The Black Sea *IOPs* based on *SeaWiFS* data

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> “ it was fifteen years ago today ... there is no doubt that this data set will continue to provide new discoveries and insights into the workings of this incredible planet that we call home.”
>
> From Gene Feldman to ocean-color community

Background

Lately substantial advance has been attained on remote sensing methods for the inherent optical properties (*IOPs*) and applications of *IOPs* in ecosystem models. Their detailed description summarizes in [IOCCG, 2006]. Below the short description of remote sensing method for the Black Sea *IOPs* has been done. This method allows retrieving extended set of *IOPs* and recognizing the regional optical properties of the seawater.

Method and Results

A regional algorithm of *IOPs*, such as particle backscattering coefficient at 555 nm, spectral slope of particle backscattering coefficient, absorption coefficient of sum of colored dissolved organic matter and non-algal particles (*CDM*) at 490 nm, spectral slope of *CDM* absorption coefficient, and chlorophyll *a* concentration derived from *SeaWiFS level-2* data, after proper flag/mask and spatial/temporal binning procedures, has been developed. The solution was retrieved in each node of the grid by iteration. To improve the stability of the solution, each iteration consisted of three steps (Table 1 and Fig. 1, Appendix). At each step, the different components of the *IOPs* were retrieved using data from different spectral bands. The key step is the first in the Table 1. To calculate the chlorophyll *a c*oncentration and *CDM* absorption coefficient, the regional algorithm developed for the Black Sea [Suslin et al., 2008a, 2008b] is used. Some examples of half-monthly binning period maps of *IOPs* are shown in Fig. 2. A complete set of bi-weekly *IOPs* maps during *SeaWiFS* lifetime is available from [Black Sea *IOPs* maps, 2012]. The relationships between the different components of Black Sea *IOPs* are displayed in Fig. 3. It has been shown that the optical properties of seawater in the Black Sea are typical waters classified as case 2. This means that in general there are no significant correlation values not only between the particle backscattering coefficient and *CDM* absorption coefficient, but also between the phytoplankton absorption coefficient and *CDM* absorption coefficient.

Application example

The obtained data set of *IOPs* can be applied to classify different phytoplankton types and other applications regarding an estimation of the Black Sea ecosystem indicators such as the downwelling diffuse attenuation coefficient [Suslin et al., 2011], the euphotic depth [Churilova et al., 2009], water heating [Dorofeev et al., 2011] and etc. Below one application is considered. In the plane of the spectral slopes (the absorption coefficient of colored detrital matter and particle backscattering coefficient) derived from *SeaWiFS* data, the features of optically active components contained in seawater of the Black Sea (in particular, taxonomic and cell-size structure of phytoplankton) are presented in Fig. 4(top-left). For joint analysis, the *in situ* measurements of bio-optical characteristics of phytoplankton during two-year monitoring (from 1998 to 1999 [Curilova et al., 2004]) in western part of the Black Sea and *IOPs* data set derived from *SeaWiFS* were used. At least four interesting situations related to (1) decreasing of the spectral slope value of the absorption coefficient of colored detrital matter in photolysis of colored dissolved organic matter or detritus impact, (2) increasing the the spectral slope value of particle backscattering coefficient during coccolithophorid blooms accompanied by the release of nano-size plates called coccoliths which well scatter the light in back part of volume scattering function, (3) low values of the spectral slope of particle backscattering coefficient when the predominance of micro-size phytoplankton (diatoms and dinoflagellates or their composition) occurs, (4) presumably with the presence of cianobacterias contained pigments which absorb light in the range from 530 nm to 560 nm, have been identified (see Fig. 5). Examples of the spatial distribution and seasonal variability of these features in half-monthly maps are given in Fig. 6. A complete set of half-monthly and half-month climatology maps during *SeaWiFS* lifetime is available from [Black Sea *BIO* maps, 2012]. Thus, under certain conditions, a set of points in two-dimensional space of the spectral slopes identifies the optically active substances contained in seawater, in particular, the different phytoplankton types.

Conclusions

A regional algorithm of the inherent optical properties, *IOPs*, such as particle backscattering coefficient at 555 nm, spectral slope of particle backscattering coefficient, absorption coefficient of sum of colored dissolved organic matter and non-algal particles at 490 nm, spectral slope of *CDM* absorption coefficient, and chlorophyll *a* concentration derived from *SeaWiFS level-2* data, has been developed.

