# Why biological time series require physical ones ?

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## INTRODUCTION

The first studies on the general circulation of water masses in the Mediterranean began in the early 1900s (Nielsen, 1912), depicting a circulation smooth and stable along the slopes. Major revisions arose only in the 1980s, after the satellite imagery revealed upwellings, meanders and eddies, that is the mesoscale dynamics (see for instance Millot, 1985, 1987a; Le Vourch *et al.*, 1992). In the western basin, its role and consequences have been assessed with satellite observations that were later confirmed by *in situ* studies using a mesoscale-dedicated sampling strategy. Besides validating the use of satellite thermal images (SST: Sea Surface Temperature) to infer circulation features (Millot *et al.*, 1994, 1997) such a strategy has shown that mesoscale must be taken into account since it can impact the general circulation (e.g. Millot, 1987b; Millot and Taupier-Letage, 2003). The revised schemes for the western basin display meandering and eddying alongslope currents in a counter clockwise circuit (Millot, 1999). In the eastern basin, a major fieldwork effort (POEM) was carried out in the 1990s (e.g. Robinson, 1991; POEM group, 1992). The resulting representations of the surface circulation showed jets crossing the central part of the basin, instead of alongslope. It is worth noting that the southern parts from the Ionian to the Levantine sub-basins were not investigated, and that the sampling strategy was not adapted to assess the mesoscale (especially with a sampling interval too large, generally half a degree), which was then most likely to be deceiving. Another revisit of the surface circulation in the eastern basin has just been completed, based on the analysis of a ~4-year time series of SST images, which provide a synoptic view with a fine spatio-temporal resolution (~1 km, ~1 day). They show that the circulation is alongslope, as one might expect from the simple application of the Coriolis effect, and is affected by mesoscale dynamics. The resulting new scheme (Hamad *et al.*, 2003) strongly differs from that mentioned above, and shows a meandering and eddying alongslope circulation forming a counter clockwise circuit, which is confirmed by modelling work carried out in the LODYC (Alhammoud, 2003).

Correctly assessing the mesoscale dynamics is not only important for general circulation studies, it is also pivotal for biology. Indeed, at this scale the dynamical phenomena drive the biological ones, at least at the lower trophic levels, as shown on Figure 1 by the very close correlation between the dynamical signatures (as seen on SST images) and the biological ones (as seen on visible/"ocean colour" satellite images). Moreover, as the intensity of the mesoscale variability of the biological parameters is generally higher than the seasonal one, allegedly well-known, it is necessary to resolve the mesoscale to correctly ascribe the observed changes to a cause/process.

