Department of Geography and Environmental Science
Department of Meteorology

University of Reading

FLY ME TO THE MOON:
A REVIEW OF ENSEMBLE FLOOD FORECASTING 10 YEARS ON

Prof Hannah Cloke
Co-Director of Water@Reading
Guest Professor Uppsala University
h.l.cloke@reading.ac.uk
@hancloke

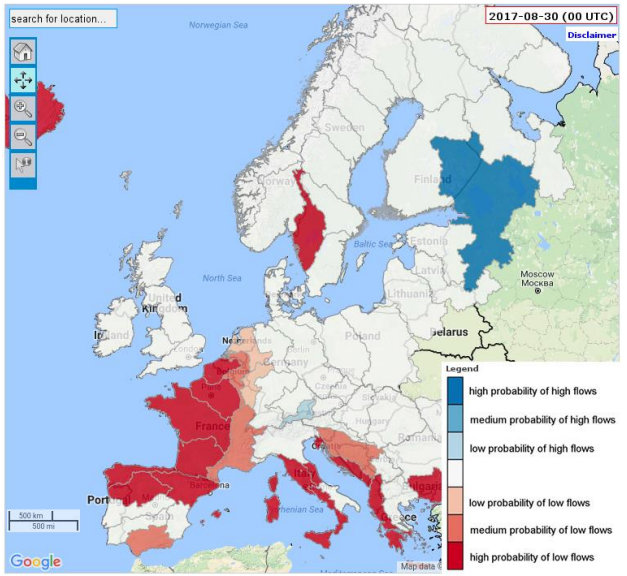
& a BIG THANKYOU to
Water@Reading,
ECMWF,
HEPEX community

HERE AT HEPEX!!

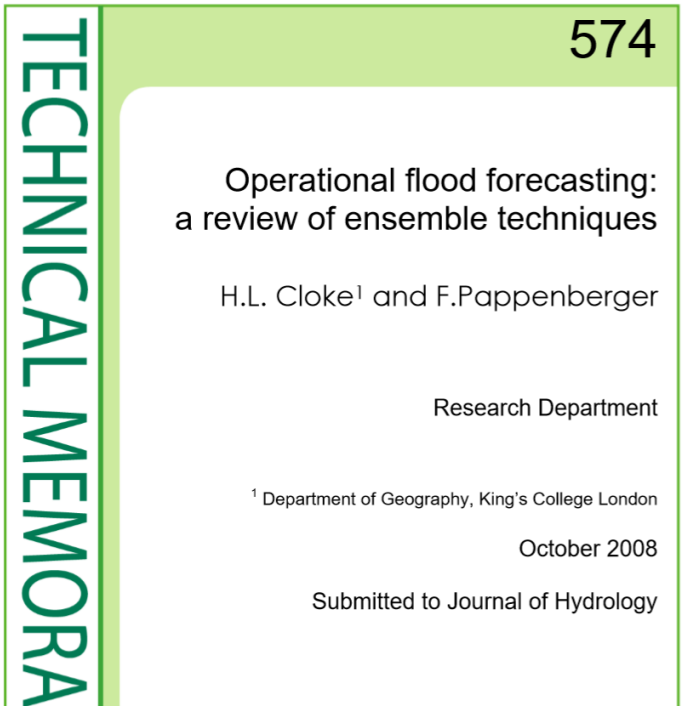
OUTLINE

- Ensemble Flood Forecasting 10 years on
- Earlier warnings & better decision making
- Going Global
- Ensembles & humanitarian decision making
- How can we fly to the moon?

Photo credit: Peruvian Red Cross



h.l.cloke@reading.ac.uk



10 YEARS AGO

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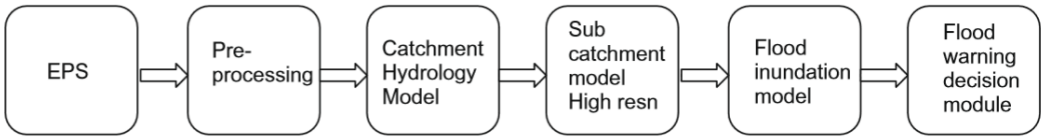
The Drivers



1. Availability of weather ensembles
2. Availability of large spatial data sets
3. Improved computing & having enough computer power
4. Political shift towards improved flood preparedness

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Review

Ensemble flood forecasting: A review

H.L. Cloke [a,*], F. Pappenberger [b]

[a] Department of Geography, King's College London, Strand, London WC2R 2LS, UK
[b] European Centre for Medium Range Weather Forecasts, Shinfield Park, Reading RG2 9AX, UK

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This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Kieran M. O'Connor, Associate Editor

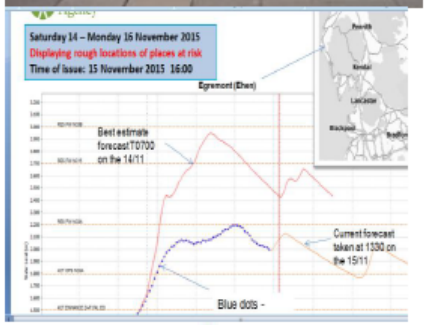
Keywords:
Flood prediction
Uncertainty
Ensemble prediction system
Streamflow

SUMMARY

Operational medium range flood forecasting systems are increasingly moving towards the adoption of ensembles of numerical weather predictions (NWP), known as ensemble prediction systems (EPS), to drive their predictions. We review the scientific drivers of this shift towards such 'ensemble flood forecasting' and discuss several of the questions surrounding best practice in using EPS in flood forecasting systems. We also review the literature evidence of the 'added value' of flood forecasts based on EPS and point to remaining key challenges in using EPS successfully.

POLITICAL SHIFT TOWARDS IMPROVED FLOOD PREPAREDNESS

- Effective decisions as early as possible to save lives and livelihoods
- Reduces exposure of extreme hazard
- Operation of assets and flood barriers
- Mobilisation of military, pumps and temporary defences
- Warning and informing communities
- £££ millions per annum damages avoided and lower risk to life through flood warning

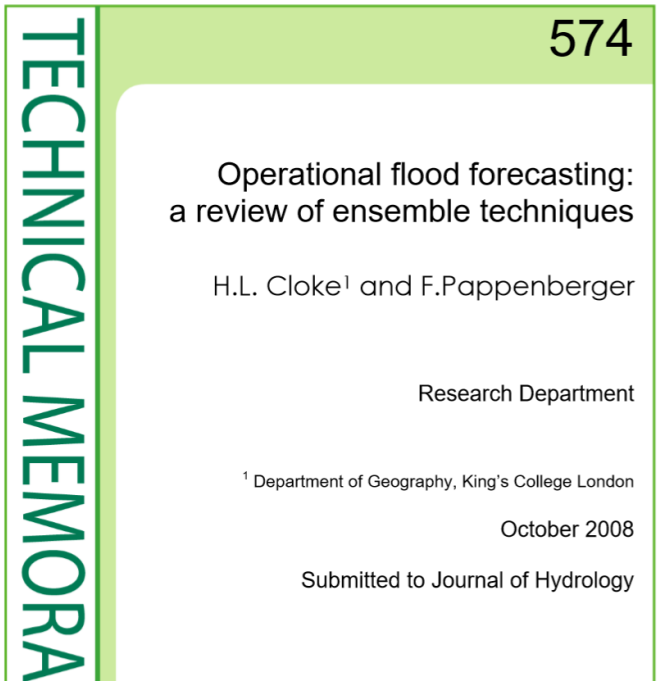


FLOOD WARNING

FLOODING IS EXPECTED. IMMEDIATE ACTION REQUIRED

Environment Agency

h.l.cloke@reading.ac.uk


TECHNICAL MEMORANDUM

574

Operational flood forecasting: a review of ensemble techniques

H.L. Cloke[1] and F.Pappenberger

Research Department

[1] Department of Geography, King's College London

October 2008

Submitted to Journal of Hydrology

10 YEARS AGO

University of Reading

The Challenges

1. Improving NWPs
2. Understanding the total uncertainty in the system
3. Data Assimilation
4. Having enough case studies (which report quantitative results)
5. Having enough computer power
6. How to use EPS in an operational setting
7. Communicating uncertainty and probabilistic forecasts


ELSEVIER

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Review

Ensemble flood forecasting: A review

H.L. Cloke [a,*], F. Pappenberger [b]

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EARLIER WARNINGS & BETTER DECISIONS