It has been shown that the optical properties of seawater in the Black Sea are typical waters classified as case 2. This means that in general there are no significant correlation values not only between the particle backscattering coefficient and *CDM* absorption coefficient, but also between the phytoplankton absorption coefficient and *CDM* absorption coefficient.

Under the certain conditions, a set of points in two-dimensional space of the spectral slopes of *IOPs* identifies the optically active substances contained in seawater, in particular, the different phytoplankton types.

A complete set of *IOPs* and *BIO* half-monthly climatology and half-monthly maps during *SeaWiFS* lifetime is available from http://blackseacolor.com [Black Sea *IOPs* maps, 2012; Black Sea *BIO* maps, 2012].

Acknowledgments

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Table 1. Description of three sequential steps of one iteration

Step	Input	Output	Local method
1	$I_s(490)$, $I_s(510)$	$a_{CDM}(490)$, C_a , class of decision	$\min\limits_{a_{CDM}(490), C_a, \text{class of decision}} \sum_{\lambda}^{490,510} [I_s(\lambda) - I_m(\lambda)]^2$
2	$R_{RS,s}(490)$, $R_{RS,s}(555)$, $a_{CDM}(490)$, C_a , class of decision	$b_{bp}(555)$, n_p	$\min\limits_{b_{bp}(555), n_p} \sum_{\lambda}^{490,555} [R_{s,RS}(\lambda) - R_{m,RS}(\lambda)]^2$
3	$I_s(412)$, $a_{CDM}(490)$, C_a , $b_{bp}(555)$, n_p , class of decision	S	$\min\limits_{S} [I_s(412) - I_m(412)]^2$

Note: the subscripts s and m represent the satellite and model inputs, respectively.

Appendix The description of the variables.

Table A. Some definitions

$I(\lambda)$	$I(412)$	$I(490)$	$I(510)$
$\frac{nLw(\lambda_0)}{nLw(\lambda)}$	$\frac{nLw(443)}{nLw(412)}$	$\frac{nLw(510)}{nLw(490)}$	$\frac{nLw(555)}{nLw(510)}$

$$nLw(\lambda) = F_0(\lambda) \cdot R_{RS}(\lambda) \quad ,$$

where $nLw(\lambda)$ is normalized water-leaving radiance at λ ,
$R_{RS}(\lambda)$ is above-surface remote sensing reflectance at λ ,
$F_0(\lambda)$ is solar constant at band λ

$$R_{RS} = \frac{0.518 \cdot r_{RS}}{1 - 1.562 \cdot r_{RS}}$$

$$r_{RS} = 0.0949 \cdot u + 0.0794 \cdot u^2 \quad ,$$

where r_{RS} is subsurface remote sensing reflectance,

$$u = \frac{b_b}{b_b + a} \quad ,$$

b_b is total backscattering coefficient,
a is total absorption coefficient,

$b_b = b_{bw} + b_{bp}$,

where $b_{bp}(\lambda) = b_{bp} \cdot \left(\frac{555}{\lambda}\right)^{n_p}$ is particle backscattering coefficient,

λ is in nm,

$n_p > 0$ is a spectral slope of $b_{bp}(\lambda)$,

b_{bw} is clear seawater backscattering coefficient.

$a = a_w + a_{CDM} + a_{ph}$,

where a_w is clear seawater absorption coefficient,

a_{CDM} is sum absorption of dissolved and derital matter,

a_{ph} is phytoplankton absorption coefficient.

$a_{CDM}(\lambda) = a_{CDM}(\lambda_0) \cdot \exp(-S \cdot (\lambda - \lambda_0))$,

where λ_0 is 490 nm, $S > 0$ is spectral slope of $a_{CDM}(\lambda)$.

