HyMeX Science Plan, Version 2.3, May 2010

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Table of content

1. Executive summary

The Mediterranean basin has quite a unique character that results both from physiographic conditions and historical and societal developments. The region features a nearly enclosed sea surrounded by very urbanized littorals and mountains from which numerous rivers originate. This results in many interactions and feedback between ocean-atmosphere-land processes that play a prominent role in climate and high-impact weather. The Mediterranean area actually concentrates the major natural risks related to the water cycle, including heavy precipitation and flash-flooding during the fall season, severe cyclogenesis associated with strong winds and large sea waves during winter, and heat waves and droughts accompanied by forest fires during summer. Such natural hazards highly impact the populations living in the area. The capability to predict such high-impact events remains weak because of the contribution of very fine-scale processes and their non-linear interactions with the larger scale processes.

Water resource is a critical issue for a large part of the Mediterranean basin. Freshwater is rare and unevenly distributed in time and space with few short duration heavy precipitation and long drought periods. Such situation occurs against a background of increasing water demand and aggravates with climate change. The Mediterranean region has indeed been identified as one of the two main hot-spots of climate change, which means that its climate is especially responsive to global change. Large decrease in mean precipitation and increase in precipitation variability during dry (warm) season are expected, as well as large increase in temperature. Climate evolution in the Mediterranean is however still largely uncertain. This region is also characterized by a rapid increase of population and urbanization, putting higher pressure on water resources. Progress has to be made in the monitoring and modelling of the Mediterranean coupled climate system (atmosphere-land-ocean) in order to quantify the on-going changes and to better predict their future evolution in order to provide guidelines for the development of adaptation measures.

These societal and science issues motivate the HyMeX (Hydrological cycle in the Mediterranean Experiment, http://www.hymex.org/) experimental programme. HyMeX aims at a better quantification and understanding of the water cycle in the Mediterranean with emphasis on intense events. HyMeX proposes to monitor and model the Mediterranean atmosphere-land-ocean coupled system, as well as the social vulnerability related to water resources and extreme event impacts. The variability of the system will be monitored from the event to the seasonal and interannual scales, and its characteristics over one decade (2010-2020) in the context of global change. HyMeX science is organized along five major topics (Figure 1.1).

The water budget of the Mediterranean basin

The Mediterranean sea is characterized by a negative water budget (excess evaporation over freshwater input) balanced by a two-layer exchange at the Strait of Gibraltar composed of a warm and fresh upper water inflow from the Atlantic superimposed to a cooler and saltier Mediterranean outflow. Light and fresh Atlantic water is transformed into denser waters through interactions with the atmosphere that renew the Mediterranean waters at intermediate and deep levels and generate the thermohaline circulation. Although the scheme of the thermohaline circulation is reasonably well drawn, little is known about its variability at seasonal and inter-annual scales. The feedback of the Mediterranean Sea basin on the atmosphere through the terms of the water budget needs also to be further investigated. In addition, the budget of the Mediterranean Sea has to be examined in the context of global warming, and in particular by assessing the impact of an increase of the ocean heat thermal content on high-impact weather frequency and intensity.

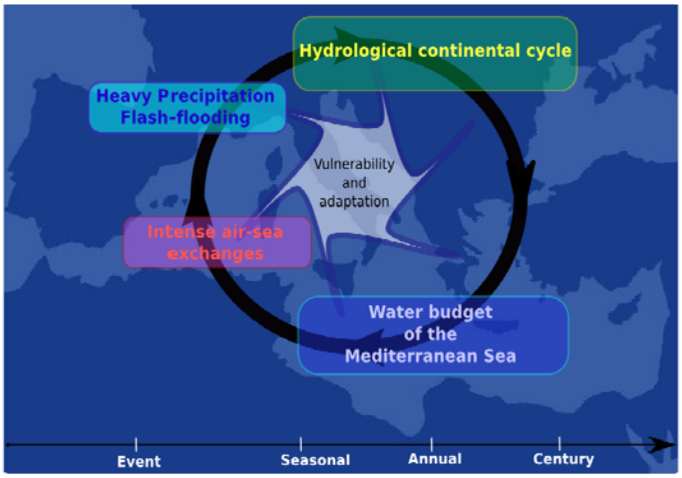

Figure 1.1. The five HyMeX research topics.

The continental hydrological cycle and related water resources

The rainfall climatology of the Mediterranean region is characterized by dry summers frequently associated with very long drought periods, followed by fall and winter precipitation that are mostly very intense. This results in high daily/seasonal variability in aquifer recharge, river discharge, soil water content and vegetation characteristics, the interaction of which with the atmosphere is not well known. This encompasses for instance the impact of large forest fires associated with summer droughts on the evapotranspiration component of the hydrological cycle. The role of the surface states (land use/land cover) and of the soils in rainfall modulation also needs to be better understood. Hydrological and hydrogeological processes are also characteristics of the Mediterranean basin, notably because of the specificities of the peri-mediterranean karstic and sedimentary aquifers. Progress in their understanding is of primary importance for the development of an integrated management of the hydrosystems, and adaptation to anthropogenic pressure and climate change.

Heavy precipitation and flash-flooding

During the fall season, Western Mediterranean is prone to heavy precipitation and devastating flash-flooding and floods. Daily precipitation above 200 mm are not rare during this season, reaching in some cases as exceptional values as 700 mm recorded in September 2002 during the Gard (France) catastrophe. Large amounts of precipitation can accumulate over several day-long periods when frontal disturbances are slowed down and strengthened by the relief (*e.g.* Massif Central and the Alps), but huge rainfall totals can also be recorded in less than a day when a mesoscale convective system (MCS) stays over the same area for several hours. Whereas large scale environment propitious to heavy precipitation is relatively well known, progress has to be made on the understanding of the mechanisms that govern the precise location of the system anchoring region as well as of those that can occasionally produce uncommon amounts of precipitation. The contrasted topography, the complexity of the continental surfaces in terms of geology and land use, the difficulty to characterize the initial moisture state of the watersheds make the hydrological impact of such extreme rainfall events very difficult to assess and predict.

Intense air-sea exchanges

The Mediterranean Sea is characterized by several key-spots of intense air-sea exchanges associated with very strong winds caused by the orographic response to large scale forcing (*e.g.* Mistral, Bora, Sirocco, Tramontana), deep cyclogenesis (*e.g.* Genoa cyclogenesis), and high/low pressure patterns. These successive intense air-sea exchange events and the associated sea surface cooling considerably affect the heat and water budgets in the Mediterranean Sea with formation of dense water and deep ocean convection during winter and early spring. Ecosystem functioning is strongly related to this complex dynamics which needs to be better understood. Hydrological and dynamical characteristics as well as inter-annual variability of the dense water and deep ocean convection formation have thus to be better documented in order to stress the respective roles of atmospheric forcing and oceanic processes. In return, how such modifications of the ocean mixed layer influence the atmospheric boundary layer should be approached.

Vulnerability factors and adaptation strategy

The Mediterranean region is characterized by an increasing demography, leading to urban sprawl especially on coastal areas. In a context of climate change, the population is exposed to challenging environmental changes, such as short-time extreme events (heavy precipitation, flash-flood, heat wave) and long-term modifications (change in water resource access, drought). HyMeX aims at monitoring vulnerability factors and adaptation strategies developed by various Mediterranean societies to accommodate themselves to the impacts of climate change and intense events.

2. Motivation and science objectives

A unique coupled system

The Mediterranean basin has quite a unique character that results both from physiographic conditions and historical and societal developments. The region features a nearly enclosed sea surrounded by very urbanized littorals and mountains from which numerous rivers originate (Figure 2.1). This results in many interactions and feedback between ocean-atmosphere-land processes that play a prominent role in climate and ecosystems and make the Mediterranean area a unique highly coupled system. Research should now not only focus on processes within each Earth compartment, but also on interface processes and feedback loops in order to make significant progress in the comprehension and prediction of the Mediterranean water cycle and related phenomena.

High impact weather events

The Mediterranean area concentrates the major natural risks related to the water cycle including heavy precipitation and flash-flooding during the fall season, severe cyclogenesis associated with strong winds and large sea waves during winter, and heat waves and droughts accompanied by forest fires during summer. The capability to predict such high-impact events remains weak because of the contribution of very fine-scale processes and their non-linear interactions with the larger scale processes. Advances in the identification of the predominant processes and particularly of their interactions at the different scales are needed in order to better forecast these events and reduce uncertainties on the prediction of their evolution (*e.g.* frequency, intensity) in the future climate. These issues are not only of primary importance for providing a tangible basis for early warning procedures and mitigation measures designed to avoid loss of life and reduce damage, but also to assess their impacts on the terrestrial and marine ecosystems, some of which may be irreversible.

Water resource issues

Freshwater is rare and unevenly distributed in time and space with few short duration heavy precipitation and long drought periods. In numerous countries, almost all the rivers are either intermittent or ephemeral. Water resource is a critical issue in a large part of the Mediterranean basin: with less than 1000 m^3 per person per year, 180 million people face water scarcity, which represents more than one half of the world's so-called water poor population. Moreover, this happens in a situation of increasing water demand and climate change. During the second half of the 20th century, water demand has increased twofold. Progress has to be made in the monitoring and modelling of the Mediterranean hydrological continental cycle in order to better predict its future evolution and impacts on water resources for appropriate management.

A hot-spot for climate change

Mediterranean regions have been identified as one of the two main hot-spots of climate change (Giorgi, 2006), meaning that climate is especially responsive to global change in this area. Large decrease in mean precipitation and increase in precipitation variability during dry (warm) season are expected as well as large increase in temperature (+1.4 to +5.8°C in 2100). Large uncertainties however remain on the future evolution of climate in the Mediterranean. Progress has to be made in the monitoring and modelling of the Mediterranean coupled climate system (atmosphere-land-ocean) in order to quantify the on-going changes and to better predict their future evolution as guidelines for the development of adaptation measures.

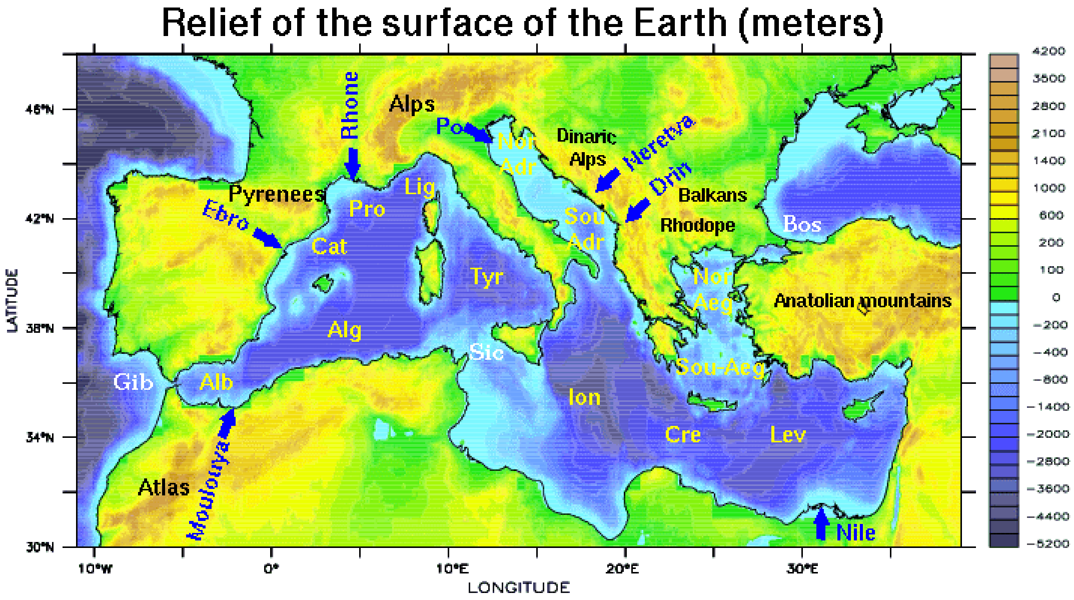

Figure 2.1. Geographical locations. The Strait of Sicily (Sic) splits the Mediterranean Sea in the Western and Eastern basins which are composed of the Alboran (Alb), Algerian (Alg), Catalan (Cat), Provencal (Pro), Ligurian (Lig), Tyrrhenian (Tyr), North and South Adriatic (Adr), Ionian (Ion), North and South Aegean (Aeg), Cretan (Cre), Levantine (Lev) sub-basins. The Mediterranean Sea is connected to the Atlantic Ocean by the Strait of Gibraltar (Gib), and to the Black Sea by the Bosphorus strait (Bos).

Hence, the Mediterranean is a globally important eco-region and an optimal test bed for new approaches to science-society partnership (Athens declaration by the Euro-Mediterranean ministers, 2002) sustained by the provision of adequate climate information (i.e., climate services) applicable to a broad range of vulnerable sectors and environments.

HyMeX Science objectives

These societal and science issues motivate the HyMeX programme which aims to:

- improve our understanding of the water cycle with emphasis on extreme events by monitoring and modelling the Mediterranean atmosphere-land-ocean coupled system, its variability from the event to the seasonal and interannual scales, and characteristics over one decade in the context of global change,
- evaluate the societal and economic vulnerability to extreme events and adaptation capacity.

The multidisciplinary research and the database developed within HyMeX should be beneficial to the improvement of:

- the observational and modelling systems, especially of coupled systems, thanks to new process modelling, parameterization developments, novel data assimilation systems for the different Earth compartments, reduction of uncertainty in climate modelling,
- the capability to predict extreme events,
- the accurate simulation of the long-term water-cycle,
- the definition of adaptation measures, especially in the context of global change.

3. Research themes

3.1 WG1: Water Budget of the Mediterranean Sea (WBMS)

Coordinators: S. Somot, A. Mariotti, W. Ludwig

3.1.1 Introduction and motivation

In the Mediterranean basin, fresh water is often either too rare (summer droughts) or in excess (heavy precipitation events). Such extreme events are part of the regional Mediterranean water cycle which connects all the parts of the regional climate system (atmosphere, sea, land, vegetation, rivers,…) and the different time scales (seasonal, interannual and decadal variability, long-term trends). This multi-compartment and multi-scale integrated character fully applies to the Mediterranean Sea which responds to the E-P-R (evaporation - precipitation - river runoff) budget at its interfaces. The HyMeX White Book (see section 2.2) underlines **the importance of the E-P-R budget of the Mediterranean Sea and its variability as they govern two key components of the Mediterranean Sea circulation:**

- the yearly dense water formation rate as well as the temperature and salinity of the water formed, this newly formed water then driving the Mediterranean thermohaline circulation; from a biochemistry point of view, the sea water characteristics also impact the biological production, fisheries and water quality;
- the density and salinity of the Mediterranean outflow water flowing at depth at the Gibraltar Strait and influencing the Atlantic Ocean characteristics at intermediate depth.

In addition it has been demonstrated that **past changes in the Mediterranean Sea water budget have had large and long-lasting effects** on the Mediterranean thermohaline circulation and on the sea biochemistry as evidenced by the sapropel sediment layers due to anoxic conditions and the recent Eastern Mediterranean Transient in the 90s.

The Mediterranean Sea also influences the atmosphere over the sea through local and remote impacts:

- locally, by loading the low level flow over the Mediterranean Sea that feeds the coastal intense precipitation events in moisture and energy;
- regionally the Mediterranean Sea is one of the main sources of moisture to surrounding Mediterranean lands (*e.g.* South-Eastern Europe in summer) and more remote regions such as the Sahel.

It is worth noting that the water budget is **not only driven by the atmospheric conditions, but also depends on the ocean characteristics** (SST, heat content of the ocean mixed layer, depth of the mixed layer), which in turn can influence the atmosphere through air-sea fluxes.

In the past, the terms of the Mediterranean Sea water budget (MSWB) and their variability at different time scales have been studied separately over land or over the sea but rarely in an integrated approach associating all the compartments of the Earth system. Up to now the **MSWB estimates performed by the various communities (meteorology, oceanography, hydrology) are not consistent.** One objective of HyMeX is to reconcile these estimates thanks to an interdisciplinary work making use of both observations and modeling tools. Data over the sea are still very few and sparse. HyMeX will provide an observational and modeling strategy that will increase observations over the sea in key areas to constrain the modeling systems. These will be used to **obtain an accurate estimation of every term of the Mediterranean water budget at every time scale (seasonal, interannual, decadal, trends,**

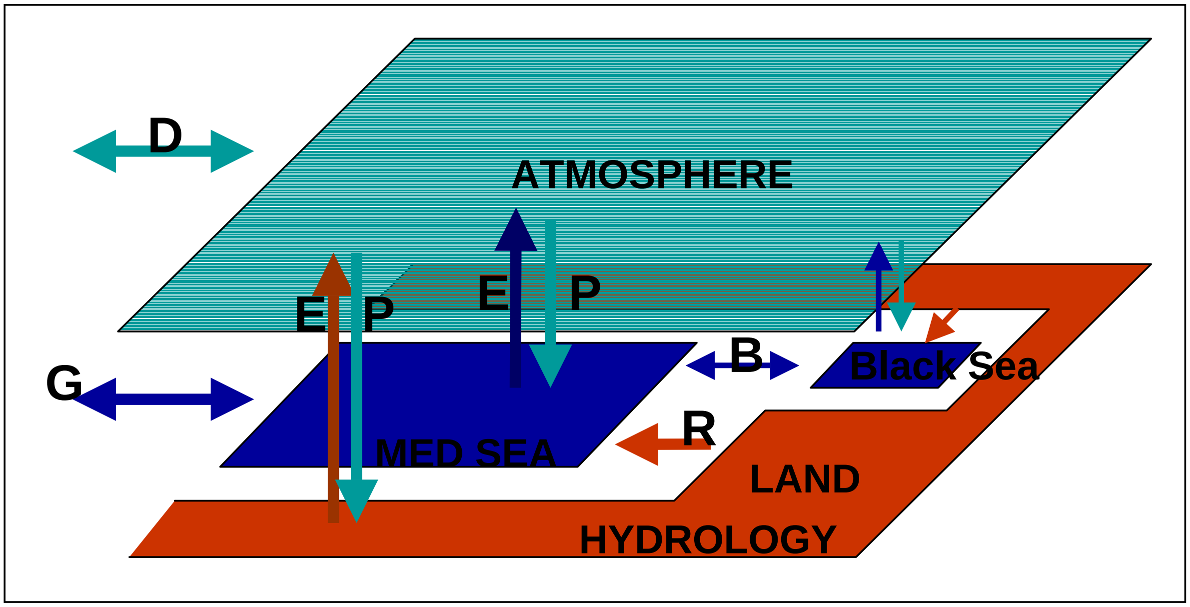

Figure 3.1. A schematic 3D box diagram illustrating the main components of the Mediterranean basin. P stands for precipitation, E for evaporation, R for river runoff, D for atmospheric water divergence, G for Gibraltar transport, B for Black Sea transport.

21st century climate change), constituting quite a challenging goal for the observational and modeling community.

Current uncertainties in the quantification of the MSWB limit our capability to detect the impact of climate change on the MSWB and clearly identify the processes controlling its evolution. The 21st century scenarios for the Mediterranean region foresee very significant changes in the MSWB with important associated changes for the sea. However, uncertainties on the MSWB have to be reduced first to validate the climate models used and to be confident on their prediction of MSWB evolution. This requires the understanding and representation of some control processes in key regions: mostly the exchanges at the Gibraltar Strait but also with the Black Sea and the local thermohaline and wind-driven circulation. **These regional physical processes may determine the future evolution of the sea temperature and salinity, and subsequently the Mediterranean feedback on the local and remote climate, their impact on the Mediterranean biochemistry and their contribution to the Mediterranean sea level change.**

Figure 3.1 shows the different terms of the Mediterranean water cycle which are the precipitation, the evaporation, the moisture convergence, the runoff flux at the river mouths and the exchanges with the Atlantic and Indian oceans and the Black Sea through the corresponding straits. State-of-the-art knowledge about these terms and their variability is first described in section 3.2. A climate point of view is adopted here, *i.e.* we focus on climate time scales from the seasonal to the century scale, without forgetting the impact of daily or extreme events on the average values. The whole Mediterranean basin (or large sub-basins) is also considered. Section 3.3 highlights the current key issues concerning the MSWB, summarised in four main scientific questions. Finally, specific research needs and proposals in terms of observation and model developments to answer these questions are detailed in section 3.4.

3.1.2 State of the art on the MSWB[1]

3.1.2.1 Precipitation

3.1.2.1.1 Over land

The precipitation observing system around the Mediterranean Sea is not homogeneous in quality nor in space, but data are generally available over a long period of time and they can be used for climate study. Homogenised station data are available in some countries (Caussinus and Mestre, 2004) but often with restricted rights. Gridded datasets such as the CRU database (New *et al*., 2002) are also available but only at a monthly time scale. Gridded datasets at a daily time scale and covering a long period of time start to be available (see the ECA&D and ENSEMBLES European projects for example) but for the Northern part of the Mediterranean area only.

For the Euro-Mediterranean area, climate studies have already been performed using the CRU dataset (Jacob *et al*., 2007; Mariotti *et al*., 2008). The local daily station data allow the study of the local trends in precipitation (Moisselin *et al*., 2002; Alpert *et al*., 2002) and daily precipitation extremes (Déqué, 2007). Studies going back to year 1500 have even been conducted for the Mediterranean area and have yielded very long time series or reconstructed indexes (see Luterbacher *et al*., 2006 for a review). These studies conclude to a high interannual variability in precipitation, often with drying long-term trends for the 20th century in many areas around the Mediterranean Sea. Further back in time, palaeoindicators such as pollens show that the Mediterranean climate has been even drier than today in periods like the last glacial period. Both the climate and vegetation have undergone abrupt and large changes at that time (*e.g.* Combourieu Nebout, 2002; Allen *et al*., 1999).

3.1.2.1.2 Over the sea

Direct measurements of precipitation over the sea are rare and indirect estimations from coastal stations can only be approximate. However using other sources of data (reanalysis, indirect estimation, blended satellite products such as CMAP, Xie and Arkin, 1997), some authors have tried to evaluate the precipitation amount for the Mediterranean sea surface (Boukthir and Barnier, 2000, Mariotti *et al.,* 2002). Mariotti *et al.* (2002) give a range of 331-447 mm/yr for the 1979-1993 precipitation average value with a seasonal cycle amplitude of 700 mm/yr (see Figure 3.2 for comparison between data and two GCMs). To our knowledge high-resolution satellite data such as the ones provided by the SEAFLUX project (http://seaflux.gfdi.fsu.edu/) have never been used up to now within the Mediterranean community.

Without long-term high-resolution robust estimates of the precipitation over the sea, it is a complex task to validate the current generation of Regional Climate Models (RCMs) run over the Mediterranean Sea (see an example of RCMs vs. observed estimates in Figure 3.2).

3.1.2.2 Evaporation

Estimation of evaporation over land will be more thoroughly discussed in WG2 "Hydrological continental cycle".

Over the sea, large latent heat surface fluxes are experienced especially in winter with the influx of northern dry and cold air masses. At short time scales, large latent heat fluxes feed

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[1] This section is mainly extracted from the HyMeX White Book.

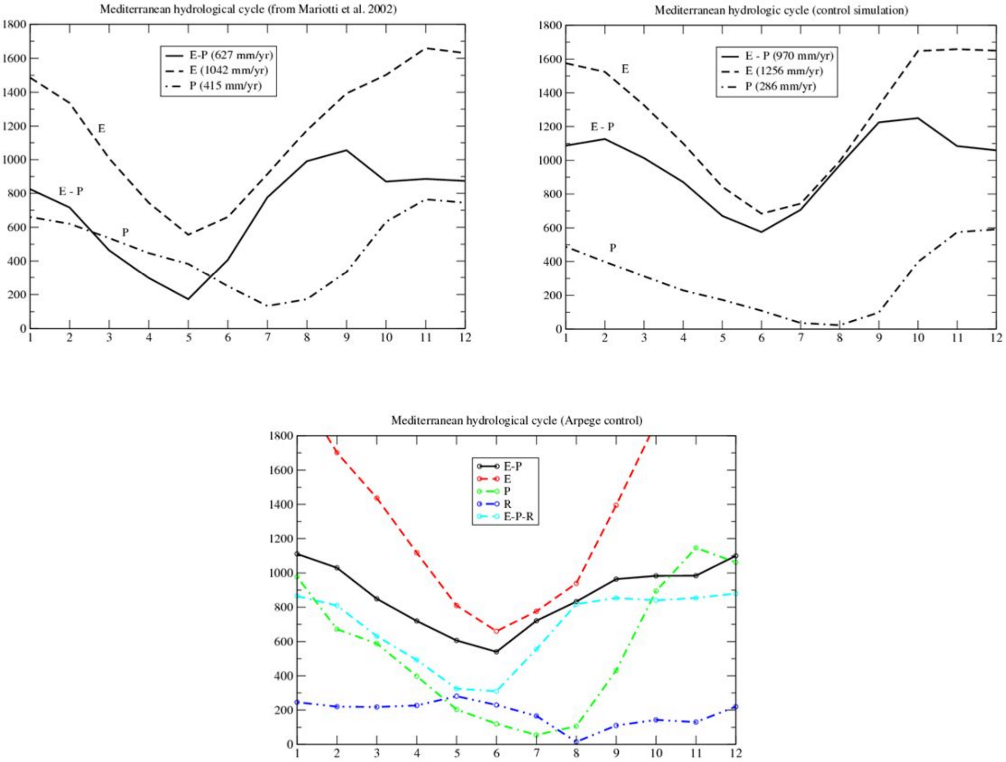

Figure 3.2. Mean seasonal cycle (over the Mediterranean Sea) of the precipitation (P), evaporation (E), river runoff flux (R), E-P budget and E-P-R budget for the observations after Mariotti *et al.* (2002) (top left), the Mediterranean version of LMDZ (top right) and the Mediterranean version of ARPEGE-Climat (bottom).

heavy precipitating systems (WG3), and govern deep water formation and impact coastal dynamics (WG4). At a longer time scale this term is also crucial because it is strongly correlated with the interannual variability of the Mediterranean Sea water and heat budgets. Few direct observations of air-sea latent heat exchange are available, mainly provided by ship campaigns (and thus limited in time and space), others retrieved from satellite imagery (Bourras *et al*., 2002a,b). Consequently, data of latent heat fluxes over the Mediterranean Sea have low space and time resolutions (see SOC and COADS database, Josey *et al.,* 1999 and da Silva *et al*., 1994) and contain biases as for reanalyses. It is also worth noting that indirect methods based on the ocean water budget for a given area could also provide evaporation estimates. These methods based on the Walin's method (1982) do not require knowing the water flux in the straits but require a well-defined experimental strategy covering the area of interest.

The estimation provided by Mariotti *et al*. (2002) is of 934-1176 mm/yr with a large seasonal amplitude (1000 mm/yr, see Figure 3.2). The latent heat flux is thus not only the largest term of the E-P-R budget and one of the most variable, but also the most poorly observed and simulated. Since a strong modification of latent heat is foreseen during the 21st century (Somot *et al.,* 2006; Mariotti *et al*., 2008), it is of primary importance that HyMeX focus on this term, with the aim to acquire a better knowledge of the factors controlling both its interannual and decadal variability. This is now made possible given the significant advances in data availability both from novel satellite-based products and new analyses of in-situ records.

3.1.2.3 Atmospheric water transport

That E-P is positive, and that E-P-R is also positive, means that the whole Mediterranean system (including the Mediterranean sea surface, the river catchment basin and the virtual atmosphere box above) exports water towards other Earth regions. Atmospheric water flux divergence has been analysed by Mariotti *et al*. (2002) and Fernandez *et al*. (2003) using reanalysis data (NCEP, ERA-15). Moisture enters the Mediterranean area from the west and northwest while it exits to the east and south (Eastern Europe, Middle East and northeastern Africa). The moisture transport is mainly zonal in winter (classical wintertime large-scale weather regimes in this area, Fernandez *et al*., 2003) and more southeast in summer explaining part of the link between the Mediterranean Sea and the African monsoon (Rowell, 2003; Peyrillé and Lafore, 2007; Sultan *et al*., 2007; Fontaine *et al*., 2010). The interannual variability of the moisture convergence, its dependence to sea conditions (SST, heat content of the ocean mixed layer) and its possible evolution under a changing climate remain largely unknown whereas it mainly drives water resources in the Mediterranean region.

The impact of the synoptic systems (Mediterranean cyclones, cyclones coming from the Atlantic) affecting the area on the long-term mean of the atmospheric water transport (or on its interannual variability) is also an open question for HyMeX (see WG3, WG4). More generally the remote influences or teleconnections between the global climate variability and the atmospheric water transport and its variability are not fully understood. Influences of these large-scale climate processes or oscillations (West African Monsoon, African Hadley cell, subtropical jetstream, Indian Monsoon, NAO, ENSO, Tropical Atlantic variability, Indo-Pacific tropical convection) on the Mediterranean area have been demonstrated (see Alpert *et al*., 2006 for a review) but still remain to be clarified and fully understood. Similarly, Mediterranean SST and moisture divergence can have an impact on some of these large-scale climate processes mainly on the Western African Moonson.

3.1.2.4 River runoff to the Mediterranean Sea

The transfer of water from the land area to the sea is performed trough a very complex system linking the vegetation, the land surface and the rivers and aquifers. This hydrological transfer function is described in details in WG2 “Hydrological continental cycle” and leads to the river runoff flux in the river mouth and, to a lesser extent, through the aquifers, both contributing to the run-off term of the MSWB. Estimates of run-off are thus needed over the whole Mediterranean basin in order to obtain the mean runoff flux term and its variability in time and space.

The river runoff flux is far from being a negligible term for the Mediterranean Sea, neither locally nor globally. For example, locally, the area of influence of the Rhône in the western basin is quite large and isolates the coastal zone from the open-sea (see WG4). The influence of the Po river on the Adriatic Sea water budget is even stronger: whereas E-P is positive (about 0.7 mm/d, estimate from a 40-year regional climate model simulation, J. Beuvier, personal communication), adding the run-off makes the water budget negative for the Adriatic Sea sub-basin (E-P-R = -1.1 mm/d). The Po river represents about 2/3 of the total river runoff fluxes. For the whole Mediterranean Sea, it is accepted that the rivers represent about 10% of the E-P-R budget. Many authors have tried to evaluate the mean annual river discharge for the whole Mediterranean Sea and aspects of its variability (Struglia *et al*., 2004; Ludwig *et al*., 2009). Estimations vary significantly: Béthoux (1979) gives a value of 270 mm/yr whereas Mariotti *et al.* (2002) propose a weaker value of 100 mm/yr. The multi-year monthly mean climatology established by Somot (2005) from the free access RivDis database (Vörösmarty *et al*., 1996) gives a total river runoff equal to 200 mm/yr. Although such database contains interannual values, the role of the river runoff interannual variability on the Mediterranean salinity evolution has never been studied so far.

Concerning the modeling efforts, some coupled atmosphere-ocean regional climate models have been (or are going to be) designed to study the Mediterranean climate (Somot *et al.*, 2008, EU FP6-CIRCE project, French ANR-MEDUP project). Few models (i.e., the Protheus group, 2009) implement the river feedback, although the River runoff to the Mediterranean sea significantly impacts our capability to simulate the sea level rise. Currently the full high-resolution regional water cycle is not accurately simulated. Progress has to be made in the run-off simulation considering the strong influence that the rivers can have on the Mediterranean salinity evolution in a climate change scenario (Somot *et al.,* 2006).

3.1.2.5 Gibraltar Strait transport and exchanges with the Black and Red seas

3.1.2.5.1 Gibraltar transport

The major impact of the Gibraltar Strait water and heat transports has been described in detail in section 2.2 of the HyMeX White Book. The conclusions are that some good estimates of these transports start to be available -at least in average- and that transports depend on a density difference between the Atlantic Ocean and the Mediterranean Sea. Again strong uncertainties remain and their temporal variability is largely unknown. Interestingly the Gibraltar Strait net volume transport gives an independent estimate of the mean value of the MSWB (E-P-R). Up to now, these Gibraltar Strait estimates (~644 mm/yr, Basheck *et al.*, 2001 from the CANIGO experiment) do not agree with the atmospheric-branch E-P-R estimates (500 mm/yr, Mariotti *et al.*, 2002).

The narrow and shallow shape of the Gibraltar Strait exerts an hydraulic control. Due to the mixing induced, the strait acts as a natural filter for the temperature and salinity exchanges between the Atlantic Ocean and the Mediterranean Sea. The Gibraltar Strait may determine how the Mediterranean (resp. Atlantic) changes can influence the global ocean (resp. the regional sea). A very high resolution (Sannino *et al.*, 2007) is needed to simulate this controlling behavior. It will drive the impact of climate change on the MSWB, the Mediterranean temperature and salinity characteristics, and on the Mediterranean sea level. It will also filter the anomalies of the Mediterranean outflow waters flowing into the Atlantic.

3.1.2.5.2 Black Sea – Aegean Sea exchanges

The Black Sea – Aegean Sea exchanges are as complex as the exchanges through the Gibraltar Strait with a two-layer flow constrained by the physical characteristics of the strait. Fresher water comes from the Black Sea at the surface while an opposite salty water flux is observed below. The heat net transport is weak and the water net transport can be summarised as a freshwater inflow for the Aegean Sea. The Black Sea – Aegean Sea exchanges are thus often simulated as a river flowing into the Mediterranean Sea. The value of the “equivalent runoff” is again not very well known, but a seasonal cycle has been evaluated from the study of the Black Sea water budget (Stanev *et al.*, 2000). As for the other rivers, this flux has an important interannual variability and also long-term trends. Moreover the decrease observed over the last decades (mainly due to the building of dams along the Black Sea rivers and irrigation) has perhaps already affected the Mediterranean Sea thermohaline circulation through the Eastern Mediterranean Transient event (see section 2.2). As this so considered river is the most important one in the Mediterranean Sea and has then a large impact on the Mediterranean water budget, it should be taken into account whatever the Mediterranean area of interest. Dedicated observing system and modeling tools should be designed for this *hot-spot* of the MSWB.

3.1.2.5.3 Red Sea – Levantine sub-basin exchanges

Up to now these exchanges through the Suez canal have always been neglected in the E-P-R estimations and in the Mediterranean Sea modeling, as they are considered very small compared with the other two.

3.1.2.6 Water mass formation and mixed layer budget as a constraint to evaluate the Mediterranean water budget

As described above, obtaining an accurate estimation of every term of the Mediterranean water budget for every time scale (seasonal, interannual, decadal, trends, 21st century climate change) is quite a challenging goal for the observation and modeling communities. However the global Mediterranean water budget, and more generally the Mediterranean air-sea fluxes, can also be estimated indirectly from heat and salt budgets of the ocean mixed layer. At least two methods are already available using in-situ observations and regional modeling tools. The first one (Walin, 1982; Tziperman and Speer, 1994; Somot, 2005; Bozec *et al.*, 2008) computes a water volume budget for different density classes. For a given area, knowing the time evolution of the volume of the density classes and the advection at the boundaries leads to constrain the value of the air-sea heat and salt fluxes. The second one is based on the estimate of the time evolution of the mixed layer heat and salt budgets during at least one year for a given area. Algorithms merging data and model outputs then allow to optimise the air-sea fluxes which led to these budgets. This method has been successfully applied during the POMME campaign (Caniaux *et al.*, 2005; Giordani *et al.,* 2005).

3.1.2.7 Influence of intense events on the global Mediterranean water budget

So far in this section, we have focused on the basin averaged and yearly averaged values of the terms of the water budget. However the impact of the local and short-duration intense events on each term on the global budget is still unknown. These intense events are frequent for the precipitation, for the latent heat flux and the evaporation under low-level jet associated with heavy precipitation, under dry and cold winter continental air masses and for the local winds (Mistral, Bora, Mediterranean cyclones). Additionally the ocean does not respond linearly to such local intense forcings. The ocean circulation is indeed mainly driven by the geostrophy and by the mesoscale features which can react in a few days to inhomogeneous forcing events of pressure, precipitation, wind or evaporation. The intense events can modify the surface layers locally and then non-linearly alter the heat and salt content of the mixed layer creating horizontal density gradients. This may lead to changes in the surface circulation, in the instability of the surface currents (Béthoux *et al*., 1988), and then in the mixed water mass characteristics for instance. The non-linear response of the sea to local intense changes of the water budget has its counter-part in the vegetation-soil-river system (non-linear hydrologic impact of intense precipitation, see WG2 and WG3), and also in the dense water formation events and coastal dynamics (see WG4). For example, the temporal variability of the extreme events (when in a given season) certainly plays a role in the dense water formation in preconditioning or not the surface layers at the right period (Herrmann and Somot, 2008). Madec *et al*. (1991b) and Artale *et al*. (2002) have shown for instance that the daily variability of the heat flux during the autumn and winter seasons influences the formation rate and the temperature and salinity characteristics of the dense water formed. This intermittent regime also plays a role during the re-stratification phase in spring, in postponing the surface layer warming and in changing the pelagic ecosystem evolution (Andersen and Prieur, 2000). The maximum SST can reach 30°C in the northwestern part of the Mediterranean Sea some years (July 2006, I. Taupier-Letage, personal communication, TRANSMED thermosalinograph data time series) and drop by 5-10 °C in only a few days due

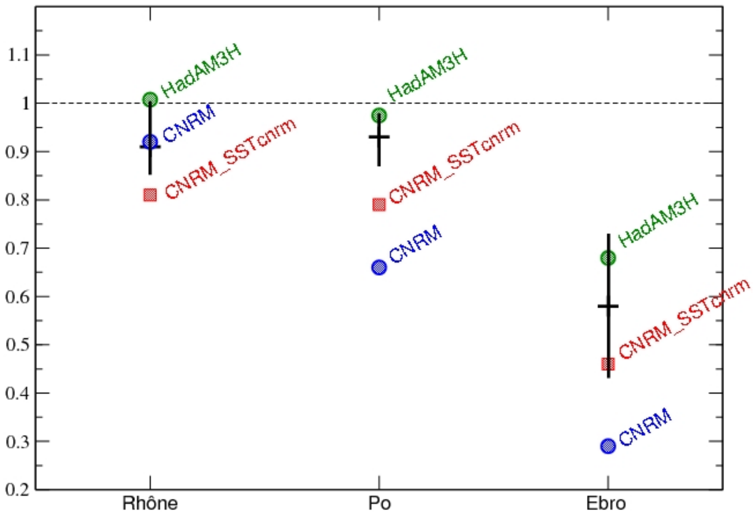

Figure 3.3. 30-year annual mean ratio of the river runoff flows between the 1960-1989 period and the 2070-2099 period in an IPCC-A2 climate change scenario (S. Somot, personal communication). The value of 1 (dashed line) means no change between the present and future climates. Lesser values mean a decrease in river runoff. The green dots represent the HadAM3H simulation forced by the Hadley Center (HC) SST anomalies, the black crosses represent the average value of 9 regional climate simulations performed with limited area models forced by HadAM3H and the HC SST (data from the PRUDENCE European project, S. Hagemann, personal communication), the black bar is the full range of uncertainty from these 9 models, the blue dots represent the CNRM simulation with the stretched version of ARPEGE-Climat (with the same resolution of 50 km as the other RCMs, and the same HC SST anomaly), and the red squares represent the CNRM simulation with CNRM SST anomalies.

to the wind gusts and the air masses crossing this area during summer. The atmospheric or river intense events show not only a temporal but also a spatial intermittent regime. Even though they are mainly local or regional, they have an impact on the global Mediterranean water budget. They can also locally modify the sea surface characteristics and have a feedback on the atmosphere and then on the water budget itself. However these scale and non-linear interactions on the MSWB have never been extensively quantified.

