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Editorial
Introduction to the HyMeX Special Issue on 'Advances in understanding and forecasting of heavy precipitation in the Mediterranean through the HyMeX SOP1 field campaign'

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1. Introduction

The Hydrological Cycle in Mediterranean Experiment (HyMeX) is a 10-year international programme devoted to improving our understanding of the hydrological cycle in the Mediterranean area, with special emphasis on the predictability and evolution of high-impact weather events (Drobinski *et al.*, 2014). Heavy precipitation is a major natural hazard in the Mediterranean. Daily surface rainfall greater than 100 mm is not uncommon for Mediterranean precipitation events, and often such amounts are recorded in only a few hours, associated with mesoscale convective systems (MCSs). The occurrence of these heavy precipitation amounts over small river catchments that are characteristic of the Mediterranean region often leads to devastating flash floods and flooding events. Each year, these heavy precipitation events (HPEs) result in up to hundreds of millions of euros in damages and many casualties. The distinctive topography and geographical location of the Mediterranean basin (Figure 1) make the region particularly prone to HPEs. Most of these events occur in autumn over the western Mediterranean when sea water is warmest and serves as an important heat and moisture source from which convective and baroclinic atmospheric systems can derive their energy. The steep orography surrounding the Mediterranean Sea aids in lifting the low-level, conditionally unstable air, thus initiating condensation and convection processes.

The HyMeX observation strategy relies on (i) heavily instrumented Special Observation Periods (SOPs) of a few months to provide detailed and specific observations to study key processes, and (ii) longer observation periods repetitively or routinely collecting observations to monitor long-term water cycle processes and rare events such as flash flooding over a few specific instrumented watersheds. The first SOP was dedicated to heavy precipitation and flash floods. This major international field campaign took place from 5 September to 6 November 2012 over the northwestern Mediterranean Sea and its surrounding coastal regions in France, Italy and Spain. Ducrocq *et al.* (2014) gave a comprehensive description of the SOP1 observation strategy and execution, as well as the detailed list of deployed instruments. The observations collected by more than 200 research instruments constitute an unprecedented dataset. Uniquely in comparison to previous field experiments in the region, the atmosphere, ocean, and land surfaces were all sampled in order to study the interaction and feedbacks between the different components of the hydrological cycle during heavy precipitation and flash floods. As a substantial improvement to previous field campaigns dedicated to heavy precipitation (e.g. MAP field experiment in 1999: Bougeault *et al.*, 2001), SOP1 collected observations also over the sea and of precipitating systems forming over the sea and affecting the coastal areas. A strong modelling component (ocean–atmosphere–hydrology, process–weather, prediction–climate models) was conceived from the beginning in HyMeX, which allowed use of the field campaign data for model validation, data assimilation, improving physical parametrizations and for advancing process understanding.

This Special Issue presents a wide range of studies carried out over the last three years exploiting the exceptional dataset of observations and model output collected during SOP1. The special issue consists of a series of 31 articles. Some major results of these articles are summarized in the following sections. Section 2 presents advances in observations and their use in characterizing HPE, section 3 highlights the advances in process understanding, and section 4 details results about predictability of HPE from numerical weather prediction (NWP) and regional climate models.

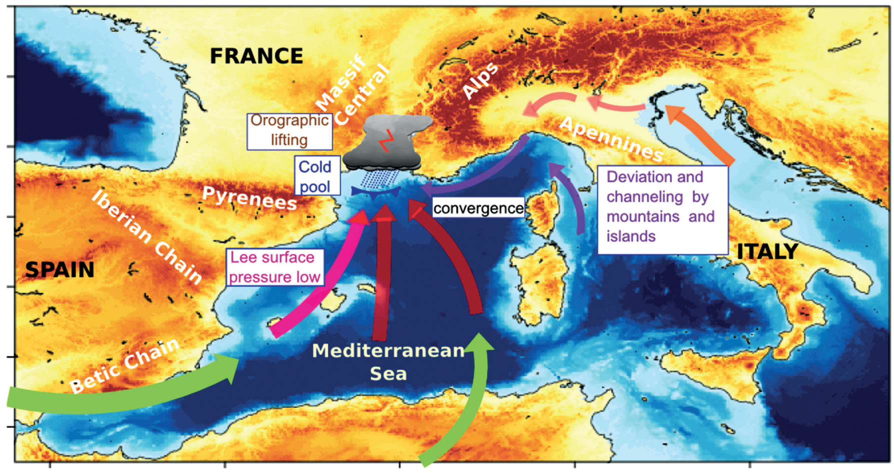

Figure 1. Schematic of the main low-level mechanisms responsible for a sample case of HPE in the western Mediterranean region together with geographical locations.

