Fully coupled high-resolution medium-range forecasts: evaluation of the hydrometeorological impact in an ensemble framework

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Abstract

Fully coupled atmospheric-hydrological models allow a more realistic representation of the land surface–boundary layer continuum, representing both high-resolution land-surface/subsurface water lateral redistribution and the related feedback towards the atmosphere. This study evaluates the potential contribution of the fully coupled approach in extended-range mesoscale hydrometeorological ensemble forecasts. Previous studies have shown, for deterministic simulations, that the effect of fully coupling for short-range forecasts is minor compared to other sources of uncertainty, however, it becomes not negligible when increasing the forecast period. Through a proof-of-concept consisting of an ensemble (50 members from the ECMWF Ensemble Prediction System) seven-days-in-advance forecast of a high impact event affecting the Calabrian peninsula (southern Italy, Mediterranean basin) on November 2019, the paper elucidates the extent to which the improved representation of the terrestrial water lateral transport in the Weather Research and Forecasting (WRF) – Hydro modeling system affects the ensemble water balance, focusing on the precipitation and the hydrological response, in terms of both soil moisture dynamics and streamflow in 14 catchments spanning over 42% of the region. The fully coupled approach caused an increase of surface soil moisture and latent heat flux from land in the days preceding the event, partially affecting the lower Planetary Boundary Layer. However, when shoreward moisture transport from surrounding sea rapidly increased becoming the dominant process, only a weak signature of soil moisture contribution could be detected, resulting in only slightly higher precipitation forecast and not clear variation trend of peak flow, even though the latter variable increased up to 10% in some catchments. Overall, this study highlighted a remarkable performance of the medium-range ensemble forecasts, suggesting a profitable use of the fully coupled approach for forecasting purposes in circumstances in which soil moisture dynamics is more relevant and needs to be better addressed.

1 Introduction

Though, traditionally, the expression 'medium-range forecast' refers to a forecast issued from three to seven days in advance (e.g., cf. https://glossary.ametsoc.org/wiki/Medium-range_forecast), the rapid skill increase of the most popular global forecasting systems de facto is modifying the meaning of the term, significantly expanding the upper limit of the time interval embraced up to two weeks (Buizza, 2018). In particular, after about 40 years from its first real-time medium-range forecasts made in 1979, the European Centre for Medium-Range Weather Forecasting (ECMWF) today provides, through the Integrated Forecast System (IFS), high-resolution operational forecasts (0.1°, approximately 9 km) up to 10 days in advance and 51-members ensemble forecasts (resolution of 0.2°, approximately 18 km) up to 15 days in advance. The ensemble approach is universally accepted to deal with the inherent uncertainty of deterministic forecasts (Palmer, 2019) because it provides an estimate of the forecast ability (Buizza, 2018), which is naturally reduced extending the forecast range, even though at the cost of multiplied computational effort.

The ECMWF Ensemble Prediction System (ENS) is operational since 1992 (Palmer et al., 1992). Since then, its performance improved steadily. Forbes, Haiden & Magnusson (2015) attributed the IFS skill enhancement of quantitative precipitation forecasts (equivalent to about one forecast day per decade in the period 2000-2015) to several contributing factors, including increasing resolution. Nevertheless, despite the growing detail of global forecasts, even in the ensemble mode, the demand for high-resolution forecasts is not yet completely fulfilled. For purposes of hydro-meteorological early warning, areas with complex topography, such most of the coastline surrounding the Mediterranean basin, are particularly challenging both because orographic liftings can cause precipitation enhancement at very local scales and the hydrological impact can vary critically among neighbour small- to medium-size catchments. Enhancement strategies for global ensemble forecasts resolution are essentially two, namely statistical post-processing techniques (e.g., Gascón et al., 2019), which are better suited for global coverage especially given their relatively low computational requirements (Hewson and Pillosu, 2020), and dynamical downscaling through mesoscale models, most useful for regional studies like that addressed in this paper.

The emerging demand for higher-detail meteorological and land surface models (e.g., Chaney, Metcalfe & Wood, 2016), even at the global scale (so-called hyperresolution; Wood et al., 2011; Bierkens et al., 2015), claims for resolutions of the order of 10^{0} km, needed to treat convection explicitly. Nevertheless, convection-permitting resolutions still are coarse to describe accurately many hydrological processes at the basin scale, which in their turn need resolutions of the order of at least 10^{-1} km. To address this issue, multiscale modelling of the overall (atmospheric and terrestrial) water cycle is an option increasingly implemented (Clark et al., 2015), leading to the development of high-resolution meteorological-hydrological ensemble forecasting systems. However, those systems usually address short-range forecasts (e.g., Vié et al., 2012; Hally et al., 2015; Olsson et al., 2017; Corazza, Sacchetti, Antonelli & Drofa, 2018; Furnari, Mendicino & Senatore, 2020). On the other hand, modelling chains dealing with medium-range forecasts generally derive the hydrological input directly from global forecasts, such as the National Oceanic and Atmospheric Administration (NOAA)/National Centers for Environmental Prediction (NCEP) Global Ensemble Forecast System (GEFS) Reforecast (Siddique & Mejia, 2017; Gomez, Sharma, Reed & Mejia, 2019; Sharma, Siddique, Reed, Ahnert & Mejia, 2019) or ECMWF ENS (Demirel, Booij & Hoekstra, 2013; Ye et al., 2014; Roulin & Vannitsem, 2015; Liu, Gao, Xuan & Wu, 2017; Emerton et al., 2017). Currently, few examples provide high-resolution meteorological downscaling for integrated meteo-hydrological forecasts exceeding three days (among them, Zappa, Jaun, Germann, Walser & Fundel, 2011; Davolio, Miglietta, Diomede, Marsigli & Montani, 2013 that provide forecasts up to 5 days). Nevertheless, recent progresses in computational capabilities, simulation strategies and, most notably for the aims of this paper, models' structure development, suggest that such systems can provide not negligible benefits even at the operational level.

