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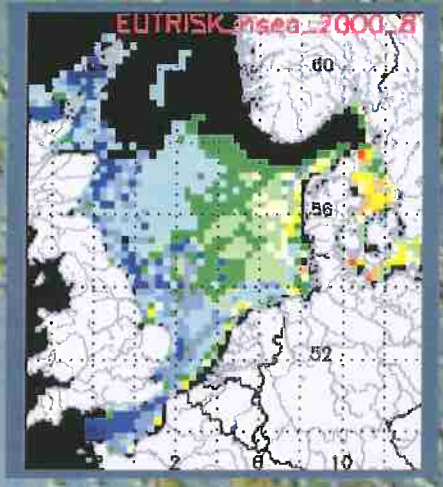
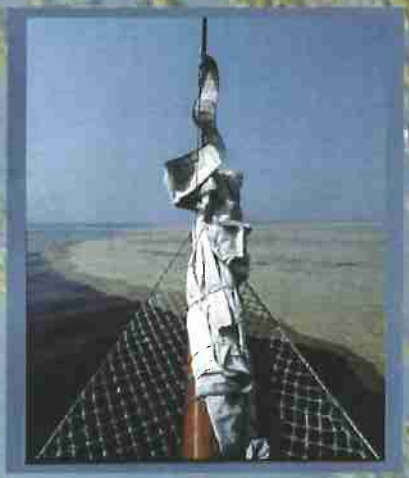
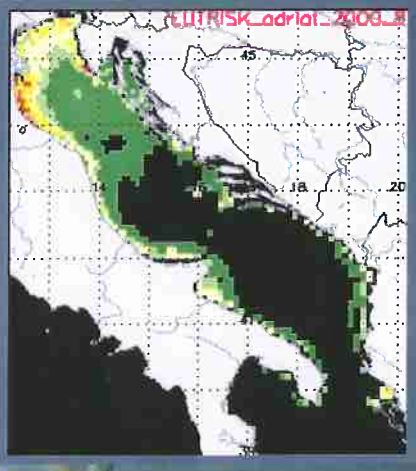
The physical environment as a key factor in assessing the eutrophication status and vulnerability of shallow Seas : PSA & EUTRISK (v1.0)

Jean-Noël Druon, Wolfram Schrimpf, Srdjan Dobricic and Adolf Stips







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Front page illustration: EUTrophication RISK (EUTRISK) indice for August 2000 in the North Sea (top left) and the Adriatic Sea (bottom right, Figure 14), and mucilage photographs of Phaeocystis in the north-east Channel (top right, photograph by Benoist Hitier, IFREMER Boulogne-sur-Mer, France, Hardelot Plage, June 1999) and of various marine organisms in the Adriatic Sea (bottom left, photograph by Michele Giani, ICRAM, summer 1997), both resulting of excess loadings of nitrate and phosphate in the marine environment. The background photograph is an assemblage of various marine phytoplankton species (courtesy of Wim van Egmond).

The physical environment as a key factor in assessing the eutrophication status and vulnerability of shallow Seas PSA & EUTRISK (v1.0)

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Abstract

Two spatial eutrophication indices of shallow marine ecosystems are proposed based on 3D hydrodynamic modelling data and satellite remote sensing data of ocean colour. The indices are derived in two systems characterized by different physical regimes: the Adriatic and the North Sea. The Physically Sensitive Area index (PSA) integrates the various supporting factors of eutrophication, i.e. the physical conditions that influences the primary production in the upper layer and the oxygen availability near the sea bottom. The PSA index portrays the location of oxygen deficiencies if both the nutrient distribution and the primary production would be uniformly distributed. The EUTrophication RISK index (EUTRISK) represents the spatial distribution of potential hypoxia for a given month integrating the physical supporting factors and the flux of organic matter estimated from satellite-derived chlorophyll-a maps, with an oxygen budget estimated on a monthly basis. The PSA and EUTRISK indices identify three main types of eutrophied waters: 1) eutrophic and sensitive, 2) eutrophic and resistant and 3) mesotrophic and sensitive. Category 1 is where the oxygen depletion occurs regularly because both the main pressure and supporting factors are unfavourable (*e.g.* coastal waters south of the Pô river mouth). Category 2 depicts areas where there is no severe hypoxia near the sea bed because of a permanent tidally-induced vertical mixing, but where the loss of biodiversity and the appearance of opportunist species are generally observed (*e.g.* Bay of Seine and Wash Embayment). In category 3, severe hypoxia or anoxia are reported due to particularly adverse physical conditions even if the primary production is relatively low (*e.g.* Kattegat and north of 45°N in the Adriatic Sea). PSA and EUTRISK are innovative and harmonized tools for the assessment, monitoring and comparison of the eutrophication status of marine/coastal waters. It should provide assistance to policy makers to improve the ecological management of coastal marine waters, notably as regards to the different European environmental legislations and policies and Regional Marine Conventions, and the scientific community to identify the impacted areas and the main mechanisms involved.

Introduction

The eutrophication process has not always been seen as a negative effect on the aquatic ecosystem, being qualified of "positive" for the fisheries globally in the 50's (Thurow 1999), and more recently on a regional scale (Marasovic et al. 1988, Josefson and Rasmussen 2000). It was associated with the "vulnerability" of the ecosystem in the 60's (Harwood et al. 1990, Hagen and Kleeberg 1994) and became a "risk society" discourse in the 90's (Cullen 1989, Archer and Marks 1997, Wilson et al. 1999). In reaction to the increasing water pollution, the first water directives of the European Commission appeared in the late 70's but were focused on water bodies used for human activities (drinking water, bathing water, shell fish water, etc.). Since 1987, water directives have focused primarily on the origin of the disturbances. The eutrophication process was clearly tackled in the Nitrates Directive (91/676/EEC) and the Urban Waste Water Directive (91/271/EEC). The Maastricht (1992) and Amsterdam (1997) Treaties have re-enforced the applicability of the Directives and the awareness of a "sustainable development", the principles of "precaution" and "prevention at source". In parallel the various Marine Conventions (OSPAR-1992, Helsinki-1992 and Barcelona-1976) were established where the combat of eutrophication represents one of the major objectives to fulfil. Nowadays, the eutrophication definition is broader to include the diversity of the disturbances, the complexity of interactions within variously sensitive ecosystems, as shown by the latest OSPAR's definition in 1998: '"Eutrophication" means the enrichment of water by nutrients causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned, and therefore refers to the undesirable effects resulting from anthropogenic enrichment by nutrients'. Because of the complexity of biology, numerous indicators of eutrophication can be found from one region to the other using different thresholds for defining the eutrophied status. A core set of indicators for water has been set by the European Environmental Agency where thirty one of eighty six concern eutrophication (Nixon 2002). The implementation of policies such as the latest and comprehensive Water Framework Directive (2000/60/EC) adopted in 2000 is dependent on the capacity of ecological indicators to capture the complexities of the ecosystem, yet remain simple enough to be easily and routinely monitored (Dale and Beyeler 2001). Existing advanced indices linked to eutrophication can be classified in three main groups: trophic indices, eutrophication indices and sensitivity to nutrient over-enrichment indices. The trophic indices are generally including attempts to find a general empirical relation between algal biomass or production and nutrient concentration or loading (Nixon 1992, Moriki and Karydis 1994). Some authors include the surface oxygen content (TRIX, Vollenweider et al. 1998) or the Secchi depth (OECD classification, Zurlini 1996). The eutrophication indices are based on monitoring of biotic or/and abiotic parameters. All biotic indices are taking advantage of the changes in the phytoplankton (Kitsiou and Karydis 2000, Danilov and Ekelund 2001, Karydis and Tsirtsis 1996, Tsirtsis and Karydis 1998) or the benthic (Grall et al. 1997) community accompanying eutrophication. The abiotic eutrophication indices use monitoring data of nutrient concentration and near bottom oxygen (Abdullah and Danielsen 1992), or surface and bottom dissolved oxygen (Justic 1991). The sensitivity to nutrient over-

enrichment indices are based on the dilution and flushing capacity of estuaries (NOAA's indices DCP - Dissolved Concentration Potential - and EXP - Estuarine Export Potential - NRC 2000, tidal index of Monbet 1992) or light an nutrient limitations for the phytoplankton growth (Cloern 1999). An index combining physical vulnerability, pelagic and benthic characteristics and trophodynamics was successfully tested for five estuaries (Ferreira 2000). However, these indices are either region specific (biotic criteria) or incomplete (physical sensitivity) and all are geographycally restricted (*i.e.* applied at the scale of a bay or an estuary) due to the necessary input of *in situ* measurement at the appropriate frequency.

An urgent need for a harmonization of criteria and indices at the European scale applied at a basin scale is expressed by decision makers and the scientific community in order to compare the status and trends of eutrophication (Cognetti 2001). In this work, a complementary pair of advanced eutrophication indices for the coastal marine areas for application at the European scale is proposed. The Physically Sensitive Area index to Eutrophication (PSA) based on 3D hydrodynamic modelling demonstrates the wide variability in the physical resistance of coastal European regions to the eutrophication phenomena. The Eutrophication Risk index (EUTRISK) represents the most probable oxygen deficiency distribution near the bottom integrating data from physical modelling and satellite-derived chlorophyll-a, the latter being considered as the main source of organic matter. Two test areas with highly diverse physical regimes are presented: the Adriatic Sea and the North Sea.

Data and Methodology

The concept of eutrophication

The simplified concept of eutrophication adopted for the indices to be applied to all shallow coastal European seas considers the main pressure, effect, impact and supporting factors (Figure 1). A high nutrient concentration induces a high level of primary production which leads, for shallow waters, to an oxygen consumption near the bottom and depletion in extreme cases. Hypoxia is the most common impact of human-induced marine eutrophication around the world which has expanded rapidly during the last three decades (see overviews of coastal marine hypoxia in Diaz and Rosenberg 1995, Diaz 2001). Moderate hypoxia and the loss of biodiversity represent together an intermediate step of eutrophied waters shown as medium values on the scale of the EUTRISK index. The supporting factors incorporated in the PSA index are defined as the surface and bottom layer physics which play a key role respectively in the phytoplankton growth and the oxygen cycle near the sea bottom.

The *in situ* monitoring of dissolved oxygen near the bottom has a very limited spatio-temporal dimension using most traditional strategies. On the opposite, the frequent observation of chlorophyll-like pigments of coastal seas by remote sensing of ocean colour provides, despite some limitations which are discussed below, a good estimate of the main vector of eutrophication. A better assessment of the eutrophication status is obtained using satellite chlorophyll-a estimates rather than a full bio-physical modelling approach, because the former strategy avoids the uncertainties linked to the largely

unknown distribution of nutrients, their respective ratio and the associated phytoplankton dynamics (light availability, growth rate and nutrient uptake). The EUTRISK index does not require the knowledge of the nutrient nor the phytoplankton dynamics utilizing the measurement of a later step in the nitrogen and phosphorus cycle: the integration in the organic matter (see Figure 1).
The basic principles of the PSA and EUTRISK indices are to use known, deductible or easily observable and non-correlated parameters with an adequate temporal and spatial resolution.

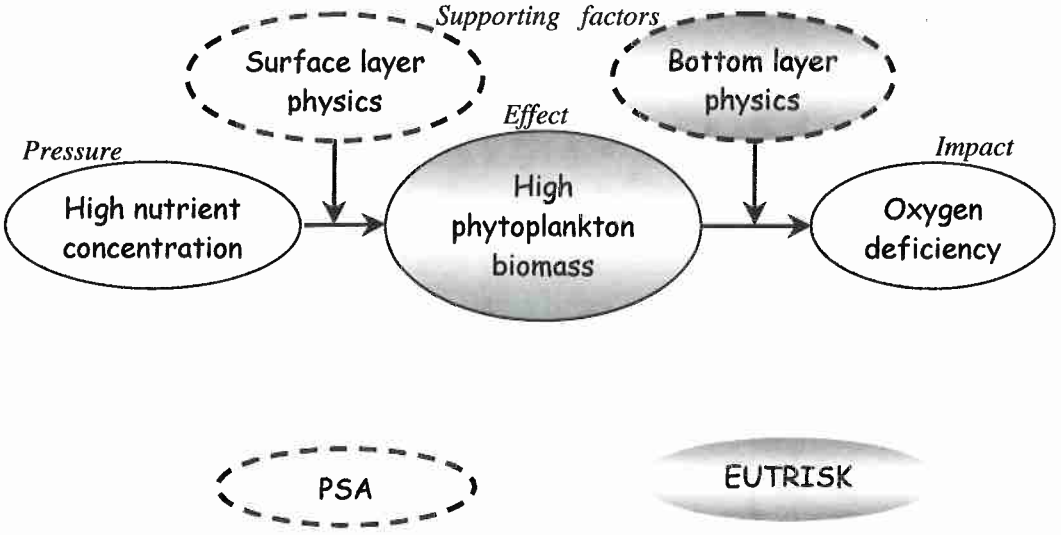

Figure 1. The simplified concept of eutrophication used for marine shallow waters. The figure shows the variables used for the Physically Sensitive Areas index to eutrophication (PSA, dashed) and the EUTrophication RISK index (EUTRISK, filled).

The numerical model data

Both models used for the Adriatic Sea (ISPRAMIX) and the North Sea (HAMSOM) are 3-D baroclinic circulation, free surface, hydrostatic models which have prognostic equations for velocity, temperature salinity and turbulent kinetic energy.
ISPRAMIX was developed to be applied together with 4-D data assimilation technique in marine coastal areas for realistic simulation. The model was applied and validated in the North Atlantic ocean at three spatial scales using a nested procedure to study the North-West African upwellings (Demirov et al. 1999) and is currently used in the Adriatic Sea (Dobricic, in preparation). The grid size for the Adriatic Sea is 85*85 cells (39.0-45.8°N, 12.2-20.3°E). The horizontal resolution is about 4 km in the north-west, which corresponds to shallow waters, and 10 km in the south-east of the basin. The model uses a z-coordinate with a maximum of forty vertical levels.

