Department of Geography and Environmental Science
Department of Meteorology

University of Reading

HYDROLOGICAL ENSEMBLE PREDICTION

Prof Hannah Cloke
Co-Director of Water@Reading
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@hancloke

& a BIG THANKYOU to the **HEPEX community**

@hepexorg

OUTLINE

- What are hydrological ensembles and how are they used?
- The HEPEX community
- The European and Global Flood Awareness Systems
- Representing uncertainty
- Early flood warnings, humanitarian action and decision making under uncertainty
- The economic value of hydrological ensemble forecasts

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HYDROLOGICAL ENSEMBLES OF….

- soil moisture, runoff, river flow (including floods), groundwater, snow, reservoir inflows/volumes…

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WHAT IS THIS THING CALLED ENSEMBLES?

EFAS

European Flood Awareness System

The “Ensembles Man”

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ENSEMBLE FLOOD FORECASTS BETTER DECISION MAKING

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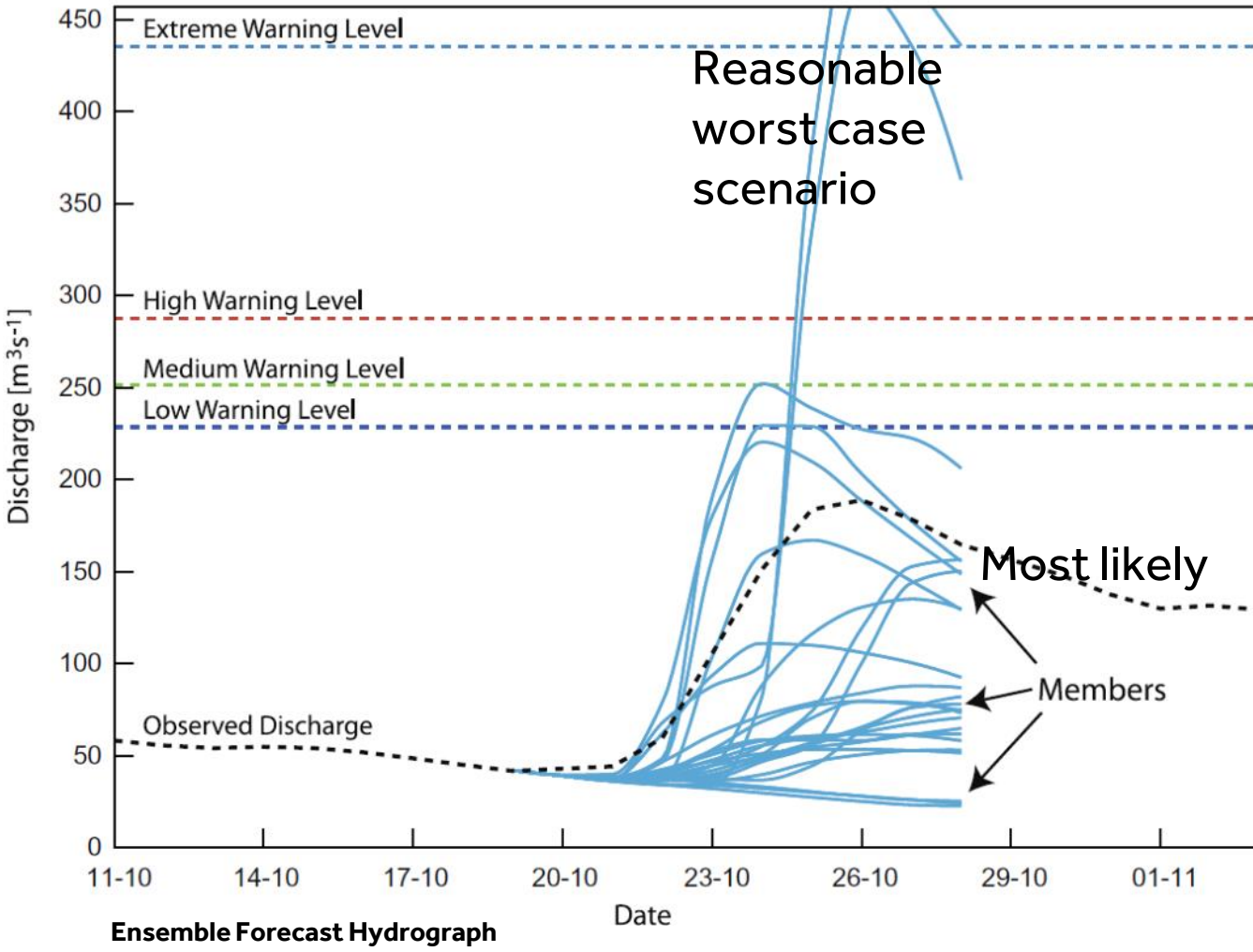

Ensemble Forecast Hydrograph

Cloke & Pappenberger (2009) Ensemble Flood Forecasting. Journal of Hydrology

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Somerset Levels, February 2014

Winter 2013/14: coastal storms and persistent large rainfall accumulations led to significant and widespread flooding across the southern UK.

BBC Sign in News Sport Weather

NEWS UK

Home World UK England N. Ireland Scotland Wales Business Politics He

UK weather: Flood misery in the Thames Valley

8 January 2014 Last updated at 20:03 GMT

Recent heavy rains and strong winds have led to severe flooding in many parts of the UK, with coastal communities and those living close to rivers especially vulnerable.

THAMES BARRIER, River Thames, London, UK
Environment Agency
Use of ensemble forecasting led to increased preparedness and a reduction in flood risk in winter 2013/14

Stephens, E. and Cloke, H. (2014) **Improving flood forecasts for better flood preparedness in the UK (and beyond).** Geographical Journal, 180 (4). pp. 310-316. doi: 10.1111/geoj.12103

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European Flood Awareness System (EFAS): Floods in Central Europe June 2013

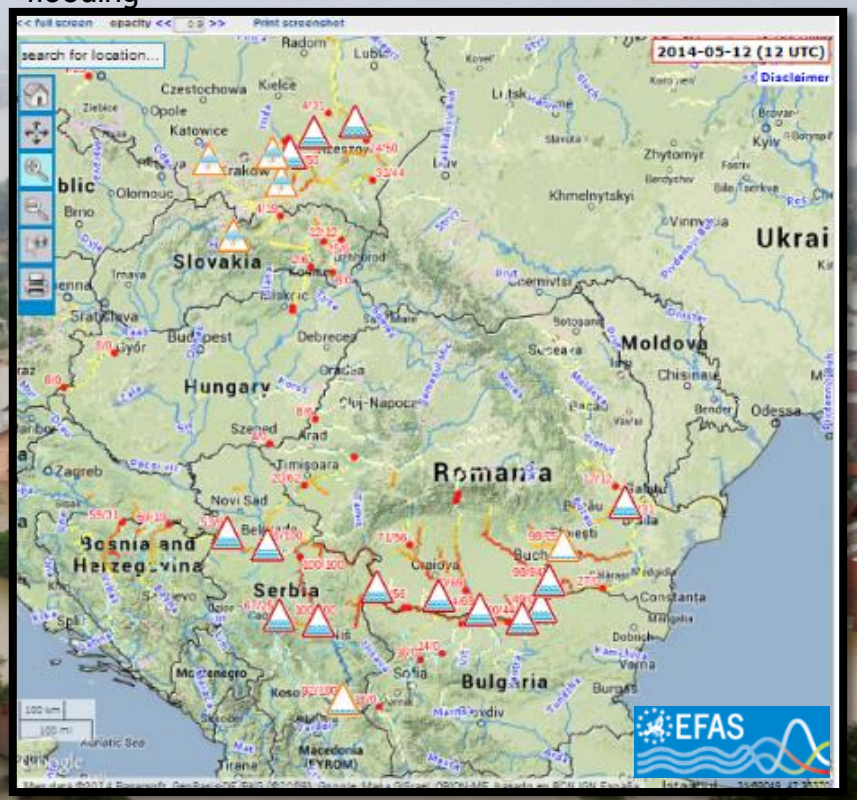
- EFAS: pioneer of ensemble flood forecasts
- June 2013, EFAS warnings and alerts were issued for all major rivers in central Europe (Elbe, Danube, Rhine) up to 8 days in advance

Pappenberger et al (2011) HP

European Commission · opernicus · EFAS · ECMWF

European Flood Awareness System
Severe floods in the Balkans, May 2014
EMERGENCY RESPONSE COORDINATION

Warnings to EC Emergency Response Coordination Centre and National Authorities, 8 days before the flooding