One of the most interesting recent advances in coupled atmospheric-hydrological modelling concerns the development of fully coupled (or two-way-coupled) systems allowing bidirectional water and energy flux exchanges between the boundary layer and land surface, subsurface and groundwater, considering with increased detail water lateral flow across the landscape and in the soil. Such systems give the possibility to investigate and understand better the feedback between land water lateral redistribution and atmospheric processes. Several studies show that the fully coupled approach enhances the physical representation of several processes, improving the comprehension of water cycle dynamics in the different compartments of the terrestrial system (Larsen, Christensen, Drews, Butts & Refsgaard, 2016; Fersch et al., 2020). Many contributions, particularly, highlight the influence on the soil moisture and energy fluxes spatial patterns (e.g., Maxwell et al., 2011; Shrestha, Sulis, Masbou, Kollet & Simmer, 2014; Senatore et al., 2015; Wagner, Fersch, Yuan, Yu & Kunstmann, 2016; Arnault et al., 2016; Larsen et al., 2016; Rummler, Arnault, Gochis & Kunstmann, 2019). Indeed, the main result of resolved surface overland flow (including possible reinfiltration of water into the soil) and subsurface flow is a general increase of soil moisture (Senatore et al., 2015). Moister soil affects near-surface variables, like 2 m temperature (Balsamo, Pappenberger, Dutra, Viterbo & van den Hurk, 2011; Keune et al., 2016), allowing the surface/subsurface hydrology feedback to convey up to the entire planetary boundary layer (Gilbert, Maxwell & Gochis, 2017), even though with variable-intensity impacts. Direct effects on precipitation are more evident in transition or dry zones such as the Central United States (Jiang, Niu & Yang, 2009) and the North American Monsoon Region (Lahmers, Castro, & Hazenberg, 2020) where local evapotranspiration processes trigger convection, while in other more humid regions larger-scale atmospheric processes determine moisture convergence that can mask almost at all local contributions (Anyah, Weaver, Miguez-Macho, Fan & Robock, 2008; Kerandi, Laux, Arnault & Kunstmann, 2017; Arnault et al., 2019; Fersch et al., 2020). In such regions, the improvements detected in precipitation forecast are small (Butts et al., 2014; Senatore et al., 2015; Barlage et al., 2015; Arnault et al., 2018) or even null (Sulis, Keune, Shrestha, Simmer & Kollet, 2018).

Literature shows that fully coupled enhancements in most variables clearly emerge additively (i.e., differences with one-way coupled variables adds up over time). Therefore, many experiments addressed extended-range periods, in the order of several months or years. So far, few examples exist using the fully coupled approach for operational hydrometeorological purposes, mainly in the short-range. Kollet et al. (2018) applied their fully-integrated groundwater-to-atmosphere Terrestrial Monitoring System with lead times up to 72 hours. Avolio, Cavalcanti, Furnari, Senatore & Mendicino (2019) did not find relevant differences between one- and two-way coupled simulations in the Mediterranean peninsula of Calabria for the 24-hour forecast of a summer convective event, which appeared to be more affected by sea-atmosphere interactions.

This study provides a proof-of-concept elucidating for the first time the potential contribution of the fully coupled approach in medium-range ensemble high-resolution hydrometeorological forecasts. The study area is the whole territory of the Calabria region, located in the central Mediterranean, which is being the subject of several case studies evaluating the short-range predictability of hydrometeorological extreme events, both through fully coupled (i.e., the above-cited Avolio et al., 2019) and one-way coupled high-resolution modeling (e.g., Senatore, Furnari & Mendicino, 2020; Senatore, Davolio, Furnari & Mendicino, 2020), even in ensemble mode (Furnari et al., 2020). The selected event concerns a typical late-autumn synoptic situation occurred in November 2019, where the main driver for precipitation was the interaction between a cold front and the still relatively warm sea surface, with the orographic uplift increasing land precipitation. For this test case, the impact of enhanced surface-atmosphere feedback representation in a 7-day forecast is disentangled, and the physical processes governing surface water balance analyzed in detail. The specific objectives are: (1) preliminarily, evaluating the medium-range predictability of the event and the benefit provided by dynamical downscaling compared to global forecasts (no matter of atmospheric-hydrological coupling); (2) isolating the impacts of surface and subsurface hydrological processes on the different compartments of the overall hydrological cycle (including the atmosphere), by comparing the one-way and two-way coupled outcomes; (3) evaluating the hydrological response, considering streamflow forecasts in several watersheds of the region.

The paper is organized as follows. Section 2 briefly describes the study area and the meteo-hydrological event addressed. Furthermore, it provides details concerning the ECMWF ENS medium-range ensemble forecasts and the mesoscale model adopted, i.e. the Weather Research and Forecast (WRF), both one- and two-way coupled with its hydrological extension WRF-Hydro. Section 3 provides results concerning the specific objectives previously mentioned, together with the related discussion. Finally, Section 4 is devoted to conclusions and outlook of the research.

2 Data and methods

2.1 Study area and event description

If the minimum and maximum latitude (30.2639° N and 45.7833° N, respectively) and the minimum and maximum longitude (6.0327° W and 36.2173° E, respectively) of the Mediterranean Sea are considered, Calabria administrative region is located almost exactly in the middle (Fig. 1), extending from 37.9156° N to 40.1436° N and from 15.6300° E to 1.2061° E. Though an overall coast length of approximately 780 km, only 9% of this 15222 km^2 wide peninsula is occupied by plains, with several mountain ranges and plateaus characterizing a rather complex morphology, which from a hydrological point of view mostly leads to small-sized catchments with steep channels rapidly descending towards the sea.

