I - EXECUTIVE SUMMARY

This synthesis, initiated during the meeting, was consolidated therafter by inputs received from the workshop participants, and in particular from John Allen, Isabel Ambar, Isabelle Taupier Letage, Marlon Lewis, Ananda Pascual and Volker Strass. Jordi Font and Frederic Briand, assisted by Carolyn Scheurle and Paula Moschella, took care of the final editing, while Valérie Gollino did oversee the physical production process.

1. INTRODUCTION

A workshop focused on the observation, understanding and prediction of mesoscale processes in the Mediterranean Sea was held from 25 to 28 May 2005 at the historical Station Zoologique, part of the Observatoire Océanologique de Villefranche-sur-mer. Nineteen scientists originating from twelve countries attended the meeting at the invitation of CIESM.

In welcoming the participants, Frédéric Briand, Director General of the Commission, stressed the exploratory nature of CIESM workshops, seeking as much as possible to capture emerging concepts and hypotheses. This guided the choice of the guests – physicists, biologists and modelers – assembled here to reflect upon the challenges raised, and the best tools available for the study of mesoscale biological and physical processes, now increasingly recognized as highly significant in the Mediterranean Sea and elsewhere. He expressed his thanks and appreciation to Michel Glass[1], Director of the Observatory, and to his staff for facilitating the preparation of the meeting. He then invited Jordi Font, Chair of the CIESM Committee on Physics and Climate of the Ocean who initially conceived the theme of the workshop, to present the scientific background and objectives of the meeting.

As revealed by many studies during the last two decades, the Mediterranean Sea is an ocean region where intermediate scales (mesoscale) play a key role in determining the characteristics of the basin-wide marine circulation, the distribution of water masses, and even ecosystem functioning. A multidisciplinary approach in the study of mesoscale structures and processes is an increasing demand of researchers. Specialists from different disciplines and with complementary backgrounds were therefore invited to this workshop to review the main issues of mesoscale research in the Mediterranean, and to propose new foci and techniques to help the entire Mediterranean community to significantly advance in this field.

Two days of individual presentations were followed by two days of general discussions and recommendations for future work. The presentations covered a wide range of topics and raised exciting discussions, including debate on issues regarding interpretation of available data and conceptual models that reveal open questions and highlight the need for collaborative efforts in mesoscale research. In the following, the main conclusions of the workshop are summarized, followed by extended abstracts of the different presentations.

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1 On the following day Dr Glass presented a survey of the fascinating history of the research carried out at the Station, from the early days traced by Russian plankton scientists, to nowadays when it has emerged as a major multi-disciplinary Center.

Mesoscale features represent the internal weather systems of the ocean. As such, their role in the distribution of water properties and life in the ocean is as important as that of the atmospheric weather in the distribution of air properties and terrestrial life.

Almost every satellite image of sea surface height, sea surface temperature or ocean colour reveals mesoscale meanders, filaments and eddies. Mesoscale eddies are low or high pressure systems associated with cyclonic or anticyclonic circulation, respectively. Like their atmospheric counterparts, they are mostly formed by baroclinic instability of larger-scale fronts. The mesoscale motions draw their kinetic energy from the reservoir of available potential energy. Additional input of kinetic energy can come from the horizontal shear of larger-scale currents through barotropic instability. As a result of the conversion of available potential energy, spectra for horizontal motions in the ocean generally reveal a maximum of kinetic energy in the mesoscale range. Because of their analogy to atmospheric weather systems, mesoscale phenomena of the ocean are occasionally also called synoptic (e.g. Kamenkovich *et al*., 1986).

The horizontal scale of mesoscale features is set solely by internal properties of the ocean, as measured by the internal Rossby radius of deformation; it is not imposed by external forcing or topography, for instance. The range of mesoscale horizontal dimensions extends from a few kilometers to a few hundreds of kilometers, where the restoring ß-effect exerts a limiting control. The vertical extent ranges from few tens to a few thousands of meters (i.e. down to the bottom). The timescales associated with mesoscale motions are typically in the range of a few days to several months (yet can reach several years).

Mesoscale dynamics is governed by quasi-geostrophic balances. While the associated motions are thus mainly horizontal, small deviations from geostrophy make a significant difference. In places where the flow changes in time, and where eddies interact with each other or with the mean flow, frontogenesis or frontolysis results, and the conservation of potential vorticity consequently induces vertical motions. Such upwelling or downwelling events can be strong enough (tens of meters per day) and last long enough (several days) to affect biological processes. The primary production by planktonic algae in particular can be affected, for instance as a result of the displacement of phytoplankton cells along the vertical light profile or as a result of a vertical flux of plant nutrients. This leads to another analogy with atmospheric weather processes, namely the creation of (phytoplankton) clouds and their subsequent (sedimentation) precipitation. That the mesoscale circulation also accounts for the advection of organisms, and hence either accomplishes or hinders completion of their life cycles, is obvious.

Although the length scale of mesoscale motions is set by internal properties of the ocean, mesoscale eddies can become trapped by topographic structures if these have matching dimensions. In the Mediterranean this seems to happen quite regularly, so that eddies attain the characteristics of stationary gyres. Prominent examples are the Alboran gyres. The Alboran Sea[2] is the region of the western Mediterranean basin adjacent to the Strait of Gibraltar, through which a two layer exchange takes place with an inflow of fresher Atlantic water in the upper layer and an outflow of saltier Mediterranean Water below. Due to the mesoscale motions that are superimposed on the thermohaline circulation, which is driven by the Mediterranean basin-scale dominance of evaporation over river runoff and precipitation, the surface inflow at Gibraltar occurs, most generally, in a narrow (25-30 km wide) north-eastward jet that later forms a meandering front, coupled to one or two large (100 km diameter) anticyclonic gyres trapped by the topography. The incoming Atlantic water mixes with the surface resident water, giving rise to the modified Atlantic waters (Gascard and Richez, 1985), known as Atlantic Water (AW – see www.ciesm.org/catalog/WaterMassAcronyms.pdf) within the Mediterranean. It fills the southern Alboran and then flows eastward to the whole Mediterranean Sea (Font *et al*., 2002; Millot and Taupier-Letage, 2005a).

On the western side of the Strait of Gibraltar, the out-flowing Mediterranean Water (MW) creates a water mass signature that can be traced throughout the Atlantic Ocean and even beyond.