3.1.2.8 Impact of climate change on the global Mediterranean Sea water budget

Studying interannual variability of the precipitation, Mariotti *et al.* (2002) have found the now established anti-correlation with the NAO index and a decreasing trend over the last decades. This trend is in agreement with the trend foreseen in the climate change scenarios for the precipitation over the Mediterranean Basin (see section 2.1; also Mariotti *et al.*, 2008). However, the quantitative value of the drying is far from being well known and the evaluation of the various uncertainty sources has just started. Atmospheric climate change might also directly impact the Mediterranean Sea. During the 21st century, the sea might experience a significant warming and salting as well as a weakening of its thermohaline circulation (Thorpe and Bigg, 2000; Somot *et al.*, 2006). The occurrence of the extreme events linked with the regional water cycle (droughts, heat waves, intense precipitation) should also be quantified. The impact of climate change on the Mediterranean water budget and the associated uncertainties remain then open issues. For example the changes in the evaporation term over the sea or the changes in the river inflows are largely unknown.

This is illustrated by the scenarios of climate change for the Mediterranean Sea which underline the key role of the rivers in changing the surface salinity of the Mediterranean Sea, then the surface density, and consequently the MTHC. Somot *et al.* (2006) have pointed out that the large uncertainties due to this earlier term should be evaluated in forthcoming studies. Figure 3.3 shows the uncertainty concerning the impact of climate change on the river runoff flows for three main Mediterranean rivers. The ratio between the present-day climate and the future climate (end of the 21st century, IPCC-A2 scenario) is plotted. The outcome is a general decrease in river runoff. However a large uncertainty is also obtained when comparing different models. The uncertainty ranges from a ratio equal to 0.3 to a ratio of 0.75 for the Ebro for instance. Using one scenario or another can thus have a completely different effect on the Adriatic surface salinity and then on the formation of the Eastern Mediterranean deep water in winter.

Evaluating the modification of the Mediterranean water budget will also contribute to estimate the regional sea level rise during the 21st century (see Tsimplis *et al.,* 2008 for a first regional estimate). This estimation is a complex but key issue within the Mediterranean framework as it could impact a large part of the Mediterranean coast inhabitants. For the Mediterranean Sea, the future evolution of the sea level will critically depend on the regional salinity changes that are still very uncertain (Marcos and Tsimplis 2008; Mariotti *et al.*, 2008; Sanchez-Gomez *et al.*, 2009).

3.1.3 Key issues and scientific questions

The above description of the state-of-the art knowledge shows that the ground motivations for improving our understanding and prediction of the MSWB within the multidisciplinary framework of HyMeX are the following:

- the MSWB concerns all Earth compartments of the Mediterranean water cycle: atmosphere, ocean, vegetation, continental surface, hydrology;
- the MSWB is not a simple atmosphere-driven budget but implies a loop of fully coupled processes between the various components, the main coupled terms being the evaporation, the water vapour, the SST and the mixed layer heat content;
- the MSWB is a complex system to study as it covers a large range of time scales, implies scale- and non-linear interactions;
- the remote influences (teleconnection) on the MSWB atmospheric components and their variability is still not fully understood nor simulated by global and regional climate models;
- the mean values of the MSWB terms as well as their interannual variability and trends are not very well known; even for mean values, inconsistencies remain between the ocean-branch estimates and the atmosphere-branch estimates;
- the impact of the processes governing MSWB on the yearly rate of dense water formation, and then on the Mediterranean Sea thermohaline circulation, are still not very well understood,
- the controlling role of MSWB in the characteristics of the Mediterranean outflow and its impacts on the Atlantic waters, and then on the global thermohaline circulation and on the global climate are still largely unexplored;
- whereas some terms of the MSWB already show detectable trends, large uncertainties remain on future projections and their impacts on the sea.

***Key Scientific Questions*:**

- ***WG1-SQ1:* What are the long-term mean values of the Mediterranean Sea Water Budget (MSWB) components and associated uncertainties?**

  The main objective is to **characterise the mean components** of MSWB with quantified and, when possible, reduced **uncertainties** by direct in-situ or remote measurements or by indirect methods associating observations and modeling.

- ***WG1-SQ2:* What is the variability of the MSWB at seasonal, interannual and decadal time-scales?**

  The main objectives are: *(i)* to **improve our understanding of the processes** (water mass formation, Gibraltar and other strait transport, ocean mixed layer dynamics, air-sea interaction, Mediterranean cyclones, local winds, humidity sources) governing the MSWB and its **variability,** *(ii)* to **improve our understanding** of the **remote influence** on MSWB and its variability, and *(iii)* to improve our **capability to simulate** the main characteristics of the Mediterranean water cycle and its variability.

- ***WG1-SQ3:* How do spatially and/or temporally localised intense events affect the MSWB?**

  The main objectives are **to measure, simulate and understand the impact of the intense events on the variability** of the MSWB (i.e., did the 2003 summer heat wave affect ocean variability below the mixed layer?).

- ***WG1-SQ4:* How will the MSWB evolve under future-climate conditions along the 21st century?**

  The main objectives are: *(i)* to identify the **key processes controlling the future changes** of the terms of the MSWB, *(ii)* to quantify and try to reduce the **uncertainties on the future regional projections** of MSWB, *(iii)* to identify and quantify the **related impacts on the Mediterranean Sea** (hydrological characteristics, circulation, sea level, Mediterranean outflow waters,…), and *(iv)* to contribute to develop an **early warning system** of Mediterranean Sea changes.

3.1.4 Observation and modeling needs

3.1.4.1 What are the long-term mean values of the Mediterranean Sea Water Budget (MSWB) components and associated uncertainties?

The major research needs to answer WG1-SQ1 are:

(a) *Development of a meta-database of existing precipitation observations over land (in collaboration with WG2)*: data in southern Mediterranean remain sparse and daily data are not always available (for scientists abroad). A meta-database dedicated to Mediterranean studies and listing the existing datasets and their availability is then needed. This effort will leverage on on-going relevant efforts by the Mediterranean Integrated Working Group and projects such as MedClivar, HyMeX or CIRCE to achieve this specific goal.

(b) *More accurate estimation of precipitation over sea*: until now, the precipitation estimates over the Mediterranean Sea are based on reanalyses, indirect measurements or blended satellite products. Reanalyses are however not accurate enough in terms of precipitation (Mariotti *et al.*, 2002; Josey, 2003) and the land-sea correction of the precipitation are rather empiric. Precipitation measurements over the sea are essential for a thorough validation of the reanalyses or of the new satellite-based products and their improvement. Coastal radar systems could be used to cross-validate these products.

(c) *Direct observations of evaporation*: ship campaigns are necessary to obtain spatial high-resolution gridded data for direct and indirect estimates, and also to calibrate climate time scale monitoring systems using fixed buoy stations or satellite measurements. These observations will be used to validate satellite-based estimates and in-situ gridded datasets such as SOC.

(d) *Assessment of the water transports at the ocean boundaries of the Mediterranean basin (Gibraltar Strait, Dardanelles Strait)*. These evaluations must be done simultaneously and over the HyMeX 10-year period for the depiction of the variability at various temporal time scales. The impact of the Black Sea – Aegean Sea exchanges on the Mediterranean water budget as well as on the Mediterranean thermohaline circulation could be evaluated through sensitivity experiments at the different time scales (as made in Skliris *et al.*, 2007 on the influence of the Nile river). These experiments must include tests on the way to model the strait exchanges in introducing at least a strait model but perhaps also a Black Sea model in the Mediterranean Sea model. For the Suez canal, first estimates from observations and first sensitivity tests in modeling have to be done in order to close or open the question of the influence of the Suez Canal. This assessment would contribute to the early warning system proposed in relation to WG1-SQ4.

(e) *Evaluation of atmospheric moisture transport*: the evaluation of moisture transport in the water budget and its contribution to the seasonal variability should be better quantified combining (suited) observations, mesoscale assimilation systems (for continental surfaces, the ocean and the atmosphere) and high-resolution regional models with thorough validation. Estimates of water vapor transport from the Mediterranean area towards the southern and eastern part of Europe differ when using a fully coupled atmospheric/oceanic model instead of an atmospheric model alone (Somot *et al.*, 2008). Impact of the air-sea coupling on the model assessment of the MSWB terms should be quantified.

(f) *Accurate estimates of the river input and underground waters*: the first goal is to estimate an accurate total river runoff flux for the Mediterranean Sea to decrease the current uncertainty. This might be achieved from already existing database in taking the decadal temporal variation of the discharge into account. The modelling work performed in WG2 will also provide some estimates of the required quantities.

(g) *Explicit modeling of the Gibraltar Strait*: this requires developing multiple-level nested ocean model approaches. In terms of modeling, the Gibraltar Strait transports are simulated either at a very high resolution by limited area models for short time periods and with idealised forcings, or at a low resolution by Mediterranean or global ocean models over longer periods and more realistic forcings (see Artale *et al.*, 2006 for a review and Sannino *et al.*, 2007). Both approaches should now converge in using nested and coupled models. A three-nested level system coupling an Atlantic Ocean model, a very high resolution and non-hydrostatic Gibraltar Strait model and a high resolution Mediterranean Sea model could be a modeling challenge of the HyMeX project. Targeted resolution for these three models could be typically of 1/2° (50 km), 1/64° (1.5 km), and 1/16° (6 km) respectively. These models already exist and should be coupled.

This complex tool and the different mesh sizes are scientifically legitimated by the physical processes to be resolved in each part of the ocean (see also Artale *et al.*, 2006). A first step towards this complex coupling is planed within the French ANR-CICLE and the FP6 CIRCE projects.

(h) *Evaluating and reducing the estimate uncertainties*: a cross-validation methodology using various techniques to estimate each term of the MSWB should be enhanced.

(i) *Regionalisation of the water budget* for some well defined sub-basins is relevant. The definition of the sub-basins must take into account the river catchment, the sea strait position and the spatial homogeneity of local climate influence.

(j) *Accurate modeling of the whole MSWB* should be achieved with non-coupled and coupled regional modeling systems. Both approaches should be compared. Specific modeling tools (including atmosphere-ocean coupled models) should be set up to re-do the LOP, EOP and SOP periods with or without assimilation of the in-situ data of temperature and salinity. Walin's method and mixed layer heat and salt budgets should be computed from the model outputs.

(k) *Improvement of the physical parameterisations over land and sea* involved in the modeling of the MSWB components (precipitation and associated schemes such as convection, atmosphere boundary layer, latent heat flux, radiative transfer code, aerosol radiative interaction, land-atmosphere feedback, runoff routine scheme). Focus on the bulk formulae and the physics of the marine atmospheric boundary layer is needed. This development requires high-resolution in-situ data on a short time scale for validation and will be beneficial to both Numerical Weather Prediction models and climate models.

(l) *Dedicated in-situ oceanographic campaigns for indirect estimate of the MSWB*: data of temperature, salinity and mixed layer depth should be acquired during a one-year period on a defined area. Heat and salt advection terms should be measured at the boundaries and air-sea flux estimates should be obtained for the same area and period of time. Spatial high-resolution measurements are required as well as two or three in-situ campaigns. The river inflow term should be taken into account in these studies.

Most of the research needs identified for WG1-SQ1 will also be useful in the other scientific questions detailed below. Some additional specific needs and proposals can be identified.

3.1.4.2 What is the variability of the MSWB at seasonal, interannual and decadal time-scales?

The major research needs to answer WG1-SQ2 are:

(a) *Lack of a suitable fine-scale and long-term dataset of precipitation over land (in collaboration with WG2)*: homogenised quality-controlled daily dataset should be assembled for the whole Mediterranean basin, including the southern part. International agreement for data exchange policy should be reached. Precipitation over land contributes to the Mediterranean Sea water budget through the catchments of the Mediterranean Sea or Black Sea rivers, which thus implies a fine-scale monitoring of precipitation over these river catchments. Increasing the density of the rainfall gauge is a solution but will never permit to recover the last 40-year high-resolution variability of this field. Therefore, approaches combining dynamical or statistical downscaling methods applied on reanalysis dataset and local validation with high-resolution station data are necessary. Indeed, a homogeneous dataset of high quality all around the basin for at least the daily time scale and over a period of time long enough to study decadal variability and long-term trends possibly due to climate change is necessary.

(b) *Quantifying the interannual to decadal variability of the MSWB components*: an approach based on in-situ observations only will never succeed to quantify the full variability of the fields due to the weak data coverage over the sea. Consequently an approach integrating in-situ observations, satellite and models seems to be required. The set-up of regional hindcast or reanalysis systems could be a good solution. An intercomparison between different modeling systems seems necessary to evaluate the uncertainties due to model-formulation errors.

(c) *Validating the interannual variability of the modeling systems*: the multi-compartment data collected during the LOP and EOP (and even the SOPs if they span over more than one year) associated with dedicated satellite products should allow a thorough validation of the coupled modeling tools. Among the useful long-term datasets, eulerian observing systems with ocean and atmosphere in-situ measurements as well as remote air-sea flux estimates from satellite over the basin are the most relevant.

(d) *Evaluate the impact of the coupling on the MSWB variability*: comparison of non-coupled and coupled regional models should allow a better understanding of the high-frequency coupling between the different components of the system (air-sea, air-hydrology-sea). Evaluation of the various terms of the budget during the LOP, EOP and SOP periods with coupled and non-coupled models will allow to answer the question of the impact of the coupling for different case studies and for long-term variability studies. *Some 1D or 2D well-documented cases* built from the EOP and SOP campaigns are required to validate the dedicated models. Moreover a goal of HyMeX could be to determine whether fully coupled regional reanalyses are required or not to simulate the MSWB.

(e) *Find alternatives to the stationarity hypothesis*: if one ambition of the HyMeX project is to go further than previous studies, then the stationary hypothesis (*i.e.* balance between the surface water flux and the Gibraltar transport, see section 2.2) should be left aside to focus on direct measurements with a high temporal and spatial resolution and over a long period of time. Multi time-scale observations are needed from seasonal to interannual variability and long-term trends.

(f) *Study the two-way interactions* linked with the MSWB components between the Mediterranean climate variability and the global climate variability at different temporal scales: *(i)* Study of the atmospheric remote influences on the Mediterranean from Pacific Ocean, such as the well-known oscillations: MJO, ENSO, PDO. *(ii)* Study of the interactions between Mediterranean and both the Atlantic and the Monsoon climate systems with a focus on the dynamical and thermodynamic processes. *(iii)* Investigation of the Mediterranean SST variability as a source of heat and moisture available to the atmosphere with a possible global response and impacts (West African Monsoon and extratropical circulation).

3.1.4.3 How do the spatially and/or temporally localised intense events affect the MSWB?

The major research needs to answer WG1-SQ3 are:

(a) *Quantify the impact of the high-frequency temporal variability* on the different terms of the water budget and on the various processes by sensitivity studies with appropriate models. Long-term continuous coupled eulerian datasets are required and should be

dedicated to this topic within HyMeX. The impact of the intense events on the interannual variability of the water budget should also be studied. Note that the intense events can be found at different time scales: daily intense events can have an impact on monthly mean, monthly intense events can influence yearly mean and then interannual variability.

(b) *Quantify the impact of high-resolution spatial variability* on the different terms of the water budget. The impact of spatially localised events on the global Mediterranean water budget should also be quantified. 2D high-resolution measurements over land and sea are then required during the SOPs. The periods of strong evaporation under dry and cold air masses, of intense precipitation events, and of floods have to be documented during HyMeX observation periods and examined with respect to the anomalies of the Mediterranean Thermohaline Circulation (MTHC).

(c) *Study of scale-interactions and non-linearities*: the study of the impact of scale-interactions on the mean values of the different terms of the MSWB implies to analyse the dependency of the MSWB to the temporal and spatial resolution of the model. The Mediterranean Sea water masses are formed locally in time and space. However, by their subduction, propagation and mixing, they influence the whole Mediterranean Sea hydrological characteristics. This non-linear effect should be better understood and quantified to decipher the memory effect of the deep layers of the Mediterranean Sea with respect to the surface mixed layer and SST.

(d) *Air-sea coupling*: the coupling effects are sensitive to the small-scale (in space and time) anomalies of the SST. These anomalies can only develop and interact with the atmosphere in a coupled model but not in an atmosphere-alone model. From that point of view air-sea coupling and scale-interaction have to be studied within the same framework. Switching from a non-coupled to a coupled regional model can modify the sea-land moisture transport. Sub-regional SST patterns and/or high-frequency regional air-sea interactions seem to be the key processes explaining this behavior. Their links with the regional water transport should be investigated during HyMeX. Specific observations should be gathered during the field campaign for monitoring both the PBL and mixed layer coupled variability.

(e) *Thermohaline regime shifts*: lessons from modeling experiments, from the Eastern Mediterranean Transient event and from the sapropel past observations lead to assume that the Mediterranean sea thermohaline circulation can have many equilibrium states with different intensity and different potential areas of deep water formation. Observing, modeling, understanding and forecasting these shifts probably driven by meteorological or climatic events are goals for the Mediterranean community. A network of long-term measurement should be set-up during HyMeX and maintained after the HyMeX 10-year period to act as a "Mediterranean watching system".

3.1.4.4 How will the MSWB evolve under future-climate conditions along the 21st century?

The major research needs to answer WG1-SQ4 are:

(a) *Detection and attribution of the observed trends in precipitation* for the Mediterranean basin are completely open questions. Regional techniques should be developed and applied to the Mediterranean dataset.

(b) *Detection and attribution of evaporation trends* over the Mediterranean Sea is a crucial element of the HyMeX strategy to understand long-term MSWB changes and the

projected impacts of climate change. Observational analyses and modeling tools will be used to establish whether it is possible to detect long-term evaporation changes in past decades, as a precursor to the major changes projected by the CMIP3 models.

(c) *Observed trends in river run-off*: as an integrated system, the rivers allow to point out long-term trends in the water cycle, even if anthropogenic changes of these rivers are a problem in that regard. Two specific questions can be raised: is it possible to isolate some long-term trend in this part of the budget and evaluate its impact on the Mediterranean Sea hydrology? Besides, can we separate in this long-term trend the direct anthropogenic changes (dam, irrigation) from the indirect changes (increase in GHG concentration)? River modeling including human activities and impacts could be required.

(d) *Early warning system*: the construction of indices based on the terms of the MSWB that are sensible to climate change associated with the definition of vulnerability thresholds could constitute a useful early warning system for the policy makers of the region. It could also help managing water resources in agreement between the northern and the southern part of the basin. A network of long-term measurement should be set-up during HyMeX and maintained after the HyMeX 10-year period.

(e) *Quantify drying and associated uncertainties with climate change*: a multi-model approach covering the wide range of uncertainties in regional climate change scenarios should be used. Sources of uncertainty include the choice of the GHG concentration scenario, of the global coupled model, of the downscaling technique (statistical or dynamical), of the regional climate model in case of dynamical downscaling, of the resolution/domain size of the RCM, of forcing or coupling with the Mediterranean Sea. In the HyMeX project, this uncertainty cascade has to be assessed for the whole Mediterranean area to increase confidence in the first results obtained on the regional impact of climate change. HyMeX will actually complete the ongoing work done in European projects such as ENSEMBLES, CIRCE and SESAME in bringing a better validation of the regional models and methods used to assess the Mediterranean climate change. This validating step is necessary if we want to reduce uncertainties in Mediterranean climate change projections. Among the key terms, a special focus should be the validation of the regional climate models on evaporation over sea. The evaluation of uncertainty on this term has not been done yet, even if multi-model datasets start to become available.

(f) *Evaluate uncertainties due to river runoff changes*: this should be done thanks to a multi-model approach (*e.g.* the PRUDENCE, ENSEMBLES, SESAME or CIRCE European projects) and in collaboration with the hydrologists, in particular in relation with the work performed within WG2.

(g) *Evaluate uncertainties due to exchanges with the Black Sea*: in the climate change scenarios, the exchanges with the Black Sea are one of the E-P-R terms for which uncertainty is the most important. Indeed this term integrates the contribution of the E, P and R terms of the Black Sea water budget. Quantifying the uncertainty on this term is then a milestone towards a more robust estimation of the possible evolution of the Mediterranean Sea salinity and THC. A detailed modeling of the Bosphorus Strait is a prerequisite.

(h) *Evaluate the changes in the water mass characteristics*: a long-term in-situ observation network of the main water masses should be perpetuated. Quantifying and attributing the already observed trends of the water masses is a key issue for HyMeX. Is the Mediterranean Sea a proxy of climate change because of its geographical position in a

hot-spot of climate change, its deep and quick overturning circulation and its low thermal inertia? In addition to trend quantification, an oceanic climate change scenario for the 21st century should be achieved with a careful evaluation of the whole uncertainty range. This can be done only by an accurate validation of the air-sea fluxes produced by the regional climate models and of the thermohaline circulation of the ocean regional models.

(i) *Air-sea coupling*: switching from a non-coupled to a coupled regional model can enhance the warming and drying simulated for Europe for the 21st century and also change the pattern of the foreseen SST anomalies (Somot *et al.*, 2008). These results should be confirmed and the coupled versus uncoupled approach should be carefully compared.

(j) *Evaluate the regional sea level change*: for the Mediterranean Sea, it requires at least the use of free-surface regional ocean models as well as the estimate of the mass exchanges with the Atlantic Ocean, and of the local sea level behavior due to the changes in the salt content, the heat content and the river inflows.

(k) *MTHC response and Mediterranean outflow waters*: monitoring and understanding the response of the MTHC to climate change and monitoring and forecasting the evolution of the hydrological characteristics of the Mediterranean waters flowing into the Atlantic should be achieved. This activity could also critically contribute to the understanding of the variability of the Atlantic Meridional Overturning Circulation (AMOC), a major international effort.

3.2 WG2: Hydrological Continental Cycle

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3.2.1 Introduction and motivation

In the Mediterranean climatic zone, also labelled as semi-arid or sub-humid (Piñol *et al.,* 1991), hydrological processes are largely variable both in time and space due to the high variability of rainfall regime, the influence of topography and the spatial distribution of geology, soil and land use (Pilgrim *et al.,* 1988; Thornes *et al.*, 1996; Kosmas *et al.,* 1997). The temporal variability of precipitation within and between years is one of the specificities of this climate characterised by a succession of drought and flash-flood periods. Precipitation is also variable in space and its variability is accentuated with altitude in mountainous regions. As an illustration, in Mediterranean southern France, the mean annual rainfall varies between 500 mm near the coast and 1950 mm at the 1567 m AMSL Mont-Aigoual.

Due to the strong spatio-temporal contrast of climate, the hydrological regime of the Mediterranean rivers is quite specific (Malanotte-Rizzoli and Eremeev, 1999; Servat *et al.,* 2003; Thornes and Wainwright, 2003). The differences between low and high water discharges can be extreme. Often, most of the water discharge occurs during short-duration floods concentrated in small to medium watersheds, the importance of the base flow being mostly related to the hydrogeological structure of the watershed. As a consequence, the ratio of peak discharge on mean annual discharge in drainage basins of 1000 to 10000 km² is frequently one order greater than for rivers in non-Mediterranean areas. This makes runoff less predictable than in other regions because of the low predictability of precipitation (mostly convective) and the complexity of surface run off processes associated with complex topography and sparse vegetation. This also represents a major difficulty for the monitoring of rivers as well as for the analysis of the rainfall-runoff processes.

At the annual scale, hydrological processes are driven by the climate and the land surface properties such as the seasonal cycle in precipitation and evaporation, and by the geological structure of the watershed that may favour or not storage in aquifers (Aunay *et al*., 2003; Bakalowicz *et al*., 2003; Blöschl and Sivapalan, 1995; Ceballos and Schnabel, 1998). Considering seasonal variability, most of the Mediterranean rivers have maximum discharge values between February and May and lowest discharge values during summer (July to September) because of strongly reduced precipitation and the elevated temperatures and evapotranspiration during this season. At this scale, the main hydrological processes in forested areas have extensively been studied (Ibáñez *et al.,* 1990; Piñol *et al.* 1991; 1992; Ávila *et al*.; 1992; Llorens and Gallart, 1992) and compared to cleared catchments (Burch *et al*., 1987); other authors have studied the impact of natural phenomena such as destruction by fire (Lavabre *et al.,* 1991), afforestation (Sorriso-Valvo *et al.,* 1995) or climate change implications (Ávila *et al.,* 1996). Evapotranspiration is a key process of the water budget at the annual scale and may represent between 50 and 75% of the total rainfall. Using a distributed hydrometeorological model driven by observed atmospheric forcing over the Rhone basin, Etchevers (2000) showed that the annual ratio between evaporation over precipitation was roughly 80% for the Mediterranean catchments. This ratio was significantly lower for the basins influenced by continental or alpine climates north of the Rhone basin. In arid Mediterranean regions, surface water flow in water courses occurs only for short periods of time and are highly variable, while stream channels are dry for long periods (Pilgrim *et al*., 1988). When floods occur in normally dry stream channels, the channel network may replenish the water table by re-infiltration of the runoff water and consequently the volume of flow is reduced by infiltration into the bed, the banks, and possibly the flood plain (Lane *et* *al.,* 1971; Jones, 1997). These losses due to aquifers reduce not only the volume of the hydrograph, but also the peak discharge. Where and when the water table is higher than the channel bed, the channel network drains the water table and a base flow is locally observed. Consequently, it is very difficult to predict the behaviour of channel-aquifer water exchanges because of the strong dependence on local conditions.

At the event scale, runoff events in the Mediterranean region are usually caused by high-intensity, short-duration thunderstorms and are dominated by hortonian overland flow and/or subsurface flow. In calcareous watersheds, karstic aquifers often greatly contribute to the floods. Many factors influence runoff genesis, including the soil surface properties, the vegetation cover, soil hydraulic properties and the initial water content. Many studies have already proved the importance of initial soil moisture on the runoff response. The impact of heavy precipitation and runoff events on the hydrological continental cycle is difficult to quantify, but can be very significant, especially for coastal rivers. The quantification of the runoff discharged to the Mediterranean from the coastal rivers remains uncertain and further studies are required to improve it.

In space, hydrological regimes depend on geographical and anthropogenic factors such as the basin size (large basins like the Nile, Rhone, Po, Ebro *vs.* small basins under 1000 km²), the topographic position (mountainous basins like the Alps, Pyrenees, Cévennes, Atlas *vs.* plain basins like Camargue), the hydrogeologic and aquifer system (*e.g.* specific processes in karstic regions), urbanization (*e.g.* Marseille, Barcelona, Napoli), islands (*e.g.* Cyprus, Sicilia, Corsica), the role of dams and reservoirs (*e.g.* Assouan), the lakes (*e.g.* more than 1000 artificial lakes constructed in Tunisia during the last two decades), human activities (farming practices, irrigation, artificial recharge of aquifers, hydroelectricity, industrial activities), and others.

In summary, the main characteristics affecting the hydrological cycle of the continental surfaces in the Mediterranean region are:

- **a water resource which is scare and unevenly distributed in space and in time** with few short duration heavy precipitation events and long drought periods,
- **the physiographic features of the watersheds** with medium to small size catchments, having a mountainous upstream area and a quite flat outlet downstream,
- **the anthropogenic pressures**, with recent changes in land use and land cover, strong urbanization and population growth, particularly in the coastal areas.

In the context of global change, the water budget is a key component to be addressed in order to design adaptation strategies within the Mediterranean area. Therefore, modeling tools able to estimate the dynamics of the different water budget components of continental surfaces (surface water, ground water and soil water) are required to characterise the trends in water resources and the impact of management options. Within the framework of HyMeX, such modeling tools will also provide relevant results useful to answer the scientific questions identified in other working groups. In WG1 there is a need to quantify the water flow arriving in the Mediterranean Sea and evapotranspiration, whereas flash-flood intensity, addressed in WG3, depends on initial soil moisture.

Within HyMeX, one of WG2 objectives is an exhaustive coverage of the whole Mediterrean region. A high resolution is needed to account for Mediterranean specificities such as the physiographic features of the watersheds and the anthropogenic pressures. The importance of extreme events and the need of understanding trends in water resources lead to consider a wide range of time scales from the event (hourly) to several decades covering past and future periods.

Improving the quantification of the continental Mediterranean water balance through the improvement of hydro-meteorological modeling is the main goal of WG2. Progress must be done in several directions:

- a finer spatio-temporal resolution,
- the coupling between climate, surface, ground compartment and anthropogenic activities,
- process parameterisation (water and energy fluxes, water storage, management, vegetation dynamics,…).

The state of the art of the knowledge about the various terms of the continental water balance, their variability and their modeling at various scales is first detailed in section 3.2.2. Then the key issues as well as the main scientific questions and objectives are proposed in section 3.2.3 in order to overcome the identified current limitations. Finally specific research needs and a general observation and modeling strategy is detailed in section 3.2.4 to answer the scientific questions.

3.2.2 State of the art

3.2.2.1 Estimation of the components of the hydrological continental cycle at the Mediterranean basin scale

The evaluation of the contribution of continental surfaces to the water budget necessary relies on hydrological modeling at the whole basin scale. Nowadays, apart from coupled land-ocean-atmosphere regional climate models deployed in WG1, few modeling systems are running over the whole Mediterranean basin. Few modeling systems have been set up at the regional scale and simulate the various components of the water budget. Within the framework of BALTEX, such an attempt has been performed, but without a full interaction between the hydrological models and the land surface models (Graham and Bergström, 2000). In France, a coupled hydrometeorological model has been built for the Rhone basin under the framework of GEWEX (Habets *et al.*, 1999). In this approach, the hydrogeological model MODCOU has been coupled to the land surface model ISBA. The meteorological analysis SAFRAN forced ISBA at a 8x8 km grid. Later, this approach (namely referred to the SIM model) has been extended to France and run on a daily basis by Météo-France (in particular for soil wetness and water resource monitoring). However this system in its present state does not account for the particularities of the Mediterranean region (fine scale hydrological processes, karstic aquifers, anthropogenic components,…). This model would be a good candidate as a regional scale model but can probably not be implemented over the whole Mediterranean, due to the difficulty in implementing the aquifer and streamflow components, which requires the availability of a large amount of data and a large effort for setting up and calibrating the model. However, networking such kind of models implemented over various Mediterranean regions would allow to have an estimation of the hydrological cycle components at the Mediterranean basin scale even if it does not completely fulfil the requirements reminded above. As far as possible, a common and/or shared framework must be set up in order to run the various coupled models that represent the flows towards the sea (stream flow at river estuary, outflow from aquifers), evapotranspiration, the aquifer water balance and soil moisture. In order to promote interoperability, standardised coupling schemes as well as input/output data should be defined.

Deploying these models demands a significant effort dedicated to the acquisition and derivation of the necessary input data as well as verification data. This includes: climate data, rainfall, land use map, soil map and soil hydraulic properties, aquifer geometry, as well as information about anthropogenic uptake and intake (irrigation, dams, potable water, sanitation water,...).

A consistent atmospheric analysis of low-level parameters and radiative fluxes, at a sufficient spatial resolution (a few km) is mandatory in order to properly handle the surface-atmosphere feedback. The needed variables are those required for calculating surface budget (temperature, humidity, wind speed, precipitation and radiative fluxes). At the scale of the Mediterranean basin, the only atmospheric data set currently available is the GSWP2 (Global Soil Wetness Project) global data set covering a 10-year period but with a spatial resolution of approximately 100 km, which is not sufficient to completely fulfil the objectives of HyMeX. Several near surface analysis systems exist in the meteorological community (*e.g.* the Mesan, in Sweden or SAFRAN, in France). SAFRAN (Quintana-Segui *et al.*, 2008) has been able to calculate the needed parameters for 1958 onward (Vidal *et al.*, 2009), but only over France. A spatial extension of this type of high-resolution analysis of low-level atmospheric variables should be promoted, provided that a relevant data base of observations could be organized for different neighbouring countries (for instance Italy, France and Spain). In addition to the use of conventional data, a special emphasis should be put on remote sensing data for precipitation (radars) and radiative fluxes (*e.g.* Land SAF developments).

As regard surface modeling, a large effort is still needed in order to obtain accurate information on land cover and land use representative of Mediterranean ecosystems. The current land cover classifications (Corinne, GLC, ECOCLIMAP - Masson *et al.*, 2003) are not accurate enough and are site-specific, which is not satisfactory in an area characterized by a very high spatial heterogeneity. A classification with an approximately 100-m pixel is needed. This is an important point since the sensitivity of the soil-vegetation surface schemes to the prescribed land cover is very high, particularly for the state-of-the-art schemes which include the CO_2 cycle and interactive biomass modeling. In this domain, the input of satellite data should be very important not only to improve existing land cover but also in order to represent the dynamic development of natural vegetation and crops (maps of Leaf Area Index, surface albedo, etc.).

Due to the difficulties linked to scale effects in time and space, experimentation and modeling are necessary in order to better understand and quantify the various components of the energy and water budgets. Long term measurements of the hydrometeorological parameters – rainfall, snow, runoff, infiltration, aquifers level, meteorological parameters including radiation, temperature, wind speed, etc. – have been conducted at various time and space scales on experimental research basins (*e.g.* ORE OHMCV, Delrieu, 2004; Delrieu *et al.*, 2005; ORE OMERE, Voltz and Andrieux, 1995; Voltz and Albergel, 2002): at the flood event scale (1h, to few days), the annual scale and multi-annual scale; and at the scales of the plot, the field, the small (1-10 km²) and medium (10-1000 km²) basins. Spatially distributed modeling approaches were also applied to simulate hydrographs at the catchment scale (*e.g.* conceptual models, transfer functions, TOPMODEL, MHYDAS, MODFLOW, MARTHE in Moussa, 1991, 1997; Obled *et al.*, 1994; Saulnier *et al.*, 1997; Moussa *et al.*, 2002). However, these studies cover part of the Mediterranean basin only and, most of the time, do not fully include evapotranspiration modeling. Progress is thus necessary in that direction.

3.2.2.2 Accounting for the Mediterranean specificities

In order to improve the parameterisation of regional scale hydrological models, several processes require further observation and modeling studies in order to be better understood and integrated into regional scale models. These questions include:

- the quantification of the water balance for different vegetation covers specific and/or often encountered in the Mediterranean region, for which a lack of knowledge has been identified; this includes the measurement and simulation of evapotranspiration over complex topography, specific reaction to water stress of Mediterranean vegetations, burnt areas,...
- the quantification of the water balance of urbanised areas,
- the simulation of the impact of karst on the hydrological cycle,
- the simulation of the impact of anthropogenic water use on hydrological processes and on the water balance,
- the role of topography on soil moisture redistribution, evapotranspiration and the interactions between water table and rivers (especially during dry periods),
- snow processes with partial and shallow cover.

3.2.2.2.1 Water balance of typical Mediterranean vegetation covers

In recent years significant progress has been made in the modeling of the role of the vegetation through field campaigns documenting the various components of the water and energy budget, especially in the Mediterranean areas. Examples are EFEDA (Bolle *et al.*, 1993), Alpilles-ReSeDA (Olioso *et al.*, 2002), and SudMed (Chehbouni *et al.*, 2007). At the same time, Soil-Vegetation-Atmosphere-Transfer models (SVATs) (*e.g.* ISBA, SiSPAT, AliBi, S-model, SECHIBA, etc.) and vegetation models (*e.g.* STICS, CropSyst, STEP, V-model, etc.) have been developed and/or improved. Recent works showed the benefit of coupling both: STICS-ISBA (Olioso *et al.*, 2005), V-S models (Cayrol *et al.*, 2000); or including vegetation growth into SVAT models: ISBA-A-gs (Calvet *et al.*, 1998; Gibelin *et al.*, 2006), ORCHIDEE (Krinner *et al.*, 2005). This category of SVATs is also able to account for the carbon cycle which is closely related to the water cycle. SVATs allow the determination of parameters controlling transpiration and root water uptake for various kinds of crops (Alpilles-ReSeDA, Sud-Med), vineyards and natural vegetation (EFEDA) for the Mediterranean areas. However, the adaptive strategies developed by natural Mediterranean vegetation species to manage water stress (*e.g.* drought avoiding or drought-tolerant strategies, Calvet, 2000; Calvet *et al.*, 2004) remain mostly unknown. Some results have been obtained on trees (*e.g.* Rambal, 2002), but they must be generalised to other Mediterranean species.