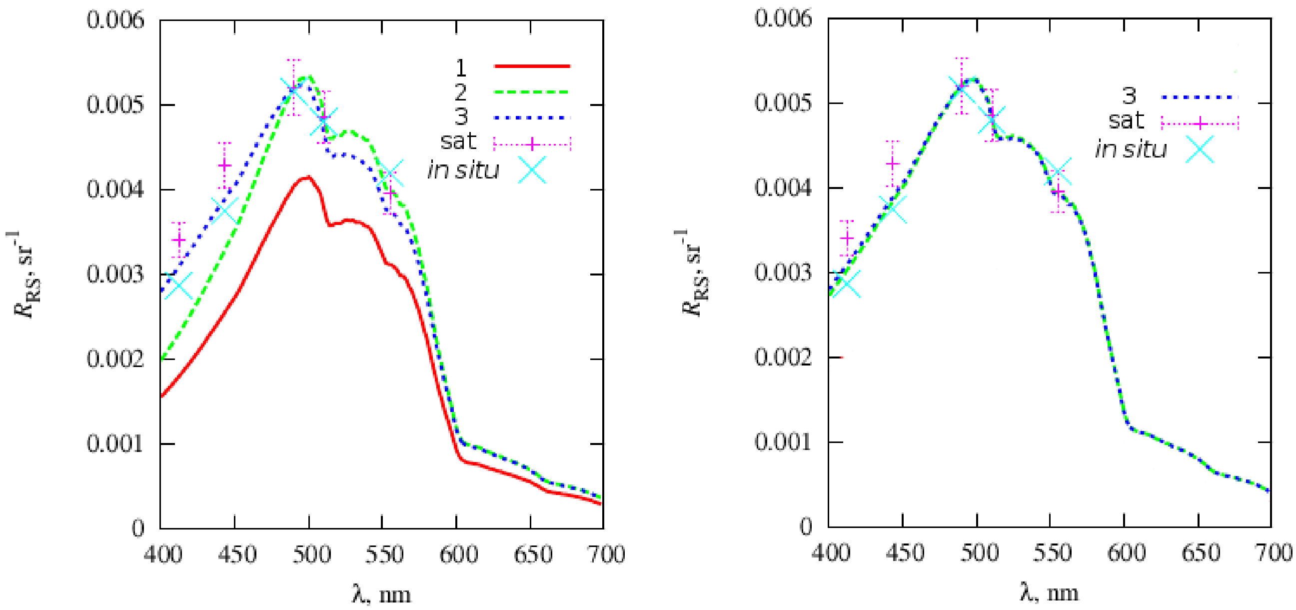
$a_{ph}(\lambda) = k(\lambda) \cdot a_{ph}(\lambda_0)$,

where λ_0 is 490 nm.

Table B. Means of k for two classes of decisions (*Deep* and *Shelf* decisions) in five *SeaWiFS*'s bands

λ, nm		555	510	490	443	412
k	*Deep*	1.2	0.7	1	1.43	1.34
	Shelf	0.5	0.88			

$a_{ph}(490) = A \cdot C_a$, where $A = 0.0274$ m^2 mg^{-1} C_a .



(a) (b)

Figure 1. Examples of model $R_{m,RS}(\lambda)$ spectrum and their comparison with *in situ* measurement (*in situ*, [Burenkov et al., 2000]) and satellite product $R_{RS}(\lambda)$: (left) step-by-step evolution of model $R_{m,RS}(\lambda)$ spectrum of the first iteration (see Table 1) and (right) retrieved model $R_{m,RS}(\lambda)$ spectrum after third iteration