2 One will remark through the course of this Monograph that different authors may use different terms to name identical type of maritime regions (sea, basin, sub-basin, etc.). CIESM is seeking ways to reach harmonization.

Mesoscale dynamics contributes significantly to the spreading of MW in the Atlantic, as a substantial fraction of this water penetrates into the Atlantic by way of the so-called meddies (for a recent account see Siedler *et al*., 2005). Meddies are long-lived, sub-surface eddies or lenses containing high-salinity water of Mediterranean origin with anticyclonic rotation and approximate diameters of 100 km, which have been observed to form off the southwestern coast of Portugal (Bower *et al*., 1995). The spreading of the Mediterranean Water in the world ocean is an example of the diffusive effect that mesoscale eddies can have in the mean over larger space and time scales.

It follows that any endeavour to improve the skill of operational modeling and forecasting requires a sufficient understanding of mesoscale processes. Developing the best strategies for observing, analyzing, and forecasting mesoscale processes was hence the aim of this workshop.

Compared to synoptic meteorology, resolving and forecasting the 'ocean weather' is complicated by the fact that the scale of the ocean weather systems is much smaller (~ 10 - 100 km) than that of the atmospheric weather systems (~ 100 - 1000 km). Per unit area, numerical ocean forecast models thus need hundred times as many grid points as atmosphere forecast models. Since computer power still is a constraint, an acceptable model resolution will be more easily achieved for an ocean basin that is as confined as the Mediterranean Sea. This, combined with the fact that the lateral boundaries are rather small and the surface forcing is comparably well defined, makes the Mediterranean Sea an ideal test bed for the improvement of ocean forecasting models. Furthermore Mediterranean waters are quite easily accessible for collecting the relevant mesoscale data sets needed for model validation.

2. Time scales, length scales and biological impact

Lewis (2002) provided a review of 50 years of research recognizing and explaining the relationship between scales of biological patchiness and physical mechanisms in the open ocean (see also LeBlanc *et al*., 2004; Strass, 1992; Steemann Nielsen, 1952). We do not attempt to summarise this here: instead we introduce some recent arguments and observations which were the subject of very recent publication and/or discussion at this CIESM workshop.

At the mesoscale, spatially considered to be 10-100 km and temporally weeks to months, the vertical disturbance of isopycnal surfaces has been referred to as 'eddy pumping' (Falkowski *et al*., 1991). On its own, this represents a single stochastic source of nutrients to the euphotic zone related to the growth component of cyclonic (in the case of a mode 1 vertical dynamic height profile) or anticyclonic (in the case of a mode 2 vertical dynamic height profile) vorticity (Gill, 1982).

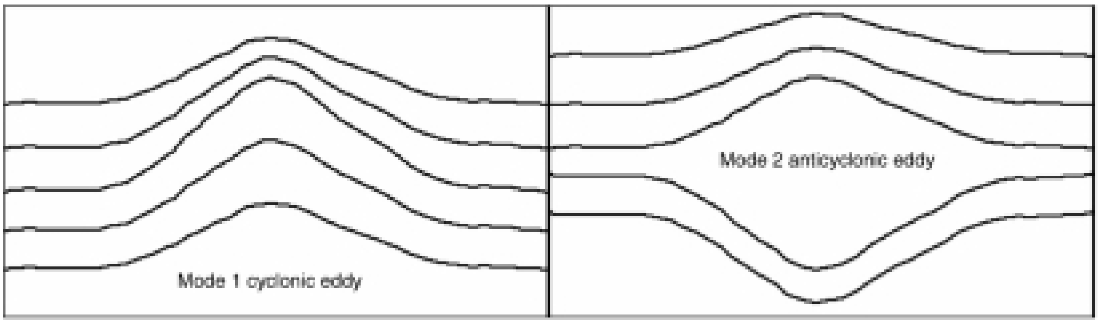

Fig. 1. Vertical structure of ocean eddies as depicted by the dynamic height isolines (from Gill, 1982).

A more sustained source of new nutrients to the euphotic layer comes from the wave propagation model of mesoscale eddies in which water is not trapped within the eddies but is moved up and down on isopycnal surfaces displaced vertically by the propagation of the eddies. This passing perturbation mode of influence for eddies has been discussed in the context of eddy permitting/resolving general circulation coupled ecosystem models (Oschlies, 2002; McGillicuddy *et al*., 2003). However, this mechanism still fails to supply enough new nutrients into the euphotic zone to get anywhere near the Jenkins (1982) estimates of new production inferred from oxygen utilization. Part of the problem with this model of eddy scale processes is that the same isopycnal surfaces are brought up and down through the base of the euphotic zone and are steadily depleted of nutrients. A further restoring mechanism is required to replenish the nutrients; along isopycnal (effectively horizontal) mixing is the logical choice, although it is difficult to see how this could achieve the restoring time scales claimed (e.g. 10 days, Seigel *et al*., 2003).

More recent studies of internal wave driven turbulent mixing and a proper parameterisation of vertical diffusivity, taking into account the inherently double diffusive nature of the Atlantic (Dietze *et al*., 2004; Schmitt *et al*., 2005), make a significant contribution to the budgets but continue to fall short of finding the nutrients to satisfy the apparent requirements for export flux based on geochemical signals in deeper waters.

Of course it may be that the approach of Jenkins (1982) was simply in error: however, there is an eddy scale mechanism that is not well represented in even the highest resolution general circulation coupled ecosystem models, and which may hold the secret to the missing production. The ubiquity of mesoscale eddies in the open ocean has been demonstrated in the length scale and persistence of sea surface height anomaly data from satellite altimeters (Kuragano and Kamachi, 2000), in eddy kinetic energy spectra (Stammer, 1997; Wunsch, 1997; Wunsch and Stammer, 1995), and most obviously in the striped nature of ADCP data plotted for trans-basin WOCE like ocean sections (Bryden *et al*., 2002). The existence of these eddies predominantly results from baroclinic instability (Stammer, 1997). Although the impact of baroclinic instability is global, it is expressed at what Lévy *et al*. (2001) termed the 'sub-mesoscale' (1-10 km spatially, and perhaps days temporally). In the atmosphere this process drives weather scales. In the ocean, baroclinic instability creates eddies and meanders in water mass boundaries (Allen and Smeed, 1996; Munk *et al*., 2000). In baroclinic instability, potential energy is released, this happens through the real exchange of water vertically, higher density waters descending under less dense waters, not a closed circulation (Lévy *et al*., 2001; Allen *et al*., 2005).