The HAMburg Shelf Ocean Model (HAMSOM), developed jointly by the Institut fur Meereskunde (Hamburg University) and Clima Maritimo, is used in the North Sea. The model is described and validated in this area in Pohlmann 1996a, 1996b and 1996c. The grid size is 58*65 cells (48.9-61.7°N, 5.1°W-13.9°E). The horizontal resolution is 20 km. The model uses the z-coordinate with a maximum of nineteen vertical levels.
Besides the water depth, the physical parameters required for the indices are climatological monthly means or at least five year monthly means of:
- the maximum of the vertical density gradient estimated from the mean daily profiles,
- the depth of the mixed layer corresponding to the maximum of the density gradient,
- the mean current velocity of the mixed layer (x and y components) or residual current in case of a tidal system and
- the mean turbulent diffusion coefficient near the bottom.

The results presented in this paper are the 1991-1998 means for the Adriatic Sea and 1982-1992 means for the North Sea.

The remote sensing data

The satellite chlorophyll-a from SeaWiFS (Sea Wide Field-of-view Sensor) is estimated using the atmospheric corrections developed at the Joint Research Centre (JRC, Sturm and Zibordi 2002) and the Ocean Colour 5 algorithm (OC5, Gohin et al. 2002). The atmospheric correction scheme is producing satisfactory normalized water leaving radiances (generally a difference satellite-derived and in situ 490 / 555 nm ratio smaller than 10%) in a wide range of atmospheric, marine (chlrorophyll-a and total suspended matter concentrations) and geometric conditions. The OC5 chlorophyll-a algorithm uses five channels (412-443-490-510-555 nm) to correct for the effect of the total suspended matter. The latter is responsible of a large over-estimation of the chlorophyll-a concentration when using the standard Ocean Colour 2 algorithm designed for oceanic waters (OC2, O'Reilly et al. 1998). The OC5 algorithm was validated for the turbid waters of the Channel and the French Atlantic waters. The root mean square error (RMS) between the estimated and measured chlorophyll-a is equal to 0.9 and the r^2 coefficient of the linear regression is equal to 0.7 for log-transformed data. The OC5 algorithm was re-calibrated as regards to the water leaving radiances obtained with the JRC atmospheric corrections using the same data set than in Gohin et al. (2002). The SeaWiFS processing made at the JRC is described in Mélin et al. (2000). The application of OC5 in the suspended matter-dominated systems such as the North Sea and the northern Adriatic Sea leads, in comparison with oceanic algorithms, to an improvement of the chlorophyll-a estimate even if the use of such an empirical approach out of the validation area increases the overall error. The uncertainties are however limited due to a good correction of the atmospheric component and the limited extension of turbid waters during the period of major interest for the EUTRISK index (summer). The monthly mean composites of the satellite observations assure a complete coverage in spring and summer for 1998, 1999 and 2000.

The indices

The choice and importance of the water depth for the indices

The term "shallow waters" in this paper applies to water depths between 5 m and 100 m. The term "deep water" refers to water deeper than 100 m. The shallower limit depends on the integration depth of the ocean colour sensor and the resolution of the numerical model. In deep water, the indices are not calculated because anoxia are resulting of a permanent natural stratification. Deep water oxygen deficiencies or anoxia are assumed not to occur due to anthropogenic origin. Deeper than 100 m, the remineralisation of the organic matter in the water column is considered to be sufficient to prevent any important oxygen deficiency near the sea bottom in the absence of a permanent stratification. A minimum remineralisation rate of the detrital organic matter during the growing season (at 15-20° C) of 0.075 d^{-1} (Ménesguen and Hoch 1997, Pondaven et al. 1999, Druon and Le Fèvre, 1999), associated to a maximum sinking velocity of senescent phytoplankton cells of 8 m d^{-1} (Fortier et al. 1994) leads to a rate of 7% surface biomass deposition at 100 m. Even if diatom aggregates are more efficient to export the organic matter with a sinking velocity ranging from 50 to 200 m d^{-1} (Alldredge and Gotschalk 1989), this mode of transport, while possibly important as a source of organic material for deep waters, always involves less than 1% of the ultraphytoplankton in the euphotic zone (Silver et al. 1986). Accordingly, no severe oxygen deficiency or depletion is reported in deep sea bottom due to anthropogenic origin (i.e. from terrestrial input of nutrients). Sill basins or sill deep fjords, like in the Baltic Proper or some Norwegian or West Canadian fjords, are anoxic due to a restricted deep water renewal associated to a permanent stratification. The hydromorphological conditions have here a major role in isolating water masses which become sensitive to eutrophication. The surplus of organic matter from anthropogenic origin reinforces the anoxia of these deep waters but is not the original main cause. The PSA and EUTRISK are aimed to detect and quantify on a comparable scale human linked eutrophication in order to give guidance for restoration. The focus is thus given to coastal waters shallower than 100 m.

The overall concept of the PSA and EUTRISK indices is based on the accumulation of favourable or adverse effects for eutrophication being expressed as comparable indices between 0 and 1. All the selected processes are considered to be critical for eutrophication, thus the weight between indices is set to 1.

The PSA index

The aim of the PSA is to assess the effect of the physical environment on the production and assimilation of the organic matter for shallow marine ecosystems. The PSA index is however assuming that the nutrient distribution is homogeneous. It provides a comparable measure of the physical resistance to eutrophication on a simple scale (value from 0 [blue, high resistance] to 1 [red, low resistance]) for shallow European seas. The main assumption for this index is that the phytoplankton growth and the oxygen cycle near the sea bottom are largely conditioned by the local physical conditions (surface and bottom layer physics, respectively). Identical loading of nutrients into shallow stratified

waters where the advection and the bottom diffusivity are low, or into a tidal (or deep) system will have diverse impacts. Different shallow marine ecosystems have a strongly disparate physical resistance to eutrophication which must be evaluated in order to assess the effort for restoration.

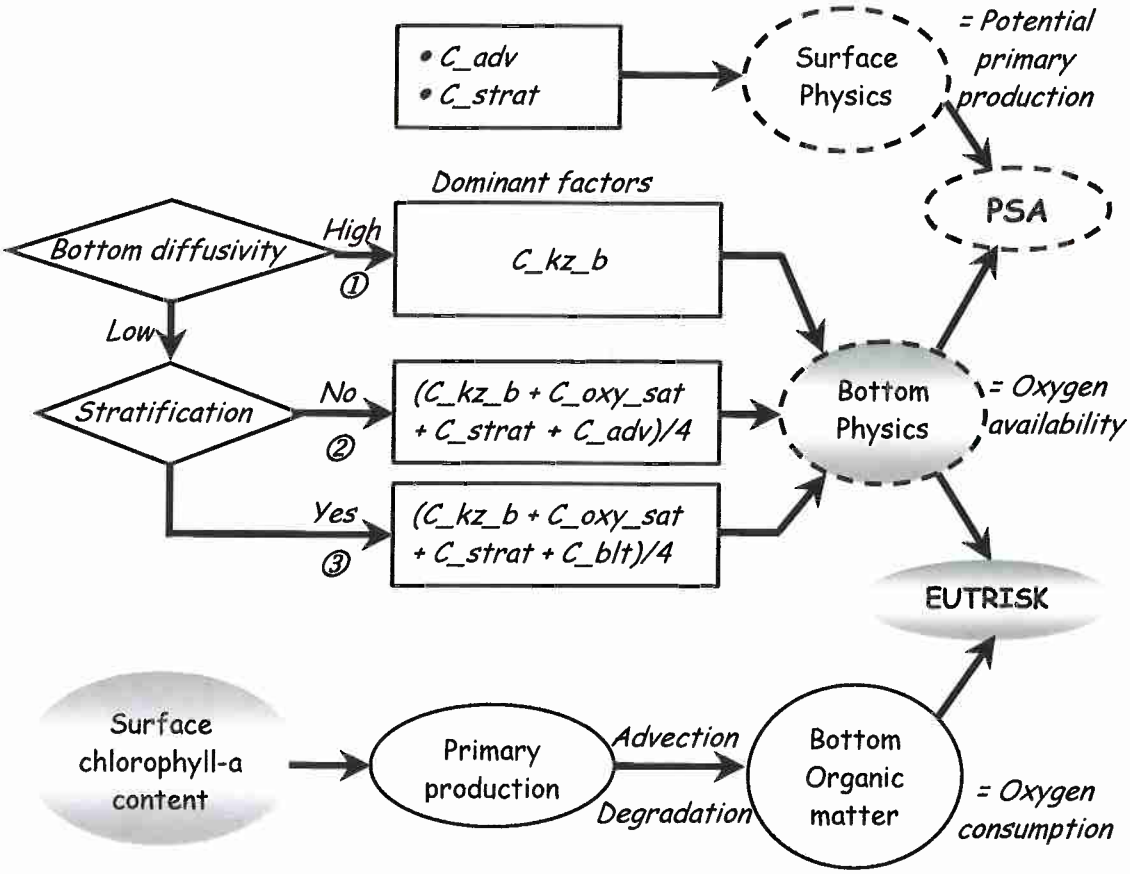

Figure 2. The conceptual model of the coastal eutrophication indices PSA (dashed) and EUTRISK (filled). Following the principle of the dominant factor, the bottom physics index (C_phys_bott) uses three different formulations (①②③) depending on the level of bottom diffusivity and stratification. C_kz_b is the bottom diffusivity index, C_oxy_sat is the oxygen saturation index, C_strat is the stratification index, C_adv is the advection index and C_blt is the benthic layer thickness index (see text for details).

A limited set of physical parameters available from numerical modelling was identified to describe the surface and bottom physics. Figure 2 presents the conceptual model of the coastal marine eutrophication indices PSA and EUTRISK. The advection and stratification define the surface physics, *i.e.* the favourable physical conditions for the phytoplankton growth beside the nutrient consideration. The advection represents the horizontal transport and diffusion of nutrients from a point source and acts as an export and dilution factor. The stratification, by retaining the phytoplankton cells in the euphotic zone, increases the relative light availability for photosynthesis. The bottom diffusivity, stratification and advection are used to characterize the vertical and horizontal oxygen

renewal capacities near the sea bottom. The effects of well established stratification for coastal eutrophication are the increase of primary production and the decrease of the capacity to regenerate the deeper layer oxygen. In contrast, the bottom diffusivity increases the vertical mixing and prevents severe oxygen deficiencies. This dynamical aspect of the oxygen cycle near the bottom is completed by an estimate of the oxygen reserve. The latter depends on the saturation (*i.e.* salinity and temperature) and on the water mass comprised between the mixed layer and the sea bottom in the case where turbulence and eddy diffusion provides enough energy for mixing the dissolved materials within that benthic layer.

Each physical variable is divided by a threshold value to derive an index (between 0 and 1) which is considered to have a linear behaviour. The threshold value defines the limit above which the parameter has no influence on the considered process (for instance, the influence of stratified or extremely stratified waters on the primary production). A value close to zero (blue) represents a high resistance to eutrophication and close to one (red) a low resistance. The general form of the indices is (except for the oxygen saturation index, C_oxy_sat and the benthic layer thickness index, C_blt, see below):

$C_i = \left(\frac{Value_i}{Thres_i} \right) \leq 1$, for the stratification index, C_strat, (unfavourable process) and

$C_i = \left(1 - \frac{Value_i}{Thres_i} \right) \leq 1$, for the bottom diffusivity (C_kz_b) and the advection (C_adv) indices (favourable processes), where C_i is the index of variable i, Value_i is its value, and Thres_i is the corresponding threshold. The Table 1 presents the threshold values for each physical variable and Figure 3 compares the monthly and spatial means for the North Sea and the Adriatic Sea for water depths shallower than 100 m.

Table1. The selected physical parameters and corresponding threshold values.

Parameter	Description	Threshold value or limits	Unit
adv	Advection (u,v)	0.10	$m\ s^{-1}$
strat	Stratification intensity $\left(\frac{\Delta \rho}{\Delta z} \right)$	0.05	$kg\ m^{-4}$
kz_b	Turbulent diffusion coefficient at the bottom	0.01	$m^2\ s^{-1}$
oxy_sat	Oxygen saturation maximum for S = 5 psu & T = 8 °C minimum for S = 38 psu & T = 22 °C	max_oxy_sat = 6.99 min_oxy_sat = 11.45	$mg\ l^{-1}$

Similar scales were chosen to better analyse the differences between the two physical environments. The monthly mean intensity of the advection (or residual current for the tidal system) for the year is similar in both seas. However, a higher seasonal variability occurs in the Adriatic Sea with two maxima in spring and autumn and a critical minimum for eutrophication in summer. The monthly mean residual current in the North Sea is, in

some respect, constant due to the tidal regime, but the variability of the neap-spring tide is not seen at the monthly time scale.