Mediterranean regions are also prone to fires which can destroy large areas of vegetation. The dynamics of vegetation recover after a fire has a potential impact on runoff and the water budget of these areas, through a modification of evapotranspiration. Improved knowledge and modeling of these areas require further observations and research, which should be addressed within HyMeX to achieve a proper handling of these areas and of the possible modifications of fire occurrence in the future.

Another complexity in quantifying evapotranspiration for some of these vegetations (mostly natural vegetations) is related to the complex topography. The direct measurement of evapotranspiration in these areas is challenging, due to fetch requirements and the dependence on wind direction. Eddy Correlation (EC) has been recognised as the most accurate method, but its spatial coverage is limited. Scintillometers offer an alternative to address larger scales as they provide an integrated measure over transects and heterogeneous terrains (Meijninger *et al.,* 2006). However, solar sensors provide sensible heat flux only, and evapotranspiration still must be derived as the residual of the surface energy balance. Micro-wave sensors are promising in giving the evapotranspiration flux directly but they require further developments

(Green *et al*., 2001; Lüdi *et al*., 2005). The combined use of Eddy Correlation and scintillometers requires an accurate determination of the footprint, including the contribution of each component to the fluxes. Nevertheless, they can provide an efficient way to validate modeling approaches at scales larger than the local one (Bsaibes, 2007).

3.2.2.2.2 Water and energy budget of urbanised areas

All around the Mediterranean, urbanised or peri-urban areas cover a large fraction of the surface. It implies impermeable soils and a modification of natural water pathways. Water consumption must also be accounted for, as well as the impact of infrastructure such as sewer networks, sewer overflow devices, etc.. During part of the year, water coming from urbanised area can be the major source of alimentation water for ephemeral rivers. Current parameterisations of water and energy balance in urbanised areas (*e.g.* TEB, among others) are often adapted to densely urbanised areas, and the underlying soil is seldom accounted for, as well as the potential interactions between underground networks and the water and energy balance. These parameterisations must therefore be improved in order to better take less densely urbanised areas, and the interactions between soils and artificial structures into account.

3.2.2.2.3 Improving the water balance of karstic and coastal aquifers

All the Mediterranean aquifers exhibit a very similar hydrogeological pattern, due to a very similar geological history. The **karstic aquifers** are widespread around the Mediterranean basin (Bakalowicz *et al*., 2003), specifically on its West, East and Northern parts; they may be very thick and they play a major hydrological role (storage during the rainy season, springs and river feeding during the dry periods). They constitute huge groundwater reservoirs, the exploitation of which is only beginning. Knowledge about the structure and functioning of karstic aquifers still needs improvement, particularly for the characterisation of the geometry of the voids, and for the development of the tools to be used for the sustainable exploitation of the groundwater resource to support economic development (needs of the population, tourism, agriculture, industries, etc.), ensure the preservation/restoration of the aquatic ecosystems (increase of low stage river discharges), and to mitigate the flood risks by quantifying their storage capacities. Evapotranspiration over these areas must also be quantified.

The deep and large valleys of the Messinian period all around the Mediterranean shore were completely filled up with porous and clayey sediments when the sea level came back up. These filled valleys constitute most of the **coastal aquifers** that are widespread all around the Mediterranean shore and are heavily exploited, even overexploited in some regions (Spain for instance; Nixon *et al*., 2003), leading to sea water intrusion. Their geological structure has recently been precisely described (Duvail *et al*., 2006; Gorini *et al*., 2005) but its influence on their hydrogeological behaviour still needs to be refined, particularly along their coastal fringe (Aunay, 2007). The quantification of the groundwater/flow is of major importance for the water budget of the Mediterranean, as this flux is expected to be responsible for a large part of the fresh water input to the Mediterranean.

3.2.2.2.4 Impact of soil moisture redistribution by topography on the water balance

The Mediterranean area has a marked topography, with a potential impact on runoff during rainfall events by redistributing water along slopes, but also after the rainfall events by modifying groundwater recharge and evapotranspiration. These effects are in general not taken into account in rainfall-runoff models dedicated to flood simulation, but they must be included into continuous water balance models. Furthermore, an improved simulation of soil moisture spatial and temporal variability is important for the initialisation of flood prediction models as well as for the simulation of heavy precipitation events.

Thus we need to better understand how water is redistributed both in space and time by topography, vegetation, fauna, soils and the subsoil (the properties of the latter being driven by its geological structure and by the impacts of the weathering processes on the rocks; see for instance Dewandel *et al*., 2006), and by man-induced pathways (ditches, roads, terraced slopes, etc.), and how this water may be further used by vegetation for evapotranspiration. The detailed knowledge of processes describing the interactions between the surface waters, the shallow aquifers and the river network is also crucial for the simulation of low flows, but is not sufficiently understood.

The second challenging task is the coupled modeling of the corresponding systems. Lots of hillslope models have been developed, but they often only represent a few dominant processes (*e.g.* VanderKwaak and Loague, 2001; Troch *et al.*, 2003; Esclaffer, 2006) and/or they are only dedicated to the modeling of rainfall events. Their coupling with SVATs and the accurate modeling of the interactions between hillslopes, shallow aquifers and streams is necessary for the representation of longer term processes. These detailed coupled models will serve as reference for the derivation of simplified representations to be included into regional models.

3.2.2.2.5 Snow processes

The snow cover can play a significant role in the water cycle, by delaying the runoff and limiting the evapotranspiration. Numerous models (included in SVATs or in hydrological models) exist, with various complexity degrees: NOAH, MOSAIC and VIC snow modules (Pan *et al.*, 2003), SNOW17 (Slater and Clark, 2006), SnowModel (Liston and Elder, 2006), ISBA, with 1 and 3 layers (Douville *et al*., 1995; Boone *et al*., 2000; Boone and Etchevers, 2001), and SWAT snowmelt parameterization (Wang and Melesse, 2005). These models consider the main processes such as energy exchanges, melting, soil infiltration, vegetation screening and in some cases a very simplified physics of the snow cover (*e.g.* albedo, density evolution, liquid water in the snow pack,…). However, present models reproduce with difficulty the evolution of shallow snow covers which are typical of the Mediterranean context, and where the interaction between the snow, the soil (heat fluxes) and the vegetation (interception, melting) are preponderant. Dry deposition may also modify albedo and hence the melting rate.

3.2.2.2.6 Anthropogenic influence

In order to be accounted for within regional scale models, anthropogenic influences on the water balance must be quantified and modelled. The goal is here to quantify water redistribution between the components of the water budget related to human activities (irrigation, water consumption, etc.) at the grid scale of regional models (from one to several km). The following questions need to be addressed:

- What is the amount of water that is transferred from aquifers to rivers (water consumption in urban areas)?
- What is the amount of water that is transferred from rivers to aquifers (irrigated areas)?
- How can we assess this flow at a regional scale and include parameterisations of these anthropogenic water transfers into these models?

3.2.2.3 Evolution of the continental hydrological cycle with global change

The human pressure on environment in the Mediterranean region is already very high. Ongoing trends (Benoit and Comeau, 2005) are towards an increase in population, especially marked in the South and East rims. The increase in urban and coastal population will be an important feature with all related effects on the environment. This will lead to an increased vulnerability of systems to the ongoing climate trends.

During this century, **global warming** over Mediterranean regions will probably cause more droughts and more precipitation during warmer winters despite shorter rainy seasons (Gibelin and Déqué, 2003; Rowell, 2005; Wang, 2005). Uncertainties about the extreme rainfall event and drought intensity in the future are still important (Neppel *et al.*, 2003; Rowell, 2005; Renard *et al.*, 2006; Renard, 2006, CYPRIM project: www.cnrm.meteo.fr/cyprim/), while some studies point out a variability increase (Jones and Reid, 2001; Voss *et al.*, 2002; Diodato, 2004). On the South shore, the main impact will be the increase in drought, the precipitation evolution (and extremes) is rather uncertain. On the North shore, several detailed impact studies (Etchevers *et al.*, 2002; Leblois, 2002; Ducharne *et al.*, 2003; Booij, 2005; Ludwig *et al.*, 2004; Zierl and Bugmann, 2005; Caballero *et al.*, 2006; Merritt *et al.*, 2006) show higher river discharges during the fall and the winter, an earlier snowmelt, longer periods of low flows and a reduced aquifer recharge. However, the impact studies only partially consider some important factors, such as a change in land use, agricultural and irrigation practices, direct CO_2 effect on plants and the evolution of water demand, and then must be consolidated by including additional processes.

Considering **non climatic trends**, change in population, industry, economic policy will modify the water demand (for domestic water, agriculture, industry and tourism), the waste water produced and land use. The general increase in vulnerability will be modulated by economic or political measures: in the EU the implementation of the Water Framework Directive (EC, 2002) which aims at restoring good ecological status for all water bodies (notably through an increase of stream water flows) is an example of this type of measures.

Furthermore, it is virtually certain that the effects of other kinds of changes -land use/land cover (Loukas *et al.*, 2002), surface states, soil degradation (Feddema and Freire, 2001), impact of forest fires and salt water intrusion due to rising sea (Bobba, 2002), human works, changes in water demand (*e.g.* Alderwish and Al-Eryani, 1999; Chen *et al.*, 2001; Loaiciga *et al.*, 2000; Meigh *et al.*, 1999; Döll, 2002; Montginoul *et al.*, 2005)- will have much more severe impacts that climate change alone. A pluridisciplinary research is needed in order to consider water resource management in a holistic approach which: “takes into account the direct and indirect contributions of climate change and socio economic change, and considering the uncertainties and potential shortcomings which are pertinent”.

3.2.3 Key issues and scientific questions

The state-of-the-art analysis has evidenced the points requiring further improvements in order to better understand and quantify the components of the continental water balance over the whole Mediterranean basin. The scientific questions listed below, must be addressed so that WG2 is able to fulfil its own objectives regarding the improvement of water resource management both in present and future climates and the requirements for the other working groups, namely provide WG1 with an improved estimation of river flow to the Mediterranean, and of evapotranspiration towards the atmosphere. An improvement of soil moisture assessment is also expected for improving initial conditions leading to flash floods. Thus, a complete handling of the water cycle is necessary in order to be able to simulate and analyse past and present evolutions and to run scenarios for quantifying the impact of global change (climatic and anthropogenic) in the near and distant futures, on the hydrological system, both in terms of **water resources** and **extreme events**. The target components of the water cycle which should be monitored, analysed, better understood and simulated are[2]:

- streamflow which represents one of the fresh water inputs to the Mediterranean and is a key variable for water resource management;
- evapotranspiration which represents the largest recycling component of rainfall and is largely unknown, especially in complex terrain and for typical Mediterranean vegetations;
- groundwater recharge/discharge and direct groundwater input to the Mediterranean (groundwater/sea interactions);
- anthropogenic components which can have a huge impact on the water balance (irrigation, water consumption, etc.);
- soil moisture which is a key variable for the continental surface-atmosphere interaction and a key component for the simulation of flash flood events.

The target spatial and temporal scales are a spatial resolution of about 1 km^2 (grid-square or sub-catchment), a daily temporal resolution for streamflow (continental surface-ocean interactions), and of about one hour for evapotranspiration (continental surface-atmosphere interactions). The HyMeX programme will cover a ten-year period but data collection and water balance simulations are also foreseen over the last two decades in order to understand the water balance variability and better assess the capacity of models to simulate the long term water balance behaviour.

***Key Scientific Questions*:**

- ***WG2-SQ1:* How to quantify the water cycle components over the Mediterranean basin through an improved hydro-meteorological framework?**

  The main objective is to better understand, quantify and **simulate the different components of the continental hydrological cycle** and if possible the corresponding uncertainties over the whole Mediterranean basin or at least a significant part of it.

- ***WG2-SQ2:* Can we better understand the specificities of the hydrological processes in the Mediterranean? Can we improve the whole Mediterranean basin simulation of the continental hydrological cycle by better accounting for specific Mediterranean characteristics?**

  The main objectives are: *(i)* to **improve our understanding of the processes** (evapotranspiration over Mediterranean vegetation, impact of karstic areas, impact of soil moisture redistribution due to topography, snow processes, anthropogenic impact) governing the continental hydrological cycle and its **variability** by appropriate experimental and modeling studies, and *(ii)* to improve our **capability to simulate** the main characteristics of the continental water cycle and its variability by using these process studies to improve their parameterisations within regional scale models.

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[2] HyMeX focuses on the water quantity, quality issues; the impact on ecosystems will be studied in connected projects, the continental water balance being the common component required to address the different projects.

- ***WG2-SQ3:* How will the continental hydrological cycle evolve in relation to global change?**

> The main objectives are: *(i)* to identify the **key processes controlling the future changes** of the terms of the continental hydrological cycle, and *(ii)* to identify and quantify the **related impacts on the Mediterranean basin.**

To answer these questions, studies should be conducted at the **whole Mediterranean scale** (for all the catchments connected to the Mediterranean). The hydrometeorological framework must be open to different kind of models having different levels of complexity in order to evaluate the added value of considering complex interactions. Spatial resolution should range from one to a few kilometers to encompass all the types of basins. The time step should allow to describe the diurnal cycle (typically 1 hour), and range from the event (required to quantify the impact of heavy precipitation events on the annual water balance) to the interannual scale (in order to quantify the interannual variability of the continental water cycle). It should cover the present period (in particular the experimental phase), but should also cover a significant period in the past (more than 10-20 years) in order to reproduce the observed inter-annual variability. Process studies at smaller scales are required to improve our understanding of key processes and improve their parameterisation within larger scale models. Work will also be conducted over large catchments where regional scale models and monitoring can be set up. This scale will allow to fill the gap between the process study scale and the whole Mediterranean scale.

The approach proposed in HyMeX is largely based on the whole Mediterranean modeling of the hydrological components over the Mediterranean basin, which needs that the following specific key issues be addressed:

- all the components of the water cycle including precipitation, runoff, evapo-transpiration, groundwater and anthropogenic influence must be taken into account within a common hydrometeorological framework;
- the Mediterranean watershed must be represented exhaustively, which implies to implement the regional models for all river basins and possibly all aquifers in connection to the sea;
- all the components of the water cycle are interdependent and their simulation should be coupled;
- the simulation of the whole continental hydrological cycle is complex as it covers a large range of time and space scales, and implies non-linear scale-interactions;
- several characteristics of the Mediterranean basin should be further studied (for instance evapotranspiration processes of Mediterranean vegetations and over complex terrain, karstic areas, etc.) in order to improve their representation in existing modeling platforms;
- the set-up and evaluation of the proposed modeling approach, which requires a specific and multi-scale experimental strategy;
- regional modeling should consider the anthropogenic pressures which are crucial around the Mediterranean Sea;
- the projection of current knowledge in terms of scenarios for the quantification of the impact of global change on the simulated continental hydrological cycle and water resource.

3.2.4 Observation and modeling requirements

3.2.4.1 How to quantify the water cycle components over the Mediterranean basin through an improved hydro-meteorological framework?

A better understanding of the continental water cycle components will rely on improved process parameterisations and reference data sets that can be either observed or simulated by detailed models implemented over limited areas. Most of the required data are already collected within every country by different organisations. So a huge effort in data gathering must be done at the international level considering existing initiatives to build an exhaustive hydro-climatic data base. In parallel, the coupled hydrometeorological modeling framework, will be developed being composed of **a meteorological analysis system**, **a modeling of the soil-vegetation continuum and a hydrological model**, including both surface and if possible groundwater components.

The strategy to achieve the spatial coverage for the modeling of the whole or a significant part of the Mediterranean basin might be two-fold:

- use the same modeling framework in order to cover the whole region; the models used should be run over the whole period (LOP) and/or in real time in order to simulate the water balance inter-annual variability;
- allow the interoperability of various models developed by different teams on different areas, covering significant parts of the Mediterranean basin. This could allow a capitalisation of modeling efforts performed in different countries. However, the corresponding modeling should fulfil the requirements of simulating, as much as possible, the variables listed above. Furthermore, these models should be flexible enough to be able to incorporate new parameterisations, as issued from WG2-SQ2 and should prefigure the future generation of regional scale models.

As for the modeling systems, we will consider two levels of data:

- datasets with a full coverage of the Mediterranean area are those required to implement spatial coverage models. This core dataset should be collected during the LOP to implement the models including model input variable, parameters and data for assimilation. Such data acquisition/derivation must be done over the whole LOP.
- datasets with a partial coverage, which may be model specific and will be acquired by the various teams involved, essentially during the EOP and SOP. As much as possible, these datasets are expected to be disseminated whenever possible.

HyMeX should put as a first priority the effort on full coverage datasets in order to offer a data framework for implementing a full Mediterranean coverage by models, for validating the different models (global coverage and partial coverage), for providing data to assimilation studies, and for completing missing data for model implementation.

Some effort is also required in order to set up, calibrate, and evaluate the models over the target areas. A certain degree of standardisation of input/output data and of coupling procedure should be required. For partial coverage models, it is assumed that the necessary data can be acquired from national or laboratory effort over the target sub-domains. Nevertheless, coordination and standardisation, and at least a common referencing of the meda-data should be performed in order to facilitate data exchange amongst HyMeX participants.

The following specific research needs have been identified:

(a) *Climate data with reanalyses of past data (1 km^2, hourly resolution)*:

Conduct an atmospheric analysis of low-level parameters over the area of interest. The approach should be implemented in all countries involved in the project: a particular emphasis should be put on high quality precipitation fields, by using radars.

Use satellite data for surface radiative flux estimation.

Build a database of high resolution regional climate scenarios for the region, in order to run impact models. A special effort should be put on dis-aggregation approaches which are mandatory in order to downscale the outputs of the GCM predictions at fine scale. Another important issue is to achieve a realistic estimation of extreme event trends (rainfall, droughts) and the associated uncertainty.

(b) *Land use and management practices*:

The impact of human activity on the water budget should be accounted for by improving the land use and land cover maps for the Mediterranean area on the basis of existing classification schemes (*e.g.* ECOCLIMAP) and high resolution satellite data. The target spatial resolution is 100 x 100 m^2.

The amount of water used for irrigation, the water origin, the irrigated surface and irrigation technology will be addressed by developing irrigation products that can be implemented in every irrigated area.

In urban and industrial areas, the water inflows and outflows need to be estimated by developing new water budget assessment methods for urban areas.

(c) *Surface description and parameters*:

Surface parameters are necessary to run hydrological models. Most of them are generic and can be implemented in different models. The goal is here to collect these data over the whole land surfaces considered in the project. Data describing the river network geometry and aquifer geometry need to be acquired. A consistent reference river network over the Mediterranean basin based on a Digital Elevation Model should also be provided. Maps of the soil hydraulic parameters inferred from soil maps and using pedotransfer functions as well as maps of surface biogeological parameters (LAI, albedo,…) from satellite data (target spatial resolution: 100 x 100 m^2) need to be derived.

(d) *Surface monitoring*:

The success of the regional approach will rely on the capacity of the community to build a comprehensive database of observations over the region of interest in order to feed, calibrate and evaluate the models. Besides climatic and surface data it will be crucial to collect as many observations as possible for calibration, assimilation and validation purposes. A special effort should be dedicated to the acquisition and gathering of *(i)* stream flow datasets for every river at the estuary and when possible along the river network, and *(ii)* ground water levels datasets. Access and development of remote sensing products (vegetation development, surface temperature, soil moisture) for data assimilation are necessary.

(e) *Common modeling framework*:

As much as possible, a common and/or shared framework must be set up in order to run the various coupled models that represent the flows towards the sea (stream flow at river estuary, outflow from aquifers), evapotranspiration, the aquifer water balance and the soil moisture. In order to promote interoperability, a standardisation of the coupling schemes as well as input/output data should be defined.

A processing chain should be designed and implemented to run the models over every river basins and coastal aquifers that are accounted for to quantify freshwater flows towards the sea. The model should be operated at least during the LOP period. The model implementation will be based on the data base built in 3.2.4.1 and should take profit of the assimilation procedures implemented in the models.

For this, standardisation of the data and tools to ensure fluent data flows must be designed, in connection with potential users of the results (other working groups of HyMeX, other projects).

3.2.4.2 Can we better understand the specificities of the hydrological processes in the Mediterranean? Can we improve the whole Mediterranean basin simulation of the continental hydrological cycle by better accounting for specific Mediterranean characteristics?

The process studies will require the set up of specific observations (mainly within the EOP and SOP), and the development of the corresponding modeling tools. Two types of modeling tools can be distinguished:

- the first type corresponds to process understanding models, able to simulate the complexity of the observed systems. Although they provide valuable understanding and knowledge, these models are in general too complex to be integrated in regional models, either because of computation limitations or difficulty to acquire the necessary parameters over large areas;
- therefore, a second type of modeling tools must be developed. These are simplified parameterisations usable in regional scale modeling. The first type of models (detailed models) will act as reference models allowing the conception and evaluation of these parameterisations at the regional scale. The development of these parameterisations must include the process formalism but also the derivation of the parameter sets from existing observations at this scale.

The specific research requirements for each type of process studies are:

(a) *Water balance of typical Mediterranean vegetation covers*:

A local scale monitoring of Mediterranean vegetation species through field experiments should be performed including measurements of the water, energy and carbon balance to document their functioning. The following vegetation should be considered: *(i)* natural vegetation over hilly terrain, *(ii)* natural vegetation over karstic areas, and *(iii)* burnt areas.

Field experiments dedicated to the evapotranspiration measurements over hilly terrain and over areas of a few km^2 should also be designed over heterogeneous and hilly catchments. The synergistic use of Eddy Corelation and scintillometer measurements needs to be developed in order to improve the relevance of upscaling methods.

The better documentation and understanding acquired from field experiments should be exploited in the development and improvement of parameterisation of the Mediterranean vegetation functioning within regional scale models.

(b) *Water and energy budget of urbanised areas*:

Design an experimental set up to monitor the various components of the water budget within urbanised and peri-urbanised areas and understand the impact of artificial structures on water pathways. These new observations should be used to improve the parameterisation of the water and energy budget of urbanised areas within regional scale models.

(c) *Improving the water balance of karstic and coastal aquifers*:

Monitoring and observation of karstic aquifers should be performed in order to better characterise the geometry of the hydrogeologically active (transmissive and capacitive) karstic network from the local scale (epikarst features) to the catchment scale, notably through deterministic speleogenesis modeling, as well as to better quantify evapotranspiration over these areas.

Based on the above observations, design of semi-deterministic or deterministic hydrodynamic models is required to include them in regional scale modeling platforms.

The structure and hydrodynamic properties of coastal aquifers should be better described and their behaviour modelled. This includes a quantification of the contribution of karstic sources and coastal aquifers to the Mediterranean. The 3D geometry of the aquifers, aquitards and aquicludes, and a better evaluation of the permeability and storativity of the aquitards should particularly be investigated through various types of monitoring, including the use of geochemical tools, and modeling.

(d) *Impact on the water balance of soil moisture redistribution by topography*:

The objective is to complement the experiments dedicated to floods with the monitoring of soil moisture and its spatial and temporal variability in order to document soil moisture redistribution. This implies to develop geological and geophysical soil and subsoil structural characterisations, long term high frequency monitoring of soil moisture, and shallow aquifers using piezometer, tensiometer, soil water content local measurements, complemented with geophysical monitoring, and also with discharge measurements at local, perennial or temporal, springs and outlets, and within the river network. Geochemical tracing is also to be used for providing information on water pathways and transfer mechanisms, highly complementary to the above described physical approaches. The flux and interaction with the river network must also be monitored in detail. The measurement of evapotranspiration should also be monitored in order to document how this process is related to soil moisture spatial patterns.

Simplified parameterisations of the major hillslope and small catchment processes to be used by regional scale models should be developed by using the knowledge acquired from the experiments and data analysis, and by addressing the upscaling of the local processes.

(e) *Snow processes*:

Characterise the effects of the high spatio-temporal variability of snow cover within mountainous semi-arid regions, or medium altitude watersheds, where the snow coverage is ephemeral and the snowline is extremely variable (Chaponnière *et al.*, 2006), which is a critical issue for adequate monitoring of snow dynamics (Sheffield *et al.*, 2003).

Improve snowmelt parameterisation to simulate shallow snow taking into account the interaction with the soil and vegetation, combined with other physical processes. This can be performed by refining the physical processes described in the model or by local calibration (*e.g.* Chaponnière, 2005, for the Atlas Mountains).

(f) *Anthropogenic influence (irrigation, groundwater pumping, water consumption,…)*:

It is needed to quantify anthropogenic water use and practices by gathering detailed data on water use on selected areas.

A methodology to collect the required information and estimate the water flows between water compartments induced by anthropogenic activity should be designed. The methodology developed should be consistent with the regional model resolution so that it can be applied extensively over the modelled domain.

Simple models of water use to be included into regional scale models should be developed.

3.2.4.3 How will the continental hydrological cycle evolve in relation to global change?

To answer this question the following specific needs have been identified:

(a) *Build a database of high resolution regional climate scenarios for the region, in order to run impact models.*

A special effort should be put on disaggregation approaches which are mandatory in order to downscale the outputs of the GCM predictions at fine scale. Another important issue is to achieve a realistic estimation of extreme event trends (rainfall, droughts) and the associated uncertainty.

(b) *Improve our knowledge on socio-economic feedback induced by global change*.

This also requires the building up of prospective socio-economic scenarios for which a key methodological challenge will lie in downscaling the socio-economic component of the SRES scenario (Arnell *et al.*, 2004) from a global to a very local level. Quantitative assumptions related to the main socio-economic drivers as well as the narrative storylines developed at the local level will have to be consistent with assumptions made at the global level. It will also require to improve the linking up of physical and socio-economic modeling tools.

(c) *Provide land-use change (and past reconstruction) scenarios consistent with the socio-economic scenarios* in order to evaluate the impact of land-use change on the hydrological cycle. Reconstruction of past land-use and of its evolution, especially in relation with urbanisation and the modifications of agricultural practices, would also be useful to assess the predictive capacity of models.

(d) *Improve impact models on both physical and socio-economic aspects.*

The models must properly simulate the physical feedback induced by climate change like the direct effect of CO2 on plants, change in sea level, change in land use,… The validation of these models on the present climate should also be focussed on aspects critical for the future (*e.g.* low flows, dry soils, aquifer recharge,…).

3.3 WG3: Heavy precipitation events, flash-floods and floods

Coordinators: G. Delrieu, A. Montanari, E. Richard, R. Romero

3.3.1 Introduction and motivation

Heavy precipitation events (HPE) and flash-floods (FF) are not uncommon phenomena over the Mediterranean region. The peculiar topography and geographical location of this area make it especially favourable to the occurrence of intense events. The Mediterranean Sea acts as a vast heat and moisture reservoir from which convective and baroclinic atmospheric systems pump a part of their energy. The steep orography surrounding the Mediterranean Sea favours the lifting of the low-level unstable air and initiation of condensation processes. Moreover, the morphology of the Mediterranean basin with numerous small and steep river catchments can turn the intense precipitation into severe devastating flash-floods and floods. These intense rainfall events result from complex interactions between the atmosphere, ocean and continental surfaces and may have severe impacts on marine and terrestrial Mediterranean ecosystems.

A clear link exists between the hydrologic response and the size of a watershed subject to a heavy rainfall event (Figure 3.4a). A relation also exists between the space-time scales of the generating rainfall events (storms, MCS, frontal systems,…) as defined by Orlanski (1975) and the hydrologic response characteristics. This fact supports the concept of scale resonance, *i.e.* a convective storm will be able to generate flash-floods for basins of some tenths of km² while a stationary MCS is required to produce flash-floods and floods over watersheds of 500-2000 km². Floods in larger settings are associated with frontal systems with much larger spatial extension and temporal duration. A classical measure of the magnitude of a flood is the maximum specific discharge, *i.e.* the peak discharge observed during the event scaled by the watershed area. A compilation of maximum specific discharge values found in the literature for extreme rain events all around the world is presented in Figure 3.4b, showing the clear dependence of the maximum specific discharge on the watershed area. Both figures illustrate the complexity of the characterization of HPEs and FFs since strong hydrologic responses are likely to occur at very small space-time scales: observation systems with high space-time resolution are therefore required over large domains.

3.3.2 State of the art

This section summarizes the HyMeX White Book published in 2008.

3.3.2.1 Heavy precipitation systems

3.3.2.1.1 Heavy precipitation climatology

Different categories of precipitating systems affect the Mediterranean areas, according to the season, region and mechanisms of formation. They include orographic precipitation, rainy frontal systems, mesoscale convective systems (MCSs) and isolated thunderstorms. This precipitating system spectrum is also enlarged by the diversity of cyclones encountered over the Mediterranean region: Atlantic cyclones, African cyclones, thermal lows, hurricane-like lows, Middle-East lows, orographic cyclones, etc.

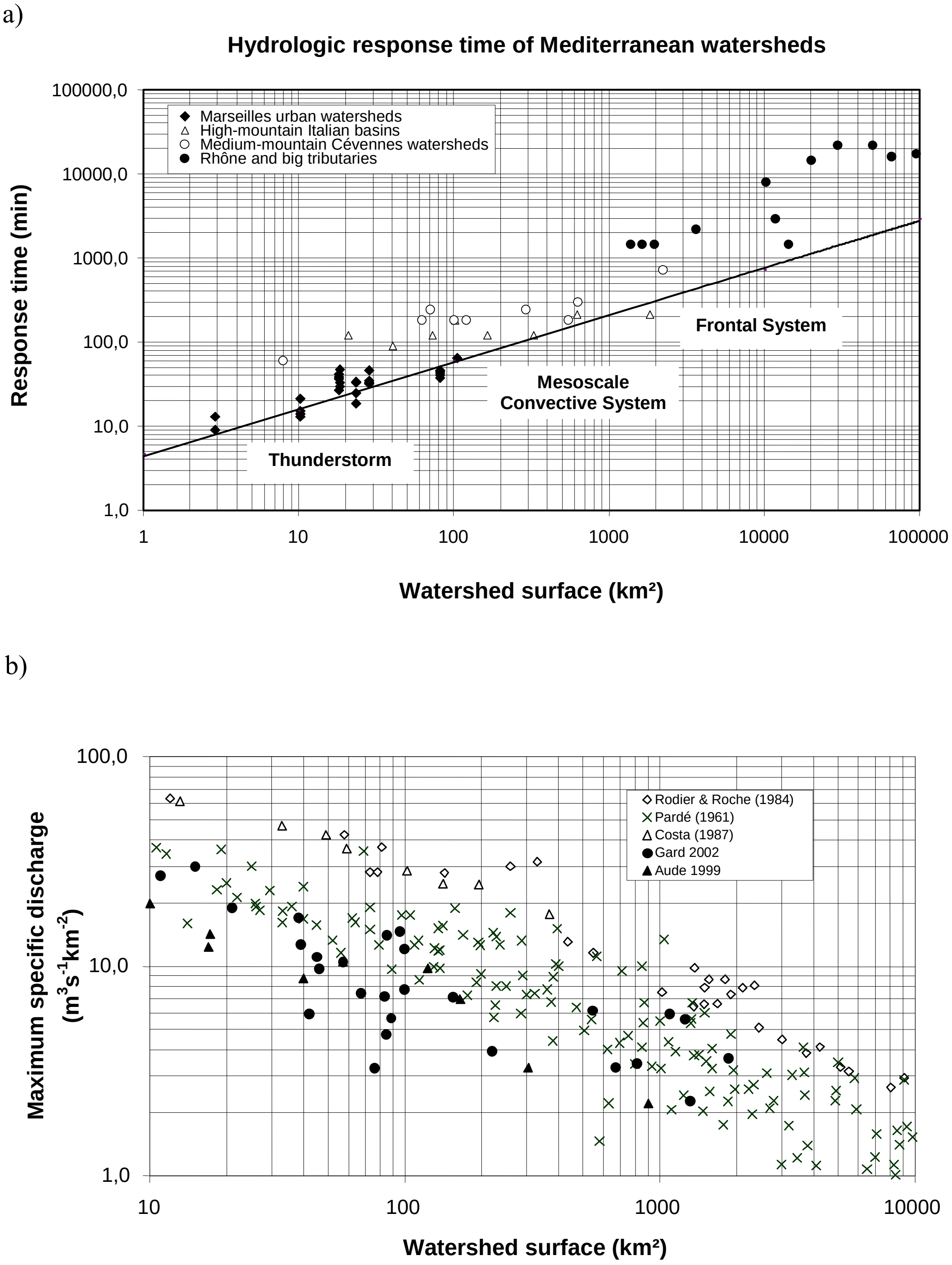

Figure 3.4. a) Response times of several urban and natural watersheds subject to high rainfall events in the Mediterranean region (compilation by G. Delrieu). The black line refers to the typical spatial extension and duration of the generating rain events, after Orlanski (1975). b) Maximum specific discharges as function of the watershed area for a number of extreme rain events reported in various regions of the world (compilation by E. Gaume). The black triangles and dots are relative to two events that occurred in the French Mediterranean region (Aude 12-13 November 1999; Gard 8-9 September 2002).

One characteristic of the Mediterranean precipitating systems is their inclination to produce heavy rain. Daily surface rainfall greater than 200 mm is not uncommon for Mediterranean precipitation events. Most of these intense precipitation events occur during the autumn season over the Western Mediterranean region while the peak of precipitation over the Eastern Mediterranean occurs between December and February.

Occurrence of HPEs is related to specific synoptic patterns. Based on automatic classification of the 500 hPa geopotential fields from ERA40, Nuissier *et al.* (2009) found that HPEs in the Gulf of Lion are found preferentially associated with a trough-ridge system, with low pressure over Spain and high pressure over Central Europe. The conditioning of heavy precipitation systems by weather regimes is a key characteristic that should help to design new strategies to understand and handle the predictability of these extreme events.

Large amount of precipitation can be accumulated over several day periods when a single or a succession of several frontal systems are slowed down and enhanced by the relief of the region. In other cases, the large rainfall amount can be recorded in only few hours when a MCS, sometimes in association with an extratropical cyclone, becomes stationary over an area during several hours (Riosalido, 1990; Rivrain, 1997). The amount of precipitation is related to the characteristics (intensity, duration, organization) of the precipitating systems and in particular to their motion. The quasi-stationary convective systems are powerful flash-flood producing precipitating systems. Frequently, these quasi-stationary MCSs are backward regenerative systems that take a V-shape in the infrared satellite imagery (Scofield, 1985) and in the radar reflectivity images. Backward regeneration is obtained by a continuous generation of new cells at the tip of the V, whereas the mature and old cells are transported towards the V branches (Rivrain, 1997; Benech *et al.*, 1993; Ducrocq *et al.*, 2003).

3.3.2.1.2 Factors leading to HPE

HPEs are multiscale atmospheric phenomena that result from a complex interaction of upper-level synoptic flow and local topography (Rudari *et al.*, 2004). The synoptic and mesoscale environmental ingredients leading to HPEs over mountainous regions are the same as those encountered for HPEs over other mountainous regions of the world (Doswell *et al.*, 1998; Lin *et al.*, 2001; Nuissier *et al.*, 2007):

- conditionally or potentially unstable air masses,
- moist low-level jets (LLJ) that impinge the first foothills,
- steep orography which helps to release the conditional instability associated with the low-level jet,
- a slowly evolving synoptic pattern that slows down the advance of heavy precipitation systems or maintains the environment favorable to heavy precipitation.

For some cases, upper-level precursors as upper-level Potential Vorticity (PV) streamers (Felhmann *et al.*, 2000; Massacand *et al.*, 1998; Homar and Stensrud, 2004) or a deep short trough can be found to approach the triggering area of convection. By reducing the static stability, intensifying low-level jets and upper-level divergence, these upper-level dynamical structures favour the upward motion and consequently convection. However, the orography as well as diabatic processes associated with convection can alter the streamer evolution (Morgenstern and Davies, 1999; Hoinka *et al.*, 2003), so that the relationship between fine scale structures of PV and heavy rainfall events remains to be clarified.

Upslope triggering is not the only process involved in the conditional instability release in this region. Romero *et al.* (2000) and Ricard (2002) have pointed out the role of the nearby mountain ridges in enhancing the low-level jet and/or inducing upwind low-level convergence. Indeed a number of convective systems form over the Mediterranean Sea before anchoring inland as examplified by the extreme rainy event that occurred in September 2002 in South-eastern France (Delrieu *et al.*, 2005). The shape and fine-scale structure of the mountain range also play a role in modulating the precipitation (Scheidereit and Schär, 2000; Cosma *et al.*, 2002; Ricard, 2005). In some cases, cold pool resulting from evaporation/ sublimation/melting of the falling precipitation may trigger new cells at its leading edge, far upstream of the mountain (Ducrocq *et al.*, 2008).