HUMANITARIAN AID AND CIVIL PROTECTION

Copernicus

EFAS

EARLY HUMANITARIAN ACTION WITH ENSEMBLE FLOOD FORECASTING – FORECAST BASED FINANCING

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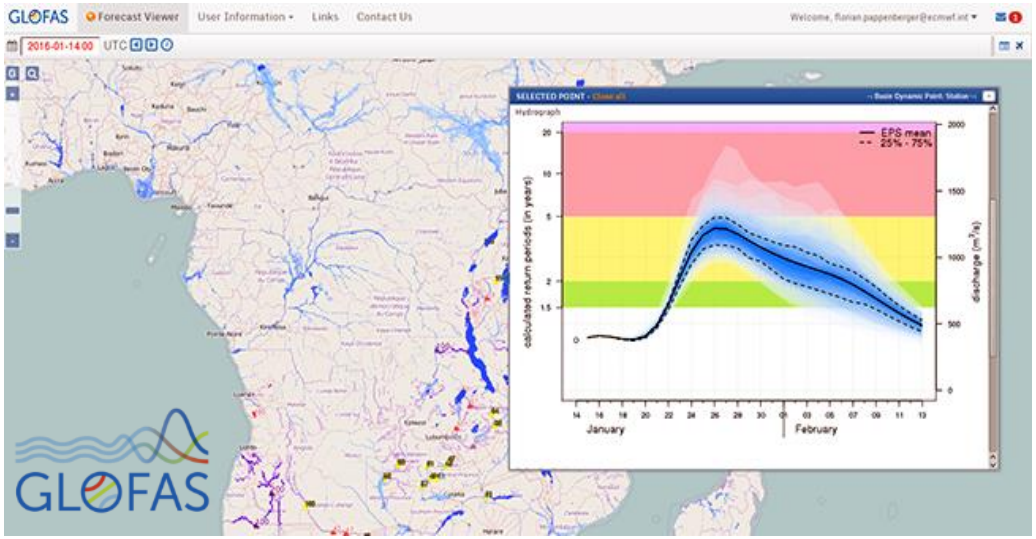
Photo credit: Peruvian Red Cross (top left, below right), Floodlist (centre), Juan Bazo (right)



European Commission | ECMWF | Copernicus Europe's eyes on Earth | Climate Centre

NERC SCIENCE OF THE ENVIRONMENT | UKaid

Project **FATHUM** Contact: Elisabeth.Stephens@reading.ac.uk

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HEPEX

a community of research and practice to advance hydrologic ensemble prediction

HEPEX *Hydrologic Ensemble Prediction Experiment*
began in 2004 at an ECMWF workshop jointly organized with the US National Weather Service (NWS) & the European Commission (EC).

It continues to connect the research community, forecasters and forecast users and facilitates the exchange of ideas, data, methods and experience.

Find out more: **www.hepex.org**


HEPEX Workshop, 6-8 June 2016, Quebec, Canada

HEPEX Chairs are:
Maria-Helena Ramos (IRSTEA, France)
QJ Wang (University of Melbourne , Australia)
Fredrik Wetterhall (ECMWF, UK)
Andy Wood (UCAR, USA)

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- The theme for the 2018 HEPEX workshop is '**breaking the barriers**' to highlight current challenges facing ensemble forecasting researchers and practitioners and how they can be overcome:
- using ensemble forecasts to improve decisions in practice,
- extending forecasts in space (including to ungauged areas) and across lead-times, from short-term to sub-seasonal to seasonal forecast horizons,
- using ensemble forecasts to maximise economic returns from existing water infrastructure (e.g. reservoirs), even as inflows and demand for water change,
- using ensemble forecasts to improve environmental management of rivers,
- applying ensemble forecasts for agriculture,
- searching for better/new sources of forecast skill,
- balancing the use of dynamical climate and hydrological models with the need for reliable ensembles,
- communicating forecast quality and uncertainty to end users.

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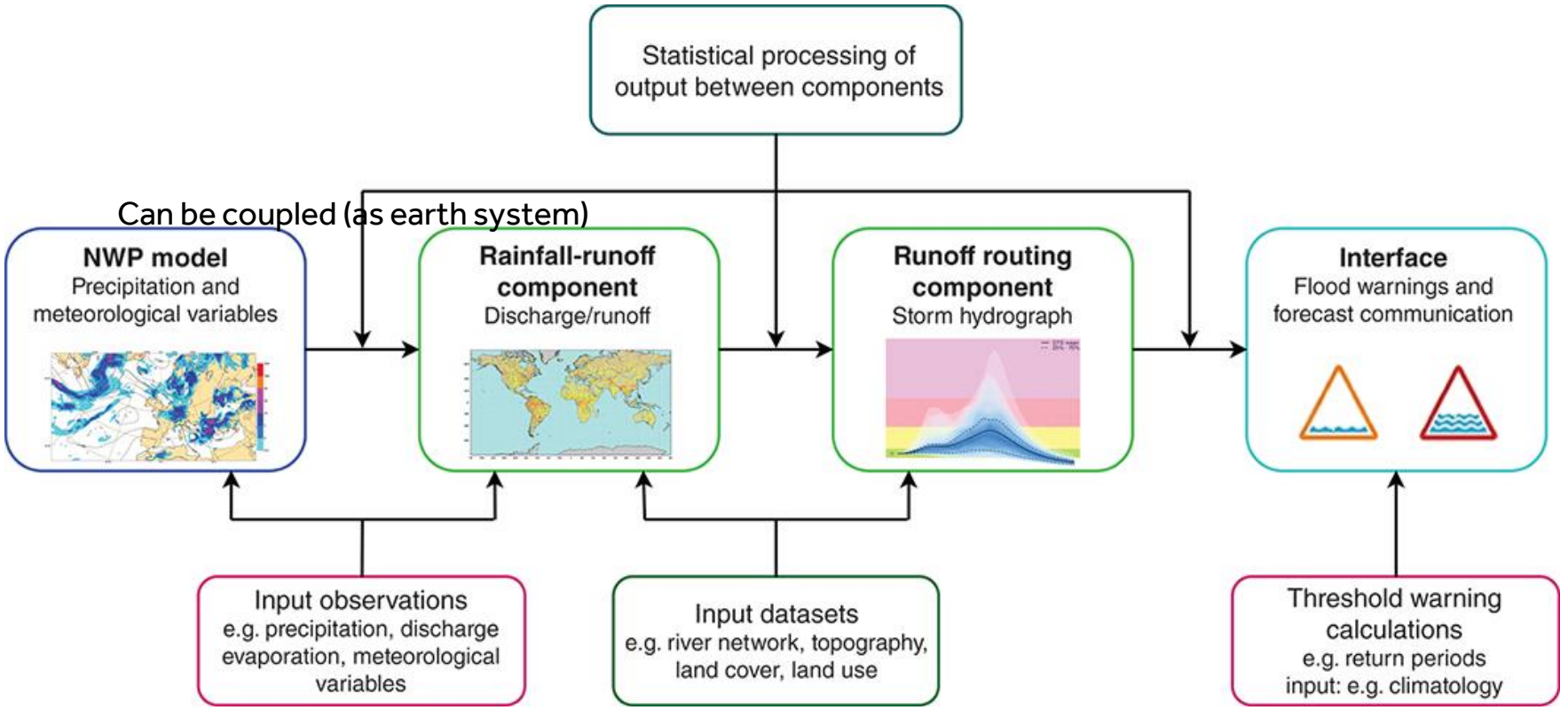

Emerton et al (2016) **Continental and global scale flood forecasting systems.** *Wiley Interdisciplinary Reviews: Water*, 3 (3). pp. 391-418. doi: 10.1002/wat2.1137

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EFAS
European Flood Awareness System

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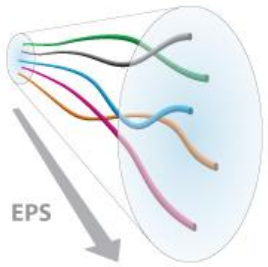
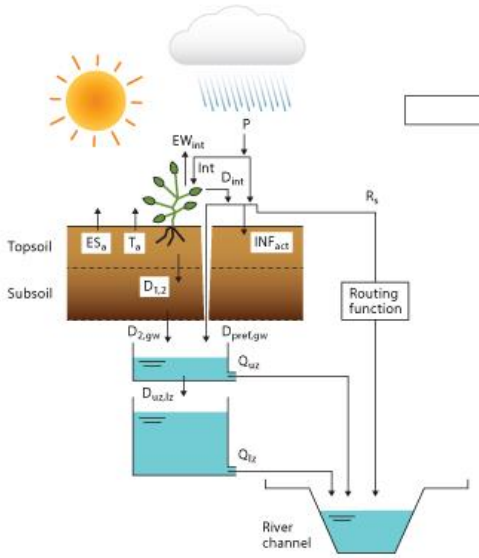


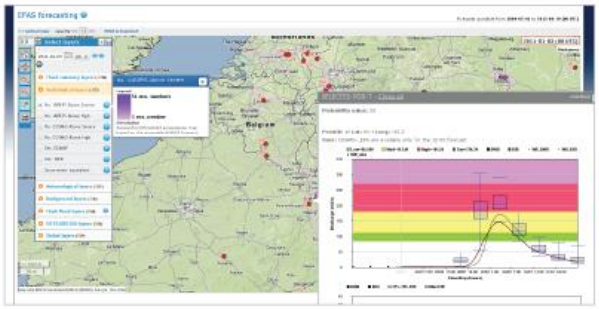
Pre-processing

Hydrological model



Post-processing

Warning



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European Commission

Copernicus

ECMWF

GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L10404, doi:10.1029/2008GL033837, 2008