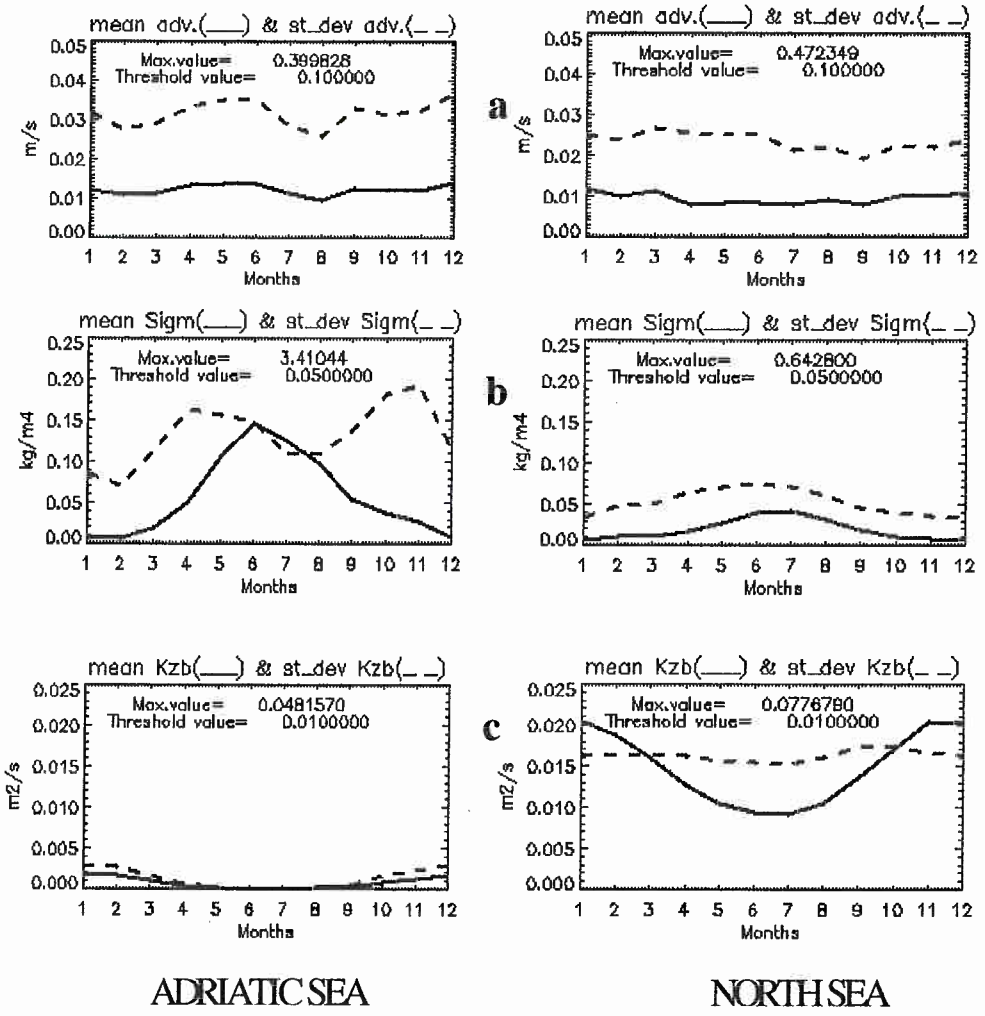

Figure 3. Monthly and spatial mean (solid) and standard deviation (dashed) of the selected physical variables for the Adriatic Sea (left) and the North Sea (right) for waters shallower than 100 m: a) mean advection of the mixed layer or residual current in case of tides (m s^{-1}), b) maximum of the vertical density gradient estimated from mean daily profiles (kg m^{-4}), and c) mean diffusivity coefficient near the sea floor (m^2 s^{-1}).

As a consequence of the two different wind and tidal regimes, the stratification and bottom diffusivity show large differences between areas. The well stratified waters in spring and summer of the Adriatic Sea contrast with the relatively highly mixed waters of the North Sea for the same period. Figure 4 presents the spatial variability of C_adv and C_kz_b for August in the Adriatic and North Seas. As shown in Figure 3a and 3b, no major temporal variability is observed. The surface advection of the Adriatic Sea is dominated by three anticyclonic gyres in the south, central and north of the basin. The advection is particularly strong in the shallow waters facing the Pô river mouth and further south along the Emilia-Romagna coast (>0.1 m s^{-1} as a monthly mean).

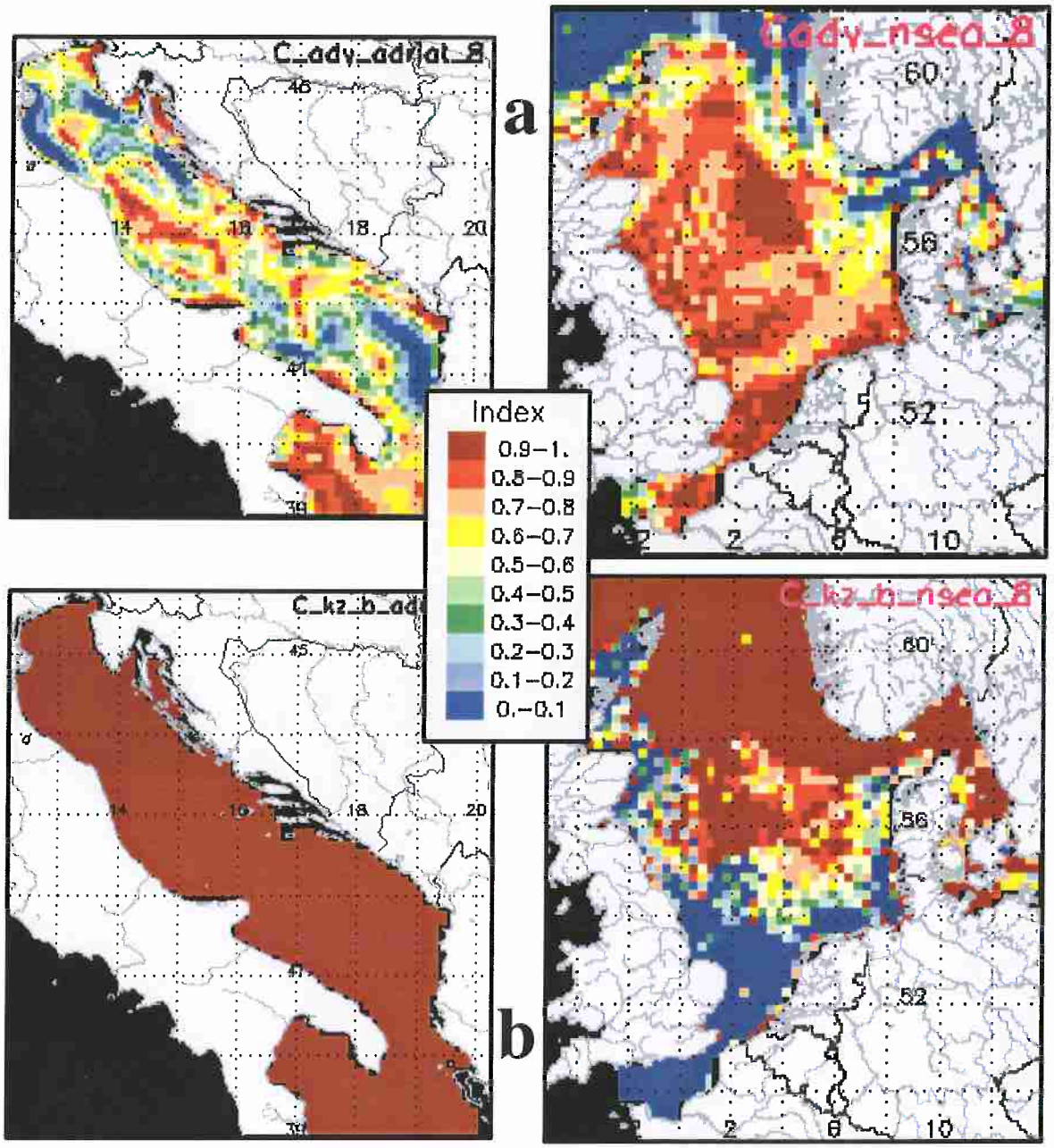

Figure 4. Comparison of the spatial distribution of a) the advection index, C_adv, and b) the bottom diffusivity index, C_kz_b, in the Adriatic Sea (left) and North Sea (right) for August.

Similar maxima of surface advection or residual current are encountered in the Skagerrak and in a few straits of the Kattegat, but most of the North Sea is dominated by low residual currents (<0.01 m s^{-1}). The tidal-induced bottom diffusivity encountered in the North Sea is globally correlated with the water depth, except for the Belt Sea where the tide is low. In the Adriatic Sea, the intensity of bottom diffusivity is comparatively 10 to

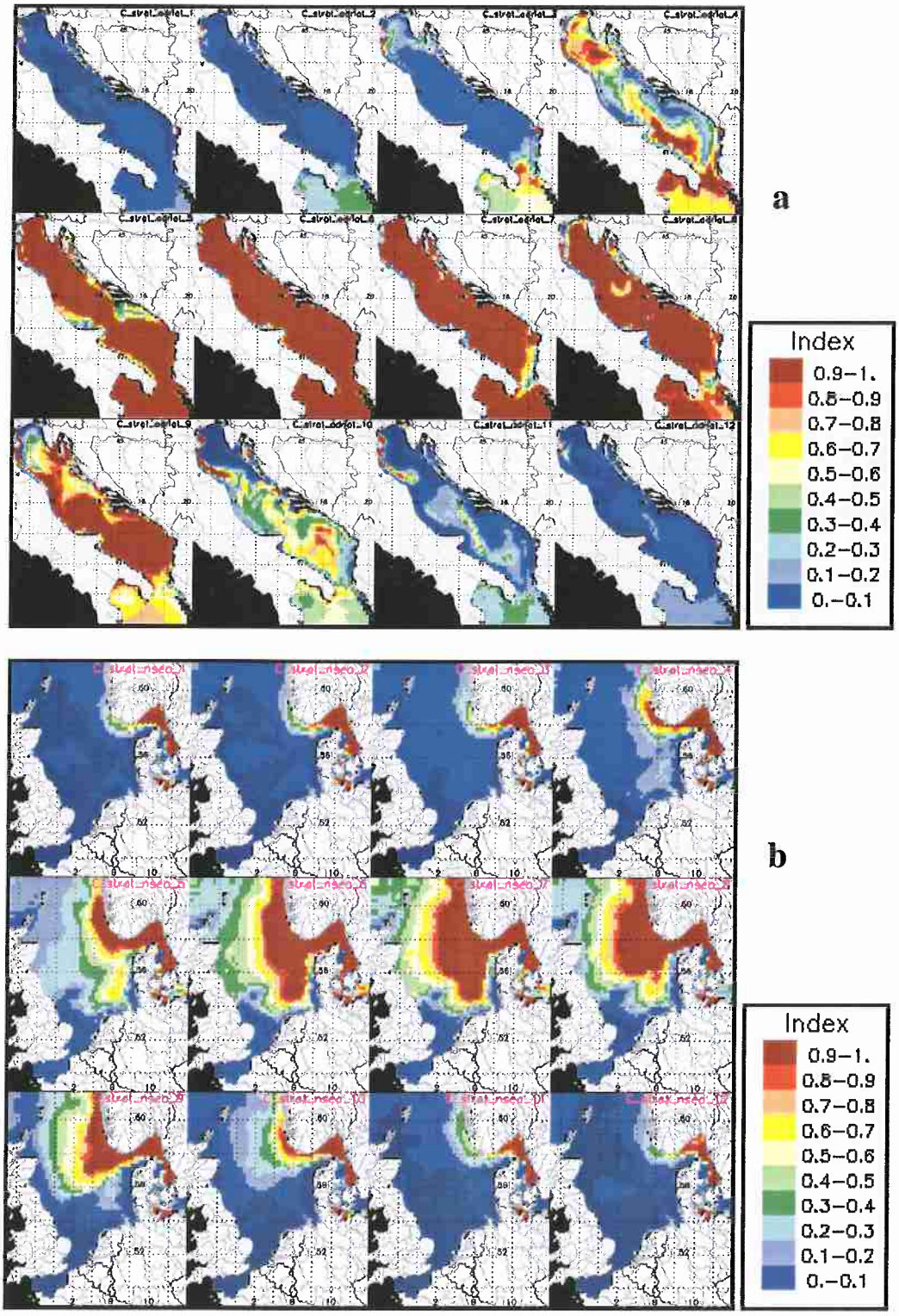

Figure 5. Comparison of the stratification index, C_strat, in a) the Adriatic Sea and b) the North Sea (right) from January to December. South-west of Italy, west Channel and west of UK are not areas covered by the models.

20-fold lower, even in the northern shallow waters where the high level of surface advection is observed. In that case, the stratification isolates the bottom layer from the wind and density currents. Like the surface advection, no major seasonal variability is encountered for the bottom diffusivity, only a small oscillation is observed around the mean value, the latter being one order of magnitude higher in the North Sea compared to Adriatic Sea. Figure 5 presents the spatial variability of the stratification index, C_strat, for both seas. For most areas in both basins stratification is a seasonal phenomenon, but its extension and duration depends on the intensity of the bottom diffusivity. In contrast, a quasi permanent halocline occurs in the major part of the Skagerrak and Kattegat, and along the Emilia-Romagna coast due to the continuous input of fresh water from the Baltic Sea and the Pô river, respectively. These permanent features dramatically increase the sensitivity of these areas to eutrophication by isolating the bottom layer from the vertical supply of oxygen.

The physical capacity of marine waters to contain oxygen is a function of temperature and salinity. As this capacity can double from warm-salty to cold-fresh systems, an index of oxygen saturation is introduced in order to estimate the oxygen reserve of each water body. The index of oxygen saturation is calculated using the monthly mean temperature and salinity at the sea floor given by the models:

$$C_oxy_sat_{x,y,t} = \left(1 - \frac{oxy_sat_{x,y,t} - min_oxy_sat}{max_oxy_sat - min_oxy_sat}\right) \leq 1$$ (x,y are referring to the model grid and t to the monthly time step), with oxy_sat the oxygen saturation given by Weiss, 1970:

$$oxy_sat = C1 * \exp\left(A1 + A2 * \frac{100}{T} + A3 * \ln\left(\frac{T}{100}\right) + A4 * \frac{T}{100} + S * \left[B1 + B2 * \frac{T}{100} + B3 * \left(\frac{T}{100}\right)^2\right]\right)$$

where

A1 = -173.4292	B1 = -0.033096
A2 = 249.6339	B2 = 0.014259
A3 = 143.3483	B3 = -0.001700
A4 = -21.8492	C1 = 1.4276 (mg l^{-1}) or C1 = 1.(ml l^{-1})

T = temperature degrees Kelvin (t degrees celsius + 273.15), S = salinity in g/kg (o/oo), *max_oxy_sat* is the maximum saturation for S = 5 psu and T = 8 °C and *min_oxy_sat* is the minimum saturation for S = 38 psu & T = 22 °C, leading to values of 11.45 and 6.99 mg l^{-1} respectively (see table 1). The distribution of C_oxy_sat for both seas in April and August (Figure 6) shows a global higher oxygen reserve in the North Sea due to lower temperature and salinity. The higher saturation of eastern Danish waters due to low salinity decreases from spring to summer due to a higher temperature. The lowest saturation levels of bottom waters (C_oxy_sat ~ 0.9) are encountered in the south-western North Sea, the Channel and in the shallow waters of the Adriatic Sea, all corresponding to the temperature maxima.