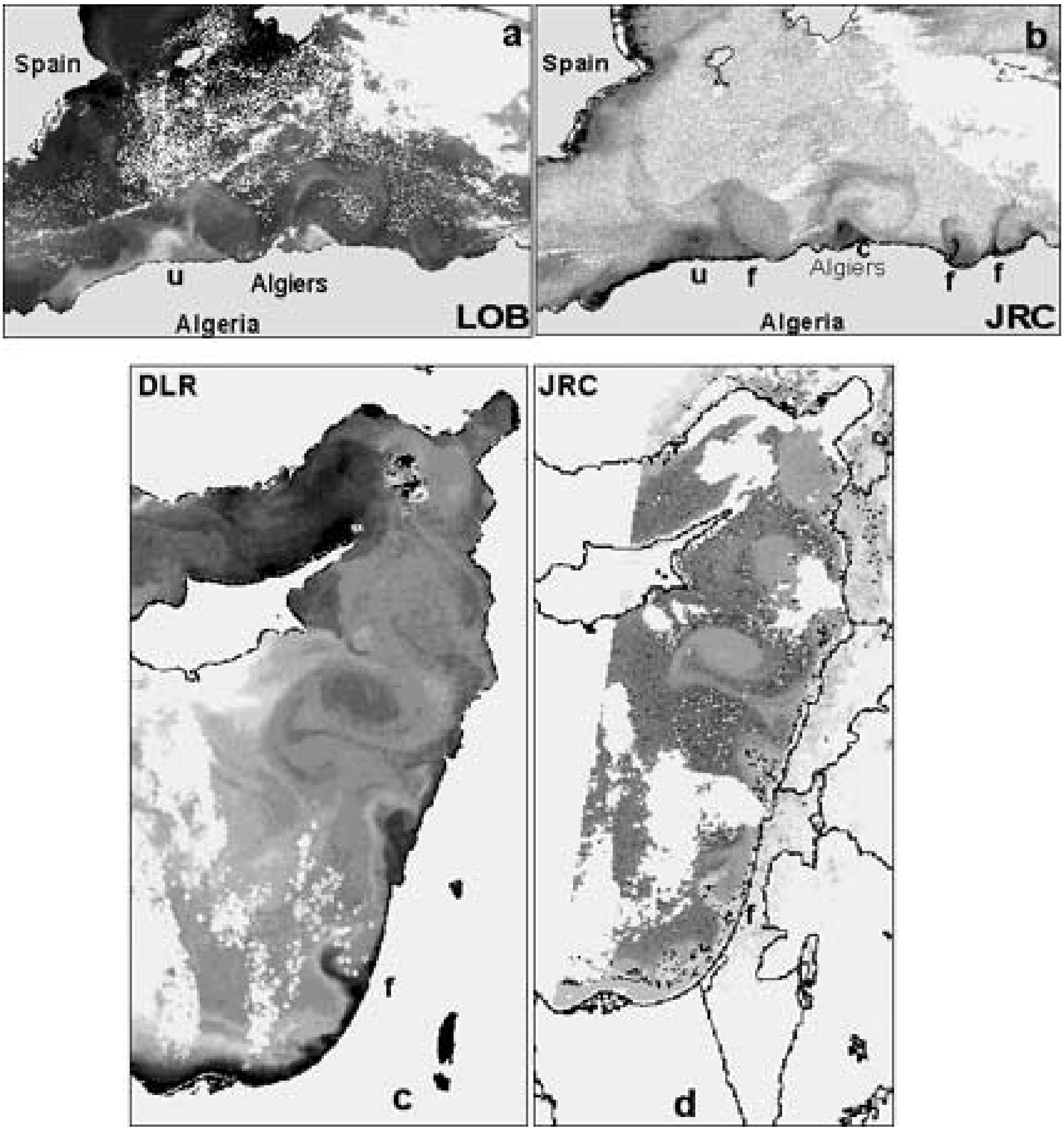


Fig. 1. SST (a, c) and surface chlorophyll concentrations (b, d) satellite images of the Algerian sub-basin on 19 July 1981 (top) and of the easternmost part of the eastern basin on 31 July 2001 (Middle-East, bottom). **a**: AVHRR image processed by LOB; **b**: CZCS image from JRC/Ocean project <www.me.sai.jrc.it/OCEAN/ocean.html>); **c**: AVHRR image (daily composite) from DLR <http://eoweb.dlr.de:8080/ servlets /template/welcome/entryPage.vm>; **d**: SeaWiFS image from JRC <www.me.sai.jrc.it/me-website/contents/shared_utilities/frames/archive_seawifs.htm>.

NB: in all images, temperature and chlorophyll concentrations increase from light to dark grey.

This requires at least acquiring biological and hydrodynamical parameters concurrently with a sampling interval adequate to resolve the important scales, or better, performing multidisciplinary and multiplatform experiments, fostering the use of satellite imageries and that of *in situ* autonomous instruments. In the following section, we will use examples from the one-year experiment ELISA (Eddies and Leddies Interdisciplinary Study off Algeria, see <www.com.univ-mrs.fr/ELISA>) which we conducted from 1997 to 1998 in the eastern part of the Algerian sub-basin.

We will first describe the main physical /dynamical phenomena that potentially translate into biological variability (with special emphasis on the mesoscale, which is generally less recognised), then we will suggest sampling strategies and list physical parameters that should be acquired in order to strengthen the interpretation of the biological time series.

**VARIABILITY OF THE DYNAMICAL ENVIRONMENT AND POTENTIAL BIOLOGICAL CONSEQUENCES.**

Although we do not focus herer on decadal scales, it is well-known that there are long-term hydrological trends in the Mediterranean (CIESM, 2002), which, in turn, are most likely to induce long-term changes in populations. Now, changes can also affect atmospheric forcings on a few-year timescale, leading to interannual changes in hydrology and circulation, as observed with the so-called “Transient” (CIESM, 2000b), or observed with the circulation pattern change in the western part of the Ionian sub-basin (Pinardi and Masetti, 2000; Hamad *et al.*, 2003). These scales will not be addressed here, as we rather focus on the seasonal and meso-scales.