The orographic influence on the sea-atmosphere interactions is critical for precipitation enhancement, periodically causing intense and damaging hydrometeorological events (Llasat et al., 2013; Avolio and Federico, 2018; Petrucci et al., 2018) especially in the eastern (Ionian) side of the region, from late summer to late autumn. The event selected for this study represents an exemplary case of this typology. Starting on the evening of 22.11.2019, the synoptic scenario over western Europe was characterized by the presence of an extended occluded frontal system, with a deep trough moving from north-west (Bay of Biscay) to the south-east, centering on 24.11.2019 over an area in between Tunisia and the two major Italian islands (namely, Sicily and Sardinia). The associated cyclonic circulation caused the advection of warm-humid air from the Ionian Sea towards the eastern coast of the Region, inducing from the late evening of 23.11.2019 intense precipitation especially along the eastern side of the mountain ranges in the central-southern part of the region (Fig. 2c). The regional weather monitoring network made up of 156 rain gauges (with a density of more than one rain gauge every 100 km^2), recorded maximum precipitation intensities of 127.2 mm/6hr, 139 mm/12hr, and 178 mm/24hr, with an accumulated maximum value for the whole event of 203.6 mm (CFM, 2019).

The impact of the fully coupled approach on the streamflow forecasts was evaluated on 14 watersheds of variable extension from O (10^2) to O (10^3) km^2, homogeneously distributed throughout the study area (Fig. 1b). Where available, data provided by stream gauges located along the river networks were used (9 cases out of 14). Unfortunately, such data consisted only of water stage observations, not convertible in discharges because of the lack of rating curves. Nevertheless, they proved useful for estimating the shape of the flood hydrographs and, mainly, for identifying the time of the peak flows.

2.2 ECMWF medium-range ensemble forecasts

Each operational ECMWF ensemble forecast (ENS) is made up of 1 control member with unperturbed initial conditions and 50 perturbed members. The initial perturbations are based on a combination of Ensemble of Data Assimilations (EDA) and singular vector perturbations (Buizza, 2008). The model uncertainties are represented with the stochastically perturbed parameterization tendency (SPPT) scheme (for details, see Leutbecher et al., 2017). The ENS is coupled to an ocean model, a sea ice model, and a wave model. It has a resolution of approximately 18 km in grid-point space up to day 15, with 91 vertical levels (the top of the model being at 0.01 hPa).

To provide the initial conditions (ICs) and boundary conditions (BCs) to the mesoscale model, the 50 perturbed members of the ECMWF ENS based on the operational cycle Cy46r1 were used (ECMWF, 2019). Lateral BCs were passed with time steps of 6 hours from 19.11.2019 00UTC to 26.11.2019 00UTC using pressure levels, while lower BCs considering the surface layer. Sea Surface Temperature (SST) fields were transformed through the ECMWF interpolation package MIR (Maciel et al., 2017).

2.3 One-way and fully coupled WRF downscaling

The mesoscale model used for downscaling the ENS forecasts is the Weather Research and Forecasting – Advanced Research (WRF-ARW) version 4.1 (Skamarock et al., 2019), both one-way (or off-line) and two-way (or fully) coupled to the WRF Hydrological (WRF-Hydro) modelling system version 5.1.1 (Gochis et al., 2020).

WRF is a very popular modelling system, whose modular structure allows many physics options for simulating the different atmospheric processes. WRF-ARW parameterization has been widely tested in the study area (e.g., Senatore et al, 2014; Avolio and Federico, 2018). In this study, it was used in two-way nested domains (D01 and D02, respectively; Fig. 1a). The outermost domain D01 encompasses the central Mediterranean area (33.04–49.85° N, 3.59–28.59° E), while the innermost domain D02 focuses on the Calabrian peninsula (37.10–40.87° N, 13.88–18.71° E). Details about the space and time resolutions in the WRF domains are reported in Table 1, together with a description of the atmospheric and soil layers schematization. Table 1 also provides information about the physics options selected, which are the same chosen by Avolio et al. (2019), except that the NOAH-MP model (Niu et al., 2011) was used for simulating the land surface processes. Furthermore, the *sst_skin* option (Zeng and Beljaars, 2005), allowing us to consider daily SST dynamics, was activated.

Such as for WRF, the WRF-Hydro structure is modular, so that this modelling system can be rather considered as a hydrological modelling architecture. Furthermore, it is a coupling architecture linking the hydrological model to the atmospheric model (Gochis et al., 2020) via the land surface model (LSM). WRF-Hydro was also extensively tested over the study area, both with long-range simulations addressing the whole hydrological cycle (Senatore et al., 2015) and short-range simulations mainly aimed at evaluating the predictability of the hydrological response (Avolio et al., 2019; Senatore, Furnari & Mendicino, 2020 and Senatore, Davolio, Furnari et al., 2020; Furnari et al., 2020), but never considering medium-range forecasts.

The WRF-Hydro domain corresponds to the WRF innermost domain (D02, in this case), sharing the same LSM with the same physical schematization (i.e., 4 parallel soil layers up to 2 m depth). In this study, the LSM was initialized for the hydrological simulations through a 2-month spin-up using the ERA5 reanalysis (Hersbach et al., 2020) for ICs and BCs. The hydrological processes were simulated increasing the LSM resolution 10 times (aggregation factor of 1/10 from the atmospheric to the hydrological model), hence the horizontal resolution was equal to 200 m.

WRF-Hydro was coupled to the medium-range WRF forecasts both in not fully coupled (NC, hereafter) and fully coupled (FC, hereafter) fashion. In both cases, input variables needed from the atmospheric model are precipitation and pressure on the ground, air temperature and humidity, wind speed and solar radiation. The difference between the FC and NC simulations is that in the first case the variables are transferred at each D02 time step (i.e., every 12 s) and the feedback of water lateral redistribution is provided real-time. On the other hand, the input time step of the meteorological forcing in the NC simulations is chosen by the user (but much higher than in FC simulations) and no feedback to the atmosphere is provided. In this study the input time step for NC simulations was chosen equal to 1 hour, as a compromise between modelling accuracy and memory storage issues management.