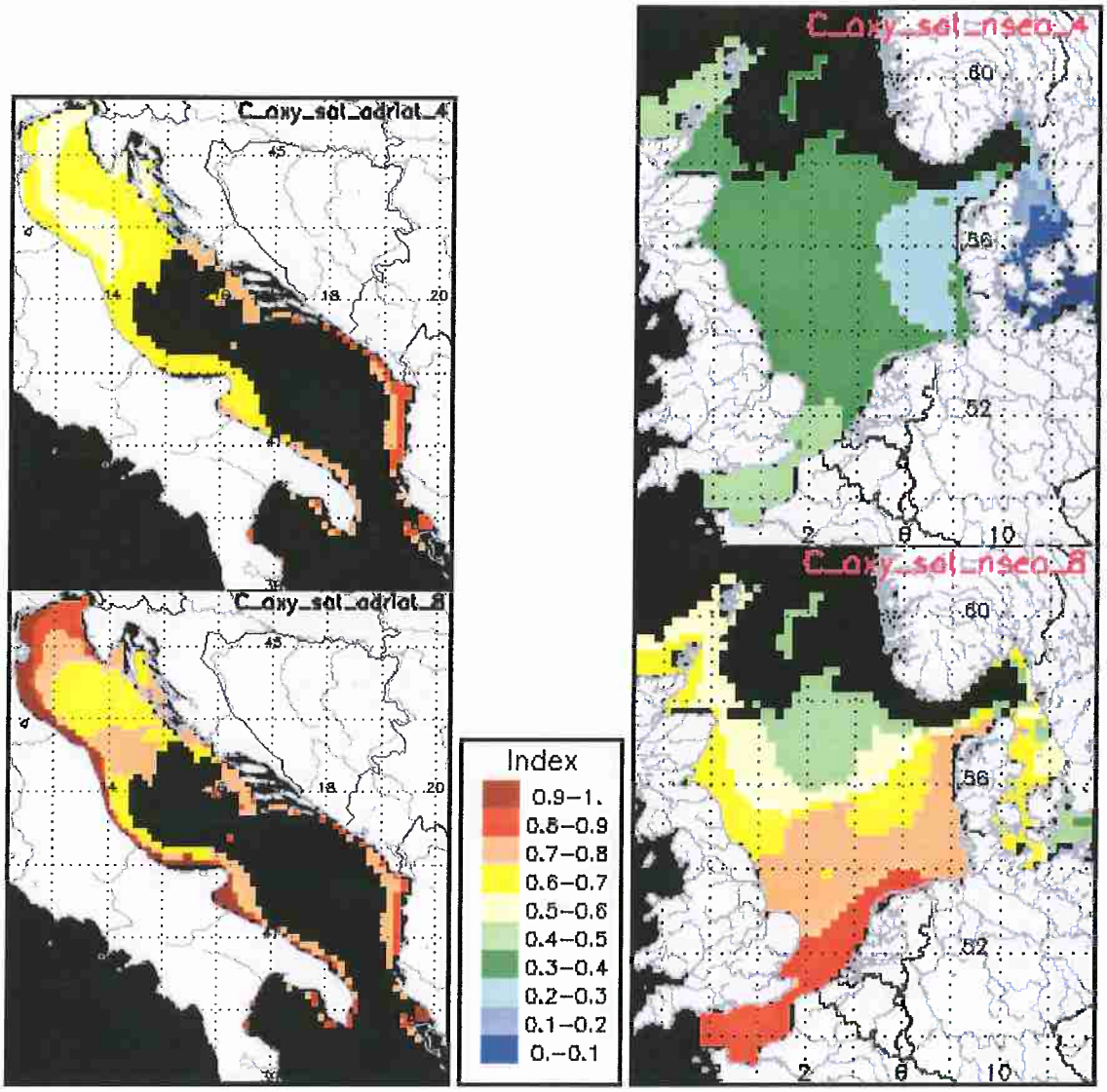

Figure 6. Comparison of the spatial distribution of the oxygen saturation index, C_oxy_sat, in the Adriatic Sea (left) and North Sea (right) for April and August computed from near bottom monthly means of temperature and salinity. Depths beyond 100 m are not calculated. South-west of Italy, west Channel and west of UK are not areas covered by the models.

The other index representative of the oxygen reserve in stratified waters is the benthic layer thickness index, C_blt, which uses, as a critical parameter for eutrophication, the thickness of the layer below stratification. The absence of turbulent diffusion at the sea bottom would be a very critical case as the benthic boundary layer (and the correspondent oxygen availability) would decrease down to a thin diffusive boundary layer, approximately 1 mm thick, through which molecular diffusion is the dominant transport mechanism for dissolved materials (Gundersen and Jørgensen, 1990). Even if very strong oxygen gradients have been reported near the bottom (from 6.0 to 0.4 mg l^{-1} for the

deepest 0.5 m in the Limfjord, Denmark, Jørgensen, 1980), eddy diffusion provides most of the time energy for increasing significantly the benthic boundary layer. The C_blt index calculation states that enough bottom turbulence is provided for mixing the entire layer below the mixed layer (*i.e.* that the oxygen contained in that layer is available). This index represents the potential oxygen reserve of the benthic layer independently of the bottom turbulence. The bottom diffusivity index, C_kz_b, is used in conjunction with the C_blt index in order to modulate the effect of various levels of turbulence in the calculation of the bottom physics index (formulation 3 of C_Phys_bott in Figure 2). Figure 7 shows the empirical relationship linking C_blt and the depth difference between the sea bottom and the pycnocline.

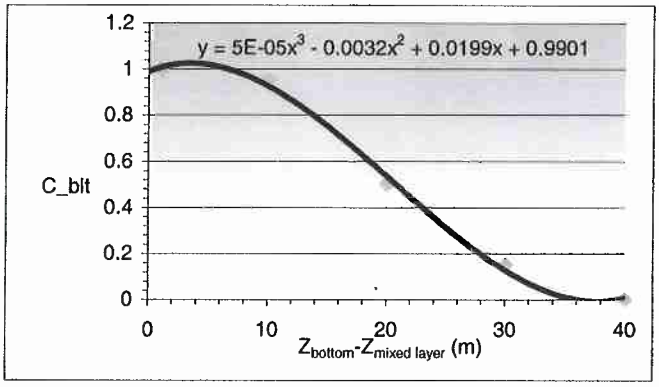

Figure 7. Variation of the benthic layer thickness index function of the depth difference between the sea bottom and the pycnocline (C_blt ≤1, see text).

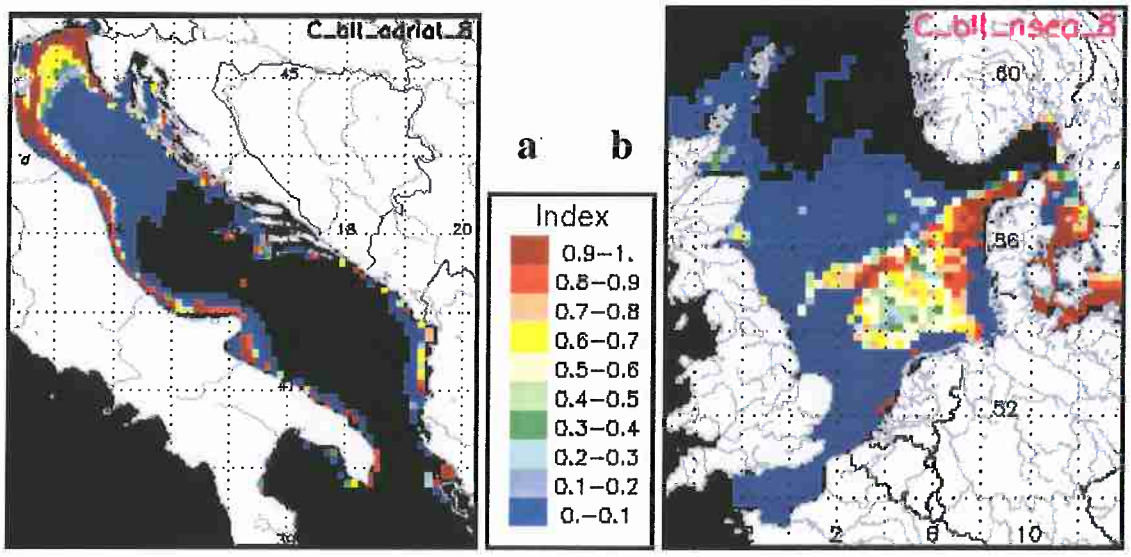

Figure 8. Comparison of the spatial distribution of the benthic layer thickness index, C_blt, in the Adriatic Sea (a) and North Sea (b) for August. Depths beyond 100 m are not calculated. South-west of Italy, west Channel and west of UK are not areas covered by the models.

From the observation of dissolved oxygen profiles, the oxygen reserve becomes critical when the thickness of the isolated water mass is few meters and that it is not a limiting factor in case of a benthic layer thicker than 40 m. Therefore, a stratified water column of 15-30 m is particularly susceptible to oxygen deficiencies and this corresponds to the depth where most depletion is observed (see the discussion section). The distribution of C_blt in August (Figure 8) emphasizes criticality of the oxygen reserve in northern Adriatic, central North Sea and west Danish waters.

The bottom physics index (C_Phys_bott), which represents the oxygen availability, is calculated using the principle of the dominant factor (see Figure 2). High bottom diffusivity (expression ①) is a dominant physical factor which protects efficiently the ecosystem from anoxia. The tidal-enriched system of the Bay of Seine in France is eutrophic with high chlorophyll concentration (up to 60-70 mg m^{-3}) from spring to autumn (Aminot et al. 1997), but buoys measuring continuously oxygen concentration do not show near bottom oxygen saturation below 65%, which corresponds to 5.0 mg l^{-1} for the considered salinity and temperature (MAREL data for 1998-1999, http://www.ifremer.fr/marel/index.html). In case of low levels of bottom diffusivity and stratified waters (expression ③), the thickness of the layer below the pycnocline limits the quantity of available oxygen. The deepening of the mixed layer for shallow waters in summer, and thus for a lower oxygen saturation, leads to a critical decrease of the available oxygen near the sea bottom. When the water column is not stratified with a relatively low bottom diffusivity (expression ②), advection is an important physical process where oxygen can be supplied horizontally. Following these considerations, the formulations of the surface and bottom physics indices are (see also Figure 2):

$$C_Phys_surf_{x,y,t} = \frac{C_adv_{x,y,t} + C_strat_{x,y,t}}{2} \quad [1]$$

if C_kz_b < 0.1 (high bottom diffusivity):

$$① \; C_Phys_bott_{x,y,t} = C_kz_b_{x,y,t} \quad [2]$$

if C_kz_b > 0.1 and C_strat < 0.1 (lower bottom diffusivity without stratification):

$$② \; C_Phys_bott_{x,y,t} = \frac{C_kz_b_{x,y,t} + C_oxy_sat_{x,y,t} + C_strat_{x,y,t} + C_adv_{x,y,t}}{4} \quad [3]$$

if C_kz_b > 0.1 and C_strat > 0.1 (lower bottom diffusivity with stratification):

$$③ \; C_Phys_bott_{x,y,t} = \frac{C_kz_b_{x,y,t} + C_oxy_sat_{x,y,t} + C_strat_{x,y,t} + C_blt_{x,y,t}}{4} \quad [4]$$

The monthly PSA formulation is a mean value of the surface and bottom physics indices for shallow waters:

$$PSA_{x,y,t} = \frac{C_Phys_surf_{x,y,t} + C_Phys_bott_{x,y,t}}{2} \quad [5]$$

This simple arithmetic approach was chosen to respect the priorities of the physical factors regulating eutrophication and to facilitate the analysis of the results.

The EUTRISK index

The EUTRISK characterizes the most probable occurrence of oxygen deficiency at the bottom in shallow sea areas due to the degradation of organic matter. SeaWiFS data are used to estimate phytoplankton primary production and numerical modelling provides data on the physical capacity of oxygen renewal near the sea bed and oxygen reserve below the mixed layer (i.e. the bottom physics defined above).

The phytoplankton is the main source of production and export of organic matter to the sea bed in coastal eutrophied waters. The other export vectors at a higher level in the food web (mainly zooplankton corps and faecal pellets) are quantitatively of a second order of importance in terms of flux of matter, particularly in shallow waters (less than 100 m) where the efficiency of the export (high sinking velocities) decreases relatively compared to the primary producer's export.

The primary production inside the euphotic zone (Π) is estimated by the expression of Eppley et al. 1985 using the satellite-derived chlorophyll-a (*Chla_sat*), and, with a lower correlation, the daylength (*DL*) and a temperature anomaly (PTA): $\ln \Pi = 3.06 + 0.5 * \ln(Chla_sat) - 0.24 * PTA + 0.25 * DL$. Focusing on the restricted August-September period for the EUTRISK index, the seasonal variability of the second order of importance parameters are neglected. A gross estimate of the primary production variability (in relative unit, Πrel) can thus be assessed by the root of the satellite-derived chlorophyll-a concentration: $\Pi rel_{X,Y,t} = \sqrt{Chla_sat_OC5_{X,Y,t}}$ (*X, Y* are referring to the SeaWiFS grid as opposed to *x, y* for the model grid).

