HyMeX, a 10-year multidisciplinary program on the Mediterranean water cycle

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Abstract

The Mediterranean countries are experiencing important challenges related to the water cycle including water shortages and floods, extreme winds and ice/snow storms that impact critically the socioeconomic vitality in the area (causing damage to property; threatening lives; affecting the energy and transportation sectors, etc.). There are gaps in our understanding of the Mediterranean water cycle and its dynamics, which include the variability of the Mediterranean Sea water budget and its feedback on the variability of the continental precipitation through air/sea interactions, the impact of precipitation variability on aquifer recharge, river discharge, soil water content and vegetation characteristics specific of the Mediterranean basin and the mechanisms that control the location and intensity of heavy precipitating systems which often produce floods. The HyMeX (Hydrological cycle in the Mediterranean Experiment) programme is a 10-year concerted experimental effort at the international level aiming at advancing the scientific knowledge of the water cycle variability in all compartments (land, sea and atmosphere) and at various time and spatial scales. It also aims at improving the processes-based models needed for forecasting hydro-meteorological extremes and the models of the regional climate system for predicting regional climate variability and evolution. It finally aims at assessing the social and economic vulnerability to hydrometeorological natural hazards in the Mediterranean and the adaptation capacity of the territories and populations therein to provide support to policy makers to cope with water related problems under the influence of climate change, by linking scientific outcomes with related policy requirements.

Capsule

HyMeX strives to improve our understanding of the Mediterranean water cycle, its variability from the weather-scale events to the seasonal and inter-annual scales, and its characteristics over one decade (2010-2020) with a special focus on hydro-meteorological extremes. It also aims to facilitate the multidisciplinary and seamless analysis needed to assess the social and economic vulnerability to hydro-meteorological hazards and the adaptation capacity of the Mediterranean territories and populations in the context of global change.

1. Motivation and major issues

The countries around the Mediterranean basin face water problems including water shortages and floods that can impact food availability, cause epidemics, and threaten life and infrastructures. These problems are due to a combination of inadequate planning and management policies and of poor capability to predict hydrometeorological and climatic hazards (poor understanding of the processes and poor capability to model them). Indeed, the Mediterranean basin has quite a unique character that results both from physiographic and climatic conditions and historical and societal developments. Because of the latitudes it covers, the Mediterranean basin is a transition area under the influence of both mid-latitudes and tropical climate variability: to the north, a large part of the atmospheric variability is linked to the North Atlantic Oscillation (NAO) and other mid-latitude teleconnection patterns (Luterbacher et al., 2006), while the southern part of the region is under the influence of the descending branch of the Hadley cell materialized through the Azores High, with in addition El Niño Southern Oscillation (ENSO) influence to the east (Rodwell and Hoskins, 1996).

[INSERT FIGURE 1]

All these influences lead to a large variability at different scales, going from the multi-decadal scale to the mesoscale. Indeed, the complex geography of the region which features a nearly enclosed sea with high sea surface temperature (SST) during summer and fall, surrounded by very urbanized littorals and mountains from which numerous rivers originate (Fig. 1), plays a crucial role in steering air flow. The Mediterranean Sea acts as a moisture and heat source for the atmosphere through air-sea fluxes, so that energetic meso-scale features are present in the atmospheric circulation which can evolve to high-impact weather systems such as heavy precipitation and flash flooding (e.g. Alpert et al., 2002; Tarolli et al., 2012; Reale and Lionello, 2013), cyclogenesis and wind storms (e.g. Trigo et al., 1999; Lionello et al., 2012a) or heat waves and droughts (e.g. Hoerling et al., 2012; Stéfanon et al., 2012a). Also on the synoptic scale, a range of phenomena contribute to the genesis of hydro-meteorological extremes in the different parts of the Mediterranean. They include, for instance, cyclones in Gulf of Genoa and the lee of the Atlas mountains (e.g. Trigo et al., 1999; Horvath et al., 2006) over the Western Mediterranean, and "Tropical plumes/cloud bands" (Ziv, 2001), active Red Sea troughs (e.g. Kahana et al. 2002) and Cyprus Lows (e.g. Krichak et al., 2007) over the Eastern Mediterranean. Some of these phenomena also point to important tropical-extratropical interactions. In contrast to the Western Mediterranean, the Eastern Mediterranean is strongly affected by several tropical processes as reviewed by Alpert et al (2005). The monsoon and Indian Ocean moisture sources (Krichak et al., 2000) as well as the Red-Sea trough (Krichak et al ,1997) play important roles. Another difference between the Western and the Eastern Mediterranean is the significant increasing recent 50-y trends in daily torrential rains in some Western Mediterranean regions while in the Eastern Mediterranean relatively high interannual variabilities prevent any trend to be significant (Alpert et al., 2002).

Heavy precipitation and flash flooding are among the most devastating natural hazards in terms of mortality (Jonkman, 2005; Doocy et al., 2013). They occur most often on the northern side of the Mediterranean Sea. Even if flash floods are usually small scale events, their suddenness and violence account for the high proportion of human losses. According to Jonkman (2005), the European and and African continents display the highest mortality rate due to floods or flash floods in the world. In France, over the last two decades, more than 100 deaths and several billion of euros damage were reported (Huet et al., 2003; Delrieu et al., 2005). The mortality in Europe can reach values as high as 10% of the population affected by the hydrometeorological hazards (Jonkman, 2005). This is consistent with findings reported by Viscus and Zeckhauser (2006) for a comparison between natural risks and car accident risks. These authors found that what characterizes natural risks is that a small fraction of the population accounts for a large percentage of the fatalities. Floods also occur at times on the southern side of the Mediterranean Sea as in October 2008 over the northeastern region of Morocco, in November 1968 in Tunisia or in Algiers on 10 November 2001 causing 886 victims. Regarding total costs of floods, Hallegatte et al. (2013) show that the most vulnerable 20 cities where the increase in average annual losses due to floods between 2005 and 2050 will potentially be greatest, are distributed all over the world, with a concentration in the Mediterranean Basin, the Gulf of Mexico and East Asia. Such events impact particularly the coasts. With its 46,000 km coastline with more than 146 million residents and another 100 million tourists in summer, the Mediterranean basin has one of the most crowded coasts in the world and is one of the most vulnerable regions to such hazards (Hinrichsen, 1998). Because the elements at risks are highly dispersed, the management of the flash flood risk by means of structural measures is difficult and often unsustainable in ecological or economic terms. Therefore there is a need in better understanding the social and natural dynamics of such events in order to improve the forecasting and warning capabilities of the exposed Mediterranean societies to increase their resilience to such extreme and frequent events. Droughts can also have very serious consequences for society with reduction of water availability, of the productivity of natural and cultivated vegetation (Ciais et al. 2005; Stéfanon et al., 2012b), and of energy supply due to water shortage (Fink et al., 2004).

Finally, because it is in such a transition area, the Mediterranean basin is very sensitive to global climate change at short (decadal) and long (millennial) time scales. Continental and marine paleorecords show that the climate and the sea state have widely varied in the past, sometimes very quickly (Combourieu Nebout et al., 2002). Regarding more recent periods, several authors have reported an increase of the mean annual temperature of about 0.005°C yr^{-1} (Quereda-Sala et al., 2000) reaching in summer the value of 0.01°C yr^{-1} for 1976-2000, one of the highest rates over the entire globe, and a decrease in annual precipitation (with different seasonal trends; e.g. Brunetti et al., 2000; Frich et al., 2002; Klein Tank et al., 2002; Klein Tank and Können, 2003; Brugnara et al., 2012; Barkhordarian et al., 2013). In the sea however the time series are too short yet to provide a reliable trend (Schroeder et al., 2013). Regarding the future projection of the Mediterranean climate in anthropogenic scenario, Giorgi (2006) defines the Mediterranean area as one of the two main “hot-spots” of climate change with an increase in inter-annual rainfall variability in addition to a strong warming and drying for 2080-2099, compared with 1980-1999. Regional water cycle has therefore been affected and will continue to be affected by decadal variations in addition to long term trends (Mariotti, 2010; Mariotti and Dell'Aquila, 2012). In this context, the exposure of the Mediterranean population may increase dramatically not only because of events conducive to floods and droughts may become more frequent (Gao et al., 2006), but also because of the demographic projections from the Mediterranean Action Plan suggesting an increase of about 22.6% until 2025.

The ability to forecast such high-impact phenomena and predict their evolution and consequences in the present climate and in a context of global climate change is still low because of the contribution of fine-scale processes and their non-linear interactions with large-scale processes as well as not well known interactions between oceanic, atmospheric and hydrological processes. In detail, this is due to the large uncertainties in the quantification of the Mediterranean Sea water budget at various time and spatial scales which limit our capability to determine its feedback on the variability of the continental precipitation through air/sea interactions and to identify the processes controlling the evolution of the Mediterranean climate. The large daily/seasonal variability of precipitation impacts aquifer recharge, river discharge, soil water content and vegetation characteristics, the feedbacks of which to the atmosphere are still not well known. Hydrological and hydrogeological transfer functions are also characteristic 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 integrated management of the hydrosystems, and its adaptation to anthropogenic pressure and climate change. Indeed, a major issue is to quantify the impact of change of land use/land cover, surface states, soil degradation, and water demand on rainfall modulation and water resources with respect to climate change alone. Regarding heavy precipitation, progress has to be made on the understanding of the mechanisms that govern the location of the precipitating system as well as of those that 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 characterise the initial moisture state of the watersheds make the hydrological impact of such extreme rainfall events very difficult to assess and predict.