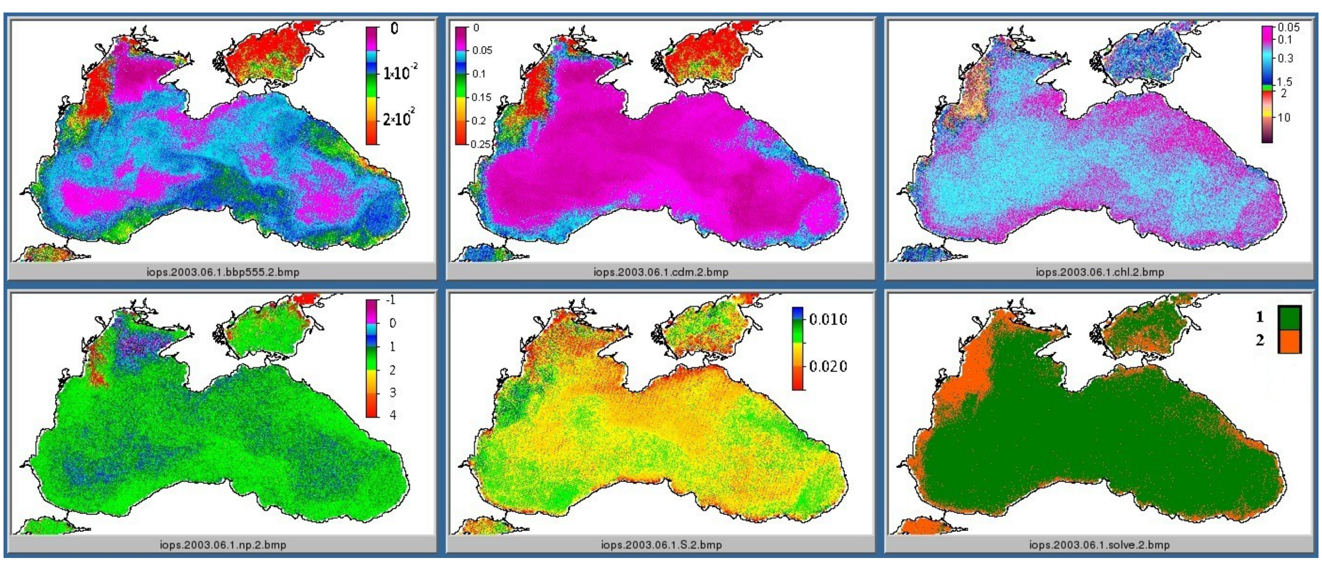
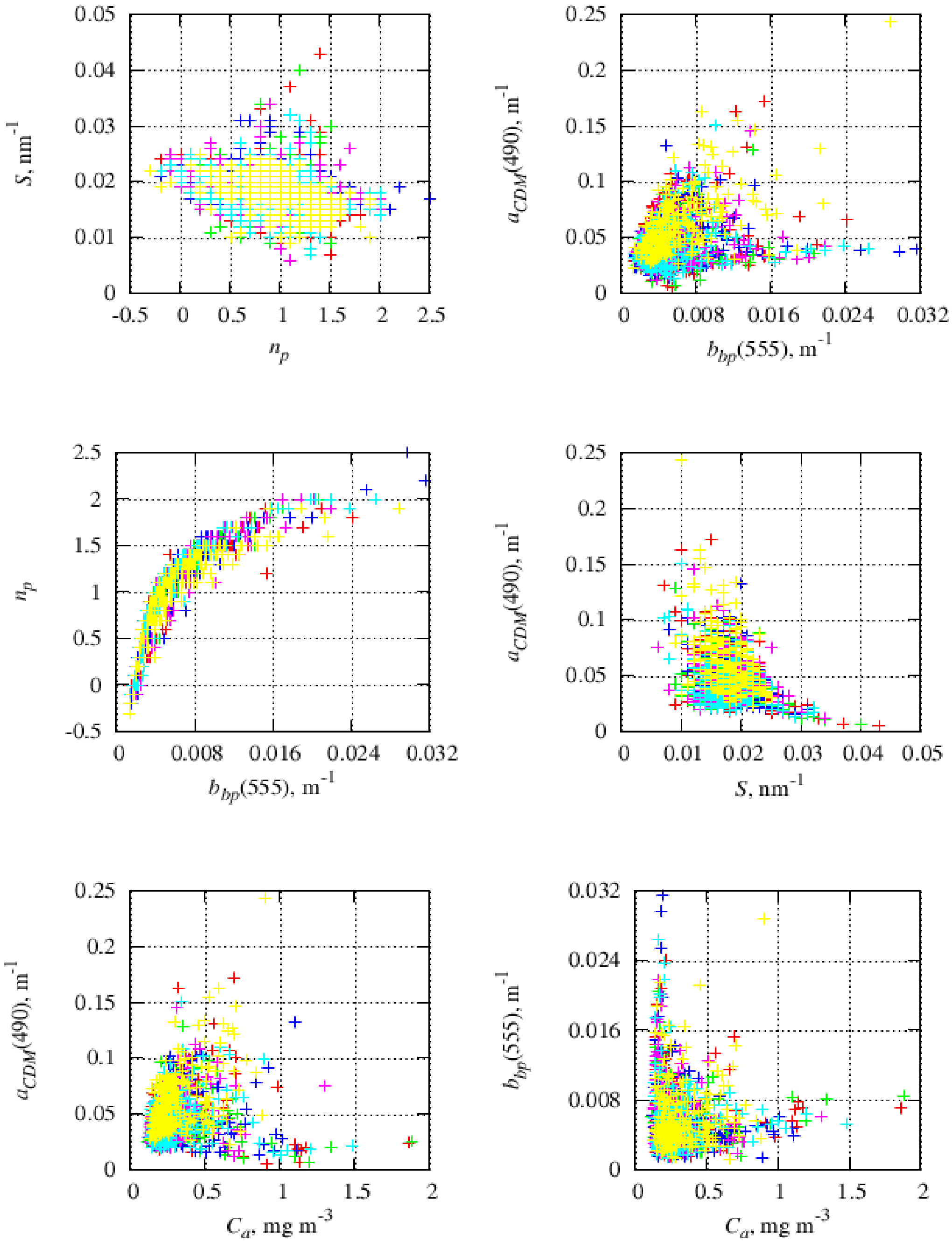


