# Seamless forecasting of extreme events on a global scale

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**Abstract** Early warning systems of extreme events, such as floods, droughts, strong winds and wild fires as well as vector-borne diseases, at the global scale, are essential due to the combined threat of increased population settlement in vulnerable areas and potential increase in the intensity of extreme weather due to climate change. The European Centre for Medium-Range Weather Forecasts (ECMWF) has in the last year developed prototype early warning systems for floods, droughts, extreme winds, wild forest fires and malaria transmission. This paper assesses the performance of these systems. By providing a comprehensive skill assessment both on a global level and in selected regions, we aim to assess their suitability for eventual integration into decision-support frameworks.

**Key words** floods; droughts; fire; malaria; forecasting; ensemble; ECMWF

## INTRODUCTION

The skill of weather forecasting has steadily improved over the last decades (Simmons *et al.*, 2002, Hoskins, 2012) and this has led to the application of weather forecasts in the anticipation of disasters. Webster (2012) has pointed to the huge potential that numerical weather predictions (NWP) have for the reduction of damage caused by floods, droughts and tropical cyclones, especially in the developing world. ECMWF issues the world's best numerical ensemble weather forecast on the medium range (Haiden *et al.*, 2012; Hagedorn, 2013). It also has a range of different forecast products with lead times of up to seven months (see Table 1 for a full list of available products). The use of these products of varying time ranges can be termed "seamless". The ECMWF high resolution forecast has a lead time of 10 days and a horizontal resolution of ~16 km (ECMWF, 2013b). Weather forecasts are often based on ensemble techniques to adequately represent uncertainties (Palmer & Leutbecher, 2008) and the ECMWF ensemble consists of 51 forecasts issued twice a day with a lead time of 15 days. The monthly forecast is integrated into this 15-day forecast by extending the forecast range to 32 days twice a week. The seasonal forecasting system is run once a month with a lead time up to seven months (S4, Molteni *et al.*, 2011). These systems are supplemented with a set of hindcasts which are forecasts run for the past 18 years with the current prediction model. Hindcasts are used to calculate model climatologies, or to calibrate the forecast before its use in driving applications. In addition to forecasting products, ECMWF produces re-analysis products, which can be used for real-time monitoring, or for analysis of past events. Re-analysis produces global fields of atmospheric, land and ocean properties using available observations assimilated by the numerical weather prediction system. The current ECMWF re-analysis product is called ERA-Interim (ERAI, Dee *et al.*, 2011) and is available from 1979 until today with a spatial resolution of ~80 km. ERA-Interim superseded the earlier ERA-40 (Uppala *et al.*, 2005). The next generation re-analysis product will be ERA-20C, which is a global re-analysis for the whole 20th century (ECMWF, 2013c). This paper describes the latest development of seamless applications of ECMWF forecasts to natural hazards, such as floods, droughts, wild fire and malaria.

## CASE STUDIES

There is a large range of forecast products which can be used and developed into applications, as illustrated in Table 1. ECMWF end-users use the NWP forecasts and re-analysis in many different sectors, such as the natural environment, agriculture, public-sector, construction, energy and transport. In recent years, there has been direct involvement of ECMWF in testing in-house applications, mostly through EU funding. Here, we highlight four areas: floods, droughts, wild fires and malaria transmission, in which ECMWF currently explores the value of its forecasts in partnership with other organisations. Table 1 summarises which ECMWF products are used within these different applications. It is important to note that longer lead times are the most useful for disaster preparedness and early warning.

**Table 1** Applications and their use of ECMWF data.

| ECMWF product | Floods | Wildfire | Droughts | Malaria |
|---|---|---|---|---|
| High resolution | ✓ | | | |
| Ensemble | ✓ | ✓ | | |
| Monthly | | | ✓ | ✓ |
| Seasonal | | | ✓ | ✓ |
| Re-analysis | ✓ | ✓ | ✓ | ✓ |

## Floods

Flooding is the natural disaster that during the last century caused the largest number of deaths and biggest economic losses (EM-DAT, 2012). Meteorological forecasts and land-surface hydrological models can be combined to predict riverine and surface runoff flooding. For this purpose, ECMWF has co-developed a Global Flood Awareness System (GloFAS), which is based on the successful European Flood Awareness System (EFAS, Thielen *et al*., 2011, www.efas.eu) using the ECMWF Ensemble forecasts and re-analysis as driving data. An important aspect of this global system is that, like EFAS, it is set-up on a continental scale but deals with the hydrological processes at the catchment scale – independent of administrative and political boundaries. This provides countries which are located downstream with information on upstream river conditions as well as continental and global overviews. The GloFAS system has been running in a test-operational mode since July 2011, producing ensemble streamflow predictions (ESP) with worldwide coverage and a forecast horizon of about one month. Since the operational set-up in July 2011, flood river forecasts have been produced on a daily basis and displayed. Probabilistic river discharge forecasts are overlaid onto three warning threshold levels (medium, high and severe) and flood warnings are derived accordingly (Fig. 1). Results are disseminated through warning maps with additional information at selected reporting points.