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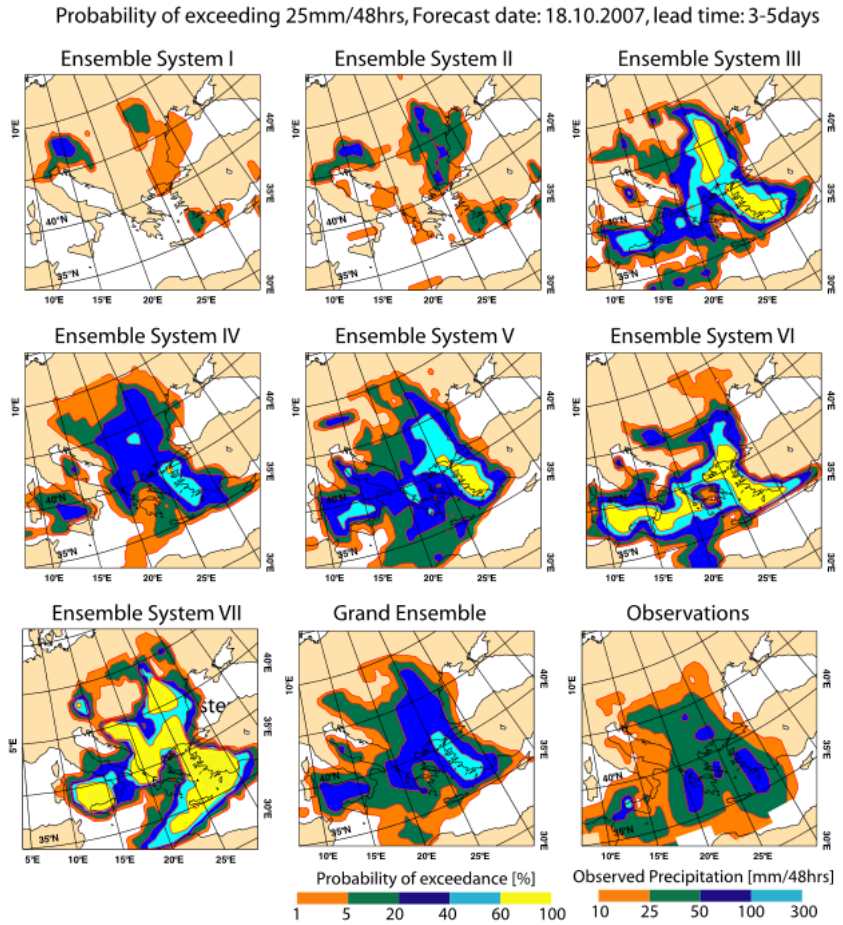
EFAS
European Flood Awareness System

New dimensions in early flood warning across the globe using grand-ensemble weather predictions

Florian Pappenberger,[1] Jens Bartholmes,[2] Jutta Thielen,[2] Hannah L. Cloke,[3] Roberto Buizza,[1] and Ad de Roo[2]

case study of a flood event in Romania in October 2007; TIGGE archive.



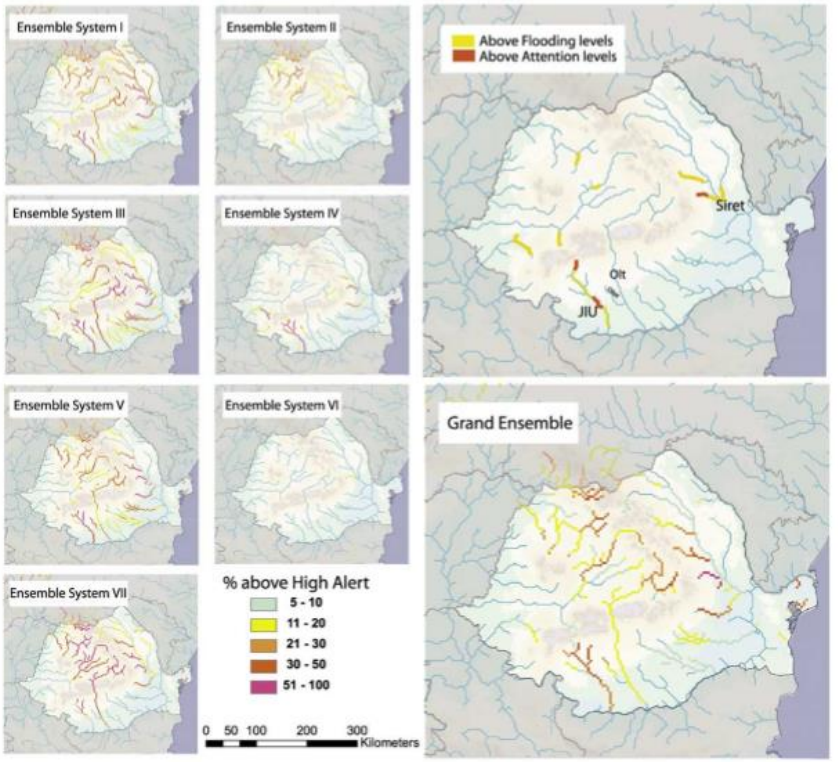


Figure 2. Probability of exceeding the high alert threshold of river discharge for TIGGE grand-ensemble and the single EPS forecasts issued at 12 UTC of 19 October 2007 valid for 24 of October. A map of observations is also shown.

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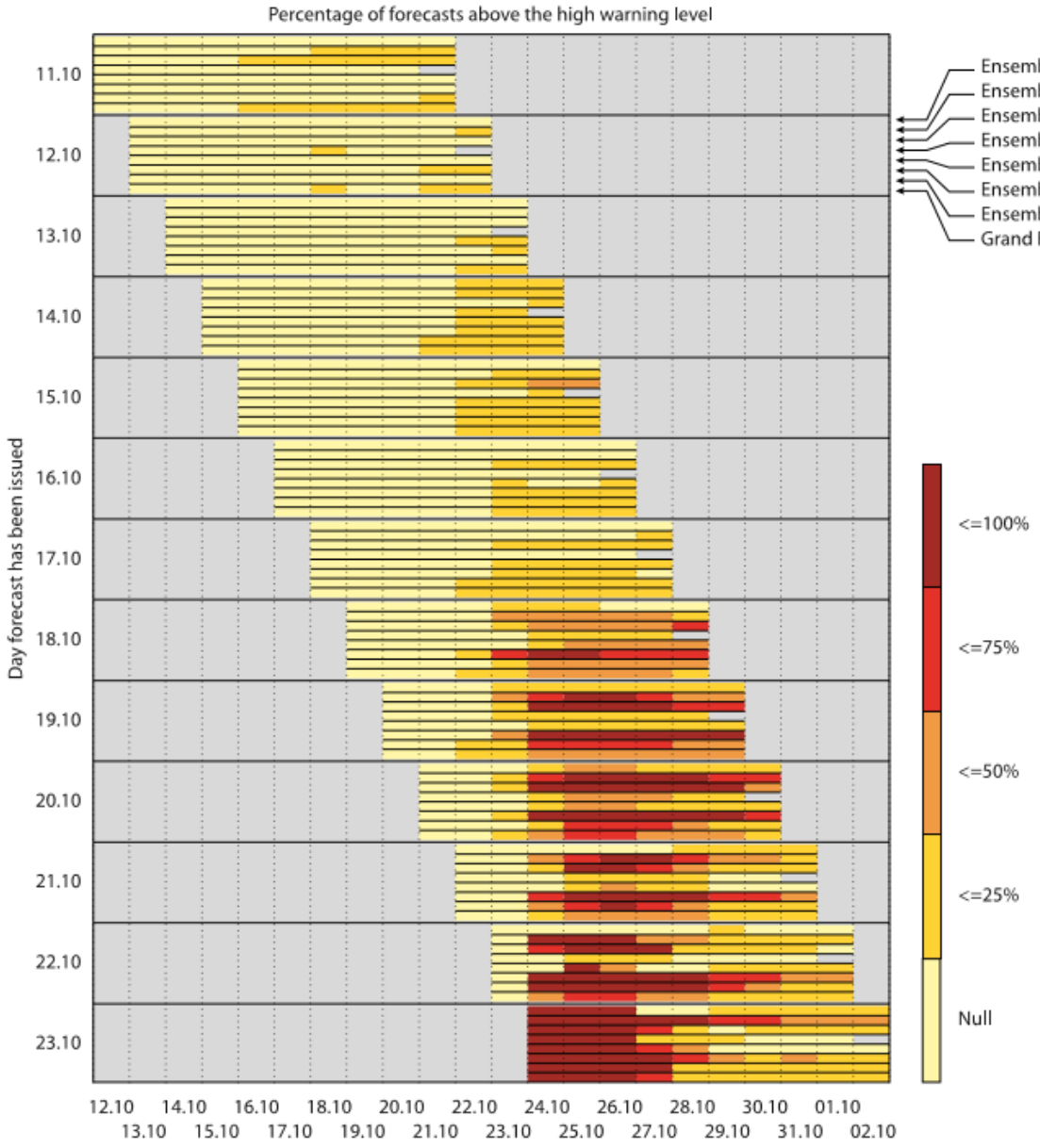

Pappenberger et al (2008), New dimensions in early flood warning across the globe using grand-ensemble weather predictions, Geophys. Res. Lett., 35, L10404, doi:10.1029/2008GL033837.