Understanding the possibilities……

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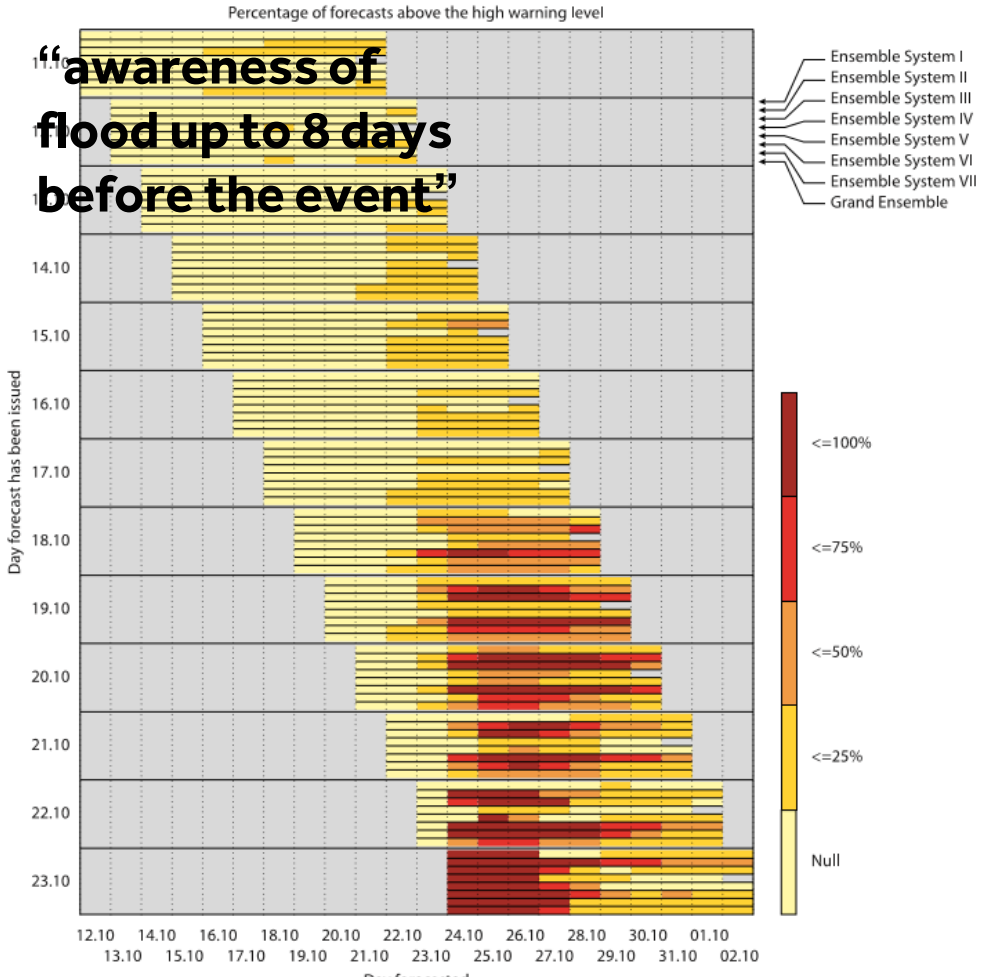
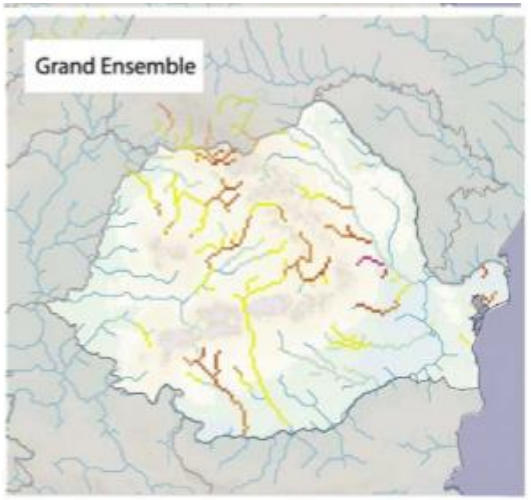


"awareness of flood up to 8 days before the event"

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.*



"better understanding of the range of flood possibilities"

h.l.cloke@reading.ac.uk

EFAS European Flood Awareness System

ENSEMBLE FLOOD FORECASTS BETTER DECISION MAKING

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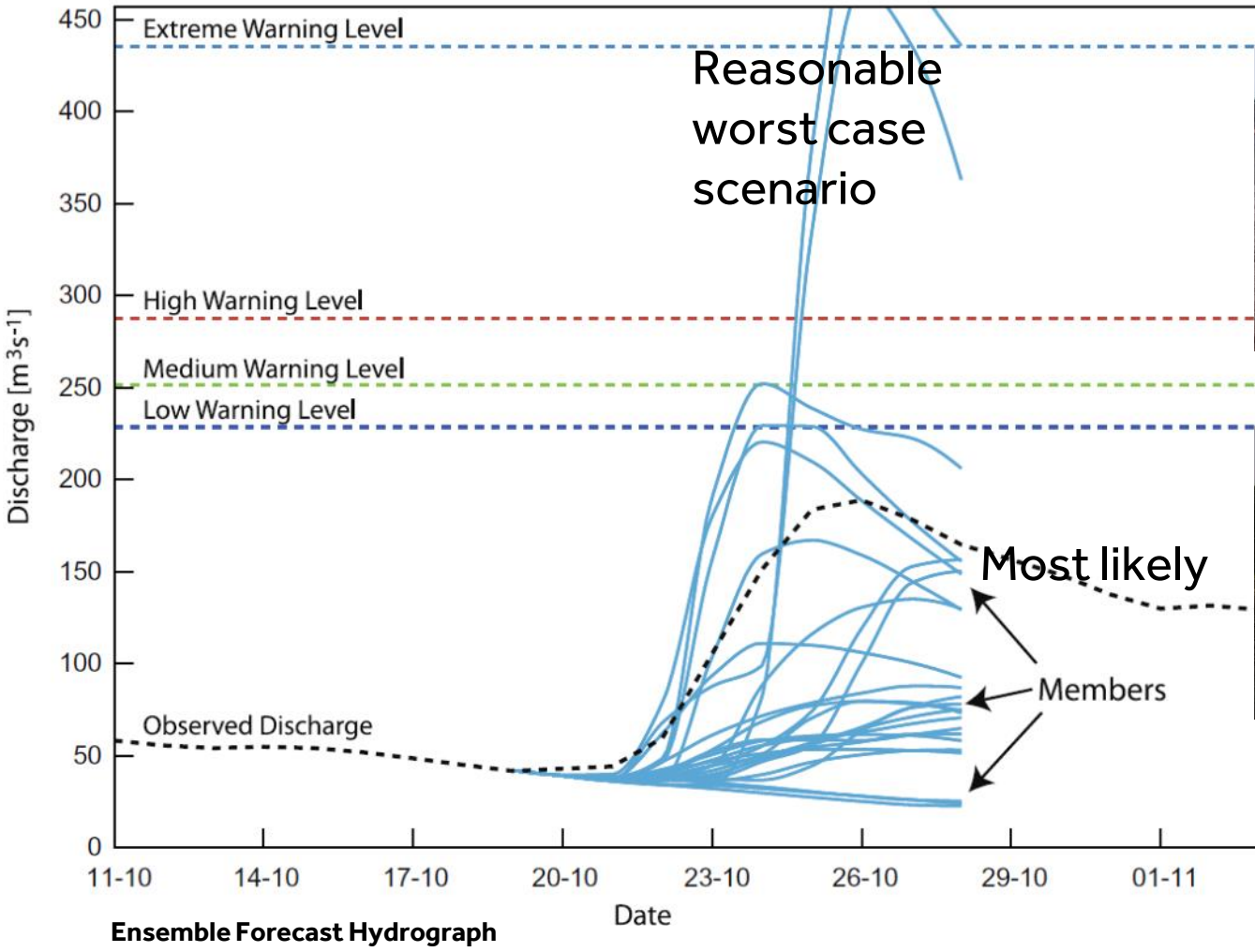

Ensemble Forecast Hydrograph

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

h.l.cloke@reading.ac.uk

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

- EFAS: pioneer of operational 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

Somerset Levels, February 2014

Winter 2013/2014 Storm Factory: 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.

