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

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HYMEX

A 10-Year Multidisciplinary Program on the Mediterranean Water Cycle

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HyMeX strives to improve our understanding of the Mediterranean water cycle, its variability from the weather-scale events to the seasonal and interannual scales, and its characteristics over one decade (2010–20), with a special focus on hydrometeorological extremes and the associated social and economic vulnerability of the Mediterranean territories.

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 from both 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 midlatitudes and tropical climate variability: to the north, a large part of the atmospheric variability is linked to the North Atlantic Oscillation (NAO) and other midlatitude 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 influence from El Niño–Southern Oscillation (ENSO) to the east (Rodwell and Hoskins 1996).

All these influences lead to a large variability at different scales, going from the multidecadal 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 airflow. The Mediterranean Sea acts as a moisture and heat source for the atmosphere through air–sea fluxes, so that energetic mesoscale 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. 2012b), 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 hydrometeorological extremes in the different parts of the Mediterranean. They include, for instance, cyclones in the Gulf of Genoa and in 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 recent increasing 50-yr trends in daily torrential rains in some western Mediterranean regions, while in the eastern Mediterranean relatively high interannual variabilities prevent any trend from being 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 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 euros of 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 Viscusi and Zeckhauser (2006) in 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, and in Algiers, Algeria, 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

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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 for 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 the reduction of water availability, the productivity of natural and cultivated vegetation (Ciais et al. 2005; Stéfanon et al. 2012b), and energy supply due to water shortage (Fink et al. 2004).

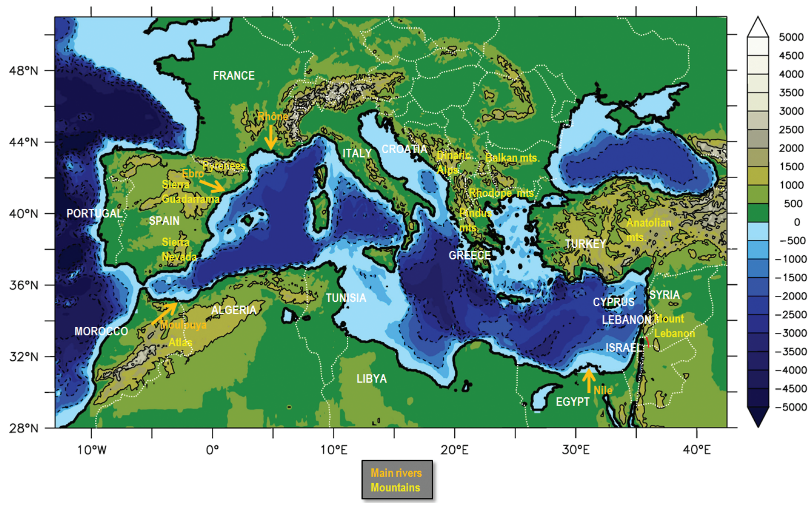

Fig. 1. Mediterranean basin (also HyMeX/MED-CORDEX simulation domain; more details in the text).

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 varied widely 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 an anthropogenic scenario, Giorgi (2006) defines the Mediterranean area as one of the two main "hot spots" of climate change, with an increase in interannual rainfall variability in addition to a strong warming and drying for 2080–99 compared with 1980–99. The 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 events conducive to floods and droughts may become more frequent (Gao et al. 2006) but also because the demographic projections from the Mediterranean Action Plan suggest 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 finescale processes and their nonlinear 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 seawater 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, and the difficulty in characterizing 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 into such coupled processes and the validation of a large variety of models, from finescale research and forecasting land surface, ocean, and weather models, to regional climate system models.

THE HYMEX PROGRAM. 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 Hydrological Cycle in Mediterranean Experiment (HyMeX; www.hymex.org) program is a concerted effort at the international level that aims to advance the scientific knowledge of the water cycle variability. It also aims to improve the processes-based models and the models of the regional climate system. Such models are needed for forecasting hydrometeorological 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 hydrometeorological extremes, by monitoring and modeling the atmosphere–land–ocean coupled system, its variability from the weather event to the seasonal and interannual scales, and its characteristics over one decade (2010–20) in the context of global change;
2) assess the social and economic vulnerability to hydrometeorological 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 the Mesoscale Alpine Programme (MAP; Bougeault et al. 2001), which is focused specifically on hydrological and atmospheric process studies driving orographic precipitation over the Alps; oceanographic programs in the Mediterranean Sea like Eddies and Gyres Paths Tracking (EGYPT; www.ifremer.fr/lobtln/EGYPT) and EGITTO (http://doga.ogs.trieste.it/sire/drifter/egitto_main.html); and Climate Change and Impact Research: The Mediterranean Environment (CIRCE; Navarra and Tubiana 2013), which is 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 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 modeling of the thermohaline circulation, including dense water formation through intense air–sea interactions. It also requires the quantification of the freshwater inputs from the continent to the sea (rivers and groundwater flows). This issue implies a better understanding and modeling 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 favorable 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 its International Science Plan (www.hymex.org).