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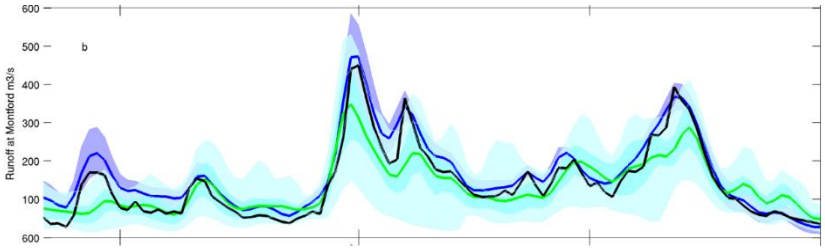
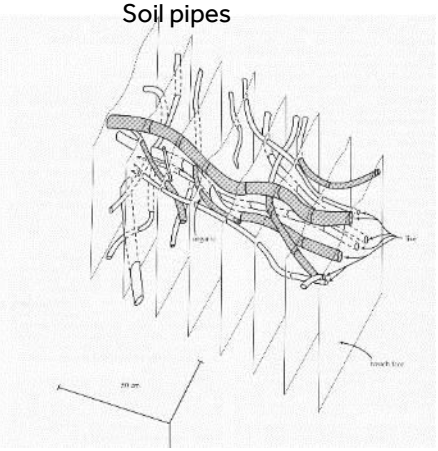
- awareness of flood up to 8 days before the event
- subsequent forecasts provide increasing insight into the range of possible flood conditions
- Flood alert issued in EFAS: when the forecast is persistent, meaning that 3 consecutive ECMWF ensemble forecasts exceed the EFAS 5 year return period threshold with a probability of greater than 30%

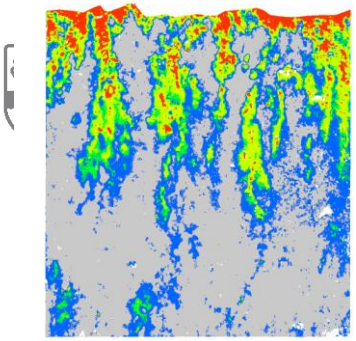
Perturbed parameter ensemble river flow forecast



Soil pipes



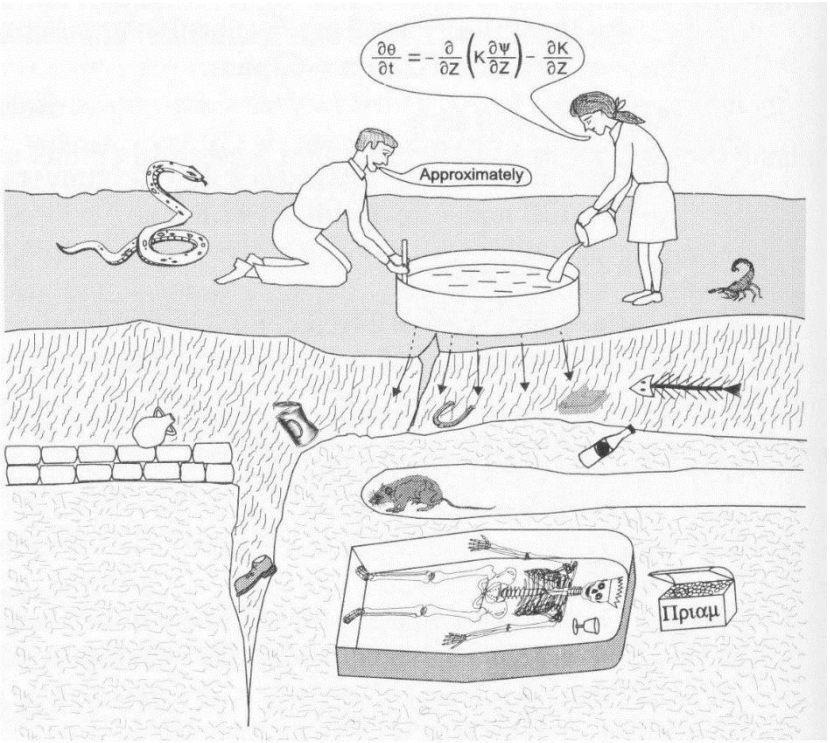
Infiltration dye experiment



Courtesy of M Weiler

REPRESENTING UNCERTAINTY

- Land surface is incredibly complex. Difficult to know what's under the ground & therefore parameterise
- lack of knowledge about the parameterisation of processes at the grid scale being used.
- Grids or hydrological response units?
- In catchment hydrology – modelling uncertainty represented by e.g. ensemble of perturbed parameter sets (10000 runs) – many realistic sets
- Aim – to combine these ideas in land surface hydrology/earth system experiments



Beven et al (2015) **Hyperresolution information and hyperresolution ignorance in modelling the hydrology of the land surface.** Science China: Earth Sciences

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LAND SURFACE UNCERTAINTY – LAND SURFACE – ATMOSPHERE FEEDBACKS

- (Challenging) experiments with parameter perturbation/stochastic techniques

- Potential for improving ensemble reliability by representing land surface uncertainty – parameter and initial conditions
- perturbed parameter approach improves the forecast of extreme air temperature for summer 2003, through better representation of negative soil moisture anomalies and upward sensible heat flux
- Perturbed parameter approach outperforms stochastic tendency experiment…

- Data assimilation and non-closure of water balance – problematic for hydrology (Kauffeldt et al, 2015, GRL)
- "**Stop hiding model error under the soil moisture carpet**" (Balsamo, 2017)
- Do we need a more holistic approach to earth system uncertainty?

Quarterly Journal of the Royal Meteorological Society Q. J. R. Meteorol. Soc. 142: 79–90, January 2016 A DOI:10.1002/qj.2631

RMetS Royal Meteorological Society

Improved seasonal prediction of the hot summer of 2003 over Europe through better representation of uncertainty in the land surface

David A. MacLeod,[a]* Hannah L. Cloke,[b,c] Florian Pappenberger[d] and Antje Weisheimer[d,e]
[a]Atmospheric, Oceanic and Planetary Physcis, Department of Physics, University of Oxford, UK
[b]Department of Geography and Environmental Science, University of Reading, UK
[c]Department of Meteorology, University of Reading, UK
[d]European Centre for Medium-Range Weather Forecasts, Reading, UK
[e]Department of Physics, National Centre for Atmospheric Science (NCAS), University of Oxford, UK
*Correspondence to: D. A. MacLeod, Department of Physics, Clarendon Lab, Parks Road, Oxford, OX1 3PU, UK. E-mail: macleod@atm.ox.ac.uk

Methods to represent uncertainties in weather and climate models explicitly have been developed and refined over the past decade and have reduced biases and improved forecast skill when implemented in the atmospheric component of models. These methods have not yet been applied to the land-surface component of models. Since the land surface is strongly coupled to the atmospheric state at certain times and in certain places (such as the European summer of 2003), improvements in the representation of land-surface uncertainty may potentially lead to improvements in atmospheric forecasts for such events.

Here we analyze seasonal retrospective forecasts for 1981–2012 performed with the European Centre for Medium-Range Weather Forecasts (ECMWF) coupled ensemble forecast model. We consider two methods of incorporating uncertainty into the land-surface model (H-TESSEL): stochastic perturbation of tendencies and static perturbation

Hydrol. Earth Syst. Sci., 20, 2737–2743, 2016
www.hydrol-earth-syst-sci.net/20/2737/2016/
doi:10.5194/hess-20-2737-2016

Hydrology and Earth System Sciences Open Access EGU

Evaluating uncertainty in estimates of soil moisture memory with a reverse ensemble approach

Dave MacLeod[1], Hannah Cloke[2,3], Florian Pappenberger[4,5], and Antje Weisheimer[4,6]
[1]Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford, Oxford, UK
[2]Department of Geography and Environmental Science, University of Reading, Reading, UK
[3]Department of Meteorology, University of Reading, Reading, UK
[4]European Centre for Medium-Range Weather Forecasts, Reading, UK
[5]School of Geographical Sciences, Bristol University, Bristol, UK
[6]Department of Physics, National Centre for Atmospheric Science (NCAS), University of Oxford, Oxford, UK
Correspondence to: Dave MacLeod (macleod@atm.ox.ac.uk)

Received: 18 January 2016 – Published in Hydrol. Earth Syst. Sci. Discuss.: 17 February 2016
Accepted: 6 June 2016 – Published: 12 July 2016

Abstract. Soil moisture memory is a key component of seasonal predictability. However, uncertainty in current memprediction. The soil moisture reservoir has a memory considerably longer than most atmospheric processes, and as a

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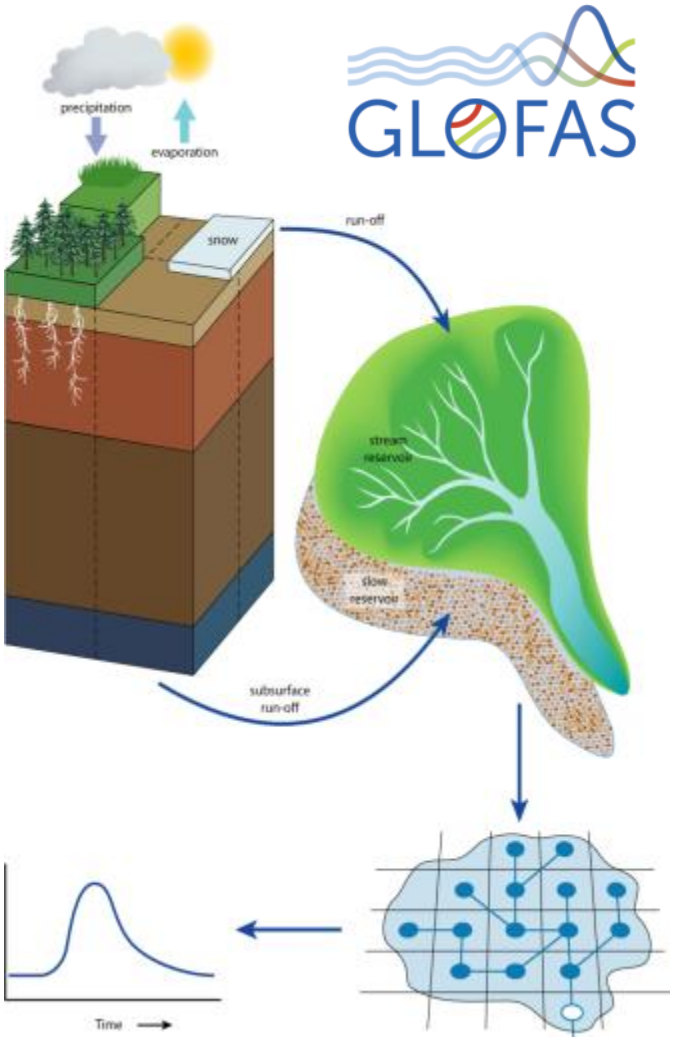
THE GLOBAL FLOOD AWARENESS SYSTEM