FLOODFORECASTINGCENTRE

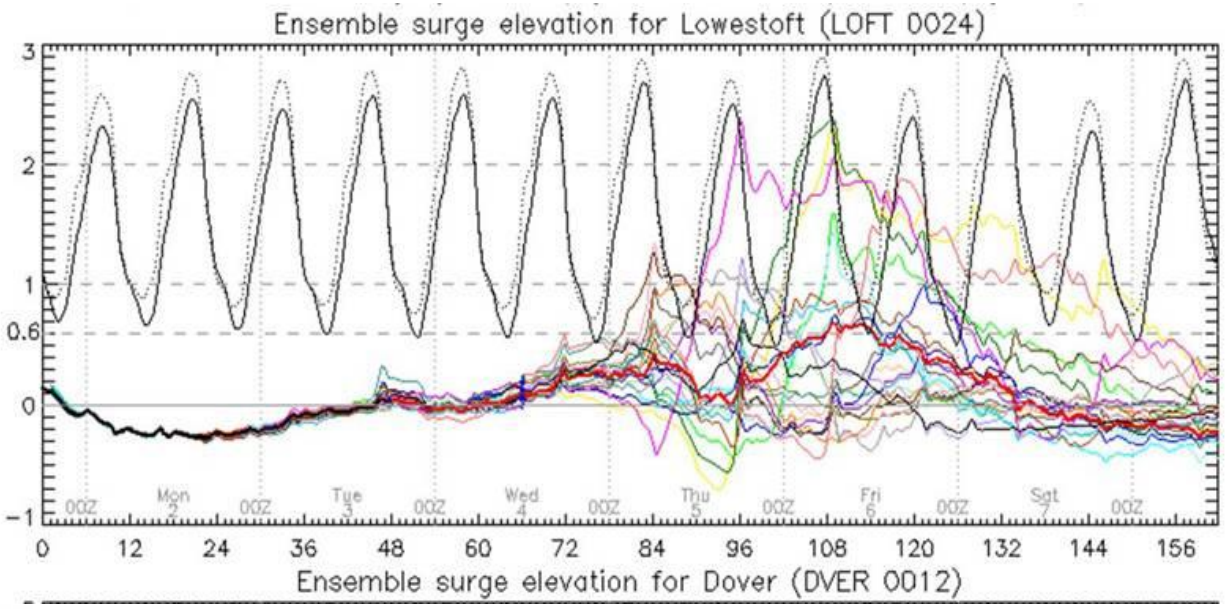
a working partnership between Environment Agency | Met Office

Somerset Levels
February 2014


Prince William and Harry sandbagging – Thames Floods, Feb 2014

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



Ensemble forecasts: 5-6 Dec surge

Increased preparedness & reduction in risk to population through:

- use of ensemble probabilistic forecasting,
- ability of the FFC and local forecasters to discuss and interpret what this complex probabilistic information actually meant in terms of impact
- 8 day lead time – indication of extreme surge
- Reasonable worst case scenario

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. ISSN 1475-4959 doi: 10.1111/geoj.12103

‘**We were organised and prepared.** From the earliest signs of a possible surge threat, Government Departments and agencies, local resilience fora and local authorities were making preparations’ (House of Commons debate, 10 December 2013, Vol. 572, Col. WS25).

Homes ruined, streets flooded, but ‘it could have been worse’

‘Without these technical advances and the ability for the surge ensembles to **capture the relative uncertainty**, we would not have had early sight of this event when we did.’ (Natural Resources Wales, NRW2014, 40);

‘Development in **improved lead time and a greater ability to understand risk** at set locations enabled us to communicate to partners general locations of concern several days ahead’ (Natural Resources Wales 2014, 47).

ENSEMBLE FLOOD FORECASTS BETTER DECISION MAKING

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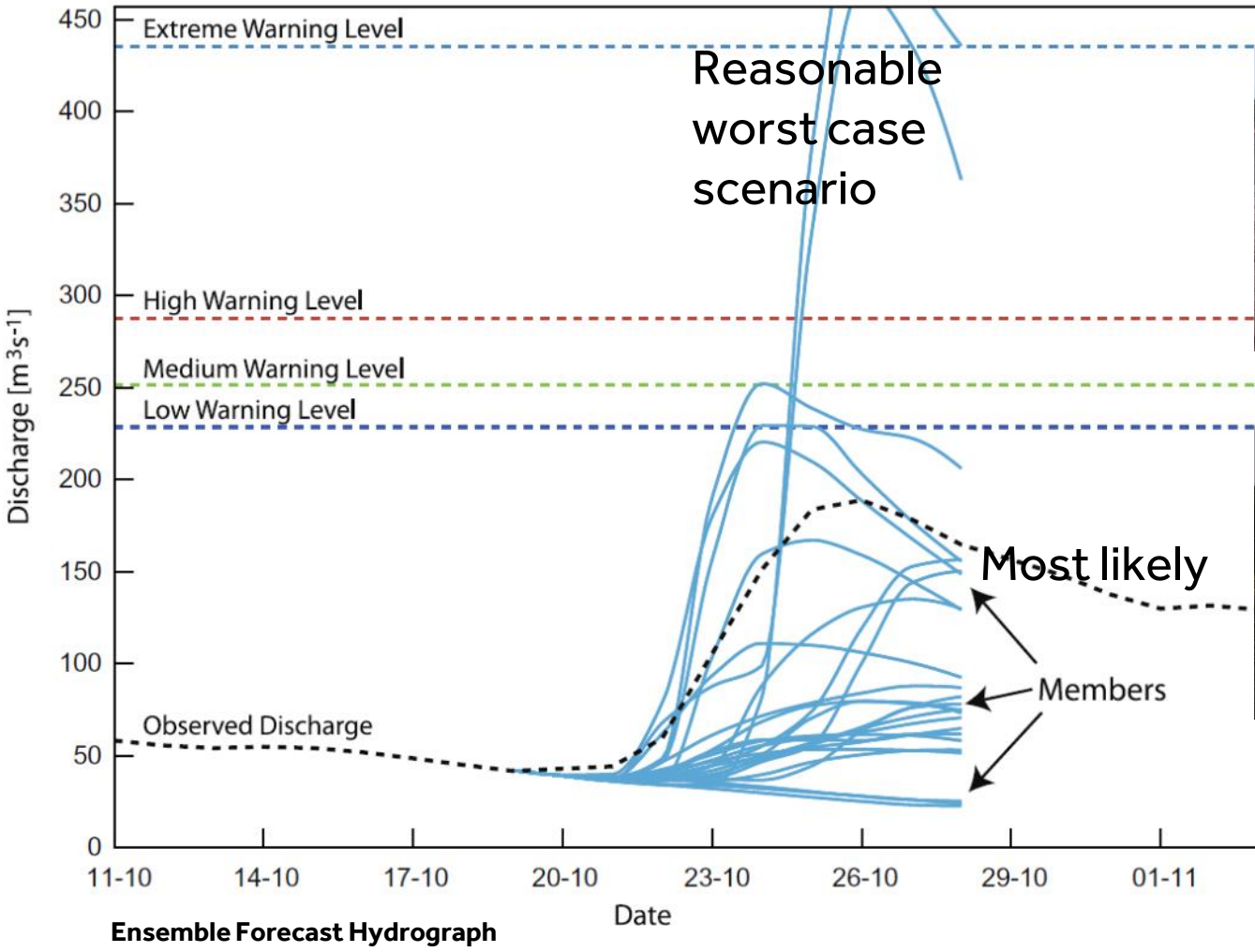