2. Observations and characteristics of SOP1

2.1. Cross-validation of observation and model datasets

As a primary stage of analysis, the consistency between co-located observations has been assessed for different research instruments measuring winds and water vapour during SOP1 (Chazette *et al.* (this SI, pp 7–22), Saïd *et al.* (this SI, pp 23–42)) and satellite products (Rysman *et al.* (this SI, pp 43–55)). Chazette *et al.* (this SI, pp 7–22) compare water vapour observations from a ground-based water-vapour Raman lidar (Chazette *et al.*, 2014), an airborne water-vapour lidar and boundary-layer pressurized balloons (Doerenbecher *et al.*, 2016). Saïd *et al.* (this SI, pp 23–42) compare winds from 11 UHF and VHF wind profiler radars, balloon radiosoundings, *in situ* aircraft or boundary-layer pressurised balloons. Airborne cloud radar measurements are used to validate the Convective Overshooting (COV) diagnostic based on passive microwave measurements from the Microwave Humidity Sounder (MHS) in Rysman *et al.* (this SI, pp 43–55).

Several studies take advantage of additional measurements from research instruments or availability of data from non-real-time networks to evaluate the performance and adequacy of current operational networks for describing the ambient low-level circulation and atmospheric water vapour. Bock *et al.* (this SI, pp 56–71) reprocessed more than 1000 ground-based Global Positioning System (GPS) receivers located in Spain, France and Italy to evaluate the accuracy of near-real-time E-GVAP GPS Zenith Total Delay (ZTD) data assimilated in operational NWP systems. They conclude that the mean differences between E-GVAP and reprocessed ZTD data are not negligible. On the other hand, the comparison of the integrated water vapour (IWV) from reprocessed GPS and radiosondes reveals no significant biases over night-time and small biases during daytime. This result gives high confidence in the quality of modern radiosonde systems in contrast to past experiments (e.g. AMMA: Agustí-Panareda *et al.*, 2009). Saïd *et al.* (this SI, pp 23–42) examine how the wind field derived from UHF and VHF wind profiler radars deployed along the French coast is able to represent the low-level circulation over the northwestern Mediterranean Sea. They clearly show that the drastically different characteristics of the winds induced by the complex terrain of the region make it difficult to retrieve wind fields from the five coastal profiler radars. The study of Khodayar *et al.* (this SI, pp 72–85) on Intensive Observing Period IOP8 concludes that the variability of water vapour and low-level wind convergence is quite adequately sampled by the operational networks inland, but not over the sea where the spatial and temporal resolution of observations is undeniably insufficient to identify and locate moisture convergence areas.

Radar observations collected during SOP1 (Bousquet *et al.*, 2015) represent a valuable dataset that is used to develop and evaluate novel radar-based products for research and operational activities. Bousquet *et al.* (this SI, pp 86–94) assess the quality of real-time multiple-Doppler radar winds retrieved from the French operational network radars over southern France with the radial velocity measurements collected by an airborne cloud radar during SOP1. The mean difference between the two three-dimensional (3D) cloud wind fields is close to zero and confirms that multiple-Doppler radar wind observations are accurate enough to be used for operational purposes such as NWP model verification. Another radar-based product, namely a hydrometeor classification algorithm, is evaluated in Ribaud *et al.* (this SI, pp 95–107). They propose an original method to derive 3D hydrometeor fields associated with convective systems from the multi-frequency single-radar hydrometeor classification. Wolfensberger *et al.* (this SI, pp 108–124) develop a new algorithm to automatically detect the melting layer based on polarimetric radar scans. Raupach and Berne (this SI, pp 125–137) present a new approach for the spatial interpolation of experimental raindrop size distribution (DSD) spectra from a network of disdrometers and a weather radar. Besson *et al.* (this SI, pp 138–152) show that the refractivity measurements collected from some weather radars during SOP1 compare well with observations from surface weather stations, and are able to capture the diurnal cycle and the low-level conditions during the pre-convection period.