Addressing these issues requires the production of a consistent database of all Earth compartments allowing a deeper insight in such coupled processes and the validation of a large variety of models, from fine-scale research and forecasting land-surface, ocean and weather models to regional climate system models.

2. The HyMeX programme

Gaps in our understanding of the Mediterranean water cycle, including the impact of a changing climate and human activity on extremes as well as on water availability are still important. The HyMeX (Hydrological cycle in the Mediterranean Experiment; http://www.hymex.org - See Table 1 for the list of acronyms) programme is a concerted effort at the international level aiming at advancing the scientific knowledge of the water cycle variability. It also aims at improving the processes-based models and the models of the regional climate system. Such models are needed for forecasting hydro-meteorological extremes, their frequency and severity and for planning adaptation strategies against the impacts of climate variability and change and human activity in the Mediterranean basin. Specifically, HyMeX aims to:

1. improve our understanding of the water cycle, with emphasis on hydro-meteorological extremes, by monitoring and modelling the atmosphere-land-ocean coupled system, its variability from the weather event to the seasonal and inter-annual scales, and its characteristics over one decade (2010-2020) in

the context of global change,

2. assess the social and economic vulnerability to hydro-meteorological extremes and the adaptation capacity of the territories and populations,
3. provide support to policy makers to cope with water related problems under the influence of global climate change.

HyMeX complements previous research projects like MAP (Mesoscale Alpone Programme; Bougeault et al., 2001) which focused specifically on hydrological and atmospheric process studies driving orographic precipitation over the Alps, oceanographic programs in the Mediterranean Sea like EGYPT (Eddies and GYres Paths Tracking; http://www.ifremer.fr/lobtln/EGYPT) and EGITTO (http://doga.ogs.trieste.it/sire/drifter/egitto_main.html) or CIRCE (Climate Change and Impact Research: the Mediterranean Environment ; Navarra and Tubiana, 2013) which aimed at performing regional climate model simulations over the Mediterranean region for impact studies in a future climate. The analysis of the water cycle in HyMeX emphasizes on key issues related to the water budget of the Mediterranean Sea which is a relevant proxy to investigate the regional water cycle at the various time scales with the integration of the contribution of all Earth compartments because of the large moisture source that the Mediterranean Sea represents for the region (Mariotti et al., 2002). It requires an accurate modelling of the thermohaline circulation, including dense water formation through intense air/sea interactions. It also requires the quantification of the fresh water inputs from the continent to the sea (rivers and groundwater flows). This issue implies a better understanding and modelling of all the components of the continental water cycle such as evapotranspiration, groundwater discharge/recharge and streamflow, particularly when impacted by extreme flood events, or during droughts which are frequent in the region. Soil moisture is also a key variable for the continental surface - atmosphere interactions, and a key driver of the hydrological response during flood events, which should be improved. Spring and summer droughts alternate with periods in fall favourable to extreme precipitation and floods, the impact of which on the Mediterranean societies are addressed in HyMeX by monitoring vulnerability factors and adaptation strategies to accommodate the impacts of such extreme phenomena. A schematic of the five scientific topics of the HyMeX project which aim at addressing these open scientific issues, is shown in Fig. 2 and a comprehensive description of the HyMeX underlying science is provided in the International Science Plan (http://www.hymex.org).

[INSERT FIGURE 2]

2.1. A multi-scale data-modelling approach

This long-term experimental program includes a series of large field experiments for process and predictability studies over specific areas, embedded in a 10-year period of data collection over the whole Mediterranean basin which allows to capture certain modes of variability and get a homogeneous observation network density as well as a good representativity of the measurements. It adopts a multi-disciplinary (oceanic, atmospheric, hydrological and social sciences) and seamless (from event scales to climate) strategy for both observation and modelling.

2.1.1. Nested observations

The HyMeX observation strategy is based on a three-level nested observation periods. The Long-term Observation Period (LOP) began in September 2010 and will continue until 2020. It spans the whole Mediterranean region to collect the long-term time series required to study the variability of the Mediterranean water cycle from the seasonal to the inter-annual scales. The Enhanced Observation Period (EOP) involves additional sites and/or instruments to increase the spatial and/or temporal resolution over three target areas (TA) during at least four years, in order to conduct both budget and process studies. The three target areas are (Fig. 3):

1. The northwestern Mediterranean where all the intense hydro-meteorological phenomena of interest for HyMeX occur. Heavy precipitation systems and flash-flooding occur over the Spanish (Romero et al., 2000), French (Ricard et al., 2012), and Italian (Parodi et al., 2012) coasts as well as islands (Barthlott and Kirshbaum, 2013) during fall (see Ducrocq et al., 2013 companion paper); The Gulf of Lions 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 (Schott et al., 1996).
2. The southeastern Mediterranean which covers areas over Western Greece notorious for heavy precipitation events (Papagiannaki et al., 2013), Crete Island with a high pressure on water demand, the trans-boundary river basin of the Evros River (marks the Greek-Turkish border) that suffers from floods, as well as the Daliya, Besor (northern Neguev desert) and Qidron (Mount Scopus in Jerusalem) basins further to the east in Israel. This target area allows the study of intense rainstorms and flash floods in dryer climatic areas of the Mediterranean (Yakir and Morin, 2011).
3. The Adriatic comprised of the Trentino-Alto Adige, Friuli Venezia Giulia and Veneto regions in Italy, and the Dinaric Alps in Slovenia and Croatia, which are target areas for the study of heavy precipitation events and flash-flooding (Vrhovec et al., 2004; Davolio et al., 2009). Mesoscale orographic perturbation in the area of Dinaric Alps also provide conditions for mesoscale cyclonic generation and the strengthening of local northeastern Bora and southeastern Jugo winds (Horvath et al., 2009; Jurcec et al., 1996). Dense water also forms in the North and South of the Adriatic sub-basin (Vilibić and Supić, 2005).

[INSERT FIGURE 3]

The Special Observation Periods (SOP) were held in fall 2012 and winter 2013 over the northwestern Mediterranean target area to provide detailed and specific observations for studying key processes of the water cycle. In addition to the LOP and EOP observation frameworks, dedicated groundbased, shipborne, and airborne means were deployed during the SOPs. The collection of new data sets and the enhancement of observation means during HyMeX provides a unique opportunity to improve oceanic, hydrological and weather forecasts as well as regional climate simulations over the Mediterranean region.

The long term observation strategy

The long-term observation strategy, including LOP and EOP, is a key component of the observation strategy since it allows one to put the events sampled during the SOPs in a climatological perspective It also allows the monitoring during a decade of the variability, enhancing, combined with other observational datasets and with climate modelling, our capability to detect possible trends of the different components of the water cycle over the whole Mediterranean in a context of global change. The LOP relies either on existing international operational and research networks (oceanic and hydro-meteorological observatories, radars, rain gauges, radiosoundings, surface weather stations, GPS, photometer and lightning networks, ...) or on platforms developed specifically for HyMeX. Over land, hydro-meteorological measurements are collected over 10 sites. They are the Catalan hydro-meteorological observatory (CA), the Valencia site (VA), the Cévennes-Vivarais hydro-meteorological observatory OHM-CV (CV) (Fig. 4a), the Ligury-Tuscany site (LT) , the Central Italy site (CI), the Northeastern Italy site (NEI, incl. Trentino-Alto Adige, Veneto, Friuli Venezia Giulia), the Crete site (CR), the Israeli site (IS) and the Dinaric Alps (DA) (Fig. 3). The CV, NEI and IS sites have been labelled by the Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Program (WCRP) (Drobinski et al., 2009, 2011). Atmospheric measurements are collected over 3 sites located in Corsica (CO; Corsican Observatory for Research and Studies on Climate and Atmosphere - ocean environment), Lampedusa (LA) (Fig. 4c) and Balearic islands (BA). These sites are complemented by multi-scale observations of the hydrological response over typical Mediterranean landscapes. This includes LOP local scale measurements of the surface energy balance focusing on evapotranspiration and soil moisture dynamics for water balance studies, such as the Crau-Camargue site (Fig. 4b).