The Mediterranean is an evaporation basin, so that less saline/lighter water enters at Gibraltar (Atlantic Water: AW, <www.ciesm.org/events/RT5-WaterMassAcronyms.pdf>). Schematically, AW flows counter-clockwise along the continental slopes to finally sink in the northern parts of both the western and eastern basins during the wintertime process of dense water formation. Characteristics of the AW circulation thus appear to be different in the southern and northern parts of both basins (more details on the comparison between the tow basins are given in Millot, 1992). The southern currents (which flow eastward) are unstable and meander, for some up to spawning anticyclonic eddies that propagate downstream at a few km/day, and/or can pinch off and drift offshore (Fig. 2). These eddies have spatial horizontal scales of 10s to several hundreds kilometres (up to diameters of ~250 km, in both southern sub-basins), and vertical extents ranging from hundreds to thousans of metres, down to the bottom (~3000m) as is now clearly demonstrated for the Algerian eddies at least (Millot and Taupier-Letage, 2003). Their temporal scales range from ~1 month to a few years (up to ~3 years observed in both western and eastern southern

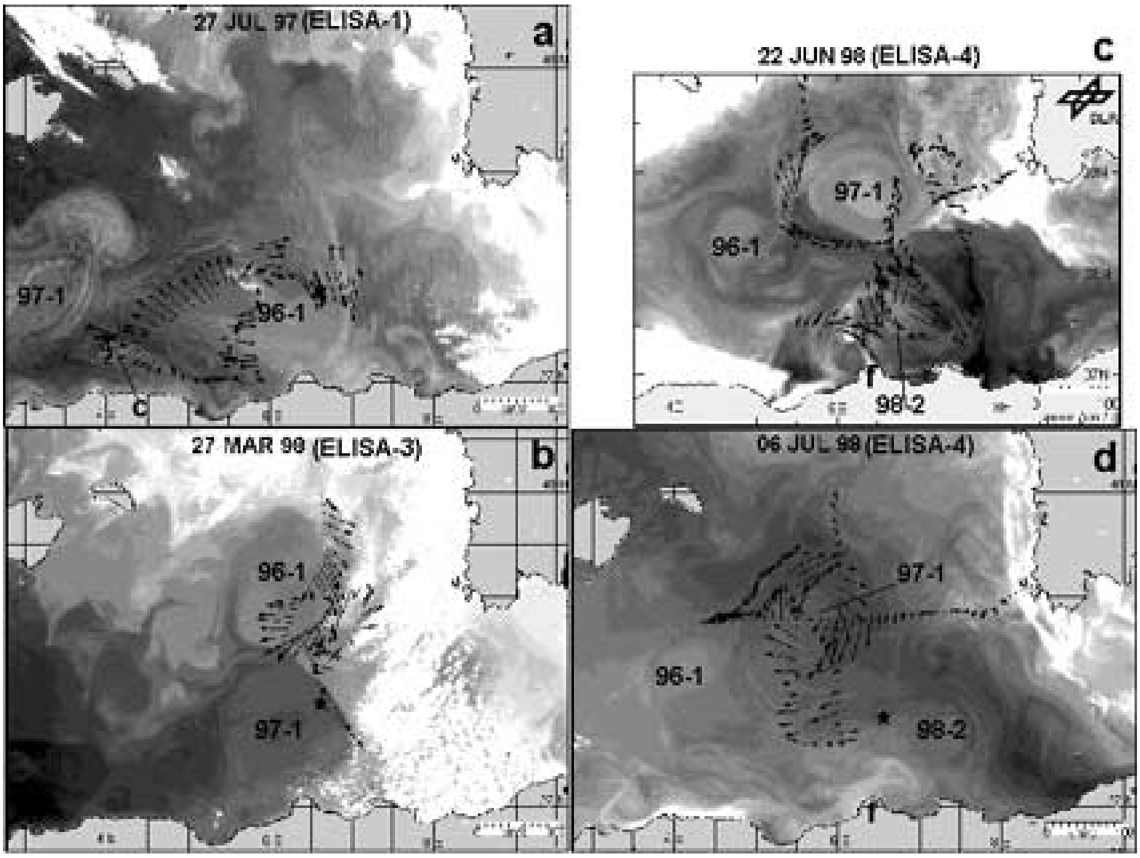


Fig. 2. A sub sample of the SST images time series, showing the successive positions of the Algerian eddies 96-1 and 97-1 from July 1997 to 1998. The arrows represent the mesoscale currents they induce (max ~1 knot), as sampled during the ELISA cruises with a shipborne ADCP. ***:** position of the mooring 8 equipped with 4 autonomous CTD/Fluorometers. Note the propagation, between 22 June and 06 July (~2 weeks) of the eddies along their general counter clockwise circuit in the eastern part of the Algerian sub-basin.