The field campaign observations have been extensively used to assess the quality of NWP analyses and forecasts, as well as high-resolution research or regional climate model simulations, before they were exploited to document SOP1 conditions and advance process understanding. In particular, the real-time HyMeX-SOP dedicated version of the convection-permitting AROME NWP system (AROME-WMED: Fourrié *et al.*, 2015) is thoroughly compared to different datasets in Bock *et al.* (this SI, pp 56–71), Chazette *et al.* (this SI, pp 7–22), Di Girolamo *et al.* (this SI, pp 153–172), Duffourg *et al.* (this SI, pp 259–274), Rainaud *et al.* (this SI, pp 173–187) and Saïd *et al.* (this SI, pp 23–42).

2.2. Characteristics of SOP1

The characteristics of the IOPs together with the large-scale circulation that prevailed during SOP1 are presented in Ducrocq *et al.* (2014). IOPs over Spain and Italy are more specifically described in Jansà *et al.* (2014) and Ferretti *et al.* (2014), respectively. Monthly precipitation totals from surface stations were well above the corresponding climatology for most regions in October and November

2012, and were near average in September. The overall temporal distribution of HPE is closely related to the Atlantic weather regimes. Rysman *et al.* (this SI, pp 43–55) shows that convective activity during SOP1, based on the Deep Convection (DC) and COV diagnostics from MHS over the Mediterranean area (including over the sea), was not notably different from the last 12 years, except for some instances in the second half of the SOP period with COV occurrence reaching two to four times the average values.

Bock *et al.* (this SI, pp 56–71) use reprocessed GPS data to examine the spatial and temporal variability of IWV during SOP1. They point out a high temporal variability in the moisture content, with higher content at Mediterranean coastal sites which are under the influence of strong low-level inland advection of moisture. IWV peaks are often observed shortly before precipitation. Saïd *et al.* (this SI, pp 23–42) highlight the high spatial variability of low-level winds along the northwestern coast, observed by the mesoscale wind profiler radar networks, strongly linked to the complex mountainous coasts and islands and their role in the low-level circulation. The mistral and the tramontane, two regional northerly and northwesterly dry winds which often blow in the northwestern Mediterranean basin, are examples of interactions of the large-scale flow with orography. During autumn, as in SOP1, the second prevailing wind of the northwestern basin is onshore wind, favouring heavy precipitation (Ricard *et al.*, 2012). Di Girolamo *et al.* (this SI, pp 153–172) study three transition events from mistral/tramontane to southerly marine flow in southern France during SOP1. Low-level wind reversals are found to have a strong impact on water vapour transport, leading to a large variability of the water vapour vertical and horizontal distributions. A noticeable result is that the increase/decrease in water vapour mixing ratio within the boundary layer may be abrupt and marked during these transition periods, with values increasing or decreasing by a factor of 2–4 within 1 h.

The high variability of water vapour associated with low-level winds impacts the air–sea fluxes. Rainaud *et al.* (this SI, pp 173–187) show that the Gulf of Lion is the area with the highest variability of air–sea fluxes during SOP1, due to the prevailing strong dry regional winds (mistral/tramontane). Another remarkable result of this study is that even though some HPEs occur without significant air–sea fluxes, all strong air–sea exchange episodes include, or occur just 1 or 2 days before, HPEs.

3. Process understanding

3.1. Initiation and sustenance of deep convection

A major ingredient in HPE is the conditionally unstable, low-level marine flow impinging on the mountainous coastal regions bordering the western Mediterranean Sea, associated with lifting that leads to the onset of deep convection at the same place. The lifting mechanisms mostly result from the interactions of the low-level circulation with the orography, which greatly depends upon the local configuration of the terrain. However, a noteworthy outcome of many of the IOP studies carried out over Spain, France or Italy is that these cases present common characteristics (Figure 1). In addition to the direct role of orographic lifting, they frequently highlight features such as the presence of pre-existing convergence lines (dynamically or orographically induced), the role of a cold pool (possibly, but not necessarily, resulting from evaporative cooling) and contributions of topographical flows (e.g. gap winds and barrier jets).

Based on IOP18, IOP19 and pre-SOP1 events over northeastern Italy (NEI), Davolio *et al.* (this SI, pp 188–205) identify two different dynamical behaviours of the flow impinging on the Alpine orography, associated with two different patterns of heavy precipitation. All the events present a similar initial phase, forced by the advancing synoptic disturbance and characterized by a weak low-level wind coming from the Adriatic Sea (sirocco wind) blocked by the Alps and deflected as an easterly/northeasterly barrier wind over the NEI plain. Then, different interactions with the orography produce two different evolutions: (i) flow-over conditions progressively establish themselves, the barrier wind disappears and the orographically forced uplift of the impinging flow produces intense orographic precipitation over the Alps, with embedded convective activity; (ii) the uplift over the pre-existing cold air over the NEI plain (blocking) is able to initiate convection well upstream of the orography where the unstable incoming flow is forced to rise over the layer characterized by the barrier wind. Blocked flow conditions persist and the convergence line between the sirocco wind and the barrier wind further triggers convection. The precipitation affects the NEI plain or even the coastal area, far from the Alps.