A multiscale data modeling 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-yr period of data collection over the entire Mediterranean basin that allows for capturing certain modes of variability

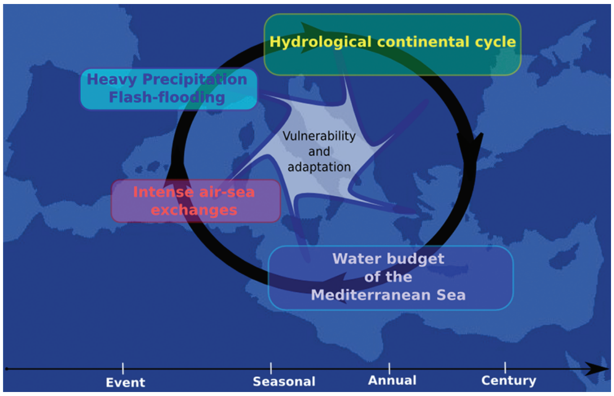

Fig. 2. Schematic of the main scientific topics of the HyMeX project.

and for getting a homogeneous observation network density as well as a good representativity of the measurements. It adopts a multidisciplinary (oceanic, atmospheric, hydrological, and social sciences) and seamless (from event scales to climate) strategy for both observation and modeling.

Nested observations. The HyMeX observation strategy is based on three-level nested observation periods. The long-term observation period (LOP) began in September 2010 and will continue until 2020. It spans the entire Mediterranean region to collect the long-term time series required to study the variability of the Mediterranean water cycle from the seasonal to the interannual 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 4 years, in order to conduct both budget and process studies. The three target areas are as follows (Fig. 3):

1) The northwestern Mediterranean, where all the intense hydrometeorological 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. 2014, a 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 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 transboundary river basin of the Evros River (marks the Greek–Turkish border), which suffers from floods; as well as the Daliya, Besor (northern Neguev), and Qidron (Mount Scopus in Jerusalem) basins farther to the east in Israel. This target area allows for the study of intense rainstorms and flash floods in drier climatic areas of the Mediterranean (Yakir and Morin 2011).
3) The Adriatic, which is composed 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 the Dinaric Alps also provides conditions for mesoscale cyclonic generation and the strengthening of local northeastern bora and southeastern jugo winds (Horvath et al. 2009; Jurčec et al. 1996). Dense water also forms to the north and south of the Adriatic subbasin (Vilibić and Supić 2005).

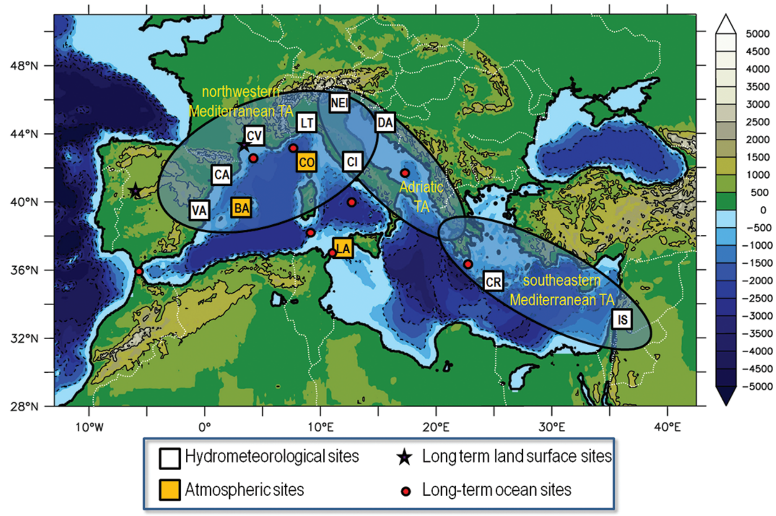

Fig. 3. Location of HyMeX target areas (ellipses). LOP covers the entire basin, the EOP (2011–15) focuses on three regions of interest (TA; northwestern Mediterranean, Adriatic, and southeastern Mediterranean), and the SOPs were held over the northwestern Mediterranean region in fall 2012 and winter 2013.

The special observation periods (SOPs) 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 ground-based, shipborne, and airborne means were deployed during the SOPs. The collection of new datasets and the enhancement of observation means during HyMeX provide 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. The strategy also allows the monitoring during a decade of variability, enhancing (combined with other observational datasets and with climate modeling) our capability to detect possible trends of the different components of the water cycle over the whole Mediterranean in the context of global change. The LOP relies either on existing international operational and research networks (oceanic and hydrometeorological observatories, radars, rain gauges, radiosoundings, surface weather stations, GPS, photometer and lightning networks, etc.) or on platforms developed specifically for HyMeX. Over land, hydrometeorological measurements are collected over 10 sites. They are the Catalan Hydrometeorological Observatory (CA), the Valencia site (VA), the Cévennes–Vivarais Mediterranean Hydrometeorological Observatory (OHM-CV; CV) (Fig. 4a), the Ligury–Tuscany site (LT), the central Italy site (CI), the northeastern Italy site (NEI, including Trentino–Alto Adige, Veneto, and 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 labeled by the Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Programme (WCRP) (Drobinski et al. 2009, 2011). Atmospheric measurements are collected over three sites, located in Corsica (CO; Corsican Observatory for Research and Studies on Climate and Atmosphere–Ocean Environment), Lampedusa (LA) (Fig. 4c), and the Balearic Islands (BA). These sites are complemented by multiscale 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