Because the production area does not necessarily correspond to the area where the organic matter is exported to the sea bed, a transport iterative procedure has been implemented. The monthly load of organic matter produced in the surface layer is exported horizontally within the mixed layer using the monthly mean advection provided by the respective model and vertically using the constant sinking velocity $Vs = 5\ m\ d^{-1}$ (Fortier et al. 1994). Between the mixed layer and the sea bed, a linear decreasing horizontal velocity is used. With a time step that respects the maximum of the horizontal current velocity *vs.* the smallest model resolution, the primary production estimate is transported horizontally using the closest current velocity of the model grid. A degradation rate of the particulate organic matter (POM) in the water column ($\tau_{deg} = 0.075\ d^{-1}$) is applied to take into account the higher deposition rate in shallower waters compared to deeper waters. Once the organic matter has reached the bottom for a given month and for waters shallower than 100 m, the distribution of the POM is obtained by computing the sum of the organic matter (i.e. the primary production estimated for each satellite pixel) contained in each model grid cell. Following these considerations, the POM flux index is defined as:

$$C_POM_{x,y,t} = \Pi rel_\exp_{x,y,t} * \tau_{depos} * Cc \ , \qquad [6]$$

where the $\Pi rel_\exp$ is the monthly mean primary production exported to the sea bottom as a result of the horizontal and vertical export calculation and sum over a model grid cell, Cc is a calibration constant (Cc=0.64) and τ_{depos} the deposition rate:

$\tau_{depos(x,y)} = 1 - \frac{(\tau_{deg}/86400) * depth_final_{x,y}}{Vs}$, where *depth_final* is the water depth to which the POM has reached the bottom.

The C_POM value is interpreted as the monthly oxygen demand at the sea bottom. The flux of organic matter near the sea bed is seen in the conceptual model as the driving force of eutrophication, opposingly to the physics indices which are supporting factors, and thus the C_POM formulation can exceed the value°1. The maximum value of C_POM for the Adriatic Sea and the North Sea is 2.72 and 1.48 respectively for the year 2000.

In order to evaluate the risk of hypoxia, the oxygen consumption is compared to the oxygen reserve and renewal during the growing season. Along the spring-summer period, the rising of temperature reduces the oxygen reserve (lower saturation), the stratification restricts the oxygen renewal and the oxygen consumption increases due to the input of phytoplankton-derived organic matter. In fact, the larger part of the POM produced occurs during the spring bloom, but oxygen depletion or severe deficiencies that are observed in August and September are explained by the decrease of oxygen reserve and renewal capacity of isolated water masses.

The EUTRISK formulation provides an estimate of the lowest potential oxygen deficiency at the sea bed striking the balance between the monthly oxygen fluxes and reserve - the index C_POM being the oxygen consumption and the index C_Phys_bott index being the oxygen reserve and renewal:

$$EUTRISK_{x,y,t} = \frac{C_POM_{x,y,t} + C_Phys_bott_{x,y,t}}{2} \qquad [7]$$

The notion of risk is introduced because the POM degradation and related oxygen consumption are processes of a daily time scale that cannot be directly assessed with monthly mean data. The variability of the physical conditions and primary production also vary daily. Nevertheless, a few hours oxygen depletion requires a succession of events allowed by a reduced mixing of a longer time scale ; the stratification establishment, the phytoplankton bloom, the sinking of organic particles and their degradation are the main steps of a daily time scale that all together require at least two or three weeks of calm weather. A seven week period of calm winds and warm temperature was necessary to generate a bottom-water anoxia and the mortality of half of the mussel population in the micro-tidal Danish Limfjords in 1997 (Møhlenberg 1999). The monthly mean data provide a satisfying first estimate of the biological and physical processes linked to eutrophication, but because the assessment is not made on a daily time scale, the estimation of the risk is proposed.

Results

Figure 9 presents the results for the surface physics index, C_Phys_surf, for both coastal seas in April, August and December estimated from the advection and stratification characteristics of the surface layer. In others words, these maps show where phytoplankton growth (towards red) will occur if the nutrient source in the top layer is uniformly distributed. Besides the seasonal variability with the most favourable conditions in summer mainly due to the intensification of the stratification, regional differences appear. The central zones of the basins or areas permanently stratified have favourable physical conditions for primary production (towards red). On the opposite, unfavourable conditions are located in strong tidal systems like in the Channel or in buoyancy currents like in the south of the Pô river (towards blue). The nutrient source is evidently not uniformly distributed, but this index emphasizes the fact that shallow areas cannot have the same biological response to the same load of nutrient due to the various characteristics of the surface physics.

The bottom physics index, C_Phys_bott, presented in Figure 10 defines the oxygen availability both in terms of reserve and renewal. This index reveals the capacity of a coastal system to absorb a load of organic matter reaching the sea bottom. In other words, these maps show where oxygen deficiencies will occur near the bottom (towards red) if the organic matter input at the water-sediment interface is uniformly distributed. As for the surface physics, a seasonal variability of C_Phys_bott is observed but the main source of variation comes from the regional scale. Stratified shallow waters with low bottom friction appear to be particularly sensitive to loads of organic matter at the sea bed. These regions are the central North Sea, the north-east Skagerrak, the north-west and south-east Kattegat, the Kiel and Mecklenburg Bays, the Northern Adriatic Sea and the eastern Italian coast.

The physical sensitivity to eutrophication is expressed by the PSA index (Figure 11) integrating the surface and bottom physics. It shows the location of oxygen deficiencies if both the nutrient distribution and the input of organic matter at the sea bottom would be uniformly distributed. The highest physical sensitivity generally occurs in summer but enclosed areas can show a quasi-permanent sensitivity like the Kiel and Mecklenburg Bays in Germany, the Gulf of Trieste, the Eastern part of the Gulf of Venice and near the Pô river mouth in Italy. On the opposite, highly resistant areas are located in the south-eastern North Sea and the Channel. The PSA index shows how unequal European shallow waters are facing the problem of eutrophication. The PSA index clearly shows the relative capacity of coastal waters to incorporate the organic matter. Similar and low nutrient loading in the Bay of Seine (France) or in the Wash Embayment (England) would be 'absorbed' by the coastal ecosystem without disturbances, but may lead to a quasi-permanent anoxia in the Kiel Bay (Germany) or in the north-eastern Adriatic Sea. The buffering capacity of coastal shallow systems for 'digesting' the organic matter is highly variable due to the variability in the physical environment ; *i.e.*, each system has its own maximum tolerance threshold that should not be exceeded.

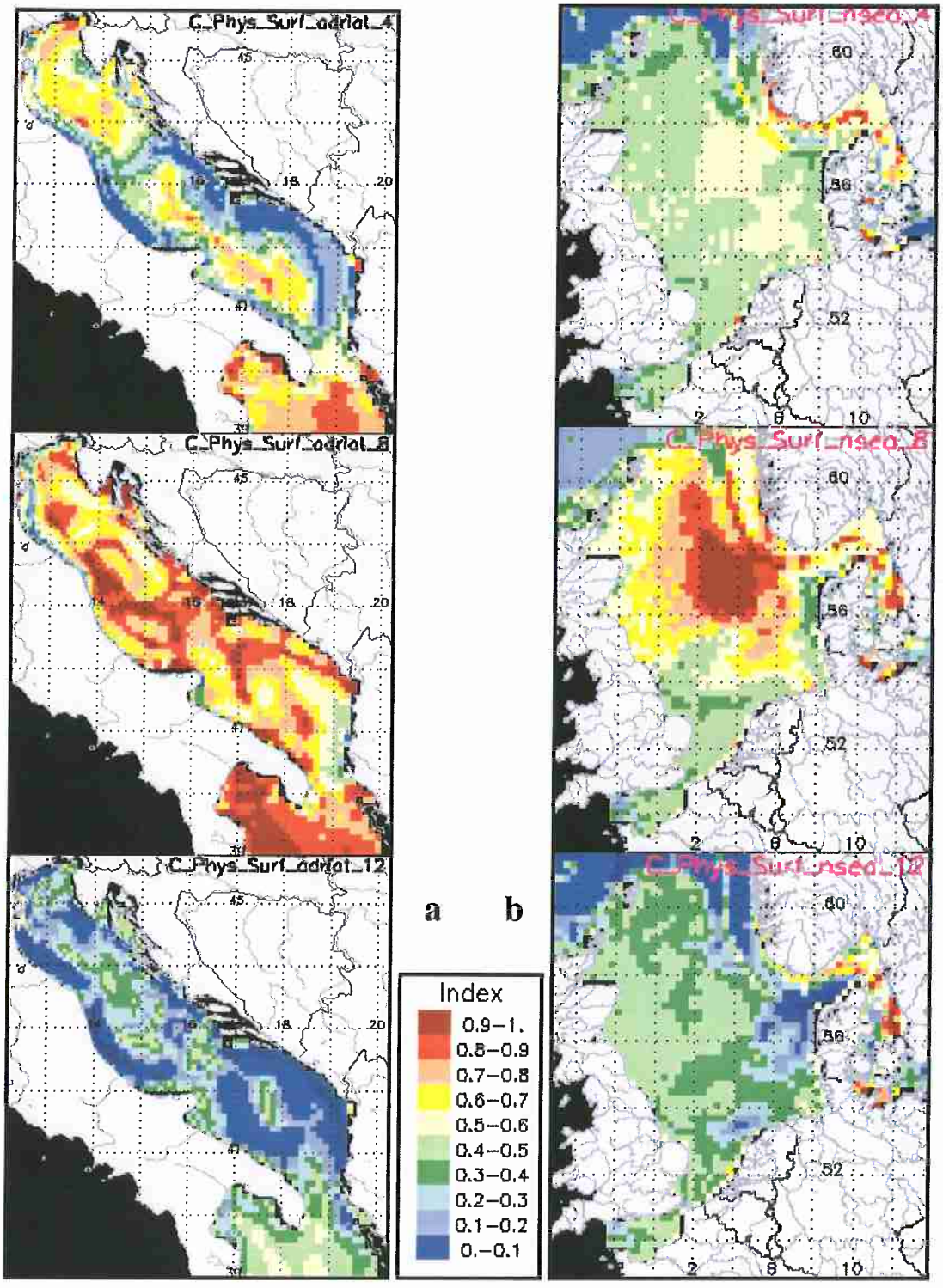

Figure 9. Comparison of the surface physics index, C_Phys_surf, in a) the Adriatic Sea and b) the North Sea in April, August and December. This index represents the favourable physical conditions for the phytoplankton growth (towards red). South-west of Italy, west Channel and west of UK are not areas covered by the models.

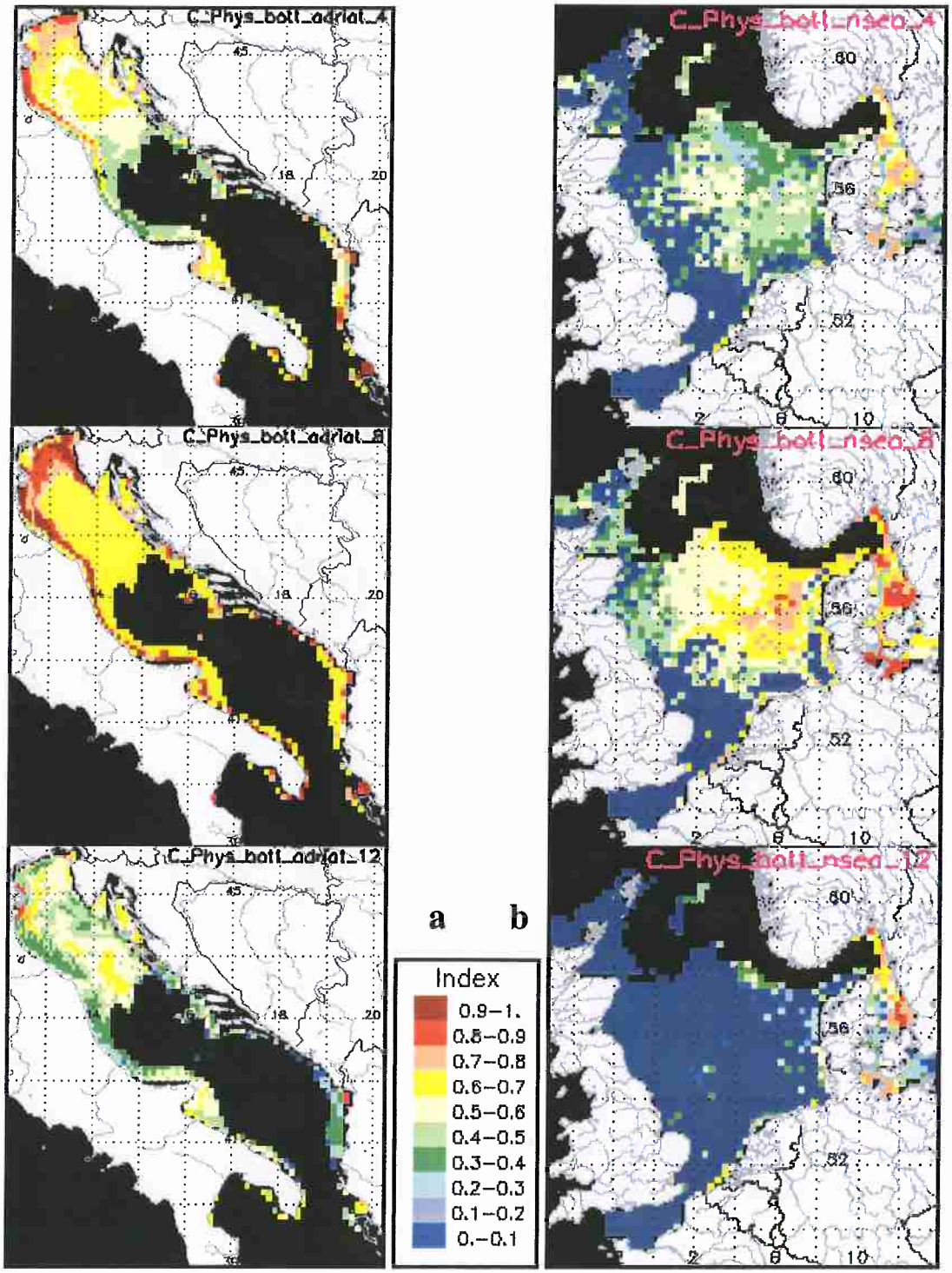

Figure 10. Comparison of the bottom physics index, C_Phys_bott, in a) the Adriatic Sea and b) the North Sea in April, August and December. This index represents the physical availability of oxygen near the sea bottom (low towards red). In black are the areas not covered by the model or are water deeper than 100 m.