Though the WRF-Hydro model was applied to the whole regional river network, it was not specifically calibrated for the catchments under study (Fig. 1b), because no discharge data are available for sufficient time. Furthermore, it is noteworthy to point out that calibration goes beyond the aims of this study, mostly focused at highlighting the effects of fully coupled approach on the coupled atmosphere-hydrological processes rather than evaluating the overall performance of the modelling system. Therefore, the WRF-Hydro parameterization selected for this study is the same used for the Ancinale catchment as described by Senatore, Furnari & Mendicino (2020), with the only addition of a fifth order Manning coefficient equal to 0.027. Based on the authors' experience, the selected parameterization is a reasonable compromise for a realistic description of river flow behaviour throughout the region.

Another point to highlight is that, due to the differences in the time intervals used for the temporal integration of the LSM, inconsistent amounts of the soil water fluxes between the

FC and NC simulations (Senatore et al., 2015; Fersch et al., 2020) can lead to not meaningful comparisons between NC and FC simulated discharges. This issue, which can be faced in various ways (e.g., different parameterization, Avolio et al., 2019; higher time steps for the hydrology part call in FC simulations, Fersch et al., 2020) was faced in this study using the following strategy:

1. NC simulations were performed using the WRF meteorological forcing as described above and activating the surface, subsurface and channel water routing modules (i.e., the groundwater module was not activated, given the relatively short simulation time);
2. FC simulations were performed activating only the surface and subsurface water routing modules, switching off the channel water routing, which however is not fully coupled to the atmospheric model;
3. The FC meteorological output aggregated at 1-hour time step was then used to run off-line hydrological simulations, which were used only for FC vs. NC discharge comparison.

Such as done for WRF, WRF-Hydro main features are summarized in Table 1.

3 Results and discussion

3.1 Global and regional ensemble forecasts

This subsection analyses the accuracy of the global ensemble medium-range forecast of the event and the relative dynamically downscaled ensemble. Fig. 2 compares the median values of the 48-h accumulated precipitation from 24.11.2019 00UTC to 26.11.2019 00UTC forecasted by both the ECMWF ENS (Fig. 2a) initialized on 19.11.2019 00UTC and the NC-WRF downscaling (Fig. 2b) with the observed precipitation achieved by spatial interpolation (Inverse Distance Weighting) of the 156 available rain gauges (Fig. 2c). Overall, the simulations, initialized approximately 5 days before the beginning of the event, perform well, forecasting with sufficient accuracy the spatial patterns of precipitation. As expected, due to the lower spatial resolution that smooths and flattens topography and given the greater extent of the space unit on which the precipitation is averaged (~18 km vs 2 km cell resolution), ENS peaks are lower than NC-WRF (all values of the map in Fig. 2a are lower than 100 mm 48-h^{-1}). On the other hand, NC-WRF-derived spatial patterns are clearly influenced by orography, so that median precipitation along the central and southern mountain ranges is closer to observations (though overestimating in the north). Furthermore, while the precipitation forecasted by ENS substantially affects the eastern side of the region, WRF downscaling permits a bigger impact on the western side, more consistent with observations (even though median values still underestimate).

Medium-range predictability can be better appreciated looking at the temporal evolution of the forecasts compared to observations. Fig. 3 shows such comparison considering both the averaged values (Figs. 3a and 3b) and the peak values (Figs. 3c and 3d) over the Calabrian area. The analysis of the averaged values (provided every 6 hours with ENS and every hour with WRF, respectively) shows a generally small underestimation, slightly less pronounced with WRF. In the latter, observations are completely within the 5^{th}-95^{th} percentile interval for the whole forecast period. The comparison between rainfall peaks concerns the rainfall evolution at the rain gauge recording the highest accumulated precipitation value (namely, Antonimina – Canolo Nuovo, located in the eastern side of the southern mountain range) and the pixels with the highest simulated values of each ensemble member falling within the Calabrian territory (therefore, these pixels can be located elsewhere). The comparison points out the differences between the global and regional forecasts in reproducing the orographic uplift. Though the onset of the precipitation event is slightly delayed, during 24.11.2019 WRF median increases more rapidly, leading to a final value approximately 15% higher than observations. On the other hand, despite its underestimation (final median value about 40%

lower than observations), ECMWF ENS reproduces in the 10% of the cases peak values higher than 190 mm and observations are almost always within the 5th-95th percentile interval. This preliminary analysis highlights both the good performance of the global ensemble forecast, and the improvements produced by high-resolution forecasts, which, however, are achieved at the cost of a significant computational burden. Even though not strictly related to the main aim of this paper, it is worth pointing out, in conclusion, that some computational strategies could be adopted to reduce calculations (therefore, the time of delivery of the forecasts). E.g., dynamical downscaling could be initialized some days (three to even five) after ENS initialization, and tools can be developed for civil protection purposes predicting what downscaled scenarios can be the rainiest based on the analysis of the ENS members so that the number of high-resolution simulations can be reduced.

3.2 Effect of the fully coupled approach on high-resolution forecasts

This subsection analyses the effects of the fully coupled approach in the coupled mesoscale-hydrological modelling system, focusing on precipitation, surface layer soil moisture, water vapor fluxes from the land surface and water vapor concentration and flux in the atmospheric layers and, finally, hydrological response.

3.2.1 Land-surface – atmosphere interactions

Fig. 4a, showing the median of the 48-h accumulated precipitation forecasted by FC-WRF in the domain D02 from 24.11.2019 00UTC to 26.11.2019 00UTC, is very similar to Fig. 2b, representing the same variable with NC-WRF. The map of differences (Fig.4b) confirms the great similarities between the spatial patterns. Differences seem randomly distributed in the space, with a probability density function almost normal (mean value of 0.02±3.15 mm, minimum and maximum differences of -17.7 mm and +19.6 mm, respectively). Higher FC-WRF values locate especially in the centre of the region. Difference maps considering other percentiles than 50% (e.g., 75%, 90%, not shown) show comparable features, even though with a wider range of differences.