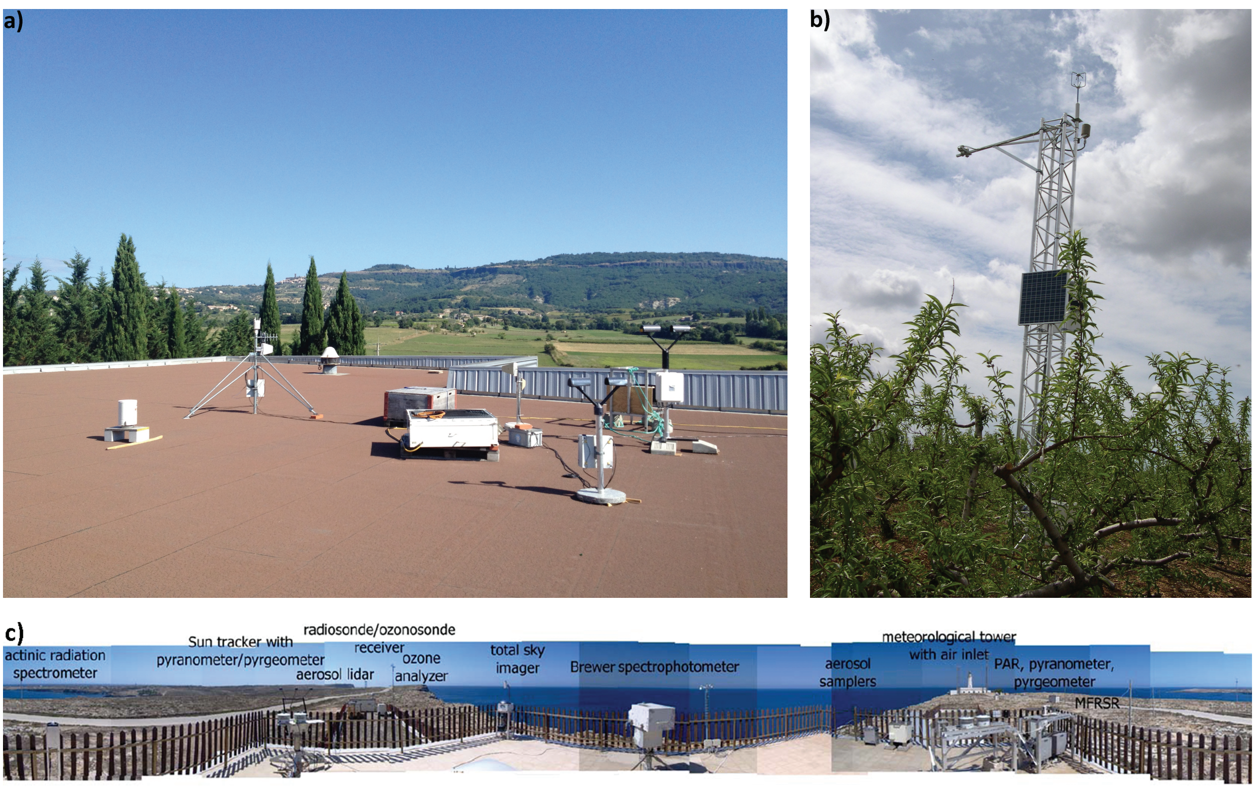

Fig. 4. Examples of HyMeX LOP and EOP sites: (a) CV, (b) flux tower deployed at the Crau–Camargue hydrological site, and (c) LA. [Source: (a) B. Boudevillain; (b) S. Garrigues; (c) A.G. Di Sarra.]

dynamics for water balance studies, such as the Crau–Camargue site (Fig. 4b).

The measurements from the instrumented sites are completed with observations from operational or research networks measuring precipitation from radars (Fig. 5a), atmospheric water vapor from GPS/Global Navigation Satellite System (GNSS) (Fig. 5b), and photometers and lightning from four operational lightning detection networks—that is, the two long-range networks, the Arrival Time Difference Thunderstorm Detection System Network (ATDnet; Met Office) and ZEUS (National Observatory of Athens); and the European operational network the European Cooperation for Lightning Detection (EUCLID) and the Lightning Detection Network (LINET; nowcast GmbH) (Fig. 5c). Indeed, a fundamental element that has been missing in past field experiments are 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