Alfieri *et al*. (2012) showed that current ensemble streamflow predictions can enable skilful detection of hazardous events with forecast horizons as long as one month in large river basins. The system has already demonstrated its potential in recent catastrophic floods. The floods in Pakistan in July–August 2010 were clearly detected by the system as a major flood event, as were the floods in South-East Asia (mainly Thailand, Cambodia and Vietnam) in September–October 2011 (when persistent heavy rainfall, induced widespread landslides upstream and submerged vast lowland areas including roads, houses and rice fields). For the lower Mekong River, probabilistic forecasts from the global simulations on 18 September 2011 showed a probability higher than 40% of exceeding the high alert level from 2–4 October, 14 days in advance of the event. The forecasts of the following days showed an increased severity of flooding and increased the confidence in the forecast (Fig. 1).

## Droughts

A drought typically results from a precipitation deficit that extends for several months (or even years) over a large area. Droughts can affect different climatic regions with differing socio-economic impacts. In some parts of the world, the effects of a drought can be catastrophic and lead to famine. Effects of droughts can be mitigated through water planning and infrastructure.

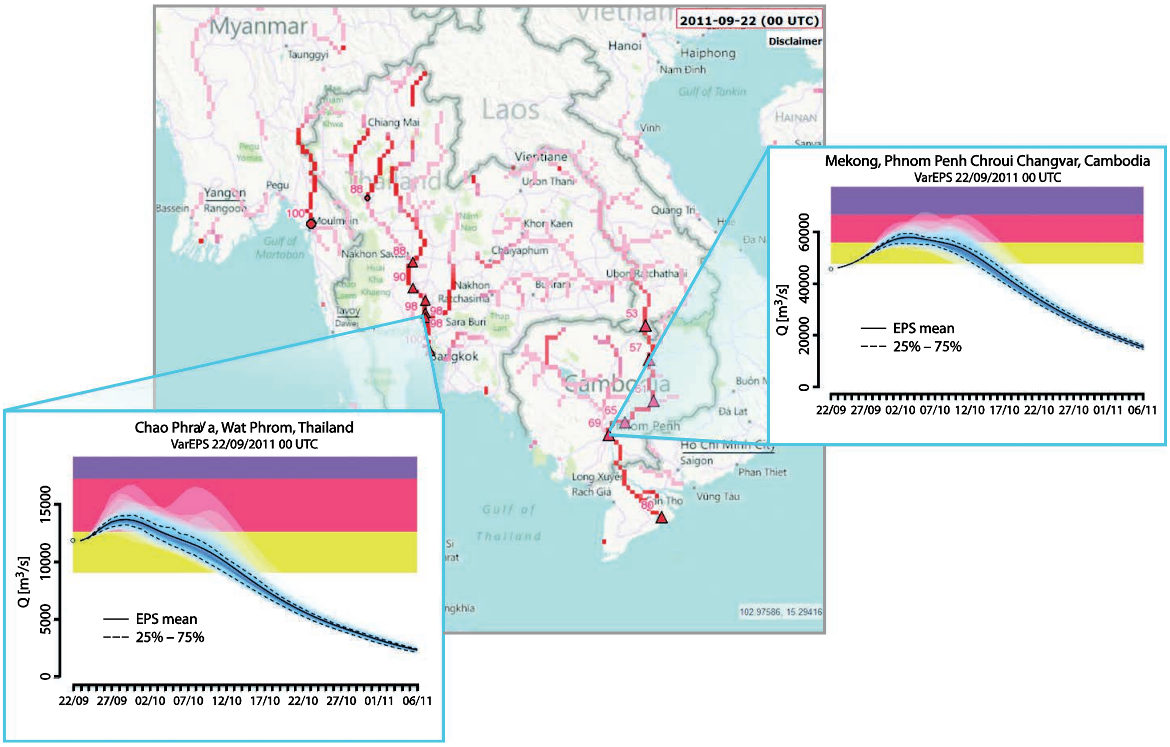

**Fig. 1** 45-day probabilistic discharge forecasts for the Chao Phraya (Thailand) and the lower Mekong (Cambodia) on 22 September 2011. Input rainfall is provided for the first 15 days only.