General circulation models do not explicitly ignore baroclinic instability, but the discrete resolution (10-15 km or greater) of the model 'reality' prevents them from reproducing physical structures at scales much smaller than 50 km. Higher resolution process models (Lévy *et al*., 2001; Lévy, 2003; Nurser and Zhang, 2000, Allen *et al*., 2001a) clearly show that the cross front and vertical exchanges driven by baroclinic instability occur at much smaller scales. Although the net large scale tendency of baroclinic instability is to flatten sloping isopycnal surfaces (Pollard and Regier, 1992), the release of this potential energy happens through filamentary tongues extending along isopycnal surfaces where the along-isopycnal potential vorticity (angular momentum for a stratified fluid) gradient is low (Allen and Smeed, 1996; Allen *et al*., 2001b). These filaments are typically 1-10 km in width but may be many tens to hundreds of km in length and extend to hundreds of metres in depth. Releasing potential energy by carrying salt and heat, these filaments also carry biogeochemical signatures; exchanging nutrient-replete with nutrient-exhausted waters (Nurser and Zhang, 2000, Allen *et al*., 2005), and stripping organic material out of the surface layers (Videau *et al*., 1994; Fielding *et al*., 2001).

Mesoscale dynamics has time scales similar to biological growth rates

Individual atmospheric weather systems generally have little ecological impact on terrestrial or marine biological systems. Grass grows, algae blooms and herbivores graze through many low pressure (cyclonic) and high pressure (anticyclonic) weather systems. In the open ocean we have a very different picture. The primary producers and herbivores have shorter life time scales (days); time scales that coincide with those of mesoscale eddies and fronts, i.e. oceanographic 'weather'. This suggests that plankton can have either good or bad weather lifetimes associated with just a single cyclonic or anticyclonic eddy system. It also suggests that species or groups may be adapted to rapid acclimation rather than niche exploitation. The magnitude of vertical motions associated with baroclinic instability is significant on biological timescales both for phytoplankton growth and the development of zooplankton grazing pressure.

True mixing, buoyancy vs. diapycnal turbulent mixing

The gravitational sinking of organic particles results from the mortality of phytoplankton populations or faecal pellet residue following zooplankton grazing. In-vitro experiments on single diatom cells indicate very low sinking rates, generally < 1 m/ day (Smayda, 1970; Bienfang and Harrison, 1984). However delicate phytoplankton aggregates may have sinking velocities ≥ 100 m/ day resulting from a critical change in flow regime and thus drag coefficient (DiTullio *et al*., 2000). A commonly held misconception is that turbulence may help to support negatively buoyant phytoplankton cells, however, the simple consideration of a random motion against a constant gravitational force can be used to dismiss this view. Indeed the most recent experimental work on the impacts of turbulence (Ruiz *et al*., 2004) shows that on the contrary, turbulence acts to increase the net sinking velocity; resulting from the particles following rotational paths and converging in regions with the same flow direction as the gravity/buoyancy force. However, Rodriguez *et al*. (2001) showed that quite small advective upward vertical velocities, < 5 m/ day, were required to support a size structure spectrum biased towards the large (less buoyant) phytoplankton particles in the Alboran Sea, and such upward velocities are commonly induced by mesoscale phenomena.

3. Observing technologies and methods

A recurrent problem in many oceanographic mesoscale studies is the difficulty to adapt the sampling needs of different aspects of a multidisciplinary program in a unique coherent observational strategy. Physical oceanographers are used to profile the ocean with CTD probes in such a rapid way that they can most often cover a 3D area affected by a mesoscale process in a time compatible with the scale of the phenomena under study. However, the classical techniques to determine chemical and biological properties are usually more time consuming and in many occasions provide data where the effects of spatial and temporal variability in a rapidly evolving mesoscale process/structure cannot be separated. The use of remotely sensed information, the development of new sensors and sampling platforms, and the availability of elaborated data analysis techniques and numerical models, are drawing an emerging scenario where building up a coherent full strategy to understand mesoscale phenomena starts to be a reality.

3.1. Remote sensing

Remote sensing has played and continues to play a key role in observing mesoscale dynamics, and thus in understanding the observed variability. Indeed satellite images provide a synoptic view at basin-scale, with resolutions in space (~ km) and time scales (day to week) that allow a correct description of the mesoscale phenomena such as filaments, fronts, eddies and gyres. Insofar as the general circulation of the water masses consists of unstable currents generating mesoscale meanders and eddies, remote sensing is also an excellent tool to study the former. Images - more generally remotely-sensed information - can be collected to build time series (duration up to several years, e.g. Marullo *et al*., 1999b; Larnicol *et al*., 2002; Antoine *et al*., 2005), making it possible to track mesoscale features (e.g. Puillat *et al*., 2002). With technological improvements it is easy now to receive the remotely-sensed information on-board oceanographic research vessels in (near) real-time, so that the sampling strategy of a cruise can be adequately defined, taking into account the mesoscale phenomena which impact both the dynamical and the biogeochemical /biological fields.

3.1.1. Data types

Exhaustive lists of available platforms and sensors, including the basic principles of the measure, are readily available (see for instance http://rst.gsfc.nasa.gov/). Here we will only offer a summary covering the most-widely used data types.

• Thermal imagery:

The AVHRR (Advanced Very High Resolution Radiometer) sensor is the most widely used to map the SST (Sea Surface Temperature). The spatial resolution (pixel) is about 1km and the thermal resolution ~0.13°C. The swath is ~2,000 km. Since several satellites fly simultaneously, most of the Mediterranean Sea can be covered several times per day. The SST retrieval is fairly easy, and data processing is mostly uniform in the receiving centers. (Near)real-time products are commonly available. Since the thermal signal only comes from the upper layer, precautions must be taken to infer circulation and mesoscale features. Examples of tracking mesoscale structures with SST will be found in the papers of Ambar and Serra, or Taupier-Letage and Millot, in this volume. Note that other sensors (e.g. most of those dedicated to ocean colour) also have a thermal band, as the ATSR (Along Track Scanning Radiometer) on board the European ERS and Envisat satellites or MODIS (Moderate Resolution Imaging Spectroradiometer) on board the NASA EOS Terra and Aqua satellites.

