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Probabilistic forecasting of reference evapotranspiration with a limited area ensemble prediction system

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ABSTRACT

The increasing availability of operational limited area ensemble prediction systems (LEPS) opens up new opportunities for the application of weather forecasts in agriculture and water resource management. This study aims to evaluate the performances of probabilistic daily reference crop evapotranspiration (ET_0) forecasts with lead times up to 5 days and a spatial resolution of 7 km, computed by using COSMO-LEPS outputs (provided by the European Consortium for small–scale modelling, COSMO), in a region of southern Italy known for its complex topography in proximity to the Mediterranean coastline. ET_0 was estimated by means of three different estimation methods, i.e. the Hargreaves-Samani (HS), Priestley-Taylor (PT) and FAO Penman-Monteith (PM) equations, in order to assess the size of the weather forecast errors with models of different accuracies. Forecasts were verified with ground-based data from 18 automatic weather stations, and for two irrigation seasons. Performances were assessed with both deterministic indices, including BIAS, RMSE, correlation coefficients and coefficients of variation of the 16-member ensemble forecasts, and probabilistic metrics, such as the Brier skill score, reliability diagrams and relative operating characteristic. ET_0 forecasts with PM equation were robust and reliable, with slight sensitivity to the forecast lead time. High performances were also achieved with HS and PT equations, except for locations close to the coastline, where large systematic errors affect the numerical weather forecasts.

1. Introduction

Predicting evapotranspiration is fundamental in hydrological applications addressing water resources and irrigation management issues. Evapotranspiration is often retrieved as a function of the daily reference crop evapotranspiration (ET_0), which is evapotranspiration from a well-watered hypothetical reference crop. An internationally recognized standard method for computing ET_0 is the FAO-56 Penman-Monteith ($ET_{0\text{-}PM}$) equation (Allen et al., 1998). $ET_{0\text{-}PM}$ is considered the best method for estimating daily ET_0 in all climates, because the FAO-56 Penman-Monteith (PM) equation follows a physically based approach incorporating both physiological and aerodynamic parameters and thus does not require any local calibration (e.g., Garcia et al., 2004). $ET_{0\text{-}PM}$ entails the availability of a complete set of meteorological data, including air temperature, wind speed, solar radiation and relative humidity. These data are often unavailable in many regions of the world or are available with large uncertainty, since they are estimated by spatial interpolation of sparse meteorological ground stations. Other equations have been proposed for estimating ET_0 with a reduced number of meteorological data, but with additional empirical parameters that, where possible, are calibrated at local scale. Allen et al. (1998) proposed the Hargreaves-Samani (HS) equation for estimating ET_0 (hereinafter referred to as $ET_{0\text{-}HS}$) solely from temperature data (Hargreaves and Samani, 1985). The Priestley-Taylor (PT) equation (Priestley and Taylor, 1972) has also been suggested as a valid alternative for estimating ET_0 (hereinafter referred to as $ET_{0\text{-}PT}$) for locations where only temperature and radiation data are available (e.g. Pereira, 2004).

One practical aspect is that ET_0, whatever equation is used for computing it, is only a function of weather variables and thus ET_0 can be regarded as a diagnostic meteorological variable. Forecast

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performance of numerical weather prediction (NWP) models have considerably improved in the 21st century, making their output a valuable source for estimating ET_0 maps, alternative to the spatial interpolation of spatially coarse ground-based weather datasets (WMO, 2012).

Recent studies have focussed on assessing the performance of ET_0 estimates obtained with output data of regional weather models, also known as limited area models (LAM), which exploit the prediction of global circulation models (GCM) for identifying the initial and boundary conditions of a small region where the meteorological phenomena are explicitly resolved with finer spatial resolution. Nesting NWP models with finer scale into coarser models is equivalent to dynamically downscaling the output of the coarser model, consistently with the physical and empirical laws numerically resolved for describing the main meteorological phenomena.

Cai et al. (2007, 2009) employed weather forecast messages produced by the China Meteorological Administration for estimating daily $ET_{0\text{-}PM}$. Ishak et al. (2010) applied the regional model MM5, nested with ERA-40 reanalysis data provided by the European Centre for Medium-Range Weather Forecast (ECMWF) global model, and found that $ET_{0\text{-}PM}$ was overestimated by 27–46%. Silva et al. (2010), also applying MM5 outputs, estimated daily $ET_{0\text{-}PM}$ in Central Chile with a root mean square error (RMSE) between 0.99 mm day^{-1} and 1.54 mm day^{-1}. They managed to reduce the RMSE by 10–20% after bias correcting raw NWP model outputs. Er-Raki et al. (2010), to overcome the scarcity of ground data in a semi-arid region of Central Morocco, employed the temperature fields produced by the ALADIN regional NWP model (nested with the ARPEGE global model) and, by applying an uncalibrated HS equation, estimated monthly ET_0 maps with an average RMSE of 16 mm. Srivastava et al. (2013) compared $ET_{0\text{-}PM}$ estimates in southeast England with weather data obtained by nesting the Weather Research and Forecasting regional NWP model with reanalysis data, respectively provided by ECMWF ERA-interim and the National Centers for Environmental Prediction (NCEP). The study suggested that $ET_{0\text{-}PM}$ estimates obtained by dynamically downscaling ECMWF reanalysis data outperform those obtained with NCEP reanalysis data.