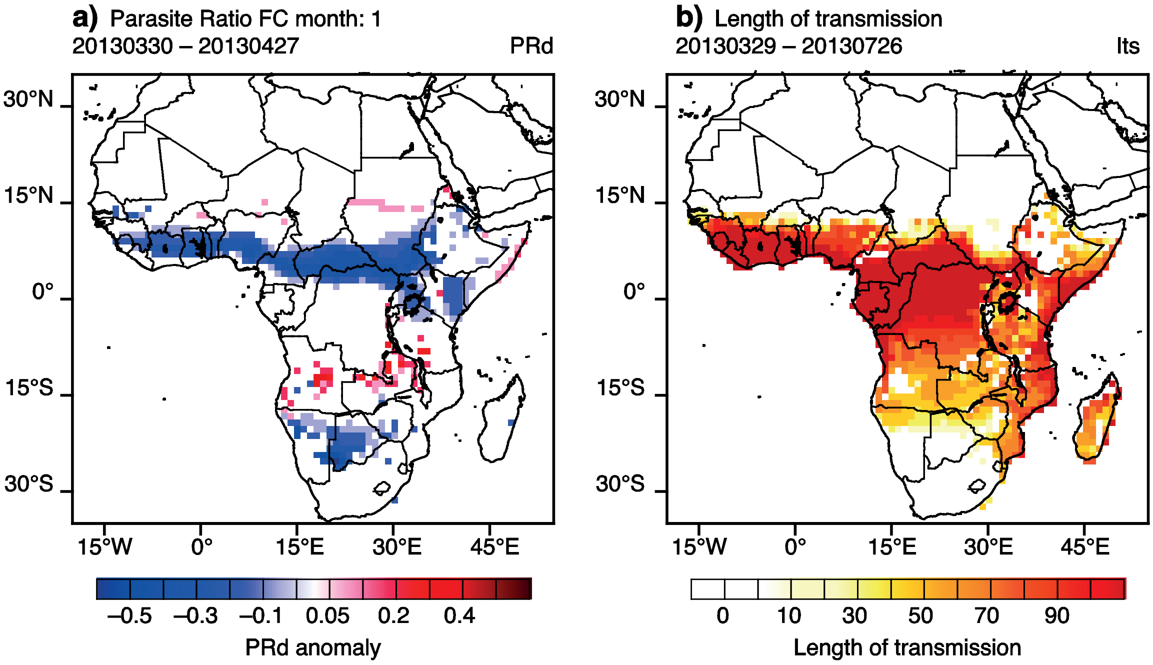

**Fig. 6** Example of malaria products from the malaria early warning system. (a) the Parasite Ratio anomaly is a measure of the intensity of malaria transmission when compared to climatic defined conditions. (b) The length of transmission is defined as the number of days in the 120 days simulations in which malaria transmission occurs (see page 9).

The long time-scales associated with droughts (from onset to recovery) differ from other weather-related hazards, such as floods. These long time-scales make drought forecasting a challenging effort which demands monitoring and long-range forecasting.

Meteorological droughts can be predicted using the Standardized Precipitation Index (SPI, McKee *et al*., 1993; Hayes *et al*., 2011). ECMWF recently developed an integrated meteorological drought monitoring and forecasting system based on the SPI. The system is constructed by extending near real-time monthly precipitation fields from the ERA-Interim re-analysis (ERAI) with monthly forecast fields, as provided by the ECMWF seasonal forecasting system. This system is implemented on a global scale and has been evaluated over four basins in Africa (Dutra *et al*., 2012b) using the Global Precipitation Climatology Project (GPCP) version 2.2 (Huffman *et al*., 2011). This study highlighted the importance of qualitative precipitation monitoring and skilful seasonal forecasts.

In this drought case study, we demonstrate the use of monitoring and probabilistic forecasting in southern Britain (UK, –5° to 0°W, 50° to 52.5°N), which led to a hosepipe ban in parts of England. From April 2012 onwards, there was a shift in the weather conditions towards wet, with England having its wettest year on record (http://www.metoffice.gov.uk/climate/uk/2012/annual.htm). The comparison between the 3- and 12-month SPI in south Britain using ERAI and GPCP precipitation (Fig. 2) shows a good agreement between the two datasets with anomaly correlations of 0.85 and 0.88 for the 3- and 12-month SPI, respectively. It is also possible to identify the 2011/12 drought and fast inversion to very wet conditions (with SPI-12 changing from –2.4 in November 2011 to 2.2 in November 2012). These results show that it is possible to use the near real-time available ERAI precipitation for drought monitoring in the region.