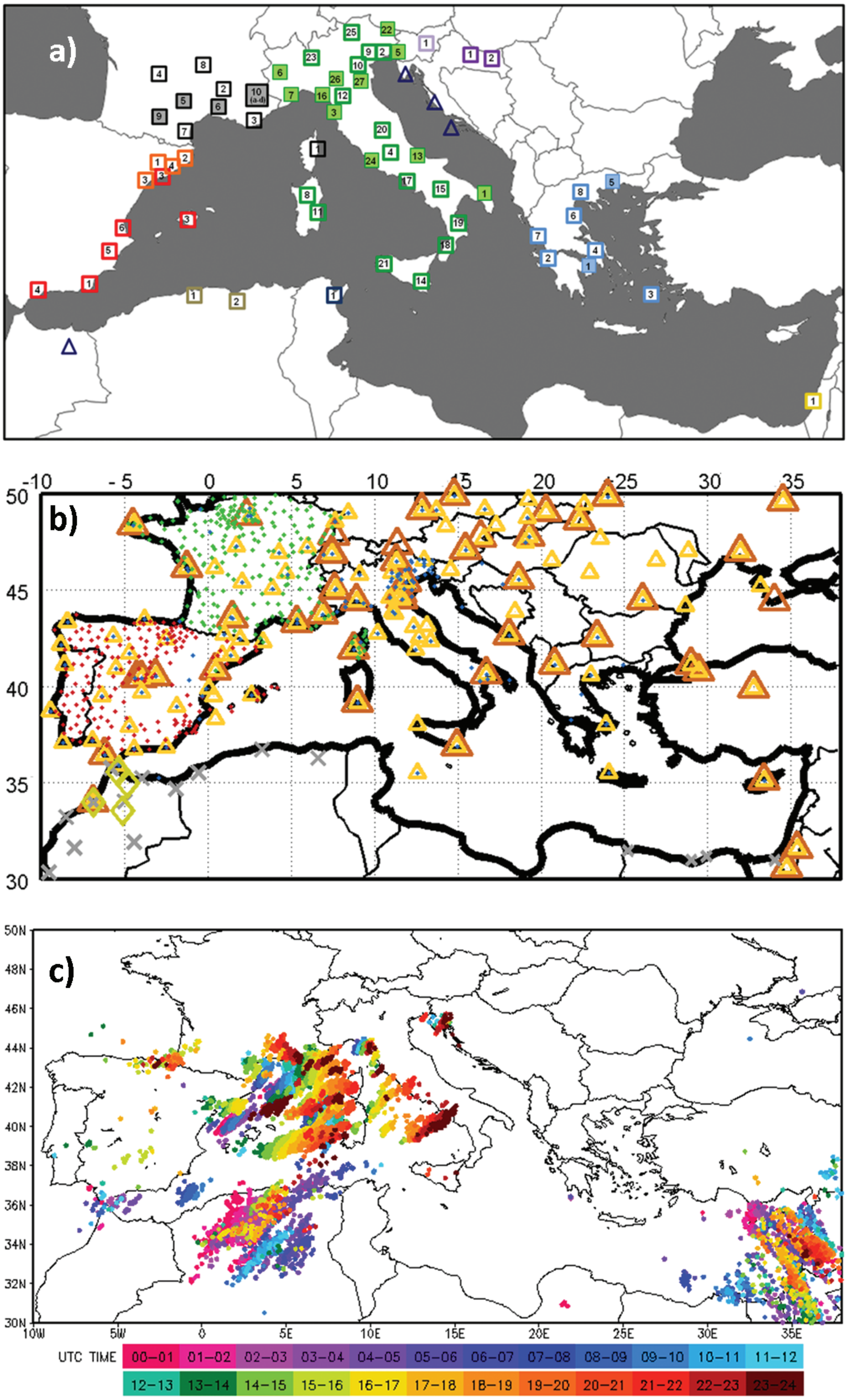

Fig. 5. (a) Ground-based network of operational radar systems in the Mediterranean (dual-polarimetric systems are shaded). (b) Permanent GPS/GNSS networks in North Africa and Europe as of Nov 2011 [orange triangles indicate the International GPS Service (IGS) network; yellow triangles indicate the European Permanent Network (EPN); green diamonds indicate the University Navigation Satellite Timing and Ranging (NAVSTAR) Consortium (UNAVCO) network; red, green, and blue dots indicate the European Meteorological Network (EUMETNET) GNSS Water Vapour Programme/Instituto Geografico Nacional de España (EGVAP/IGE), EGVAP/Service de Géodésie et Nivellement (EGVAP/SGN), and EGVAP/Agenzia Spaziale Italiana (EGVAP/ASI) networks, respectively; and gray crisscrosses indicate North African stations]. (c) ZEUS network observations collected on 26 Oct 2012 over the Mediterranean Sea. It must be noted that all the data from these networks are still not accessible and effort is ongoing to collect them (especially in some southern and eastern Mediterranean countries). [Source: (a) O. Bousquet; (b) O. Bock; (c) V. Kotroni.]

component of HyMeX, which involves research and operational radars together with the GPS/GNSS and Aerosol Robotic Network (AERONET) photometer networks, represents the most ambitious field project to date in the endeavor to collect such basic but hard-to-obtain information to advance understanding of