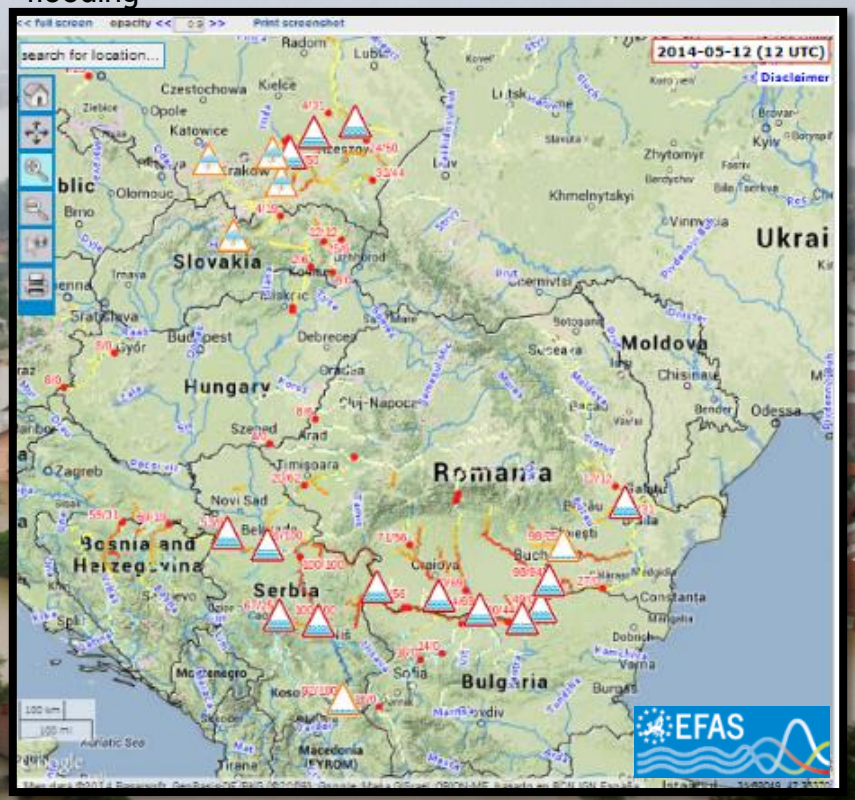
Ensemble Forecast Hydrograph

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

h.l.cloke@reading.ac.uk

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

opernicus

EFAS

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.

ENVIRONMENTAL SCIENCE & POLICY 51 (2015) 278–291

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/envsci

The monetary benefit of early flood warnings in Europe

Florian Pappenberger [a,f,], Hannah L. Cloke [b,c], Dennis J. Parker [d], Fredrik Wetterhall [a], David S. Richardson [a], Jutta Thielen [e]*

[a] European Centre for Medium-Range Weather Forecasts (ECMWF), Shinfield Park, Reading, United Kingdom
[b] Department of Geography and Environmental Science, University of Reading, Reading, United Kingdom
[c] Department of Meteorology, University of Reading, Reading, United Kingdom
[d] Flood Hazard Research Centre, Middlesex University, United Kingdom
[e] European Commission, Joint Research Centre (JRC), Institute for Environment and Sustainability (IES), Climate Risk Management Unit, Ispra, Italy
[f] School of Geographical Sciences, University of Bristol, Bristol, United Kingdom

ARTICLE INFO

Keywords:
Probabilistic flood forecasting
Europe
Monetary benefit
Hydrological Ensemble Prediction

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

IOP Publishing Environ. Res. Lett. 12 (2017) 044006 https://doi.org/10.1088/1748-9326/aa625a

Environmental Research Letters

LETTER

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

Hannah L Cloke[1,4], Florian Pappenberger[2,3], Paul J Smith[2] and Fredrik Wetterhall[2]

[1] University of Reading, Reading, Berkshire, United Kingdom
[2] European Centre for Medium Range Weather Forecasts, Reading, Berkshire, United Kingdom
[3] School of Geographical Sciences, University of Bristol, Bristol, United Kingdom
[4] Author to whom any correspondence should be addressed.

E-mail: h.l.cloke@reading.ac.uk

OPEN ACCESS

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PUBLISHED 28 March 2017

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

h.l.cloke@reading.ac.uk

HYDROLOGICAL ENSEMBLES & ECONOMIC VALUE - HYDROPOWER

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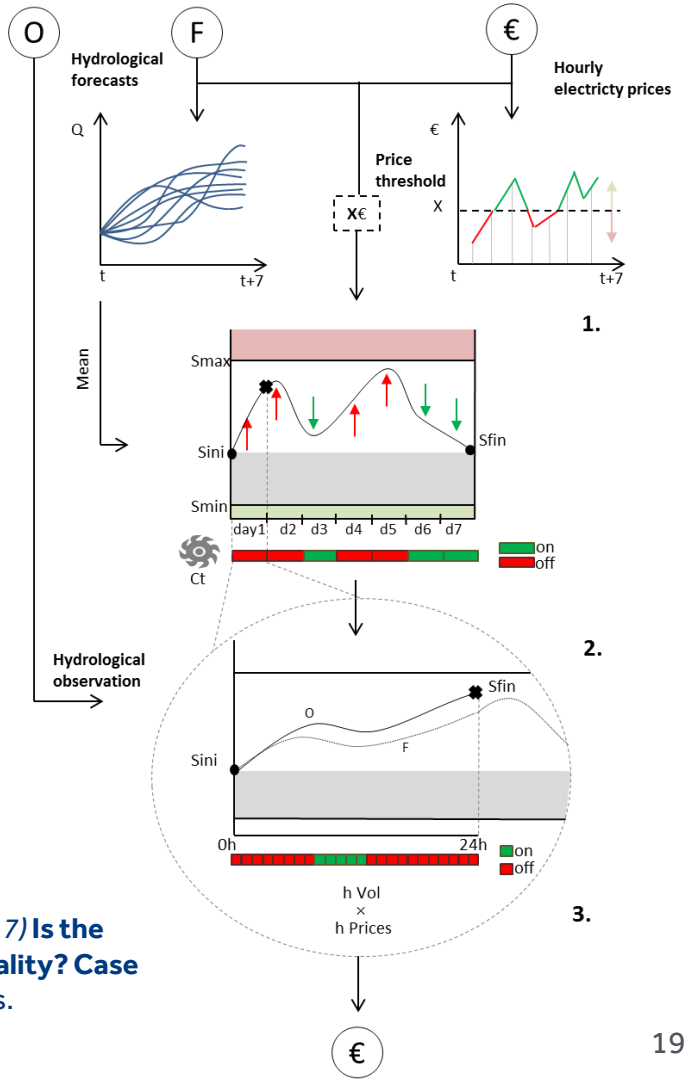
- Need to better understand the links between forecast quality and forecast value
- To evaluate the impact of ensemble inflows of different quality on a water reservoir management model built to optimize revenues from hydropower production

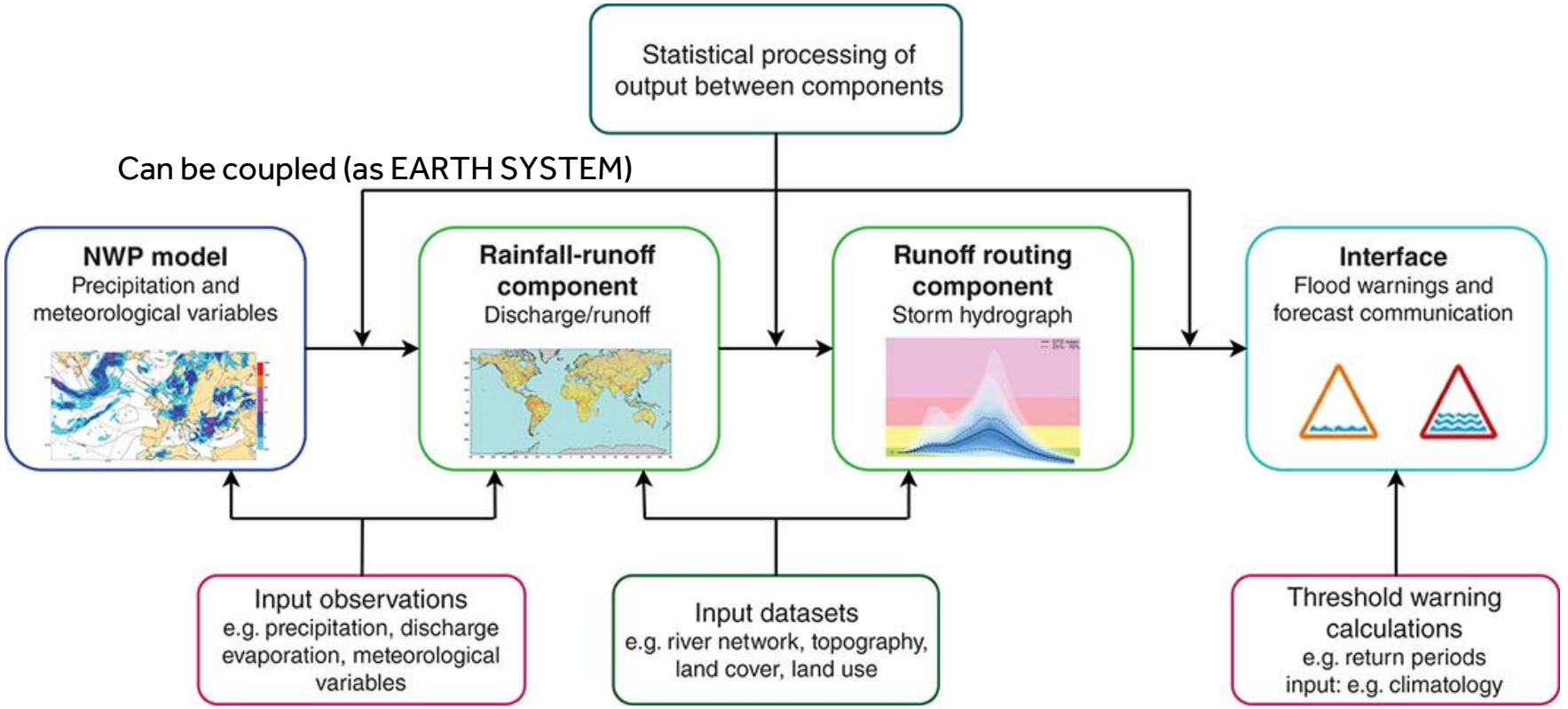
- Ensemble forecasts of lower quality result in lower economic gains in hydropower production
- Losses in forecast value are more important when streamflows are overestimated: up to 3% of economic loss