The role of forecasting is demonstrated in Fig. 3, where four seasonal forecasts of precipitation in 2012 are shown demonstrating modest skill. The forecast issued in January missed the dry February and March, while the forecast issued in the beginning of April missed the rainy end of April. The forecasts issued in July and October indicated (but underestimated) wet conditions. An evaluation of past forecasts (using hindcasts from 1981 to 2010) confirms that the SPI probabilistic forecasts are comparable with a forecast based on climatology (not shown).

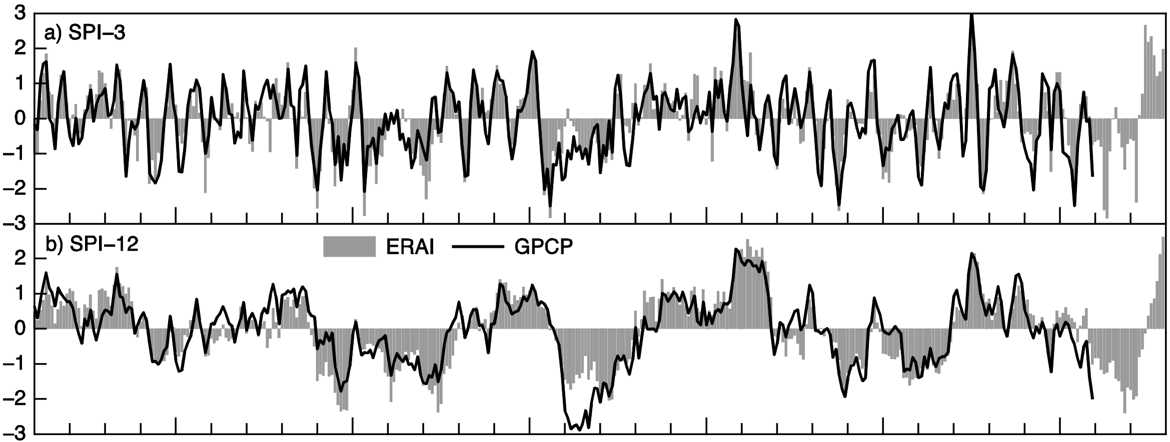

**Fig. 2** Evolution of the 3-month (a) and 12-month (b) SPI in South Britain given by GPCP (line) and ERA-Interim (black bars).

## Wildfire

A wildfire is defined as an uncontrolled fire of vegetation outside urban areas. Apart from Antarctica, wildfires occur in every continent causing extensive financial damage and humanitarian suffering; but they are also part of the natural environment and essential for biodiversity (Bento-Goncalves, 2012). Despite accounting for only a small percentage of deaths and economic damage relative to other disaster types, their impacts can be devastating. For