• Visible/ocean colour imagery:

After a long gap between CZCS (Coastal Zone Color Scanner, 1978-1986) and SeaWiFS (Sea-viewing Wide Field-of-view Sensor, launched in 1997), nowadays there are several sensors flying simultaneously to map the surface distribution of algal pigments, dissolved organic matter and particulate matter. For a review of the parameters that can be computed and the sensors available see http://www.ioccg.org/. Examples of such images can be seen in the papers by Allen, Oguz, Poulain, Ribera *et al.*, or Taupier-Letage and Millot, in this volume. The spatial resolution (pixel) ranges from less than 1km to ~4km. The Mediterranean is fully covered within 1-2 daytime period(s). The retrieval of the marine signal which amounts to less than 10% of the total is complex, and the nature of the matter (living- non living, particulate-dissolved) can be so specific, that algorithms are likely to be site-specific, and/or specific to a processing center. Due also to the longer processing chain, commercial concerns or administrative roadblocks, (near) real time products at full spatial resolution are seldom proposed on a regular basis. Because of the close relationship between physical and biological phenomena at mesoscale, the distribution of phytoplankton can also be used to infer horizontal advection, as shown by the correlation of both signatures on Figure 2 *(SST and CHL 28 Feb. 1998)*. Ocean colour images are even a better tracer than SSTs, since the signal comes from a thicker layer (1 optical depth, nominally 2-30 meters in the Mediterranean, depending on the level of biomass).

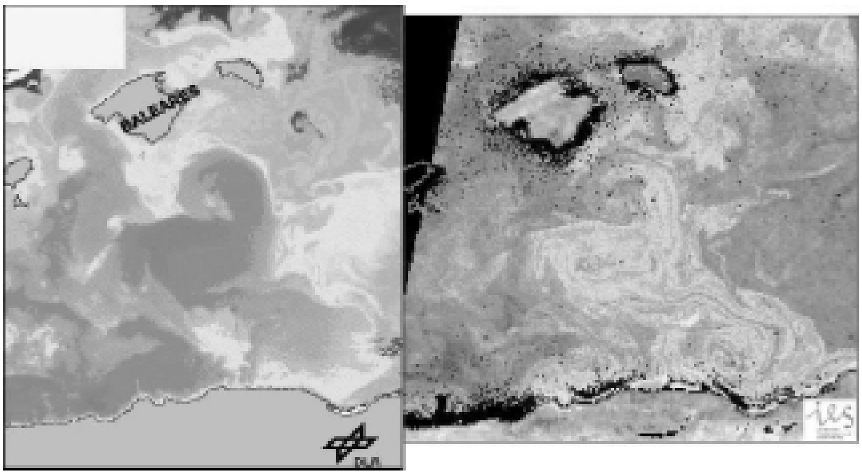

Fig.2. (See page 108 for original color plate) Thermal/SST (left, NOAA/AVHRR image, processed at DLR and LOB) and biological (right, SeaWiFS image, processed at IES/JRC) signatures of Algerian mesoscale (anticyclonic) eddies, on 28 February 1998. Temperature and chlorophyll content increase from blue to red.

• Altimetry:

Satellite altimetry is a useful tool providing sea surface topography measurements from which geostrophic velocities can be estimated. One of the big advantages of altimetry is that it can be used independently of cloud conditions. However the spatial and temporal resolutions are lower than for SST products. Typically, the along-track spatial resolution is 7 km whereas the distance between adjacent tracks is about 240 km at the latitudes of the Mediterranean for a mission like Jason-1 and TOPEX/POSEIDON, with a 10-day repeat orbit. Other altimeters, like ERS-1/2 or ENVISAT, are characterized by a higher spatial resolution at the expenses of a lower temporal resolution (35 days). Thus, in almost all the applications of altimetry, several missions are merged in order to increase both the temporal and spatial sampling and to produce gridded fields (see Larnicol *et al*., 2002, for the merging of TOPEX/POSEIDON and ERS-1/2 and Pascual *et al*., 2005 for the combination of up to four altimeters).

• Scatterometry:

Scatterometers are used to estimate the vector wind fields at the sea surface, from which gridded wind stress fields can be generated and used to force the momentum equation at the sea surface. Models of surface wave dynamics and air-sea gas exchange critically depend on the wind stress field at the sea-surface as well, and mesoscale variations in SST can generate feedback into the atmosphere and induce wind stress curls at the same scale. The current SeaWinds instrument onboard the NASA QuikSCAT satellite generates standard vector wind data products at 25 km resolution based on measurements of the radar backscatter at the sea surface (see http://podaac.jpl.nasa.gov/cgi-bin/dcatalog/fam_summary.pl?ovw+qscat). Coastal products have been achieved with a resolution to 12.5 km on a near-to-real time basis in support of operational oceanography, albeit with somewhat greater errors. In comparison with surface buoy observations, accuracies of 0.8 m/s in wind speed and 5.4 degrees in direction are achieved with the satellite observations, with root mean square deviations of ~1.6 m/s and 30 degrees respectively.

• Shore-based radars:

The measurement of surface currents in nearshore environments has been repeatedly identified as critical for future ocean observing systems. Surface currents can be mapped with a radio Doppler-frequency technique called variously HF Radar, surface current radar, or CODAR (the dominant commercial system), which operates at 3-50 MHz. These are remote sensing observations, albeit with observing stations situated on the coast looking out to sea, or alternatively fixed onto stable buoys or platforms. A backbone-level coverage network requires shore installation sites spaced about every 100 km along the coast, assuming offshore ranges of 100-180 km. Radial currents relative to individual sites are derived by microwave scattering; vector currents are available for the region of overlapping coverage from two or more individual sites. At present there are over forty individual HF radar systems presently operated in US EEZ waters by research institutions with many more planned, and also in Europe there is an increasing deployment either in fixed or mobile locations. While many are long-range (~200 km) others are more regional-scale (30-60 km), higher resolution systems (see, for example: http://www.gomoos.org/codar/). The ultimate objective is to provide full coverage of coastal waters for operational purposes. Such highly resolved observations in time and space complement the less frequent and broader scale satellite scatterometer measurements, and as well, permit observations near the coast which are problematic for scatterometers.

3.1.2. Remote sensing products for end-users available on the Mediterranean

In the following table we provide information on satellite derived products (sea surface temperature, ocean colour, surface wind, and sea surface height) over the Mediterranean Sea that can be downloaded for research use. We list here only the products that i) cover the Mediterranean, ii) are ready-to-use, and iii) are freely available (possibly after registration). They can be either images or data files, and include real time and archived data.