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**

h.l.cloke@reading.ac.uk

GOING GLOBAL



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

h.l.cloke@reading.ac.uk

THE GLOBAL FLOOD AWARENESS SYSTEM

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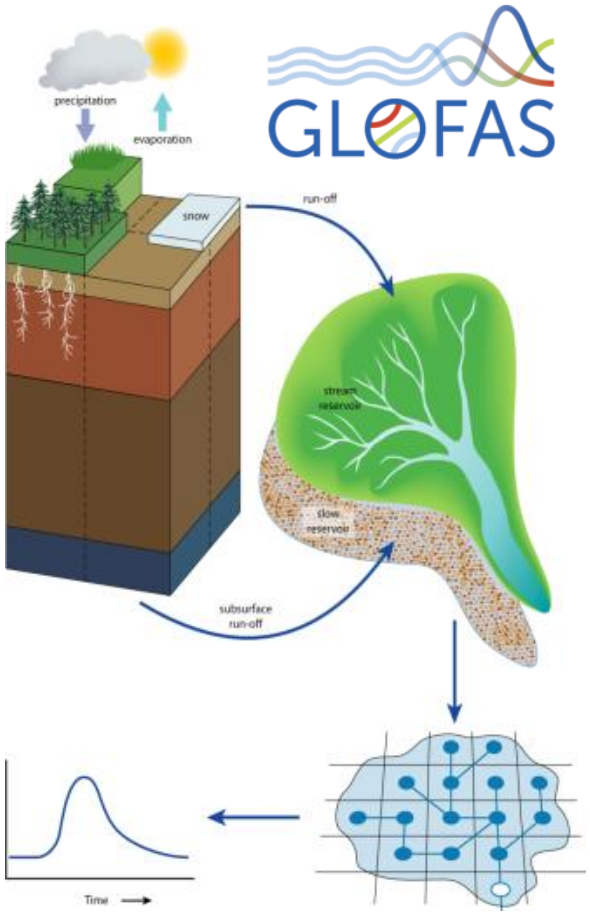
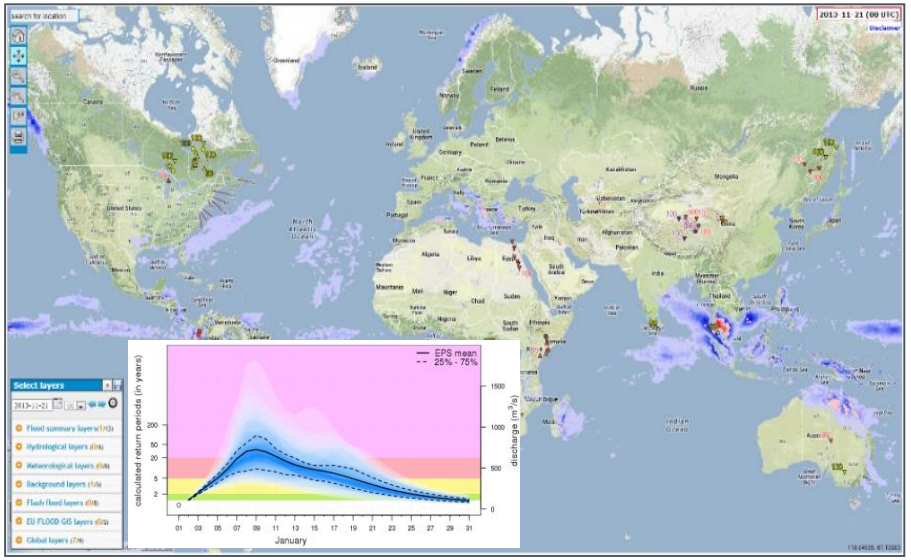




Made possible by the archiving of hydrological variables from forecasts and reanalysis at ECMWF

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

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

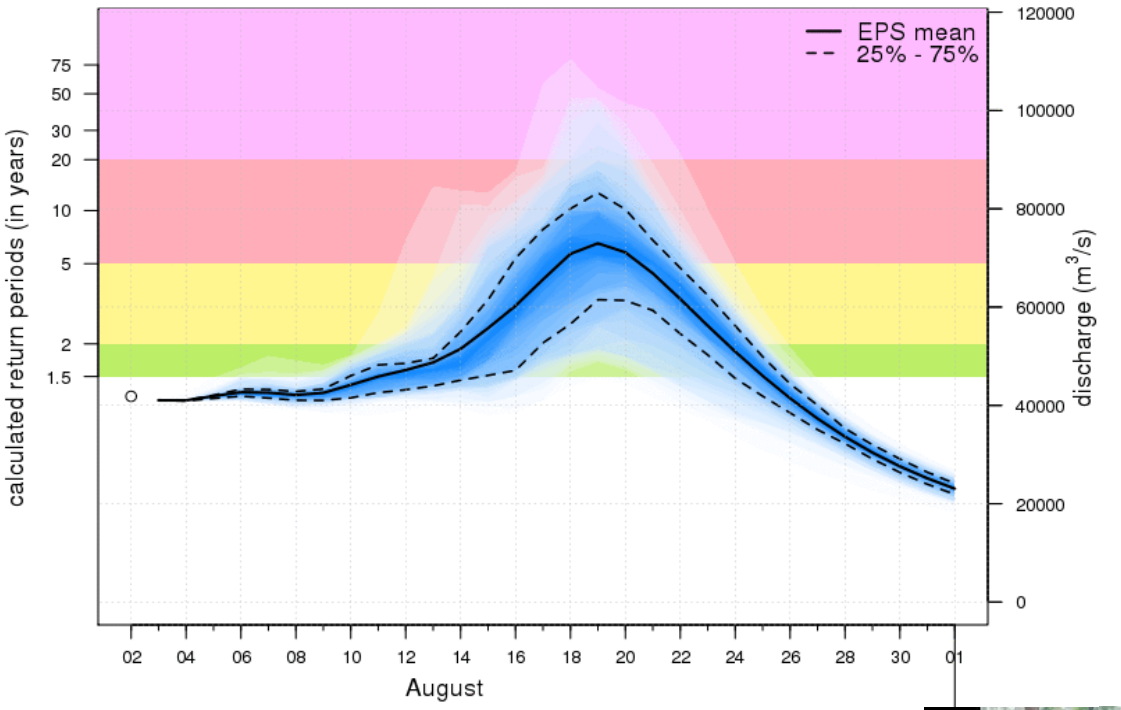
h.l.cloke@reading.ac.uk

European Commission

Copernicus

ECMWF

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"

h.l.cloke@reading.ac.uk

University of Reading

- 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.