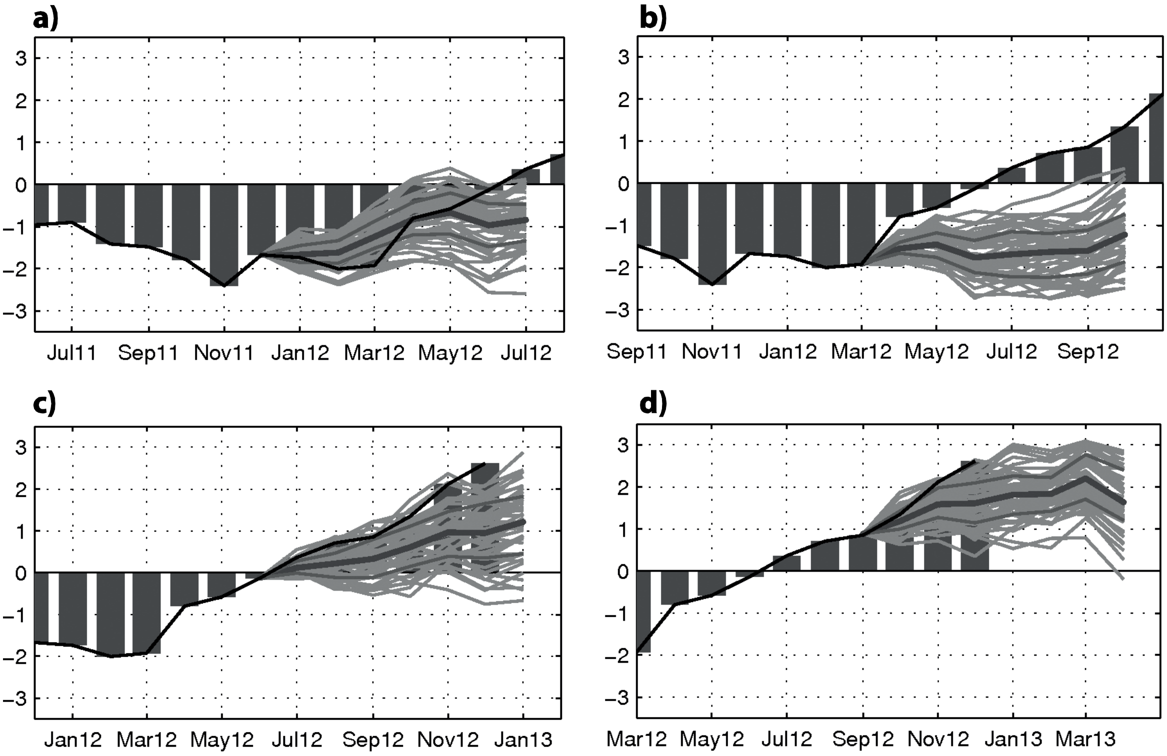

**Fig. 3** 12-month SPI seasonal forecasts in Southern Britain issued in (a) January 2012, (b) April 2012, (c) July 2012 and (d) October 2012. The black line (and bars) indicates the monitoring as derived by ERA-Interim. The grey lines show the ensemble members of the seasonal forecasting system, the blue lines the ensemble mean (tick) and the 20th and 80th percentiles

example, a fire in the USA in 2007 caused damage in the excess of US$2500 million and the forest fires in Macedonia FYR in the same year affected over one million people (EM-DAT 2012). The risk and behaviour of wild fires is strongly influenced by hydrological and meteorological conditions. Droughts and heat waves can increase the fire hazard risk. ECMWF's ERA-Interim re-analysis and medium range forecasts (Table 1) can be useful for this hazard.

In this case study, we demonstrate the usefulness of probabilistic medium range numerical weather predictions for fire danger forecasting by using the Canadian Forest Fire Weather Index (FWI) system (van Wagner *et al.*, 1987; Stocks *et al.*, 1989). The index consists of several components, as discussed by van Wagner *et al.* (1987). The FWI has a magnitude that largely depends on global regions with a clear seasonal pattern (Fig. 4). Despite the fact that ERA-Interim data display trends in temperature (Simmons *et al.*, 2004) and that there is a reported impact of climate change on the FWI (Flannigan *et al.*, 2009), no temporal trend in the FWI is seen. However, the FWI is a non-linear transformation of precipitation, relative humidity, wind speed and temperature; hence it is not surprising that the trend of an individual variable is not reflected in the composite, especially with large spatial variability (Flannigan *et al.*, 2009). Predictability largely depends on the region (Fig. 5), with some regions providing skilful predictions with lead time up to 10 days, whereas others do not seem to achieve that even beyond a lead time of 1 day.

## Malaria

According to the World Health Organization's *World Malaria Report 2008* (Aregawi *et al.*, 2008), 3.3 billion people (half the world's population) live in areas at risk of malaria transmission in 106 countries and territories. In 2010, malaria caused an estimated 216 million clinical episodes, and 655 000 deaths; about 86% of deaths globally were in children (Aregawi *et al.*, 2008).

Malaria has distinct environmental drivers. Rainfall defines the transmission season by providing breeding sites for mosquitoes that are the vector of the disease, while temperature