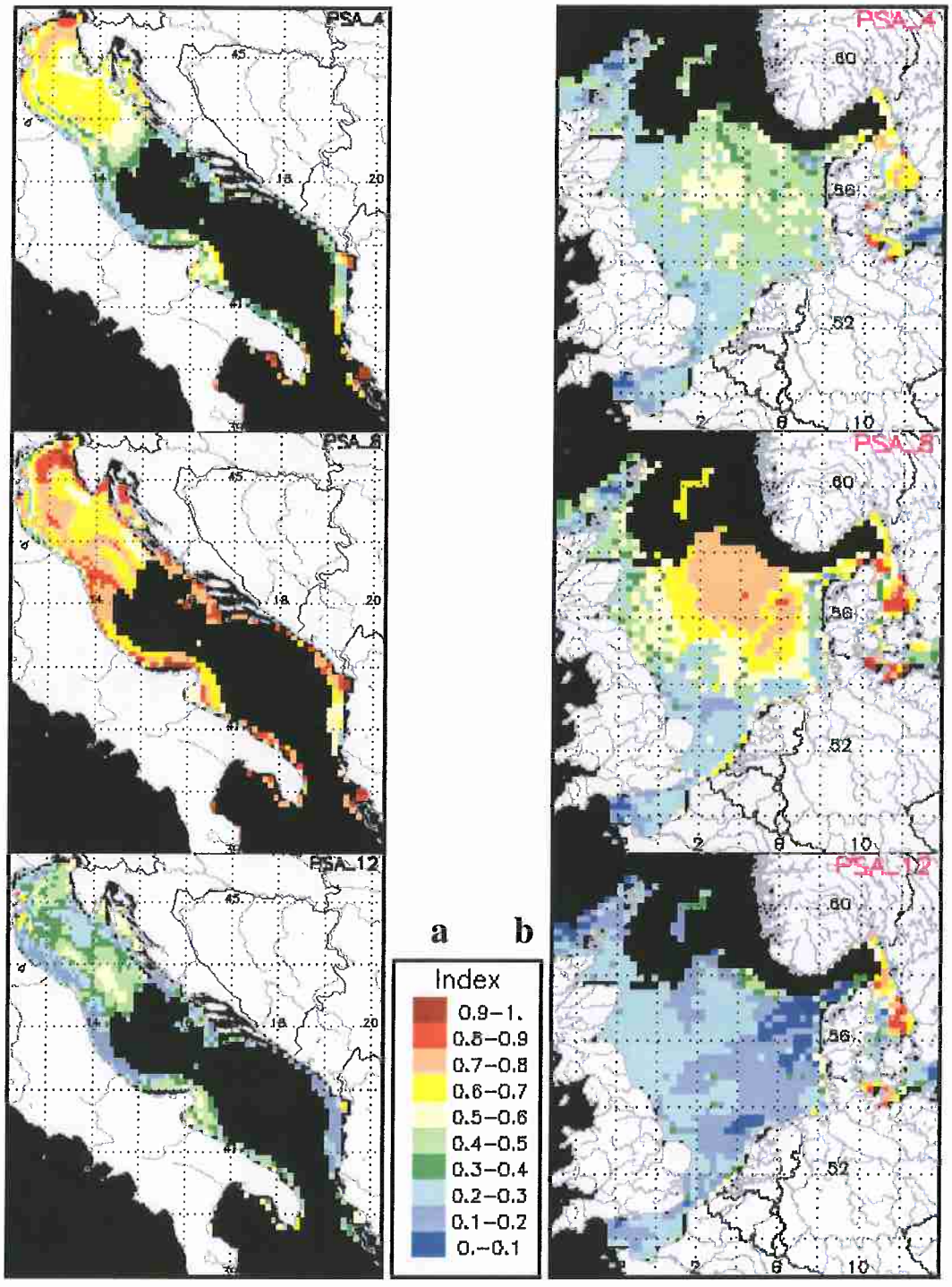

Figure 11. Comparison of the physically sensitive areas index to eutrophication, PSA, based on 3D hydrodynamic modelling results in a) the Adriatic Sea and b) the North Sea in April, August and December. This index represents the physical sensitivity to eutrophication (high towards red) due to the diverse physical conditions. In black are the areas not covered by the model or are water deeper than 100 m.

After the assessment of the supporting factors of eutrophication (PSA), the assessment of the eutrophication risk itself is proposed (EUTRISK). The EUTRISK index uses the phytoplankton biomass as the main vector of the oxygen consumption near the bottom. In order to locate where the organic matter produced at the surface is sinking at the sea bed, an export calculation is implemented using the advection given by the model. Figure 12 presents the results of the export in the northern Adriatic Sea.

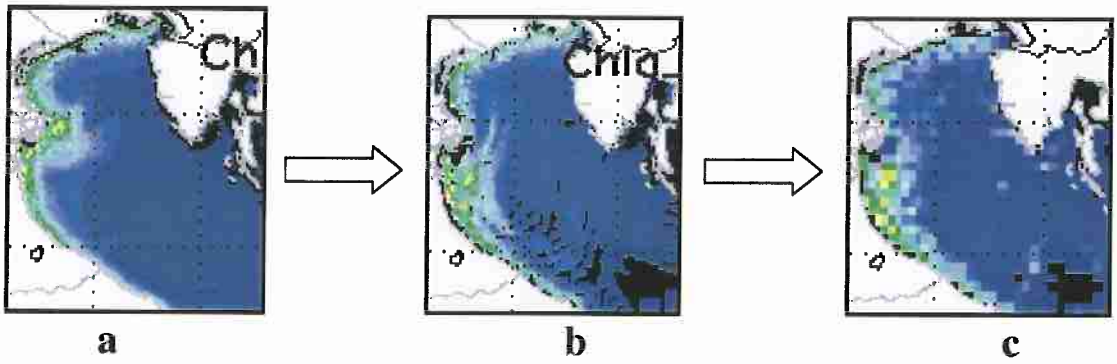

Figure 12. The export procedure is particularly required for the northern Adriatic Sea where the organic matter production and sinking areas are different: a) monthly mean of primary production estimated for August 2000 (in relative units), b) final distribution of the POM after the horizontal and vertical advection procedure (see also Figure 4 a for the advection field) and c) the sum on the model grid to derive the load of organic matter at the sea bottom.

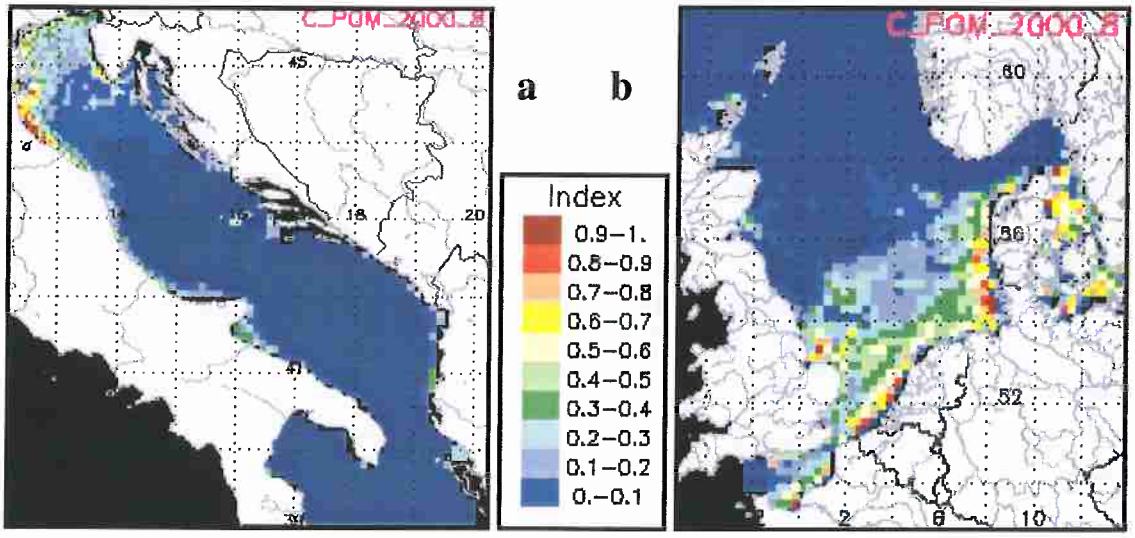

Figure 13. Comparison of the particulate organic matter index, C_POM, in a) the Adriatic Sea and b) the North Sea in August 2000. The C_POM index is the monthly relative organic load of matter which reaches the sea bed estimated from remote sensing of ocean colour using the model advection for the horizontal export. In black are areas not covered by the model.

The monthly mean satellite chlorophyll-a of August 2000 (SeaWiFS-OC5, Figure 12a) shows a maximum of biomass in front and south of the Pô delta. After the export procedure (Figure 12b), the estimated organic matter which has reached the sea bed is concentrated exclusively in the south of the Pô river mouth and further south along the Emilia-Romagna coast. Figure 12c shows the final sum of the bottom organic matter on the model grid in order to compute the physical and biological components of the index on the same grid. A comparison of organic matter load for August 2000 in the North Sea and Adriatic Sea (C_POM, Figure 13) shows the limited extension of the highly productive areas: the Emilia-Romagna coast in the Adriatic Sea, the Bay of Seine, the Wash embayment, the southern North Sea coast, the German Bight and, to a lesser degree, the Danish coastal waters and the German coastal waters in the western Baltic Sea.

The estimate the lowest concentration of dissolved oxygen of a considered month, *i.e.* the EUTRISK index, is composed of the oxygen consumption at the sea bottom, *i.e.* C_POM, and the oxygen availability, *i.e.* C_Phys_bott. Figure 14 presents the EUTRISK index for August 2000 in the study areas. Confronting the C_POM (Figure 13), the C_Phys_bott (Figure 10) and EUTRISK (Figure 14) indices, three main types of eutrophied waters are revealed: 1) eutrophic and sensitive, 2) eutrophic and resistant and finally 3) mesotrophic and sensitive. The first category is where the oxygen depletion occurs regularly because both the main pressure and supporting factors are unfavourable. This case is encountered in the Emilia-Romagna coastal waters south of the Pô river mouth. The second case are areas where there is no severe hypoxia near the sea bed because of a permanent strong vertical mixing ; however the loss of biodiversity and the appearance of opportunist species are generally observed, like in the Bay of Seine and in the Wash Embayment. In the third case, severe hypoxia or anoxia are reported due to particularly adverse physical conditions even if the primary production is relatively low. In spite of the low chlorophyll-a summer levels of the south-east Kattegat, the permanent stratification leads to a seasonal severe hypoxia (Baden et al. 1990a) inducing a reduction of the benthic fauna (Baden et al. 1990a and 1990b, Rosenberg et al. 1992).

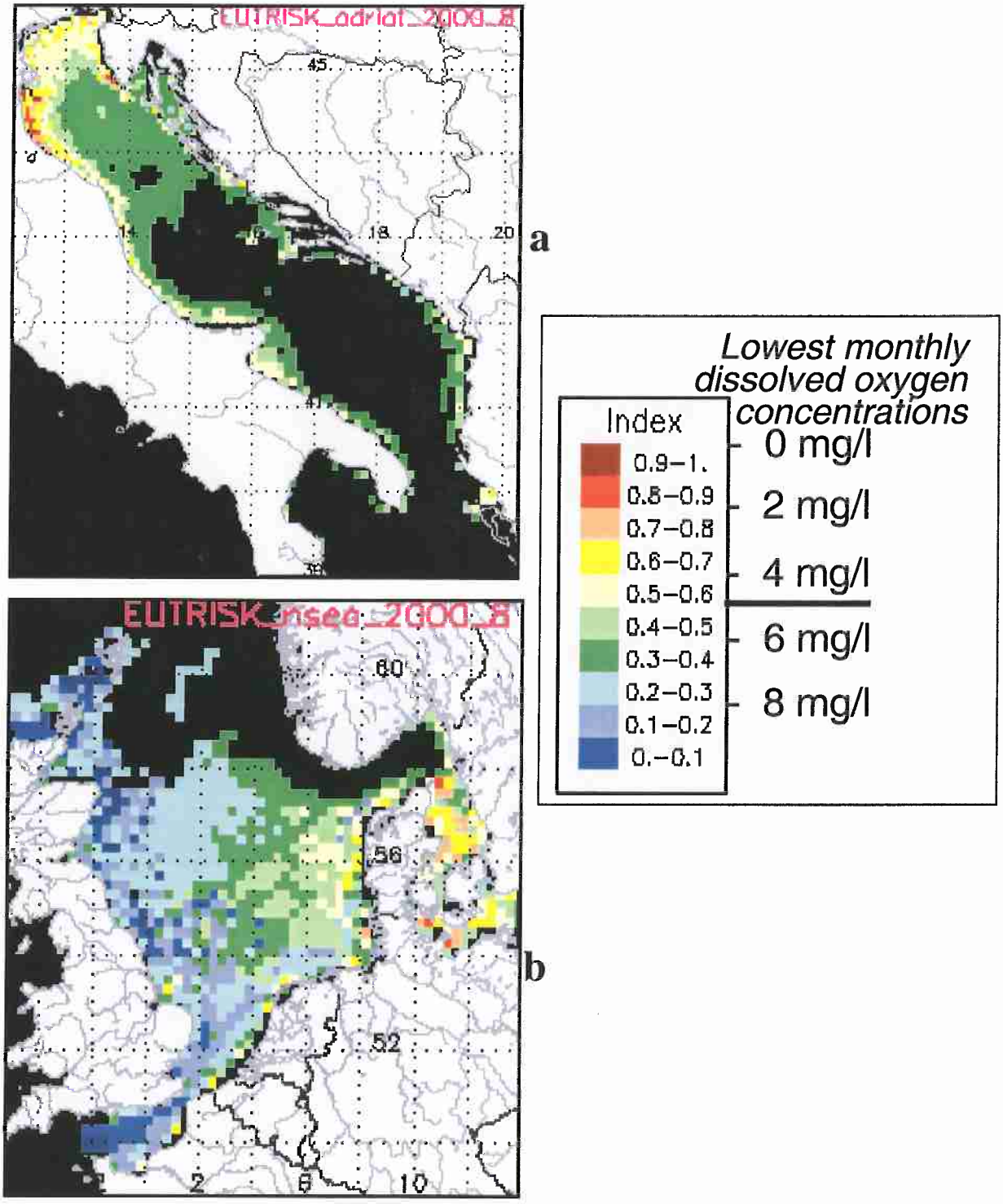

Figure 14. Comparison of the eutrophication risk index, EUTRISK, based on 3D hydrodynamic modelling results and remote sensing of ocean colour in a) the Adriatic Sea and b) the North Sea in August 2000. The EUTRISK index represents the most probable oxygen deficiency distribution near the sea bottom for the considered month. In black are the areas not covered by the model or water deeper than 100 m.