parts of the Mediterranean (Puillat *et al.*, 2002; Hamad *et al.*, 2003). Analyses of satellite images show that mesoscale activity is intense in nearly all parts of the Mediterranean (e.g. Le Vourch *et al.*, 1992; Millot *et al.*, 1994) and present all year-round, with a peak in winter in the northern parts (demonstrated at least in the western basin) in relation with the deep water formation process. The northern currents (that flow westwards) are less unstable. They mainly generate meanders which evolve into mesoscale eddies of relatively small scale only in the eastern basin (Hamad *et al.*, 2003). Both the southern and northern currents are, when roughly stable, "only" a few tens of km wide, so that sampling interval must be fine enough and adjusted to the physical phenomena expected to drive markedly the biological ones.

As it can be deduced from Fig. 1 and is shown on Fig. 2, the current does not flow smoothly along the coast: it is disturbed by eddies in a direction opposite to the general circulation (see Fig. 2a). Most of the gradients created are oriented cross-shore, with an offshoreward current (and upwelling) on the upstream (resp. shoreward and downstream) side of the eddy. Besides the temperature and salinity changes at the edges of the eddies, one must expect changes/ alternation of open-sea/saline/nutrient-depleted/low chlorophyll water populations with coastal/fresher/nutrient-rich/high chlorophyll ones as the eddies are passing by. This is clearly shown by the physical and biological time series collected during ELISA with four autonomous CTD/fluorometers fixed on top of one mooring (see location in Fig. 2) between 30 and 80 m (Fig. 3).