Output from global NWP land-surface scheme forecast: HTESSEL (ECMWF)

-Surface heat & evaporation
-Soil water budget
Output: surface flux & subsurface flux

Routing models
Simplified LISFLOOD (JRC) / CAMAFLOOD

Post-processing for end users

Made possible by the archiving of hydrological variables from forecasts and reanalysis at ECMWF

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TAKING DECISIONS FROM FLOOD FORECASTING: GLOFAS

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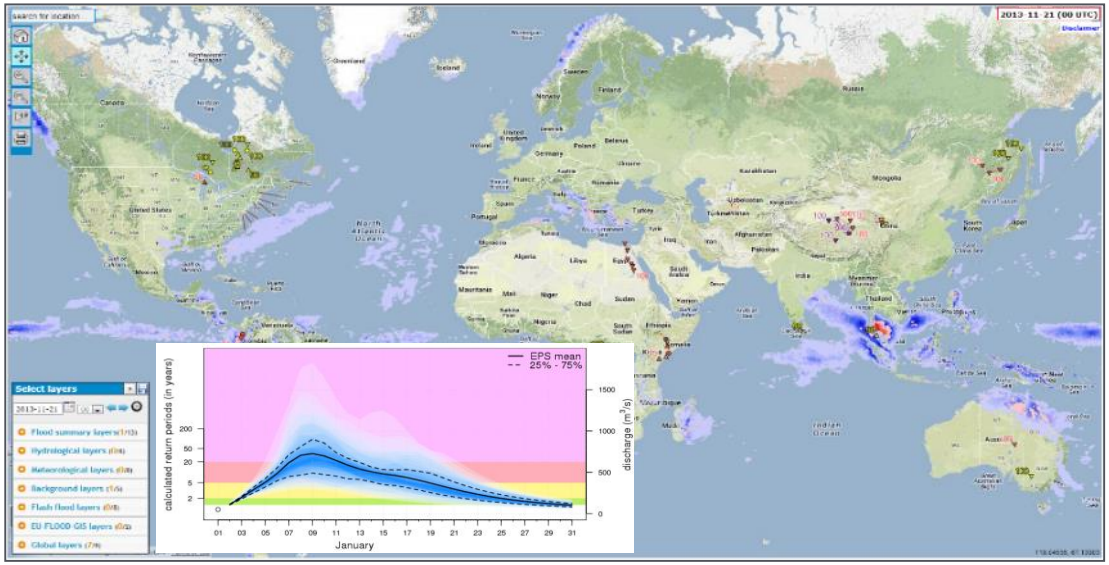
- Global scale probabilistic (ensemble) forecasts provide:
  - Global overviews of upcoming flood events in large river basins
  - Early warnings and info on upstream river conditions to downstream countries



Forecast frequency:
Updated daily

Forecast lead time:
Up to 30 days

Forecast variable:
River Flow

Forecast type:
Probabilistic

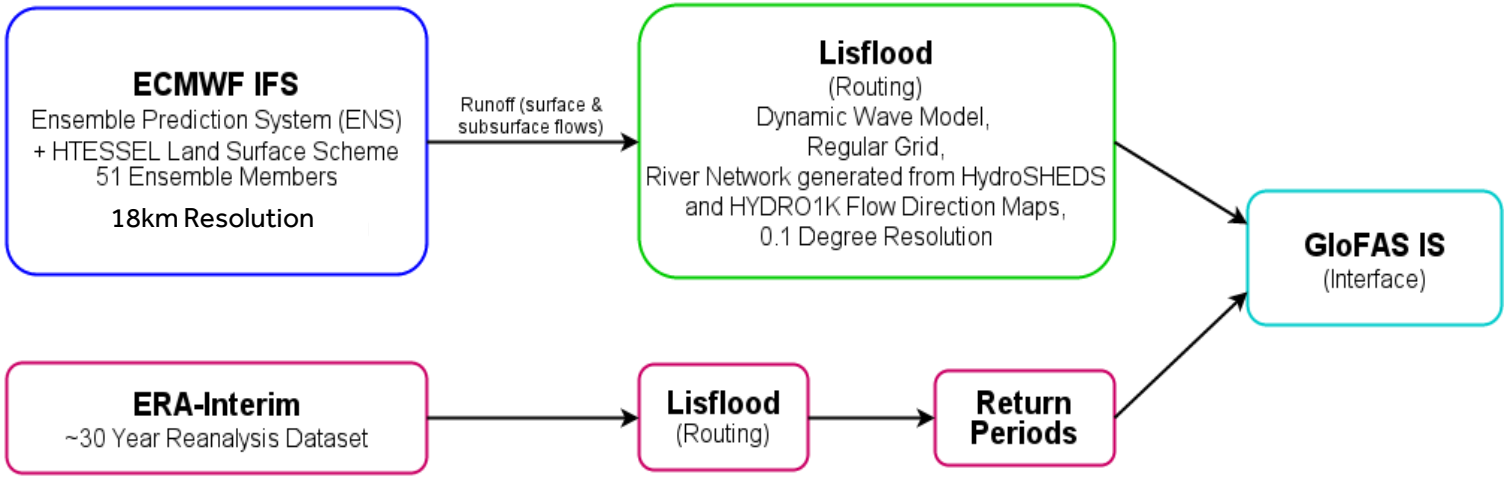
Forecast resolution:
0.1° (~11km at equator)

ECMWF

University of Reading

GLOFAS: MODEL SET-UP

- ECMWF ensemble forecasting system contains land surface scheme producing gridded runoff
- Lisflood hydrological model routes this runoff through the global river network
- Return period thresholds (flood severity classification) calculated using 30-year reanalysis

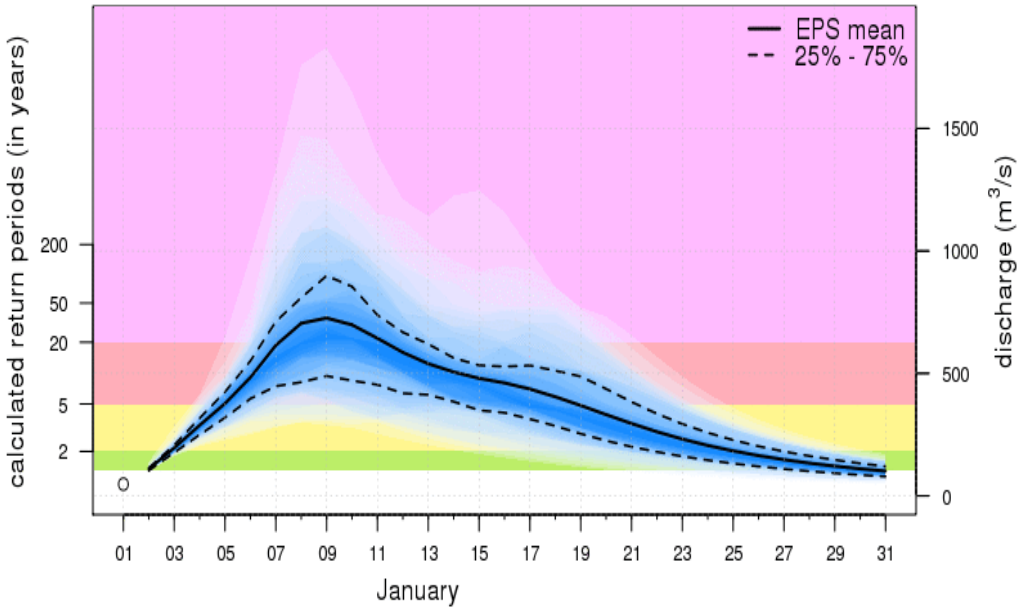


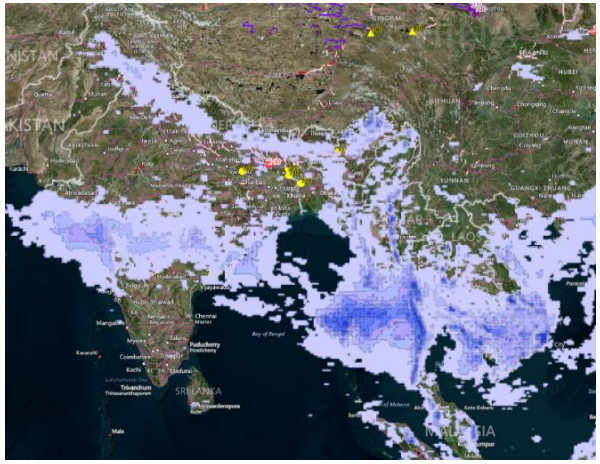
Emerton et al (2016) **Continental and global scale flood forecasting systems.** *Wiley Interdisciplinary Reviews: Water*, 3 (3). pp. 391-418. doi: 10.1002/wat2.1137