Temporal evolution of the forecasted precipitation averaged over the domain D02 also does not highlight relevant differences between FC-WRF and NC-WRF ensembles (not shown). The median of the FC-NC accumulated precipitation differences ranges between -3.6 mm and +1.3 mm during the whole forecast period, while the standard deviation reaches a maximum value of 18.5 mm at the end of the simulation. These results indicate that corresponding members of the two ensembles not only provide similar final accumulated precipitation fields but also simulate almost simultaneous weather dynamics.

The analysis of the precipitation peaks provides some more insight. Fig. 5 shows, for every member of the ensemble, the evolution during the whole forecast period of the difference between the cells with the highest accumulated precipitation values modelled by FC-WRF and NC-WRF, respectively. Besides considering the whole domain D02 (Fig. 5a), the analysis also isolates only the cells within the Calabrian borders (Fig. 5b), because (i) the fully coupled approach modifies process representation only on land, not over the sea, and (ii) evaluating precipitation peaks on the mainland is crucial for civil protection purposes. In all cases, FC-NC differences are negligible until the onset of the event, i.e. at the turn between 23 and 24.11.2019. Later, the variability of hourly differences increases considerably. The range between the 1^{st} and the 3^{rd} quartiles reaches values of 48.8 mm (from -10.9 mm to +37.8 mm) and 42.6 mm (from -20.3 mm to 22.3 mm), for the whole domain D02 and the Calabrian subdomain, respectively. Analogously, the range between the 5^{th} and 95^{th} percentiles increases up to 182.3 mm (from -62.1 mm to +120.2 mm) and 171.6 mm (from -67.8 mm to +103.8 mm). However, median values are not too far from 0, reaching slightly positive values of +14.1 mm at 25.11.2019 03UTC considering the whole domain and +5.6 mm at the end of the simulation considering only Calabria.

Overall, the accumulated precipitation peaks are slightly higher with FC-WRF (29 out of 50 members within Calabrian borders). Such an increase can be related to the fact that the moister soil modelled with the fully coupled approach influences to a certain extent the water vapour exchange between the land surface and the atmosphere, hence the precipitation process. Fig. 6 shows the differences between the median values of the 1st layer soil moisture simulated by FC-WRF and NC-WRF ensembles on 24.11.2019 00UTC, i.e. at the beginning of the event for most of the ensemble members (with no meaningful antecedent rain). The map clearly shows that the differences are mainly positive (74.8% of the total area) and the highest positive differences (up to 0.22) are in the eastern coastal area, at the foot of the mountain ranges where surface and subsurface lateral flow processes take a more important role. The inset shows the distribution of the median 1^{st} layer soil moisture at the same time for all the cells of the FC-WRF and NC-WRF ensembles. FC-WRF values are higher (median values of 0.28 and 0.30, for NC-WRF and FC-WRF, respectively) and encompass a wider range of values (1^{st} to 3^{rd} quartile range equal to 0.016 and 0.036, for NC-WRF and FC-WRF, respectively), indicative of the dynamic water lateral transport in the soil and over the surface with the fully coupled approach.

Moister 1^{st} soil layer causes several effects on the near-surface atmospheric layer. Fig. 7 shows the differences throughout the whole forecast period between FC-WRF and NC-WRF simulations concerning 2m mixing ratio (Q2), 2m temperature (T2) and latent heat flux (LH) values averaged over Calabria, along with the NC-WRF values (shown as a reference). Especially during daytime, the days preceding the event are characterized by higher air humidity, lower air temperature and higher latent heat flux with FC-WRF. These differences increase until 23.11.2019 because of the increasing temperatures (Fig. 7c). Then, during the event (i.e., on 24-25.11.2019) cloudy and rainy conditions smooth differences. Overall, median values of daytime (from 07UTC to 17UTC) Q2 in the period 20-23.11.2019 increase of approximately 1.6% with FC-WRF, while median daytime T2 values reduce of 0.11 K. Most notably to our purposes, the median daytime latent heat flux provided in addition by FC-WRF is 8.7 Wm^{-2} greater than NC-WRF (+10.5%). Overall, the median LH increase leads to a supplementary evapotranspiration flux of approximately 0.6 mm on an extension of more than 15000 km^2.

The impact on atmosphere water vapor concentration of the WRF-FC modelled land surface as enhanced moisture source can be evaluated calculating the integrated water vapor in the atmospheric column above Calabria. Fig. 8 shows a comparison between the evolution of this variable with the WRF-FC and WRF-NC ensemble simulations during 23-24.11.2019, that is the onset of the event. In particular, the graph of differences (Fig. 8c) shows that the signal of the enhanced moisture flux from soil can be appreciated especially on 23.11.2019, when it modulates the initial conditions met by the moist air advected from the sea. However, this signal is rather low. The highest value of the median of the FC-WRF minus NC-WRF difference, though being always positive until 23.11.2019 18UTC, is +0.05 kg m^{-2} (equal to 0.3% more than the corresponding NC-WRF value) at 23.11.2019 14UTC, i.e., when the evapotranspiration rate is at its maximum. Approximately at the same time, the highest FC-WRF minus NC-WRF differences reach values approximately one order higher (i.e., +0.5 kg m^{-2}), but never 2.5% higher than NC-WRF values. During the evening of 23.11.2019, the integrated atmospheric water vapor content increases rapidly, due to the shoreward moisture transport, and land moisture signal is lost, though the median of the FC-WRF minus NC-WRF difference slightly increases again during the warmest hours of 24.11.2019.