Figure 2. Example of $IOPs$ maps for first half of June, 2003

Top: (left) $b_{bp}(555)$, m^{-1}; (center) $a_{CDM}(490)$ m^{-1}, and (right) C_a , mg m^{-3}
Bottom: (left) n_p dimensionless, (center) S , nm^{-1}, and (right) class of decision, dimensionless



Fugure 3 . Links between *IOPs* bi-weekly data set [3] : (top-left) n_p and S ; (top-right) $b_{bp}(555)$ and $a_{CDM}(490)$; (middle-left) $b_{bp}(555)$ and n_p ; (middle-right) S and $a_{CDM}(490)$; (bottom-left) C_a and $a_{CDM}(490)$; (bottom-right) $a_{CDM}(490)$ and $b_{bp}(555)$ in the six domains (Fig. 4, each domain marks own color) of the Black Sea during *SeaWiFS* lifetime

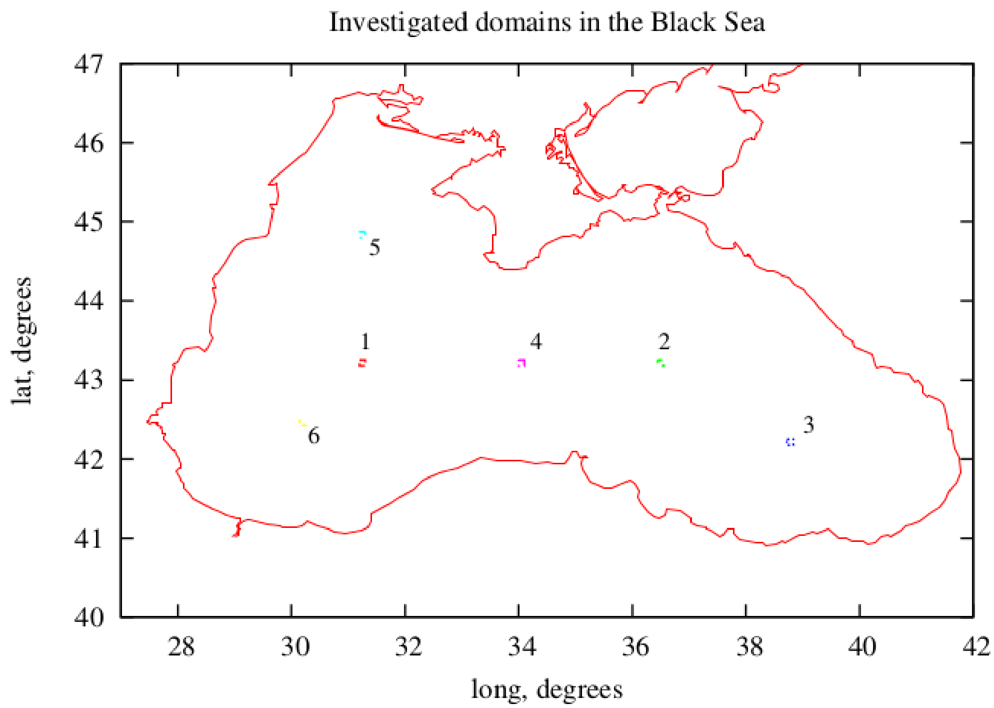


Figure 4. Geo-location of the six investigated domains in the Black Sea