3.3.2.1.3 Moisture origin

The Mediterranean Sea constitutes an important local source of moisture which is transported by low-level flows towards the target region where heavy precipitation occurs (Rudari *et al.*, 2004). Besides the local sources, some recent studies have shown a possible influence of tropical-extratropical interaction on moisture advection. Reale *et al.* (2001) showed that several cases of severe floods over Western Mediterranean could be related to hurricanes. Turato *et al.* (2004) investigated the role of large-scale moisture sources on a major precipitating and flooding event that affected Piedmont. Using water vapor backward-trajectory, they found that a large amount of moisture originated from outside the Mediterranean region. According to Pinto *et al.* (2001), recurring tropical depressions can influence the formation of trough-ridge systems over the Atlantic and enhance moisture transport across the Atlantic into Southern Europe. Also, mid-level dry air masses are worth being documented and their interaction with convective systems better understood. Evapotranspiration over continental surfaces may also constitute a local source of moisture and has been previously found to have an impact on the development and evolution of convection over continental areas (Clark and Arrit, 1995; Pan *et al.*, 1996; Gallus and Segal, 2000).

3.3.2.1.4 Impact of the Mediterranean Sea on severe precipitation events

In the fall season, the Mediterranean Sea is generally warm after the long sunshine periods of the summer, whereas, upper cold air, transported from Northern Europe, begins to concern the area; both factors produce propitious conditions to HPEs occurrence (low static stability, large scale lifting and sustain of moisture). It is well known that a warmer (colder) SST increases (decreases) air-sea surface heat fluxes which in turn moisten (drain) and destabilize (stabilize) the marine atmospheric boundary layer. This results in an increase (decrease) of the available energy and moisture for atmospheric convection and thus precipitation. Lebeaupin *et al.* (2006) highlighted some dynamical important effects of the SST on the low-level jet and the motion speed of the precipitating systems. If a SST increase (decrease) induces systematically a CAPE increase (decrease), the link between the SST and the displacement speed of the precipitating system is not so univocal. In fact, a SST anomaly can induce different atmospheric responses which seem mainly associated with different types of precipitating systems.

As for tropical cyclones, the thermal heat content of the oceanic mixed layer (rather than the SST) could be the discriminating factor in explosive cyclogenesis or heavy precipitation events. The thermal heat content can be considered as an energy tank available for the atmosphere (CAPE) via the surface turbulent heat fluxes (sensible and latent). The spatial distribution of the energy sources seems to play a as important role as their intensities.

3.3.2.1.5 Role of aerosols

Increase in atmospheric input from various sources (Saharan dust; pyrogenic particles, in relation to increasing heat waves; anthropogenic particles, due to increasing demographic pressure) will act on atmospheric physics and marine biogeochemistry. Concerning atmospheric physics, and in particular precipitating systems, the question is how these higher concentrations of aerosols in the atmosphere will affect cloud formation. Marine aerosols may in particular play a significant role in terms of potential cloud condensation nuclei (CCN) and ice nuclei (IN). More generally, the types of CCN and IN encountered during heavy precipitation events have to be documented as well as their ability to induce more or less efficient rainfall-producing systems. High aerosol concentrations also act to reduce the incoming solar radiation and therefore may reduce the energy available to trigger atmospheric convection.

3.3.2.1.6 Modelling and predictability issues

Non-hydrostatic models employing grid-spacing of about several kilometers have shown substantial success in simulating realistic heavy precipitation systems (Stein *et al.*, 2000; Richard *et al.*, 2003; Asencio *et al.*, 2003, among others). Several national weather services use or plan to use such models in the near future in their operational suite. The success of high-resolution modelling however strongly depends on the initial conditions. Ducrocq *et al.* (2002) found that assimilating high resolution observations to produce detailed initial conditions results in more realistic simulations of HPEs (Chancibault *et al.*, 2006). Even though high-resolution models make a step forward in the simulation of convective systems by removing the need for a convective parameterisation, progress is still needed on how the model simulates the initiation phase (cumulus stage), the details of the microphysical processes within the precipitating systems, or the high-gradient interface at the periphery of the convective cells. High-resolution observations inside precipitation systems and within the boundary layer are currently missing for the validation and improvement of parameterisations of physical processes involved in HPEs (microphysical parameterisation, subgrid scale condensation and turbulence, etc).

Predictability limits result from the nonlinearity and instability of the dynamics of the atmosphere, together with the lack of a precise knowledge of the atmospheric state at any time and location. The atmospheric predictability depends on flow regime. Synoptic and large mesoscale systems possess more intrinsic predictability than cloud-scale convective systems (Tennekes, 1978). However, some factors can increase the predictability on the mesoscale, such as surface heating, synoptic-scale disturbance or topography forcing which are often present for Mediterranean HPEs. The management of the risk occurrence of a flash-flood event requires early warnings. Since the dynamical and physical processes associated with HPEs involve small-scale processes that have a low predictability on a long-term, a risk assessment should necessarily be calculated by indirect strategies combining weather regimes and ensemble prediction at various scales. Open questions concerning such a system would be how to design the ensemble prediction systems optimally for mid- and short-term forecasts.

3.3.2.2 Floods and flash-floods

Flash-floods represent the most destructive natural hazard in the Mediterranean region. These events are poorly understood due to the lack of experimental sites and long-term hydro-meteorological data with adequate space-time resolution (Gheith and Sultan, 2002; Foody *et al.*, 2004; Delrieu *et al.*, 2005).

3.3.2.2.1 Quantitative precipitation estimation (QPE)

QPE can be broadly decomposed in Quantitative Precipitation Forecasting (QPF) and Design Rainfall Estimation (DRE). The former is needed within integrated flood forecasting systems. Indeed, the short concentration time of many Mediterranean river basins often makes a flood forecast based on flood formation and propagation scarcely useful for practical implementation. The availability of QPF within an integrated system for flood forecasting allows one to increase the lead time of the flood forecast therefore increasing the possibility to set up effective countermeasures.

Rainfall monitoring at the regional scale is essential to provide accurate and localized information for flash-flood warnings, in particular to assess the hydrologic impact of the heavy rain events. Although rain gauges represent the reference sensors for measuring rainfall at ground level, their use for the spatial estimation of rainfall in mountainous regions poses a number of problems: (i) the network density needs to be adapted to the required time resolution (Berne *et al.*, 2004); (ii) there is often an altitude bias in terms of sampling since the maintenance of the rain gauge networks is more difficult at high altitudes; (iii) the respective contributions of liquid and solid precipitation is difficult to assess at high altitudes. The spatial resolution of existing rain gauge networks is generally not adequate for providing valuable spatial QPE. Compared to rain gauges, weather radar systems offer a number of advantages in the real-time monitoring context with spatial and temporal resolutions of typically 1 km^2 and 5 min, a large spatial coverage and an immediate availability. However, in mountainous regions, the radar measurement of rainfall is even more complex than in flat regions and the radar QPE quality varies strongly, depending on the location and notably the range to the radar site (Joss and Waldvogel, 1990; Pellarin *et al.*, 2002). During the last three decades, research efforts have been devoted to optimize the radar sitting and operating protocols, develop identification and correction algorithms for the various error sources and assess radar QPE with reference to rain gauge measurements (*e.g.*, Andrieu *et al.*, 1997; Delrieu *et al.*, 2009). During the same time, an important effort has been dedicated to develop weather radar networks in the Mediterranean region and improve the operational radar data processing algorithms (*e.g.*, Germann *et al.*, 2006; Tabary, 2007; Tabary *et al.*, 2007).

Due to the fast hydrologic dynamics of Mediterranean watersheds, quantitative precipitation forecasts (QPF) are critically needed for lead times ranging from several days (early warning) down to some tens of minutes (nowcasting). Regarding radar nowcasting techniques, those based on the "frozen-field" hypothesis are likely to be of limited interest to improve QPF in Mediterranean regions due the strong influence of the sea-land transition and of the relief on convection triggering. The development of Doppler and polarimetric capabilities for operational radar networks (*e.g.*, Bousquet *et al.*, 2007) combined with the assimilation of such "non-conventional" data by high-resolution atmospheric models is a more promising track.

DRE is needed in order to obtain design variables, that is, peak river flows, for river engineering works and flood protection measures. In fact, the estimation of such design variables is often carried out by using event scale rainfall-runoff models, for which a design rainfall (DRE) is needed as model input. DRE is usually based on the statistical analysis of historical data and an uncertainty is often introduced to take data scarcity into account. Relevant perspectives are today offered by advanced monitoring techniques, including satellite rainfall estimation, and data assimilation methods, including new techniques for the acquisition of historical data. DRE can be performed by using at-site analysis or regional studies. The former has a long history of application. Its reliability is strictly connected to the representativeness of the available historical data. It is often the case that only a few observations are available when one refers to short storm durations. In fact, there is a urgent need to gain more insights about the scaling properties of intense storms over the Mediterranean area. On the other hand, regional methods have the significant advantage of pooling together the hydrological information observed at regional scale, therefore increasing the reliability of the statistical analysis. However, in this case also the estimation is affected by a relevant uncertainty when there is no or only limited information about the storm properties at local scale.

3.3.2.2.2 Hydrologic response to HPE

There is no unique and simple theory about the runoff production on watersheds during flood events. The main reason is that a variety of processes can be involved which are usually grouped in two categories: saturation excess (Dunne process) or infiltration excess (Horton runoff). Due to the high heterogeneity and space variability of the watershed characteristics (land use, soil type and depth, subsoil, local slope, usptream contributing area) and to antecedent moisture conditioning, these processes are likely to be active at the same time in various combinations (Ambroise, 1999). In addition, the karstic terrains, that are widespread in the Mediterranean regions, lead to specific behavior with non-linearities, the response being strongly dependant on the initial conditions (status of the epikarst and, if any, of the saturated zone of the aquifer). At the catchment scale, watersheds for which Hortonian process is dominant are characterized by hydrologic responses rather directly related to the rainrate time series while the response of Dunnean watersheds is more determined by the cumulated rain amounts. Both processes may originate a quick response to the river stream. Fast transfer in the subsoil can also be observed however. This can be explained by the formation of temporary perched watertables and the existence of preferential flows within soil macropores that can be activated when thresholds of connectivity are exceeded. A characterization of the sub-soil and in particular of the bedrock topography may be important in this context (Freer *et al.*, 2002). The riparian aquifer is also a sensitive interface between the hillslopes, the river and the watertables with a complex behavior (threshold effects and non-linear responses). There is today an increasing attention to the use of isotopes to obtain a better understanding of the residence time of water within a catchment. This type of information is potentially useful to separate the event water from the pre-event one in a flood hydrograph.

The reliability of a hydrological analysis is strictly connected to performing an efficient calibration procedure, which requires the availability of extended hydrological information. Mediterranean rivers are characterized by very intermittent regimes which make their observation particularly difficult. The classical technique for discharge measurement is based on a water stage measurement in a river section not prone to backwater effects, coupled with a calibration of the stage-discharge relation. The so-called rating curve is established point by point for a series of stage-discharge values by means of flow velocity sampling over the river section. The establishment of the rating curve is therefore time-demanding, especially to sample the medium to high discharge range. During floods, the velocity probing methods (current meters, ADCP techniques,…) are basically impracticable for obvious reasons of safety of the operating staff and preservation of the probing equipment. The rating curves are therefore extrapolated for medium and high discharges by means of hydraulic formulas that require the subjective evaluation of river roughness. The presence along the river bed of river engineering works like check dams often offers the possibility of identifying cross sections with fixed geometry (control cross sections). In this case, reliable discharge estimation can be obtained by applying the hydraulics law regulating the outflow (weirs, sills, sluice gates, etc). However, whatever the measurement method used, recent research activity in hydrology has highlighted that river flow measurement obtained through rating curves is affected by a significant uncertainty (Di Baldassarre and Montanari, 2009). Therefore, there is the need for improving the measurement techniques on the one hand, and estimating the effects of uncertainty on hydrological studies on the other hand.

Other factors making the flooding river characterization difficult are linked to: (i) overflows in the major river beds, (ii) solid transport that modifies the water viscosity, (iii) turbulence, (iv) modification of the river beds, and (v) the often-observed destruction of the stage equipment during floods. A profound lack of knowledge results in terms of river discharge, particularly for high waters which are of special importance for the scientific question of interest.

The Mediterranean rivers react quickly, but the flow period is usually short, because of the generally reduced catchment size. Erosion and sediment transport processes are obviously active mostly during floods and may profoundly modify the river morphology and impact their ecosystems. The absence of base flow during the long dry period and the discontinuity of the flow (even during floods) are the main characteristics of these rivers. The hydrological regime does not allow the evacuation of the pollutant downstream and the river sediments constitute a reservoir of pollutants which could be potentially available during the flood events. The beginning of the flowing period must be considered as a critical period for the hydrological and hydrochemical behavior of the river. The peculiar hydrological behavior of these intermittent rivers has a significant impact on the direct pollutant inputs during low flow conditions but also on their remobilisation and transport to the downstream environment (coastal lagoons, coastal zones) during the flood events. These temporary rivers have not been sufficiently recognized until now, especially in terms of their impact on the quality of receiving waters, and of the distinctive dynamics which are introduced when severe flood events follow dry periods.

3.3.2.2.3 Modelling and predictability issues

The hydrological literature proposes many mathematical models for schematizing the rainfall-runoff transformation. Broadly speaking, such models can be grouped accordingly to three different classifications. On the one hand, it is possible to distinguish between spatially distributed and lumped models. On the other hand, one may distinguish between physically based, conceptual and black box models. Finally, a distinction is often made between continuous simulation versus event scale approaches. Model selection is usually driven by the purpose of the analysis and data availability.

Today, there is an increasing interest in hydrology for the development of regional models that can simulate the rainfall-runoff transformation over wide geographical areas. This purpose can be achieved by either increasing the spatial domain of an assigned model or developing a regional procedure for the estimation of the parameters of local models. The recent research activity in hydrology has been mainly focused on this latter solution.

Besides the development of regional hydrological modelling aimed at assessing the water budget (see WG2) of Mediterranean watersheds at the seasonal, inter-annual and decadal time-scales, there is undoubtedly a need for implementing flood-event hydrological modelling systems able to efficiently convolve rainfall and landscape space-time structures and perform warnings in a distributed way at the regional scale in the real-time context. Such models can also serve for estimating design variables.

In the Mediterranean region, lumped models were applied in order to simulate flood events or to calculate and regionalize peak-flows return period (Prudhomme, 1995; Neppel *et al.*, 2003; Arnaud and Lavabre, 2000; Perrin *et al.*, 2003). These models are parsimonious in terms of parameterisation and proved to be efficient provided that long rainfall-runoff time series are available for their calibration. However, they cannot predict hydrographs for each single point in space while the hydrological risk is diffuse by nature (*e.g.*, urban settings, roads and bridges, camp sites, etc). In addition, they cannot take the spatial variability of input data into account. Distributed hydrological models, including the original and adapted versions of TOPMODEL (Beven and Kirby, 1979), were successfully implemented in the Mediterranean region to simulate flood events for catchments of some tenths up to some hundreds of km^2 (*e.g.* Todini, 1996; Moussa *et al.*, 2002; Obled *et al.*, 1994; Saulnier *et al.*, 1997; Chahinian, 2004). Based on hydrological similarity, this modelling approach is efficient in terms of computation compared to fully distributed models (Beven, 2001). Both the quality of the rainfall estimation in time and space and the characterization of the initial moisture state of the watersheds were found to have a dramatic impact on the performance of such models (Hébrard, 2004; Hébrard *et al.*, 2006; Le Lay and Saulnier, 2007). New modelling approaches are currently initiated to better take into account heterogeneities (*e.g.*, land use, soil properties,…) in the space discretization and to build tailor-made models adapted to the available data and the dominant hydrological processes (*e.g.*, Dehotin and Braud, 2008).

Flood-event hydrological models include routing components (transfer functions) that allow a simplified representation of the hydraulic processes occurring in the rivers. More complete solutions are required when larger catchments are considered: the most popular approach to model flood routing has been one-dimensional solutions of the full De Saint-Venant equations (Fread, 1993; Moussa and Bocquillon, 1996). In order to overcome the limitations of the one-dimensional model in the simulation of overflows in the inundation zones, the 1D/2D combination model LISFLOOD (Bates and De Roo, 2000), 1D models with inundation cells (*e.g.*, CARIMA - Belleudy *et al.*, 1986; STREAM - http://www.egis-bceom.com) and the two-dimensional finite difference and finite element models such as TELEMAC (Galland *et al.*, 1991) were developed.

Spatially-distributed data are needed for their implementation (rainfall, snow cover, soil hydrodynamic properties, land use, vegetation cover and geometric properties of the channel network). Rigorous parameterisation, calibration and validation procedures are also required (Chahinian, 2004; Moretti and Montanari, 2007).

3.3.2.3 Impact of climate change on HPE and FF

Extreme climate events receive increased attention. The main focus is to identify if extreme heavy precipitation events and subsequent floods are increasing or not in frequency.

3.3.2.3.1 Extreme rainfall and discharge: characterization and trends

A considerable amount of quantitative and qualitative information is available on extreme rainfall, flash-flood and flood events that occurred in the past. This includes the “systematic” observations of the last 50 years, the observations that can be reconstructed more locally from historical data sources and paleo-hydrological observations.

Rain gauge data from networks operated during the last 50 years allowed the production of maps of extreme rainfall parameters, *e.g.* point rainfall with decennial or centennial return periods for various integration time steps (*e.g.*, Bois *et al.*, 1995; Frei and Schär, 1998; Kieffer *et al.*, 2001). Using a set of 20 long French rainfall series with at least 100 years of record, Muller (2006) discussed the choice of the statistical distributions (Gumbel, GEV). Flood frequency analysis of extreme discharges in France is generally based on hydrometeorological approaches, such as the Gradex (Guillot and Duband, 1967), the Agregee (Margoum *et al.,* 1994) and the Shypre methods (Arnaud and Lavabre, 2002). Regional approaches aggregate flood records from a homogeneous hydrological area at a regional scale (*e.g.*, the index flood method; Dalrymple, 1960). A multi-disciplinary work associating historians, hydraulicians and hydrologists was conducted during the SPHERE project (Benito *et al.*, 2004) to explore historical archives up to the 16th century for detecting past events and the water levels reached for specific hydraulic sections. Hydraulic models are then used to estimate the corresponding maximum discharges. Finally, statistical analyses are performed over such heterogeneous time series to refine the discharge frequency curves. An interesting example of this approach is provided by Naulet *et al.* (2005) for the Ardèche river at Sauze Saint Martin. Regarding paleo-hydrology, Sheffer *et al.* (2003) studied flood deposits in a number of caves for the Ardèche river. More generally, since catastrophic flood events bring tremendous amounts of sediments to the karstic systems, deltas and lagoons, the study of sediment records from these media should help obtaining the long records necessary to study the evolution of such events. Precise description of the sediment archive, based on measurements of its physical properties, allows determination of the nature and the origin of the sediment, a critical piece of information for the identification of the climatic extremes. In addition, geo- and bio-indicators can be used to reconstruct past climatic conditions (temperature, precipitation,…). These sedimentological analyses, complemented by analyses of the malacofauna have already given promising results for the reconstructions of extreme events in the Mediterranean region (Dezileau *et al*., 2005; Sabatier *et al*., 2007).

The detection of trends within flood and drought regimes has been examined on a set of 200 long discharge series in France. Renard (2006) showed that no consistent trend can be detected at a local scale, but a new regional methodology allowed detection of significant changes in the Alps and Pyrenees area and the North-East of France. At the current time, no significant trend has been found in the Mediterranean area, but increasing of temperature is expected to major rainfall and flood risk. One should also consider the relevant uncertainty that affects trend analysis of hydroclimatic time series (Koutsoyiannis and Montanari, WRR, 2007).

3.3.2.3.2 Projections of HPE and FF in climate scenarios

The results of climate models tend to indicate an increase in the relative variability of seasonal and annual precipitation as well as an increase of the frequency of heavy precipitation events with global warming. Gao *et al.* (2006) found both shift and broadening of the precipitation distribution, suggesting an increased probability of occurrence of events conducive to both floods and droughts. Confidence on these results must however be considered with respect to the current limitations of the climate models in reproducing the observed patterns of variability and especially in simulating precipitation at regional scales so that it is still beyond our reach to conclude to an increase or decrease of extreme precipitation events due to global warming for the Mediterranean regions.

3.3.3 Key issues and scientific questions

One key issue regarding heavy precipitation and flash-flooding is to progress in the identification of the processes and on how they interact or combine to make a precipitation event an intense one, both in terms of precipitation and flooding. Such knowledge is needed to progress in the predictability of intense events, in particular by improving the modelling of processes, data assimilation and ensemble hydrometeorological forecasting chains.

One other key issue is to reduce the still large uncertainties on the future evolution predicted by climate change scenario regarding intense hydrometeorological events both in terms of frequency and intensity.

***Key Scientific Questions*:**

- ***WG3-SQ1:* What are the characteristics of extreme hydro-meteorological events in the Mediterranean?**

It is necessary to improve the characterisation of intense hydrometeorological events in terms of (i) **nature of flooding-induced precipitating systems** and related large scale **meteorological environment,** and (ii) **inter-annual variability and trends** of precipitation and flooding.

- ***WG3-SQ2:* How can we improve heavy rainfall process knowledge and prediction?**

  It is necessary to investigate the role of **synoptic-scale and upper level dynamics**, as well as the **low-level environment at the mesoscale**, leading to HPEs by making use of fine scale data through **mesoscale reanalyses** and **high-resolution numerical simulations**. Understanding the role of the **complex orography** of the region and identifying mechanisms leading to **stationary convective systems** and high-accumulated surface rainfall are of critical importance.

- ***WG3-SQ3:* How can we improve hydrological process knowledge and prediction?**

  We need to better understand and model **how the large heterogeneity of the continental surfaces** (in terms of geology, geomorphology, vegetation, land use and anthropogenic structures) **controls the hydrologic and hydraulic response** to heavy precipitation events **over a range of scales** (local to regional). Physically-based **distributed hydrological models** need in particular to be further developed, implemented and assessed with respect to spatially and temporally enhanced measurements of the various terms of the water cycle. **Coupling meteorological and hydrological models** is another challenging issue.

- ***WG3-SQ4:* How will extreme hydrometeorological events evolve under future climate conditions during the 21st century?**

  Statistical and dynamical downscaling methods need to be developed, in order to combine **observed trends on rainfall and flood extremes** with the evolution predicted by **climate models**. To further increase confidence in those model results for the rainfall over the Western Mediterranean regions, the development of precursor-based approach based on **weather regimes** should be encouraged.

3.3.4 Observation and modelling requirements

3.3.4.1 What are the characteristics of extreme hydro-meteorological events in the Mediterranean?

(a) *Rainfall re-analyses*: Efforts to elaborate long-term rainfall space-time series from radar and rain gauge data should be undertaken. Rain gauge networks with acceptable densities exist since the 60s in some parts of the Mediterranean region. Radar QPE at the regional scale starts to be feasible since the end of the 90s. Rainfall estimation overseas is an important objective. Refined merging techniques accounting for the physical and sampling properties of the sensors and the space-time structure of rainfall still need to be developed.

(b) *Relationship between weather regimes/cyclogeneses and HPEs*: Identify weather regimes prone to HPEs by extending classification methods to other more characteristic fields of Mediterranean weather events and using mesoscale rainfall analyses to identify HPEs; Use long term meteorological reanalyses (ERA40, NCEP/NCAR) and satellite data to document the link between cyclogeneses and HPEs;

(c) *Nature, organisation and life cycle of precipitating systems*: Determine the proportion of HPEs that can be attributed to quasi-stationary MCSs, slow moving frontal rainy systems, or combination of different precipitating systems by documenting the lifecycle (initiation, mature and dissipation stages) and internal dynamics of precipitating systems. Document the inter-annual and seasonal variability of the various types of precipitating systems with regard to those of large-scale meteorological conditions and sea surface temperature. Characterize the intermittency and space-time structure of Mediterranean rain fields for various rain types (useful for implementing downscaling procedures, developing stochastic rainfall models and better understand the flood genesis as the convolution of rain and geomorphological factors).

(d) *Extreme rainfall assessment*: The compilation of rain gauge data from the networks available during the systematic observation period is in progress for various Mediterranean regions (*e.g.*, the Cévennes and Languedoc-Roussillon regions in France; Sardinia region in Italy). The availability of automatic techniques for the digitalisation of old rainfall paper records will allow to re-assess extreme rainfall parameters and their spatial dependence and variability. Such information will be linked with geomorphological factors, rain physical processes and vulnerability considerations.

(e) *Intercomparison of extreme rainfall and flood distribution assessment*: Various approaches can be compared: standard application of extreme value distribution on systematic records, rainfall-runoff approaches, and regional approaches. The long historical discharge series available in the Mediterranean area will be used as a reference.

(f) *Paleo-hydrometeorology*: A strategy has to be defined for collecting and analysing sediment records in a number of Mediterranean media (karstic systems, deltas, lagoons,…) to elaborate information on extreme events and the climatic variability for a long duration (last millennium, at least). Such paleo series and proxies should be put in relation with historical records, when available.

3.3.4.2 How can we improve heavy rainfall process knowledge and prediction?

(a) *Better understanding the role of upper-level dynamics on HPEs*: Investigate the role of synoptic-scale and upper level dynamics on the triggering of HPEs, by better documenting PV streamers and their fine scale structures, and studying their interaction with orography and condensation processes.

(b) *Characterization of the low-level mesoscale environment*: Improve the knowledge of mesoscale features such as LLJ (intensity, orientation, moisture transport,…) and other key ingredients (CAPE, Precipitable Water,…) related to HPEs by making use of fine scale data through mesoscale reanalyses and high-resolution numerical simulations.

(c) *Understanding the role of the complex orography of the region*: Analyse the individual role of the mountain ridges under different flow regimes, but also those resulting from their combination (including small and low-mountains).

(d) *Identifying mechanisms leading to high-accumulated surface rainfall*: Further investigate the mechanisms leading to stationarity of the MCSs, in particular study the interaction between cold pool dynamics, incident low-level flow, and relief. Investigate the interactions between the large-scale upper-level dynamics and the low-level mesoscale circulation. Identify dominant microphysical processes and environmental factors that lead to highly efficient precipitating systems.

(e) *Moisture monitoring*: Explore new capabilities of instruments and promote mesoscale assimilation of their data together with satellite observations to provide 3D mesoscale moisture fields.

(f) *Identification of water vapour origin*: Determine the part of local source for moisture and heat (Mediterranean Sea) and that of remote influences (tropical-extratropical interaction) by performing water vapour budget and backward trajectory analyses. Study the impact of soil moisture on the life cycle of precipitating systems.

(g) *Role of mid-level dry air masses*: Identify origin of mid-level dry air masses and investigate their interaction with the dynamics of convective systems.

(h) *Impact of the sea surface temperature and thermal heat content on strong atmospheric events (HPE and cyclogeneses)*: Develop coupling between mesoscale atmospheric and oceanic layer models to study the impact of thermal heat content (and SST) during the different phases of the life cycle of strong atmospheric events. Acquire the observations needed for validation of the coupled models. Determine the spatial scales and amplitude of THC/SST anomalies that influence the atmospheric events.

(i) *Validation of surface fluxes parameterisations*: Acquire the observations needed for validation of surface fluxes parameterisations suitable for conditions encountered during the Mediterranean heavy precipitation and intense marine low-level winds that often prevail during HPEs.

(j) *Role of aerosols as cloud condensation nuclei*: Document the types of aerosols encountered during HPEs (marine, industrial and urban, dusts, erosion aerosols,...). Study the aerosol indirect effect in contributing to increase/decrease precipitation production. Are the marine aerosols injected in the boundary layer able to modify significantly cloud development, through their possible role as cloud or ice condensation nuclei?

(k) *Radiative effect of aerosols*: Better quantify the aerosol impact on the sea surface temperature (SST) in reducing the incoming solar radiation. Can the aerosol direct effect contribute to inhibiting convection by reducing the surface latent/heat fluxes?

(l) *Mesoscale data assimilation within cloudy and precipitating systems*: Progress in the assimilation of non-conventional data (cloudy radiances, radar, lidar, etc.). Assess the benefit of rapid update high-resolution data assimilation cycle.

(m) *Improving physical parameterisations of mesoscale models*: Perform sensitivity tests on different parameterisations of microphysical schemes and turbulence.

(n) *Predictability of HPEs*: Design and assess ensemble prediction systems for mid-term and short-term that will help to refine the prediction of the position, evolution and the rainfall amount of the HPEs. Characterize the predictability of HPEs by investigating the characteristics of initial conditions errors and of uncertainties in model physics on perturbation growth. Develop advanced methods for the estimation of depth-duration-frequency curves for rainfall, in order to improve the estimation of design rainfall.

3.3.4.3 How can we improve hydrological prediction?

(a) *Quantitative precipitation estimates (QPE) and predictions (QPF) with high spatial and temporal resolution at the regional scale*: This need covers both the rainfall re-analyses previously mentioned (WG3-SQ2) and the real-time rainfall estimation. QPE error models need to be established to assess uncertainties on spatial rainfall estimates. It should be recognized that such uncertainties are radar range, relief, intensity, integration

time step and rain-type dependent. Due to the fast hydrologic dynamics of Mediterranean watersheds, QPF are critically needed for lead times ranging from several days (early warning) down to some tens of minutes (nowcasting).

(b) *Evaluation procedures for QPE and QPF*: Reference QPE provided by high-quality rain gauge networks with adequate densities are required over large parts of the regions of interest (hydrometeorological observatories) to assess the quality of QPE and QPF derived from observations and numerical models.

(c) *Hydrologic experiments at the hillslope scale*: Field experiments are needed to further understand hydrologic processes at very small scales from the hillslope down to the riparian aquifer and to the river. The newly available hydrogeophysical probing techniques (Robinson *et al.*, 2006) should be used together with more classical hydrologic instrumentation for a non-destructive characterisation of the subsoil and the water fluxes.

(d) *Develop models of the water fluxes within the soil and subsoil and their interactions with the surface water network (common with WG2)*: Develop and validate coupled models representing soil water transfer and storage at the surface, within soils, subsoil and the interactions with the river network. The modelling of ephemeral networks and springs, flux and storage at the interfaces, etc. which can significantly modify the dynamics of water transfer, is also a challenge. Inclusion of hydrological discontinuities such as ditches or roads must also be achieved. Special attention must be paid to the efficiency of the numerical solutions, in order to be able to use the models from the hillslope to the small catchment scale (up to a few km^2) and also for short time scales. Coupling with SVATs must be performed to model the whole hydrological cycle.

(e) *Characterisation of soil properties at the scale of the modelling units*: Soil characteristics are difficult to obtain although some effort has been dedicated towards the constitution of soil data bases and landscape classification. Research is still needed to be able to derive quantitative information about soil hydraulic properties which are crucial for water transfer within soils and to develop pedo-transfer functions adapted to the Mediterranean region.

(f) *Use of remote sensing data and GIS layers to represent the heterogeneity of the surface, derive water pathways (common with WG2)*: Describe the sub-grid scale variability of elements which are not resolved explicitly (*e.g.*, anthropogenic networks such as ditches, ephemeral river networks, roads, etc.), and define modelling units. Appropriate methods must be proposed in order to represent such heterogeneity of the surface. Techniques such as multi-objective calibration or adjoint modelling, Kalman filtering can be used to assimilate remote sensing data (about vegetation characteristics, surface soil moisture, etc.) to constrain or to initialise the models.

(g) *Linking the hydrologic response and the landscape characteristics (common with WG2)*: Such experiments should be performed for various types of landscapes. High-resolution products concerning topography, geology, soil, land use, vegetation cover need to be considered to link the hydrologic response to the landscape characteristics and hence allow extrapolations/parameterisations for ungauged basins. Compiling data on past FFs and performing intensive post-flood campaigns for the extreme events to occur in the Mediterranean region with a unified methodology is a complementary way for increasing such knowledge.

(h) *Development of parameterisation, calibration and validation strategies (common with WG2)*: Acquire the complementary observations needed for a multi-site, multi-scale

(plot scale, hillslope, small and large basins), and multi-tools (physical parameters, tracers, etc.) approach. Specific parameterisation strategies must be developed in order to avoid over-parameterisation and "equi-finality" problems. Error propagation analysis must be conducted (error on input variables and parameters).

(i) *Remote sensing techniques for flooding-river characterisation*: Due to the lack of knowledge concerning high-flood discharges, the development of remote sensing techniques for discharge measurement of flooding rivers should be encouraged. Performing velocity measurements is especially critical: large scale PIV techniques based on video imagery (Creutin *et al.*, 2003) or radar techniques need to be developed and implemented for estimating surface velocities. Bathymetry of the changing river beds is also a concern. Light and mobile hydrometry equipment should also be assembled for opportunistic discharge rough estimates during floods.

(j) *Distributed hydrometry*: The capability to measure discharges in many places is certainly a very important subject to constrain distributed hydrologic and hydraulic modelling at the regional scale. In a first step, one can imagine to implement new remote sensing systems over already operational control points in order to assess the new techniques with direct flow measurements for low to medium floods and increase the existing rating curves robustness for high floods. In a second step, distributed hydrometry plans should be established to drastically increase the number of control points over selected watersheds for an in-depth spatial characterisation of their response.

(k) *Karst and flooding river interactions*: The karstic parts of a watershed may strongly modulate the river regime during floods through fast or delayed transfer of the rainfall to the stream, localised losses and intermittent or perennial springs, and non linear behaviours. It is thus very important to integrate this knowledge to the classical hydrological analyses/studies in order to better understand the processes involved in the concerned watershed.

(l) *Initial soil moisture characterisation*: A critical point for the flood-event models is related to the determination of the initial moisture state of the watersheds. Research needs to be realized to assess the ability of regional water-budget models to provide such an initial state.

(m) *Use of real-time quantitative precipitation forecasts (QPF)*: Due to the fast response times of the Mediterranean catchments, the use of QPF is compulsory to extend the forecasting lead times further than the watershed response times. QPF provided by numerical models and nowcasting techniques may take diverse forms and generally need to be disaggregated in space and/or in time prior to be used as forcing variables. A number of research and practical questions arise from this necessary adaptation.

(n) *Use of proxi data*: The hydrogeomorphological approach (Garry *et al.*, 1996) is based on an analysis of the 1:25,000 topographic maps, aerial stereophotographs and ground reconnaissance by a geomorphologist, enabling one to distinguish the various units in the flow channel of the river: the low-flow channel corresponds to the usual section of discharge, the mean water channel forms a transition between the low-flow channel and the high-water channel. This latter zone is active during major floods, and corresponds to the flood plain. The limits of this last unit give an idea of the maximum extent of the area of flooding.

(o) *Use of physically-based and spatially-distributed rainfall-runoff models at regional scale*: The availability of computing powers allows today to extend the application of spatially-distributed, physically-based rainfall-runoff models at wide spatial scales. In

fact, the hydrological literature has proposed many solutions for applying such models for simulating the surface and sub-surface water cycle at local scale. In the recent past advanced modelling solutions were devised in order to limit the calibration requirements of physically-based models, therefore opening new research perspectives. In the near future, the application of regional rainfall-runoff models, capable of simulating the river flow along complex river networks, might allow to increase the efficiency and robustness of integrated flood forecasting systems.

3.3.4.4 How will extreme hydrometeorological events evolve under future climate conditions during the 21st century?

(a) *Heavy precipitation and flood frequency analysis in a non stationary context*: Statistical models need to be developed, in order to combine observed trends on rainfall and flood extremes and the predicted evolution by climate models, using co-variables. A specific work is expected to model the dependence of extreme values, and to infer the spatial extent of such catastrophic events.

(b) *Climate change impact on frequency and intensity of heavy precipitation and flash-flood extreme*: To further increase confidence in climate model results for the rainfall over the Western Mediterranean regions, through the use of regional climate models, the development of precursor-based approach based on weather regimes as the one developed within IMFREX for the Atlantic region should be encouraged. Such approach is currently investigated for Western Mediterranean heavy precipitation within the CYPRIM project.

3.4 WG4: Intense sea-atmosphere interactions

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3.4.1 Introduction and motivation

The Mediterranean Sea is characterized by several key spots of intense sea-air exchanges associated with very strong winds which are caused by deep cyclogenesis, combination of high and low pressure systems or by the orographic response to the large scale forcing (*e.g.* Mistral, Bora, Jugo, Sirocco, Etesian, Genoa cyclogenesis). These intense sea-air interactions and the associated sea surface cooling affect considerably the heat and water budgets of the Mediterranean Sea through the formation of dense or deep winter oceanic convection in coastal or offshore areas. Modifications of the oceanic mixed layer characteristics within the oceanic convection regions in their turn influence the lower part of the atmosphere. Hydrological and dynamical characteristics and inter-annual variability of the oceanic convection, as well as the strong wind systems, need to be better documented in order to stress the respective roles of the atmospheric forcing and oceanic processes, together with their interactions, and to advance in the modelling of these processes. These processes are modulated by the inputs of continental rivers and aquifers, oceanic dynamics (boundary currents, submesoscale, cascading) and feedback of aerosols and biomass. Transport and distribution of particulate and dissolved elements are strongly related to this complex dynamic, which need to be better understood.

The state of the art given in the HyMeX White Book is summarised in section 3.4.2. The main scientific questions and objectives are proposed in section 3.4.3. Finally, specific research needs and the general observation and modeling strategy needed to address the scientific questions are detailed in section 3.4.4.