A first version of this table (near-real time products only) was prepared by the European MAMA research network (Mediterranean network to Assess and upgrade Monitoring and forecasting Activity in the region, http://www.mama-net.org/).

In http://vosdata.santateresa.enea.it:54321/mfs/mama/id19.htm examples will be found of the products and readme files with downloading instructions. In a few cases where specific arrangements were achieved to allow data access to MAMA partners for evaluation purposes (e.g. with the Coastwatch project http://www.enviport.org/GMES/services/coastal/index.htm through ACRI), these might not be available after the conclusion of Coastwatch and MAMA.

Table 1. Satellite products available over the Mediterranean region.

Product and provider	Images	Data files	Spatial resolution	Time step	Area	Coverage of a single map	Web site for download
SST							
ICM-CSIC	*		1.1 km	several per day	35N-46.2N 15W-16.5E	Western Barcelona at Nadir Mediterranean + part Atlantic (depending on pass)	http://ers.cmima.csic.es/saidin/
CYCOFOS Univ. of Cyprus	*	* (free, users can register)	1.85 km	daily night time	30N-41N 15E-36E	Eastern Mediterranean	http://www.ucy.ac.cy/cyocean/
GOS-ISAC Rome / ADRICOSM	*	* (passwd)	1.1 km at Nadir	daily	39N-46N 12E-20E	Adriatic sea	http://gos.ifa.rm.cnr.it/adricosm/
GOS-ISAC Rome	*		5 km	several per day	30N-48N 10W-40E	entire Mediterranean	http://gos.ifa.rm.cnr.it/index.php?id=292
LOS-IFREMER Brest	*	* 400 Kb	2 km	several per day	NE Atlantic + Mediterranean	E + W Med. (uncomplete)	http://www.ifremer.fr/cersat/en/index.htm
GOS- ISAC + CMS / MFSTEP		*	1/16° (~7 km)	daily optimally interpolated map	30.25S-46N 18.125W- 36.25E	entire Mediterranean +East Atlantic	http://www.bo.ingv.it/mfstep/WP3/
CMS +GOS- ISAC / MFSPP	*	* (free, users can register)	1/8° (11-14 km)	weekly composite	30N-46N 5W-37E	entire Mediterranean	http://www.bo.ingv.it/mfstep/WP8/sst.htm
ACRI Sophia-Antipolis	*	* 5-10 Mb	1 km	weekly composite (updated daily)	30N-45N 6W-37E	entire Mediterranean	http://www.acri.fr/ + icm server to download images and data
ESA/MEDSPIRATION	*	*	L2P 2-10 km L4 -2 km	daily L2P L4	30N-46N 5W-37E	L2P entire Mediterranean + Atlantic L4 entire Mediterranean	http://www.medspiration.org/
OGS/ Trieste	*		1.1 km at Nadir	several per day	30N-48N 10W-40E	entire Mediterranean, Adriatic, Gulf of Trieste	http://doga.ogs.trieste.it/doga/sire/sato.html
DLR/Oberpfaffenhofen	* gif (free, re-gistration) 03/1993-present		1.1 km	daily, weekly and montly composites		entire Mediterranean	http://eoweb.dlr.de needs color contrast adjustment
Ocean Colour							
ACRI Sophie-Antipolis	*	* 5-10 Mb	1 km	weekly composite (updated daily)	30N-45N 6W-37E	entire Mediterranean	http://www.acri.fr/ + icm server to download images and data
GOS-ISAC	* (free)	* (available on agree-ment)	1 km	daily MODIS passages	30N-46N 5W-37E	entire Mediterranean + Adriatic	http://gos.ifa.rm.cnr.it/index.php?id=373
IES-JRC Ispra	*		2 km	single, ten-day, monthly	30N-46N 6W-36.5E	entire Mediterranean	http://marine.jrc.cec.eu.int/frames/archive_seawifs.htm
Wind							
KNMI Netherlands / QuikSCAT	*	* (passwd)	100 km	3 days or less	30N-46N 6W-37E	1700 Km wide strip	http://www.knmi.nl/scatterometer/qscat_prod/
KNMI Netherlands / ERS-2	*	*	25 km	daily (30 min delay)	global	variable	images in http://www.knmi.nl/scatterometer/ers_prod/ data files in ftp://scatuser:Scat4any@ftp.knmi.nl/prescat1_0
LOS-IFREMER Brest		* 3 Mb per orbit	25 km	daily (5-6 day delay)	global	along swath	http://www.ifremer.fr/cersat/en/data/overview/swath/l2b.htm
LOS-IFREMER Brest	*	* 2100 Kb	0.5°	daily (6-7 day delay)	global	gridded data	http://www.ifremer.fr/cersat/en/data/overview/gridded/mwfqscat.htm
SSH							
CLS Toulouse / MFSTEP		* real time	1/8° (11-14 km)	twice per week	30N-46N 5W -35E	entire Mediterranean	http://www.cls.fr/html/oceano/general/applications/mfstep_en.html ftp://ftp.cls.fr/pub/oceano/Mfs_Ingv274F4P2D6K8G/maps/oer/merged/h/
CLS Toulouse		*delayed. Time from 1993 (avai-lable on agreement)	1/8° (11-14 km)	weekly maps	30N-46N 5W-35E	entire Mediterranean	http://www.cls.fr on request to Gilles Larnicol: *Gilles.Larnicol@cls.fr*

3.2. *In situ* technologies

The mesoscale variations observed in the Mediterranean Sea are generated largely by baroclinic instabilities, with spatial scales order 10-100 km and time scales order 10 to 100 days. In turn, variance at these scales cascades to higher wave-numbers. As a result, isopycnals can be locally uplifted, nutrients are brought near the surface, and the resulting primary production of organic matter then propagates to higher trophic levels. Resolution of the physical and biological dynamics associated with mesoscale processes requires both an adequate observational base, and appropriate parameterizations of mesoscale variability for inclusion in larger scale climate and food chain models.

Shipboard observations are and will remain extremely useful for process oriented studies and for a wide variety of oceanographic experiments which cannot be carried out without them. However, by themselves they are not suitable for resolution of biogeochemical variability over the mesoscale. Autonomous platforms, instrumented with appropriate sensor arrays, hold the most promise for complementing ship-based systems for observation of mesoscale variability.