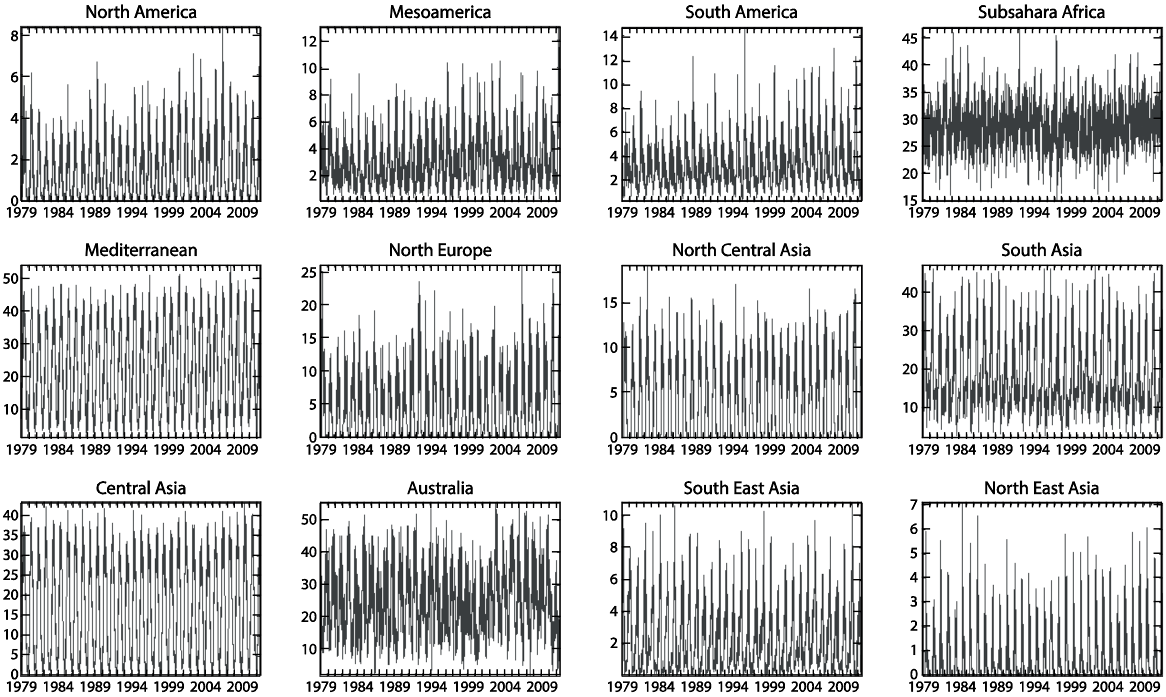

**Fig. 4** Temporal evolution from 1979 to 2010 of the Fire Weather Index using ERA Interim re-analysis data as forcing for 15 world regions (daily data).

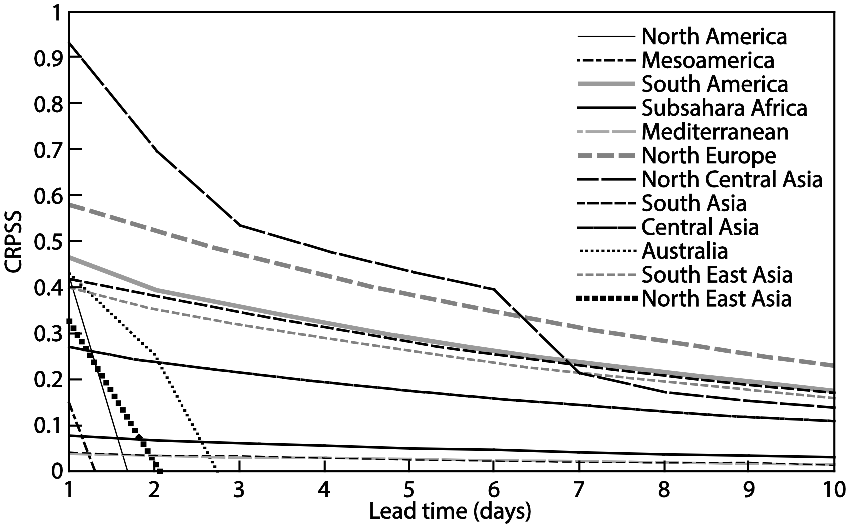

**Fig. 5** Continuous Rank Probability Skill Score for the period July–September 2008. Values above 0 indicate that there is skill in predicting fire hazards.

impacts on both the larva and adult life cycles. Many other geographical factors play a role, including soil type and terrain topography. There is clear evidence that risk of epidemic increases in tropical countries shortly after a season of good rainfall when heat and humidity allow insects to thrive and spread diseases such as malaria. In the last decades, there has been a vast effort to understand the mechanisms responsible for malaria transmission and to improving modelling of these mechanisms for early warning. Simultaneously, there has been a drive to improve the collection, analysis and quality control of epidemiological data on malaria distribution in Africa, which is essential for the task of validation of malaria forecasting.

ECMWF has developed a first prototype pan-African operational forecasting system for malaria by coupling the malaria model VECTRI (Tompkins & Ermert, 2013) to seamless bias-corrected monthly and seasonal forecasts (Di Giuseppe *et al.*, 2012). Since July 2012, the system has run weekly malaria predictions with African coverage and forecast lead times of up to four months. In addition, each week the system is also run for the previous 18 years using the hindcast set. These supplementary simulations are used to establish the relevant climatic malaria conditions for a region of interest so that anomalous transmission conditions can be diagnosed. Figure 6 (page 5) shows some of the products available on the dedicated website.