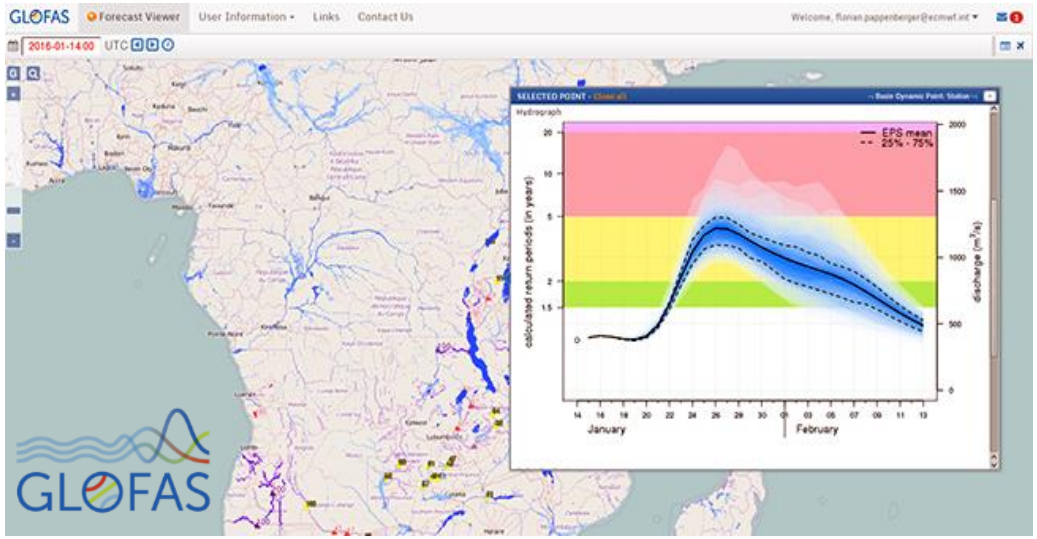
NEW APPLICATIONS, NEW DECISIONS

h.l.cloke@reading.ac.uk

EARLY HUMANITARIAN ACTION WITH ENSEMBLE FLOOD FORECASTING – FORECAST BASED FINANCING

University of Reading

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 from the British people

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

h.l.cloke@reading.ac.uk

FLY ME TO THE MOON

University of Reading

h.l.cloke@reading.ac.uk

BEING BRAVE

- *"It can't be done"*
- *"It's too difficult"*
- *"Nobody wants it"*
- *"The users don't understand probabilities"*
- *"We should just concentrate on higher resolutions"*
- *"It's not our core business"*
- *"Let's just focus on what we know"*
- *"Your ideas are not important [or words to that effect]"*
- *"We're too busy"*

Photo credit: Peruvian Red Cross

- Stretching our capabilities…
  - Seasonal Forecasting
  - Flash flood forecasting
  - Providing evidence for policy (e.g. for natural flood management - NERC LANDWISE)

h.l.cloke@reading.ac.uk

EFAS SEASONAL

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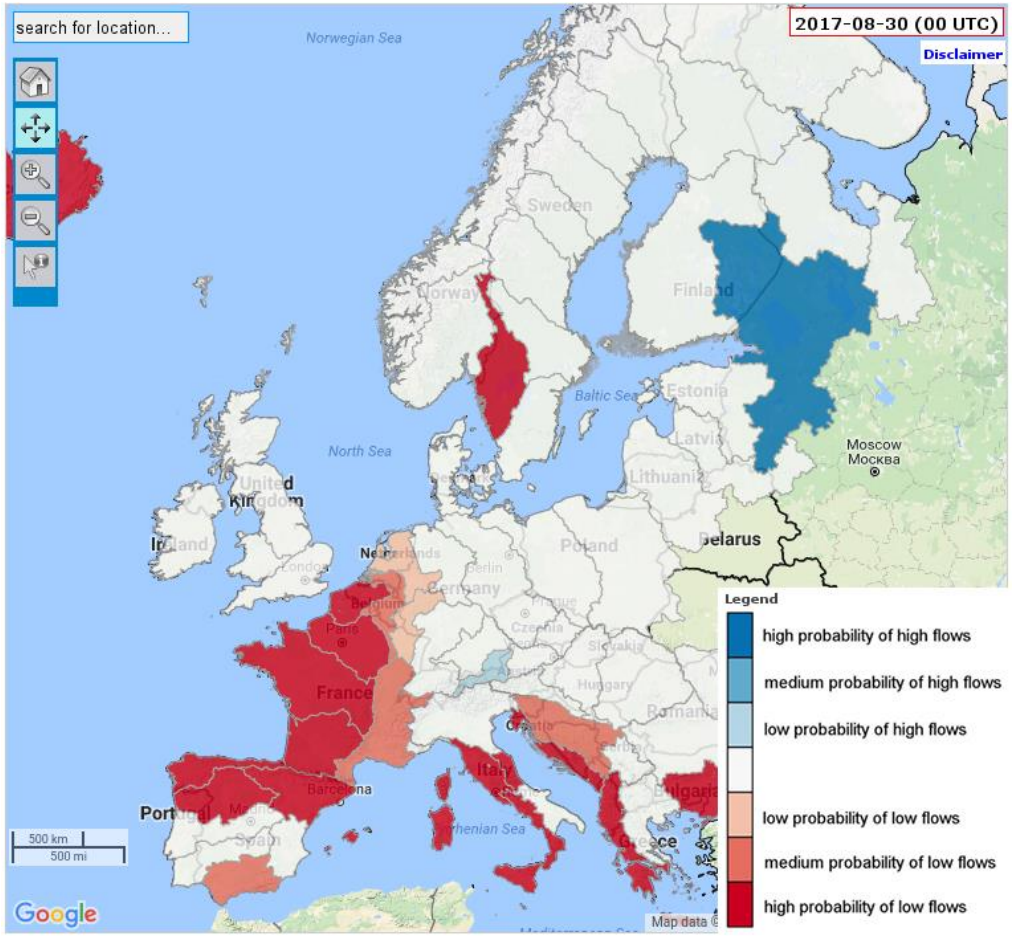


Arnal et al (in review) **Skilful seasonal forecasts of streamflow over Europe?** *Hydrology and Earth System Science* & **here at HEPEX**

Neumann et al (in review) **The 2013/14 Thames basin floods: Do improved meteorological forecasts lead to more skilful hydrological forecasts at seasonal timescales?** *Journal of Hydrometeorology*

Louise

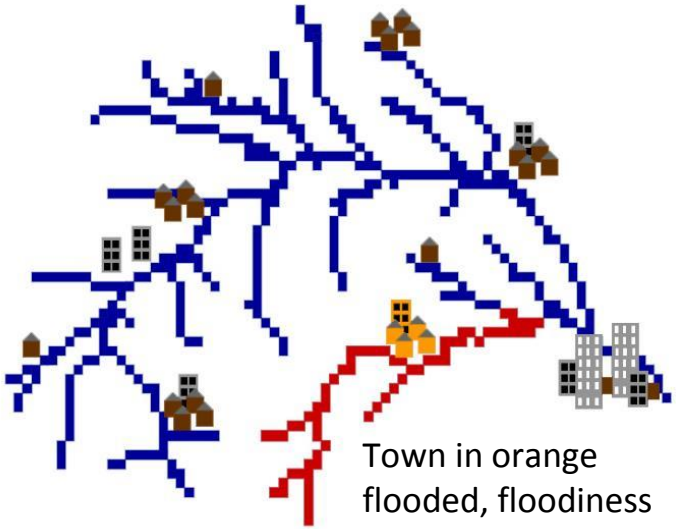
h.l.cloke@reading.ac.uk

Photo credit: Peruvian Red Cross (left)

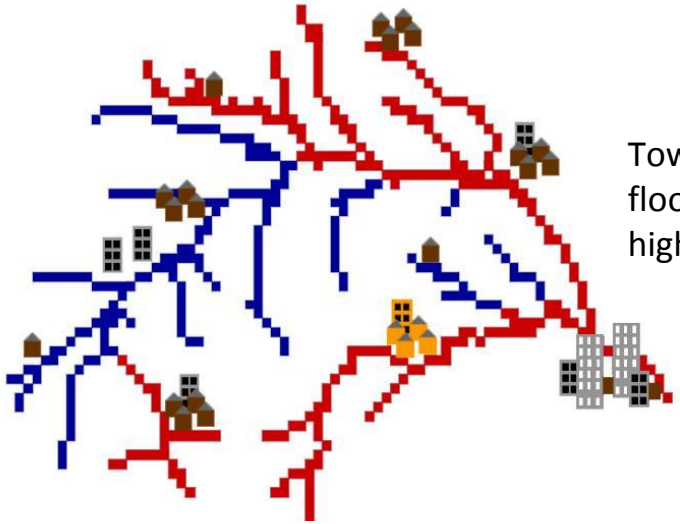
FLOODINESS

- 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.*



Town in orange flooded, floodiness low



Town in orange flooded, floodiness high

Liz

h.l.cloke@reading.ac.uk

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

nature COMMUNICATIONS

ARTICLE

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DOI: 10.1038/ncomms14796 OPEN

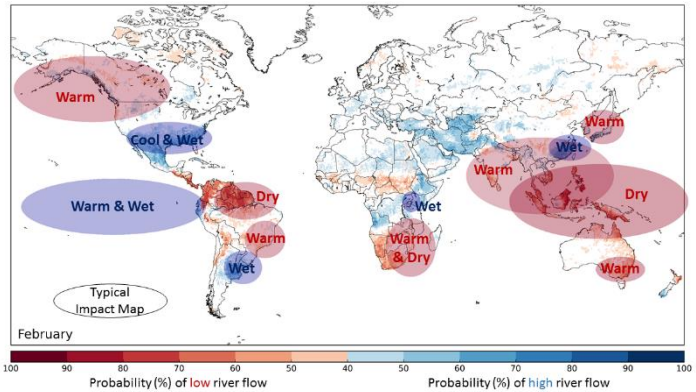
Complex picture for likelihood of ENSO-driven flood hazard

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.