ECMWF

GLOFAS: FLOOD SEVERITY CLASSIFICATION

- Return period thresholds used to give severity of flood compared to past events
  - **Model reanalysis (climatology) used to derive return period statistics**
- This approach
  - Helps to deal with systematic biases
  - Simple to use
  - Can be linked more easily to national levels
  - Better link to potential flood impact
- Shading indicates return period exceeded:
  - < 2 year (green)
  - > 2 year (yellow)
  - > 5 year (red)
  - > 20 year (purple)





Clickable hotspot maps
Flood probability maps
Accumulated rainfall maps
Persistence plots

Forecast Day	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1
08/09/2016													2	6	10	14	16	18	16	12				
09/09/2016											2	10	22	27	35	47	51	59	63	59	47			
10/09/2016											2	2	10	18	27	29	41	47	59	65	61	41		
11/09/2016													6	12	16	20	20	25	31	37	43	35	25	
12/09/2016													4	14	24	37	47	59	65	73	75	84	76	57

Find out more at
WWW.GLOBALFLOODS.EU

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Ensemble forecasts and warnings can only reach their full potential if they are understood and acted upon by the person receiving

Communication of uncertainty

Coproduction of warning systems

Demeritt D, Nobert S, Cloke HL, Pappenberger F (2013) **The European Flood Alert System (EFAS) and the communication, perception and use of ensemble predictions for operational flood risk management.** Hydrological Processes, 27 (1). pp. 147-157.

Wetterhall F, Pappenberger F, Cloke HL et al + 30 authors (2013) **Forecasters priorities for improving probabilistic flood forecasts**, Hydrology and Earth System Sciences, 17, 4389-4399

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Learning Framework

With support from

With funding from

Two way knowledge transfer between GloFAS developers, forecasters and users

Fiorella Vega Jacome and Carlos Antonio Fernandez-Palomino
Hydroclimate scientists at SENAMHI (Peru)

The principal thing we have learnt is the way that GloFAS works, also how to use the GloFAS forecast and to evaluate the performance in different basins of Peru – this is very important to us.

We would like to learn more about the hydrological model used by GloFAS because currently, we only use aggregated models for our simulation and flow predictions. We would also like to be part of the GloFAS Community so we can give feedback to GloFAS for the improvement of the forecasting in our country's rivers.

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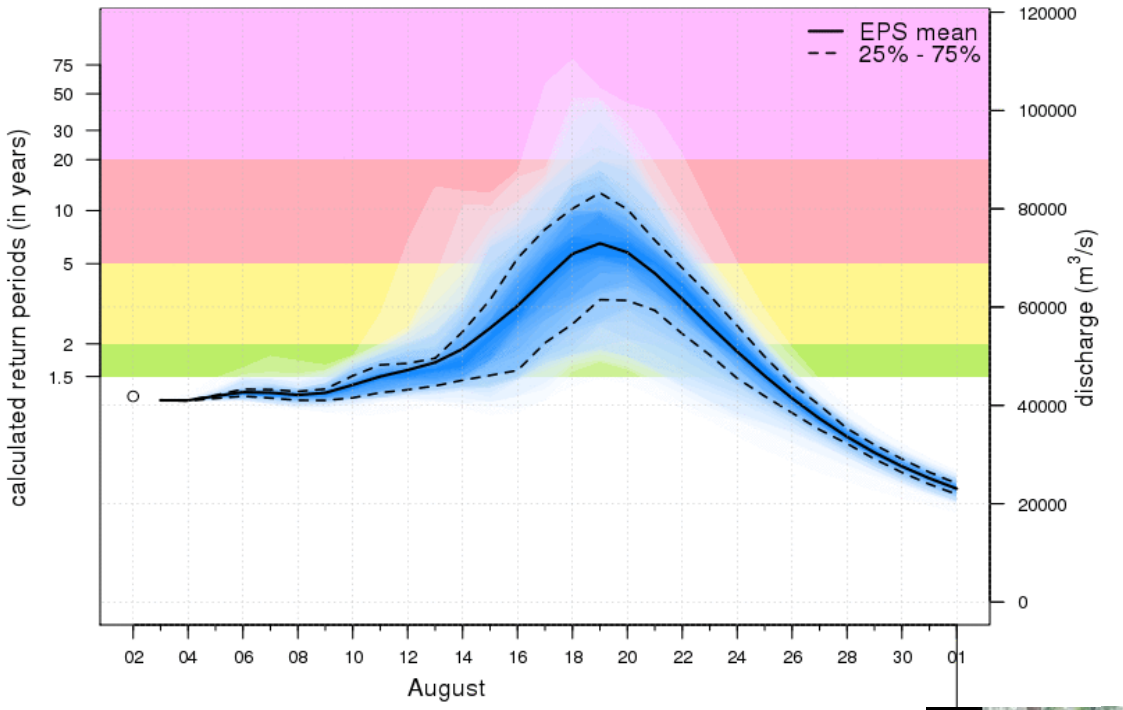
Floods in Bangladesh August 2017



Sazzad Hossain,
Flood Forecasting and Warning Center (FFWC)
Bangladesh Water Development Board
September 2017

"FFWC follows the GLOFAS forecast every day during the flood period. The potential flood event information was disseminated to BWDB's field level offices to take proper care of flood management infrastructure"

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GLOFAS AND EARLY HUMANITARIAN ACTION

Coughlan de Perez et al (2016) **Action-based flood forecasting for triggering humanitarian action**, Hydrol. Earth Syst. Sci., 20, 3549-3560, https://doi.org/10.5194/hess-20-3549-2016, 2016

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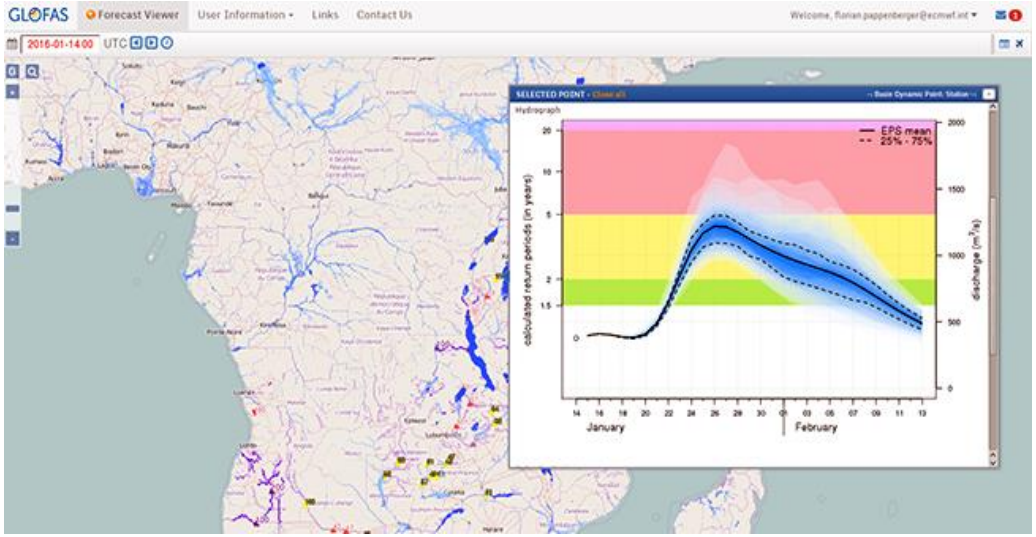
Photo credit: Peruvian Red Cross (top left, below right), Floodlist (centre), Juan Bazo (right)



European Commission | ECMWF | Copernicus Europe's eyes on Earth | Climate Centre

NERC SCIENCE OF THE ENVIRONMENT | UKaid

Project **FATHUM** Contact: Elisabeth.Stephens@reading.ac.uk

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UNDERSTANDING LARGE SCALE FLOODINESS

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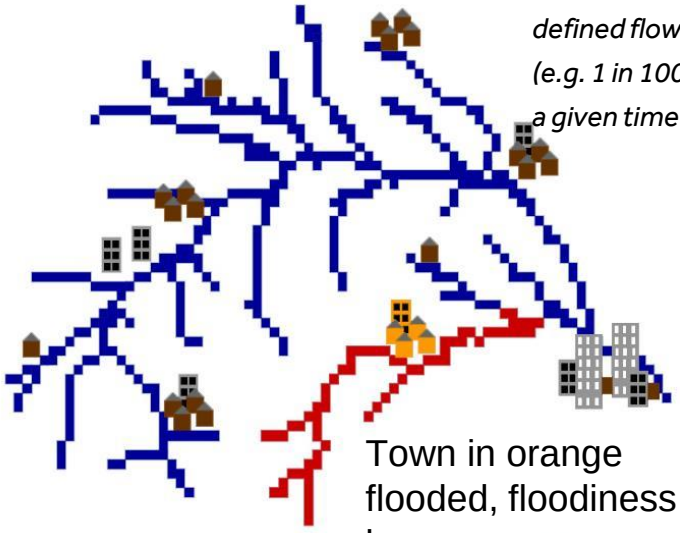
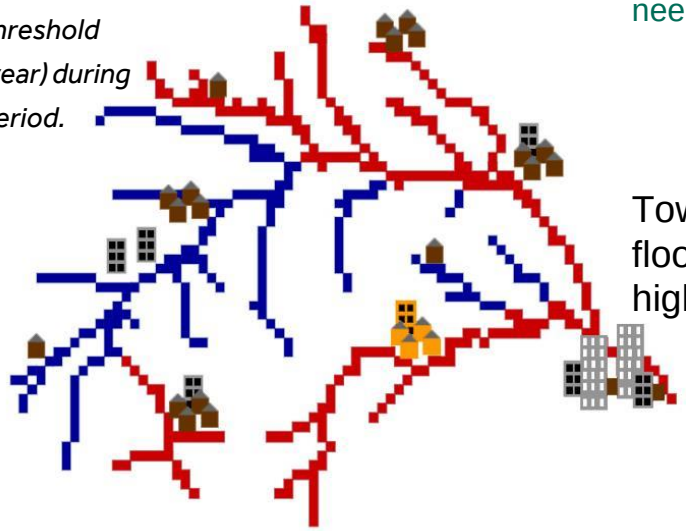
- Precipitation forecasts should not be used as a proxy for floodiness
- When floodiness during a rainy season is higher than normal, it can put pressure on humanitarian resources