The system is still in its infancy and validation tasks are yet to be completed (in collaboration with the ministries of health in Malawi, Uganda and Rwanda). Figure 6 already highlights its potential for operational use: the system can correctly locate where malaria is either: endemic and stable transmission occurs (Fig. 6(b)), or epidemic (Fig. 6(a)). The current momentum and investment in strengthening health systems and reducing disease in sub-Saharan Africa is unprecedented. Investment in research and operational delivery of climate information products for climate-sensitive disease control is highly valuable in helping to maximize the effectiveness of control programme planning and implementation. However, experience to date has shown that it is difficult in terms of availability, timing and cost to obtain meteorological observations from national meteorological services in Africa. The forecast system implemented at ECMWF could serve to fill this gap.

## DISCUSSION AND CONCLUSIONS

Forecasting is an important component of a natural hazard prevention and early warning system. In particular, NWP systems have great potential for the reduction of the impact of disasters, including: floods, drought, fire and malaria. In all areas, the potential benefits are great given adequate technical infrastructure (computers, network connections, etc.). However, there are also great challenges to overcome in making such forecasts useful and skilful:

**Developments** Applications of weather forecasts cross a large number of cutting-edge research fields and novel methods to post-process weather forecasts to make them suitable for applications are required (Di Giuseppe *et al.*, 2012). Other areas of development are data assimilation, representation of uncertainties and post-processing of results, which are often application specific, requiring the collaboration of multidisciplinary teams (e.g. statistics, Earth observations, health modelling, hydrology, etc. (see e.g. Cloke *et al.*, 2013).

**Evaluation/Verification** Downstream applications such as those herein are non-linear filters of the output of weather models. For example, droughts integrate a forecasting signal temporally and spatially. Hence, forecast evaluation has to be performed within the context of these applications (see e.g. Pappenberger *et al.*, 2008). This will be particularly challenging in the prediction of extremes due to the very limited sample size and, hence, not necessarily statistically robust results.

**Communication/Decision making** Improving forecasts is an important scientific endeavour, but unless results are communicated to the agencies involved or to the individuals affected, any effort of improvement is in vain. In particular, communicating the unavoidable uncertainty is challenging (Ramos *et al.*, 2010), and involves the need to overcome institutional barriers (Demeritt *et al.*, 2012). These challenges can only be addressed in the framework of international collaboration and local knowledge.

**Acknowledgements** The Global Flood Awareness System is run in collaboration with the Joint Research Centre of the European Commission under the umbrella of the European Flood Awareness System (www.efas.eu). The work of the drought forecasting is supported by the FP-7 European projects on "*Improved Drought Early Warning and Forecasting to Strengthen Preparedness and Adaptation to Droughts in Africa (DEWFORA)*" and "*Global Water Scarcity Information Service (GLOWASIS)*". The analysis of fire risk forecasting was financed by the Joint Research Centre of the European Commission under the umbrella of the European Forest Fire

Information System (effis.jrc.ec.europa.eu/). The malaria forecasting system is developed in close collaboration with ICTP and University of Liverpool, and financed by the FP-7 European projects "*Quantifying Weather and Climate Impacts on Health in Developing Countries (QWeCi)*". Hannah L. Cloke's sabbatical at ECMWF was supported by the NERC project on "*Developing enhanced impact models for integration with next generation NWP and climate outputs (DEMON)*" (NE/I005366/).

## REFERENCES

Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J. & Pappenberger, F. (2012) GloFAS – global ensemble streamflow forecasting and flood early warning. *Hydrology and Earth System Sciences Discussions* 9(11), 12293–12332, doi:10.5194/hessd-9-12293-2012.

Aregawi, M., Cibulskis, R., Otten, M., Williams, R., Dye, C. *et al.* (2008) *World Malaria Report*. World Health Organization.

Bento-Goncalves, A., Vieria, A., Ubeda, X. & Martin, D. (2012) Fire and soils: Key concepts and recent advances. *Geoderma*, 191, 3–13.

Connor, S.J., Ceccato, P.N., Dinku, T., Omumbo, J.A., Grover-Kopec, E.K. & Thomson, M.C. (2006) Using climate information for improved health in Africa: relevance, constraints and opportunities. *Geospatial Health* 17–31.

Cloke, H.L, Pappenberger, F., van Andel, S.J., Schaake, J., Thielen, J. & Ramos, M.H. (2013) Hydrological Ensemble Prediction Systems (HEPS). *Hydrol. Processes* (in press).

Dee, D. P., *et al.* (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* 137(656), 553–597, doi:10.1002/qj.828.