3.2.1. Sensors for observation of biogeochemical variability

In addition to the routine measurement of the four dimensional temperature and salinity fields, new technologies have emerged for the measurement of key biogeochemical properties and processes from autonomous platforms. General requirements for such instruments are a solid theoretical and practical basis for the measurement and its relationship to the property or process of interest, low power, resistance to environmental degradation (e.g. biofouling, corrosion), an ability to maintain calibration for extended periods, and a general robustness for untended operations. As the numbers of autonomous platforms increases, costs will decrease as well.

A number of sensors either currently deployed on in development are listed in Table 2.

Table 2. Current sensors for autonomous platforms.

Sensor	**Principle**	**Product**	**Power**	**Data**	**Relative Cost**	**Status**
Meteorological Sensor Suite	Varied	Wind speed, Direction, Air temperature, Humidity, Solar Radiation, Air pressure	Low	Low	Low	Mature
CTD	Varied	Conductivity, Temperature, Salinity, Depth (Pressure)	Low	Moderate	Moderate	Mature
ADCP	Doppler shift	Depth-resolved currents	Moderate	High	Moderate-High	Mature
Radiometer	Photodiode, CCD	Solar irradiance, upwelling radiance (ocean color), light attenuation, penetration, and reflectance, particle size/type	Low	Low-Moderate	Low-Moderate	Mature
Scattering/Absorption Sensors, Optical	Photodiode, CCD	Spectral absorption and scattering, particle size/type, POC, PIC	Low	Low-Moderate	Low-Moderate	Mature
Nutrient Sensors	Optical, and Chemical	Concentration of nutrients	Moderate	Low-Moderate	Moderate-High	Experimental
Oxygen, pCO_2	Varied	Concentration of gases	Low-Moderate	Low	Low-Moderate	Experimental-Mature
Fluorometers	Fluorometric	Concentration of Chlorophyll, CDOM	Low	Low	Low	Mature
Fluorescence Induction , Pulsed Fluorometers	Fluorometric	Properties of photosynthesis	Moderate	Moderate-High	High	Experimental
Scattering Sensors, Acoustic	Acoustic	Particle size/type	Moderate	Low-Moderate	Moderate	Mature
Sediment Traps	Gravity collection	Sediment fluxes and type	Low	Low	Moderate	Mature-Experimental
Plankton Recorder (e.g. CPR)	Net	Particle concentration/type	Low	Low	Moderate	Mature
Flow Cytometer	Laser enhanced microscope	Particle concentration/type	High	High	High	Experimental
Microstructure	Piezoelectric, thermistor, inductive	Velocity, temperature, conductivity microstructure/turbulence	Moderate	High	Moderate	Mature-Experimental
Imagers, Optical Plankton Counter	Optical, Varied	Particle Type/Concentration	High	High	High	Mature-Experimental

3.2.2. Observational platforms

There are a variety of autonomous observation platforms available, which can provide complementary approaches to the resolution of mesoscale variability in biogeochemical and physical processes. These include ships of opportunity, fixed moorings, drifting buoys, profiling floats, gliders and powered autonomous vehicles. Current capabilities of platforms are summarized in Table 3.

Table 3. Observational platforms for autonomous deployment.

Type	Deployment	Spatial Scales	Power Avai-lable	Payload Mass	Cost	Strengths	Weaknesses	Maturity
Ships of Opportunity	Instrumented ferries, cargo vessels	Small along track	High	High	Moderate for inst. only	Repeat transect, low cost	Restricted track, no spatial control	Mature
Fixed Moorings	Anchored instrument package	N/A, fixed location	Low-Moderate	Moderate – High	Moderate – High	Long time series at high temporal resolution	Limited spatial resolution unless arrays	Mature
Drifting surface buoys	Floating instrument package	Regional, global if arrays	Limited	Low	Low	Surface properties, velocity	Limited depth resolution, power, payload	Mature
Profiling Floats	Profiling instrument package	Regional, global if arrays	Limited	Low	Moderate-Low	Time – series w/ vertical resolution	Limited power, payload	Experimental – mature
Gliders	Profiling instrument package with limited lateral control.	Regional to global if arrays	Limited	Low	Moderate	Time-series with resolution in horizontal and vertical	Limited power, payload	Experimental
Powered AUV's	Profiling package with powered control of position	Small, unless in swarm	Moderate	Moderate	High	Can execute defined mapping, high payload	High cost	Experimental

3.2.3. Future directions

The unbiased sampling of the oceanic mesoscale variability will require a complementary array of platforms, with autonomous instrumented devices playing a useful role. Future efforts to reduce the size, power and cost of instruments will remain a high priority, as well as integration of data into information products that relate directly to outstanding questions regarding the importance of mesoscale processes in the ocean.

3.3. Sampling strategies

For nearly three decades it has become increasingly common place to make physical (hydrographic) measurements of regions of the oceans sufficient to observe horizontal scales of order (10 km) and in a time frame that, to a first approximation, allows us to assume synchronism of the measurements (Tintoré *et al.*, 1991; Pollard *et al.*, 1995 and others). As a result, our knowledge of the storm (eddy) scale in the ocean has increased dramatically. Just like storms in the atmosphere, eddies in the ocean are created by, and affect, the release of energy across a front and the eventual mixing of two adjacent water masses (Hoskins *et al.*, 1985; Gill, 1982). Similarly, large vertical circulations are associated with eddies, and frontogenetic processes in general (Leach, 1987; Pollard and Regier, 1992; Viudez *et al.*, 1996; Allen and Smeed, 1996); these were hitherto only predicted through applied mathematical theory. In the past decade we began to develop and deploy novel instrumentation and analysis techniques to make biogeochemical measurements synchronised with the physical (hydrographic) measurements (Griffiths and Roe, 1993; Fielding *et al.*, 2001). The resulting interdisciplinary observations demonstrated that frontogenetic physical processes play a significant role in the vertical and horizontal transport of phytoplankton, and either directly transport zooplankton or indirectly interfere with their behavioural habits (Fielding *et al.*, 2001).

At the mesoscale, a significant component of the flow cannot be measured directly; this includes the vertical flow. Instead we derive this flow from a combination of our primitive equations of motion, a suitable balance condition and some assumptions about the conditions on the boundary of our region of interest. Thus the hydrographic and biogeochemical data follow a very different analysis/processing route than the derived three-dimensional flow field. Our first approximation, that the measurements were synoptic, is no longer wholly valid. The error in this approximation affects the hydrographic and biogeochemical data through a route different from that in which it affects the derived three dimensional flow field.

