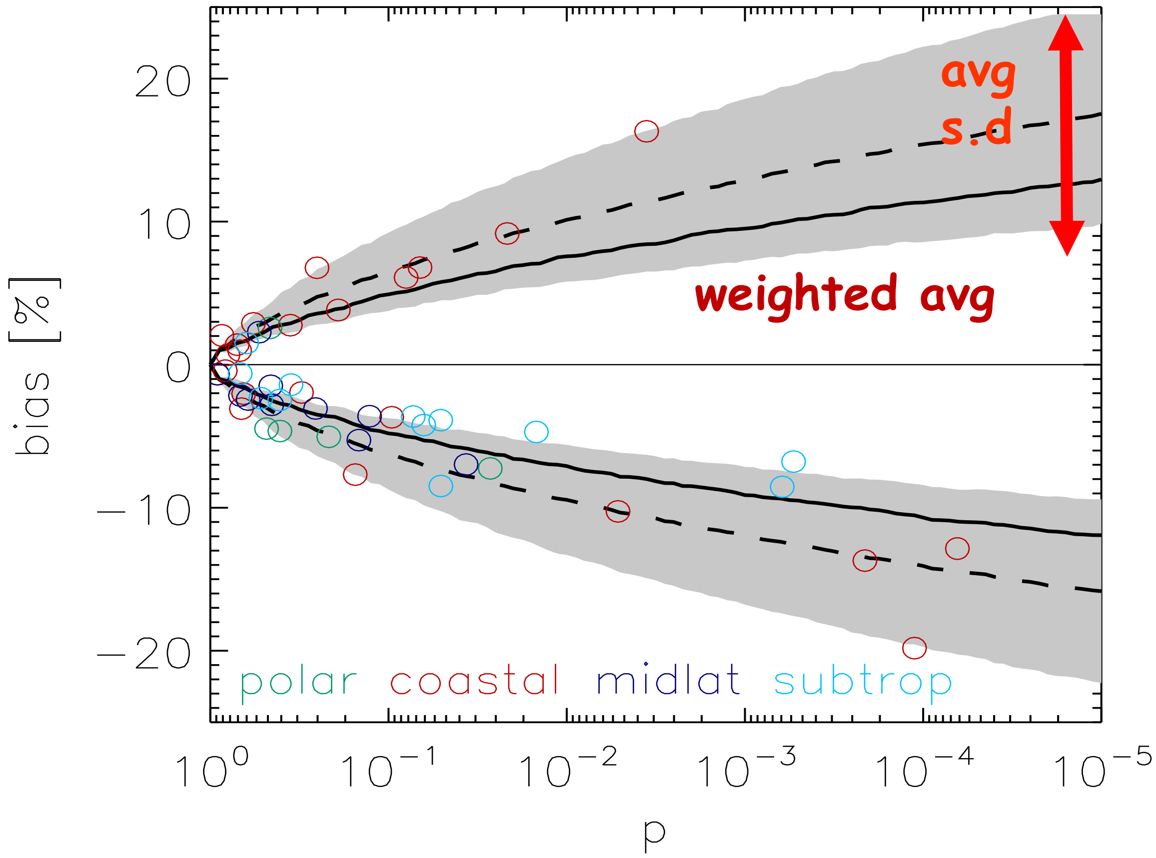


95% (p<0.05)
N. Atlantic Tropical
NATR
S
A
A+S
A+S[c]
+5%
−5%
−1.55%a−1**
+0.03%a−1
−1.84%a−1**
−0.82%a−1**$
Chla [mg m−3]
0.20
0.15
0.10
0.05
0.00
98
99
00
01
02
03
04
05
06
07
08
09
10
11
12

matrix [province, probability = fn(bias)]

→ matrix [province, bias = fn(probability)]

average bias = fn(probability)