***FLOODINESS**: the percentage of major river cells that exceed a defined flow threshold (e.g. 1 in 100 year) during a given time period.*

Variations in floodiness can put different pressures on humanitarian resources: We need to be able to forecast this



Town in orange flooded, floodiness low



Town in orange flooded, floodiness high

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AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL066779

Key Points:
- Indices of floodiness are introduced to assess large-scale flood hazard
- Precipitation anomalies do not correlate well with those for floodiness
- A skilful seasonal precipitation forecast may not reflect flood hazard

Precipitation and floodiness

E. Stephens[1], J. J. Day[2], F. Pappenberger[3], and H. Cloke[1,2]

[1]School of Archaeology, Geography and Environmental Sciences, University of Reading, Reading, Berkshire, UK, [2]School of Mathematics and Physical Sciences, University of Reading, Reading, UK, [3]European Centre for Medium-Range Weather Forecasts, Reading, UK

Abstract There are a number of factors that lead to nonlinearity between precipitation anomalies and

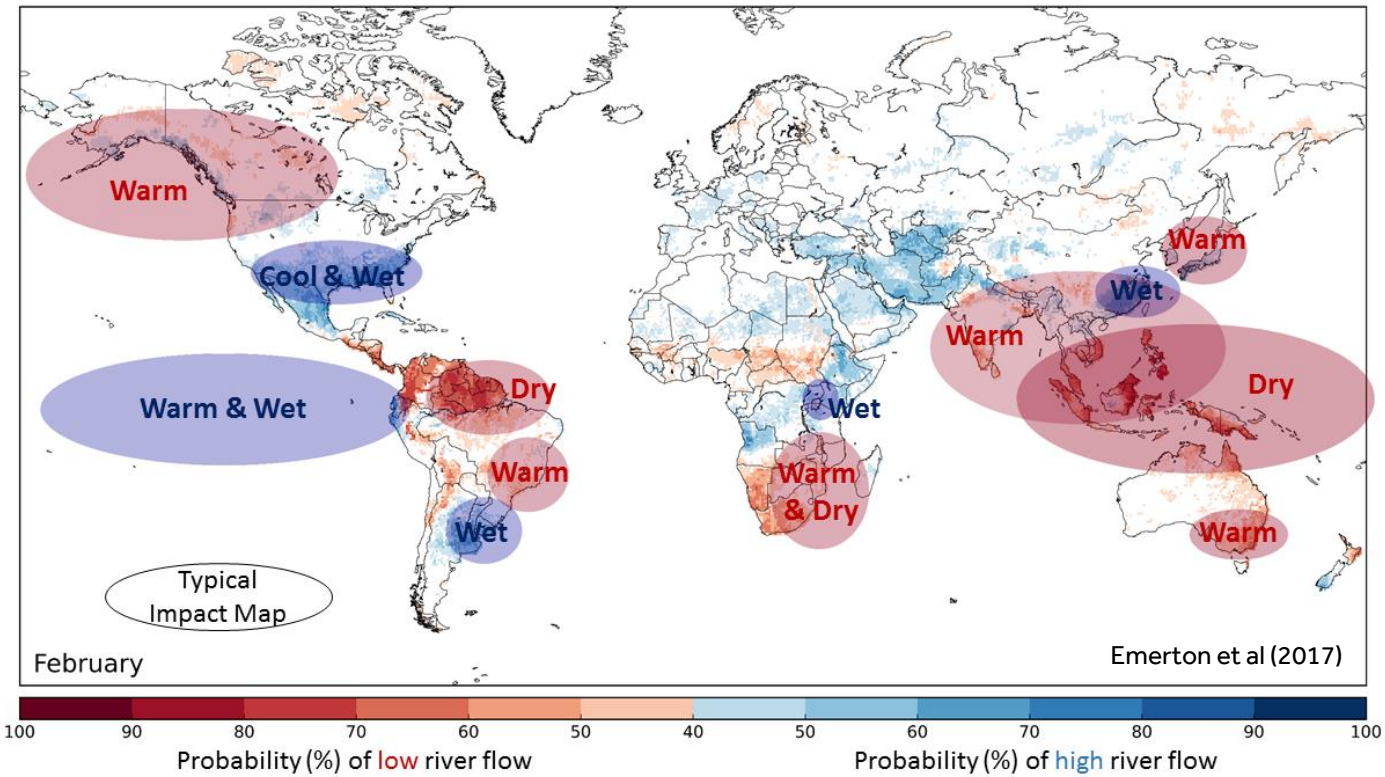
Photo credit: Peruvian Red Cross (left)

USING TELECONNECTIONS FOR FLOOD EARLY WARNING

- Global links between El Nino and flooding widely discussed but not well understood.
- Blobs of impact used for decision making
- Emerton et al - Detailed analysis of link for humanitarian decision making from ERA20CM-R reanalysis river flow

What is the probability that a region will experience abnormally high or low river flow during an El Niño, in any given month?

(February following an El Niño)



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nature COMMUNICATIONS

ARTICLE

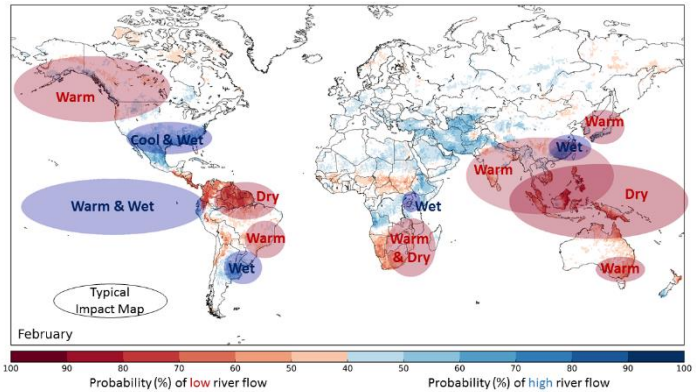
Received 9 Nov 2016 | Accepted 31 Jan 2017 | Published 15 Mar 2017

DOI: 10.1038/ncomms14796 OPEN

Complex picture for likelihood of ENSO-driven flood hazard

R. Emerton[1,2,3], H.L. Cloke[1,2], E.M. Stephens[1], E. Zsoter[1,3], S.J. Woolnough[4] & F. Pappenberger[3]

El Niño and La Niña events, the extremes of ENSO climate variability, influence river flow and flooding at the global scale. Estimates of the historical probability of extreme (high or low) precipitation are used to provide vital information on the likelihood of adverse impacts during extreme ENSO events. However, the nonlinearity between precipitation and flood magnitude motivates the need for estimation of historical probabilities using analysis of hydrological data sets. Here, this analysis is undertaken using the ERA-20CM-R river flow reconstruction for the twentieth century. Our results show that the likelihood of increased or decreased flood hazard during ENSO events is much more complex than is often perceived and reported; probabilities vary greatly across the globe, with large uncertainties inherent in the data and clear differences when comparing the hydrological analysis to precipitation.



"We conclude that **while it may seem possible** to use historical probabilities to evaluate regions across the globe that are more likely to be at risk of flooding during an El Niño/La Niña, and indeed circle large areas of the globe under one banner of wetter or drier, **the reality is much more complex**."

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Learn from today to anticipate tomorrow

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Pathways to running a flood forecasting centre: an adventure game!