3.4.2 State of the art

3.4.2.1 Strong winds over the Mediterranean Sea

Regional strong winds are frequently observed to extend as far as a few hundred kilometers from the coast (Jansa, 1987), and during winter they bring cold and dry continental air over the warm western Mediterranean basin, generating intense air-sea heat exchanges (Flamant, 2003) and sea surface cooling (Schott *et al.*, 1996) during short time. Such wind gusts can trigger the formation of ocean deep convection. These regional winds are the Mistral and Tramontana (*e.g.* Georgelin and Richard, 1996; Drobinski *et al.*, 2001, 2005; Guénard *et al.*, 2005, 2006), Cierzo (Masson and Bougeault, 1996), Ponent, Levanter, Sirocco, Etesian (Kotroni *et al.*, 2001), Bora (Smith, 1987; Grubišić, 2004), Jugo (Jurcec *et al.*, 1996), Shamsin, Sharav and others (see Reiter, 1975 for a general description).

The high frequency, recurrence and physical identity of the Mediterranean local winds suggest a close link of these winds to geographical factors. When the large-scale or synoptic-scale flow interacts favorably with the orography, a primary pressure perturbation, the lee depression, and/or the associated windward high-pressure is induced. The orographic perturbation breaks the geostrophic balance that prevails at synoptic-scale and can create local areas of strong gradient which provide the acceleration that lead to the intense local winds. Beyond the narrow accelerating zone, the winds continue blowing and spreading in an inertial way which permits to find intense local winds even far from the orographic region of origin (Campins *et al.*, 1995).

Despite the fairly known basic ingredients giving birth to these regional strong winds, there is a need to better understand and predict the time and spatial variability of the strong local winds in order to better quantify the air-sea exchanges. The frequent occurrence of these wind storms in the Mediterranean region is primarily due to the high frequency of apparition of lee-warm-primary-depressions and low-level-PV-positive-banners, both being the consequence of the particular geography of the Mediterranean region. There is a need to evaluate the respective roles of the large-scale circulation, atmosphere stratification, and topographical elements in the intensification of the winds and cyclogenesis, and to quantify the water vapor and heat transport associated with them.

Intense air-sea exchanges are also produced by strong winds associated by Mediterranean cyclogenesis. Latent heat release is usually a mechanism to sustain and intensify most of the cyclogenetic processes. The effect seems to be quite important in the eastern Mediterranean region (Alpert and Ziv, 1989; Lagouvardos *et al.*, 2007). Nevertheless it is only a secondary effect in the case of the most important orographic cyclogeneses, both Alpine (Dell'Osso and Radinovic, 1984; Stein and Alpert, 1993; Alpert *et al.*, 1995) and non-Alpine (Garcia-Moya *et al.*, 1989). It should be noted that the succession of such events during fall and winter certainly contributes in some way, not fully understood though, to the pre-conditioning of ocean water for ocean convection triggering.

3.4.2.2 The fast response of the Mediterranean Sea

3.4.2.2.1 Surface processes

The hydrological properties of the oceanic mixed layer mainly evolve at the seasonal scale in response to the annual cycle of the heat and water budget. However the strong wind storms occurring from autumn to late winter can be responsible for first, rapid destratification of the strongly stratified mixed layer formed in summer, followed by ocean convection at some specific spots of the open sea and dense water formation near the coast.

Due to the strong wind storms, the sea-surface sensible and latent heat fluxes change very quickly, thus. However, the response of the Mediterranean Sea is not well known since typical time and spatial scales of the dynamical processes differ between the atmosphere and the ocean.

As a consequence there is a large uncertainty on the spatial coverage, the occurrence and the duration of intense air-sea exchanges at very fine spatial and time scales. In particular large uncertainties remain during deep oceanic convection events (Schott and Leaman, 1991; THETIS group, 1994; Schott *et al.*, 1996; Mertens and Schott, 1998; Robinson *et al.*, 1991; Artegiani *et al.*, 1997; Manca *et al.*, 2006) in each major region. During these events, oceanic plumes, sub-mesoscale/mesoscale eddies and baroclinic instabilities actively contribute to vertical mixing. Moreover, coastal waters can be mixed with matter and sink down to the seabed, either following the slope or trapped into canyons during some extreme events that occur at interannual scale.

There is a need to monitor the hydrological properties of the oceanic mixed layer, of the thermocline depth, of the air-sea surface buoyancy, and water (E-P) fluxes at fine temporal and spatial scales over a long period of time in order to better document the different scales of variability, the correlation of the oceanic processes with the atmospheric forcing (heat and water advection with winds) and the possible lag between the atmospheric forcing and the oceanic response.

3.4.2.2.2 Modulation of air-sea fluxes and DWF by the ocean dynamics

The time-evolution of surface temperature and salinity as well as mixed layer depth and associated thermal heat content cannot be regarded as the result of 1D processes simply induced by the buoyancy loss. During convection and between successive convective events, oceanic dynamical features such as eddies, submesoscale coherent vortices (SCVs), filaments, boundary currents - which inhibit or enhance part of the atmospheric contribution to oceanic convection - are at best partly understood (Madec *et al.*, 1996; Marshall and Schott, 1999; Lascaratos and Nittis, 1998; Wu *et al.*, 2000; Mantziafou and Lascaratos, 2004; Testor and Gascard, 2005). These oceanic (sub) mesoscale features and currents can cause mixing inhibition by re-stratification due to isopycnal/horizontal mixing or can increase vertical mixing by exporting upper mixed waters downward and uplifting intermediate/deep waters (with different T,S) to the surface, affecting in turn the air-sea exchanges.

3.4.2.3 The slow branch of the Mediterranean water cycle

Strong wind induced cooling and evaporation allow vertical mixing to occur down to intermediate and great depths. This ventilates the intermediate and deep layers of the Mediterranean Sea and noteworthy, brings deeper waters in contact with the atmosphere again. Four major sites of deep offshore winter convection have been identified: The Gulf of Lion (and sometimes the Ligurian Sea) in the western Mediterranean basin, and, in the eastern Mediterranean basin, the Adriatic, Aegean and Levantine sub-basins. Dense water is also formed in shallow sites submitted to strong winds and protected of high freshwater discharge. These water masses cascade downslope as gravity currents. The presence of canyons channeling dense water is favorable to a rapid transfer to great depths as in the Gulf of Lion (Canals *et al.*, 2006) or the Catalan margin (Ulses *et al.*, 2008) or in the Adriatic (Vilibic *et al.*, 2004). Other coastal sites of dense water formation have been identified as in the northern Aegean (Estournel *et al.*, 2005). A potential additional (though limited) point could be located between Corsica and Sardinia.

After the winter convection, the oceanic re-stratification occurs and several water masses spread into the Mediterranean Sea, contributing to the thermohaline circulation. The transport of dense waters away from the region where they formed is mainly achieved by boundary currents (Herrmann *et al.*, 2008). If the main pathways of the intermediate and deep waters are generally well described in the Western basin, they are still mainly hypothetical in the Eastern basin (Millot and Taupier-Letage, 2005a). Transport of deeper waters can also be achieved through not yet well understood interactions with (sub) mesoscale oceanic eddies or SCVs (*e.g.* Testor and Gascard, 2003; Millot and Taupier-Letage, 2005b; Demirov and Pinardi, 2007). Transport of deeper waters can also be modified when water with a maximum density is created: as this denser water fills the deepest layer, it uplifts the formerly densest water (as for the EMT, see *e.g.* Klein *et al.*, 1999; Astraldi *et al.*, 2002; Manca *et al.*, 2006). This new shallower depth may then allow the water to exit through sills. Finally, the deeper waters will be involved in winter deep convection events several years after their formation in another sub-basin as for instance in the case of the Levantine Intermediate Water, a component of the WMDW.

The density and volume of coastal dense water formed in winter is highly variable from one year to another. These waters can form intermediate waters but have also been found after especially cold winters near the seafloor of the deep basin, below the newly dense water formed by offshore convection (Canals *et al.*, 2006).

3.4.2.4 Air-sea feedback

3.4.2.4.1 Atmospheric and oceanic circulations

The sea-surface sensible and latent heat fluxes change very quickly during wind storm and may modulate the intensity of the lee-side surface cyclone and the wind storm (*e.g.* Genoa cyclone for the Mistral wind) as well as the thermal properties of the upper oceanic layer. It is known that a warmer (colder) SST increases (decreases) air-sea surface heat flux exchanges which in turn moisten (drain) and destabilize (stabilize) the marine atmospheric boundary layer. Lebeaupin *et al.* (2006) highlighted some dynamical important effects of the SST on the low-level jet and the displacement speed of the mesoscale convective systems. Giordani *et al.* (2001) have shown that the differential surface heating/moistening and thus the spatial variability of surface fluxes can be a significant source of ageostrophy, vertical velocity, and vorticity for the atmosphere that plays a fundamental role in the cyclone development. The Thermal Heat Content (THC) can thus be considered as an energy tank available for the atmosphere via the surface turbulent heat fluxes (sensible and latent). For example, the interaction of a significant THC and a polar low expelled over the Mediterranean Sea can induce tropical-like cyclogenesis. Nevertheless, some more advanced studies have also shown that the THC spatial distribution and specially the THC gradient play an as important role in explosive cyclogenesis or tropical cyclones as the single THC (Goni and Trinanes, 2003). The impact of air-sea feedback on the wind storm dynamics and cyclogenesis, as well as on oceanic circulation due to the possible modulation of the buoyancy fluxes is unknown and has never been addressed in this context.

3.4.2.4.2 Role of marine aerosols on air-sea fluxes

Marine aerosols are mechanically produced by the interaction between wind and waves. When the wind speed increases, the energy of the wind becomes too large to be absorbed by the waves which break to dissipate the excess of energy. This is characterised by the occurrence of whitecaps (Monahan and O'Muircheartaigh, 1980). Three varieties of marine aerosols are then generated: film, jet and spume droplets. Film and jet droplets derive from air bubbles entrained below the sea surface by the breaking waves. These bubbles then rise to the sea surface and burst. This process becomes active from wind speeds about 4-5 $m.s^{-1}$ and produces droplets with sizes ranging roughly from 0.5 to 50 hm. For wind speeds of about 10 $m.s^{-1}$, spume droplets are torn from the wave crest resulting in larger droplets of 20 to about 500 hm. All these droplets compose the sea spray generation function (SSGF) commonly denoted as dF/dr0 which quantifies how many droplets with initial radius r0 are produced per square meter of the surface per second per micrometer increment in droplet radius. Various relationships have been proposed for this function, but there are still strong uncertainties although they were recently reduced from a factor of 5 (Andreas, 2004).

As soon as they are introduced in the first air layer above the sea surface the droplets exchange an amount of heat and moisture depending on their initial size, the temperature and humidity of the thin air layer above sea (about 1/3 of the mean wave height) and their life time above the sea, leading to a decrease in size of all the droplets. However, the behavior of the spume droplets differs from that of film and jet droplets. The smallest (film and jet) evaporate quickly and little participate to heat and moisture exchange (Andreas and Monahan, 2000). Most of them are transported into the boundary layer and may subsequently act as cloud condensation nuclei (CCN). Part of the spume droplets may fall down to the sea by sedimentation but they are much more efficient in terms of heat and moisture exchange due to their initial size. According to Andreas and Decosmo (2001) the “spume” latent heat flux may represents 10% of the total turbulent flux for a wind speed of 10 $m.s^{-1}$ and 10 to 40% for 15 to 18 $m.s^{-1}$ wind speeds, the sensible heat flux being estimated to 10%, at least, of the total flux at 15 $m.s^{-1}$.

It is then obvious that marine aerosols play a significant role in terms of heat and moisture exchange. Nevertheless large uncertainties remain to quantify more precisely these effects. Among them, the source function is likely the most important and needs to be assessed. So far the relation proposed by Monahan in 1986 is still considered as the best for film and jet droplets and the Smith *et al.* (1993) function modified by Andreas (1998, 2004) could be used as reference for spume droplets.

3.4.3 Key issues and scientific questions

The previous state of the art implies a series of key scientific questions that have to be addressed within the framework of HyMeX.

***Key Scientific Questions*:**

- ***WG4-SQ1:* How Mediterranean cyclogenesis, local topography and land-sea distribution interact to produce strong winds?**

  The main objectives are: (i) to improve our understanding of the processes leading to the Mediterranean cyclogenesis, using direct (in-situ) and/or remote sensing observations and meteorological modeling, (ii) to study local winds in the Mediterranean, modulated by local topography (*e.g.* acceleration between mountain gaps, channeling between land surfaces, etc.), using in-situ observations and high resolution meteorological modeling, and (iii) to assess the evolution of the Mediterranean cyclogenesis process under future climate conditions along the 21st century, using climate scenarios for the Mediterranean region.

- ***WG4-SQ2:* How air-sea fluxes are modulated?**

  The main objectives are: (i) to improve the parameterisation of air-sea fluxes, (ii) to investigate the role of the THC (thermal heat content) as an energy tank for the atmosphere, and (iii) to study the role of the air-sea fluxes on the intensity of cyclogenesis and associated winds. All objectives will make use of in-situ as well as remote observations, plus meteorological and oceanic modeling.

- ***WG4-SQ3:* How does the Mediterranean Sea response to the atmosphere?**

  The main objectives are: (i) to improve our knowledge of the oceanic convection and the coastal dense water formation, (ii) to understand the role of (sub) mesoscale processes on the formation/inhibition of dense water, (iii) to study the processes participating in the slow branch of the water cycle, especially the dispersion of dense water at the basin scale, and (iv) to assess the evolution of dense water formation and of the thermohaline circulation under future climate conditions. All objectives will make use of in-situ as well as remote observations, plus oceanic modeling.

3.4.4 Observation and modeling needs

3.4.4.1 How Mediterranean cyclogenesis, local topography and land-sea distribution interact to produce strong winds?

(a) *Development of a database of multi-scale space-time series of near-surface winds, temperature and humidity*: Elaboration of an extensive dataset of surface winds, temperature and humidity over land and sea combining in-situ measurements (buoys, weather stations), and airborne and spaceborne remote sensor measurements (SAR, QuikSCAT, lidar), as well as wind profilers to identify the upper-level features (mountain waves, wave-breaking, critical levels, turbulence, etc.) contributing to low-level wind reinforcement and vertical profiles of temperature, humidity and pressure to analyse the role of stability in the low-level wind dynamics. These observations should cover the Mediterranean water bodies, in order to cover the aspect of Mediterranean cyclogenesis, plus selected coastal areas, where in-situ observations and high-resolution meteorological modeling will provide information for severe local winds.

(b) *Creation of a high-resolution reanalysis of Mediterranean cyclones*: Extensive use of high-resolution operational meteorological models over the Mediterranean, in order to build a reanalysis dataset (covering at least a 10-year period), in order to investigate the processes of Mediterranean cyclogeneses, the associated winds and the tracks of cyclones over the area.

(c) *Assessment of the relation between strong surface winds and large/meso-scale predictors*: Derivation of predictors (large/meso-scale circulations, local topography, coastline shape, etc) of the regional strong winds (including the relationship between cyclones and strong winds). The physical or statistical relationship between the predictors and the other variables (surface wind and heat transport) may be determined and/or validated using the collected dataset and be evaluated as forecast systems. Special focus should be made on the sensitivity of the local wind response to any change of the set of predictors.

(d) *Derivation of scenarios of the evolution of the Mediterranean cyclogeneses under future climate conditions*: Use of climate models at high resolution for the study of possible

changes in cyclones intensity and track over the Mediterranean Sea, under the future climate conditions of the second half of the 21st century.

3.4.4.2 How air-sea fluxes are modulated?

(a) Development of a database of: Meteorological parameters, momentum and surface heat fluxes, precipitation, sea state, SST, SSS, aerosols. During EOP, measurements will be collected through remote sensing (*e.g.* QUIKSCAT, SSM/I, AVHRR, SMOS, MODIS/MERIS), and buoys. During SOPs, measurement of high resolution accurate fluxes is necessary as well as THC trends.

(b) *Investigation and improvement of existing parameterisations*: There is need to check existing parameterisations and/or modify them (including the effect of sea state, surface salinity, the impact of precipitation and ground water inputs).

(c) *Improvement of the understanding of*: Time and space scales at which the air-sea interactions modulate the wind, the oceanic mixing and the thermal heat content of the upper ocean (and vice-versa). High temporal resolution measurements of atmospheric and oceanic parameters (surface and atmospheric boundary layer, air-sea fluxes, sea state, temperature, salinity, oxygen profiles) are required.

(d) *Comparison of non coupled and coupled simulations*: Investigation of the frequency required for forcing/coupling as well as of the impact of spatial resolution of forced or coupled configurations**.** Determination of the optimal configuration of atmospheric and oceanic models. High resolution meteorological and oceanic modeling is required.

(e) *Investigation of the role of aerosols*: quantification of the correlation between heat fluxes with aerosol concentration and properties and to suspension efficiency (directly related to the wind speed). Evaluation whether marine aerosol and heat and moisture exchange are linked to the Mediterranean meteorological conditions that prevail during strong wind events. Measurement of aerosol properties (*e.g.* speciation, size) is required.

3.4.4.3 How does the Mediterranean sea response to the atmosphere?

The major research needs pertaining to WG4-SQ3 are:

(a) *Development of space-time series of oceanic hydrological characteristics*: Elaboration of a database of temperature and salinity profiles at moorings deployed at selected (offshore and coastal) key points in conjunction with measurements of air parameters and surface heat fluxes during several annual periods (EOP). Use of autonomous (possibly relocatable) profilers and repeated glider sections to broaden this 1D monitoring. Seasonal surveys of the hydrological characteristics at regional scale (as far as possible in the different regions of the Mediterranean concerned by DWF).

(b) *High resolution modeling of convection and dense water formation and cascading* (associated to dedicated measurements) to investigate the effect of Earth rotation, non hydrostatic processes, intermittent forcing and provide improved parameterisation of mixing in low resolution models. Also the interaction between offshore convection and dense water cascading needs to be document.

(c) *Better characterisation of the large scale circulation* (boundary currents) and its variability in the DWF regions and of the mesoscale processes affecting it and inducing lightening (by lateral mixing) of the water involved in DWF. Characterisation of (sub) mesoscale processes involved in re-stratification and dispersion of dense water. This point should benefit from drifters, gliders, and satellite (SST, water colour and new altimetric products), and is important to validate models.

(d) *Investigation of the dilution of (fate and) dense waters* formed on the shelf: shelf formation sites and water export towards the slope or offshore by sub and mesoscale dynamics.

(e) *Exploration of new potential sites of DWF*: hypothesis of a DWF area in the southeast of Corsica, around Sardinia, in the Ionian Sea, etc. according to high resolution satellite data like SST or water colour and modelling.

(f) *Derivation of scenarios of the evolution of the DWF under future climate conditions*: Use of climate models at high resolution for the study of possible changes in convection and coastal dense water formation (frequency and intensity of events), under the future climate conditions of the second half of the 21st century.

3.5 WG5: Social vulnerability and adaptation capacity

Coordinators: M.C. Llasat, C. Lutoff, I. Ruin

3.5.1 Introduction and motivation

The Mediterranean area is characterised by an increasing demography, leading to urban sprawl especially on coastal areas. Mediterranean countries are very diverse socially and politically. In a context of climate change, this population is confronted with challenging environmental factors, such as short-time extreme events (heavy precipitation, flash-flood, heat wave,…) and long-term modifications (change in access to water resources, drought,…).

Studies on adaptation capacity from an economic and societal perspective are in progress at the international level (Tompskins and Adger, 2004; Bazermann, 2006; Berkhout *et al.*, 2006). Nevertheless, systematic observation of social vulnerability and resilience has still to be organised. Thanks to its diversity the Mediterranean area appears as particularly well adapted for this observation.

One should recognize that the social and natural science communities involved in this topic in Europe and around the Mediterranean basin are currently fairly limited. Taking account of the current scientific resources available, this first draft focuses on social vulnerability and resilience. It targets vulnerability factors and adaptation capacity developed either by individuals or societies to cope with extreme events. A meeting has been organized in late 2009 to enlarge the scope of WG5 towards the social impacts of climate change, droughts and water scarcity. This meeting has insisted on the need of further development of the social dimensions of HyMeX and enhanced collaboration between natural and social scientists.

3.5.2 State of the art

3.5.2.1 Impacts of disasters

Floods are the most dangerous hydrometeorological hazard affecting the Mediterranean countries, followed by windstorms and hail (Llasat, 2009). This is due not only to a high flood frequency, but also to the vulnerability created by various human activities. These regions have widespread and intensive economic activity and high population densities in flood prone areas. This results in important economic losses and numerous fatalities following flood events. If flash-floods usually affect limited areas, these phenomena are characterized by one of the highest mortality rates among all the natural disasters (Jonkman, 2005). The

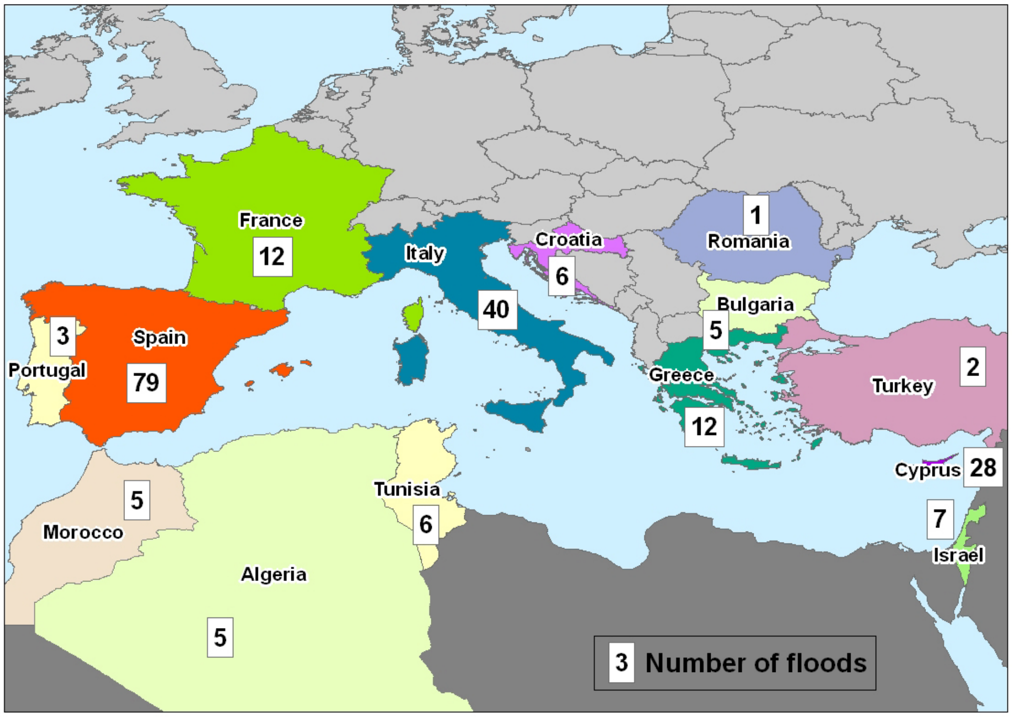


Figure 3.5. A preliminary distribution of flood cases between 1990 and 2006 (Llasat *et al.*, 2010).

Mediterranean basin is especially prone to flash-flooding. A recent preliminary report presented within the framework of the European project FLASH records more than 175 flood events between 1990 and 2006 in the Mediterranean region, some of them affecting more than one country (Llasat *et al.*, 2010). Of these events, 59% have affected Spain, the South-East of France and Italy (Figure 3.5). Although this inventory is far from being exhaustive for all the Mediterranean countries, it provides a good insight of the prominence of floods in the region.

The most typical estimation of social impact is drawn on the basis of direct economic damages and casualties. The analysis carried out within the FLASH project estimated over 29 billion euros the material damages produced by floods in the Mediterranean region during the 1990-2006 period, Italy being the most affected country followed by France, Romania, Turkey, and Spain (Llasat *et al.*, 2010). The total number of casualties has been estimated over 4,500, concentrating in the Mediterranean African countries especially. The highest number of casualties was recorded in Algeria, mainly as a consequence of the November 2001 event, followed by Morocco, Egypt and Italy. As an example, the November 2001 event that affected Algeria, Morocco and Spain, caused more than 600 fatalities and thousands of homeless people in Algiers. In Spain, four fatalities, 220,000 trees uprooted, up to 60% of sand washed away from beaches, and €162 millions of private-sector damages were registered. The differences in terms of human and economic losses between the two countries illustrate how some countries are more vulnerable from a human point of view or from an economic point of view.

It is not difficult to find examples of the damages caused by floods in other Mediterranean countries. On 8-9 September 2002, more than 600 mm were recorded in the Gard region (Southeastern France) with more than 200 mm on a surface of 5,393 km² (Delrieu *et al.*, 2005). A total of 6 departments were affected, with damages reaching €1,200 millions (€830

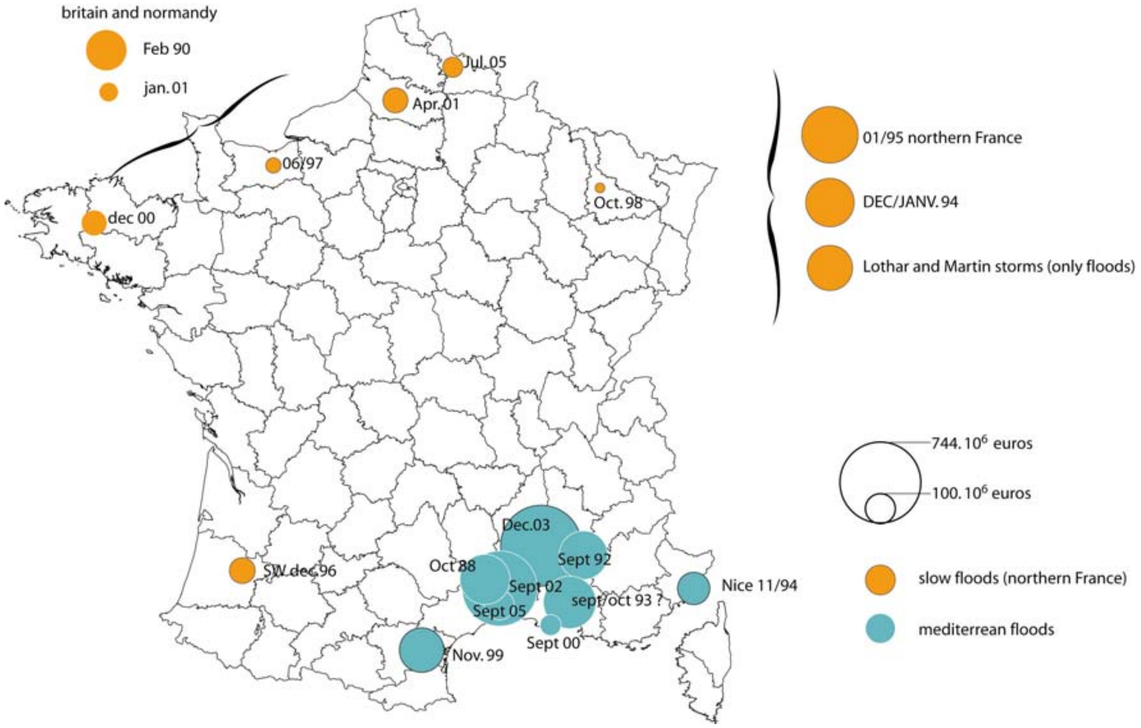


Figure 3.6. The cost of flood damage on private properties (1983-2005) (source: CCR). From Vinet (2007).

millions for the Gard department alone), and 23 casualties reported. In Italy, during the 20th century, approximately 3,000 places were affected by a flood event (Guzzetti *et al.*, 1994). In France, a recent study based on insurance data has shown that two-thirds of the damages due to flooding occur in Mediterranean regions (Figure 3.6). In Croatia, the damages caused by floods between 1980 and 2002 have been estimated to US$ 409 billions. The floods in Athens in October 1994 caused damages amounting to €13 millions in commercial and industrial premises and €1 million in private houses. In Israel, the floods on 21-22 February 1997 caused 11 casualties and major losses in agriculture, while on 21-27 May 1998, flooding in Turkey caused more than 17 casualties and left 3,000 homes ruined or evacuated, with a total evaluation of losses of US$ 250 millions.

Beside floods, landslides and debris flows produced by intense rainfall are also an important phenomenon in the Mediterranean region, particularly in Italy (Guzzetti and Tonelli, 2004, Guzzetti *et al.*, 2005). In 1998 the Sarno landslide caused 300 deaths in a urban area in which most buildings had been built illegally.

Droughts are also an important risk in Mediterranean countries, mainly in the Southern part. Although tragedies like the drought that affected Syria in 2009 (with about 800,000 people severely affected and 50,000 replaced) are not usual in the Mediterranean, droughts are frequent, and could become even more in future scenarios of climate change. In the past, they have also produced a lot of deaths and important emigration flows in European Mediterranean countries, whereas they can nowadays usually be mitigated thanks to water management systems. However, in some occasions, regular measures like water reservoirs or desalinization systems are not enough and special actions must be taken or drought management plans activated (Iglesias and Moneo, 2005; Pereira *et al.*, 2002; Bazza, 2002). It has been the case of the last drought period recorded in Spain between 2004 and 2008 leading authorities to

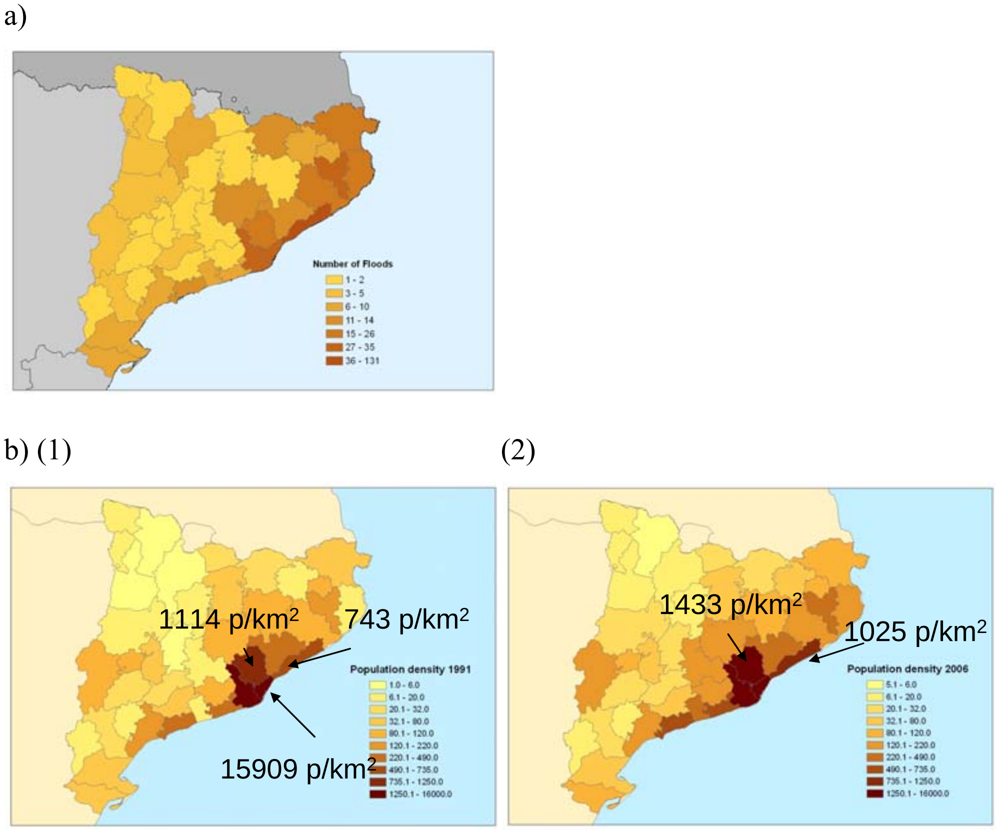


Figure 3.7. a) Flood events in Catalonia in the 20th century (from Barnolas and Llasat, 2007). b) Population density in Catalonia (people/km²) in 1991 (1) and 2006 (2) (from Llasat *et al.*, 2008).

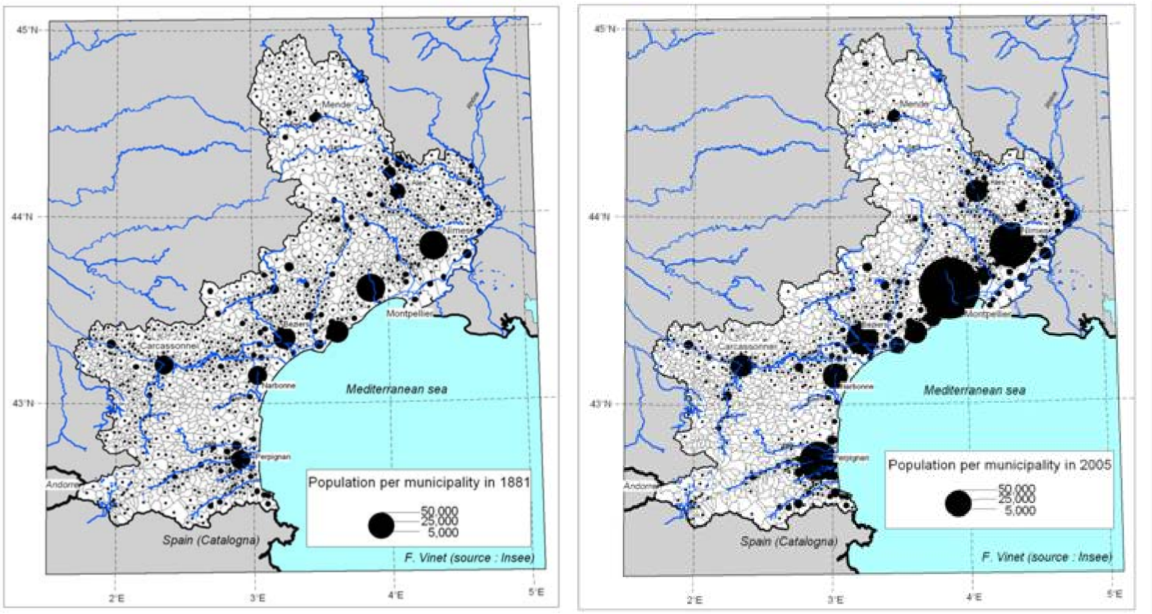
contemplate the transfer of water from other Spanish and French places to Barcelona. European projects like ARIDE, MEDROPLAN, or XEROCHORE have dealt or are dealing with drought management.

3.5.2.2 Vulnerability and flood risk assessment

3.5.2.2.1 The human impact in flood risk

Human impact is not only important considering the increasing vulnerability to floods, but also in contributing to the flood hazard itself. The effects of deforestation are much greater in some Mediterranean countries than in those of Central and Northern Europe. Besides this, one of the most important changes in soil use is the urbanisation of rural lands. Zones of natural storage or marshy zones are being eliminated gradually, and infiltration is reduced .These effects are particularly critical if urban areas are located in the headwaters of basins, increasing the flow of the river during intense rainfall events. This becomes more frequent along the Mediterranean coast which shows one of the most important urban increases.

Although this problem affects the Mediterranean basin in general, it is critical in Catalonia (Spain), Languedoc-Roussillon and PACA (France), Liguria (Italy), and in several places in Greece. As an example, Figure 3.7a shows the flood spatial distribution in Catalonia for the period 1901-2000. The greatest number of floods has been recorded along the coast, where the population has been increasing continuously (Figure 3.7b). For one century, the



a) b)

Figure 3.8. The population of Languedoc-Roussillon region in a) 1881, b) 2005 (Vinet, 2010).

population has shifted from the high valley to the coast plain as show the population maps in region Languedoc-Roussillon in 1881 and 2005 (Figures 3.8, from Vinet, 2010). In the past disasters took place in valleys and mountains like in October 1940 in Catalunia. Forthcoming disastrous flooding may occur in floodplains where assets and economic activities get concentrated, such as for the Gard event in September 2002.

If some human activities increase flood hazard, measures like dams, channeling, or the covering of torrential rivers can diminish it. Any trend analysis of the social impact of floods should then consider the entire range of the factors that can affect both hazard and vulnerability, that is not only rainfall trends but also the population changing features (growing age *e.g.*), change in land use, economic activities,…

3.5.2.2.2 Current approaches for the analysis of social impact

In order to reduce human and economic losses, different research directions should be explored. On the one hand, the atmospheric and hydrological mechanisms generating flash-floods should be better understood to improve forecast and warning for these events (objectives of WG3). On the other hand, human behavior facing flash-floods is considered by several authors as the most relevant factor to explain the still high level of fatalities (Gruntfest, 1977; Coates, 1999; Jonkman and Kelman, 2005). It should be better understood and anticipated to reduce human losses (Montz and Gruntfest, 2002).

The most typical approach consists in the generation of databases including information about the physical features of the event (peak of discharge, rainfall distribution,…) and data about the damages produced. This kind of approach is usually followed by both natural and social scientists. Two examples would be the flood database of Catalonia (1900-2008) (Barnolas and Llasat, 2007; Llasat *et al.*, 2008) and the systematic collection of data concerning damage caused in Calabria during the past centuries by floods and landslides, ASICal (Italian acronym for Historically Flooded Areas), available on the web (http://www.camilab.unical.it) (Petrucci and Polemio, 2003, 2007, 2009; Petrucci and Gullà, 2009; Petrucci and Pasqua, 2008;

Petrucci *et al.*, 2008). More recently, a database for the period 1900-1990, HistArc (Historical Archive), has been built. It contains more than 10,000 paper documents concerning both damage caused by floods and designs of structural works carried out along the river network during the past century.

Another typical approach lies in economic analysis. An in-depth economic analysis of the losses encountered following an extreme event, as well as a comparison between different events or countries is not easy to carry on. The different insurance criteria or GDP should be considered.