[INSERT FIGURE 4]

The measurements from the instrumented sites are completed with observations from operational or research networks measuring precipitation from radars (Fig. 5a), atmospheric water vapour from GPS/GNSS (Fig. 5b) and photometers and lightning from 4 operational lightning detection networks, i.e. 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) network (Fig. 5c). Indeed, a fundamental element that has been missing in past field experiments is nearly simultaneous measurements of the moist inflow as a function of time, height and along-barrier distance with measurements of the precipitation over the orography. The weather radar component of HyMeX, which involves research and operational radars, together with the GPS/GNSS and AERONET photometer networks represent the most ambitious field project to date in the endeavor to collect such basic, but hard-to-obtain information, to advance understanding of variability and predictability of precipitation. Even though, all data from these networks are still not accessible and effort is on-going to collect them, the available radar and GPS/GNSS data are post-processed for climate and process studies, water budgets computations, and verification with other techniques (radiosondes and satellite for water vapor; rain gauges for rainfall). Finally, one original aspect of HyMeX is to perform multi-scale and multiple-year intracloud and cloud-to-ground lightning detection for observational- and modeling-based multi-disciplinary studies of maritime and continental Mediterranean storms and analysis of the complex relationships between precipitation (dynamics, microphysics, interaction with aerosols), electrification and lightning occurrence. It encompasses all HyMeX observation periods (LOP, EOP and SOP).

[INSERT FIGURE 5]

Over the sea, observations are collected with a combination of platforms navigating, drifting or fixed. At the Mediterranean Sea scale, the LOP relies on the ARGO network for a permanent pool of floats (http://www.argo.ucsd.edu) and on the HydroChanges network of moorings (Schroeder et al., 2013). At the western Mediterranean basin scale, HyMeX made a major effort to develop autonomous systems to be used on ships of opportunity: the Sea Embedded Observing System developed by Météo-France measures and transmits the radiative fluxes, sea surface temperature, humidity, wind and precipitation; the TRANSMED system supported by the Mediterranean Science Commission (CIESM) measures and transmits hourly the surface temperature and salinity; a GPS system enables deducing the integrated water vapour content. To date the weekly service Marseilles - Algiers (Fig. 6c) is equipped, Rome - Barcelone is next. Hydrographic cruises are also carried yearly by an Italian companion program for a reference on the evolution of the water masses on the whole water column. At the northwestern part of the basin, observatories such as MOOSE (Mediterranean Ocean Observing System on Environment; http://www.moose-network.fr/) and SOCIB (Balearic Islands Coastal Observing and Forecasting System; http://www.socib.es/) provide a backbone to the HyMeX LOP. The network of gliders (submarine autonomous platforms piloted remotely and equipped with multiple sensors) documents the dynamics of the water column over ~1000m along two mains transects, complemented by the dense network of CTD (temperature and salinity) casts performed every 6 months by the MOOSE cruises. Off Nice and in the centre of the Gulf of Lions where deep convection occurs, the equipment of the 2 anchored buoys from Météo-France that record measurements in the atmospheric and oceanic surface layers was enhanced with sensors measuring radiation, salinity and precipitation at the surface, and a thermistor chain down to 250 m depth (Fig. 6b).

[INSERT FIGURE 6]

As part of the EOP, an effort is made at sea to deploy additional ARGO floats and gliders. Regarding EOP hydrological measurements, two main catchments (Gard and Ardèche) in the CV area, are instrumented in order to document the hydrological response during and between floods based on a nested-subcatchments strategy. Small catchments of a few km^2 are instrumented to follow soil moisture dynamics and runoff response (both surface and sub-surface flow) during and between floods. This includes the Pradel site (Ardèche catchment), representative of lowland covered with vineyards and natural vegetation on limestones soils and the Valescure and Tourgueille sub-catchments (Gard catchment) representative of forested mountainous areas over granites and schist respectively. At an intermediate scale (10-100 km^2), raingauges network such as the HPiconet network around Le Pradel site (Fig. 4a) and limnimeter netwoks measuring the water height dynamics and, for some of them, discharge dynamics have been installed to document the variability of the hydrological response associated with the variability of rainfall, land use and geology. The largest scale (100-1000 km^2) is documented based on operational networks measuring rainfall and discharge data. In the context of the EOP, several post-flood surveys have been carried out after major flash floods in the Mediterranean area and will continue until 2015. Indeed, flash floods have spatial and temporal scales of occurrence which are difficult to observe with the conventional measurement networks of precipitation and discharge (Borga et al., 2010). These post-survey measurements will contribute to increase our understanding of the factors affecting the basin response to heavy rainfall, as well as the factors determining the consequences of Mediterranean flash floods, thus contributing to improving the risk assessment and the predictability of this hazard.

The special observation period strategy

The first SOP (SOP1) spanned 8 weeks (5 September - 6 November 2012) and was dedicated to documenting the heavy precipitating events (HPE) and associated flooding, in relation with the ocean heat content. In addition to the LOP and EOP measurements, their investigation involved dedicated platforms, including aircrafts (French Falcon 20 and ATR-42 and German Do128; see Fig. 7a,b), pressurized boundary layer balloons and the French buoy tender Provence. Additional radiosoundings completed those performed in the Cévennes-Vivarais, Corsica and Central-Italy sites, with some launched at sea from the buoy tender Provence. During SOP1, 18 orographic or heavy precipitation events associated with floods were documented over France, as well as 11 over Italy and 6 over Spain. The detailed objectives of SOP1 and specific means deployed are described in a companion article (Ducrocq et al., 2013). The second SOP (SOP2) spanned 6 weeks (1 February -15 March 2013). It was dedicated to intense air-sea interactions, mainly under strong winds in the Gulf of Lions that cause ocean convection process resulting in dense water formation. Luckily, dense water formation occurred in winter 2013, and was intense enough to reach the sea floor (~2500m). During the field campaign, the French research vessels Le Suroît (companion Marine Ecosystems Response in the Mediterranean Experiment - MerMeX), Tethys-2 and the buoy tender Provence (Fig. 7c) contributed to sampling the water column and the air-sea fluxes, complemented by Marisonde buoys SVP drifters, and ARGO profilers specifically modified to allow deeper and more frequent profiling when drifting in the area of oceanic convection. The French aircraft ATR-42 measured boundary layer fluxes and waves over the region of oceanic convection in synergy with pressurized boundary layer balloons measuring the temperature, pressure, humidity and wind along a quasi-lagrangian trajectory (Fig. 7d).

[INSERT FIGURE 7]

2.1.2. Modelling

The HyMeX modelling strategy has been designed to be consistent with the observation strategy. It aims, through an approach integrating numerical models of the atmosphere, ocean and land surfaces, to better simulate and predict the evolution of the environment at all scales of time and space, not only as separate processes within each Earth compartment, but as coupled mechanisms with feedback loops. This requires an approach that combines a variety of models ranging from small-scale models to models of the regional climate system. Small-scale models that represent more explicitly the oceanic, hydrological and atmospheric phenomena under scrutinity in HyMeX will be directly compared to the SOP measurements (see details in Ducrocq et al., 2013 for SOP1) and will be used in the development of parameterizations of these processes in climate system models. This also requires the coupling of the models of the atmosphere, ocean and land surfaces, at different various resolutions to analyse how the fine scale feedbacks associated with air-sea-land interactions can substantially influence the spatial and temporal structure of the regional climate. Past European projects like CIRCE have initiated this approach with atmosphere-ocean regional climate modelling exercise over the Mediterranean (Gualdi et al., 2013). HyMeX aims at going one step further by increasing the horizontal resolution of the different models and by developing regional climate system models, which consists in complementing atmosphere-ocean regional climate models by tools representing other parts of the planetary makeup, as for example vegetation models and river routing schemes.

This effort to improve the representation of processes in models is essential to better predict extreme hydrometeorological events, but also the variability of the water cycle at intraseasonal to interannual scales and its evolution in the context of global climate change. The modelling strategy therefore includes the set-up, validation and improvements of multi-components regional climate models dedicated to the Mediterranean area: ocean, atmosphere, land surface, hydrology in order to study interannual variability, past trends and future climate change. Basin scale regional climate modelling, a large part of the HyMeX activities is common with the MED-CORDEX program (Ruti et al., 2013; see http://www.medcordex.eu) which is the regional declination of the Coordinated Downscaling Experiment (CORDEX) program of the World Climate Research Program (WCRP) (Giorgi et al., 2009). The joint HyMeX/MED-CORDEX activity consists in the downscaling of ERA-Interim reanalysis (hindcast simulations including the HyMeX period between 2010 to present and until 2020) and CMIP5 simulations at a horizontal resolution of 50 km or less (the resolution of the atmospheric model can be as low as 12 km and the ocean components have much higher resolutions which can be as low as 6-7 km) for improving our knowledge of the variability of the hydrometeorological processes in the Mediterranean (e.g. Dubois et al., 2012; Gualdi et al., 2013; Flaounas et al., 2013; Stéphanon et al., 2013). About 14 modeling groups contribute to the HyMeX/MED-CORDEX regional climate modeling activity including groups in Italy, Spain, France, Israel, Turkey, Germany, Tunisia and Serbia. Among them, 11 use regional climate system models coupling at least land surface/ocean/atmosphere models and some also including river runoff (Artale et al., 2009; Herrmann et al., 2011; Kržič et al., 2011; Drobinski et al., 2012, L'Hévéder, et al., 2012). At present, 7 groups have already performed the simulations and 4 plan to do so. In addition, stand alone atmosphere, ocean and land surface models have been run or are planned to run in forced mode at various horizontal resolution for process studies. They also serve as reanalysis tools for land surface and ocean properties and help in delineating error propagation in atmosphere/land/ocean regional coupled models. HyMeX being a processed-based project, the analysis of the hindcast simulations together with HyMeX observations will also help for the improvement and uncertainty reduction of MED-CORDEX downscaling of CMIP5 simulations. As an example, Fig. 8 shows Taylor diagrams comparing rainfall from ERA-Interim reanalysis, ECA&D gridded dataset and HyMeX/MED-CORDEX simulations performed with WRF to the rainfall measured at three station observations at the Cévennes-Vivarais observatory in France, in Northeastern Italy and Israël for the period 2003-2008 (GEWEX labelled HyMeX stations).