Scheffknecht *et al.* (this SI, pp 206–221) explicitly highlight the role of the deflection of flow around the mountainous islands by studying the localized convective system of IOP15c, which led to severe flooding over southern Corsica. They clearly identify the splitting of the northerly low-level wind around the Corsican orography and the resulting lee-side convergence at the southern tip of the island as key mechanisms for this event. Heavy precipitation ceased only when the balance between the eastern and western branches of the flow was disrupted, and when gap winds blowing from the Apennines started to intensify. Barthlott *et al.* (this SI, pp 222–237) study the role of Corsica in initiating nocturnal offshore convection for two cases, including IOP13 from SOP1. For the first case, the island's katabatic flow facing marine winds induces low-level convergence responsible for the convection initiation, whereas the flow around the island and the resulting lee-side convergence is the main triggering mechanism for the second case (IOP13). Another notable influence of the orography is emphasized also on IOP13 by Barthlott and Davolio (this SI, pp 238–258)'s study, which emphasize the sheltering effects of the Corsica and Sardinia islands as a mechanism modulating the rainfall distribution over Liguria and Tuscany.

Duffourg *et al.* (this SI, pp 259–274) study the mesoscale convective systems that formed over the sea and produced heavy precipitation over the French coastal region during IOP16a. The convective systems are fed, during their stage over the sea, by moist and conditionally unstable air carried by a southwesterly to southeasterly low-level jet. The low-level wind convergence in this flow situation is the main triggering mechanism acting to continuously initiate and maintain the renewal of trailing convective cells contributing to the back-building convective system. The convergence line appears when a surface pressure minimum forms in the lee of the Iberian mountains, associated with the eastward progress of an upper-level potential vorticity (PV) anomaly. In addition, near-surface evaporative cooling reinforces low-level convergence and thus upward motion. This mechanism is found to play a key role in organising into MCSs, the deep convection embedded within the larger-scale comma-shaped cloudy band associated with the cyclone. Flaounas *et al.* (this SI, pp 275–286) compare this Mediterranean cyclone to another deep Mediterranean cyclone also associated with heavy precipitation and comma-shaped frontal clouds. Although both cyclones developed over the same region and shared the same intensity (in terms of central mean-sea-level pressure), the associated heavy rainfall was produced by two different dominant mechanisms: (i) deep convection for IOP16a, and (ii) warm conveyor belt ascent associated with stratiform precipitation for the second case.

IOP8, the most damaging event of SOP1, was also characterized by an upper-level cut-off associated with a depression and low-level convergence zone within which an MCS formed over the eastern Spanish coast (Jansà *et al.*, 2014). Röhner *et al.* (this SI, pp 287–297) identify two main trigger mechanisms leading to heavy precipitation in this case: (i) a wind convergence line over the sea served to release the potential convective instability, and (ii) the interaction of the low-level winds with the Spanish orography reinforced the heavy precipitation.

3.2. MCS dynamics and microphysics

During SOP1, more than 30 instruments were deployed over southern France to describe the lightning activity associated with convective systems. Among them, the Lightning Mapping Array (LMA) provided exceptional insights into the 3D structure of the lightning flashes, with a large variety of flashes recorded during SOP1 (Defer *et al.*, 2015). Ribaud *et al.* (this SI, pp 298–309) investigate the relationship between lightning activity and microphysics for the IOP6 bow-echo convective line using 3D LMA lightning observations, wind and hydrometeor observations deduced from the weather radars. The results suggest that the transport of electrically charged ice crystals from the convective area toward the stratiform area of the MCS is at the origin of a lower lightning activity since the detrainment of charged particles from the top of the convective area would reduce the intensity of the electric field within this area. Wet hail growth may also have inhibited the non-inductive charging leading to a weaker lightning activity. On the contrary, the passage of the system over a small hill may have strongly enhanced the updraught resulting in suddenly very intense lightning activity at very high altitude. Zwiebel *et al.* (this SI, pp 310–319) further study the impact of terrain elevation on precipitation structure from DSD observations of IOP7a over southern France. They show that both the orography and the rainfall regimes play a role in the rainfall structure and in the associated microphysical processes. The coalescence mechanism seems dominant above the height of the local topography, whereas other microphysical processes, such as break-up, evaporation or updraught effects, compete with the coalescence mechanism near the ground.