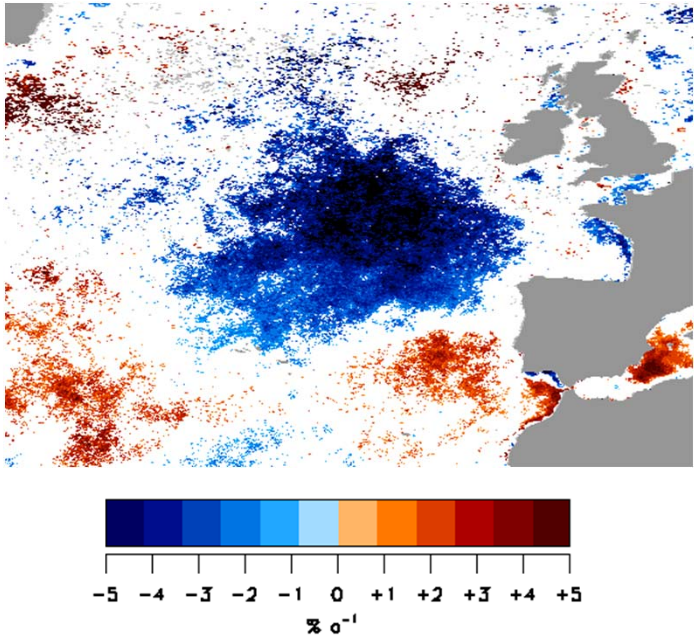
		avg	weighted avg
p<0.01	99%	±9.7%	±7.3%
p<0.05	95%	±7.5%	±5.6%
p<0.1	90%	±6.3%	±4.9%
p<0.5	50%	±2.9%	±2.3%

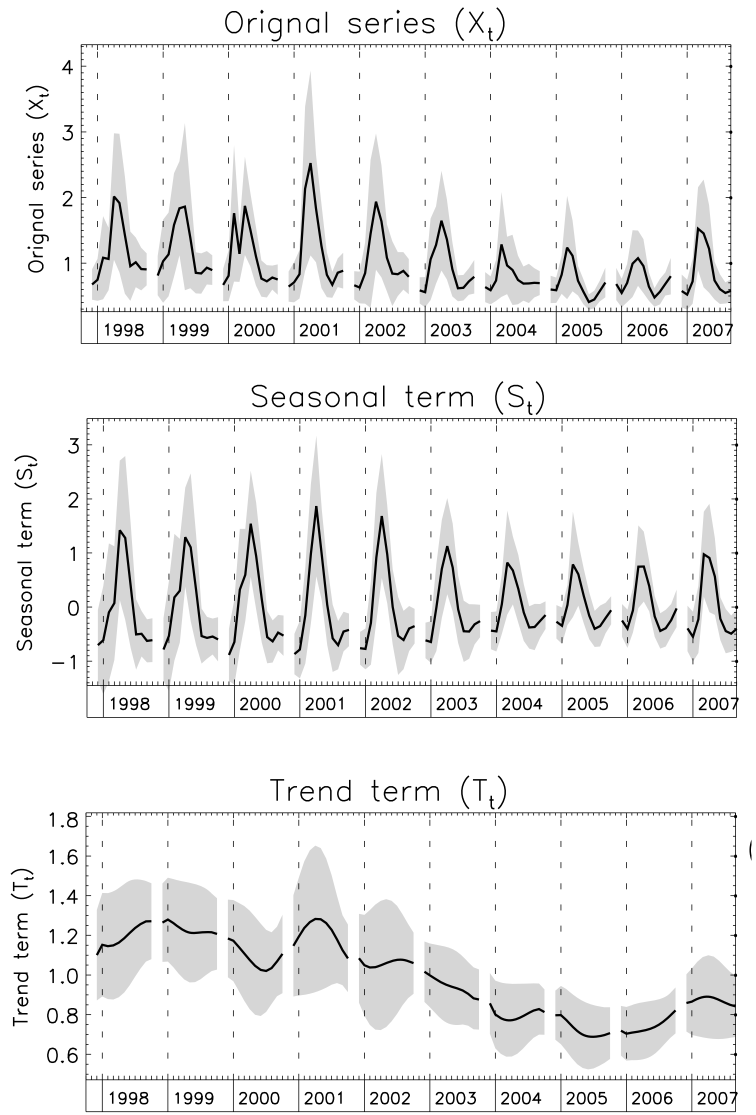
50% 90% 99% ***p***

Mélin, in prep

Decomposition of the signal into seasonal, trend and irregular terms (Census X-11)