[INSERT FIGURE 8]

Finally, regarding forecasting, the modelling strategy includes the refinement of convective-scale deterministic forecast systems to improve the prediction capabilities of Mediterranean high-impact weather event. The SOP data provide an unique high-resolution database to validate these new numerical hydro-meteorological prediction systems. It also aims at designing high-resolution ensemble modelling approaches coupled with hydrological models to issue probabilistic forecasts of the impact in terms of hydrological response and at developing new parameterizations, and novel data assimilation systems for the different Earth components. EOP and LOP data are also used to develop and improve models of the hydrological response at various scales and to propose a regional modeling strategy which will contribute to the improvement of hydrological forecasting and water balance models.

2.2. Basin-scale monitoring of water cycle: from satellite to data assimilation

Satellite data for Earth observation are an essential means of access to observations at time scales ranging from one day to several years throughout the Mediterranean basin, particularly over the Mediterranean Sea where few in-situ data are available. They allow to integrate in situ measurements and evaluate models used in HyMeX at various spatial and temporal scales (e.g. Claud et al., 2012). For the atmosphere, ocean and land surfaces, many satellite products are already available at various data centers (cloud classifications, air temperature and humidity, wind speed deduced from cloud motions, precipitation, temperature and wind at the sea surface, radiative fluxes, aerosols, soil water content, ...). However, some of these products are difficult to use over the coasts, which limits significantly the use of these data in complex terrain regions. Initiation of precipitating systems often occurs over the Mediterranean Sea which are also not well documented by ground observations (e.g. due to the limited quantitative range, 150 km, of coastal radars). Access to new satellite rainfall measurements by National Aeronautics and Space Administration (NASA)-Japan Aerospace Exploration Agency (JAXA) Global Precipitation Measurement (GPM; Hou et al., 2008) and improvements through ground validation over complex coastal and mountainous regions supported by HyMeX observations, constitute a major progress towards the quantification of Mediterranean water cycle. Indeed, GPM aims to provide global precipitation data at a quality and scale that can facilitate flood modeling and water management applications in the mountainous terrain of the Mediterranean region. The primary contribution from GPM over the currently available satellite rainfall observations is the core satellite (dual-frequency radar and radiometer) from which is expected to advance the detection and quantification of snow and light precipitation from space, which are in fact not trivial issues in the Mediterranean. In addition to the core observations, GPM will facilitate advancements in the high-resolution merged products due to the availability of more frequent observations.

To overcome the lack of reliable data or the existence of sparse data in space and time, satellite and in-situ data merging or assimilation is an essential action in the HyMeX project. It includes for instance improved assimilation of satellite radiance from IASI (Vincensini et al., 2012) or ozone data from GOME2 (Sbii et al., 2010) as well as background error modelling. Over the ocean, one objective is to build a high-resolution reanalysis of the Mediterranean Sea circulation. It will use the oceanic Mediterranean basin-scale NEMO-MED12 model (Beuvier et al., 2012), and the SAM2 assimilation scheme of MERCATOR Ocean. The horizontal resolution of the model is about 7 km, allowing the simulation of mesoscale patterns. The assimilated data will come from the Coriolis/MyOcean in situ database, altimeter data and satellite SST products. The in-situ data collection with peer-to-peer contacts with our European and African partners will also be enhanced. The reanalysis will be compared to independent datasets which are not assimilated (e.g. drifter trajectories, tide-gauges, HF radars, ...). A similar action is taken for land-surface properties. Vegetation variables and the surface soil moisture are now routinely produced from satellite observations, in near-real-time. Integrating these observations into land surface models (e.g. ORCHIDEE, ISBA-A-gs models) is a way to assess the modeling uncertainties and to consolidate monitoring systems able to describe land climate variables. The characterization of droughts requires the elaboration of a climatology of the land variables affected by droughts, such as surface soil moisture, leaf area index, the fraction of absorbed photosynthetically active radiation. Satellite-derived variables have been measured since the end of the 80s and are available through the HyMeX data base. A whole land data assimilation system over the Europe-Mediterranean area and coupled to river discharge model will permit the characterization of meteorological, hydrological, and agricultural droughts (Wilhite, 2000). Comparison with observations of river discharges and of soil moisture will allow the assessment of the added-value of the inclusion of the satellite products and of various versions of the land surface model and will contribute to the verification of long-term hindcast simulations. Finally, specific reanalyses will be conducted for the SOPs using the collected data.

2.3 Social vulnerability and resilience

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 confronted with challenging environmental changes, such as short-time extreme events (heavy precipitation, flash-floods,...) and long-term modifications (change in access to water resources, droughts,...). Potential security problems and migrations produced as a consequence of floods, water scarcity and droughts are in the agenda of National and International administrations (i.e. European Commission, 2008, 2009). Studies on adaptation capacity from an economical and societal perspective are in progress at the international level (Adger, 2006; Bazermann, 2006; Berkhout et al., 2006), but systematic observation of social vulnerability and resilience has still to be organized at a more local scale (e.g. Llasat et al., 2008; e.g. Ruin et al., 2008). The HyMeX program is in part dedicated to this aspect, focusing on the development of methods to integrate environmental and social dynamics across scales. The results of the HyMeX project will provide new achievements on the dynamics of the water cycle and its impact in population and economic activities, ecosystems and water resources, including the improvement of seasonal forecasting and future scenarios. On the other hand, the last IPCC report on extremes (IPCC, 2012; Hallegatte et al., 2013), has insisted in the important roles played by changes in vulnerability and exposure in the increasing flood impact detected in the last years. The HyMeX project deals with such issues and is expected to produce different kind of products that will have social benefit. Indeed, the improvement of the knowledge on Mediterranean storms and floods and their potential increase and synergies in future climate and the creation of databases and post event surveys will add to analyse the societal impact as well as the perception and resilience of population. Besides the own outreach activity of the project, this new knowledge and information can be integrated in local and national strategies like Climate Change Adaptation Plans and Laws, updating European

Water Directive and associated Directives on floods and droughts, and Civil Protection strategies, including warning channel improvement.

The HyMeX approach consists in studying all factors that can influence the impact of such floods and droughts. In order to monitor social vulnerability to such extreme events and learn from continuously evolving adaptive capacity and resilience processes at various space and time scales, social sciences techniques (interviews, surveys, impact reports...) are used to collect behavioral, perceptual and disaster impact data. The aim is to build a database suitable for analyzing social processes in connection with natural dynamics ranging from short-fuse and small scale weather events (e.g. flash floods) to longer and larger scale events (e.g. water scarcity and drought). A flood database is also developed with special consideration to the societal impact (Llasat et al, 2013a, 2013b). Starting from the work developed in MEDEX program (Mediterranean Experiment; Amaro et al., 2010; Llasat et al, 2010), the database focuses on four regions representative of the Northwestern Mediterranean Region (Catalonia and the Balearic Islands in Spain; Calabria in Italy; and Languedoc-Roussillon, Midi-Pyrenées and Provence-Alpes-Côte d'Azur in France). Besides the catastrophic impact of some flash floods, this database highlights the importance of minor but frequent events that produce casualties and damages, which increase as a consequence of land-use changes and enhanced vulnerability and exposure. Figure 9 shows an example of behavioral analysis for the 15 June 2010 flash-flood event at the beginning of the HyMeX LOP which occurred in the Var region in Southern France (Ruin et al., 2013). It shows that space-time sequences of actions, classified in five categories (usual, information, organization, protection, recovery) based on respondents narratives, mostly follow the pace of change of environmental conditions. During this event, most of the people avoided dangerous situations based on their own perception of environmental cues or thanks to unofficial warnings and emerging solidarity which took place locally and spontaneously.

[INSERT FIGURE 9]

3. International organization

More than 400 scientists from over 20 countries from both sides of the Mediterranean Sea, Europe and the USA participate in HyMeX in atmospheric sciences, hydrology, oceanography and human and social sciences. They contributed to the working groups (WG) addressing the five topics of the HyMeX international science plan (ISP) which describes the scientific questions to be tackled and defines the general program strategy (Fig. 2). To implement the ISP, task teams (TT) have been set up to plan and put into operation specific types of instruments and modelling tools. Transversal task teams called task support (TS) coordinated the activities carried out by the TT. The TT and TS elaborated the international implementation plan (IIP). Such organization has therefore been set up at an international level as shown in Fig. 10 and is composed of:

- an International Scientific Steering Committee (ISSC) which is responsible for the formulation of well defined and coherent scientific objectives and ensures the fulfillment of HyMeX objectives.
- an Executive Committee for Implementation and Science Coordination (EC-ISC) which ensures consistency and communication between the cross-cutting activities lead in the scientific WG, TT and TS as well as the link with the ISSC. It is composed of WG leaders and TS leaders for aircraft and ocean

operations, major sites, and operation centers. Executive Committees at the national level coordinate HyMeX activities in participating countries.
- a HyMeX Project Office (PO) which provides support to the coordination and communication of the program by assisting the committees.