In situ observations of mesoscale processes in the ocean are traditionally both difficult and expensive to make. The trade-off between spatial resolution, vertical excursion and synopticity of the measurements leads to compromises which, although frequently assumed to be acceptable, in practice rarely are. Satellite observations may be made at the required temporal and spatial resolution but the connection between surface signature and subsurface flow is often not clear and in many areas there is no unique solution. New techniques however, for re-locating data relative to the observed motion, for designing optimum sampling strategies and for making *in situ* observations from autonomous vehicles, are being developed to overcome these difficulties in the immediate future if they are suitably exploited.

An attempt to examine the impact of a lack of synopticity on the computation of derived parameters such as the vertical velocity was undertaken by Allen *et al*. (2001). Rixen *et al*. (2003) checked the errors derived from different sampling strategies such as 'cross-front' and 'along-front' radiator style surveys. Pascual *et al*. (2004) used the QG tendency equation to estimate the propagation velocity of a meander sampled during an intensive survey. The estimated propagation speed was then used to relocate stations in order to produce a 'synoptic' map. More recently, Gomis *et al*. (2005) have evaluated synopticity errors for different sampling strategies applied to simulated unstable baroclinic waves and have proposed and tested two methods aimed at reducing the impact of the lack of synopticity. Counter-intuitively, Rixen *et al*. (2003), showed that downstream and upstream 'cross-front' sampling can produce larger errors than' along-front' sampling. In their particular case study, the along-front sampling resulted in errors in vertical velocity of more than 50% in places. These values are significantly higher than those obtained for typical observation errors and sampling limitations (between 15 and 30% for vertical velocity as obtained in Gomis and Pedder, 2005). By combining the relocation of stations (based on a system velocity) and the correction of observations (through the estimation of a growth rate), the authors were then able to eliminate practically all synopticity errors in the case of the along-front sampling. In practice, the error reduction is likely to be less effective, since actual fields cannot be expected to have a system velocity as homogeneous as for the single-mode waves simulated in this work.

3.4. Modeling support

Financial, technical and human resource constraints demand efficient measurements, an issue of particular concern in oceanography. Efficient sampling requires *a priori* knowledge of scales, for the physical processes, life cycles and trophic interactions of the pelagic ecosystem. The adaptive sampling brings together *in situ* sampling and multiple platforms including remote (satellites, aircraft and shore-based), stationary (moorings), moveable (ships and AUVs), and drifting (surface or vertically mobile) with advanced ocean models to improve our ability to observe and predict the ocean. The operational data collection system relays information to a shore and/or to a ship in near real-time (hours) where it is assimilated into numerical models that create four dimensional fields and predict future conditions. The time series of the sea conditions derived from operational forecasting and observing systems may show trends and changes in mesoscale features, and thus helps adaptive sampling to focus on places where the data will be most useful and well matched to the phenomena of interest for the ability to predict ocean properties.

In general, there is a tendency for environmental systems to be 'patchy' that is, the ecological constituents, their structure and their relationships vary from place to place according to the influences of the local dynamics. They also tend to be highly heterogeneous, with biogeochemical characteristics varying rapidly over space and time. The data collection exercise itself adds uncertainty due to human and instrumentation errors as well as by limitations involved in the resolution and the synopticity of measurements. Trying to capture all of that variability in a field survey is incredibly challenging. Time and resource constraints for most field exercises limit the number of sample points which we can realistically visit and measure.

If scales are known for intermittent episodic phenomena, adequate uniform and efficient sampling is possible. Coarser sampling misses entirely, or aliases the phenomena. Finer sampling is redundant and time consuming especially for many biogeochemical parameters, and rates. The adaptive sampling strategy attempts to minimize a selected error measure which depends on data type, sampling and assimilation scheme and a suite of interdisciplinary dynamical models. During the 1990s, the opportunities and requirements for multi-scale, interdisciplinary ocean forecasting have sharpened, the term 'adaptive sampling' for ocean observational networks was articulated, and the concept of Ocean Observing and Prediction Systems has firmly emerged. The systematic and long term observations of mesoscale phenomena cannot be done without the existence of a network of monitoring and or forecasting systems on local, sub-regional and regional level. Operational oceanography, which is defined as the activity of routine observations and forecasting of the sea water conditions and their near real time interpretation and dissemination on-line, may contribute substantially to the study of mesoscale phenomena.

Data assimilation, which melds observations with dynamics, provides the only feasible basis for obtaining accurate synoptic mesoscale realizations over the space-time scales and domains of interest. The near real time transmission and assimilation of the observed in-situ or remotely sensed data into the numerical models has made it possible to provide nowcasts on the present state of the sea characteristics, forecasts on the near future (days and weeks) conditions of the sea and hindcasts on the past state of the sea conditions.

Data assimilation dynamically adjusts and interpolates data inserted into models. In modern ocean adaptive sampling, a goal is to characterize the ideal future sampling among the possible choices in an adaptive accord with the constraints and available forecasts that have assimilated all of the past data. This goal can be achieved either subjectively, with forecast information being combined with the a priori experience to intuitively choose the future sampling, or quantitatively, where forecast capabilities serve as input to a mathematical sampling criterion whose real-time, continued, optimization routines predict the adaptive sampling. The parameters of the adaptive sampling procedure are therefore the available forecasts, new data acquired during the forecast, the constraints and the goal, i.e. the properties to be optimized and the metrics used to measure these properties.

The rapid development of operational ocean monitoring and forecasting systems will obviously support a better management of the marine environment and assist decision makers and public end-users against problems that arise from the various economic activities in the marine sector. It will also assist scientists in studying the spatial and temporal variability of the mesoscale phenomena, as for example the major flow dynamic features in the Eastern Mediterranean, such as the Rhodes gyre, the so-called Mid Mediterranean Jet, etc.

Today adaptive sampling is in its infancy and methodological advances in the forthcoming years will be related to advances in the observing and prediction systems components, the overall system concept and system integration, as well as dedicated theoretical research on objective, automated sampling. The experience gathered in recent decades suggests that the first decade of this century should result in the maturing and evolution of the ocean observing and prediction system concept, which ultimately provide the basis for effective and efficient management of multi-use of the Mediterranean Sea. In Europe, several operational oceanographic forecasting and observing systems (such as MERCATOR, FOAM, MFS, CYCOFOS, POSEIDON, TOPAZ) have been implemented recently, providing regularly on-line in-situ, remote sensing and numerical products, useful also for mesoscale studies on coastal, sub-regional and regional level.