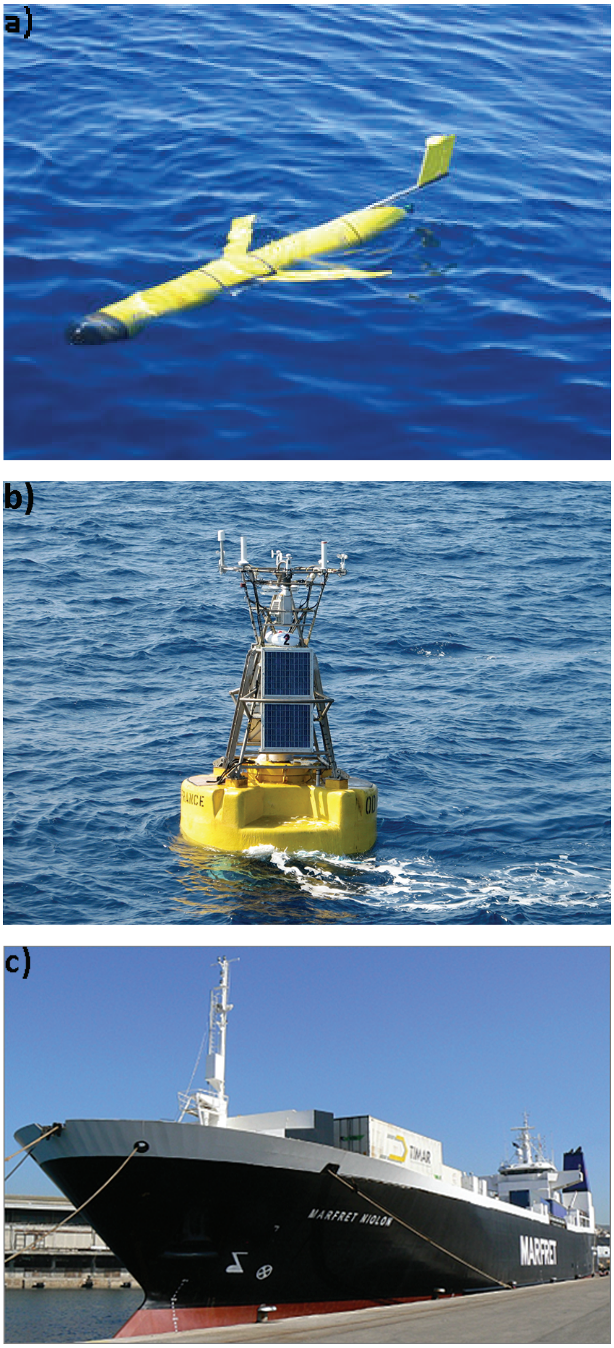

Fig. 6. (a) Gliders and (b) instrumented buoy deployed in the Gulf of Lions in the frame of the HyMeX EOP and LOP. (c) Instrumented commercial ship *Marfret Niolon* carrying the weekly service from Marseille to Algiers in the frame of the HyMeX LOP. [Source: (a) P. Testor; (b) C. Dubois; (c) I. Taupier-Letage.]

variability and predictability of precipitation. Even though all data from these networks are still not accessible and the effort is ongoing to collect them, the available radar and GPS/GNSS data are postprocessed 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 multiscale and multyear intracloud and cloud-to-ground lightning detection for observational- and modeling-based multidisciplinary 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 the HyMeX observation periods (LOP, EOP, and SOP).

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 (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, a network of low-cost thermosalinometers in the Mediterranean and supported by the Mediterranean Science Commission (CIESM), measures and transmits hourly the surface temperature and salinity; and GPS enables deducing the integrated water vapor content. To date the weekly ferry service from Marseille, France, to Algiers (Fig. 6c) is equipped; the ferry from Rome, Italy, to Barcelona, Spain, is next. Hydrographic cruises are also carried out yearly by an Italian companion program for a reference on the evolution of the water masses in the entire water column. At the northwestern part of the basin, observatories such as the Mediterranean Ocean Observing System on Environment (MOOSE; www.moose-network.fr/) and the Balearic Islands Coastal Observing and Forecasting System (SOCIB; 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 ~1000 m along two main transects, complemented by the dense network of CTD casts performed every 6 months by the MOOSE cruises. Off Nice, France, and in the center of the Gulf of

Lions, where deep convection occurs, the equipment of the two 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).

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 square kilometers are instrumented to follow soil moisture dynamics and runoff response (both surface and subsurface flow) during and between floods. This includes the Pradel site (Ardèche catchment), representative of lowland covered with vineyards and natural vegetation on limestone soils; and the Valescure and Tourgueille subcatchments (Gard catchment), representative of forested mountainous areas over granites and schist, respectively. At an intermediate scale (10–100 km^2), rain gauge networks such as the HPiconet network around the Le Pradel site (Fig. 4a) and limnimeter networks 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 postflood surveys have been carried out after major flash floods in the Mediterranean area, and they will continue until 2015. Indeed, flash floods have spatial and temporal scales of occurrence that are difficult to observe with the conventional measurement networks of precipitation and discharge (Borga et al. 2010). These postsurvey measurements will contribute to increasing 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 Figs. 7a,b), pressurized boundary layer balloons, and the French buoy tender *Le Provence*. Additional radiosoundings completed those performed in the Cévennes–Vivarais, Corsica, and central Italy sites, with some launched at sea from *Le 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. 2014). 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 (~2500 m). During the field campaign, the French research vessels *Le Suroît* [companion to the Marine Ecosystems Response in the Mediterranean Experiment (MerMeX)], *Tethys-2*, and *Le Provence* (Fig. 7c) contributed to sampling the water column and the air–sea fluxes, complemented by Marisonde buoys, surface velocity program (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).

Modeling. The HyMeX modeling 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 scrutiny in HyMeX will be directly compared to the SOP measurements [see details in Ducrocq et al. (2014) 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 analyze how the