Discussion

The validation

The EUTRISK validation is done using dissolved oxygen concentration at the sea bottom. An oxygen scale (in mg l^{-1}) is linked to the EUTRISK index (see Figure 14) that represents the risk of oxygen deficiency, *i.e.* the lowest near bottom oxygen content for the considered month. The high temporal and spatial variability of the oxygen content in shallow waters makes the validation difficult especially at the pan-European scale. The ideal set of measurements is given by buoys which provide a quasi-continuous monitoring (hourly sampling) on a fixed location. The buoys should be located in a rather homogeneous area in order to be comparable with model results or satellite observations. As already mentioned in the previous section, due to the tide-induced vertical mixing the buoys in the Bay of Seine did not measure bottom oxygen contents below 5.0 mg l^{-1} despite the high phytoplankton biomass recurrently sampled. Comparatively, the corresponding EUTRISK index for August 2000 (Figure 14b) and August 1998 (result not shown) is estimating a minimum bottom oxygen value between 4 and 5 mg l^{-1} (light yellow) and between 3 and 4 mg l^{-1} (dark yellow) for August 1999 (result not shown). The high variability of oxygen content near the sea bed is illustrated on Figure 15 in the Adriatic Sea. The weekly campaign done in the summer months along the Emilia-Romagna coast reported the occurrence of oxygen depletions or severe deficiencies with a duration of few days. Figure 15 shows the sequential succession and the two main locations of oxygen depletion (dashed and solid white lines). On August 4th and 13-14th 1998 the depletion was located in the southern part of the area between Ravenna and Cesenatico (corresponding to the two southern transects), but between these two dates on August 8th, the depletion has been measured along the coast south of the Pô delta (between the two northern transects). This variability can be explained by a change of the wind conditions and the induced vertical mixing. Before August 5th and after August 8th, a light variable wind (Figure 16) induced a low vertical mixing and the regions where the input of organic matter was maximum (southern part, Figure 13a) were the more impacted. Between August 5th and 8th a moderate wind event occurred from the north-east which increased the vertical mixing in the southern part. On the opposite, the protection offered by the Pô delta limiting the fetch and the wave-induced mixing led to an oxygen depletion on the northern part which corresponds to the second maximum of the organic matter deposition (Figure 13a). The variability after August 14th could probably be explained by the conjunction of the reduced wind and the hydrodynamics, the oxygen deficiencies becoming less severe. The overlay of the EUTRISK index on the oxygen depletions measured in August 1998 (Figure 15) shows a good agreement as regards to the sampling network (pink dots and lines). This example reveals how cautiously the EUTRISK validation must be done.

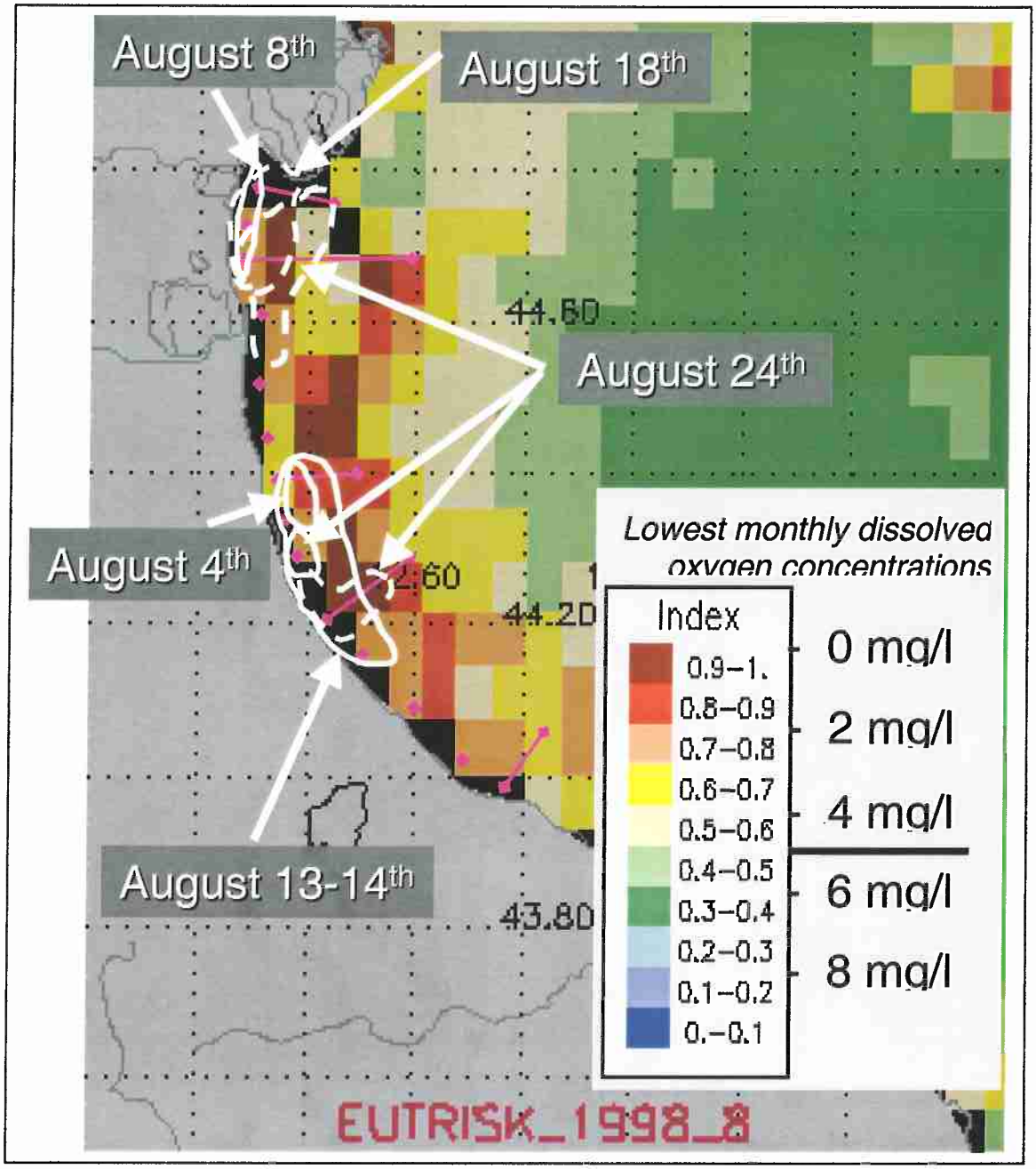

Figure 15. Comparison of the eutrophication risk index, EUTRISK, and in situ measurements of bottom dissolved oxygen in August 1998 in the Emilia-Romagna coast area (south of the Pô delta): the measured hypoxia (< 2 mg/l) are represented in dashed white line and the anoxia are in solid white lines. The monitoring stations (pink squares and lines) were sampled every week by the ARPA (Agenzia Regionale Prevenzione e Ambiante dell'Emilia-Romagna). Note the temporal and spatial variability of the oxygen deficiencies.

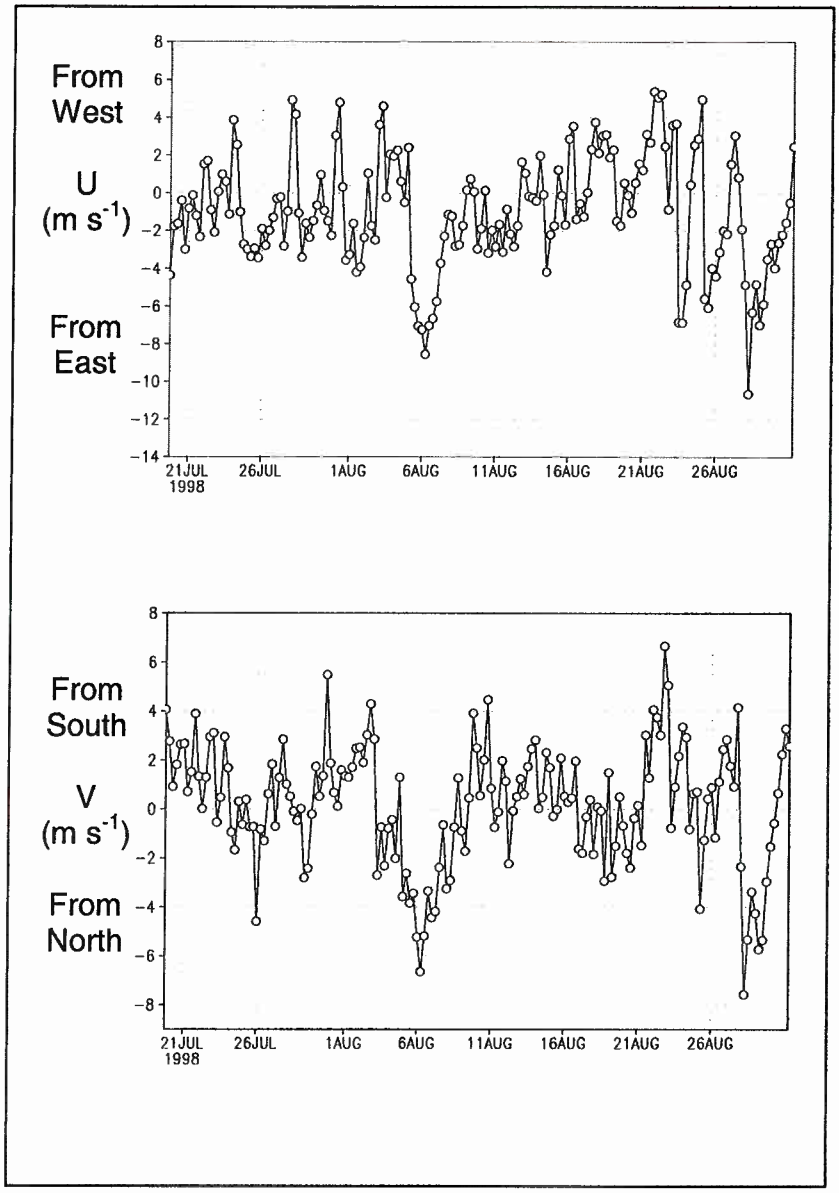

Figure 16. Wind components at 10 m from the ECMWF re-analysis of a point located South of the Pô river delta (44.6°N, 12.5°E). Note the wind change on August 6th in relation with the variability of the oxygen deficiencies in Figure 15.

Another investigation to test the applicability of the approach is to simulate the EUTRISK index with a half primary production as it was the level reported in many European coastal seas between the 50's and the 70's. The test also assumes that the past physical conditions were comparable which is a reasonable approximation. A doubling of the primary production between the 50's or the 70's and the 90's is reported in the southern Kattegat (Richarson and Heilmann 1993, Richardson 1996), in the Belt Sea (Halskov Rev, Rydberg et al. 1990), in the Dutch Wadden Sea (de Jonge 1990). A doubling of the algae biomass occurred during the same period along the Dutch coast

(Cadée 1992, Riegman 1995) and a four-fold increase at a permanent station near Helgoland (German Bight 1962-1980, Anonymous 1981). The increased production of organic matter is associated with a decrease of dissolved oxygen concentrations in bottom waters over the same period in the southern Kattegat (Christensen 1988), in Kiel Bay (Babenerd 1990, Funen County Council 1991), in the northern Adriatic Sea (Justić 1987, Legović and Justić 1997, Degobbis et al. 2000). The same evolution was retrieved from the foraminiferal record in the northern Adriatic Sea (Barmawidjaja et al., 1995). Figure 17 shows the results of the EUTRISK index with a half primary production to be compared with the result of August 2000 (Figure 14). The EUTRISK index with a half primary production shows that all severe hypoxic areas disappear in agreement with the historical evolution of eutrophication. The maximum assimilating capacity of organic matter has been reached and largely surpassed in many European marine waters in the last 50 years. Some physically more resistant water bodies only show signs of eutrophication (like red tides) during particularly unfavourable meteorological conditions because tidal-induced vertical mixing prevents severe hypoxia near the sea bottom. But the loss of biodiversity (yellow in the EUTRISK scale) which occurs in these highly mixed waters constitutes by itself a strong adverse effect of eutrophication that is already beyond the acceptable limit to be considered for a healthy ecosystem. This type of eutrophied area is reflected in (see Figure 14b) the western Danish waters, the German Bight, the Dutch and Belgian coastal waters, and some coastal waters of France (near the Bay of Somme and the Bay of Seine) and of UK (near the Humber and Southampton estuaries and the Wash Embayment). Such systems are all relatively resistant (generally dark green colour in August for PSA, Figure 11b) but highly impacted by the production of organic matter (red colour for C_POM, Figure 13b).