Demeritt, D., Nobert, S., Cloke, H. L. & Pappenberger, F. (2012) The European Flood Alert System and the communication, perception, and use of ensemble predictions for operational flood risk management. *Hydrol. Processes* 27, 147–157, doi: 10.1002/hyp.9419.

Di Giuseppe, F., Molteni, F. & Tompkins, A. M. (2012) A rainfall calibration methodology for impacts modelling based on spatial mapping. *Quarterly Journal of the Royal Meteorological Society*, doi:10.1002/qj.2019

Dutra, E., Magnusson, L., Wetterhall, F., Cloke, H. L., Balsamo, G., Boussetta, S. & Pappenberger, F. (2012a) The 2010–2011 drought in the Horn of Africa in ECMWF reanalysis and seasonal forecast products. *Int. J. Climatol.*, doi: 10.1002/joc.3545.

Dutra, E., Di Giuseppe, F. Wetterhall, F. & Pappenberger, F. (2012b) Seasonal forecasts of drought indices in African basins, *Hydrol. Earth Syst. Sci. Discuss*. 9(9), 11093-11129, doi:10.5194/hessd-9-11093-2012.

ECMWF (2013a) The ECMWF operational analysis and forecasting system, http://www.ecmwf.int/products/data/operational_system/, accessed 23/01/2013.

ECMWF (2013b) http://www.ecmwf.int/products/data/operational_system/index.html, last accessed: 23/01/2013.

ECMWF (2013c) http://www.ecmwf.int/products/data/operational_system/index.html, last accessed: 23/01/2013.

EM-DAT (2012) The OFDA/CRED International Disaster Database, Universite catholique de Louvain, Brussels, Belgium, http://www.emdat.be/, last accessed on 22 January 2012

ERACLIM (2013) European Reanalysis of Global Climate Observations, http://www.era-clim.eu/, accessed 23/01/2013.

Hagedorn, R., Buizza, R., Hamill, T., Leutbecher, M. & Palmer, T. (2012) Comparing TIGGE multimodel forecasts with reforecast-calibrated ECMWF ensemble forecasts. *Quarterly Journal of the Royal Meteorological Society* 138(668), 1814–1827, doi:10.1002/qj.1895.

Haiden, T., Rodwell, M. J., Richardson, D. S., Okagaki, A., Robinson, T. & Hewson, T. (2012) Intercomparison of global model precipitation forecast skill in 2010/11 using the SEEPS core. *Monthly Weather Review* 140(8), 2720–2733.

Hoskins, B. (2012) The potential for skill across the range of the seamless weather–climate prediction problem: a stimulus for our science. *Quarterly Journal of the Royal Meteorological Society*, doi:10.1002/qj.1991.

Leutbecher, M. & Palmer, T. N. J. (2008) Ensemble forecsting. *Comp. Phys*. 227, 3515–3539 (2008).

Mckee, T. B., Doesken, N. J. & Kleist, J. (1993) The relationship of drought frequency and duration to time scales. Eighth Conference on Applied Climatology, Anaheim, California, 179–184.

Molteni, F., *et al*. (2011) The new ECMWF seasonal forecast system (System 4). *ECMWF Tech. Memo*., 656, 49 pp.

Pappenberger, F., Scipal, K. & Buizza, R. (2008) Hydrological aspects of meteorological verification. *Atmospheric Science Letters* 9, 43–52.

Ramos, M.H., Mathevet, T., Thielen, J. & Pappenberger, F. (2010) Communicating uncertainty in hydro-meteorological forecasts: mission impossible? *Meteorological Applications* 17(2), 223–230.

Simmons, A. J. & Hollingsworth, A. (2002) Aspects of the improvement in skill of numerical weather prediction. *Quarterly Journal of the Royal Meteorological Society* 128(580), 647–677.

Thielen, J., Pappenberger, F., Salamon, P. Bogner, K., Burek, P. & De Roo, A. (2011) State of the art of flood forecasting: from deterministic to probabilistic approaches. In: *Flood Hazards: Impacts and Responses for the Built Environment* (ed. by Proverbs, D., Lamond, J., Hammond, F. & Booth, C.). Taylor and Francis.

Tompkins, A.M. & Ermert, V. (2012) A regional-scale, high resolution dynamical malaria model that accounts for population density, climate and surface hydrology. *Malaria Journal* 12, 65, doi:10.1186/1475-2875-12-65.

Uppala, S. M., Kallberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. D., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Van De Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Holm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., McNally, A. P., Mahfouf, J. F., Morcrette, J. J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P. & Woollen, J. (2005) The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society* 131, 2961–3012, doi:10.1256/qj.04.176.