On-going studies on fatalities due to flood in southern France show that they are mainly due to dangerous behaviors rather than a passive vulnerability of people exposed to flood (Boissier and Vinet, 2009; Ruin, 2007; Ruin *et al.*, 2008). This kind of analysis linking the number of casualties with the circumstances of their death can be very useful to improve resilience and propose adaptation strategies.

Perception analysis is one of the different approaches to analyze the social impacts of natural risks. Literature on flood hazard demonstrates that personal experience is the most important factor in the development of flood risk perception by people living in floodplains. In fact, in communities with a "flood-culture", pre-event adaptations and adequate in-event responses minimize tangible and intangible damages (Nunes Correia *et al.*, 1998). The critical point is that many inhabitants of floodplains do not know or ignore the fact that they are living in floodplains, and often take decisions neglecting the actual conditions (Fordham, 1992). This problem is amplified with tourism and immigration, newcomers being unaware of the risks. A number of perception studies in connection to floods have already been carried out (Skiple Ibreek *et al.*, 2005; Krasovskaia *et al.*, 2001; Morris-Oswald and Siminovic, 1997). The studies on floods were the first to include the psychological aspects accompanying flood events (Brilly and Polic, 2005). Whyte (1986) distinguished three groups of factors influencing amplification of the perceived risk: personal characteristics, situational factors (*e.g.* media attention), and risk characteristics. The media are the most important sources of information on disasters and significantly influence or shape how the population and the government view, perceive, and respond to hazards and disasters. An example of this kind of treatment is the work being developed in Catalonia (Llasat-Botija *et al.*, 2007; Llasat *et al.*, 2009a) which gathers a systematic database of all the news related to natural hazards since 1982. Other authors go even further and claim that the perception of climate change is reflected by the media's coverage of these events (Tàbara, 2005). If an increase in the number of events is detected, it must be decided whether this is due to an actual increase in the frequency of the phenomenon (which may or may not be related to climate change), or rather whether the increase is due to changes in the vulnerability of the study zone (changes in land management, or even changes in the drainage basin due to different land uses, or to new infrastructures), or if it is related with changes in the editorial politics of the newspapers (Llasat *et al.*, 2009b).

Another approach recently developed within the framework of the MEDEX project analyses the social impact of heavy rainfall events through the requests received by the Meteorological Services (at the moment, AEMET of the Balearic Islands and the Meteorological Service of Catalonia). A useful indicator that considers the population density as well as the maximum rainfall has been defined (Gayà *et al.*, 2008).

Interestingly, another kind of analysis being developed focuses on people's mobility as a vulnerability factor. Based on the events in Europe in the last decades, Antoine *et al.* (2001) showed that mobility concerned more than 40% of the deaths during flash-floods. Ruin *et al.* (2008) showed that these circumstances of death concerned more specifically young (43 years old in average) and active people surprised in their daily travels in very small watersheds. This specific vulnerability factor has been observed in the United States as well, and mobility during flood has become one of the factors to consider in vulnerability analyses.

Finally, another kind of analysis contemplates the impact of man's activity and works on flood generation and flooding patterns, as well as the analysis of adaptative measures taken by the population in front of flood hazards.

3.5.2.3 The assessment of mitigation measures

3.5.2.3.1 A need for the assessment of prevention measures

As a consequence of the increasing damage of floods, a European Directive was drawn up in October 2007 to implement a policy for flood-risk assessment and prevention in the European Union (EU, 2007). Member States are invited to assess and to map flood risk in order to implement flood-risk management plans. Flood management has become a relevant issue for many European countries. Most of them have been reviewing their policy and some of them are eager to launch real actions in this field.

It is important for scientists to gather data in order to answer whether flood prevention policies are efficient or not. Flood prevention measures such as dikes, dams,… are very expensive and stakeholders and granting organisations need to know the effectiveness of such measures.

3.5.2.3.2 Relationship between physical data, damage and prevention

Both cost of damage and cost of prevention must be compared at different scales in a cost/benefit approach. Many economic studies have already been led on the relationship between damage and flood depth at the local level (Grelot, 2004; Penning-Rowsell, 1999). However, stakeholders have few studies at the catchment scale. Depending on catchments and region, the triggering threshold of damage is not the same. For example, in the Gard department in southern France, the threshold that triggered damage in upper basins is estimated to be around 250 mm per 24h whereas in the Aude department, the threshold is 150 mm per 24h (Vinet, 2008). This relationship between physical data and damage is an important field for the future and policy makers are eager to collect related decision making tools.

3.5.2.4 Analysis of the drought impact and ecosystem services

The analysis of the social impact of water scarcity and droughts requires a long term observation period. Dryland ecosystems are characterized by a high degree of ecological vulnerability and high sensitivity to human-induced water and land degradation (Falkenmark *et al.*, 2009). For the sake of this analysis, the concept of Ecosystem Services (ES) defined as the conditions and processes through which ecosystems sustain and fulfill human life provides a link between humans and the environment. Some potentially relevant ES in the Mediterranean region include (MA, 2005):

- food, wood and biofuel production
- carbon sequestration
- climate protection
- protection from floods and other hazards
- water provisioning or purification

Dry-spell	**Drought**
Occurrence: [2/3 years] Two out of three years	***Occurrence:*** [1/10 years] One year out of ten
Impact: Yield reduction	***Impact:*** Complete crop failure
Cause: Rainfall deficit of 2-5 week periods during crop growth	***Cause:*** Seasonal rainfall below minimum seasonal plant water requirement

Table 3.1. Differences between droughts and dryspells according to Falkenmark *et al.* (2009)

- erosion reduction (maintaining soil productivity and preventing siltation of reservoirs *e.g.*)
- biodiversity
- recreation

ES and their vulnerability[3] strongly depend on the status of the respective (agro-)ecosystem, and its bi-directional interactions with water and climate. While ES can be objectively measured with the same metrics across the Mediterranean, the dependence of people and livelihoods on ES and as a consequence the resilience[4] of social-ecological[5] systems is place-specific. Droughts and dry-spells (Table 3.1) have a strong impact on ES. The analysis of the effects of different drivers of ecosystem status can generate new information on desertification in the Mediterranean.

3.5.2.5 Forthcoming issues: global change and evolution of vulnerability

There is a general agreement that damages produced by natural risks, and particularly by floods, have increased, revealing an imbalance between the measures taken to diminish the risk and increasing factors, like the building of houses and facilities for various human activities in flood-prone areas. Figure 3.9 shows the evolution of extraordinary and catastrophic floods in Catalonia since the 14th century. Even though this figure provides a qualitative approximation of the damages produced by floods (Barriendos *et al.*, 2003), a clear trend is found for the extraordinary events that produced minor damages and disturbing of the usual life. On the contrary, any trend has been found for those events leading to catastrophic infrastructural damages (Llasat *et al.*, 2005). Such difference can be attributed to the evolution of the management of torrential rivers near the coast and of preventive measures, but also probably to rainfall evolution.

Another important issue is the analysis of the societal and ecological vulnerability to water resources and, particularly, to droughts. The fact of having an improved representation of the

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[3] Vulnerability depicts the degree to which an ecosystem service is sensitive to change, plus the ability to adapt of the sector that relies on this service (ATEAM project report, http://www.pik-potsdam.de/ateam/ateam_final_report_sections_5_to_6.pdf).

[4] Resilience (as it applies to social-ecological systems) is the amount of change a system can undergo (*e.g.*, land degradation) and still remain within the same state (*e.g.*, avoid desertification by continuing to produce essentially the same ecosystem services).

[5] The term "social-ecological systems" describes the fact that humans and the environment are closely interlinked.

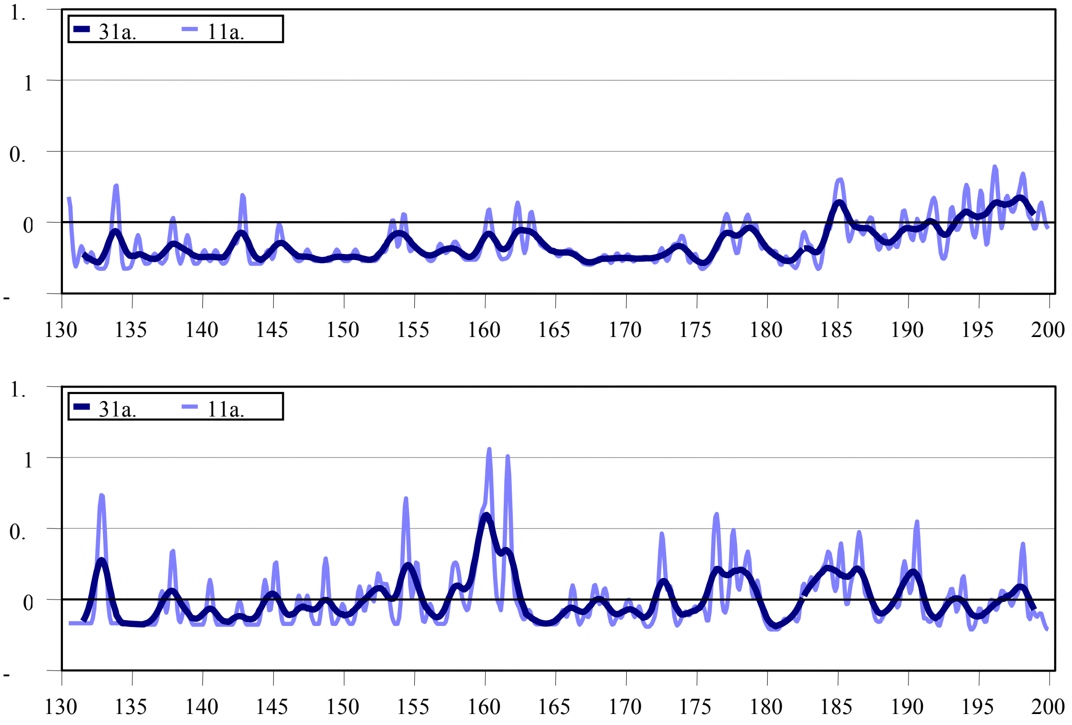

Figure 3.9. Evolution of extraordinary (top) and catastrophic (bottom) flood frequency in Catalonia from 1300 to 2000. A low-pass smoothing filter of 10 and 30 years has been applied (from Llasat *et al.*, 2005).

water cycles within the Mediterranean region is a key point. One important feature to highlight is then how can we take profit from this information to improve social vulnerability assessment and forecast.

The IPCC (2007) points to an increase of drought periods in Mediterranean countries for future scenarios due to a major water scarcity joined to high temperatures. It is necessary to combine such climate change scenarios to future scenarios of land use and surface management practices. The description of management practices and water use are also factors to be considered.

These points require a good collaboration with the other working groups, like WG2 and WG3.

3.5.3 Key issues and scientific questions

HyMeX aims at monitoring vulnerability factors and adaptation strategies developed by different Mediterranean societies to accommodate themselves to the impacts of climate change and intense events. The key issues that HyMeX would address in WG5 are as follows.

Key Scientific Questions:

- ***WG5-SQ1:* What methods, indicators and sensors may be used to monitor short-term and long-term adaptation strategies at various space scales and for different cultural contexts?**
- ***WG5-SQ2:* What lessons can be learnt from the experience of different societies and individuals to better cope with climate change and hydrometeorological extreme events around the Mediterranean Sea?**

- ***WG5-SQ3:* How can we make these lessons beneficial and relevant for all Mediterranean communities?**
- ***WG5-SQ4:* How can we define plausible scenarios (land use, economy,...) to quantify the impact of global change on the Mediterranean hydrological cycle and extremes?**
- ***WG5*-SQ5: How is vulnerability of humans and ecosystems going to change under future global change?**

3.5.4 Observation and methods needs

(a) *Build a comprehensive database of flood events and their associated impact*

First, a list of the flash-flood events that occurred in the Mediterranean countries should be established. As much as possible homogeneous data about the social impact of floods should then be collected. Data from insurance companies, previous bibliography and results from international or national projects, and present databases (ESWD, EMDAT, etc) each alone are not sufficient as their information are partial and inhomogeneous about the impact of heavy rain and floods. When possible their cross-validation should be encouraged to bring light on the contradictions between the different sources. The study of the relationship between damage and hazard data (flood depth and rainfall depth) must be enhanced at different scales (house, basin, region, country) to give tools to assess the effectiveness of prevention measures.

Some criteria should then be established that allow to homogenize information. A threshold should be considered against these criteria to select the flood events analyzed, the region of interest (all the Mediterranean countries or only some specific regions), and the kind of damages considered (human, ecological, economic, direct or indirect).

(b) *Discriminate all the factors driving the evolution of flood social impact*

It is needed to discriminate all the factors that are involved in the social impact produced by floods as well as their own trends. Vulnerability aspects should be disaggregated into aspects related with hazard. Natural aspects (like rainfall) should be distinguished from human aspects that can change the hazard. This will be useful to establish relevant indicators to monitor vulnerability.

(c) *Analyse social perception*

Even if risk perception has been studied for decades, few studies are using the same sample of people and the same questionnaire to analyze the evolution of risk perception both in time and space. Now, such an analysis appears essential in order to understand social ability to accept or refuse risk on the one hand, and to assess how the events and their treatment in the media impact such ability on the other hand.

Meanwhile, a systematic analysis of the press coverage of weather instability (both flood and drought) has to be developed in order to better understand the social context of people's perceptions of risk.

(d) *Observe social ability to cope with intense weather events*

Beyond the institutional structure of warning and forecast, individuals and communities are able to organize themselves to cope with extreme events, particularly in the region where these events occur regularly. How do they do? What are the practices and the time and space scales of social adaptation? To better understand, integrated indicators able to inform globally on the social ability to cope with the event are needed. Different kinds of indicators can be proposed, like the number, time and geographic origin of the requests received by the Meteorological or Civil Protection services, the evolution of mobility on the road networks. Such indicators have to be observed and their relevance tested. Other indicators have to be defined as well, in order to operate a real monitoring of social adaptation to extreme events. New methodologies have to be proposed and tested on different experimental sites.

(e) Monitor vulnerability factors and their evolution

Better understand adaptation capacities and vulnerability factors requires to develop social observation during crisis, but also in daily situation (to evaluate the level of adaptation and to qualify this adaptation). One of the most important question is data accessibility, especially concerning small scales (individual or family scales). Table 3.2 gives a panel of the different types of data needed to observe social adaptation and vulnerability. A specific point refers to the study of life losses due to flash flood events in Mediterranean countries (mainly in the North western part) along the last decades. The objective is to improve our understanding of the causes and circumstances of flood disaster deaths for prevention purposes. Collected information could describe the victims (age, sex, origin,…), the place of death (river, watersheds,…), the circumstances of death (car, home, camping,…). Fatalities are then compared to parameters like climatological parameters (rainfall depth and intensity), characteristics of watersheds, social and economic data: population in flooding area, preventive measures such as flood warning systems, land use planning,... This proposal could contribute to answer questions of the topic 4.2 of the White Book and the need to progress on:

- mapping the evolution of vulnerability during the last decades,
- progressing in the understanding of loss of life process in extreme events in order to create a “loss of life” model and to develop a methodology for mapping life risks in time and space,
- better understanding how communities cope with flash flood events by performing surveys about risk perception of population, experts and decision makers and by studying recent past events in order to characterize human behavior during crisis and public warning responses -.

(f) Analyse the space-temporal factors of adaptation

One of the main problematic characters of the extreme events developing in the Mediterranean area is the rapidity and brutality of the phenomena. This characteristic induces for people to be able to react in a very short time. Another characteristic is the spatial specificity of the phenomena. The spatio-temporal scales of flash-floods suppose dedicated warning procedures and fast reactions.

(g) Analyse the impact on Ecosystem Services

The HyMeX observation period provides the unique opportunity to study bio-physical and socio-economic parameters consistently across the Mediterranean. ES and how they support livelihoods can be monitored, as well as vulnerability and adaptive[6] capacity, *e.g.* in response to variations in climate, water, vegetation and land. This can be done by means of modeling, observations, questionnaires, focus groups,… for specific locations.

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[6] The ability of a social-ecological system to cope with novel situations without losing options for the future. Adaptive capacity also depends on the degradation status of land and water.

Adaptation / vulnerability factors	Indicators
Socio demographic and economic attributes Demography, land use, cohesion of social structures, land values	Population density Building density Association density Age, gender, professions
Psycho-socio-cultural factors	Hazard knowledge Risk perception, press coverage
Warning systems, Crisis and recovery process	Lead-time, Spacial accuracy Emergency response quality Communication relevency
Public policy and risk management	System of actors Decision making process
Practices at different scales (individuals, meso-scale,…)	Evolution and adaptation of travel patterns
Infrastructure quality and accessibility	Type of building, protection structures
Space and time circumstances of the event	Time of the day / night Urban / rural area

Table 3.2. Panel of vulnerability and adaptation factors and indicators.

A 10-year monitoring period will enable correlations of livelihoods, ES, and ecosystem status with parameters such as climate, hydrology, vegetation, land use, urbanization, estimated by some indicators like maximum temperature, onset and length of rainy season, soil moisture, moisture recycling rate, water scarcity[7], LAI, percent of irrigated land, or rates of change in urbanization or land abandonment. From those correlations, the effects of different drivers of ecosystem status may be distinguished, generating new information on desertification[8], in the Mediterranean[9]. Furthermore, the effects of droughts and dry-spells on ecosystems and ES for different social-ecological systems can be analysed. If the (shorter term) effects of floods can also be detected, hotspots of vulnerability can be mapped.

If strong extreme events occur during the HyMeX observation period, we may observe the crossing of critical thresholds of ecosystems and ES and social-ecological systems, beyond which strong non-linear responses occur (*e.g.* shifts to a much drier or much less productive system such as in desertification or savannization). If the results of the HyMeX monitoring are combined with historical time series, new information can be derived on the "memory" of social-ecological systems or their vulnerability to climate risks, as a function of previous land use, degradation and adaptation.

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[7] Water scarcity may be defined here as the extent to which specific ecosystem services are water limited.

[8] Land degradation in arid, half-arid and dry sub-humid areas, resulting from various factors, including climatic variations and human activities" (UNCCD) or also as "a mismatch of demand for and supply of ecosystem services" (MA 2005).

[9] 80% of all drylands in the southern/eastern Mediterranean are affected by desertification (Plan Bleu).

(h) *Monitor drought events*

Although droughts are characterized for their different temporal and spatial scales in comparison with flood events, the major part of the observation and methodologies proposed before for flood events, could be applied to monitor and analyse drought events as well as their consequences. Bearing in mind that future scenarios points to an increase of drought periods, a good monitoring and database is needed.

(i) *Facilitate the mutual comprehension between social and natural scientists*

While it would be probably utopian to propose a shared common language it is also true that more attention to the specificities of both views would likely benefit integration and therefore management.

Finally, It is important to remind the transversal feature of WG5 that requires a permanent collaboration with the other WGs of HYMEX, as well with other projects like MEDEX, FLASH, CIRCE, MedCLIVAR, among others.

4. Programme strategy

4.1 The general observation strategy

4.1.1 A three-level observation strategy

The HyMeX programme foresees the monitoring of all relevant atmospheric, oceanic and hydrological variables during a long observation period, with additional means deployed during enhanced and special observing periods. The general observation strategy is thus based on a three-level nested observation scheme:

(1) A Long-term Observation Period (LOP) lasting about 10 years to gather and provide observations on the whole coupled system in order to analyse the seasonal-to-interannual variability of the water cycle and to estimate the water budget. The LOP will enhance the current operational observing systems and existing long-term observatories in hydrology, oceanography and meteorology, not excluding the set-up of additional networks. The LOP will have to cover the whole Mediterranean basin, and will be devoted to develop and maintain the acquisition of the long-term time series required to study seasonal and interannual variability.

(2) Enhanced Observation Periods (EOP) for both budget and process studies. The EOP is envisaged to last at least 4 years, embracing the SOP periods (see below). However EOP periods may cover specific parts of the year only, *e.g.* autumns for heavy precipitation, extending to winter for severe cyclogenesis and strong winds. The EOP is based on the enhancement of existing research observatories and operational observation networks.

(3) Special Observation Periods (SOP) lasting several months. They will aim at providing detailed and specific observations to study key processes of the water cycle in Target Areas (TA). In addition to the EOP observation framework, dedicated ground-based, shipborne and airborne means will be deployed during the SOPs.

4.1.2 The sites and supersites of the Target Areas

Instruments will be deployed in specific locations within the Target Areas (TA). During the 3rd HyMeX Workshop in June 2009, the following definitions have been adopted in order to have a common language whatever the Earth compartment considered:

- a *site* over land is defined as a region affected by the same hydrometeorological events (heavy precipitation, flash-flood) with a good radar coverage and surface station network (meteorological surface station, soil moisture and discharge measurements,…). A *hydrometeorological site* should contain at least one hydrological pilot-site / supersite (see definition below). In addition to these hydrometeorological sites, some specific *atmospheric sites* over the Meditrranean islands gather instruments to document the upstream atmospheric conditions associated with the hydrometeorological events.
- a *site* over the ocean is a region affected by the same hydrometeorological events (dense water formation, cyclogenesis and regional winds) with a good coverage in ocean and air-sea measurements (buoys, moorings,…).
- a *supersite* over land or the ocean is a specific place that gathers research instruments dedicated to the study of specific processes. For hydrology, a supersite is basically an instrumented catchment of one to ten km^2. For the atmosphere, supersites are either within or outside the site to document the upstream atmospheric conditions for instance.

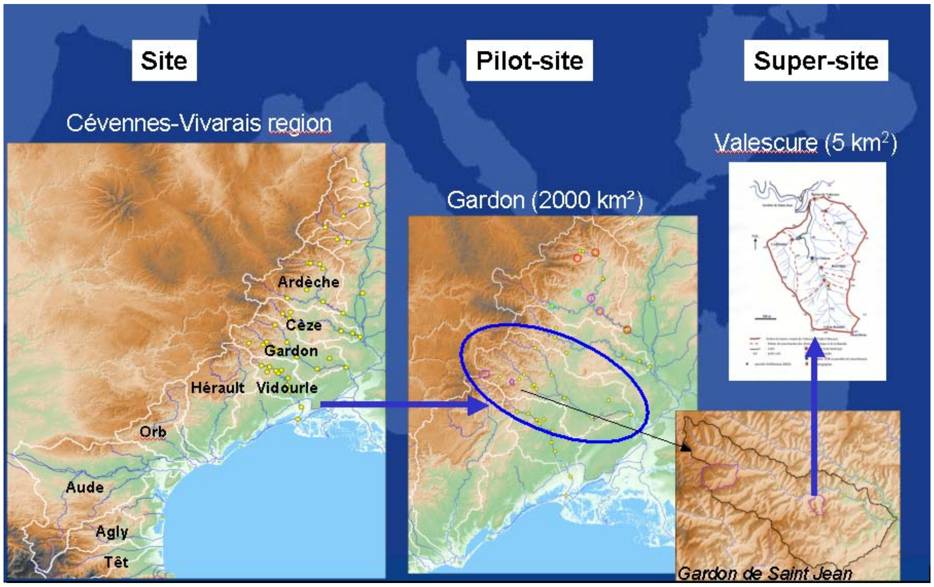


Figure 4.1. An example of hydrometeorological site, pilot-site and supersite.

- for hydrology, the term *pilot-site* is used for medium-size watersheds (typically several thousands km²) for observational and distributed hydrological modeling studies at the regional scale. Figure 4.1 illustrates this concept for the Cévennes-Vivarais site.

4.1.3 The Target Areas of the first EOP/SOP series

During the 3rd HyMeX Workshop in June 2009, three Target Areas (TA) have been proposed as candidates for the first EOP/SOP series (Figure 4.2):

- *the North-Western Mediterranean TA*: North-Western Mediterranean concentrates all the intense hydrometeorological phenomena of interest for HyMeX: heavy precipitation systems and flash-flooding occur over the Spanish, French, Italian coasts during the autumn, and the Gulf of Lions (~42N, 5E) is one of the four major sites of dense water formation and deep ocean convection at the end of winter under the influence of the Mistral and Tramontana regional winds, and of the Gulf of Genoa cyclogenesis. Also the region includes the largest river of the Mediterranean basin, the Rhone, as well as the Ebro and many intermittent rivers with fast and strong response to heavy precipitating systems, which poses specific forecasting issues.
- *the South-Eastern Mediterranean TA*: The target area covers the Eastern and South-Eastern Mediterranean area. The sites consist of the western part of Crete Island, the transboundary river basin of Evros river and three basins in Israel. The Crete site is proposed as a site for the study of heavy precipitation events and flash-flooding. In addition, this target area will allow to study intense rainstorms and flash floods in the dryer climate areas of the Mediterranean (*e.g.* Israrel region). The TA includes also the Evros River in Northern Greece as it is the second biggest river in Eastern Europe and will allow to study larger scale floods and the effectiveness of water managemet practises in flood mitigation. Concerning the ocean, there are also two areas of formation and propagation of dense water in the North and East of Crete that are worth documenting and understanding.

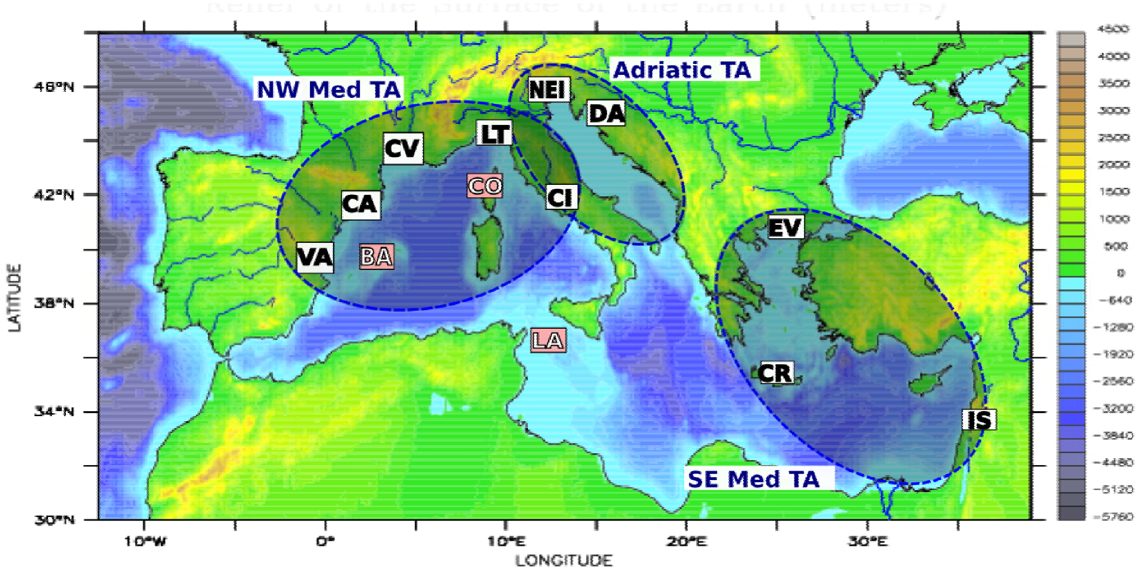


Figure 4.2. The Target Areas (dashed areas), including hydrometeorological sites (white boxes) and atmospheric upstream sites (pink boxes).

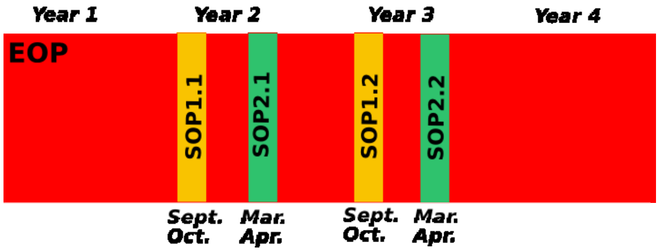


Figure 4.3. Calendar of the SOP series and EOP over North-Western Mediterranean.

- *the Adriatic TA*: North-Eastern Italy (Friuli, Veneto, Trentino, Alta Adige) and the Dinaric Alps in Slovenia and Croatia have been proposed as a target area for the study of heavy precipitation events and flash-flooding. This region is affected by strong regional Bora and Jugo winds. The mean annual precipitation > 3000 mm have been recorded over the Northern Adriatic, particularly over the area of Kvarner Bay in the eastern Adriatic Sea, its mountainous hinterland Gorski Kotar and Istra Peninsula. The dynamics of the interplay between the local mountain attached winds Bora and Jugo, and influence of mountains on the cyclone formation and motion over the Adriatic Sea is still not well understood. Dense water also forms in the Adriatic sub-basin. Particularly, the NAdDW is formed in the northern Adriatic while SAdDW is formed in the south Adriatic Pit.

This list of TAs is still open, notably regarding North-African sites. It is worth noting that the LOP covers the whole Mediterranean, with sites already identified outside the TAs (*e.g.* Gibraltar and Sicily straits, watersheds in Morocco, Israel,...).

4.1.4 The EOP/SOPs over the NW Med TA

A first series of three to four SOPs will take place in the North-Western Mediterranean TA over a period of one year and a half in a 4-year EOP (Figure 4.3).

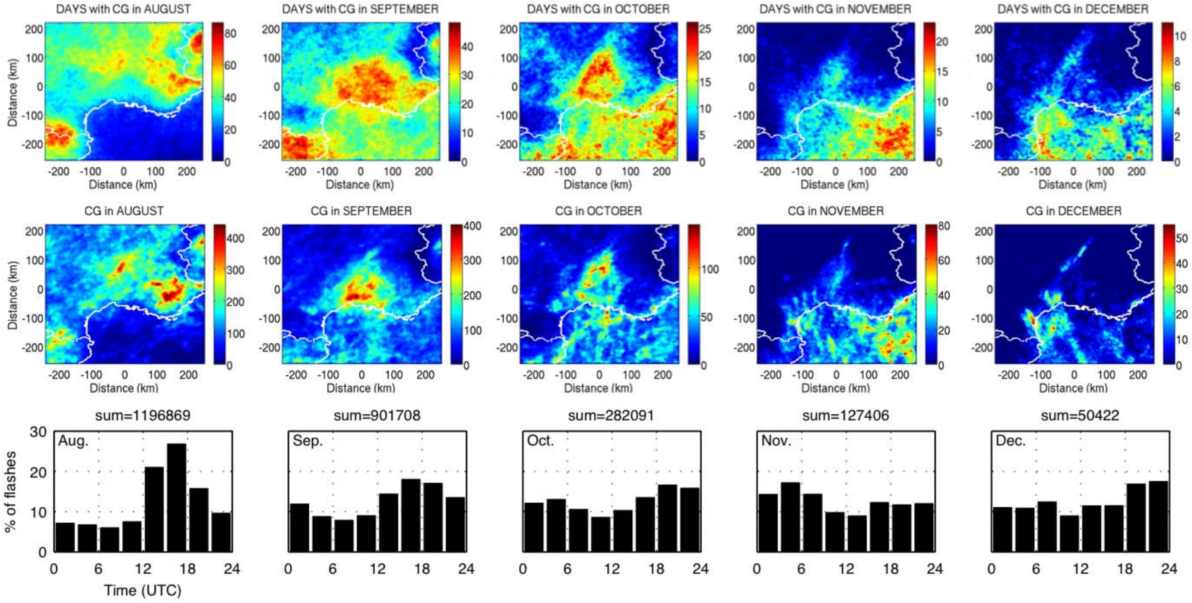


Figure 4.4. Monthly distribution of the number of lightning days per 5 km x 5 km (top panels), monthly distribution of the number of lightning flashes per 5 km x 5 km (middle panels), and diurnal cycle of the monthly lightning activity per 3-h period, based on records from the operational lightning detection network Météorage from 1992 to 2008 over South-eastern France. The diurnal cycle is expressed in % of lightning flashes relative to the total number of lightning flashes recorded during a given month over the 17 years of reports. From Defer *et al.* (2009).

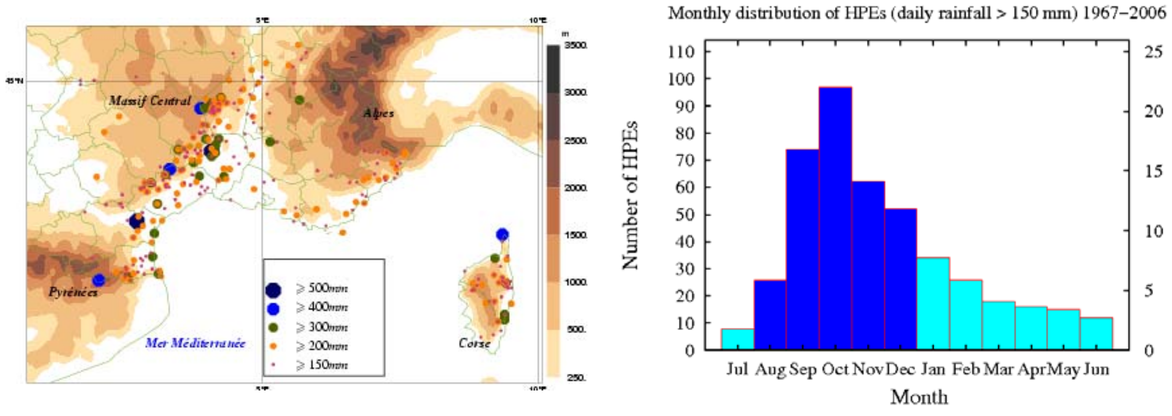


Figure 4.5. Location of the maximum of daily precipitation (left panel) and number of days (right panel) with daily precipitation above 150 mm over Southern France over the 1967-2006 period. From Ricard *et al.* (2009).

The SOP1 series coincides with the climatologic occurrence peak of heavy precipitation and flash-flooding (Figures 4.4 and 4.5). This period of the year is also favourable to sample the ocean state prior to dense water formation (preconditioning, SOP1.1) and to quantify the propagation of the dense water formed the previous spring (SOP1.2).

The SOP2 series covers the end of the ocean deep convection and dense water formation period (Figure 4.6). These periods of the year would also allow to document Mediterranean

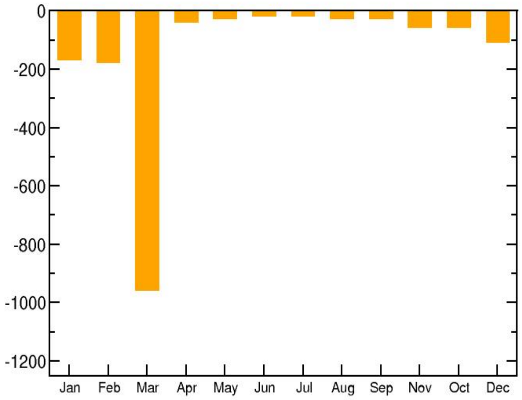


Figure 4.6. Monthly average of the ocean mixed layer depth in Gulf of Lions. From D'Ortenzio *et al.* (2005).

cyclogenesis, as the fall and winter/early spring seasons are propitious to cyclogenesis over the Western Mediterranean Sea.

The first HyMeX SOP over North-Western Mediterranean is planned for September-October 2012 (SOP1.1). Then, SOP2.1 is planned for March-April 2013 and SOP1.2 for September-October 2013. SOP2.2 is still under discussion among the HyMeX community.

4.1.5 The EOP/SOPs over the SE Med TA

The Eastern Meditterenean sites consist of the North-West part of the island of Crete, the transboundary river basin of Evros and three sites in Israel. Specifically, the Crete site is associated with (a) Mediterranean maritime climate, (b) complex terrain triggered storms, (c) small catchments vulnerable to flash floods, (d) ephemeral streams, and (e) special topographical and hydrogeological conditions (*e.g.* steep slopes and karstic aquifers). The average annual rainfall ranges from 600 to more than 900 mm on the high mountainous ridges. Rain season is from November to April and consists of several low intensity and few heavy rainfall events (constituting about half of the annual rainfall) associated with westerly systems. The region is covered by an operational C- band, Doppler weather radar, under the authority of US Naval Base. The operational hydrometeorological network for the region includes 25 rain gauges and a few hydrometric stations due to the ephemeral characteristic of the river regime. During the first Enhanced Observation Period (EOP) the radar observations from the C-band weather radar will be augmented using observations from a mobile X-band dual-polarization weather radar (X-POL) providing local high-resolution data over targeted mountainous river basins in the region.

Evros River is the second biggest river in Eastern Europe. The total length of the river is 528 km, of which 310 km belong to Bulgaria, while 218 km determine the borders between Greece, Bulgaria and Turkey. The total river basin has a surface area of 53.000 km², its maximum altitude is 2915 m while it has a mean altitude of 411 m and a mean slope of 11%. The main tributaries are: Tundja (7980 km², 350 km) in Bulgaria, Ardas (5200 km²,240 km) in Bulgaria with a small part in Greece, and Ergene (10200 km², 280 km) in Thracian Turkey. Evros river is heavily exploited from the aforementioned countries (it has more than 15 large dams along its course) while the average annual discharge reaches approximately 7 km^3 and in combination with poor management practices leads to the frequent occurrence of extensive floods (approximately one major flood every two years during the last decade). In the southeastern part of Evros prefecture, next to the border with Turkey, Evros River creates an extensive delta of international ecological importance with a total surface area of 188 km². Evros Delta is a National Park and belongs also to Natura 2000 network and to Ramsar Convention, constituting therefore one of the most important wetlands in Europe. The region is covered by an operational C-band, dual-polarization and Doppler weather radar located at Xrisoupolis, under the authority of the Hellenic National Meteorological Services.