The international HyMeX program benefits from several national and pan-national projects (e.g. HyMeX-France, HyMeX-Spain) or coordination at national level (e.g. Italy). HyMex has an inclusive approach, aiming at enlarging the contribution and participation to the south-eastern Mediterranean institutions. HyMeX fits into a large interdisciplinary international program MISTRALS (Mediterranean Integrated STudies at Regional And Local Scales) dedicated to the understanding of the Mediterranean Basin environmental process under the planet global change (http://www.mistrals-home.org). It aims to coordinate, across the Mediterranean Basin, interdisciplinary research on atmosphere, hydrosphere, lithosphere and paleo-climate, including environmental ecology and social sciences. The objectives are (i) to achieve a better understanding of the mechanisms shaping and influencing landscape, environment and human impact of this eco-region, (ii) to predict the evolution of habitable conditions in this large ecosystem, (iii) to meet the public policies concerning resources and environment, (iv) to anticipate evolution of the societies and (v) to propose policies and adaptation measures that would optimize them.

[INSERT FIGURE 10]

HyMeX is endorsed by the World Climate Research Program (WCRP) and World Weather Research Program (WWRP) of the World Meteorological Organization (WMO). Within WCRP, HyMeX develops in association with MEDCLIVAR (Mediterranean Climate Variability; Lionello et al., 2012b) and GEWEX programs, and is at the origin of the "Mediterranean" component of the CORDEX program called MED-CORDEX. Within WWRP, it is also endorsed by the Observing System Research and Predictability Experiment (THORPEX).

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Side bar: HyMeX data base

The HyMeX database (http://www.hymex.org/database/) implemented by OMP (Observatoire Midi Pyrénées) and IPSL (Institut Pierre Simon Laplace) includes a meta-catalogue that gathers together information about historical, LOP, EOP, SOP, satellite and model data; a field data relational database; a database portal website including user registration and management, access to the data catalogue, dataset ordering thanks to a multicriteria data request interface. It is ruled by the HyMeX data policy which gives open access to the data for research activities once the 2-year period of exclusive access is over. For the LOP, the provision of data is sometimes performed by interoperability with data centers collecting observations or by the provision of metadata. The storage of the regional climate model simulations is performed at ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) in the frame of MED-CORDEX (http://www.medcordex.eu) with interoperability with HyMeX database. The HyMeX database should foster collaboration between the scientists of the different disciplines (meteorology and climate, oceanography, hydrology, human sciences) and cross-cutting activities. Its general objectives are to provide the easiest possible access to all the data sets and their associated documentation that will facilitate their use for scientific studies beyond the HyMeX project.

Table caption

Table 1: List of acronyms

Figure caption

Figure 1: Mediterranean basin (also HyMeX/MED-CORDEX simulation domain; more details in the text)

Figure 2: Schematic of the main scientific topics of the HyMeX project.

Figure 3: Location of HyMeX target areas (ellipses). The long observation period (LOP) covers the whole basin, the enhanced observation period (EOP; 2011-2015) focuses on 3 regions of interest (TA target areas) (northwestern Mediterranean; Adriatic: Adriatic; southeastern Mediterranean) and the special observation periods (SOPs) were held over the northwestern Mediterranean region in fall 2012 and winter 2013.

Figure 4: Examples of HyMeX LOP and EOP sites: Cévennes-Vivarais hydrometeorological observatory (a), flux tower deployed at the Crau-Camargue hydrological site (b) and Lampedusa atmospheric site. (Source: panel a: B. Boudevillain; panel b: S. Garrigues; panel c: A.G. Di Sarra).

Figure 5: (a) Ground-based network of operational radar systems in the Mediterranean (dual-polarimetric systems are shaded). Permanent GPS/GNSS networks in North Africa and Europe as of Nov. 2011 and (b) ZEUS network observations collected on 26 October 2012 over the Mediterranean Sea. It must be noted that all the data from these networks are still not accessible and effort is on-going to collect them (especially in some Southern and Eastern Mediterranean countries). (Source: panel a: O. Bousquet; panel b: O. Bock; panel c: V. Kotroni).

Figure 6: Gliders (a) and instrumented buoy (b) deployed in the Gulf of Lions in the frame of the HyMeX EOP and LOP. Instrumented commercial ship Marfret Niolon carrying the weekly service Marseilles-Algiers in the frame of the HyMeX LOP. (Source: panel a: P. Testor; panel b: C. Dubois; panel c: I. Taupier-Letage).

Figure 7: French (a) and German (b) aircrafts deployed during SOP1, R/V Le Provence operated during SOP2 (c) and pressurized boundary layer balloons launched from Candillargues during SOP2 (d) (c). French ATR42 (foreground) and Falcon 20 (background) were based at Montpellier airport and German Do128 was based in Corsica at Solenzara airport. (Source: panels a and d: P. Drobinski; panel b: C. Kottmeier; panel c: I. Taupier-Letage).

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Figure 10: International organization of HyMeX.

CAPTIONED TABLE

List of acronyms

HyMeX-related acronyms

EC-ISC	Executive Committee for Implementation and Science Coordination
EOP	Enhanced Observation Period
HyMeX	Hydrological cycle in the Mediterranean Experiment
IIP	International Implementation Plan
ISP	International Science Plan
ISSC	International Scientific Steering Committee
LOP	Long Observation Period
MerMeX	Marine Ecosystems Response in the Mediterranean Experiment
MISTRALS	Mediterranean Integrated STudies at Regional And Local Scales
PO	Project Office
SOP	Special Observation Period
TA	Target Areas
TS	Task support
TT	Task Team
WG	Working Group

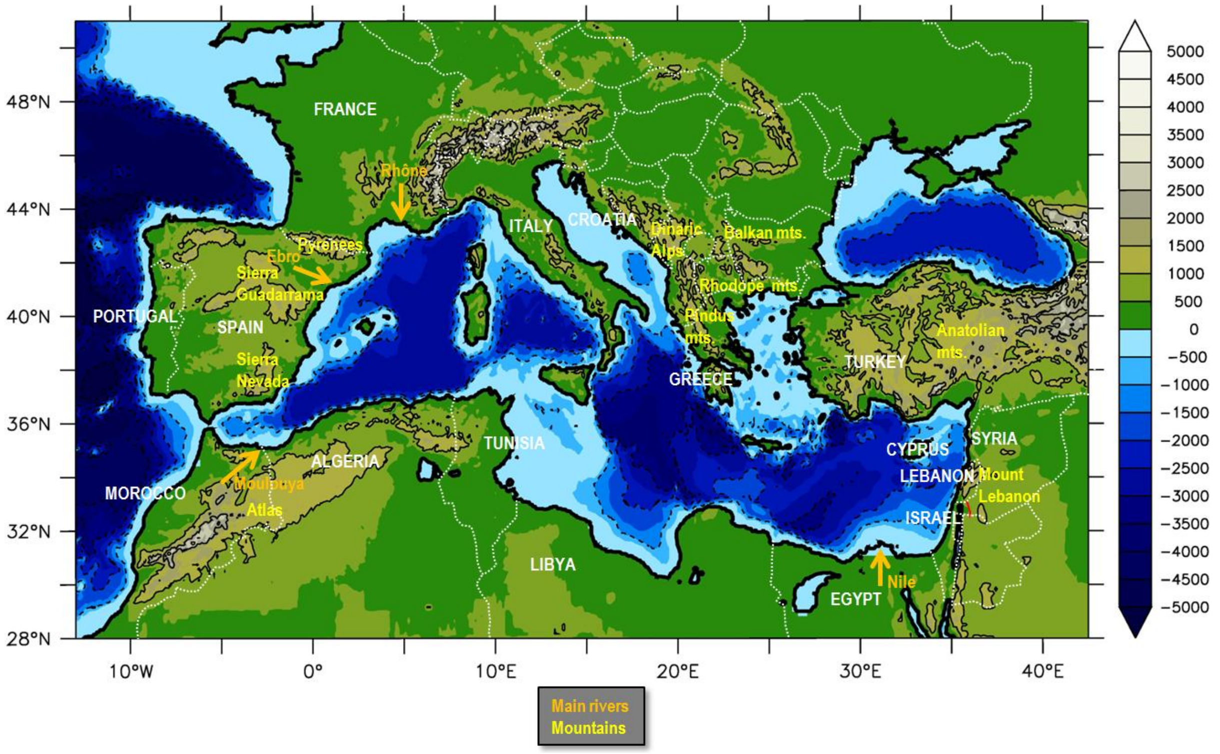
International projects and networks acronyms

AERONET	AErosol RObotic NETwork
ARGO	Observation system for the Earth's oceans- named after Greek mythical ship
ATDnet	Arrival Time Difference Thunderstorm detection system network
CMIP5	Coupled Model Intercomparison Project – phase 5
CIRCE	Cilmate Change and Impact Research: the Mediterranean Environment
CORDEX	COoRdinated Downscaling Experiment
EGITTO	----------
EGYPT	Eddies and GYres Paths Tracking
EUCLID	EUropean Cooperation for LIghtning Detection
GOME-2	Global Ozone Monitoring Experiment-2
GPS/GNSS	Global Positioning System/Global Navigation Satellite System
GPM	Global Precipitation Measurement
IASI	Infrared Atmospheric Sounding Interferometer
LINET	LIghtning detection NETwork
MAP	Mesoscale Alpine Programme
MEDEX	MEDiterranean Experiment
MOOSE	Mediterranean Ocean Observing System on Environment
OHM-CV	Observatoire Hydro-Météorologique – Cévennes-Vivarais
SOCIB	Balearic Islands Coastal Observing and Forecasting System
TRANSMED	Network of low-cost thermosalinometers in the Mediterranean (no aconym)
ZEUS	Lightning detection network- named after named after the mythological Greek God of Gods.