- **Global links between El Nino and flooding widely discussed but not well understood**
- **Blobs used for decisions**

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



Rebecca

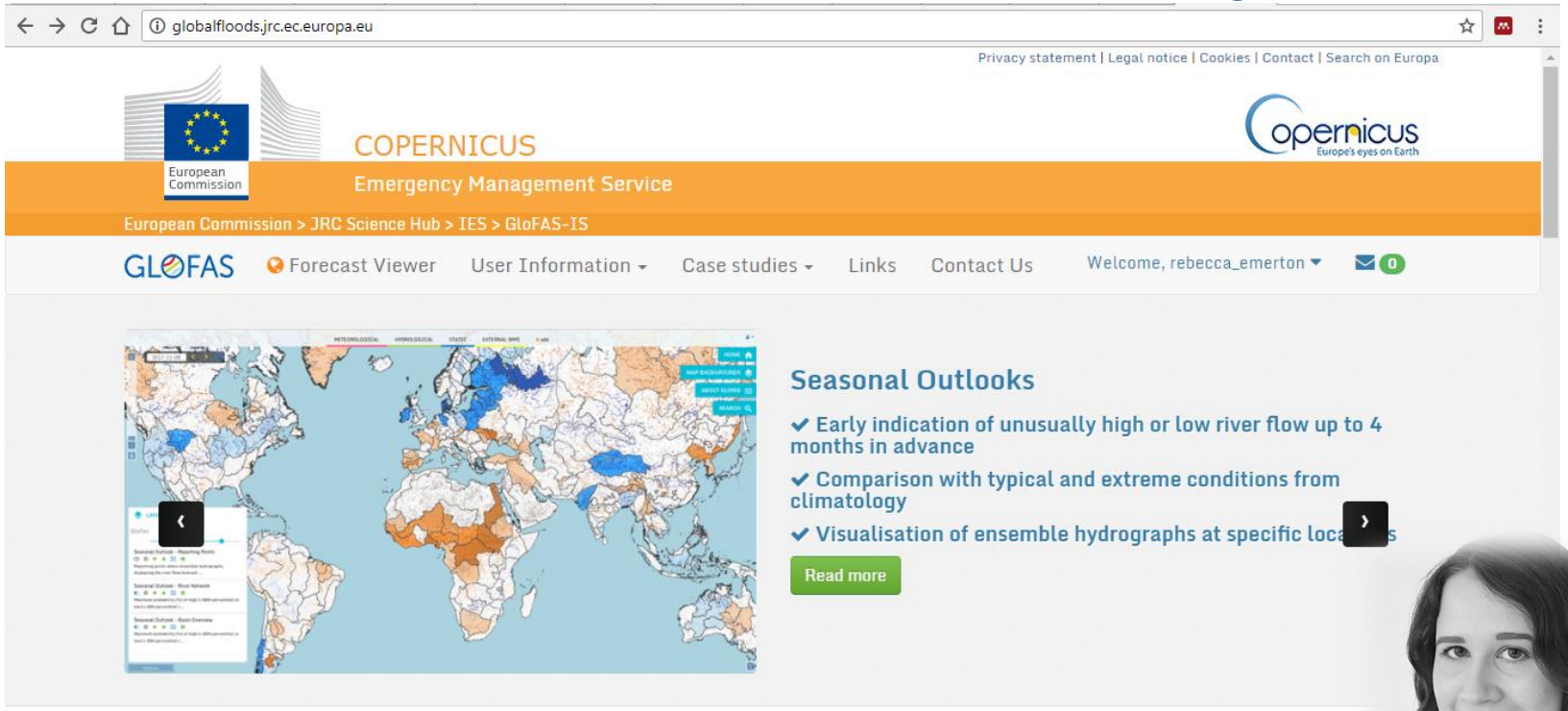
"We conclude that **while it may seem possible** to use historical probabilities to evaluate regions across the globe that are more likely to be at risk of flooding during an El Niño/La Niña, and indeed circle large areas of the globe under one banner of wetter or drier, **the reality is much more complex.**"

h.l.cloke@reading.ac.uk

GLOFAS-SEASONAL: FORECAST PRODUCTS

University of Reading

www.globalfloods.eu



Rebecca

Emerton et al (in prep) & here at HEPEX!

@BeccaLizE

ECMWF University of Reading
r.e.emerton@pgr.reading.ac.uk

University of Reading

HOW COULD WE GET TO THE MOON?

- Communication
- Hydrological model uncertainties in operational models
- Towards Earth System modelling with ensembles

h.l.cloke@reading.ac.uk

GETTING TO THE MOON - COMMUNICATION

- 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
- Explaining the difference between variable skill and uncertainty to partners

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

h.l.cloke@reading.ac.uk

Learning Framework

With support from

With funding from

Two way knowledge transfer between GloFAS developers, forecasters and users

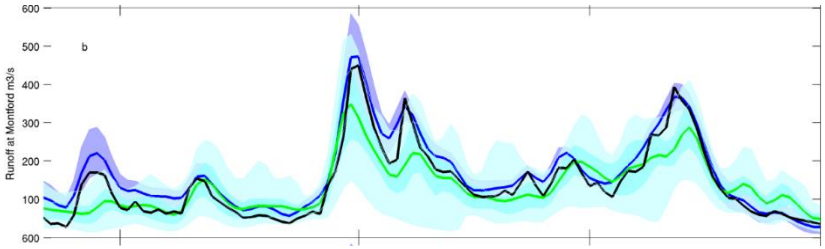
Fiorella Vega Jacome and Carlos Antonio Fernandez-Palomino
Hydroclimate scientists at SENAMHI (Peru)

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.

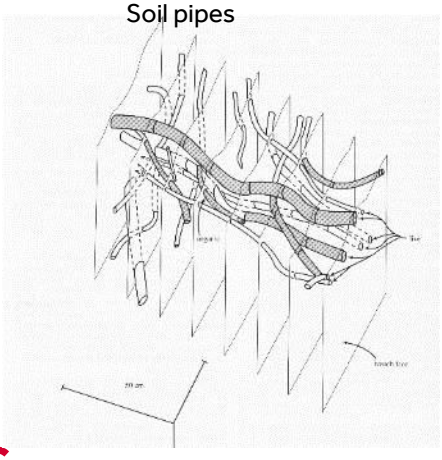
We would like to learn more about the hydrological model used by GloFAS because currently, we only use aggregated models for our simulation and flow predictions. We would also like to be part of the GloFAS Community so we can give feedback to GloFAS for the improvement of the forecasting in our country's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

h.l.cloke@reading.ac.uk

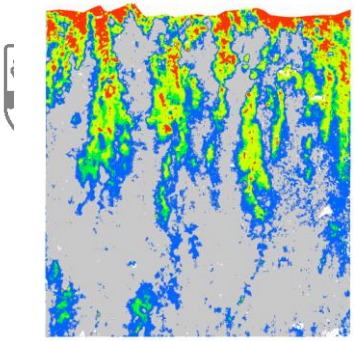
Perturbed parameter ensemble river flow forecast