Other recent studies evaluated the possibility to exploit operational numerical weather model outputs for real-time forecasting ET_0 in the short-medium range, i.e. with a lead time up to 1–2 weeks. Perera et al. (2014) applied output data provided by the ACCESS-G global model output operated by the Australian Bureau of Meteorology with a spatial resolution of 80 km, to estimate $ET_{0\text{-}PM}$ with lead times up to nine days. The study showed good forecast performances with average RMSE less than 1 mm day^{-1} for lead time up to four days, after removing systematic bias of the numerical weather output data with respect to the ground weather stations.

In the last two decades, ensemble prediction systems (EPS) have become increasingly popular in operational decision-making processes. Unlike traditional deterministic forecasts where the numerical weather prediction model is run only once, in EPS the NWP model is run several times from very slightly different initial conditions and perturbed model parameters, to produce an ensemble of forecasts that are used to account for uncertainty in initial atmospheric conditions and NWP model errors (Buizza et al., 1999).

Tian and Martinez (2012a,b) employed Global Forecast System (GFS; Hamill et al., 2006) ensemble reanalysis data provided by NCEP to generate 1–15 day probabilistic ET_0 forecasts and then statistically downscale the forecasts by means of the analog approach (Hamill and Whitaker, 2006) in the southwestern United States. The GFS data set consisted of 15 members with a spatial resolution of about 200 km. Since the GFS dataset did not include all meteorological data required for estimating $ET_{0\text{-}PM}$, ET_0 forecasts were produced by using both the PM equation with alternative approximations of some of its main variables as well as the Thornthwaite equation (Thornthwaite, 1948). The statistical downscaling method was calibrated and verified with a set of $ET_{0\text{-}PM}$ produced with a 32 km grid reanalysis dataset provided by the North American Regional Reanalysis dataset (NARR; Mesinger et al., 2006). The results showed that most of the forecasts were skilful in the first five lead days.

Tian and Martinez (2014) replicated the experiment with a second GEFS reanalysis dataset, which was operationally available from 2012 (Hamill et al., 2013), with 11 ensemble members and a spatial resolution of 100 km. Tian and Martinez (2014), compared with the previous experiment (Tian and Martinez, 2012a,b), managed to improve the skill of the probabilistic $ET_{0\text{-}PM}$ forecasts as well as the accuracy in estimating the soil water deficit for irrigation scheduling in the first five lead days, thanks to the availability of a complete meteorological dataset produced by a more advanced NWP model at higher spatial resolution.

Compared with the dynamic downscaling, statistical downscaling as the analog method has an advantage in requiring much less computational resources. However, simultaneous ground observations and forecast reanalysis data are required for a long period of time (e.g., about 25 years) in order to achieve a good calibration and verification of the statistical techniques. Such datasets are available with difficulty: indeed, Tian and Martinez (2012a,b, 2014) resorted to model data generated at higher resolution as a surrogate for ground observations. No studies evidenced that statistical downscaling of forecasts performs better than dynamic downscaling of forecasts. Statistical downscaling is also exposed to limitations in tracking the effects of changing climatic conditions as well as weather conditions that are not represented by the sample data set employed for its calibration.

In recent years, limited area ensemble prediction systems (LEPS) have been developed as dynamic regional downscaling of global ensemble prediction systems. The development of operational LEPS was mainly motivated by the need to support decision makers with forecasts of high-impact weather events and particularly precipitation fields, at higher resolution and greater reliability than what could be achieved with single deterministic regional forecasts. The operational availability of LEPS opens up new opportunities for the application of weather forecasts in agriculture and water resource management, since high resolution probabilistic forecasting allows water irrigation managers to set-up agrometeorological advisory services based on a more reliable risk analysis.

One of the first examples is the limited area ensemble prediction system, developed by the Consortium for small-scale modelling (COSMO-LEPS), which is now operationally used by several countries in Europe (Montani et al., 2011; Marsigli et al., 2014). COSMO-LEPS is nested on selected members of ECMWF EPS and is designed to combine the advantages of the probabilistic EPS approach with the high–resolution details gained in the mesoscale integrations (Montani et al., 2011).

This study aimed to evaluate the performance of probabilistic reference evapotranspiration forecasts based on numerical weather predictions produced by COSMO-LEPS. To our knowledge this is the first study explicitly examining the probabilistic performance of numerical weather predictions produced by dynamic downscaling of global ensemble forecasts for evapotranspiration studies.

The performance analysis focused on two irrigation seasons in southern Italy where a simultaneous set of meteorological data from 18 ground automatic weather stations and COSMO-LEPS forecasts was collected within a research programme to develop an advanced irrigation advisory service (Vuolo et al., 2015). ET_0 forecasts with lead times up to five days were computed with the PM