International programs and panels acronyms

CIESM	Mediterranean Science Commission
CLIVAR	CLImate VARiability and predictability
GEWEX	Global Energy and Water Cycle Experiment
IPCC	Intergovernmental Panel on Climate Change
THORPEX	The Observing System Research and Predictability Experiment
WCRP	World Climate Research Program
WWRP	World Weather Research Program

CAPTIONED FIGURES



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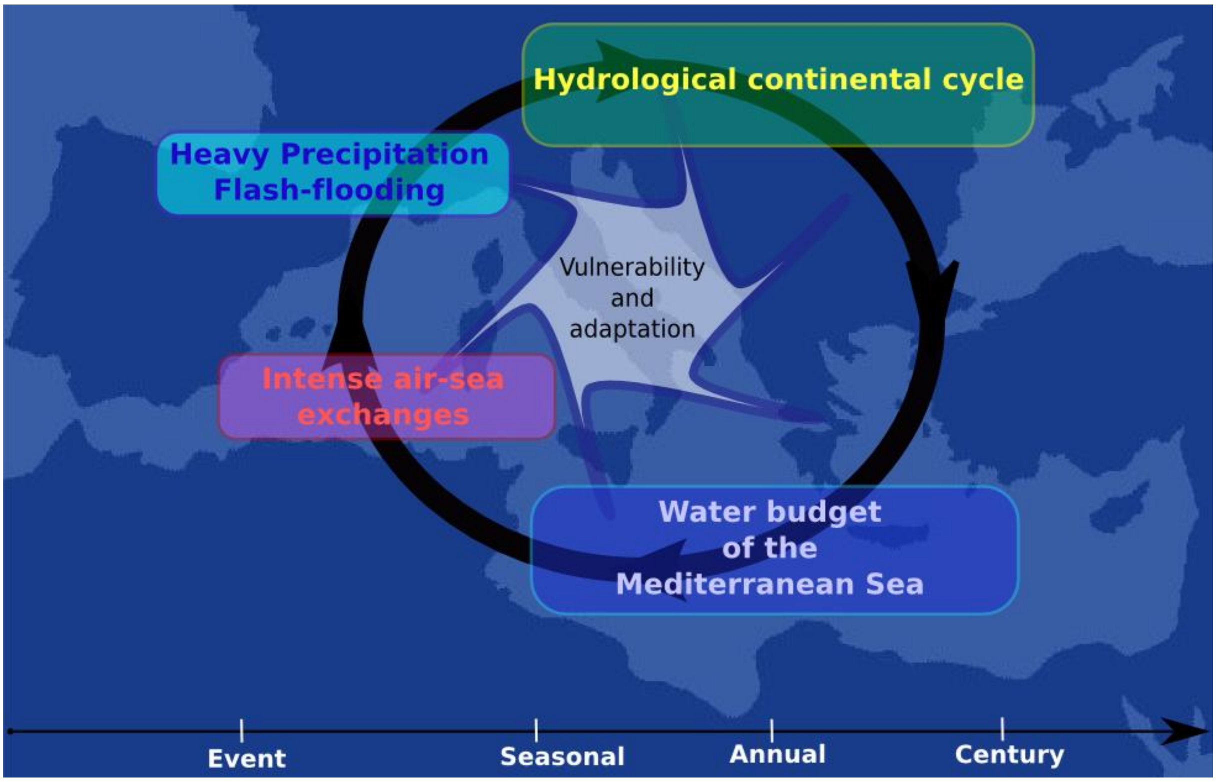

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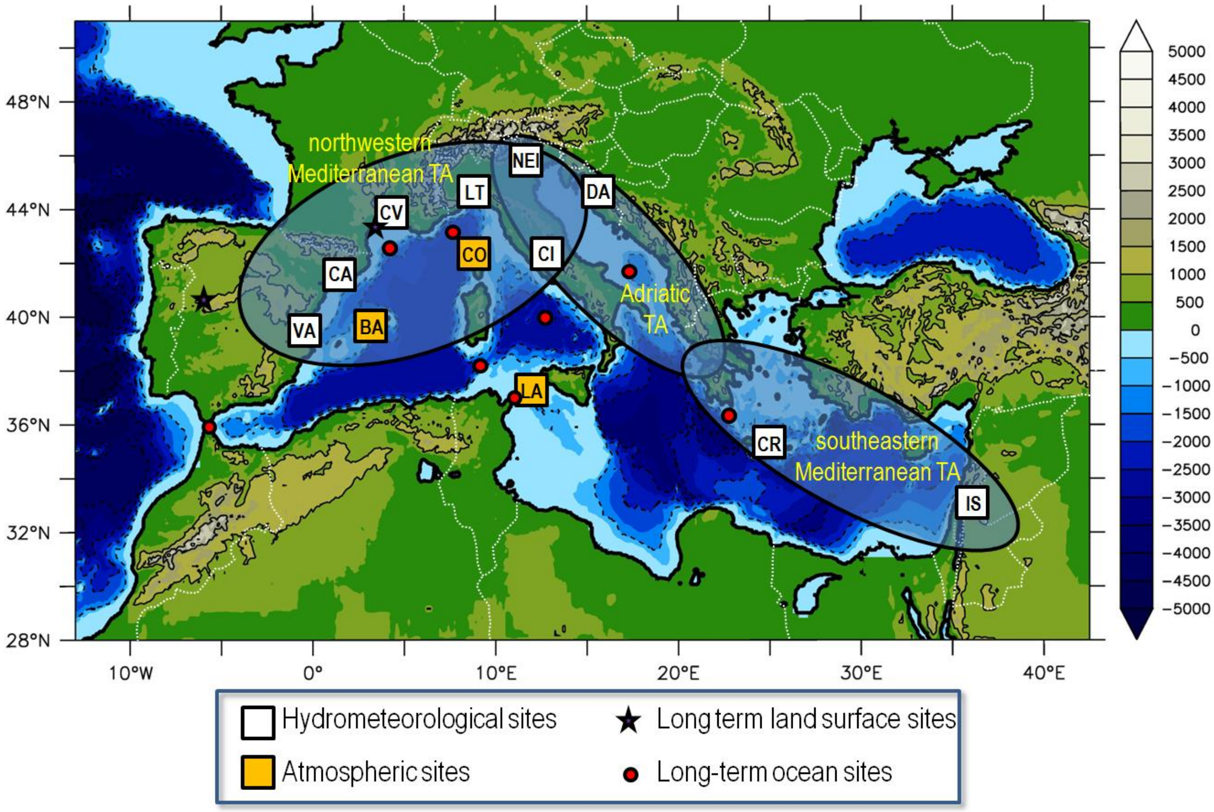