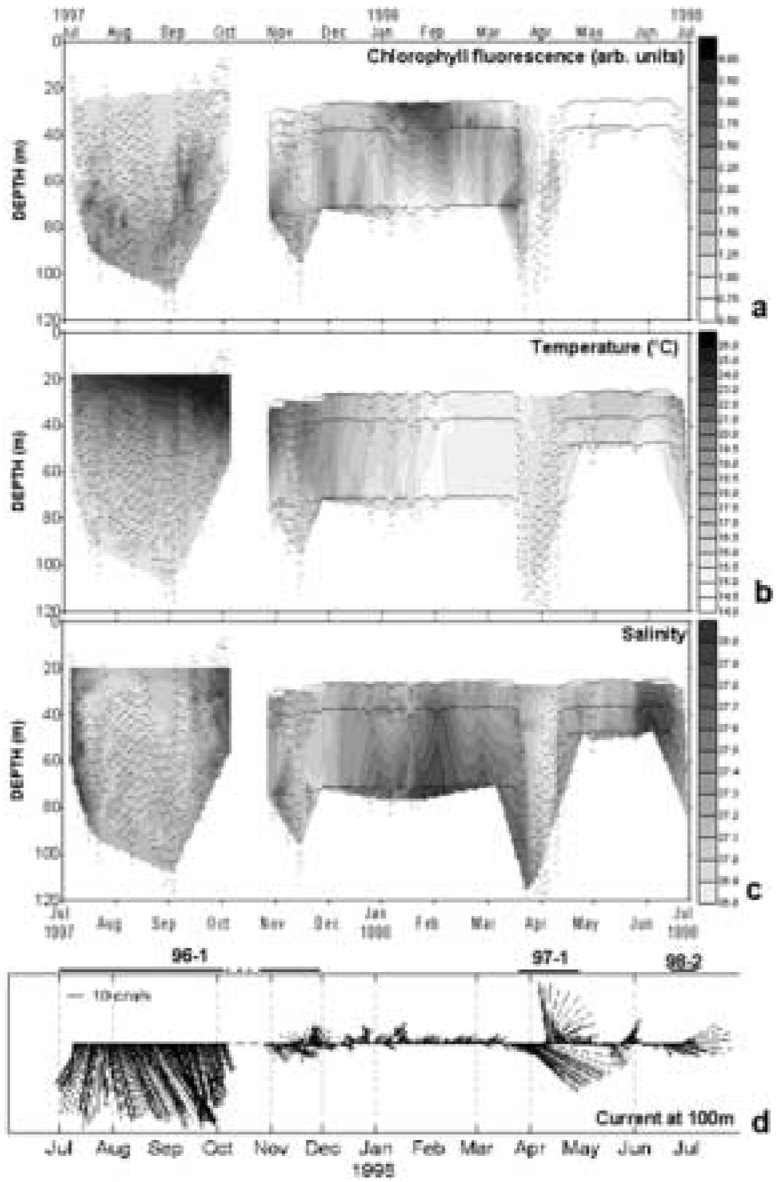


Fig. 3. The concurrent biological and hydrodynamical time series recorded during ELISA on mooring 8. **a**) chlorophyll fluorescence, **b**) temperature, **c**) salinity, **d**) current at 100 m (North points upward). The dots represent the immersions (subsampled) of the CTD/Fluorometers.

For what concerns the biological response of the eddies, the fact that they are anticyclonic is significant. Indeed, their dynamical structure is a depression (~150 m deep), so that, after the phytoplankton has depleted the nutrients from the euphotic zone, it cannot grow further as the deeper nutrient-rich water is kept below the euphotic depth. In the eddy 96-1, which was sampled in July 1997 close to the Algerian slope (Figs. 2, 3), the oligotrophy was as severe as in the eastern basin. When it was sampled in March 1998 offshore (Fig. 2b) it was there that the maximum integrated chlorophyll values were found (Taupier-Letage *et al.*, 2003). It has been shown for the Algerian eddies, at least, that their biological response depends, in a complex way, upon their history (age and trajectory), the season, their location and the dynamical environment (interactions with their parent current or with other eddies).

Interactions of meanders and eddies with other eddies or with coastline breaks can generate smaller-sized and shorter-lived features, such as cyclonic shear eddies "c" and/or filaments "f" in Figures 1 and 2. In the "c" sampled during ELISA -1 (Fig. 2a), the chlorophyll maximum concentrations reached ~ 8-10 mg/m3, when the maximum recorded during the seasonal bloom was ~1-4 mg/ $m^3$ (Fig. 3a).

Eddies can also disturb the general circulation for months, hence the local hydrodynamical situation. For instance, in 1984 close to Algiers (3°E), the huge eddy W (up to 250 km, Fig. 4) has been disturbing the alongslope flow of AW during 9 months at least, diverting it offshore so that colder (~ 17-18°C in summer) and fresher water reached the southern coasts of Mallorca (Taupier-Letage and Millot, 1988). Concurrently, along the Algerian slope downstream W, as long as the Algerian Current was diverted offshoreward there was no strong mesoscale activity, reducing drastically the number of associated upwellings. Most likely this specific situation, generated by mesoscale dynamics, had a time scale long enough to impact the food web and local fisheries.