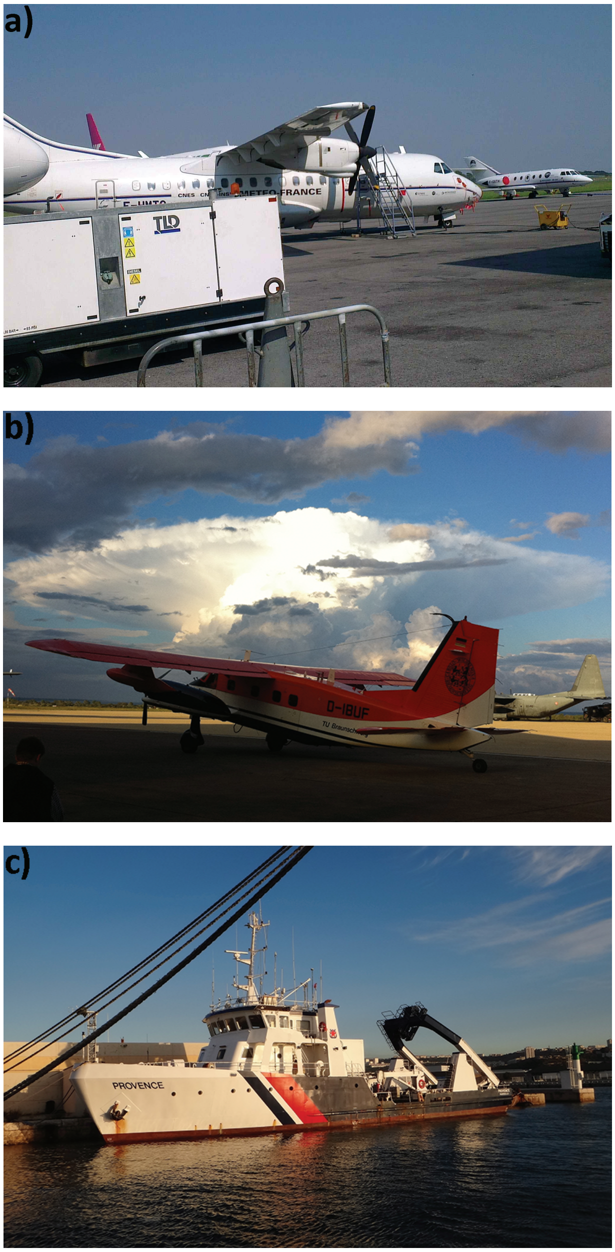

Fig. 7. (a) French and (b) German aircrafts deployed during SOP1, (c) *Le Provence* operated during SOP2, and (d) pressurized boundary layer balloons launched from Candillargues during SOP2. The French ATR42 (foreground) and Falcon 20 (background) in (a) were based at Montpellier airport and the German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

finescale 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 an atmosphere–ocean regional climate modeling 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 consist of complementing atmosphere–ocean regional climate models with tools representing other parts of the planetary makeup, 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 modeling strategy therefore includes the setup, validation, and improvements of multicomponents' regional climate models dedicated to the Mediterranean area: ocean, atmosphere, land surface, and hydrology in order to study interannual variability, past trends, and future climate change. Basin-scale regional climate modeling, a large part of the HyMeX activities, is common with the Mediterranean region of the Coordinated Downscaling Experiment

(MED-CORDEX; P. M. Ruti 2011, personal communication; see www.medcordex.eu) program of the WCRP (Giorgi et al. 2009). The joint HyMeX–MED-CORDEX activity consists of the downscaling of the Interim European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-Interim; hindcast simulations including the HyMeX period between 2010 to present and until 2020) and simulations from phase 5 of the Coupled Model Intercomparison Project (CMIP5) 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. 2014). 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 include river runoff (Artale et al. 2009; Herrmann et al. 2011; Kržič et al. 2011; Drobinski et al. 2012, L'Hévéder et al. 2013). At present, seven groups have already performed the simulations and four 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 in 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, the European Climate Assessment and Dataset (ECA&D) gridded dataset, and HyMeX/MED-CORDEX simulations performed with the Weather Research and Forecasting Model (WRF) to the rainfall measured at three station observations, at the Cévennes–Vivarais observatory in France, in northeastern Italy, and in Israel for the period 2003–08 (GEWEX-labeled HyMeX stations).

Finally, regarding forecasting, the modeling strategy includes the refinement of convective-scale deterministic forecast systems to improve the prediction capabilities of Mediterranean high-impact weather events. The SOP data provide a unique high-resolution database to validate these new numerical hydrometeorological prediction systems. It also aims to design high-resolution ensemble modeling approaches coupled with hydrological models to issue probabilistic forecasts of the impact in terms of hydrological response, and to develop 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 that will contribute to