During the first EOP, radar data will be augmented by observations from a hydrometeorological network that includes approximately 50 daily rain gauges (several more over Bulgaria), 5 high-frequency automatic meteorological stations and several hydrometric and water quality stations downstream of the dams in Greece and Bulgaria. In addition five high-resolution stream gauges with meteo and water quality sensors are available along the Greek part of the Evros river network. Data from the C-band polarimetric weather radar will be used to monitor precipitation up to 200 km range, while the network of daily rain gauges will be used to calibrate and verify the polarimetric radar-rainfall estimates. Precipitation data from further ranges over the basin will be available from high-resolution satellite products through calibration against rain gauges and the polarimetric radar. Satellite observations of snow cover and land use will be used along with GIS-based data on watershed characteristics to model the watershed processes for the Ardas, Tountzas and the main Evros sub-basins. In situ hydrologic data from the area (*e.g.* river flows, soil moisture and ET observations from selected sites within the network) will be used for assessment of the model predictions and for assimilation purposes in order to improve the predictability of the water cycle in the basin.

Three Israeli sites have been proposed within the SE Med TA covering the first EOP and representing different climate conditions of the southeast Mediterranean: Mediterranean climate (650 mm annual rainfall), semi-arid climate (150-200 mm annual rainfall) and Mediterranean mountainous climate (550 mm annual rainfall). Each of these sites includes meteorological surface station, recording rain gauge and daily rain gauge network. The sites are also under the cover of a C-band meteorological radar system. Runoff discharge measurements are available for two sites.

During the first EOP the three Israeli sites will provide data for documenting and investigating intense precipitation, flash floods and continental hydrological cycle over the drier climate areas of the Mediterranean basin. These regions are prone to flash floods resulting from convective storms with typically limited coverage areas and high rain intensity for relatively short durations. Because of the high local nature of these storms radar data are crucial for investigating such events. Rain gauges provide ground data to calibrate the radar and to estimate uncertainties in rainfall estimates. Discharge measurements at two catchments (42 and 95 km²) allow studying rainfall-runoff characteristics during extreme flash flood events and on the annual basis. The site data will be used also in hydrometeorological models for the two catchments to investigate hydrological responses during extreme events.

4.1.6 The EOP/SOPs over the Adriatic TA

The region is covered by the operational meteorological and oceanographic measurement network.The EOP series of measurements in the Adriatic Sea will be performed every second month in the four year EOP period. In the first year of measurements, the SOP1 series of measurements will be carried out monthly from September to December (Figure 4.7).

The SOP1 series coincides with the climatologic occurrence peak of heavy precipitation and flash-flooding (Figure 4.8). This period of the year is also favourable to sample the ocean preconditioning phase in the Adriatic Sea (SOP1.1) and to control generation and spreading of the newly formed dense water in the two targeted areas of the Adriatic Sea (SOP2.1). This

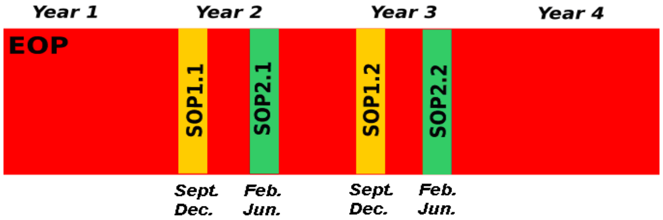


Figure 4.7. Calendar of the SOP series and EOP over the Adriatic Sea.

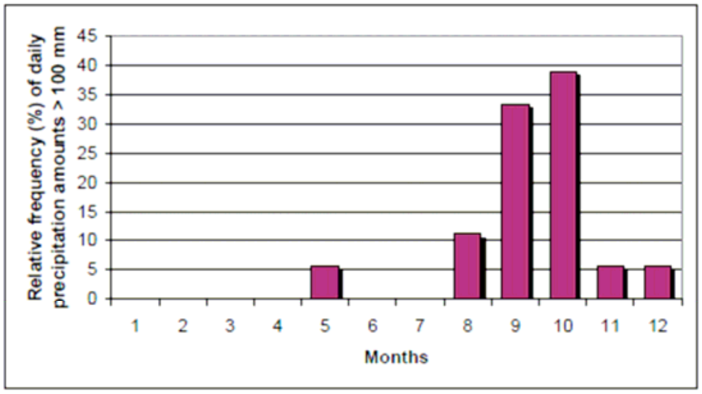


Figure 4.8. Relative monthly occurence frequency of daily precipitation amounts greater than 100 mm, for the 10-year period (1991-2000) in the northern Adriatic area (Kozaric and Ivancan-Picek, 2006).

period at the end of winter and beginning of spring coincides with strong cyclogenesis and related severe Bora wind (Horvath *et al.*, 2008, 2009).

The first HyMeX SOP over Adriatic area is envisaged for September-December 2012 (SOP1.1). The SOP2.1 is planned for February-April 2013 and SOP1.2 for September-December 2013. SOP2.2 is planed for February-April 2014.

4.2 Observation strategy overview for the sea water budget

The main objective is to set up a strategy that will tackle the scale problem (spatial and temporal) of combining the already existing long-term datasets and the future HyMeX field campaign data in order to both:

- *estimate the Mediterranean Sea Water Budget (MSWB) components and their variability,*
- *validate the various components of the Regional Climate Models developed within the HyMeX context.*

Since the MSWB cannot be completely disconnected from the Mediterranean Sea heat budget, the latter will thus be studied too. In particular the radiative fluxes will be measured when and where the latent and precipitation fluxes are measured. In addition to the objective of estimating the sea water budget for the whole Mediterranean, WG1 aims also to close sub-basin water budgets depending on the available datasets. The Western and Eastern parts of the Mediterranean (cut at the Sicily Strait), the North-West of the Mediterranean Sea, the Adriatic Sea and the Aegean Sea are targeted.

The general WG1 observation strategy takes benefit of and combines short-term in-situ direct measurements of the poorly known components of the water budget (precipitation over sea, evaporation, evapotranspiration, atmosphere water divergence), eulerian long-time series (1D ocean-atmosphere buoys, deep-sea mooring, strait transport, repeated CTD sections, coastal radars), reanalyses of already-existing database (heat and salt content of the Mediterranean Sea, river runoff fluxes, strait measurements), and combination of in-situ data, satellite products, regional modelling, and global or regional reanalyses:

- Among the different in-situ datasets planned to be collected during the HyMeX campaign period, WG1 will mainly use long-term measurements (LOP) to be able to sample the temporal variability and to ensure the robustness of the measurements at climate scales: coastal radars, fixed surface buoys, deep-sea moorings, repeated CTD sections, ships of opportunity on repeated tracks, long-term river inflow measurements, fixed meteorological stations, GPS network.
- The EOP-SOP observations (research ships, network of radiosoundings, aircraft, lagrangian buoys or balloons) will be dedicated to three tasks: firstly, the intercalibration with the long-term measurements (for example the research ships with high-quality air-sea flux measurements will spend 24 hours close to fixed buoys), secondly the validation of the regional earth system model (or of its components) for some carefully chosen case studies, and finally the study of the scale interaction issue that is to say the impact of time or space localized events on long-term estimate of the MSWB components.
- One challenge of HyMeX WG1 is to combine 3D model reanalyses, fixed long-term measurement points, satellite products and SOP high-resolution datasets in an innovative and relevant way to bridge the scale gap between the in-situ campaign measurements and the regional climate models.
- Estimation of the water budget needs access to various kinds of data (in-situ, satellite, modelling, oceanography, continental surface, hydrology, atmosphere, climate) by users from different communities. It is thus necessary to ensure that the project's metadabase and database are user-friendly and efficient embrace this variety. Data rescue for at least river runoff datasets, meteorological observations from the countries of the South and East of the Mediterranean Sea and for ocean data is also included in WG1 observation strategy to obtain long-term series.

4.3. Observation strategy overview for the continental hydrological cycle

The main objective is to set up a multi-scale experimental strategy allowing to increase our knowledge of the water balance components at various scales and the evaluation and improvement of regional models simulating the continental hydrological cycle. The observation set up must allow:

- *the collection of data required to run the various models,*
- *the collection of data required for process understanding improvement, the verification of parameterisations and model simulations,*
- *the collection of data required for parameter estimation/calibration/assimilation.*

To achieve these goals, a multi-scale (spatial and temporal) observation strategy must be set up, based on nested catchments covering areas ranging from a few km² (super-sites) to about 100-1000 km² (pilot-sites) and about 10000 km² (sites). The objectives of these nested observation levels are to document and describe the continental surface, and monitor the state variables relevant to compute the water balance. To benefit from longer time series, these catchments could preferably be included in hydrometeorological observatories. For each nested level, the objectives and typical instrumentation can be described as follows:

Instrumented super-sites for the monitoring of the various components of the water balance and, if possible, closure of the water and energy balance.

These data will be used in process scale models in order to enhance process understanding and achieve the integrated modelling of the water balance. These small catchments will also be used for the development and evaluation of new metrology such as evapotranspiration over complex terrain, distributed hydrometry, hillslope monitoring. The target instrumentation for these super-sites which will mainly be deployed within the EOP/SOP periods includes:

- densely instrumented hillslopes to study the role of topography in water redistribution and groundwater/river interactions, including piezometers, tensiometers, soil water content and temperature, evapotranspiration, surface and sub-surface flow, geochemistry, geophysics (EOP/SOP).
- documentation of soil depth and soil hydraulic properties using in situ measurements, geophysics,...
- enhanced rainfall measurements to increase spatial and temporal resolution (radars,…) with the possibility to increase the number of sensors during the SOP.
- measurements of evapotranspiration using eddy correlation and scintillometers (EOP). During the SOP, this network could be complemented with additional scintillometers in order to increase spatial resolution.
- evaluation of the potential of new techniques (lidar for topography).
- gathering of information about anthropogenic effects (agricultural practices, water pumping and withdrawal, etc…).
- documentation of land use practices with a fine spatial scale resolution using very high resolution imagery.

Pilot-sites with a lighter monitoring than over super-sites, but able to document the main components of the water balance such as rainfall, streamflow (distributed) and groundwater. The data collected on these catchments will serve for the validation of the parameterisations of regional scale models, and the evaluation of strategies for parameter estimation at a larger scale. The target instrumentation for these catchments which will be deployed within the EOP/LOP framework is:

- enhanced rainfall measurements to increase spatial and temporal resolution (radar,…).
- groundwater level measurements.
- distributed hydrometry and/or sensors of water levels.
- documentation of soil moisture using airborne sensors (radiometers) during the SOP; the aim could be to document soil moisture variability before and after a major rainfall event.
- documentation of land use practices using remote sensing information at lower resolution…

Sites for which the monitoring will mainly rely on existing operational networks. The aim is the collection of input data for regional scale models. Operational data such as streamflow will also be used for model verification. This monitoring in mainly associated with the LOP and will consist in collecting and producing the data required for running the regional scale models: climate data with reanalyses of past data (1 km^2, hourly resolution) and prospective for future climate, rainfall, groundwater levels, streamflow, water use, land use and soil moisture from satellite data, soil and groundwater geometry and properties.

Most of the pilot- and super- sites are shared by WG2 and WG3. Up to now, the identified pilot- and super- sites have a wide coverage of the whole Mediterranean basin, although sites in the Southern Mediterranean are still lacking. In relation with WG2, the following sites have been identified:

4.3.1 Pilot-sites

Gard and Ardèche catchments (within the French OHM-CV Observation Service led by LTHE) which are catchments of about 1000 km^2 and for which the nested catchment strategy is being implemented. This pilot-site is primarily dedicated to flash-flood studies, but it is planned to add evapotranspiration and soil moisture measurements, so that it will be suitable to study one scientific question related to WG2: the impact of topography on soil moisture redistribution and on evapotranspiration. On the Ardèche catchment, a network of LS-PIV gauging stations is set up to densify streamflow measurements.

Crau-Camargues area (in France, led by UMR EMMAH-Avignon). This area is being instrumented to study the relationship between surface land use and groundwater, focusing on the monitoring of agricultural practices (mainly irrigation) and groundwater table. Several sites are equipped with surface fluxes measurements on contrasted land use (dry and irrigated areas).

Rhemedus area (Duero catchment in Spain led by the University of Salamanca). Several catchments from about 30 to 100 km^2 corresponding to various land use are already monitored and should be extended to cover a larger area. A network of soil moisture measurements is also available.

4.3.2 Super-sites

Within the OHM-CV Observation Service: the **Valescure-Saumane catchment (Gard catchment)** densely instrumented with soil moisture, piezometers, discharge and evapotranspiration measurements and the **Pradel catchment (Ardèche catchment)** densely instrumented for the study of runoff are identified. Measurements of evaportranspiration are also foreseen.

Some other super-sites with various Mediterranean vegetations are also proposed: CarboEurope sites, Avignon (crops), Tour du Valat (salt marshes), Crau (dry grasslands), Lecce (mixed periurban), Bari (crops), Tor Vergata (grass), Lampedusa (dry grassland),…

This list is of course not closed and all the proposals are welcome, provided they suit the HyMeX experimental strategy and the criteria listed above. In order to get a more precise idea of the data available, an inventory of the sites and of their instrumentation will be conducted soon.

4.4 Observation strategy overview for heavy rainfall and flash-flooding

The main challenge is to set up an experimental strategy that is adapted to the observation of coastal heavy precipitation and flash-flood events with quite low frequency over a specific region. To this purpose the main objective of WG3 observation strategy is to:

- *ensure a sufficient level of observation of heavy precipitation and flash-flooding based on existing operational systems and observatories and their enhancement during LOP/EOP,*
- *conceive instrument deployments during the SOPs that allow to sample events over all the sites in a given TA to maximize the chance to catch several intense events during the two-month-long SOPs,*
- *fill the observational gaps over the sea to document the initial development of precipitating systems and the upwind offshore moist flows that feed these systems.*

4.4.1 Operational meteorological observation systems

Existing meteorological observation networks will form the backbone of the observation strategy to characterize the Heavy Precipitation Events (HPE) meteorological environment at the synoptic and meso scales. Besides the operational sounding stations, these networks include a lidar network devoted to the monitoring of aerosols and water vapor, a GPS network complementing moisture observations, a weather radar network, quite dense over the North Western Mediterranean, allowing to track the precipitation systems, and different lightning detection systems providing complementary information on the convective activity. Most of these systems are operational or quasi-operational. They will be at use during the HyMeX LOP and significantly reinforced during the EOP and SOPs.

4.4.1.1 Sounding network

The operational sounding network (Figure 4.9a) is reasonably dense along the Mediterranean coasts. However, some effort will be made to increase the frequency of the ascents and to enhance the network in places where it is too coarse. Special attention will be paid to redesign the network according to the needs of the budget studies. In addition, the understanding of the role of the complex topography may require low level soundings in specific locations (*e.g.* valleys).

4.4.1.2 Lidar network

A lidar network is currently operated operationally to monitor aerosol and water vapor. It includes 10 sites, mainly distributed over Italy and France but covering a relatively wide range of situations representative of coastal and open ocean areas in the Mediterranean (Figure 4.9b). Among these lidars, two of them can be moved to different sites to fulfill the HyMeX objectives. This network will be used to document the spatial and temporal variability of the water vapor vertical distribution of the Mediterranean during the EOP.

4.4.1.3 GPS network

GPS receiver networks have been extensively developed in Europe during the last decade. The processing of GPS data produces tropospheric delays which contain valuable information on the total water vapour column and are now currently assimilated in NWP models. HyMeX will make full use of this data set, will promote the extension of the existing network, especially over North-African countries (Figure 4.9c). The possibility of shipborne GPS receivers is also being investigated.

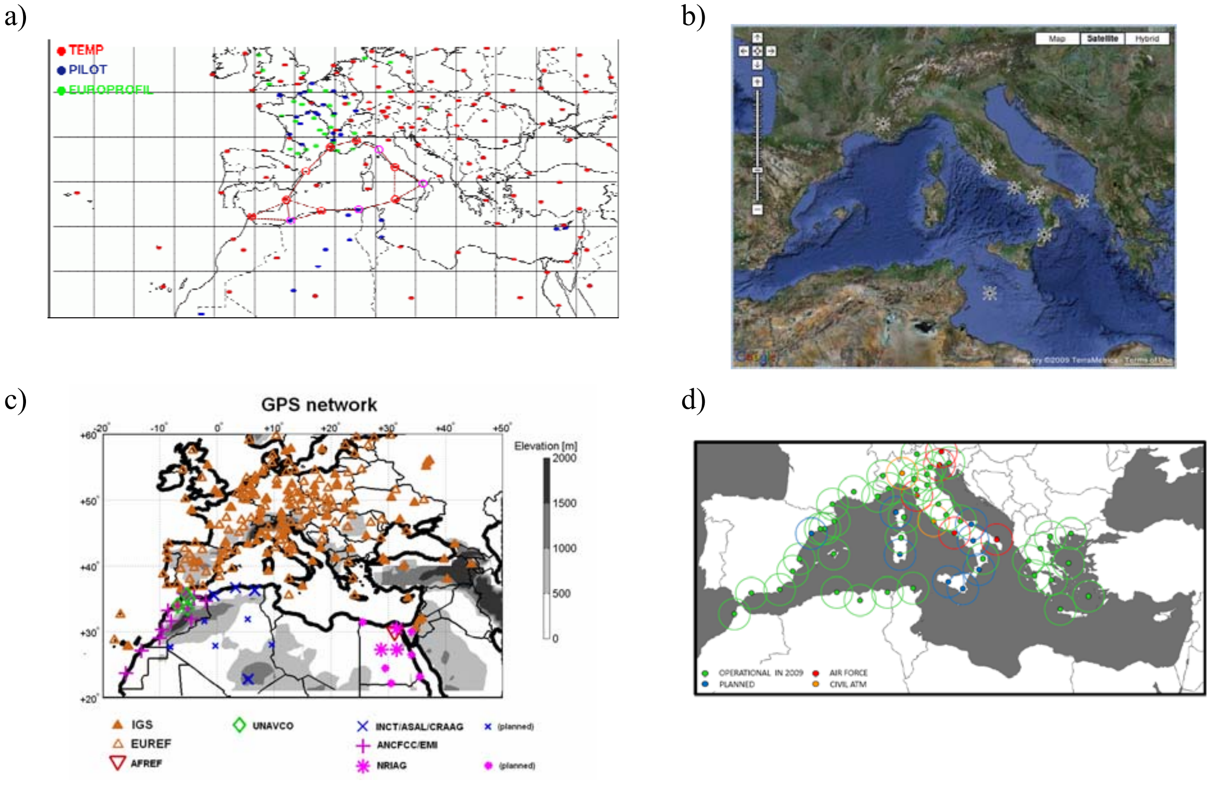


Figure 4.9. a) Operational sounding network (red bullets) and its envisaged extension (magenta circles) for water budget studies; b) The current lidar network; c) The GPS network and its planned evolution; d) Operational weather radar network and its planned evolution.

4.4.1.4 Radar network

The different European weather radar networks will be relied upon to investigate the amount and spatial distribution of rainfall over the Mediterranean. So far more than 20 radars have been identified along the North-Western Mediterranean coasts (Figure 4.9d). They will provide high-resolution (~1 km^2) reflectivity and quantitative precipitation estimates along the coastal regions. As most of these radars are equipped with Doppler capabilities, vertical wind profiles will be used to complement the wind observations provided by the soundings and the wind profilers. Again HyMeX will seek for more involvement from Northern-African and Eastern Mediterranean countries.

4.4.1.5 Lightning network

Four operational lightning detection networks -the two long-range networks ATDnet (UK Met Office) and ZEUS (National Observatory of Athens), the European operational network Euclid and the LINET (nowcast GmbH)- operating at different radio frequencies and using different technologies will record the lightning activity over the Mediterranean Basin, including all Target Areas, hydrometeorological sites and ocean sites during the LOP, EOP and SOPs. Research-oriented instruments (lightning locating, ground-based electric field, electrical charge on rain drops and acoustic sensors) will be deployed during the SOPs to provide additional observations to document the properties of electrical activity over the SOP domain.

4.4.2 Hydrometeorological observatories, super-sites and pilot-sites

In addition to the operational instruments, the concept of hydrometeorological observatory (HO) is proposed to support and refine the HyMeX observational activities over specific sites during the entire LOP.

This should include the following tasks:

- Collection, critical analysis and dissemination to the HyMeX international scientific community of the meteorological and hydrological datasets from operational observation systems. Depending on the TAs, such observation systems are more or less rich. In addition, barriers to data exchange at the national and international levels are still very present and need to be overcome as far as possible.
- Contribute to establish and operate a set of so-called super-sites devoted to meteorological and/or hydrological process understanding studies:
    - meteorological super-sites are foreseen within or far upstream the main TAs (*e.g.* Corsica, Balearic Islands, Montpellier). During the EOP and more intensively during the SOPs the existing observations will be considerably reinforced with the deployment of additional instruments (*e.g.*, wind profiler, water vapour lidar, densification of the GPS network, vertically pointing radars, Doppler Radar on wheel, aircraft in situ and remote measurements) with the major goal of providing a 4D documentation -as exhaustive as possible- of the convective systems leading to HPE and to orographic rainfall as well. Special effort will be put in the systematic delivery of elaborated products such as 3D wind field and microphysical retrievals from radar measurements, quantitative radar rainfall estimate, or water vapour tomographic analysis. Most of the meteorological super-sites will be specifically set up for the HyMeX EOPs and SOPs.
    - in a similar way, hydrological super-sites (small watersheds of some km^2) will be devoted to hydrological process understanding, e.g. flash-flood genesis in specific geological formations (primary era formations, karsts,…), and in catchments influenced by anthropic activities (urban areas, agriculture), erosion and sediment transport in mountainous catchments. The hydrological super-sites will be equipped with specific instrumentation to characterize the various terms of the water, mass and energy budgets from the plot and/or the hillslope scales up to the scale of small catchments. Most of the hydrological super-sites already exist and need to be reinforced.
- Establish a set of so-called pilot-sites (geographical areas and/or watersheds of some 1000 km^2) devoted to multi-disciplinary integrative studies associating geoscientists and socio-economists, *e.g.* about water resources and risk assessment and prediction at the regional scale in a changing climate and with increasing anthropogenic pressure. Due to limited manpower and funding, one should try to select a number of complementary pilot-sites among the various TAs and sites, *e.g.* urban, coastal, medium-elevation, high-elevation catchments representative of the various Mediterranean climates (from alpine to semi-arid).
- Organize to perform post-event surveys after the most extreme events wherever they occur in the Mediterranean during the LOP. A methodology, mostly based on the reconstruction of rainfall-runoff dynamics, will be upgraded with indirect methods for peak discharge estimates, geomorphic analysis (*e.g.* mapping erosion and deposition,

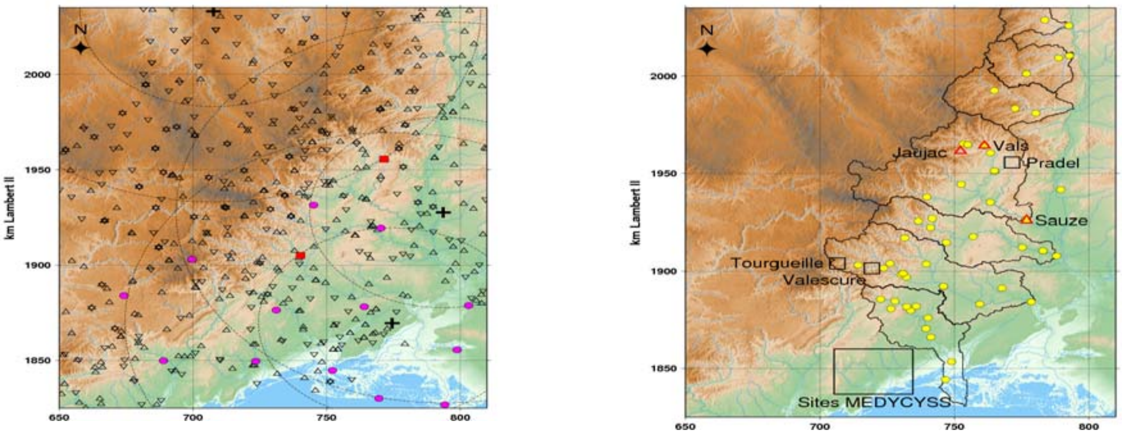


Figure 4.10. The OHM-CV: a) hourly raingauge network (open bottom-pointing triangles), daily raingauge (open top-pointing triangles), disdrometers (red boxes), ARAMIS weather radar network (black crosses and 50-km/100-km range circles), GPS receivers (pink bullets); b) operational hydrological stations (yellow bullet), LSPIV hydrological stations (red triangles), from top to bottom, in black lines are delimited the main watersheds of the Vivarais (Doux, Cance, Eyrieux) and of the Cévennes (Ardèche, Cèze, Gardons, Vidourle). The HyMeX hydrological super-sites included in the region are indicated by the black boxes.

displaced volumes, destructions induced) and documentation of individual and organizational vulnerability.

The "Observatoire Hydrométéorologique Méditerranéen Cévennes-Vivarais" (OHM-CV Observation Service) is such an example of HO included in the North Western Mediterranean TA (Figure 4.10). It contains two pilot-sites (Ardèche and Gardons) with several hydrological supersites (Valescure, Pradel, Tourgueille) and upstream meteorological supersites (*e.g.* the Montpellier supersite) included in the so-called Cévennes-Vivarais site. For the study of hydrogeological processes, two additional existing pilot-sites are considered in the region to document the karstic aquifers (the MEDYCISS pilot-site) and the coastal multi-layer sedimentary aquifers, respectively. A third-one (Draix-Bleone) is dedicated to the study of sediment fluxes.

4.4.3 Upstream monitoring

In their mature phase most of the convective systems leading to HPE in the selected TAs can be well monitored with the existing ground based observational networks. However their initial development usually occurs offshore in areas which are basically void of observations. Filling these observational gaps will be one of the most challenging tasks of HyMeX. For that, several observational platforms will be operated during the SOPs:

- offshore observations (buoys, ships) will be enhanced and/or developed.
- two island supersites (Corsica and Balearic Islands) will be used to characterize the far upstream conditions for continental HPE.
- different aircrafts instrumented with dropsondes capabilities, water vapour lidar, and if possible, wind Doppler lidar will provide essential information regarding: i) the structure of the low-level inflow coming from the Mediterranean sea including air sea fluxes, ii) the structure of the upper level flow with a specific focus on the southern tip of the upper-level thalweg or cut off low.

- instrumented balloons (boundary layer pressurized balloons and aeroclippers) will be launched from upstream sites (African coasts, Balearic islands or Corsica) and will complement the documentation of low-level inflow.
- a wind profiler network will be used to derive the horizontal wind field divergence and vorticity above the Mediterranean independently of any analysis product.

4.4.4 Aircraft operations

Aircrafts deployment is a crucial element of the observational strategy for various reasons: i) some major HPE may occur outside of the selected sites and would be very poorly sampled without aircraft, ii) HPE are often related to offshore development and/or synoptic scale systems extending at least partially over the sea, iii) in situ measurements are critically needed to assess and/or validate some of the products derived from the ground based observation system, iv) while ground-based systems provide continuity in time, aircrafts allow to gain high temporal and spatial resolution measurements.

Currently the following platforms are being considered for the North Western Mediterranean TA: the French SAFIRE FALCON and ATR 42, the German Gulf Stream HALO and KIT Dornier 28, and also possibly but still pending the US NRL-P3.

- In the pre-initiation phase of a HPE, the NRL-P3 and HALO (both long range, and high ceiling aircrafts) will be used to study the upper level precursors (*e.g.* PV anomalies, cutoff lows,…)
- During the initiation phase, the DO28 and ATR 42 will primarily sample the upwind low-level flow and will focus on the pre-convective environment. Depending upon the level of cloudiness, the ATR 42 will switch from water vapour lidar measurements to microphysical measurements.
- During the mature phase, the NRL-P3 and SAFIRE FALCON will observe the precipitating systems making use of their microphysical probes and radar systems (ELDORA and RASTA respectively). For safety reasons, the FALCON will mainly operate in the stratiform anvil.
- As an alternative or in complement to the NRL-P3, the British BAE 146 could be solicited (via the EUFAR programme).

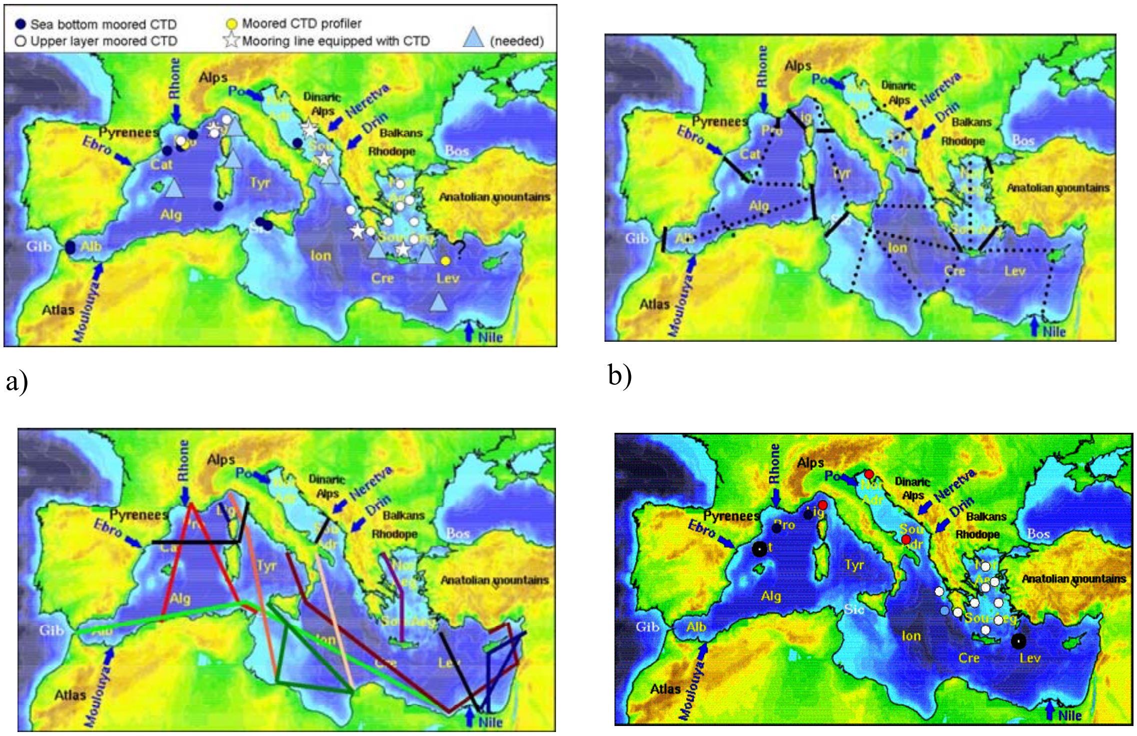
4.5 Observation strategy overview of the intense air-sea fluxes

The main objective is to set up a multi- Earth compartment experimental strategy allowing simultaneous measurements:

- *in the marine atmospheric boundary layer,*
- *in the oceanic mixed layer depth,*
- *at the air-sea interface,*
- *where the heat, salt and momentum exchanges need to be quantified through the measurement of the radiative, turbulent and water fluxes.*

In addition, deep water formation needs to be explored at different time scales.

In contrast to radiative fluxes and precipitation that are measured, the evaluation of turbulent fluxes (wind stress, sensible and latent heat fluxes) may result either from the use of meteorological and oceanic parameters together with a bulk formulation, or more directly



a)

b)

c)

d)

Figure 4.11. Strategy at the basin scale for the LOP: a) moored CTDs to monitor the mixed layer depth variations, the dense water formation characteristics and spreading (circles). The present network, involving many different partners, has to be maintained and extended (additional planned moorings are indicated by blue triangles). The monitoring of the straits should include ADCP measurements too; b) yearly or bi-yearly CTD transects performed by gliders or vessels to monitor the mixed layer depth variations, the hydrological characteristics of the water masses over the whole water column, the dense water formed and its spreading; c) hypothetical network of ships of opportunity carrying autonomous instruments to measure meteorological, air-sea and sea surface parameters, episodically performing XBT transects to monitor the mixed layer depth variations and the thermal heat content (for SOP1). The surface variables that should be available in (near)real time are: air temperature, air pressure, humidity, wind, sea surface temperature (to derive bulk turbulent fluxes), radiative fluxes, sea surface salinity, tropospheric delay (with GPS); d) surface buoys (measuring Tair, SST, P, RH, wind, SSS, SWR, LWR) that exist and should be maintained to measure strong local winds: (dark blue) France, (red) Italy and Croatia, (white) Greece POSEIDON network, and (light blue) Greece Pelops supersite. In black circles, areas which need to be instrumented.

from turbulence measurements, using both the inertio-dissipative method (IDM) and eddy correlation method (ECM). As the direct estimation of IDM and/or ECM turbulent fluxes requires expensive instrumentation together with a careful analysis of the high frequency measurements of temperature, humidity and wind, this approach will be restricted to the SOPs, while the bulk estimation of the turbulent fluxes will be performed for the LOP/EOP/SOP periods. More generally, two strategies will be used, depending on the observational periods.

The LOP observational strategy should allow the documentation of the interannual variations and the long-term evolution of the deep water formation in the three Target Areas of the Mediterranean Sea. The LOP strategy is based first on an increased deployment of CTD mooring (vertical profiles of temperature, salinity, oxygen and nutrients) to obtain a basin scale network (Figure 4.11a). This network should be reinforced by annual or bi-annual transects at several locations using vessels or gliders (Figure 4.11b), and by XBTs from ships of opportunity (Figure 4.11c). Sea surface measurements (temperature, humidity, pressure, wind, solar and infra-red heat fluxes, sea surface temperature, sea surface salinity) will be provided by the buoys network (Figure 4.11d). Sea rain measurements will be collected from a network gathering buoys equipped with rain gauges (RG), weather radars along the coast and moored passive acoustic listeners (PALs). The EOP should enhance the network at the basin scale with continuous transects in regions of dense water formation, mainly using gliders or Voluntary Observing Ships (VOS).

The SOPs are dedicated to document the seasonal changes at a regional scale and focus on air-sea process studies in the three Target Areas (the North Western Mediterranean, the Adriatic Sea and the far Eastern Mediterranean). During the SOP, the previously described network for sea surface parameters, ocean vertical profiles and precipitation will be complemented with:

- measurements performed by instruments from R/V (atmospheric mast, CTD profiles, XBTs,…),
- airborne measurements of the vertical thermodynamic structure of the marine atmospheric boundary layer (vertical profiles of temperature, humidity and pressure), together with microphysical parameters and turbulent fluxes.

4.5.1 The observation strategy for the North Western Mediterranean TA

Concerning the North Western Mediterranean TA, the LOP strategy should be reinforced by the MOOSE initiative aiming at gathering and harmonizing the continuous monitoring of this area (from the coastal to deep waters). MOOSE is an appropriate framework to ensure the long term observation of regional processes, namely shelf dense water and offshore dense (likely deep) water formations. The backbone of MOOSE (Figure 4.12) will be permanent deep offshore moorings, a first one at the center of the Gulf of Lions convection area (42°N 5°E, investigated since the 60s but not on a regular basis), another one in the Ligurian Sea (DYFAMED area), the latter ensuring the continuity of an existing 20 year-long time series. These two lines are moored in the vicinity of the meteorological buoys of Météo-France. They are equipped with CTD and currentmeters from about 150 m under the surface to the seafloor and then should monitor the mixed layer depth and convection during the different stages (pre-conditioning, mixing and restratification). The key point of monitoring the upper 100 meters is not solved yet but should be addressed by adding T measurement chains to the meteorological buoys down to 200 m, together with a few conductivity sensors (for salinity). The monitoring of shelf dense water cascading on the margin is also an objective of MOOSE which should be ensured through: maintaining the moorings deployed in canyons on the continental slope of the Gulf of Lions for more than ten years; if possible, new deployments either in areas which have been recognized recently as the main conduits of dense water, or in new sites suspected to contribute significantly. In complement for the LOP, several ARGO profilers measuring temperature and salinity will document the water mass distribution and its seasonal variability linked to mixing and convective processes. A large number of ARGO profilers should be launched by SOO or R/V prior and during the SOPs to monitor the time evolution of mixed layer depths and water masses characteristics (down to 2000 m).

The objective of the EOP is to assess the convection variability and the volume of dense water formed, which cannot be captured by one mooring even if it is deployed at the optimal location. Thus the convection area should be regularly covered by gliders transects. Gliders will provide vertical profiles (max. 1000 m deep) of temperature and salinity (and some

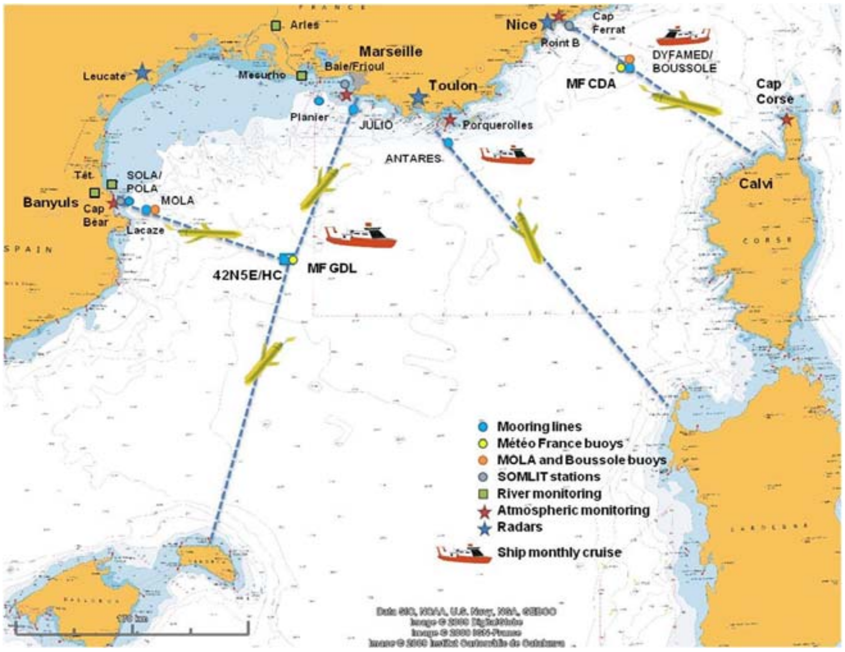


Figure 4.12. The observation network proposed for MOOSE

biogeochemical parameters) along a pattern that has yet to be discussed with other components (MOOSE, MERMEX) in order to best address all the needs. These glider surveys should also help to constrain high resolution processes models.