3.3. Water vapour origin and transport

A low-level moist flow is a common ingredient for HPEs. The origin of the moisture over the Mediterranean Sea is however quite diverse (Duffourg and Ducrocq, 2013) and originates from (i) evaporation from the Mediterranean Sea, (ii) transport from the North Atlantic Ocean, and (iii) transport from North Africa. Chazette *et al.* (this SI, pp 320–334) highlight a tropical origin of high water-vapour content air associated with the slow eastward propagation of a south/north elongated upper-level trough and strong low-level southeasterly winds over the Mediterranean within which MCSs formed during IOP15c. Röhner *et al.* (this SI, pp 287–297) identify for IOP8 two moisture uptake regions: one in the eastern North Atlantic for the early part of the event and one from the Mediterranean Sea for the latter part.

Adler *et al.* (this SI, pp 335–346) study more specifically the spatio-temporal variability of IWV over Corsica and particularly elucidate the asymmetric IWV distribution between the west and east coasts. Thermally driven circulations and associated mesoscale transport processes as well as advective venting explain the strong increase of IWV in the interior of the island and downstream of the mountains, while on the upstream coast only small variations were observed. These spatial inhomogeneities are more favourable for the development of deep convection in the interior of the island than at the west coast.

4. Predictability

4.1. Numerical weather prediction

Considerable efforts to improve forecast skill for heavy precipitation have been made in recent years and significant progress has been realised through the development of convection-permitting NWP systems. However, the accuracy of short-range forecasts is still insufficient to satisfy the societal demands in terms of amount, timing, and basin-specific locations of rainfall and flash flooding. Several studies in this special issue aim at improving the short-range forecasting systems and studying the processes and modelling components that influence predictability.

The potential of assimilation of new types of observations has been investigated, starting by the development of 'observation operators', which simulate observations from model outputs as a first step towards assimilation. Augros *et al.* (this SI, pp 347–362) develop a dual-polarization weather radar simulator accounting for a wide spectrum of effects such as realistic scattering by considering inhomogeneous spheroidal scatterers, (differential) attenuation, beam broadening with range, etc. The performance of the simulator with a one-moment bulk microphysical scheme has been evaluated against dual-polarization measurements at S, C and X bands from the French operational weather radar network and also disdrometers, for IOP6 and IOP16. The results show a good consistency between observations and their simulated equivalents, but with a larger spread in observations caused by instrumental noise and microphysical variability, the latter being poorly represented by a one-moment microphysical scheme.

Campins *et al.* (this SI, pp 363–376) study the impact on short-term forecast quality of the assimilation of targeted observations, including additional SOP1 radiosoundings and enhanced satellite measurements. In general, a positive but small impact is found. The magnitude of the impact depends on the weather regime that determines the location of the sensitive areas as well as their correspondence with routinely sparse data areas.

Scheffknecht *et al*. (this SI, pp 206–221) study for IOP15c the sensitivity to initial conditions and model grid-spacing of convection-permitting simulations. They find a high sensitivity to initial conditions. Only one of the nine initial conditions accurately simulates the timing and location of the event. On the contrary, decreasing the grid spacing from 2.5 km to 500 m does not clearly improve the simulation results. Barthlott and Davolio (this SI, pp 238–258) find also a weak impact of a higher horizontal resolution (1 km vs. 2 km) on total precipitation amount or timing of IOP13.

Rainaud *et al.* (this SI, pp 173–187) evaluate the low-level atmospheric parameters from AROME–WMED forecasts over sea using the moored and drifting buoys and ship measurements performed during SOP1. A general good agreement is found, except during strong mistral/tramontane wind situations due to (i) a non-evolving sea-surface temperature (SST) in the forecasts and (ii) an overestimation of the sensible heat flux in these cold and dry strong wind regimes by the turbulent flux parametrization. Thévenot *et al.* (this SI, pp 377–389) investigate the impact of the sea state on the low-level turbulent fluxes during IOP16a. Comparison of the convection-permitting atmospheric simulations using the turbulent flux parametrization (i) without any wave effects on the roughness length, (ii) with theoretical wave effects, and (iii) with realistic wave effects using wave model output as forcing, show that the location of the heavy precipitation on the French Riviera is modified when a realistic wave forcing is used due to the clear impact on the friction velocity, resulting in a slowing down of the surface wind of the upstream low-level flow.