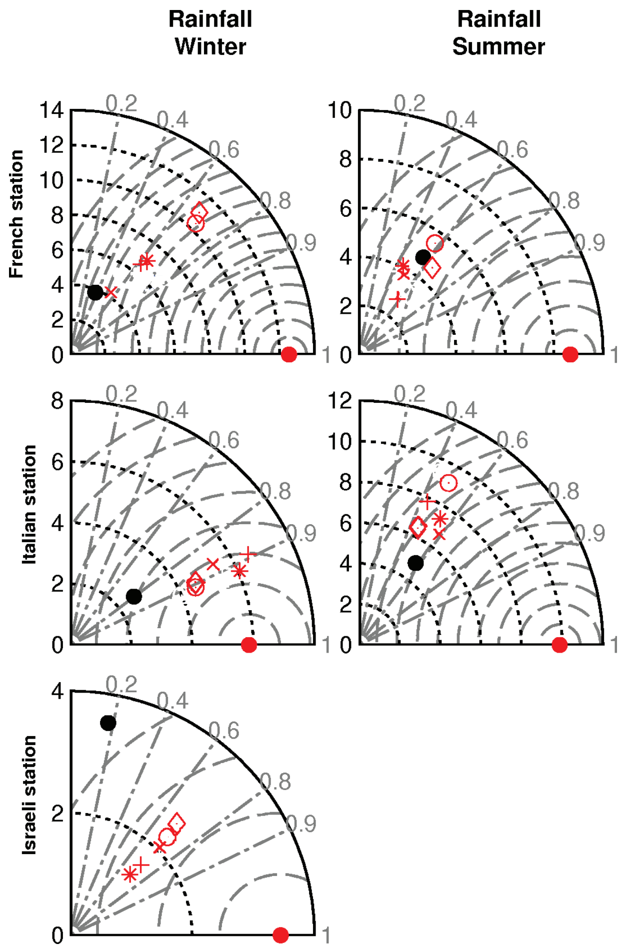

Fig. 8. Taylor diagrams for (left) winter and (right) summer rainfall showing standard deviation (dotted black lines), centered root-mean-square difference (dashed gray lines), and correlation (diagram angle) of ERA-Interim, ECA&D, and WRF outputs with respect to three station observations at (top) the Cévennes–Vivarais observatory in France, (middle) in northeastern Italy, (bottom) Israël for the period 2003–08 (GEWEX-labeled HyMeX stations; Drobinski et al. 2009, 2011; Flaounas et al. 2012, 2013). Black dot = ECA&D; red symbols = WRF and ERA-Interim, where red dot = station observations, × = ERA-Interim, star (*) and circle (o) = two configurations of WRF at 50-km resolution; cross (+) and diamond (◊) = two configurations of WRF at 20 km. (Source: E. Flaounas.)

the improvement of hydrological forecasting and water balance models.

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 for integrating in situ measurements and evaluating 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, etc.). 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, but the systems are 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 the 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 major progress toward the quantification of the 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), 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 Infrared Atmospheric Sounding Interferometer (IASI) (Vincensini et al. 2012) or ozone data from the Global Ozone Monitoring Experiment-2 (GOME-2) (Sbii et al. 2013) as well as background error modeling. Over the ocean, one objective is to build a high-resolution reanalysis of the Mediterranean Sea circulation. It will use the Mediterranean basin-scale 1/12° resolution ocean model on the Nucleus for European Modelling of the Ocean (NEMO-MED12; Beuvier et al. 2012), and the Mercator Assimilation System, version 2 (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 that are not assimilated (drifter trajectories, tide gauges, HF radars, etc.). 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

HYMEX DATABASE

The HyMeX database (www.hymex.org/database/) implemented by Observatoire Midi Pyrénées (OMP) and L'Institut Pierre-Simon Laplace (IPSL) includes a metacatalogue that gathers information about historical, LOP, EOP, SOP, satellite, and model data; a field data relational database; a database portal website including user registration and management; and access to the data catalogue with 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-yr 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 the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) in the frame of MED-CORDEX (www.medcordex.eu) with interoperability with the 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 of the datasets and their associated documentation, which will facilitate their use for scientific studies beyond the HyMeX project.

into land surface models [e.g., Organizing Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE) model; Interactions between Soil, Biosphere, and Atmosphere (ISBA)-Ags model] 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 1980s and are available through the HyMeX database (see the sidebar for additional information). 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.

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, etc.) and long-term modifications (change in access to water resources, droughts, etc.). Potential security problems and migrations produced as a consequence of floods, water scarcity, and droughts are on the agendas 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; Bazerman 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 Intergovernmental Panel on Climate Change (IPCC) report on extremes (Allen et al. 2012; Hallegatte et al. 2013) has insisted on 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 kinds 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 postevent surveys will add to analyzing the societal impact as well as the perception and resilience of populations. Besides our own outreach activity of the project, this new knowledge and information can be integrated into local and national strategies like climate change adaptation plans and laws, updating the European water directive and associated directives on floods and droughts, and civil protection strategies, including warning channel improvement.

The HyMeX approach consists of studying all factors that can influence the impact of such floods and droughts. To monitor social vulnerability to such extreme events and to learn from continuously evolving adaptive capacity and resilience processes at various space and time scales, social sciences techniques (interviews, surveys, impact reports, etc.) 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,b). Starting from the work developed in the Mediterranean Experiment (MEDEX) program (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-Pyrénées, 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. 2014). It shows that space–time sequences of actions, classified into five categories (usual, information, organization, protec-