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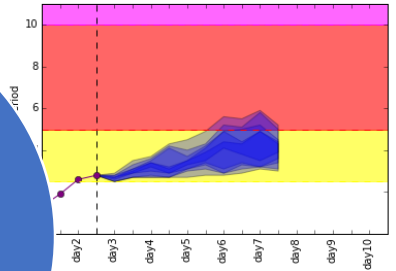
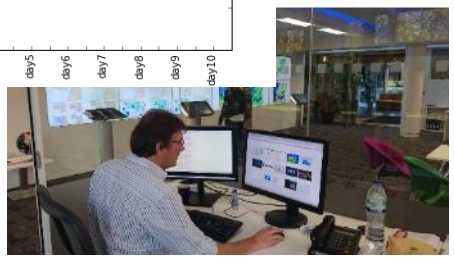
@ArnalLouise

Aim of the game

To **understand** this process through **real life decisions** & in a **fun** environment





Information

e.g. forecast, expert advice

Decision

e.g. flood defences

Consequences

positive vs. negative

Game setup

- You are hired as head of a flood forecasting centre & your task is to protect a city from floods
- You have to manage 2 teams:

the forecasters can

- show you the latest forecast
- improve the forecast

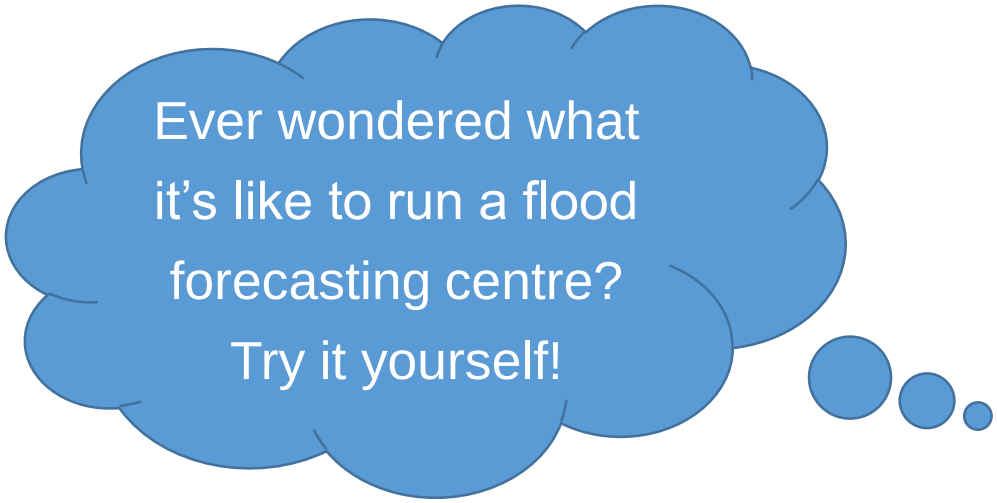
the flood response team can

- tell you what the situation on the ground is
- install temporary flood defences
- evacuate the population

- You have an initial budget & popularity level and are responsible for all actions taken

Game results & where to play it!

- Players' decisions based on forecast rather than expert advice
- Players used forecast with intuition (rather than looking at statistics of the forecast)



At: https://goo.gl/bfZISB

*doesn't work on phones

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HYDROLOGICAL ENSEMBLES AND ECONOMIC VALUE - FLOOD FORECASTING

University of Reading

- potential monetary benefits of early flood warnings estimated based EFAS reforecasts, warnings & damage datasets
- The benefits are **of the order of 400 EUR for every 1 EUR** invested (with uncertainties)
- forecast **skill is not correlated with the value of warnings** & need to evaluate using both forecast skill and warning value
- full **multi-forcing ensemble** is recommended for operational forecasting, but, there are spatial variations in the optimal forecast combination
- **model diversity and ensemble size** are both important in achieving best overall performance.

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The monetary benefit of early flood warnings in Europe

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ABSTRACT

Effective disaster risk management relies on science-based solutions to close the gap between prevention and preparedness measures. The consultation on the United Nations post-2015 framework for disaster risk reduction highlights the need for cross-border early warning systems to strengthen the preparedness phases of disaster risk management, in order to save lives and property and reduce the overall impact of severe events. Continental

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Environmental Research Letters

LETTER

How do I know if I've improved my continental scale flood early warning system?

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Keywords: flood early warning systems, forecast skill, monetary value, european flood awareness system, copernicus, multi-forcing ensemble, flood resilience

Supplementary material for this article is available online

Abstract

Flood early warning systems mitigate damages and loss of life and are an economically efficient

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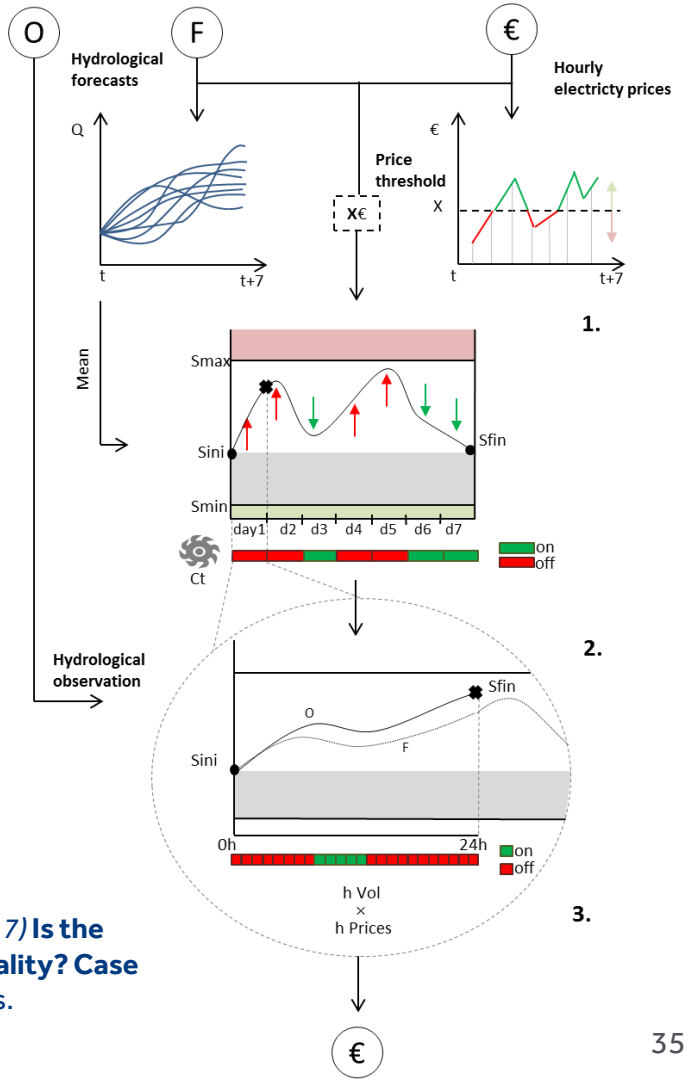
HYDROLOGICAL ENSEMBLES & ECONOMIC VALUE - HYDROPOWER

University of Reading

- Need to better understand the links between forecast quality and forecast value
- To evaluate the impact of ensemble inflows of different quality on a water reservoir management model built to optimize revenues from hydropower production

- Ensemble forecasts of lower quality result in lower economic gains in hydropower production
- Losses in forecast value are more important when streamflows are overestimated: up to 3% of economic loss



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irstea EDF

Cassagnole M, Ramos M-H, Thirel G, Gailhard J, Garçon R (2017) **Is the economic value of hydrological forecasts related to their quality? Case study of the hydropower sector.** EGU GA Abstracts.
Contact: **maria-helena.ramos@irstea.fr**

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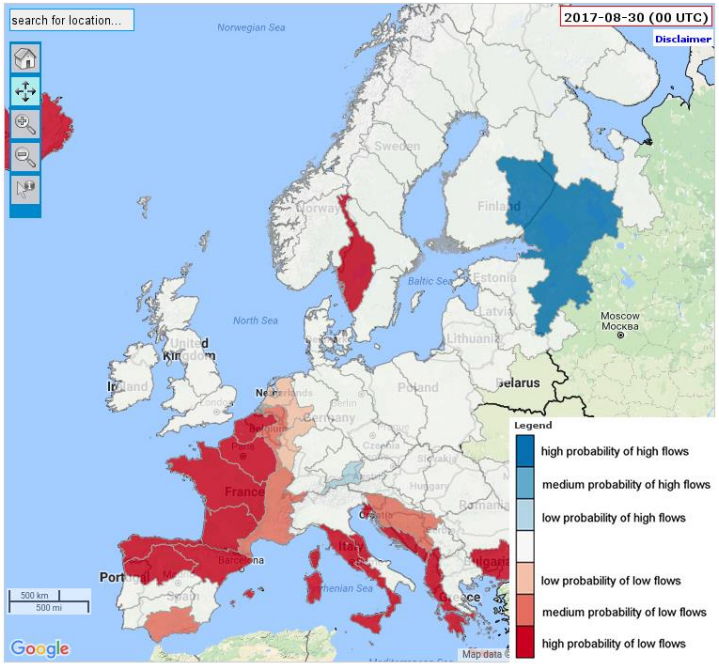
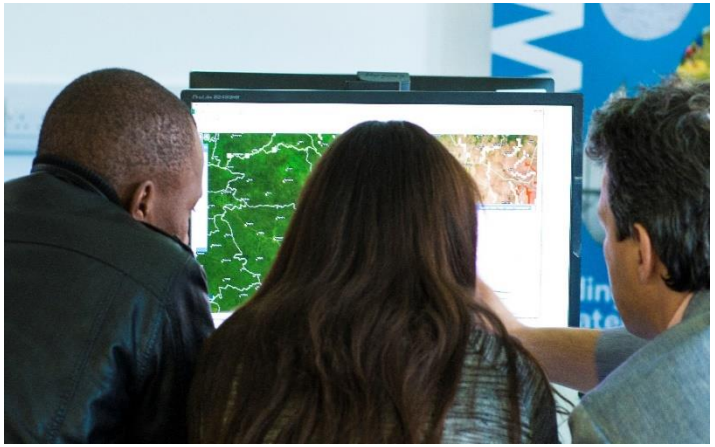
OUTLOOK

- Melbourne!
- Ever wider application of ensembles
- Seasonal systems for EFAS and GloFAS in development
- Improving skill, warnings
- Communication and decision making under uncertainties
- Improving land surface hydrology & uncertainty as a holistic part of Earth System
- Look for proxy variables (atmospheric rivers, teleconnections)



Arnal et al (in prep) EFAS seasonal outlook



Coproduction of ensemble forecasting systems

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HYDROLOGICAL ENSEMBLE PREDICTION

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& a BIG THANKYOU to the **HEPEX community**

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