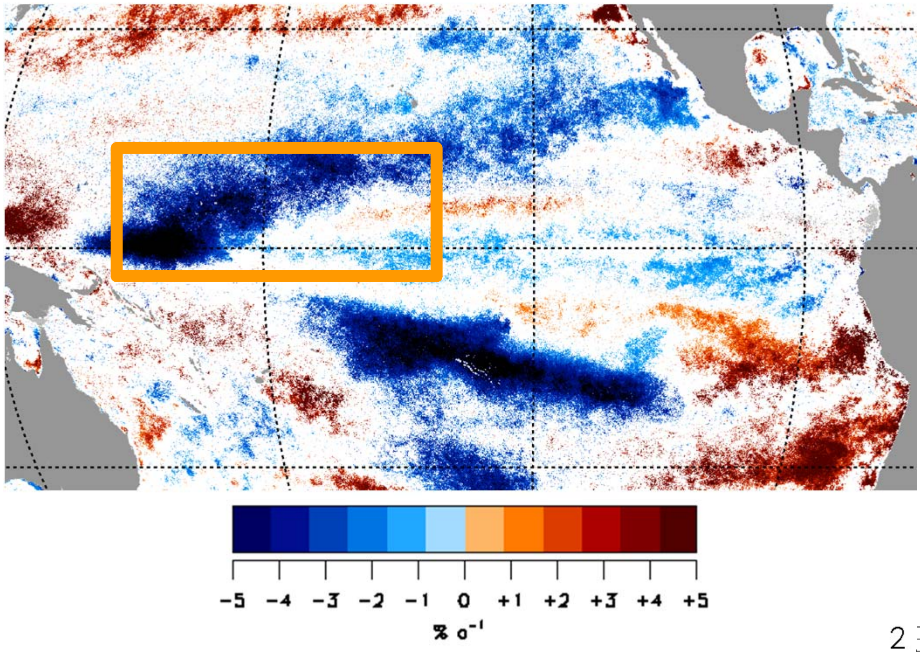
NE Atlantic
Linear Trend SeaWiFS Chla 1998-2007





Vantrepotte & Mélin, *CSR* 2010, *DSR* 2011,
Mélin et al., *PO* 2011

W EQ Pacific
Linear Trend SeaWiFS Chla 1998-2007

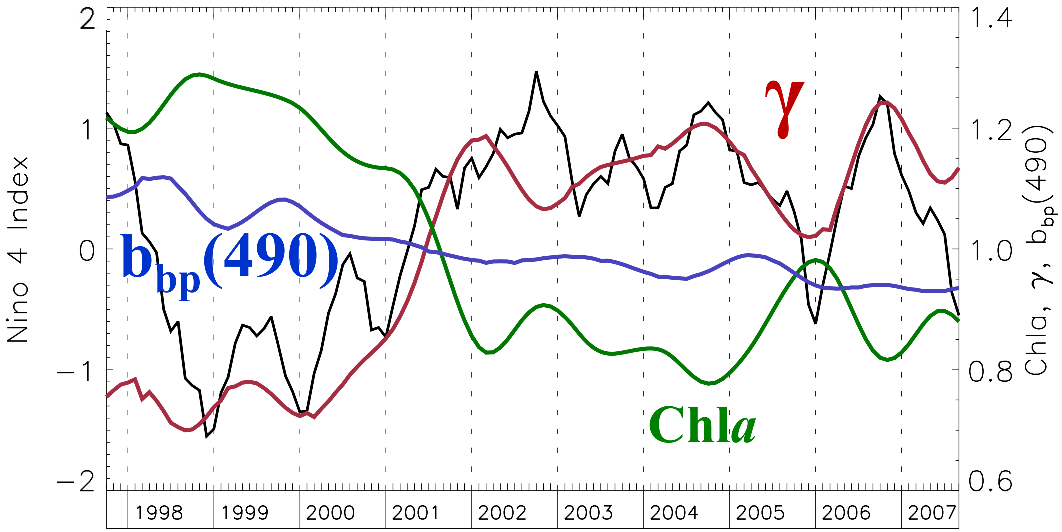


Decomposition of the series:

155E-150W; 5S-20N

Chl*a*
b_{bp}(490) Loisel & Stramski, *LO* 2000
γ = exponent of $b_{bp}(\lambda)$

Niño-4 index (SST anomaly; 160E-150W; 5S-5N)



Vantrepotte et al., *GRL* 2011

Conclusions / Recommendations

❖ Maintain effort at sensor calibration, characterization and temporal stability

INSITU-OCR White Paper 2012

"adequately sampled, carefully calibrated, quality controlled, and archived data for key elements of the climate system will be useful indefinitely"

Wunsch et al., *PNAS* 2013

❖ Ensure full inter-mission consistency through the entire processing chain

❖ Need to thoroughly characterize inter-mission differences and address/integrate them properly in our analyses

❖ Relies on mission overlaps (>1 year!)

Corollary: a gap in the data record is a disaster

Beaulieu et al., *BGSD* 2013

❖ Develop research on relationships between OC-derived variables and the other ecosystem variables, particularly in the context of climate oscillations

“Statistics are no substitute for judgment”

Henry Clay (1777-1852)