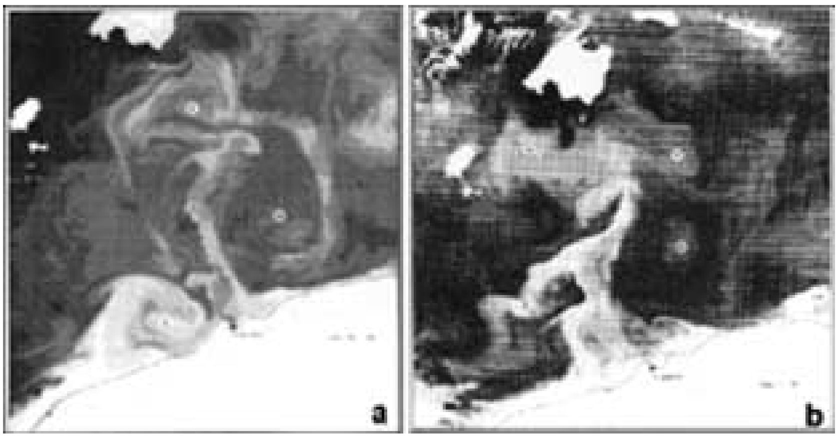


Fig. 4. The Algerian sub-basin in summer 1884: SST from 29 July (a) and 07 August (b) 1984 (from Taupier-Letage and Millot, 1988). The younger/smaller eddy c propagates eastward up to impinging on W, and disintegrates. On the other hand the eddy A succeeds in propagating around W.

Seasonal variations occur everywhere, and the season is probably the spatial scale that has focussed the most efforts for biological time series. Mesoscale variability is always superimposed on better-known seasonal varirability, and is likely to appear like "noise" to the untrained eye, and disregarded as such, so that in many cases the seasonal variability cannot be considered as well known. Now, as the biological variability associated with the mesoscale can be higher than the seasonal one, as shown above with the ELISA data, this argues for the adoption of a sampling interval resolving the local mesoscal. This should cover a few years at least, so as to get a biological time series describing seasonal cycles reliably, noting that seasonality for biology is not only that induced directly by the earth orbit. Seasonality for biology also results from seasonality in dynamics, as an indirect consequence of the earth orbit.

## RECOMMENDATIONS FOR CONCURRENT TIME SERIES ACQUISITION

The quality of a time series depends first on the adequacy of its sampling interval with the spatio-temporal scales of importance. The analysis of satellite images time series (especially thermal, visible, altimetry) prior to the in situ data collection ensures that this condition is met. A second condition is the absence of gaps. To this all steps must be taken to decrease the enornous effort required for sampling, especially switching to autonomous sensors whenever possible, and to autonomous platforms whenever relevant. The quality of the interpretation of the biological time series requires the understanding of the dynamical environment (on a large domain) at least, and better, of the trophic conditions too. This can be achieved by analysing concurrent data sets such as satellite images, and acquiring concurrently basic parameters such as temperature and salinity, chlorophyll fluorescence, nutrients, ... If we take the example of the interdisciplinary ELISA experiment, we had a good a priori knowledge of the spatio-temporal scales and phenomena, gained from our previous analyses of the SST and ocean colour images. We combined a one-year network of nine moorings (3 to 5 currentmeters each, plus one equipped with four autonomous CTD/fluorometers) and four cruises (total ~100 days) year-round. We received the SST images in near-real time on board to track the eddies and associated phenomena, and thus decided about the most-adapted sampling scheme. About 250 casts were made along ~ 30 transects, with a sampling interval ranging from 5 to 14 km. During the first cruise the investigation of the eddy 96-1 was also carried out (team from Southampton Oceanographic Center) using a Seasoar device and a towed LHPR (Longhurst and Hardy Plankton Recorder). More than 500 SST images were analysed (Puillat *et al.*, 2002) to track the eddies and interpret the time series recorded on the moorings (Taupier-Letage and Puillat, 2001; Aubertin *et al.*, 2003) ... and of course processing is still going on, and will go on for a few more years yet!

Details on platforms and sensors can be obtained for instance on websites (<www.pml.ac.uk/globec/main.htm>, <www-ocean.tamu.edu/GOOS/goos.html>, <www.opl.ucsb.edu/tommy/pubs/hawaii01/dickey.pdf> and <www.bom.gov.au/OceanObs99/Papers/Send. pdf>). We will only list here what we consider as the most efficient platforms and strategies (i.e. requiring a minimal effort for a maximal understanding) to collect and/or improve biological time series.

**• Satellites**

Satellite images – mainly sea surface temperature (SST) and colour – easily provide essential information about the local spatio-temporal characteristic scales and the representativity of the sampling site. Time series of images provide a description of the evolution of the dynamical (SST) and biological (surface chlorophyll) phenomena, and allow targeted sampling to check hypotheses. Satellite images are also sometimes the only means to get information on the poorly known/sampled areas, such as the southeastern Mediterranean.