The differences in the representation of land-surface and atmospheric processes immediately before the event onset can be understood more clearly looking at cross-sections showing moisture content and wind speed and direction evolution within the planetary boundary layer (PBL). The figures in the left and central columns in Fig. 9 show cross-sections of equivalent potential temperature, water vapor mixing ratio and wind speed and direction along the segment AA′ (shown in Fig. 1) for the NC-WRF and FC-WRF ensemble members no. 35. These are the corresponding members of the two ensembles with the highest latent heat flux differences. Moreover, the right column in Fig. 9 shows the differences in vertical velocities. Cross-sections refer to different times of 23.11.2019, namely: 12UTC, corresponding to the hour with the highest latent heat flux; 15UTC, broadly the last hour with daylight; 20UTC, when latent heat flux was negligible and shoreward moisture transport increased; finally, 24.11.2019 00UTC, when the precipitation event over Calabria was closer to begin. At 12UTC and 15UTC, the higher FC-WRF surface latent heat flux increases lower PBL moisture in the eastern side of the region up to the same values reached over the nearby sea surface (Figs. 9b, e). This pattern is less pronounced with NC-WRF (Figs. 9a, d). Vertical velocity over the eastern side of the region is also positively (upwards) biased with FC-WRF (Figs. 9c, f). The increased WRF-FC land surface moisture flux also affects medium and upper PBL layers overlying land, where mixing ratio values are slightly higher (not shown). At 20UTC (Figs. 9g, h), however, latent heat contribution from land surface is much reduced, and the shoreward moisture flux is by far the dominant process. Vertical wind velocities do not differ over land, but leeward, over the Tyrrhenian Sea, without a clear trend (Fig. 9i). At 24.11.2019 00UTC mixing ratio increases also over the Tyrrhenian Sea in a similar way for both simulations (Figs. 9j, k), with chaotic differences in vertical wind velocities nearby and over the land (Fig. 9l). At the beginning of the precipitation event, no clear signature of previous daytime WRF-FC-simulated higher surface latent heat remains into PBL.

3.2.2 Hydrological response

The streamflow differences induced by the fully coupled approach strongly depend on the related differences in precipitation spatial and temporal patterns. For the catchments shown in

Fig. 1b, Fig. 10 and Table 2 provide information about peak flows and peak flow times of both the one-way and fully coupled ensembles. It is worth recalling that, given the absence of discharge observations (only water stages are available), peak flow comparison (Fig. 10a) involves only model data, while the available observed hydrographs allowed to include in the comparison also 9 (out of 14 catchments) observed peak flow times (Fig. 10b). In both Fig. 10 and Table 2, the catchments are ordered following the coastline from the north-west to the north-east, counterclockwise.

Concerning peak flows, Fig. 10a shows difference results of the whole ensembles in terms of specific discharge (i.e., normalizing values with respect to the different catchment areas, varying from 79.8 to 2447.6 km^2), while Table 2 highlights actual average values for both NC-WRF and FC-WRF. Considering the selected catchments, enclosing approximately 42% of the whole region, no statistics clearly indicates that one of the ensembles prevails on the other concerning peak flow magnitude. E.g., Table 2 shows that average peak flow is higher with the FC-WRF ensemble only 8 times out of 14. Furthermore, absolute percentage differences are almost always lower than 5%. As highlighted in Fig. 10a, peak flow differences increase not negligibly (up to approximately 10%) only for three catchments falling on the centre of the eastern side of the region, i.e. Ancinale, Corace and Tacina river catchments. These catchments are among the four ones with the greatest median accumulated precipitation differences (Fig. 4b), with +2.3 mm, +6.9 mm and +5.4 mm, respectively. The fourth catchment is the Savuto river, having a median difference similar to the Ancinale (+3.1 mm). Nevertheless, while in the Ancinale river catchment the simulated FC-WRF accumulated precipitation is higher than NC-WRF in 29 cases out of 50, in the Savuto river catchment it is only 25. Furthermore, rainfall intensity differences between FC-WRF and NC-WRF reach values up to +11.1 mm hr^{-1} for the Ancinale river catchment, and only up to 3.8 mm hr^{-1} for the Savuto river catchment.

Both Figs. 10b and Table 2 highlight similar behaviours between NC-WRF and FC-WRF ensembles concerning peak flow times, which differ mostly by a few hours (even in the abovementioned catchments with the highest peak flow differences). According to Table 2, average peak flow times completely agree for half of the cases (7 catchments), while FC-WRF simulations delay peak flow time 4 times. Both NC-WRF and FC-WRF generally delay the observed peak flow times of a few hours, which is expected observing the overall temporal evolution of precipitation forecasts (Figs. 3b, d). However, it is still a remarkable result considering that such estimates come from forecasts issued 7 days in advance.

3.3 Discussion

Whether the one-way or the fully coupled approach is considered, the ECMWF ENS-WRF-Hydro modelling chain provided skillful medium-range forecasts for the selected test case, accurate enough for civil protection purposes. Compared to observations, the hydrological response forecasted seven days in advance looks timely. More accurate calibration of the hydrological model could concur to modify the peak flow times but only of a few hours, since almost all the small-to-medium-size catchments examined have a rapid response time. Nevertheless, to the aims of this study, it does not matter what configuration (either NC-WRF or FC-WRF) reproduces better the observations since other sources of uncertainty (e.g., model parameterization) concur to improve performances of both modelling chains. Here we aim to highlight how much the terrestrial (surface and subsurface) lateral flow affects high precipitation events in a case study where other moisture sources, besides and more than land surface, play an important role.