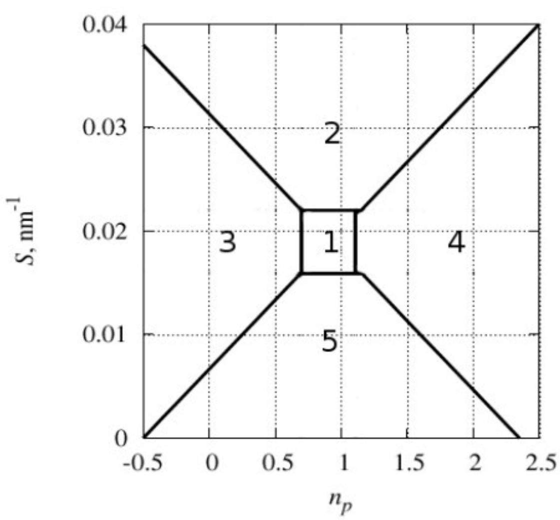
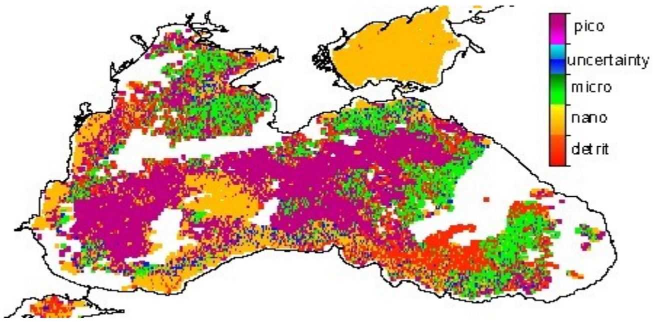
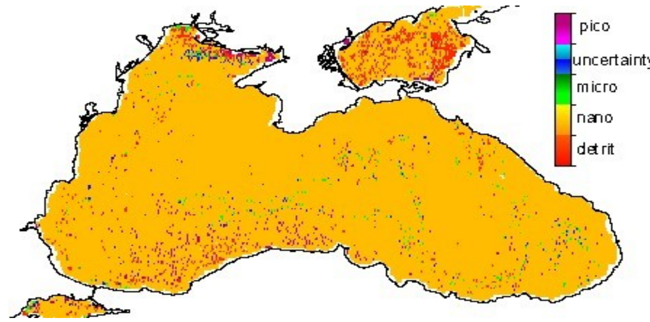


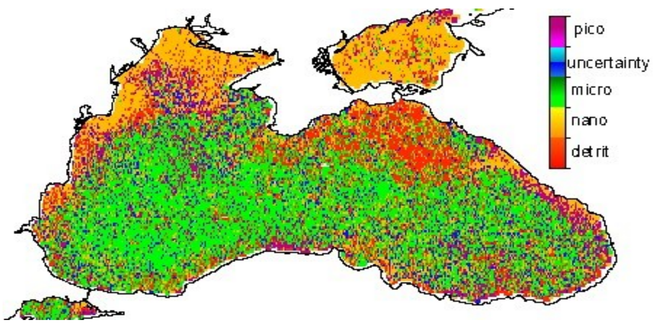
Figure 5. Five clusters of possible realizations in the plane of $\{n_p, S\}$ in the Black Sea as results of joint analysis of in situ measurements and *IOPs* product : (1) uncertain zone; (2) picoplankton (supposedly cyanobacteria); (3) microplankton (diatom, dinoflagellate or their mixture); (4) nanoplankton (coccolitophoride); (5) detrit



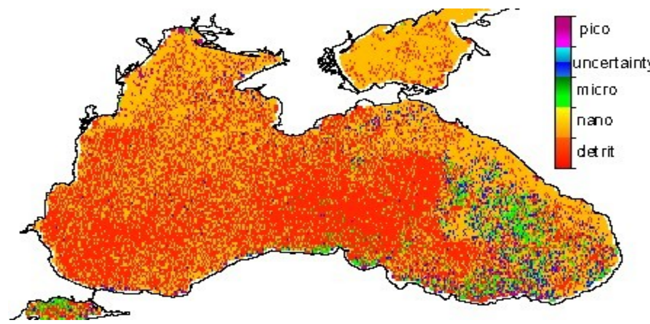
Second half of March , 1998



First half of June, 2002



Second half of August , 2004



Second half of June , 2001

Figure 6. Map examples of temporal/spatial variability of five clusters from Fig. 5