Whenever possible the in-depth analysis of the images times series must precede the start of any biological time series acquisition, so that i) the area/site most representative of the signal which is looked for is clearly identified, and ii) the observational effort can be optimised (i.e. larger adequate sampling spatio-temporal interval). Images should be used too in (near) real time to guide any shipborne additional complementary sampling. A posteriori, time series of images must be used to describe the spatial environment of the sampling site, to check its representativity, and to interpret the observed biological signal variability. Many satellites/sensors are available to back biological studies, the images processing is now much easier and faster, and their availability has improved as some can be obtained from the web for free. The images to be sought first are the thermal ones from AVHRR (Advanced Very High Resolution Radiometer, on board satellites NOAA, see <http://www.ipo.noaa.gov/>, since the SST they provide is representative of the temperature of the whole mixed layer as soon as waves mix the surface layer (which is most often the case). Then the visible "ocean colour" ones such as SeaWiFS, MERIS and MODIS (see <http://www.ioccg.org>) since they provide phytoplankton concentration distributions, integrated over a layer ranging from a few metres in very turbid waters up to several tens of metres in very oligotrophic (clear) waters. These medium-resolution sensors provide images with a ~1 km pixel on an area ~ 2000 km wide, at least once per day (i.e. any point of the Mediterranean is covered at least once per day). The analysis of images (cloud cover permitting) such as the

SSTs is relatively easy, as currents can be deduced intuitively, either by following the isotherm contours (e.g. rotation of currents associated with an eddy), or by tracking the displacement of a structure (e.g. progression of the tip of a tongue). Note that the visible images are also good tracers, although indirect, of the dynamics (of mesoscale dynamics on Figures 1b, d, and of seasonal dynamics on Fig. 5b). The analysis of time series of images provides the indispensable description of the spatio-temporal variability of the area at scales ranging from meso- to seasonal and interannual.

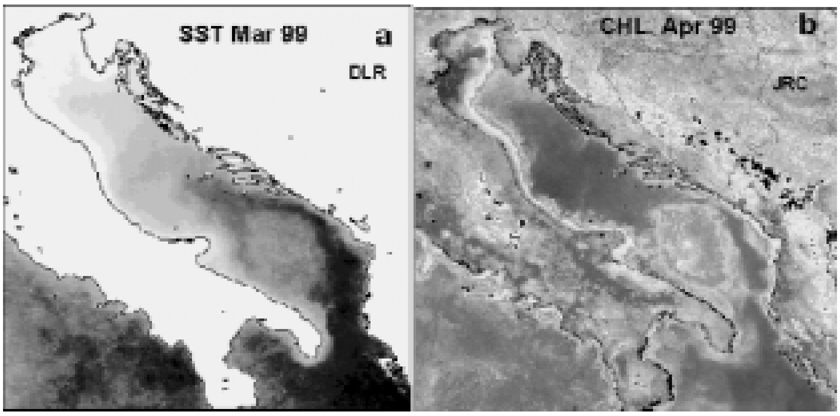


Fig. 5. Monthly composite images of **a**) STT for March 1999 (AVHRR from DLR) and **b**) surface chlorophyll concentrations for April 1999( SeaWiFS from JRC).

The critical gap is the availability of full resolution (1 km) products for end-users. As far as the AVHRR images are concerned, daily, weekly and monthly SST composites can be found (free) on the DLR server <http://eoweb.dlr.de:8080/servlets/template/welcome/entryPage.vm>. Daily composites are usually posted within a few days, so that they can be used to determine the hydrodynamical context in preparing a campaign at sea. As for the ocean colour images, the closer ones found on the web are the SeaWiFS images posted (free) on the JRC site <http://www.me.sai.jrc.it/>. There are daily, decadal and monthly composites at a 2-km resolution. Unfortunately there is a one-year delay (at least), and a few of the orbits only are processed, so that the daily coverage of the Mediterranean is incomplete. Full resolution data are available of course in archiving centres, but imply to undertake a large part of the processing chain, which is not within the reach of most end-users. Several projects process images at high resolution up to end-user products, however it is either for a limited duration or dedicated to a limited public. As several institutions across the Mediterranean have receiving stations, there should be a coordinated effort to cover the whole Mediterranean to ensure the availability of final products to end-users (possibly in near-real time).