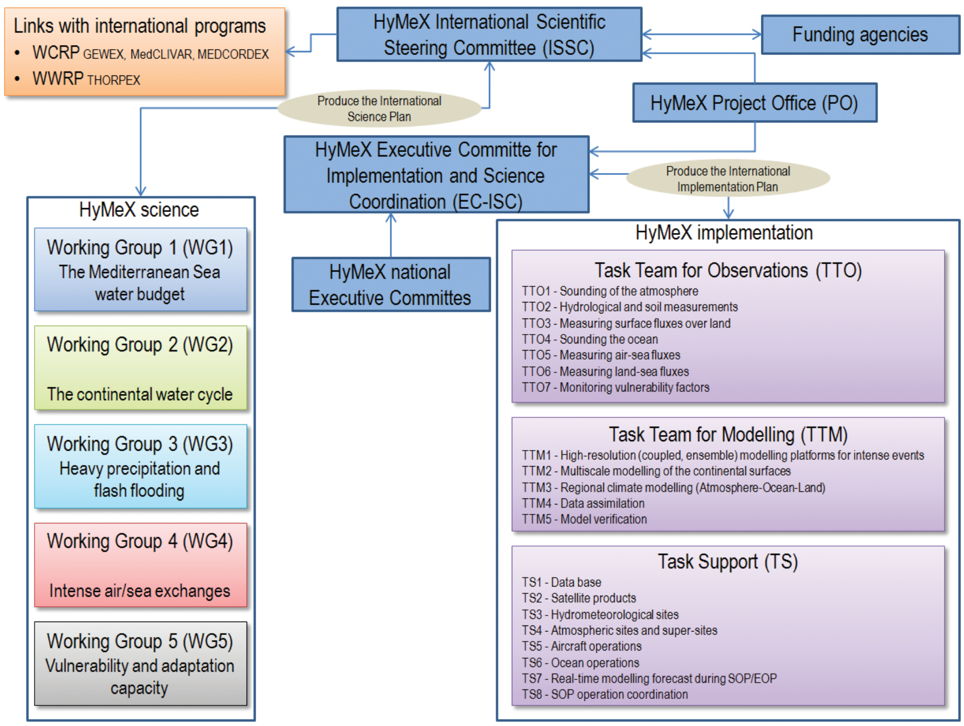

Fig. 9. Time evolution of the percentage of respondents by type of activity and corresponding areal rainfall intensity and time of peak flows over the Nartuby River basin (196 km²) in the Var area (southern France) during the 15 Jun 2010 flash-flood event at the beginning of the HyMeX LOP. Time step is 15 min. (Source: Ruin et al. 2014.)

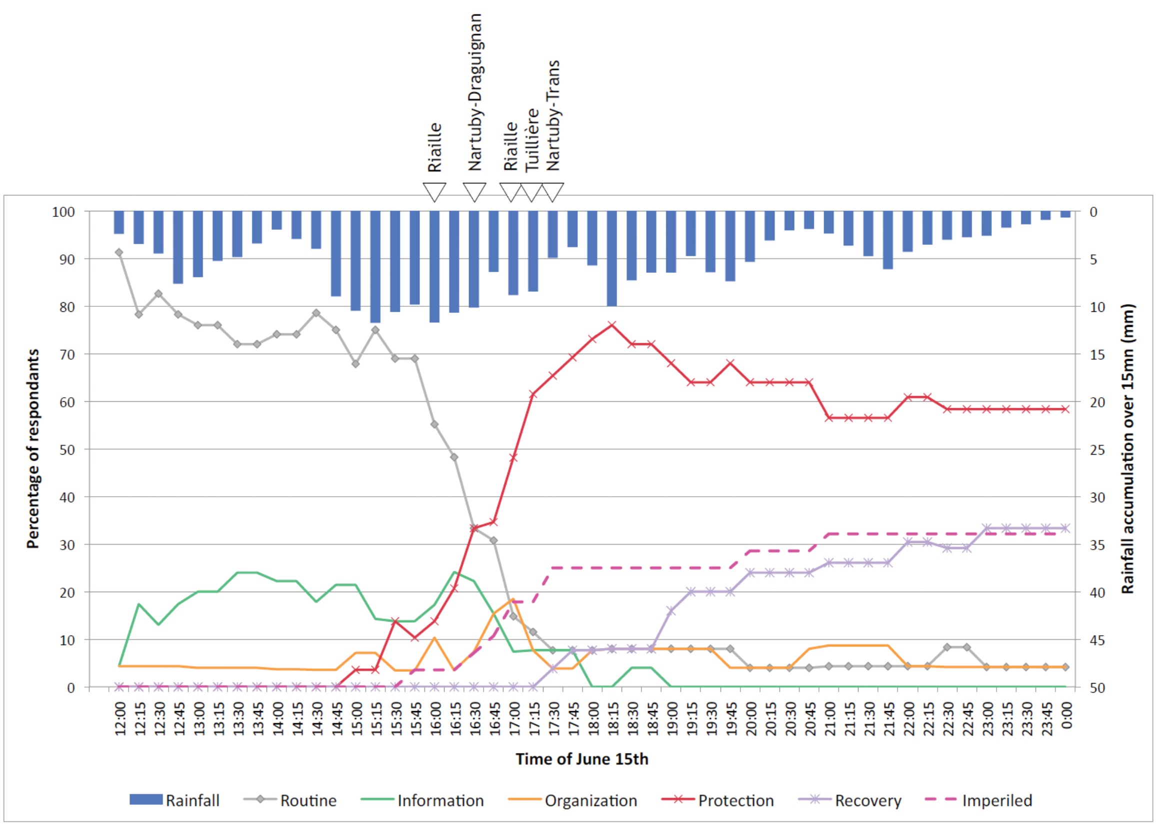

Fig. 10. International organization of HyMeX.

tion, 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 that took place locally and spontaneously.

INTERNATIONAL ORGANIZATION. More than 400 scientists from over 20 countries from both sides of the Mediterranean Sea, Europe, and the United States 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 modeling 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 the following:

- An International Scientific Steering Committee (ISSC) that 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) that ensures consistency and communication between the cross-cutting activities leading 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) that 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 the national level (e.g., Italy). HyMex has an inclusive approach, aiming at enlarging the contribution and participation to the southeastern Mediterranean institutions. HyMeX fits into the large interdisciplinary international program the Mediterranean Integrated Studies at Regional and Local Scales (MISTRALS), which is dedicated to the understanding of the Mediterranean basin's environmental process under the planet's global change (www.mistrals-home.org). It aims to coordinate, across the Mediterranean basin, interdisciplinary research on the atmosphere, hydrosphere, lithosphere, and paleoclimate, including environmental ecology and social sciences. The objectives are i) to achieve a better understanding of the mechanisms shaping and influencing the landscape, environment, and human impact of this ecoregion; 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 the evolution of local societies; and v) to propose policies and adaptation measures that would optimize them.

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

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