3.5. Information retrieval

Over the past 30 years, a major effort has been made to describe mesoscale variability at global ocean scale. To a large extent, this is the result of new satellite sensors that are able to measure parameters like sea surface temperature, surface elevation or ocean colour at enough high resolution to resolve mesoscale variability with global coverage. Monitoring the seas with these powerful sensors reveals the presence of mesoscale features everywhere. The overall impact of these ubiquitous features on the ocean ecosystem and on the role this has in the biogeochemical cycles of the earth is a research challenge which cannot be ignored, since satellites show an ocean pregnant with mesoscale eddies, jets, filaments and dipoles.

The analysis of sea surface temperature maps has proven to be essential in order to identify and track these structures and to support the description of surface circulation features from large to sub-basin and mesoscale (see Ambar and Serra, Taupier-Letage and Millot, this volume). Similarly, the possibility to accurately measure the sea surface elevation through satellite altimeter data has led to a much deeper comprehension of the ocean circulation in terms of energy involved in mesoscale processes and direct estimates of the surface velocities, at an increased space and time resolution, in the last years, due to the simultaneous flight of several altimeter missions. In this context, it is clear that the number of active sensors available and the merging techniques used represent a crucial issue for the future scientific and operational plans (Pascual *et al*., this volume). As a consequence, a serious concern related to the uncertainties of future altimeter missions (both mounting traditional sensors and introducing innovative concepts as the Wide Swath Ocean Altimeter or Ka-band sensor constellations) was expressed during the workshop.

Actually, much has already been learnt from the remote sensing data by themselves, but the analyses of single sensors and parameters cannot clearly be considered exhaustive. In some sense, the merging of complementary information coming from different platforms, both space-borne and *in situ*, is a key tool to extend our knowledge, for example, from the sea surface to the deeper layers (Buongiorno Nardelli, this volume). To this aim, several methods have already been proposed, that are mainly based on statistical or empirical techniques. However, there is a clear need to optimize and extend the existing methodologies, also exploring the possibility to identify simpler descriptors or parameterizations of the system from theoretical considerations.

Within this context, two complementary approaches can be generally followed. One concerns the assimilation of observed data in the numerical models. The other approach is purely observational, and consists in the attempt to retrieve as much information as possible from the measurements alone. The complementarity of these two paths lies in the necessity for the experimental oceanographers to learn from the more consolidated experience of modelers in the statistical treatment of multivariate data, and in the need for the modelers to fully understand what information is contained in the observations which they must assimilate, in order to design more efficient algorithms.

In addition, encouraging results have already been obtained in retrieving relevant information from across disciplines, as a natural consequence of the strengthened collaboration between physicists, biologists, chemists, etc. A few straightforward examples were presented during the workshop: it has now become quite common for any physical oceanographer to use phytoplankton distribution estimated from space-borne ocean colour measurements as a tracer of the surface dynamics. Similarly, simplified biological models have allowed estimating the vertical velocities associated to upwelling events through sequences of satellite images of SST and chlorophyll concentration (Ruiz and Navarro, this volume).

Nevertheless, the fundamental issue concerning the impact of mesoscale processes on the global ecosystem dynamics still remains almost completely unanswered. Our present inability to provide a reliable answer to such a complicated question is not only due to the many unknown processes relating the biological responses to the different scales of ocean variability, but also, largely, to the limited data coverage of the global oceans at these scales (as satellites only provide surface measurements of a few variables). This lack of data makes it quite difficult to test hypotheses regarding the physical and biological interactions and their impact on a global scale. New technologies for biological sensors in conjunction with *in situ* autonomous platforms for ocean observation (Lewis and Claustre, this volume) will surely play a significant role in the next decades to escape from an undersampled ocean, especially in its biological component. Therefore, one of the priorities for future research activities will be to transfer the new experimental findings obtained with these new tools into more realistic parameterizations of the mesoscale biological and physical dynamics for adoption in the numerical schemes for global studies.

4. Workshop recommendations

From the presentations and discussions held during the four days workshop, the participants highlighted some recommendations to research teams and institutions that can help improving the present and future activities on mesoscale research in the Mediterranean:

- develop the acquisition of time series with autonomous platforms/sensors;
- upgrade the existing system packages with new sensors for biological and chemical variables. Take into account specific Mediterranean problems, as biofouling and high corrosion;
- measure by default some JGOFS parameters (as database for climatic change studies) in all oceanographic field programs;
- ensure efficient and rapid preprocessing/tagging/standard formatting and archiving of all kinds of observational data collected in experimental surveys, to allow immediate and easy use to all involved researchers;
- adopt a common terminology for mesoscale structures, such as vortex, eddies, gyres, etc. for clarification and avoiding misunderstanding;
- organize an "operational analysis" of remote sensing data to compare with model outputs (validation purposes);
- promote the continuation of satellite altimetry missions, at present not guaranteed. There are similar concerns with respect to scatterometer winds and ocean color missions, and this could have devastating effects on mesoscale research;
- facilitate access to remote sensing data. All research teams should have rapid and easy access to a wide range of satellite products (at adequate spatial and temporal resolution for mesoscale studies, at adequate stage of processing, i.e. ready-to-use), with additional information on quality control/reliability;
- support monitoring programs at Mediterranean scale (such as CIESM Transmed http://www.ciesm.org/marine/programs/transmed.htm), as regular monitoring is essential for mesoscale studies;
- ensure the future operational effectiveness of existing relevant sampling programs (e.g. MedARGO, etc.) and data centers (e.g. MEDATLAS, etc.) beyond presently funded projects;
- examine the possibility that an international agreement forces all new ships (above a certain capacity) carry an environmental sampling package (at least a fully autonomous thermosalinometer, up to a "Ferry Box" more complete package);
- foster North-South cooperation to fill the monitoring gaps in the southern Mediterranean sub-basins (where mesoscale is crucial and data are scarce). Especially foster national programs dedicated to regular CTD transects (at least) across the current off southern coasts/slope, in order to get a good description of the variability at mesoscale. Typical period would be one month (2 weeks better), sampling interval ~5 miles, duration 1 year at least;
- organize a proposal to the European Union 6th Framework Program for a Research Training Network on mesoscale studies, to allow efficient cooperation between research teams in the Mediterranean countries.