**• Moorings**

Moorings provide a way to sample continuously and objectively with a temporal interval as fine as necessary, in an unattended mode and over a “long” period. Variations in time only are recorded, which provides an unbiased measure and is convenient to compare data with models (as opposed to drifters where variations in both space and time add). Technological progress has provided a great variety of autonomous sensors easy-to-use and relative cheap (at least as compared to the value of the information provided, and/or to the cost of hand-collected time series, and/or to the cost of a small ship). Basic parameters such as temperature and salinity must be acquired to provide the hydrological environment (autonomous CTD probes are now easy to use and cheap). Currentmeters are also easy to use, as well as the current profilers (ADCPs) that provide a description of the structure of the water column. Chlorophyll fluorescence is also a basic parameter to record. Several autonomous fluorometers have been developed and have been used (cf. Fig. 3a). However, for the bio-optical sensors (including cameras) in general there appear to be no fully satisfying solution to avoid biofouling on long-term deployments (1 year). Nevertheless this will not hinder bio-optical moorings in the coastal zones, as periodic operations for the maintenance of the sensors are easier to set up there. As for the biogeochemical sensors, it seems that the sensors developed up to now have sensitivity and detection limits not fully adapted to the (extreme) oligotrophic conditions of the Mediterranean. A 1-hour sampling interval provides a sound description of the mesoscale variability.

For biology the surface layer is critical. Collecting biological time series in that layer will be advantageously made, in regions where waves are not too high, with moorings equipped with surface buoys (this requires an efficient signalisation), thus allowing sampling up to the surface. In deep waters and in unprotected coastal zones and shelves, however, surface buoys will need to be relatively large. The corresponding price and required logistics are (too) high, so that subsurface moorings are preferred, which prevents from sampling the critical upper few tens of metres. During periods of strong current, the mooring head deepens as the drag on the mooring line increases. The drawback is that the immersion of the sensors is not constant, but the great advantage is that, during these periods, each sensor profiles a few 10s of metres, thus increasing the vertical resolution (see Fig. 3). A critical gap for the mooring strategy is the absence of device that allows profiling in the upper layer up to the surface (carrying thus only one set of sensors). One profile per day with a vertical step of 50cm in the upper 200m would provide an adequate resolution of the mesoscale variability.

It must be noted that a CIESM co-ordinated action to monitor the long-term hydrological trends in the Mediterranean has just begun this year, using small moorings to be recovered every one or two years (<www.ciesm.org/newsroom/2201.html>). This information will be very useful in the future for the interpretation of local biological time series.

**• Shipborne**

If the biological parameter constituting the time series requires a ship, a CTD should be systematically used (they have become cheaper and easier to use, some models work in stand-alone mode) to collect a water column profile. There is a great variety of sensors that can equip the CTD for chlorophyll fluorescence (high priority), dissolved oxygen, etc. However there is no profiling nutrient sensor on the shelf. A complementary structure-oriented sampling, as defined upon the (near)real time analysis of satellite images, will significantly improve the understanding of the distribution of the biological parameters.

Biological time series can also be collected along regular tracks, at regular intervals and over long periods, using autonomous instruments on board ferries. Collection of plankton has been carried out for a long time on ferries across the Channel with a LHPR, for instance. This is certainly a strategy to foster, as it is very cheap, the domain sampled is larger (the surface layer along the whole ship track, potentially the whole basin), the data set is homogeneous (the same track is sampled repeatedly), and the effort for sampling is extremely reduced (but full automation must be sought, as the intervention of a crew member cannot be envisaged on ferries). There is nearly no risk of data gaps due to bad weather, as a ferry must cross. And finally the issue of biofouling of sensors can be addressed properly as the opportunities for maintenance are frequent (regular port calls). Such a strategy is all the more valuable when the relationships between the surface and deeper layers are well understood. The use of a thermosalinograph (TSG) must be systematic, especially since Salat and Pascual (2002) have shown that a long-term hydrological trend could be extracted from the surface water temperature signal.

Such a project which will cover the the routes Marseilles-Algiers and/or Marseilles-Tunis is currently in its pilot-phase with the support of CIESM.

In conclusion, efforts must be made to develop the biological and biogeochemical autonomous sensors, to develop the availability of satellite final products, and, in some cases, to develop discussions and joint work between physicists and biologists.

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