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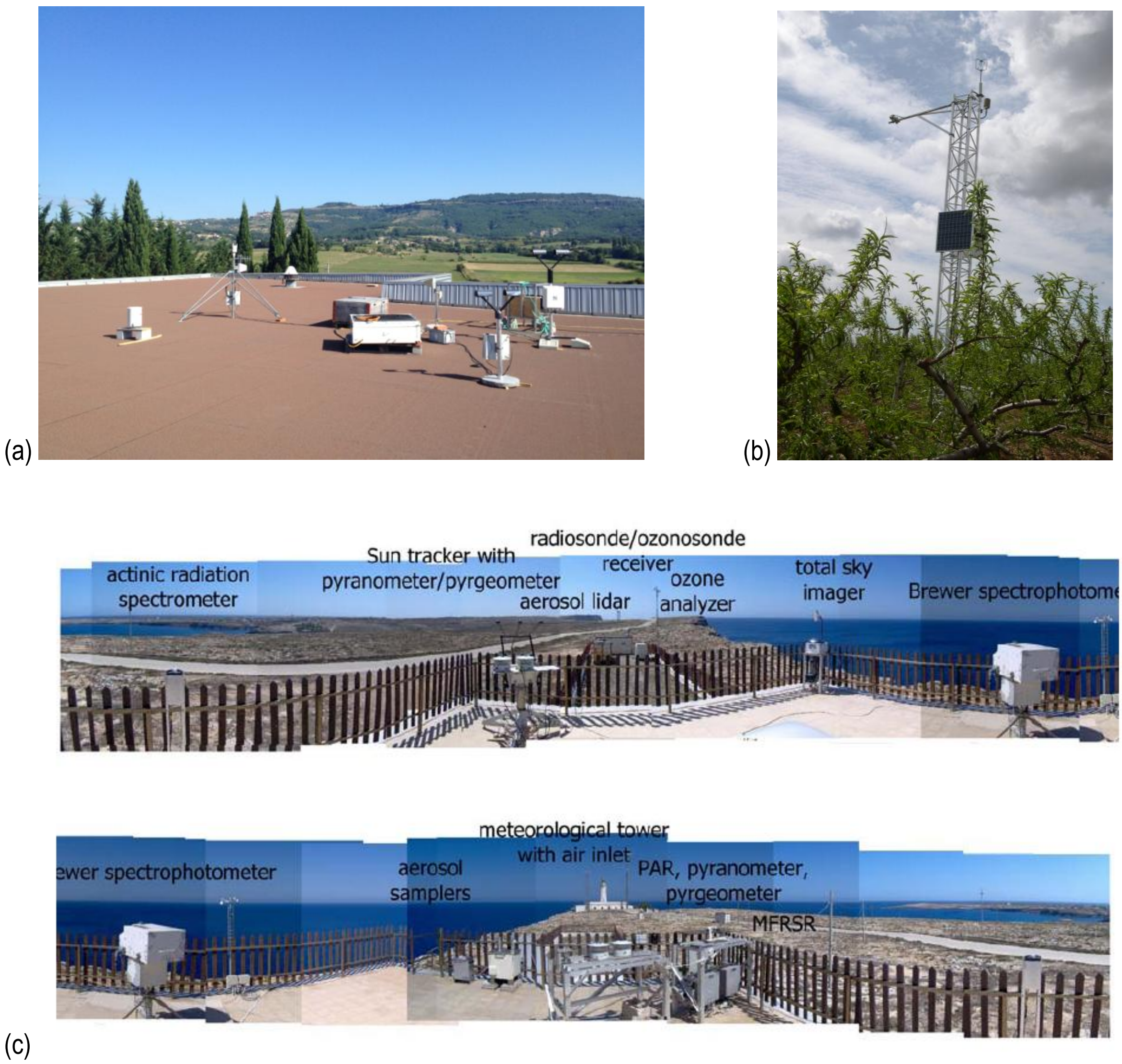

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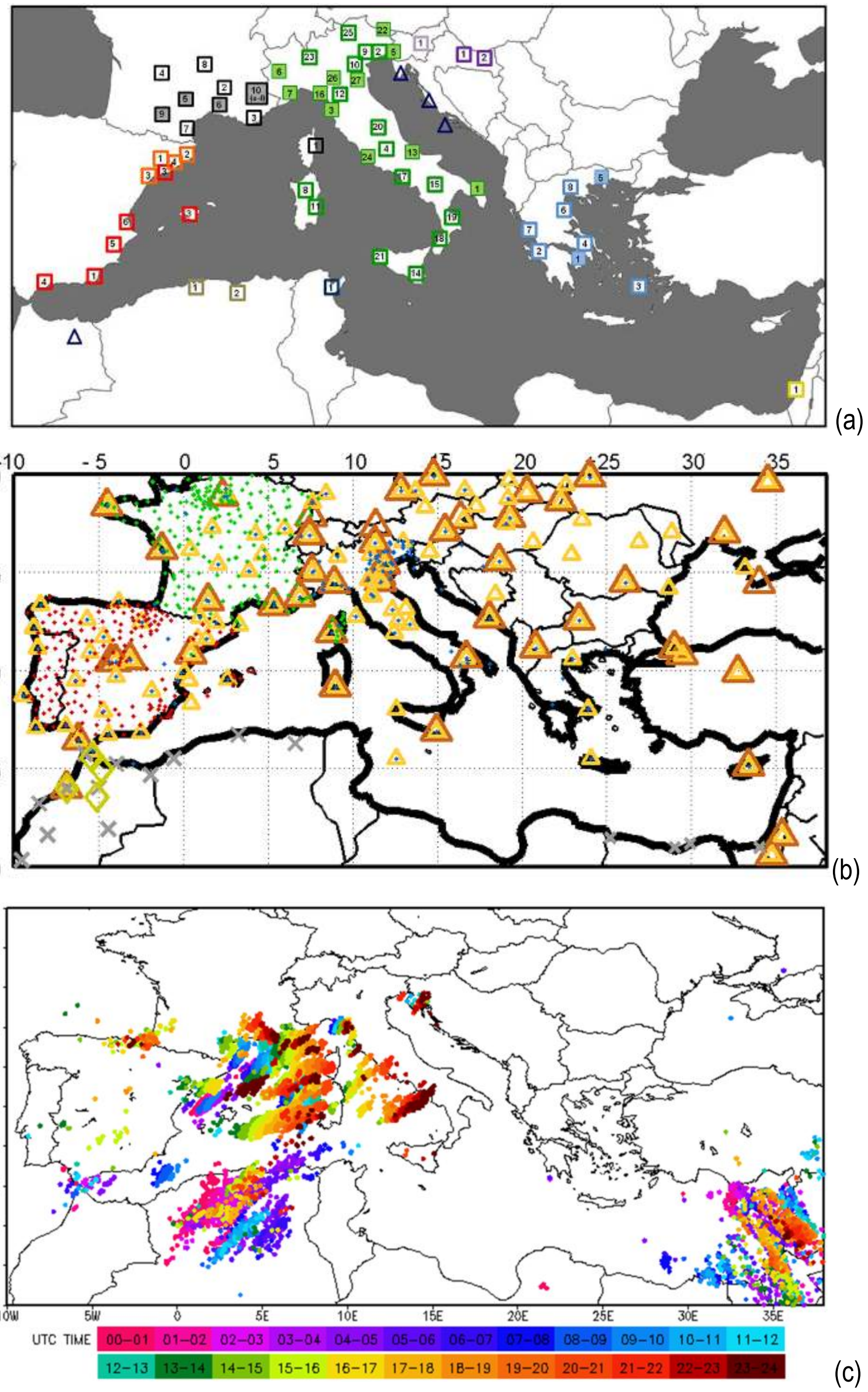

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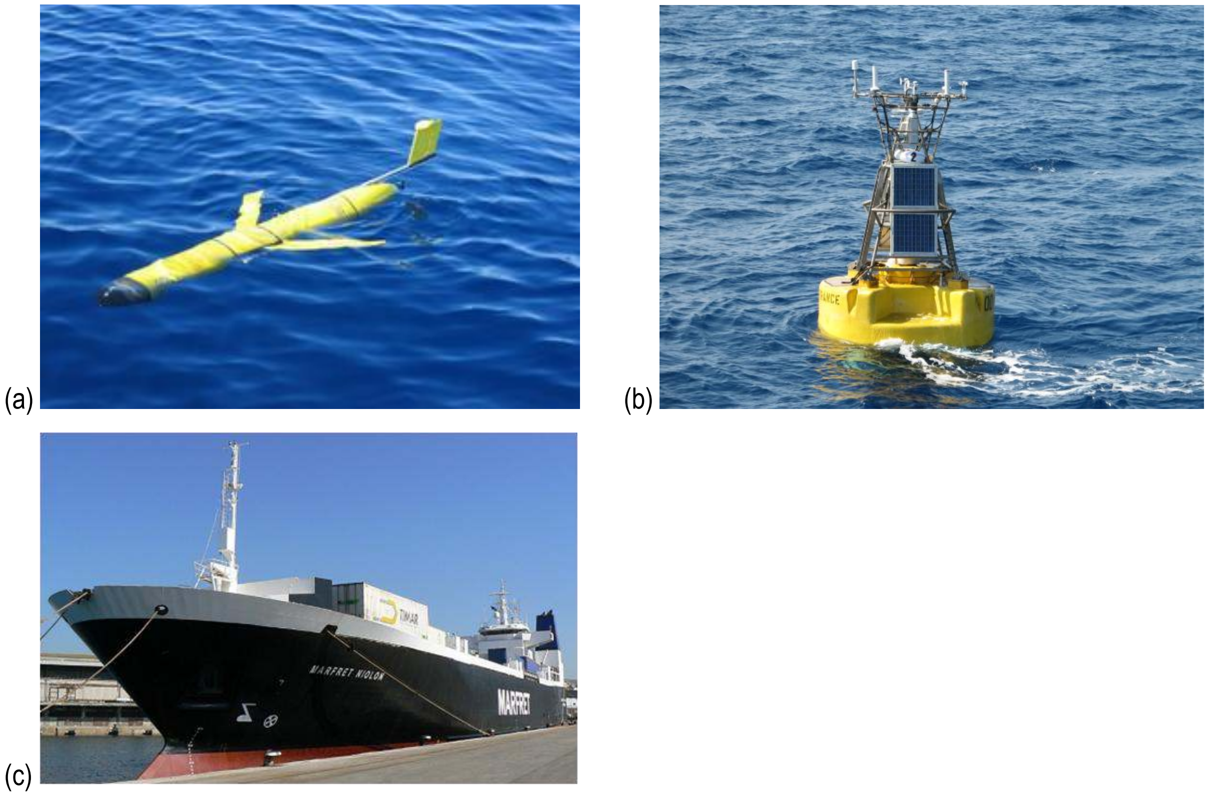