The SOPs are dedicated to the formation and dispersion of dense water. The campaigns at sea will be organized jointly with MERMEX to optimize the requests for shiptime, so-called HYMEReX. The expected result is to evaluate uncertainties on the different terms of the budget, to estimate corrections to bring to our models and to estimate the minimum observations needed to constrain the models on the long-term. Several scientific cruises should help to monitor this basin-scale process at different time steps: enhanced monitoring of water masses and mixed layer depth evolution before (SOP1.1) and at the end of the convection (SOP2.1) when the dense water volume is maximum; annual cycle budget closure and estimation of the volume of dense water that has been dispersed out of the formation area (with SOP1.2); documenting the effect of intense events on the early destratification of upper layers (SOP1.1 and SOP1.2). A preliminary sampling plan has been proposed for the North Western Mediterranean based on an array of CTD stations dense enough to detect and characterize the mesoscale eddies (Figure 4.13). The research vessels might also be used to retrieve and re-deploy ARGO floats and gliders at strategic points.

During SOP2 over the North Western Mediterranean TA, cyclogenesis over the Genoa Gulf and the Mistral and Tramontana wind events will be also documented, including the air-sea fluxes during these events. The observation strategy for the atmospheric compartment during Mediterranean cyclones and regional wind events is close to the one developed for heavy precipitation. The observation strategy involves the same observation platforms and means as the ones deployed during SOP1, even though the international aircraft involvement is expected to be more important for the fall 2012 SOP1.1.

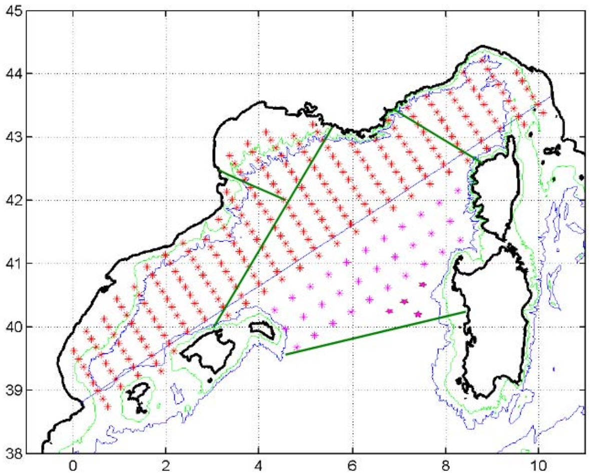


Figure 4.13. The HyMereX cruise for the Northwestern Mediterranean TA. The array devoted to one RV ("L'Atalante" will be requested) includes about 300 stations located every 8 miles (or narrower) along transects distant of 20 miles (narrower in the vicinity of topographic slopes to better describe the structure of the boundary currents). The potential glider transects are indicated by the green lines.

4.5.2 The observation strategy for the Adriatic Sea TA

The Adriatic is the formation site of the important component of the Eastern Mediterranean Dense Water (EMDW) and its efficiency is a function of the air-sea heat fluxes and the buoyancy advection from the Ionian. The Adriatic and Ionian interact as a unique feedback system and thus the observation strategy should cover appropriately both areas. In the Adriatic Sea (Figure 4.14), the LOP aims at monitoring the dense water formation rate and the characteristics (T, S) of the dense water formed (near the coast and in open sea) as well as interaction with the Ionian. The observation strategy is based on deep CTD moorings located near Split, Dubrovnik, and in the center of the South Adriatic Pit. Another slope mooring is planned in the Northern Adriatic to monitor the formation of North Adriatic Dense Water (NAdDW). The outflow of Adriatic Deep Water (AdDW) can be recorded by ADCP moorings in the Otranto Strait (to be maintained). In addition the EOP strategy will be based on CTD transects: one at the Palagruza Sill, one across the South Adriatic Pit (Bari-Dubrovnik) and one across the Ionian Sea along the 38°N. The NAdDW formed during strong Bora events in the Northern Adriatic flows southward along the West Adriatic coast and crosses the Palagruza section few weeks after. This transect is a key point of the process monitoring. The SOP strategy is based on the CTD network of the EOP, but at a higher frequency, and will be coupled to measurements and calculations of evaporation during winter and summer Bora and Sirocco events. Thanks to the multidecadal time-series of T-S and biogeochemical data, it will be possible to detect long-term trends and regime shifts. It is also important to record the outflow of deep water at the Strait of Otranto with three ADCP moorings.

As regards the strong winds -Bora in this region, the LOP will make use of the existing instruments deployed along the coast: surface data (air temperature, wind, humidity, pressure, precipitation, etc), radio sounding data (two stations Zagreb-Maksimir and Zadar-Zemunik), radar data (15 minutes, reflectivity and velocity data), additional measurements by sonic anemometer would be available (Geophysical Institute, University of Zagreb). It is also planned to setup a transect perpendicular to the Adriatic coastal mountains to monitor Bora wind using high sampling rate measurements (20 Hz) of wind, temperature and humidity.

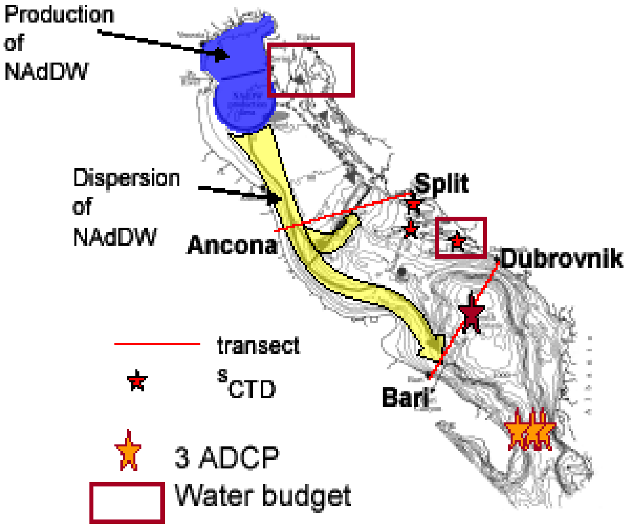


Figure 4.14. Strategy for the Adriatic Sea. For the LOP, several CTD moorings have to be maintained and three transects have to be done bi-annually or annually to record the stratification and water mass changes. For the EOP and SOP, the frequency of measurements has to be increased to bi-monthly to monthly. The ADCP in the Otranto Strait will inform on the volume of ADW that exits the Adriatic Sea toward the Ionian basin.

During SOP over the Adriatic TA, cyclogenesis and the local winds (Bora and Jugo) will be also documented, including the air-sea fluxes during these events. The observational strategy for the atmospheric compartment during cyclones and regional wind events is close to the one developed for heavy precipitation. International aircraft involvement is expected to be more important for the spring and autumn 2013 and 2014 SOPs.

The lidar measurements should be performed either as a permanent establishment of lidar measurements in Croatia or as a temporary solution. The existing lidar network is covering the southern part of Adriatic. However it is necessary to cover the northern Adriatic also. Since Italy already operates a large network of lidars, it is necessary to have one in Croatia in Istria Peninsula that is located at the head of the Adriatic between the Gulf of Trieste and the Bay of Kvarner. This area is characterized with highest yearly and seasonal precipitation amounts in Croatia (Climate Atlas of Croatia).

4.5.3 The observation strategy for the Aegean Sea TA

For the Aegean Sea and the Levantine basin (Figure 4.15), the strategy for the LOP is based on deep moorings. Three of them should be deployed in the Cretan Arc Straits and in the Rhodes Gyre. Bi-annual to annual surveys could be planned in the Aegean Sea and in the Cretan Passage to document the water mass spreading. The monitoring from Cyprus to Alexandria will inform on the dense Levantine water spreading in the Levantine basin. The SOP is based on CTD transects in the Aegean Sea and glider tracks in the Levantine basin, at high frequencies, to catch the water mass formation process.

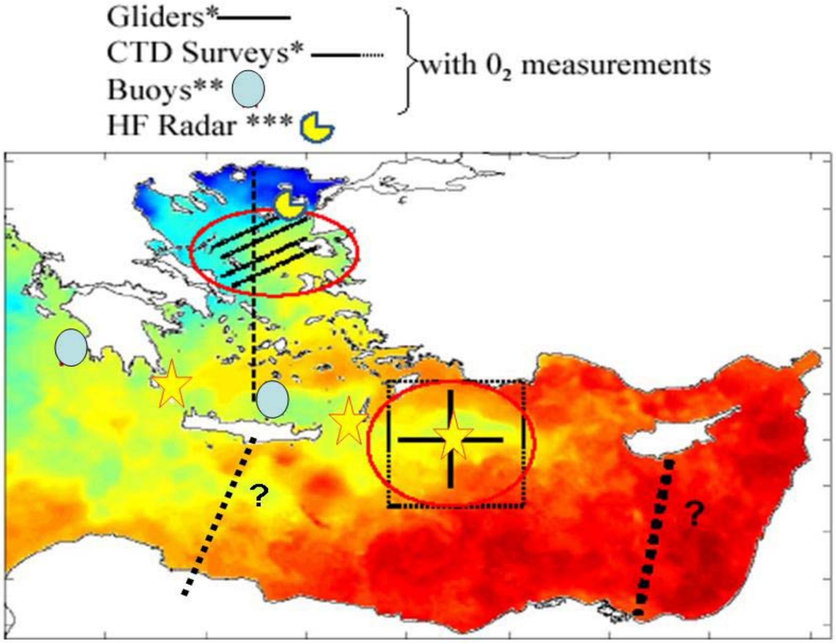


Figure 4.15. Strategy for the Aegean Sea and the Levantine basin. Yellow triangles correspond to moorings (CTD + ADCP) that have to be deployed.

4.6 Observation strategy overview for monitoring vulnerability and adaptation capacity

Concerning the social vulnerability and resilience to intense impact events , the observation strategy follows the multi-scale approach of the other WGs based on LOP/EOP/SOP and pilot-sites and sites, aiming at enhancing the collaboration between societal impact scientists and geophysical scientists.

The LOP is needed to establish common criteria to select the events and required information to monitor vulnerability factors in space and time. For this period it would be needed to have data about damages and their social impact, but also rainfall and hydrological data. Similar sites and pilot-sites as in WG3 have thus to be selected. The strategy is to lead regular surveys or investigations in order to collect data on “internal” and “personal” factors of vulnerability in flash-flood situations.

Besides data required for the LOP, supplementary data for learning from post-event investigation are also required for the EOP. Press and mass-media coverage as well as reports required to Meteorological Services and Civil Protection would be exploited in this period.

Intensive observation periods focused on warning systems and communication processes are required to progress on data collection concerning: i) communication during crisis, ii) mobility observation and more particularly adaptation of travel patterns during crisis, iii) vigilance and warning period observation, iv) crisis management. These activities will be concomitant to the heavy rain and flash-flood SOPs. Participative observations concerning warning processes will complement the traditional interviews after crisis or outside crisis.

4.7 Modelling and data assimilation strategy

4.7.1 Regional Climate Modelling strategy (WG1)

The HyMeX project wants to promote the development of Regional Earth System Models in order to provide a better description and understanding of the Mediterranean water cycle and its variability and trend, and to develop a new set of regional climate change scenarios.

The HyMeX modelling strategy will be based on the following considerations:

Higher-resolution AORCMs (30-50 km) represent our best shot at including process information, and are favoured for simulations of contemporary and future conditions as well as time-slice simulations of decadal climate prediction. Single model components (ORCM, ARCM,...) working at different levels of spatial, temporal and process resolution are seen as complementary. Hindcast runs (1960-2010) will be considered mandatory within the HyMeX context.

The higher-resolution AORCM models will be based on the experience of the CIRCE project. They will provide a first stream of regional scenarios based on the AR4-A1B emission scenarios. HyMeX will promote the development of a new set of climate projections (stream2 scenarios) based on the AR5 emission scenarios (Med-CORDEX under the WCRP and MedCLIVAR umbrella).

A grand ensemble of simulations of present day and projected Mediterranean climate (new AR5 scenario) will be provided using high-resolution (30-50 km) and very high resolution (7-15 km) ARCMs in order to develop a reliable data-base for investigating uncertainties in future climate projections and extreme events.

HyMeX will also be a unique opportunity to test the skill of the newly-developed decadal forecast techniques for the Mediterranean area. Simulations performed in other contexts (IPCC-AR5, FP7-COMBINE projects, national efforts) will be evaluated over the Mediterranean area for their capability to foreseen decadal evolutions of the MSWB and associated extremes.

The HyMeX project intends to improve the modelling components of the Regional Earth System by implementing a set of experiments which enhance the possibility of comparing model outputs with the data gathered during the field campaign. This issue requires an ad-hoc strategy for the numerical experiments (the climate models should be run at normal and at very-high resolution, with ad hoc outputs) and for the types of data to be measured and the way all the field campaign data will be synthesized (regional assimilation system, data-base tailored for modelling comparison). The simulations (RESM and very high resolution ARCM-ORCM) for the LOP/EOP/SOP should be considered as mandatory. Using the unique set of in-situ data collected during the field campaign as well as well designed regional climate models should allow to improve the various physical components of the RESM working on the physical parameterizations (atmospheric boundary layer, air-sea flux bulk formulae, ocean turbulence and convective scheme), on the optimal design of the models (resolution, driving mode, coupling) and on the balance of the Mediterranean water and heat budget.

Based on these HyMeX RESM, we could also start interacting with the marine ecosystems and chemistry and aerosols Mediterranean community: modules will indeed be developed to express the interactions of the physical climate system and the biosphere through physical coupling, biosphere and atmospheric chemistry, taking into account current research on aerosols and land-surface processes and models.

Besides within the context of the HyMeX field campaign, high-resolution ocean (or coupled) models running for coastal area or straits or even for the Mediterranean will provide process studies to support the LOP or SOP and to be used as a useful test bed for the RESM or the AORCMs.

4.7.2 Continental hydrological cycle modelling (WG2)

For WG2, the modelling strategy is organized according to three scales.

4.7.2.1 Whole Mediterranean catchment

Model	Characteristics	Group
ARPEGE-SURFEX (use of ERA-Interim 80 km reanalysis)	Improved resolution 10 km, use of high quality forcing, near real time satellite products, inclusion of a routing module	CNRM, France (J.F. Mahfouf)
ARPEGE-SURFEX (use of near real time analysis at 16 km)	Simulation of streamflow, evapotranspiration, soil moisture, extend existing catchments to the whole Mediterranean (near real time simulation for the LOP)	CNRM, France (J.C. Calvet)
LISFLOOD (possibly)	Simulation of streamflow, evapotranspiration, soil moisture, extend existing catchments to the whole Mediterranean	JRC, Italy

Note that the Regional Climate Modelling community is already running coupled climate/ ocean/continental surfaces regional models over the whole Mediterranean. In particular, those models already provide discharge simulation of the major rivers flowing to the Mediterranean and it is also planned to take irrigation and dams into account. The WG1 and WG2 initiatives complement each other as follows:

- WG1 is interested not only in the simulation of the continental water cycle during the 10 years of the LOP, but also in simulations of a climatology covering ca. 25-30 years.
- One of the proposals of WG2 fits these objectives. It is the proposal by CNRM/Météo-France to perform a reanalysis from 1989 to the present days using the coupled ARPEGE/SURFEX/River routing scheme modelling approach forced by the new ERA-Interim reanalysis at 80 km, improved forcing, like SAF data for radiation. This reanalysis will provide a climatology of soil moisture, river discharge and all the components of the water balance, which can be used by WG1 modellers to assess the quality of their models. Other initiatives using alternative models are also welcome.

4.7.2.2 Regional/pilot site scale

Model	Area	Simulated processes	Contact
SIM	France	Surface energy balance, evapotranspiration, soil moisture, streamflow, groundwater flow	CNRM, France
LIQUID platform	Gard and Ardèche river	Evapotranspiration, soil moisture, streamflow.	Cemagref HHLY, France

Model	Area	Simulated processes	Contact
AFFDEF	Secchia, Reno, Samoggia and Sieve rivers in Italy. Extension to the Emilia Romagna region	Evapotranspiration, soil moisture, streamflow.	University of Bologna, Italy
Safran-SURFEX	Ebro basin, internal basins of Catalonia	Surface energy balance, evapotranspiration, soil moisture, streamflow?	Ebro Observatory, Spain AEMET, Spain
CHyM	Set up over Croatia	Streamflow, others?	Hydrometeorology Services, Croatia
	Set up over the Duero basin		To be determined

4.7.2.3 Local scale/super-site scale

With the data collected at the local and super-site scales, the scientific questions about process studies listed in the ISP will be tackled. From a modelling point of view, the objective is to derive parameterizations adapted to regional scale modelling (for instance improvement of Mediterranean ecosystem functioning, improvement of snow representation, better account of lateral soil moisture redistribution by topography, etc,...)

The above lists are not closed and contributions are welcome.

4.7.3 Heavy precipitation and flash-flooding modelling (WG3)

A wide range of modelling issues will be addressed during HyMeX both in terms of atmospheric and hydrological modelling but also in terms of coupled hydro-meteorological modelling.

4.7.3.1 Atmospheric modelling

A wide range of activities will be implemented, spanning from idealized simulations to real time data assimilation and operational forecasting. Idealized simulations will focus on the understanding of the physical processes leading to HPE and on the identification of control parameters. They will provide the essential reference framework for analyzing real case studies. Going one step further, hindcasting or post event analyses will allow to investigate the full complexity of HPEs and to rank the different processes at work. Finally various real time forecast systems will be developed and operated during the HyMeX SOPs (e.g POSEIDON at 5 km resolution over the full Mediterranean basin, AROME and MOLOCH at 2.5 km resolution over the Western Mediterranean). In addition, many new observations (*e.g.* radar reflectivities, GPS, and non conventional data like research aircraft observations) will be taken into account in the data assimilation systems. In parallel, ensemble forecast systems will be developed to address the predictability of the HPEs. Specific attention will be paid to upper level potential vorticity anomalies.

4.7.3.2 Hydrological modelling

Hydrological modelling will be implemented at a variety of scales, with modelling solutions that will be adapted to the considered scale and data availability. In terms of spatial scales, modelling will be implemented at the continental, regional and local scale. In terms of temporal scale, simulation will be performed at time step varying from a few minutes for physically-based models to one day for a simulation of the whole water cycle (including evapotranspiration) in order to get a better estimation of initial soil moisture before extreme events.

For the purpose of flood modelling, simulations at the regional scale are required at a fine time step. Therefore conceptual models will be used in order to minimise computational requirements. Model calibration will be carried out at regional scales, but variations of the model parameters from catchment to catchment will be allowed. An innovative experiment will be carried out by developing a spatially distributed rainfall-runoff model at regional scale, where the model parameters will be assumed of the same value over the whole region therefore ensuring an increased robustness. To this purpose, the parameters will be calibrated against a regional data base. Distributed modelling requires a high computation effort that will need to be reduced in order to allow the application at extended spatial scales. In this case the simulation will refer to a daily time step, thus significantly reducing the computational requirements for flow routing. An innovative approach will also be proposed for estimating the global uncertainty of the simulation. As a matter of fact, uncertainty estimation in hydrology is today considered an essential requirement and is the subject of significant research efforts.

4.7.3.3 Hydro-meteorological modelling

TBD

4.7.4 Intense air-sea fluxes modelling strategy (WG4)

Basin-scale models are needed to study the general ocean-atmosphere-land circulations. These models should resolve the **mesoscale** in order to reproduce the cyclogenesis processes, the strong local winds influenced by topography, the convection and the coastal oceanic currents. A specific effort should be dedicated to **reanalyses** for the last decades. Another point is to make **sensitivity experiments**. On one hand, these basin-scale models could provide boundary conditions of regional models of higher resolution. These **higher resolution regional models** and **process models** have to be developed now to prepare the EOP/SOP and to work on the air-sea interactions through the parameterizations. On the other hand, these basin scale models will support the development and performances of **operational tools** dedicated to assist the EOP and SOP. In particular for the ocean part, there is a strong need of **updated in situ data** before doing a realistic reanalyzed product. Another point concerns the need of a **new higher resolution Mean Dynamic Height** of the sea using satellite and in situ data to increase the assimilation performance in simulating the coastal Mediterranean currents.

Concerning the basin-scale models:

- At this step, some tools are already planned in operational mode. For the atmospheric part, the future ECMWF analyses should be at a resolution of 15 km in 2010. For the oceanic part, Mercator operational ORCA12 should deliver oceanic daily fields at about 8 km resolution which can be used as a first guess to provide high resolution reanalyses for the high-resolution regional models. During the SOPs, the use of the Atmospheric Adaptative Observation and regional weather modelling could be planned.
- In research mode, the NEMO-MED12 (8 km) oceanic model forced by WRF (7-20 km), ARPERA (50 km) and future ECMWF (20-60 km) could provide boundary conditions for regional models.

Concerning the regional models:

- At this step, some proposals have been made for the Adriatic Sea, the North Western Mediterranean and the far Eastern Mediterranean. These models more or less cover the area covered in the SOPs and EOP.
- For the Adriatic Sea, atmospheric models at very high resolution are proposed (ALADIN/HR 8 km; WRF 1 km) and one coupled model at ~300 m horizontal resolution should be dedicated to process studies and air-sea parameterisations.
- For the Aegean Sea and Crete areas, the atmospheric models ALERMO-ARPERA (3-50 km) and BOLAM (7-15 km) in research mode and the WRF (1 km) in operational mode.
- For the North Western Mediterranean, the atmospheric models WRF (7 km) in research mode and AROME (2 km) in operational mode, and the oceanic model SYMPHONIE in research mode.
- Embedded regional models in operational basin-scale models, like in MFTEP for the ocean, have to be prepared in order to be able to run during the SOPs in forecast mode during several days after being initialized by the first SOP observations.
- For the ocean part, regional models of higher resolution ($\Delta x = 1$ km) will be also implemented in the hydrological network area and run during the year-long HyMeX experiment in order to provide a set of reference simulations for process studies in line with WG4-SQ2 and WG4-SQ3. Two strategies are considered. The first one is based on the grid-nesting technique used to downscale the hydrological network region or any other region (the Aegean Sea for example). This can be done by embedding a high resolution model into a large resolution basin-scale model (like MED12) using the AGRIF tool. The second strategy is to directly implement a high resolution limited area model as SYMPHONIE or GDLAzur64 over the hydrological network zone. It is very important to note that both numerical approaches need to be initialized and forced at their lateral boundaries by high resolution reanalyses derived from the hydrological measurements during HyMeX. Realism of the high-resolution regional simulations depends on ad-hoc heat and momentum surface forcing.

5. Coordination with other entities and programmes

Since the premise of HyMeX in 2005, the coordination of the project has sought for international cooperation by promoting the HyMeX project at international conferences and before international programmes, in particular the THORPEX programme of WMO (through the T-NAWDEX and MEDEX programmes) and the ESF networking MedCLIVAR programme, and by early opening the HyMeX workshops to the international community. These initiatives have led to the organisation of HyMeX at the international level with an International Scientific Steering Committee (ISSC), working groups and task teams, and representatives of HyMeX in MedCLIVAR scientific steering committee and vice-versa.

WMO programmes: WCRP/GEWEX and WWRP/THORPEX

In 2009, the HyMeX coordination has sought to carry out HyMeX under the umbrella of two major international programmes of WMO dealing with the water cycle and high-impact events: WCRP GEWEX (Global Energy and Water Cycle Experiment of the World Climate Research Programme) objectives cover the main scientific questions of WG1, WG2 and part of WG5 of improving the understanding of the global hydrological cycle and prediction of its evolution; WWRP THORPEX (The Observing System Research and Predictability Experiment of the World Weather Research Programme) seeks to accelerate improvements in the accuracy of 1-14 day forecasts of high-impact weather for the benefit of society, economy and environmental stewardship and, as such, covers the questions raised in WG3, WG4 and part of WG5. HyMeX has obtained WWRP and WWRP-THORPEX endorsement from the WWRP Joint Scientific Committee (JSC). HyMeX has also been formally labelled in summer 2010 as a regional hydroclimatic site within the framework of the GEWEX programme. Several HyMeX hydrometeorological sites in Italy, France, and Israel are long-term reference sites of the HyMeX RHP.

WWRP related programmes

From its beginning, HyMeX has worked towards coordination with THORPEX related programmes. A phasing of the periods of intense observations between HyMeX and THORPEX/T-NAWDEX is wished. The T-NAWDEX field experiment is tentatively scheduled for autumn 2012, at the same time as the first HyMeX SOP (SOP 1.1) dedicated to the observation of high-impact events over North-western Mediterranean. Mutual scientific and practical benefits of a collaboration between T-NAWDEX and HyMeX are obvious. The T-NAWDEX field campaign could provide HyMeX with the documentation of the upstream large-scale meteorological environment one to several days prior to the Mediterranean intense events, while HyMeX could provide observations on the downstream impacts over the Mediterranean of the Atlantic waveguide disturbances studied in T-NAWDEX.

The idea of a multi-scale large field experiment to finalise THORPEX/MEDEX was collected in the MEDEX second phase proposal (2005). The HyMeX field experiment can be considered in making this idea concrete even though HyMeX is much larger in terms of disciplines and scales. The current Data Targeting MEDEX campaigns will benefit to the enhancement of operational observation systems foreseen during the HyMeX EOP. These Data targeting MEDEX campaigns are carried out with the financial and operational support of EUMETNET Composite Observing System (EUCOS, http://www.eucos.net/) for the enhancement of the frequency of radiosoundings (Europe and North Africa operational soundings), observations onboard commercial aircraft (AMDAR) and ships (ASAP). A similar support from EUCOS to the EOP/SOP of HyMeX is sought.

WCRP related programmes

The HyMeX regional climate modelling activities contribute to the MED-CORDEX initiative included in the WCRP/CORDEX programme which aims to improve the coordination of international efforts on regional climate downscaling.

CIESM

CIESM (Commission Internationale pour l'Exploration de la Méditerranée, www.ciesm.org) is an intergovernmental organism. CIESM has corresponding scientists in nearly all riparian countries, and fosters Mediterranean-wide research programmes (www.ciesm.org/marine/programmes). The synergies between HyMeX and CIESM rely on 2 programmes: i) HYDROCHANGES aims at recording continuous, long-term measurements of temperature and salinity of Mediterranean deep waters with moorings in key areas -a priority, considering global warming uncertainties. Up to now about 10 moorings are being maintained in Dense Water Formation areas and in straits and channels. HyMeX is seeking funding to implement moorings on missing key places; ii) TRANSMED aims at developing a network of ships of opportunity for automated monitoring of the surface waters of the Mediterranean. Complementary to the HYDROCHANGES programme, it allows recording time series of cross basin transects, with a very high resolution in both space and time.

French research agencies

In France, the HyMeX programme is part of a cluster of research programmes called « Chantier Méditerranée ». The general objective of this cluster, coordinated and funded by the National Institute for Earth Science and Astronomy (INSU) of CNRS on behalf of the Committee of research on environment organisations (CIO-E[10]), aims to improve the prediction of the evolution of life conditions in the Mediterranean. HyMeX mostly addresses the specific transverse questions of the « Chantier Méditerranée » on natural hazards and Mediterranean climate. HyMeX also contributes to the other "Chantier Méditerranée" transverse questions on water resources management in the Mediterranean, human-climate-environment interactions, impacts of climate change on the biodiversity and on the coastal zone.

US National Science Foundation

US participation in HyMeX has been sought through collaboration with US universities and national laboratories on the basis of National Science Foundation proposals. Specifically, a proposal has been submitted to the National Science Foundation Partnership for International Research and Education (PIRE) programme by the University of Connecticut, the University of Maryland, the Smithsonian Institute and the Chapman University on a US-Mediterranean partnership under HyMeX umbrella to advance climate change research through a novel synthesis of studies on the hydrological cycle, extreme events, and effects on ecosystem processes in the Mediterranean. The proposal was rated competitive, but not recommended for funding in the 2009-2010 cycle. It will be resubmitted in the 2011 PIRE competition by further enhancing the linkage with the HyMeX science community and strengthening further its focus on hydrologic extremes. A science programme proposal to NSF is under development and led by the National Centre for Atmospheric Research with participation of

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[10] CIO-E is composed of the following institutions: ANDRA, BRGM, CEA, CEMAGREF, CIRAD, CNES, CNRS, IFP, IFREMER, INRA, IRD, IRSN, LCPC, Météo France.

several US academic institutions. The proposal seeks contributions from NSF to participate in HyMeX field campaigns aiming at the third priority of the HyMeX programme (i.e., heavy precipitation and flash-flooding).

Activities in Greece

The scientists from Greece involved in HyMeX have set up a research group to facilitate the formulation of a national research agenda on the Mediterranean water cycle aiming to address aspects of air-sea exchanges and impacts on storms and floods under changing climate and land use/cover conditions. A first meeting of the group took place on July 22 2009 at the Hellenic Centre for Marine Research. A whitepaper is under preparation that summarises the objectives of the Greek-HyMeX group which will be used to seek national funding for the field observations of HyMeX programme in the Eastern Mediterranean.

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Glossary

ADCP: Acoustic Doppler Current Profiler

AdDW: Adriatic Deep Water

AeDW: Aegean Deep Water

Alpilles-ReSeDA: Alpilles Remote Sensing Data Assimilation (http://w3.avignon.inra.fr/reseda/)

AMSL: Above Mean Sea Level

AOGCM: Atmosphere-Ocean General Circulation Model

ARAMIS: Application RAdar à la Météorologie Infra-Synoptique

ARIDE: Assessment of the Regional Impact of Droughts In Europe (http://www.hydrology.uni-freiburg.de/forsch/aride/)

ATI: Atmospheric and Terrestrial Influx

AUV: Autonomous Underwater Vehicle

AW: Atlantic water

BALTEX: The Baltic Sea Experiment (http://www.baltex-research.eu/)

CAPE: Convective Available Potential Energy

CCN: Cloud Condensation Nuclei

CDW: Cretan Deep Water

CICLE: Calcul Intensif pour le CLimat et l'Environnement (http://dods.ipsl.jussieu.fr/omamce/CICLE/)

CIRCE: Climate Change and Impact Research: the Mediterranean Environment (http://www.circeproject.eu)

CIW: Cretan Intermediate Water

CMAP: CPC Merged Analysis of Precipitation (http://www.cgd.ucar.edu/cas/guide/Data/xiearkin.html)

COADS: The Comprehensive Ocean-Atmosphere Data Set Project

COPS: Convective and Orographically-driven Precipitation Study

Corine: Coordination of information on the environment (map of land cover)

CRU: Climatic Research Unit

CYPRIM: Intense CYclogeneses and heavy PRecipitation In Mediterranean regions

DWF: Dense water formation

DYFAMED: DYnamique des Flux Atmosphériques en MEDiterranée (http://www.obs-vlfr.fr/sodyf/)

EC: Eddy Correlation

ECA&D: European Climate Assessment and Dataset (http://eca.knmi.nl/)

ECOCLIMAP: dataset of surface parameters

EFEDA: Echieval Field Experiment in a Desertification Area

EMDW: Eastern Mediterranean Deep Waters

EMT: Eastern Mediterranean transient

ENSEMBLES: Ensemble-based predictions of climate changes and their impacts (FP6 project)

ENSO: El Niňo Southern Oscillation

ERA-15: ECMWF ReAnalysis - 15 years (1979-1993)

ERA-40: ECMWF ReAnalysis - 45 years (mid-1957 to mid-2002)

FF: Flash-Flood

FLASH: Observations, Analysis and Modeling of Lightning Activity in Thunderstorms, for use in Short Term Forecasting of Flash Floods (FP6)

GCM: Global Circulation Model

GEV: Generalized Extreme Values

GEWEX: Global Energy and Water Cycle Experiment

GHG: GreenHouse Gas

GPR: Ground Penetrating Radar

GPS: Global Positionning System

GSWP2: Global Soil Wetness Projectmoose ocean observation

HPE: Heavy Precipitation Event

HYDROCHANGES: continuous, long-term measurements of temperature and salinity of Mediterranean deep waters in key areas (http://www.ciesm.org)

HYMEREX: Joint HyMeX-MERMEX campaigns at sea

HYMEX: Hydrological cycle in Mediterranean Experiment

ICN: Ice Condensation Nuclei

IN: Ice Nuclei

INSU: Institut National des Sciences de l'Univers

IMFREX: IMpact des changements anthropiques sur la FRéquence des phénomènes EXtrêmes de vent, de température et de précipitations (GICC project)

IPCC: Intergovernmental Panel on Climate Change

ISBA: Interactions Soil Biosphere Atmosphere

ISBA-A-gs: Interactions between Soil, Biosphere and Atmosphere, CO2-reactive

LAI: Leaf Area Index

LDW: Levantine Deep Water

LIW: Levantine Intermediate Water

LLJ: Low-Level Jet

OMERE: French acronyms for Research Observatory of the Environment "Mediterranean Observatory of Rural Environment and Water"

MADDW: Middle Adriatic Deep Water

MAP: Mesoscale Alpine Program

MARTHE: Modélisation d'Aquifères avec Maillage Rectangulaire, Transport et Hydrodynamique

MCS: Mesoscale Convective System

MedClivar: Mediterranean CLImate VARiability

MEDEX: The Mediteranean Experiment on cyclones that produce high-impact weather in the Mediterranean

MEDROPLAN: Mediterranean Drought Preparedness and Mitigation Planning (http://www.iamz.ciheam.org/medroplan/)

MERMEX: Marine Ecosystems Response in the Mediterranean Experiment

Mesan: Meso scale analysis (used in Sweden)

MHYDAS: Modélisation HYdrologique Distribuée des AgroSystèmes

MOBHYDIC: French acronym for Distributed Hydrological Modeling and Observing within Cropped Areas

MODCOU: MODèle hydrologique COUplé surface-souterrain (hydrogeological model)

MODFLOW: USGS Modular Three-Dimensional Groundwater Flow Model (http://www.modflow.com/)

MOOSE: Mediterranean Ocean Observing System on Environment

MSWB: Mediterranean Sea Water Budget

MTHC: Mediterranean Thermohaline Circulation

MW: Mediterranean water(s)

NAO: North Atlantic Oscillation

NAdDW: Northern Adriatic Deep Water (formerly NADW)

NCEP: National Centers for Environmental Prediction

OGCM: Ocean Global Circulation Model

OHMCV: French acronyms for Research Observatory of the Environment " Hydrometeorological Observatory for the Mediterranean Cevennes-Vivarais region"

ORCHIDEE: ORganizing Carbon and Hydrology In Dynamic EcosystEms (land surface model by IPSL)

PRUDENCE: Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects (FP5 project)

PV: Potential Vorticity

QPE: Quantitative Precipitation Estimate

QPF: Quantitative Precipitation Forecast

RCM: Regional Climate Model

R/V: Research Vessel

SADDW: Southern Adriatic Deep Water

SAF: Satellite Application Facility

SAFRAN: Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige (meteorological analysis system)

SEAFLUX: WCRP/GEWEX project for producing a high-resolution satellite-based data set of surface turbulent fluxes over the global oceans (http://seaflux.gfdi.fsu.edu/)

SECHIBA: Schématisation des Echanges Hydriques à l'Interface entre la Biosphère et l'Atmosphère (land surface model by IPSL)

SEVE: Sol Eau Végétation Energie (land surface model)

SIM: SAFRAN-ISBA-MODCOU land surface model

SiSPAT: Simple Soil Plant Atmosphere Transfer (land surface model)

SMOS: Soil Moisture and Ocean Salinity

SMOSMANIA: Soil moisture observing system Meteorological Automatic Network Integrated Application

SNOW17: National Weather Service River Forecast System (NWSRFS) snow model

SOC: Southampton Oceanography Centre

SOO: Ship of opportunity

SRES: Special Report on Emission Scenarios

SSGF: Sea Spay Generation Function

SST: Sea Surface Temperature

STICS: Simulateur mulTIdisciplinaire pour les Cultures Standard

Sud-Med: Fonctionnement et ressources hydro-écologiques en région semi-aride (Tensift, Maroc): caractérisation, modélisation et prévisions (http://www.irrimed.org/sudmed/)

SVAT: Surface-Vegetation-Atmosphere Transfer

TDW: Tyrrhenian Deep Water

THC: Thermohaline Circulation

TOPMODEL: TOPography-based hydrological MODEL

TR: Thermal Infrared

TRANSMED: network of ships of opportunity programme (http://www.ciesm.org)

VIC: Variable Infiltration Capacity

WIW: Western Mediterranean Intermediate Water

WMDW: Western Mediterranean Deep Water

XBT: Expendable Bathythermograph

XEROCHORE: An Exercise to Assess Research Needs and Policy Choices in Areas of Drought (http://www.feem-project.net/xerochore/)

NB: for the water masses acronyms, see also https://www.ciesm.org/catalog/WaterMassAcronyms.pdf