Bouttier *et al.* (this SI, pp 390–403) make use of the SOP1 rain-gauge dataset of HPEs to evaluate the skill of a future operational convection-permitting ensemble prediction system. A notable result is that a convection-permitting ensemble with a few members can outperform a lower-resolution ensemble with many more members. Ensemble data assimilation is found not as effective as a simpler surface perturbation scheme; both approaches could be however beneficently combined. Nuissier *et al.* (this SI, pp 404–418) evaluate and compare precipitation forecasts from two convection-permitting ensemble systems over the whole of SOP1. The predictability of heavy precipitation of IOP16a is found to be strongly related to how the ensemble members simulate the surface low-pressure systems, highlighted also by Duffourg *et al.* (this SI, pp 259–274) and Flaounas *et al.* (this SI, pp 275–286).

Pantillon *et al.* (this SI, pp 419–432) study the mechanisms that reduced the 5–10 day predictability over the Atlantic and Mediterranean regions from mid-September to the beginning of October during SOP1 when hurricane *Nadine* was meandering around the Azores region. A major outcome about the HPE predictability is that the degree of interaction between the hurricane and the Atlantic cut-off controls the track of *Nadine* and thus the downstream conditions over the Mediterranean.

4.2. Regional climate models

Long-term hindcast simulations forced at the boundaries by reanalyses have been produced using several regional climate models and covering a 30-year period including the SOP1 period within the MED-CORDEX/HyMeX initiative (Ruti *et al.*, 2015), with the aim of evaluating these regional climate models against observations and higher-resolution NWP or research models. Khodayar *et al.* (this SI, pp 433–452) perform a multi-model comparison of regional climate models, parametrized-convection and convection-permitting NWP models on IOP12. Although the hindcast simulations from the regional climate models capture the occurrence of the precipitation event, they produce notably lower precipitation totals and hourly intensities than the NWP models. High-intensity short-duration convective events are not well reproduced by the regional climate models. The differences with the NWP models seem to originate mainly in the physical parametrizations (convection triggering, variability and vertical distribution of moisture) rather than in the initial or boundary conditions.

Berthou *et al.* (this SI, pp 453–471) evaluate two ocean–atmosphere coupled regional climate models against gridded precipitation datasets over 24 years. They find that 70–90% of the 30 most intense HPEs simulated were also observed HPEs for most regions. By comparing the atmosphere–ocean fully coupled simulation and one atmosphere-only simulation, they study the relation between sub-monthly SST differences and simulated precipitation differences over the 24 years and for SOP1 events.

5. Concluding remarks

This Special Issue demonstrates the broad range of advances we have made in the documentation, understanding and predictability of HPEs. SOP1 provided a remarkable and unique dataset that has been cross-analysed to make outstanding advances in process understanding, giving rise to new conceptual models for heavy precipitation events in the western Mediterranean. Significant progress has also been made in development and evaluation of state-of-the-art NWP and regional climate models, such as convection-permitting ensemble prediction systems or regional ocean–atmosphere coupled models.

Many more studies and much progress are expected in the coming years. The exploitation of observations from the innovative research instruments deployed during SOP1, such as those from the LMA or the airborne instruments, is still ongoing and will probably bring further advances in understanding and modelling of heavy precipitation events. The role of the Mediterranean Sea and the origin and transport of water vapour feeding the precipitating systems will be studied with more integrated approaches thanks to the newly developed ocean–atmosphere coupled models at kilometric scale. The regional climate models, and more specifically the future convection-permitting climate runs, will be further evaluated, through development of process-oriented and verification methods inherited from NWP. Several ongoing studies aim also at improving the key physical parametrizations that strongly influence the forecasts of deep convection at kilometric and sub-kilometric scales (microphysical process modelling and turbulence modelling in its 'grey zone'). Other studies aim at reducing uncertainties in the initial conditions, by developing data assimilation of new observation types or new-generation data assimilation methods. The overarching objective of these studies is to improve kilometric and sub-kilometric NWP suites, including ensemble prediction systems, to achieve more reliable forecasts of heavy precipitation and of its impacts. As for previous major field experiments, it will still take several years to fully exploit the field campaign dataset (LeMone, 2003) that will remain available long-term through the MISTRALS/HyMeX database (www.hymex.org/database).

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