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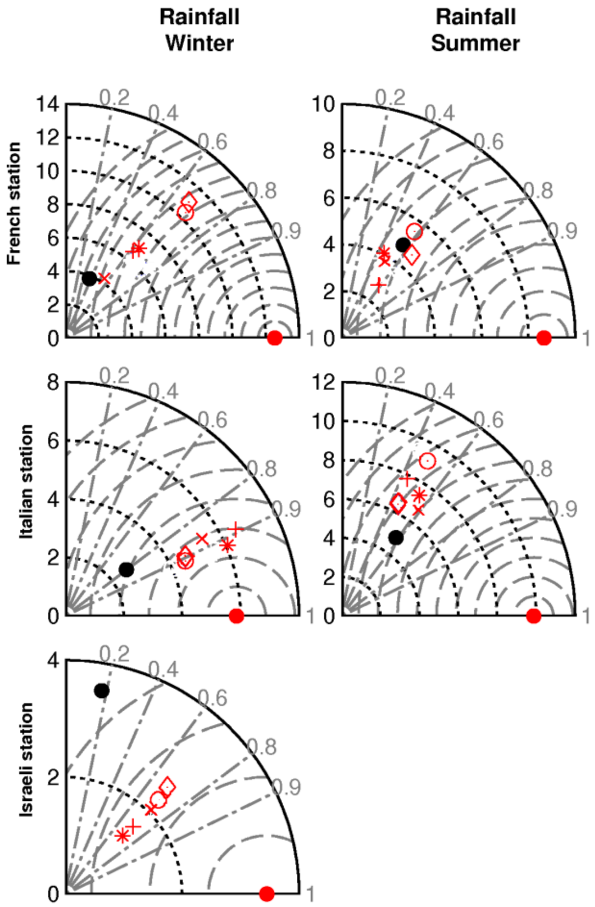

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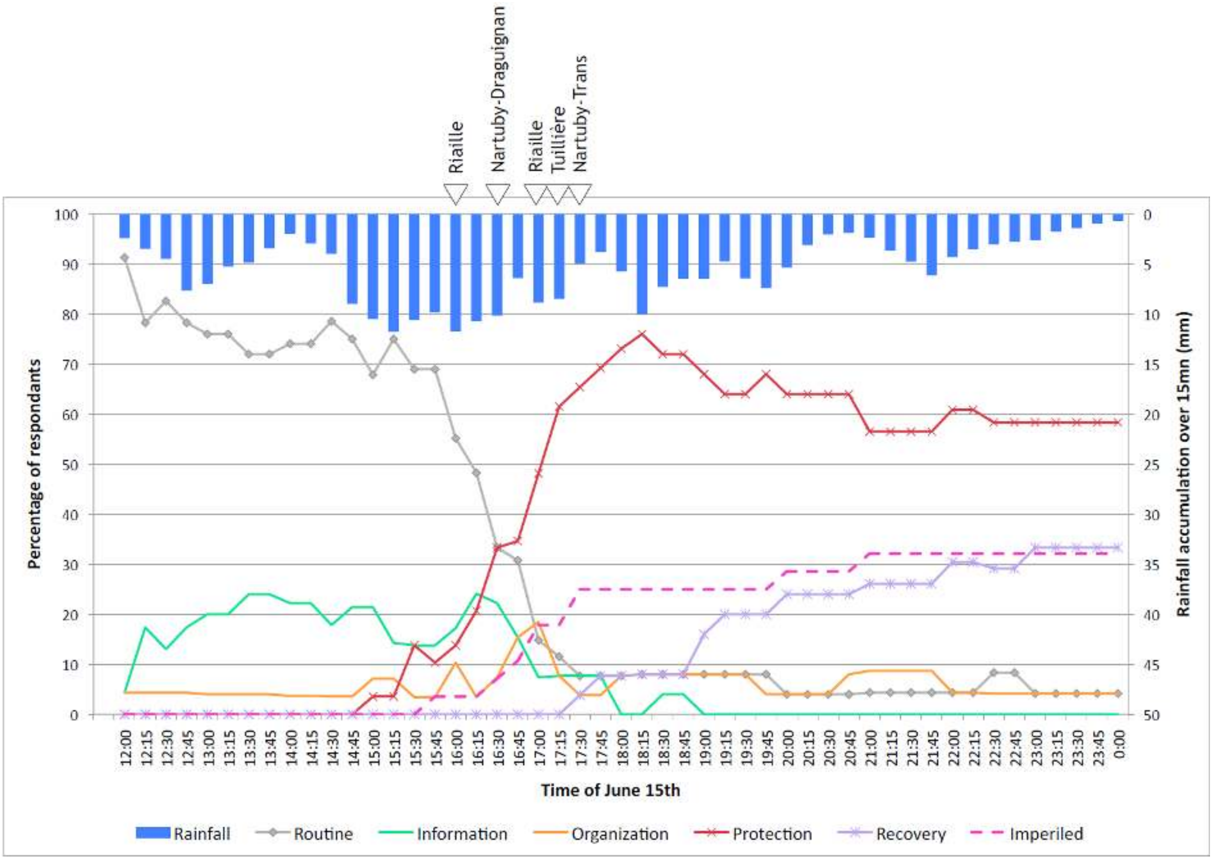

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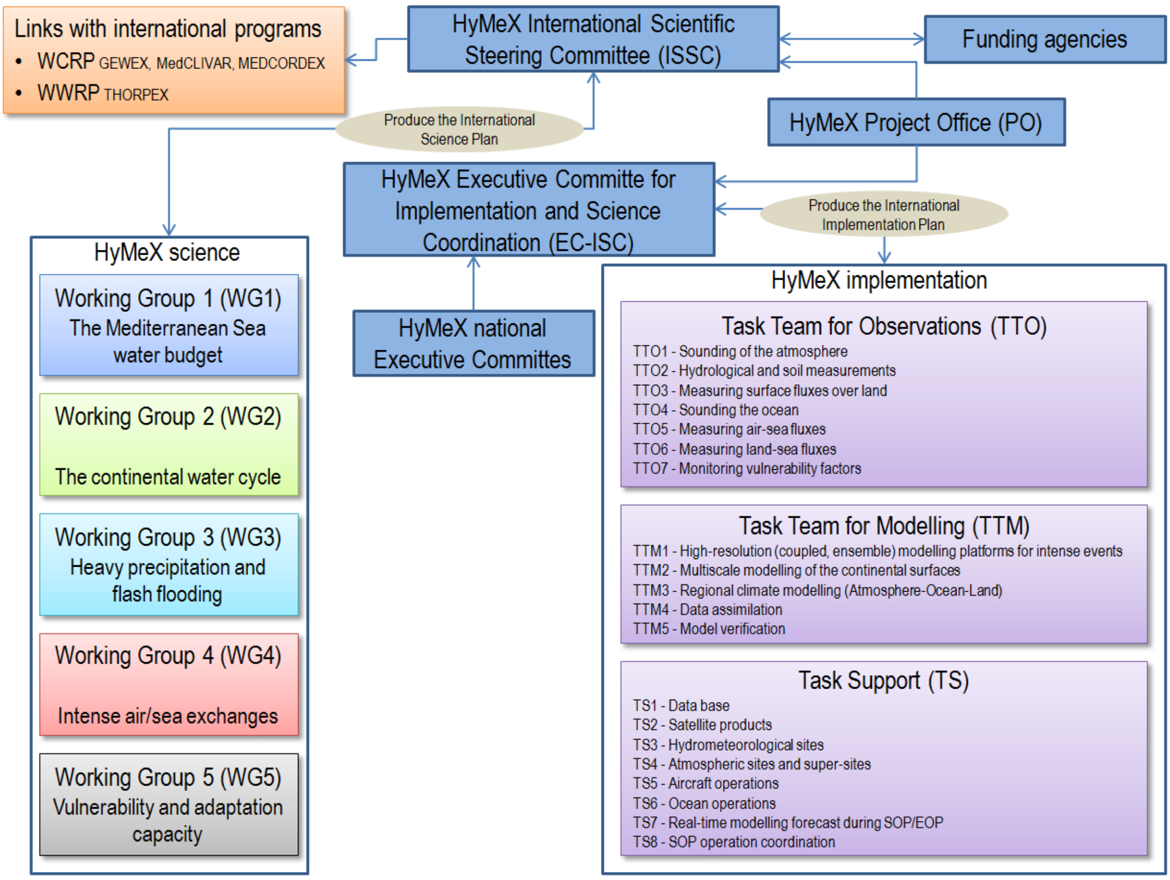

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