Another category of eutrophied area is shown by EUTRISK in the extreme north of the Adriatic Sea (north of 45°N, see Figure 14a). This type of system which has the same status (yellow colour in the EUTRISK scale) is mesotrophic, or even oligotrophic, but highly sensitive (see Figures 13a and 11a). Anoxic events (<2 mg l^{-1}) are reported by Šimunović et al. (1999) where fish kills were linked to the lower level of circulation in the centre of current eddies. In the Bay of Trieste, the authors are referring to the work of Malej (1993) who stated that the occurrence of hypoxia and anoxia appeared not to be related to eutrophication but rather to the combined impact of morphological and hydrographic factors. The physical characteristics given by the model based on climatology support this hypothesis. The circulation is low (Figure 4a), there is no bottom friction (Figure 4b), the water column is stratified in summer (Figure 5a), the oxygen saturation is minimum (Figure 6) and the thickness of the benthic layer is critical (Figure 8a). Consequently, the high values of the C_Phys_bott and PSA indices reveal the high physical sensitivity of the extreme northern Adriatic and particularly its low oxygen reserve and renewal capacity in the deeper layer.

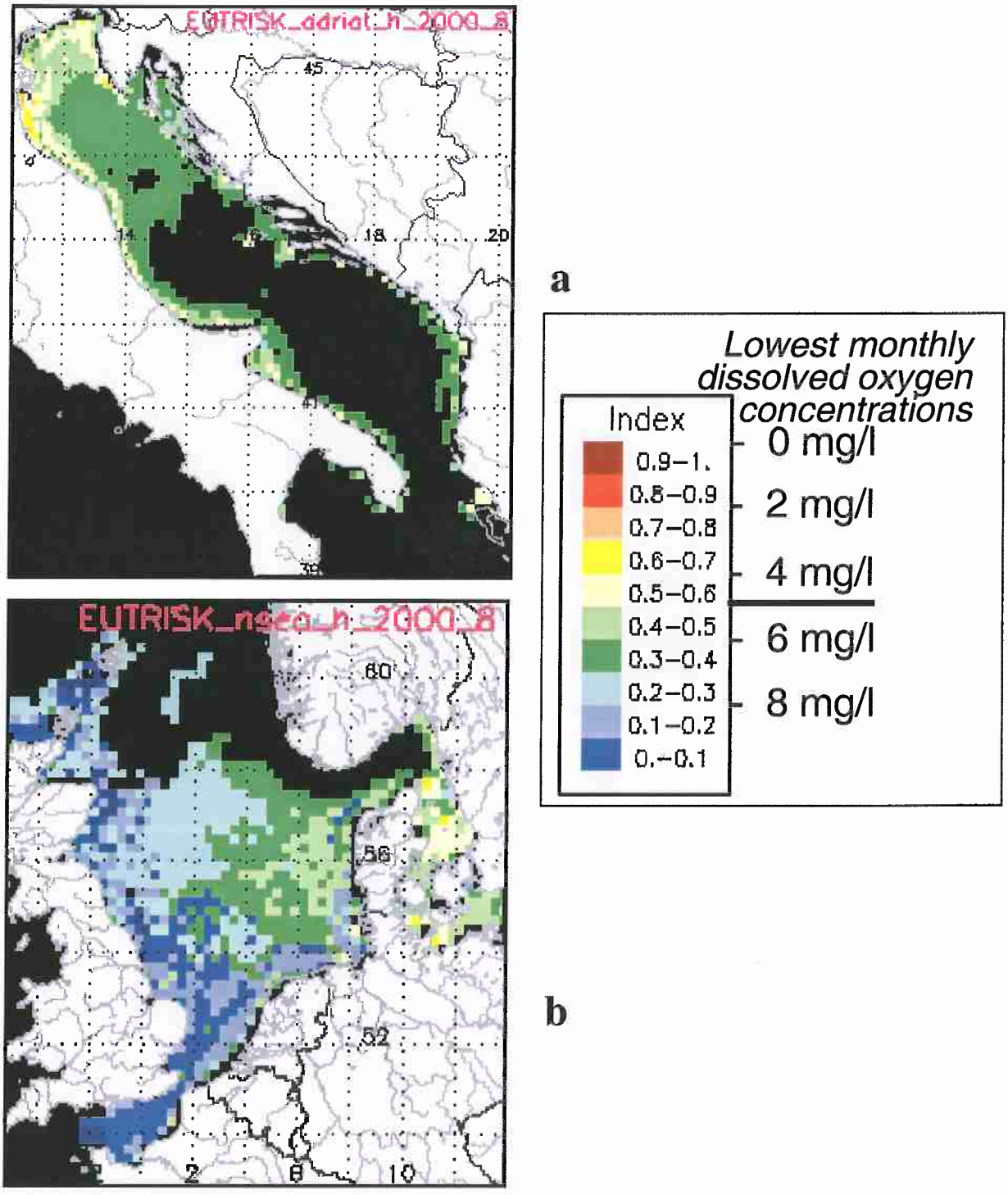

Figure 17. Comparison of the eutrophication risk index, EUTRISK, with a 50% biomass reduction scenario in a) the Adriatic Sea and b) the North Sea in August 2000. The EUTRISK index represents the most probable oxygen deficiency distribution near the sea bottom. In black are the areas not covered by the model or are water deeper than 100 m.

The limits

The first limitation of PSA and EUTRISK is geographical and comes from the limitations of the modelling and remote sensing techniques. No data are available near the coastline for both tools. With a spatial resolution from 4 to 20 km, the physical model cannot provide accurate information in the first kilometres along the sea shore, and the satellite ocean colour is 'polluted' by a land contribution.

Another more spatially restricted limitation occurs for very shallow waters where the penetration depth of light (Z_{90}) is deeper than the water depth, and the remote sensor sees the sea bottom. The penetration depth being defined for an homogeneous ocean as $Z_{90} \approx k^{-1}$ (Gordon and McCluney 1975), if the attenuation coefficient for the downwelling irradiance (k) is low, i.e. if the water is clear, Z_{90} is high and might exceed the water depth. This phenomenon can arise locally in the Belt Sea but this concerns very low chlorophyll contents as Z_{90} drops from 13 m for 0.20 mg Chl-a m^{-3} to 2.5 m for 2.0 mg Chl-a m^{-3} (data not shown), and the penetration depth is even smaller for turbid waters.

The model resolution is also an important limitation especially for the actual North Sea results (20 km cell size) where the hydrodynamics below that scale cannot be correctly represented. The missing local hydromorphology introduces approximations that impact the results of PSA and EUTRISK particularly in the Belt Sea where the hydrodynamics characteristics are defined by the complex archipelago.

The interannual variability of the physical environment is an important component that influences eutrophication and is not currently contained in the climatology of the model results. The German Bight experienced large events of anoxia and hypoxia in 1981, 1982 and 1983 and to a lower degree in 1989 and 1994, that were related to warm calm weather periods during summer (Dethlefsen and von Westernhagen 1983, Brockmann and Eberlain 1986, Hickel et al. 1989, Gerlach 1990, Niermann 1990). No severe hypoxia was monitored in that area during the 90's in agreement with the EUTRISK estimate for August 2000 and as for summer 1998 and 1999 (results not shown). This example reveals how important is the interannual variability of the physical supporting factor that should be taken into account for an accurate assessment of marine/coastal eutrophication.

The monthly temporal resolution constitutes a limitation of the indices considering the rapid fluctuations of the nitrogen and oxygen cycles in shallow ecosystems. The discussion previously exposed explains why a risk evaluation is proposed rather than a direct assessment. A weekly time scale would be without doubt a significant improvement of the results, therefore technical problems would have to be resolved like the remote sensing coverage and the temporal integration of the organic matter. It appears that the increase of the temporal resolution requires the modelling of the involved chemical elements (nitrogen and oxygen) and is not adapted to the index approach.

Besides the temporal resolution, the main approximation made is the conversion of surface chlorophyll-a to primary production. The primary production depends on the chlorophyll-normalized rate of carbon fixation, the photosynthetically available radiation (PAR), the euphotic depth, the chlorophyll-a vertical distribution and the photoperiod (Behrenfeld and Falkowski 1997). Thus, the correlation between the primary production and the surface chlorophyll-a content is not valid during the entire growing season due to the variability of the dominant phytoplankton group and the available light in the upper

water column. Therefore, for a limited period the primary production variability is assumed to depend mainly on the surface chlorophyll-a content. The EUTRISK index was calibrated for August-September months and consequently is not valid for spring months in the present version.

Towards a PSA and EUTRISK version 2

The first type of improvement will consist in feeding the PSA and EUTRISK indices with model results of a higher spatial resolution. The North Sea area will benefit of a 4 km model resolution instead of 20 km. This improvement will considerably increase the indices accuracy in complex hydrodynamic systems like in the Belt Sea and in case of particular features of the coastline like enclosed bays. In order to avoid any loss of information contained in the 2 km resolution ocean colour data, the physical parameters extracted from the models (of about 4 to 8 km resolution) will be interpolated to match the remote sensing grid. This step will allow a better estimate of the organic matter flux sinking to the sea bed using an improved advection field and the original high resolution satellite grid.

The second type of improvement concerns the methodology itself. The set of physical parameters will be completed by the mean advection of the benthic layer (between the mixed layer and the sea bottom) to improve the estimate of organic matter flux below the mixed layer and the horizontal capacity of the system to renew its oxygen near the bottom (C_Phys_bott index). Similarly, the vertical advection will allow to take into account the influence of coastal recurrent upwelling and downwelling in the transport of organic matter and dissolved oxygen. Some resurgence of oxygen-depleted deep waters in a shallow stratified system, like the deep marine waters of the Skagerrak entering the Kattegat region, are suspected to decrease the oxygen availability in the benthic layer (Nordberg et al., 1999). In such areas, the vertical and horizontal hydrography is playing a key role in the oxygen budget bringing in the benthic layer of shallow systems already oxygen depleted waters.

The daily sea surface temperature (SST) from satellite remote sensing seen as a tracer of the high frequency changes of the upper hydrodynamics will provide the interannual and the sub-monthly variability of the physics which is currently missing in the model results. The SST archive from AVHRR sensors has the same high resolution than the SeaWiFS archive of the JRC (2 km) and thus is fully adapted.

A temporal extension of the methodology of EUTRISK to other months than August and September will be allowed by a improved estimation of the primary production by introducing the seasonal PAR variation, the photoperiod and two classes of chlorophyll-normalized rates of carbon fixation. This last step will include the development of the modelling of nitrogen and oxygen cycles in coastal marine waters which will contain the limited number of required processes and will take benefit of the appropriate tools. A geographical extension of PSA and EUTRISK is in preparation for the rest of the coastal marine European waters using outputs of models with a resolution comprised between 4 and 8 km.

Conclusion

The PSA and EUTRISK indices are assessing the ecosystem sensitivity and status as regards to eutrophication, its trend over time, and are to be applied on a European scale. The common methodology of the indices identifies the main characteristics of the eutrophication phenomena that occurs in two shallow seas characterized by different hydromorphological conditions: the Adriatic Sea and the North Sea. The various types of shallow marine ecosystems submitted to eutrophication separated by EUTRISK and PSA are: hypertrophic and sensitive (recurrent anoxia), hypertrophic and resistant (only exceptional severe hypoxia), hypertrophic and hyper-resistant (light hypoxia), eutrophic and sensitive (aperiodic anoxia or severe hypoxia), and finally mesotrophic and hyper-sensitive (recurrent anoxia). Even the types of eutrophied ecosystem which are not suffering from severe hypoxia are subject to a significant loss of biodiversity leading to the appearance of blooms of toxic or nuisance algae.

The agreement of EUTRISK with measurements of near bottom dissolved oxygen is generally good at the regional scale but diverse at smaller scale due to weak in situ sampling compared to the oxygen variability and to the spatial resolution of the models. The use of the surface chlorophyll-a content as an approximation of the primary production does not allow to extend the EUTRISK methodology for other months than those for which it has been calibrated for (August and September). Improvements of the physical modelling results (better resolution) and of the methodology, mainly concerning the introduction of the short term and interannual physical variability contained in the SST data, will allow to increase the accuracy of the indices spatially and quantitatively. An improved estimate of the primary production will allow the seasonal extension of EUTRISK.

The PSA and EUTRISK indices constitutes an ecological tool for policy managers from the Regional level to the European level. The first promising results aimed to test the robustness of the approach. The extension to all European shallow marine systems will allow a comparison of eutrophication types and intensity as well as their evolution in time. It also should attempt to fill the gap in areas where the research effort on eutrophication is relatively poor (Black Sea, Baltic Sea and Mediterranean Sea, Vidal et al. 1999). It should help the scientific community to focus on areas of particular interest and to guide their sampling strategy. The indices are also showing where to invest efforts for restoration and help to estimate the cost for rehabilitating towards the pristine ecological status. This approach of marine eutrophication provides an answer to a fragment of the phase III conceptuel model exposed in the excellent review of Cloern (2001). The latter concept includes multiple stressors, a filter that modulates the ecosystem responses, the multiple responses themselves, the impacts on the Earth System including aspects that influence sustainability of the human population, and the scientifically sound tools for building rational management strategies. PSA and EUTRISK are focusing on the main stressor of eutrophication, i.e. the nutrient enrichment, they include the physical environment as a filter, and provide a large scale and temporal view of the major ecosystem responses, i.e. the production of organic matter and the oxygen budget. The quantitative assessment of the mechanisms involved allows the estimate the relative cost for restoration which is the prerequisit for building efficient management strategies.

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