Results confirm that the basic difference provided by a more realistic representation of terrestrial lateral flow is higher soil moisture in the first layers, which in turn increases latent heat near the surface (Senatore et al., 2015; Arnault et al., 2018; Fersch et al., 2020). In theory, higher soil moisture has a dual, opposite effect on ‘dynamic’ (due to change in atmospheric motion) and ‘thermodynamic’ (due to change in atmospheric moisture content) processes in the atmosphere (Emori & Brown, 2005). Previous analyses in the same study area (e.g., Senatore, Furnari & Mendicino, 2020) show that warmer SST temperature can both accelerate horizontal air masses flow and feed atmospheric moisture, thus increasing the overall precipitation amount. Near-surface warming also fosters deep convection reducing static stability (Meredith et al., 2015). On the contrary, higher soil moisture, though enhancing the role of land as humidity source for the atmosphere, reduces near-surface temperature. The experiments performed show that no appreciable differences in the timing of the one- and two-way coupled precipitation events emerge. This outcome is due to the influence of mesoscale conditions on humid air masses circulation, which largely prevail on local vertical moisture transport from the land surface. However, increased near-land-surface humidity with FC-WRF simulations partially affects higher tropospheric levels before the event onset. Air masses overpassing Calabria (roughly from south-east to the north-west) are slightly enriched with humidity, thus producing patches of reduced lifting condensation level (LCL; a supplementary video highlights such behaviour, showing the differences between FC-WRF and NC-WRF LCLs for simulation no. 35 on 23.11.2019). However, additional humidity provided by the land surface is not enough to trigger convective precipitation. This process is governed by south-east shoreward humid air fluxes, which once reached the coast allow the detection only of a residual signal of enhanced near-surface moisture over land, causing very slight precipitation increase. Consequently, the hydrological response is generally not greatly affected, even though, interestingly, the three catchments showing the highest peak flow increase FC-WRF (i.e., Ancinale, Corace and Tacina) all lay roughly downwind of the areas with the greatest increase in humidity (Fig. 6).

Overall, the impact of terrestrial lateral flow representation on medium-range precipitation forecasts would be higher (possibly critically) when the surface soil moisture's role is more important than in the analysed test case (i.e., when the land is the main moisture source; Wang et al., 2020; Lahmers et al., 2020). However, the study suggests that the fully coupled approach retains its relevance even in settings with stronger sea-atmosphere interactions, especially when the soil moisture dynamics needs to be better addressed (e.g., spring-summer drying in Mediterranean climates and related convective storms).

4 Conclusions

This paper investigated the effects of surface and subsurface soil moisture lateral redistribution on medium-range hydrometeorological forecasts by comparing the outcomes of one-way coupled and two-way coupled (i.e., allowing land surface feedback to lower atmosphere processes) mesoscale atmospheric-hydrological forecasting systems, forced by the same boundary conditions. The experiment concerned a proof-of-concept carried out in a Mediterranean area characterized by strong sea-atmosphere interactions. The ensemble approach with 50 ENS members permitted to deal with the inherent uncertainty of the medium-range forecasts, disentangling the signal provided by the added representation of surface/subsurface lateral flow to the overall atmospheric-terrestrial hydrological cycle.

Referring to the specific objectives of the research, we showed that:

1. the medium-range ensemble forecasts of the ENS-WRF-Hydro system performed reasonably well, and the high-resolution simulations proved their importance (regardless of the adoption of the fully coupled approach) for reliable forecasts of rainfall peaks, which are significantly enhanced by the orographic effect and are of course relevant for an accurate representation of the hydrological impact. Also, the

simulated hydrological response proved timely considering peak flow times, with small delays of a few hours;

2. the improved representation of land surface and subsurface hydrological processes modified the local water balance causing noteworthy increases of first-layer soil moisture and water vapor fluxes to the lower atmospheric layers, but the enhanced flux provided only a weak contribution to precipitation enhancement, even considering rainfall peaks. The selected test case significantly influenced such an outcome, since the dominating process that generated land precipitation was the shoreward movement of large humid air masses that almost completely hid the land surface moisture flux signal;
3. consequently, the impact of the enhanced hydrological modeling within the coupled system on river streamflow was barely detected, with averagely increased peak flows only in 8 out of the 14 catchments considered. Nevertheless, the most relevant peak flow differences (up to 10%) were in favor of the fully coupled simulations, affecting catchments with relatively high precipitation increase close to the areas of the region with the most relevant soil moisture increase determined by the fully coupled approach.

This study showed that the effect of soil moisture lateral redistribution, hence of a fully coupled approach enhancing the representation of such a process, can be potentially significant on precipitation on the medium-range, as long as land surface moisture fluxes are relevant compared to other moisture sources (i.e., advection of external humid air masses). On the other hand, if other hydrological variables are considered, such as soil moisture and evapotranspiration (inherently connected to latent heat flux), the impact of the fully coupled approach is much more evident. Therefore, it could be useful also in the Mediterranean areas for unravelling summertime drying feedbacks and enhance seasonal forecasts, to which further studies will be devoted.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Tables

Table 1. Main features of the WRF and WRF-Hydro (both off-line – NC – and fully coupled – FC) models.

WRF physics parameterization	
Component	Scheme
Microphysics	New Thompson (Thompson, Field, Rasmussen & Hall, 2008)
PBL	MJY (Janjić, 1994)
Shortwave Radiation	Goddard (Chou & Suarez, 1994)
Longwave Radiation	RTTM (Mlawer, Taubman, Brown, Iacono & Clough, 1997)
Land Surface Model	NOAH-MP (Niu et al., 2011)
Surface Layer	Eta Similarity (Janjić, 1994)
Cumulus	Tiedtke (D01) (Tiedtke, 1989)
WRF domains space and time resolutions	
D01	10 km (205 × 187 grid points), 60 s
D02	2 km (200 × 200 grid points), 12 s
Vertical layers	44 terrain-following layers above the surface up to a 50 hPa pressure top and 4 layers in the soil
WRF-Hydro main features	
Land Surface Model	NOAH-MP (Niu et al., 2011), 2 km resolution
Active modules	– FC-WRF: subsurface and surface water routing – NC-WRF: subsurface, surface and channel water routing
Input time step	– FC-WRF: each time step of the domain D02 (12 s) – NC-WRF: 1 h
Resolution	200 m (2000 × 2000 grid points), disaggregation factor with respect to the atmospheric model of 1/10

Table 2. For each of the selected watersheds, the Table indicates: the extent, the 50-members ensemble mean peak flow and mean peak flow time and, if available, the observed peak flow time. NC stands for not coupled (off-line) WRF-Hydro, FC for fully coupled WRF-Hydro.

Watershed	**Area [km^{-2}]**	**FC mean peak flow [m^{3}s^{-1}]**	**NC mean peak flow [m^{3}s^{-1}]**	**Observed peak flow time [UTC]**	**FC mean peak flow time [UTC]**	**NC mean peak flow time [UTC]**
Savuto	411.7	111.3	111.9	24.11.2019 21:00	25.11.2019 01:00	24.11.2019 21:00
Amato	444.0	77.6	80.6	N/A	24.11.2019 20:00	24.11.2019 19:00
Mesima	694.6	138.2	135.1	24.11.2019 13:00	25.11.2019 00:00	25.11.2019 00:00
Budello	79.8	17.0	16.0	24.11.2019 10:00	24.11.2019 17:00	24.11.2019 19:00
Petrace	422.5	102.5	98.4	N/A	24.11.2019 22:00	24.11.2019 22:00
Ammendolea	150.5	32.5	32.6	N/A	25.11.2019 00:00	24.11.2019 23:00
Bonamico	138.0	46.4	44.9	N/A	24.11.2019 17:00	24.11.2019 17:00
Ancinale	116.0	53.9	49.6	24.11.2019 13:00	24.11.2019 19:00	24.11.2019 21:00
Corace	185.8	96.0	87.2	24.11.2019 14:00	24.11.2019 16:00	24.11.2019 17:00
Tacina	414.9	173.6	157.8	24.11.2019 16:00	24.11.2019 20:00	24.11.2019 20:00
Neto	840.4	316.1	325.0	24.11.2019 16:00	24.11.2019 21:00	24.11.2019 21:00
Crati@S.Sofia	1281.0	187.1	184.7	24.11.2019 21:00	25.11.2019 04:00	25.11.2019 03:00
Coscile	303.4	195.9	201.8	N/A	24.11.2019 22:00	24.11.2019 22:00
Crati@Sibari	2447.6	345.3	349.8	25.11.2019 03:00	25.11.2019 03:00	25.11.2019 02:00

Figure captions

Figure 1. Study area: (a) WRF outermost (D01) and innermost (D02) domains. State borders are shown and, only for Italy, the regional borders; (b): zoom on the Calabria region, highlighting the borders and the river networks (light to dark blue colours indicate higher Strahler stream orders) of the catchments included in the analysis. Red dots indicate the available stream gages. The segment AA′ refers to the cross-sections shown in Fig. 9.

Figure 2. Accumulated 48-h precipitation fields (from 24.11.2019 00UTC to 26.11.2019 00UTC) over Calabria and WRF domain D02: (a) median values simulated by ECMWF ENS forecasts; (b) median values simulated by NC-WRF 2 km forecasts; (c) spatial interpolation from the rain gauge network (observations).

Figure 3. Comparison between ECMWF ENS and NC-WRF precipitation evolution over Calabria from 19.11.2019 00UTC to 26.11.2019 00UTC: (a) ECMWF ENS averaged values; (b) WRF averaged values; (c) ECMWF ENS values of the cell with the highest accumulated value; (d) as for (c), but with WRF. In each graph, the thin blue lines represent a single simulation, the thicker blue line the median value. The light blue band represents the 1^{st} - 3^{rd} quartile interval, the cyan band in the background the 5^{th}-95^{th} percentile interval. The black lines represent observations.

Figure 4. a) Median values of the accumulated 48-h precipitation fields (from 24.11.2019 00UTC to 26.11.2019 00UTC) over Calabria simulated by FC-WRF; (b) differences between accumulated 48-h precipitation fields (median values) simulated by FC-WRF and NC-WRF.

Figure 5. Temporal evolution of the differences between the cells with the highest accumulated precipitation values modelled by FC-WRF and NC-WRF: (a) the whole domain D02 is considered; (b) only cells within the Calabrian borders are considered. Lines and bands have the same meaning of Fig. 3.

Figure 6. Differences between the median values of the 1^{st} layer soil moisture simulated by FC-WRF and NC-WRF on 24.11.2019 00UTC in Calabria. The inset shows the distribution of the median 1^{st} layer soil moisture at the same time for all the cells within the Calabrian borders, for both the FC and NC ensembles (the circles represent the mean values of the distributions).

Figure 7. Temporal evolution of 2m mixing ratio (Q2), 2m temperature (T2) and latent heat flux (LH) values averaged over Calabria in the NC-WRF ensemble and related differences considering the FC-WRF ensemble (FC minus NC). Left column: NC-WRF values; right column: differences. Upper row: Q2; middle row: T2; bottom row: LH. Light colour bands represent the 5^{th}-95^{th} percentile intervals, darker bands the 1^{st} - 3^{rd} quartile intervals. The median values are represented with thicker lines.

Figure 8. Evolution of the Integrated column Water Vapor (IWV) averaged over Calabria from 23.11.2019 00UTC to 25.11.2019 00UTC: (a) NC-WRF; (b) FC-WRF; (c) differences between FC-WRF and NC-WRF. As usual, light colour bands represent 5^{th}-95^{th} percentiles intervals, darker bands the 1^{st} - 3^{rd} quartile intervals, while the median values are represented with thicker lines.

Figure 9. Cross sections along the segment AA′ of equivalent potential temperature (contours; K), water vapor mixing ratio (colour shaded; kg kg^{-1}) and wind speed and direction (arrows); for the FC-WRF ensemble member no. 35: (a-b) 23.11.2019 12UTC; (c-d) 23.11.2019 16UTC; (e-f) 23.11.2019 20UTC; (g-h) 24.11.2019 00UTC. First column: NC-WRF simulations; second column: FC-WRF simulations.

Figure 10. (a) Specific peak flow differences between FC and NC simulations for the selected catchments shown in Fig. 1b and listed in Table 2; (b) peak flow time differences between FC and NC simulations for the same catchments. Furthermore, differences between FC simulations and observations are shown, where available (red circles: differences between the FC ensemble mean values and observations; red triangles: differences between the FC ensemble median values and observations).