Soil pipes



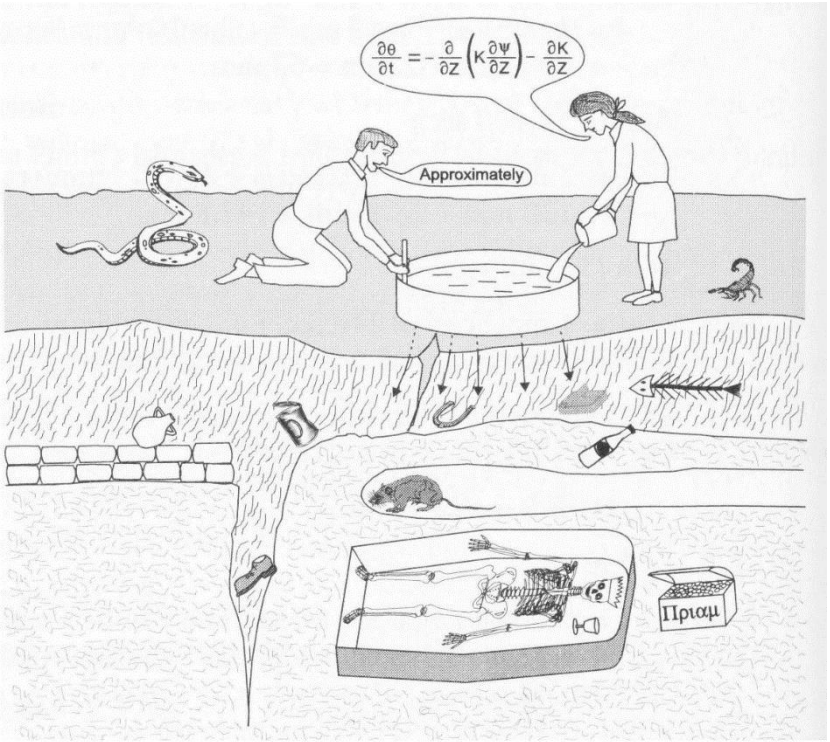
Infiltration dye experiment



Courtesy of M Weiler

GETTING TO THE MOON
(1) REPRESENTING UNCERTAINTY & (2) USING EARTH SYSTEM MODELS

- 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?
- Ensembles of parameter sets, model structures and including data assimilation
- Understanding the role of initial conditions
- Arnal et al (2017) **An efficient approach for estimating streamflow forecast skill elasticity**. *Journal of Hydrometeorology*, 18 (6) doi: 10.1175/JHM-D-16-0259.1



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

h.l.cloke@reading.ac.uk

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?

Work of Ervin Zsoter here at HEPEX

h.l.cloke@reading.ac.uk

Ervin

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

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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)

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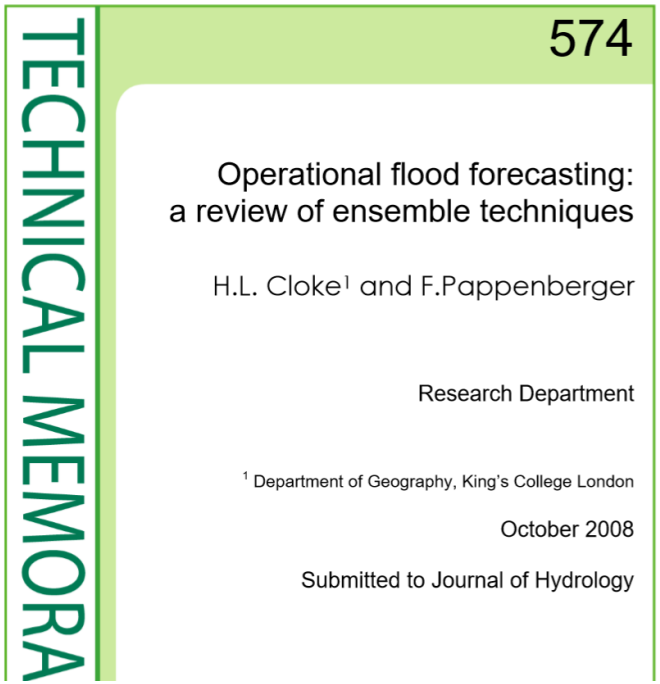
Abstract. Soil moisture memory is a key component of seasonal predictability. However, uncertainty in current memprediction. The soil moisture reservoir has a memory considerably longer than most atmospheric processes, and as a


TECHNICAL MEMORANDUM

574

Operational flood forecasting: a review of ensemble techniques

H.L. Cloke[1] and F.Pappenberger

Research Department

[1] Department of Geography, King's College London

October 2008

Submitted to Journal of Hydrology

10 YEARS AGO

University of Reading

The Challenges

1. Improving NWPs
2. Understanding the total uncertainty in the system
3. Data Assimilation
4. Having enough case studies (which report quantitative results)
5. Having enough computer power
6. How to use EPS in an operational setting
7. Communicating uncertainty and probabilistic forecasts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Review

Ensemble flood forecasting: A review

H.L. Cloke [a,*], F. Pappenberger [b]

[a] Department of Geography, King's College London, Strand, London WC2R 2LS, UK
[b] European Centre for Medium Range Weather Forecasts, Shinfield Park, Reading RG2 9AX, UK

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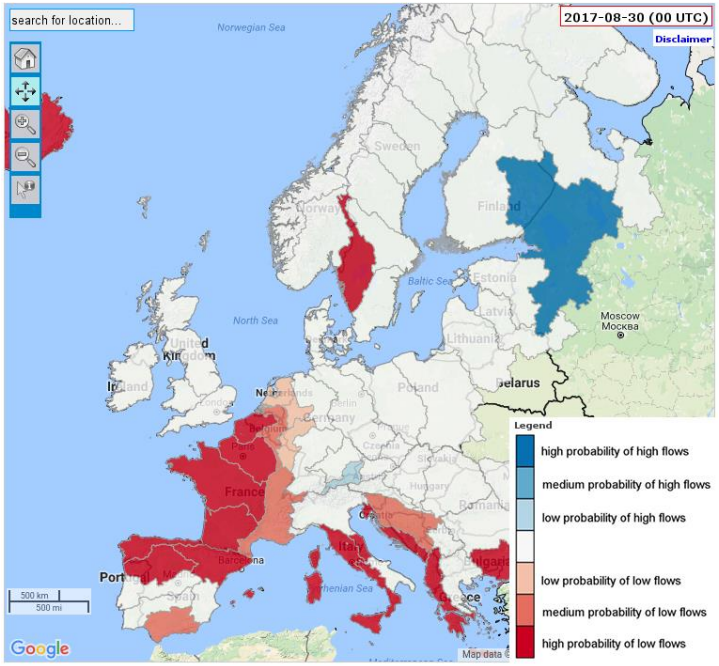
SUMMARY

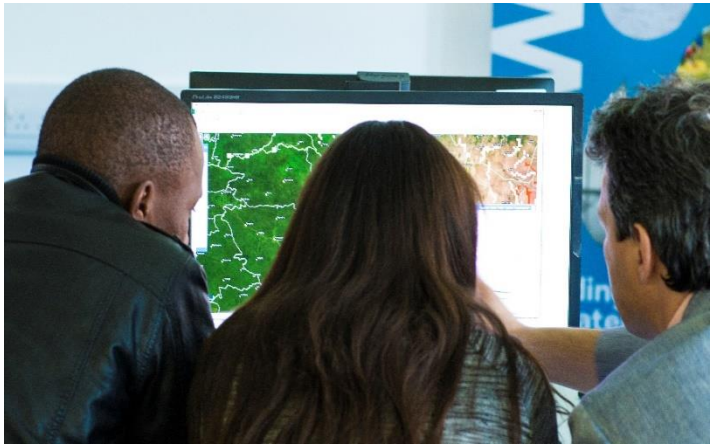
Operational medium range flood forecasting systems are increasingly moving towards the adoption of ensembles of numerical weather predictions (NWP), known as ensemble prediction systems (EPS), to drive their predictions. We review the scientific drivers of this shift towards such 'ensemble flood forecasting' and discuss several of the questions surrounding best practice in using EPS in flood forecasting systems. We also review the literature evidence of the 'added value' of flood forecasts based on EPS and point to remaining key challenges in using EPS successfully.

OUTLOOK

- Enjoying Australia with vibrant HEPEX community
- Ever wider application of ensembles
- Improving skill and value of warnings
- Communication and decision making under uncertainty
- Improving land surface hydrology & uncertainty as a holistic part of Earth System
- Keep innovating – combine dynamic and statistical ideas e.g. look for proxy variables (atmospheric rivers, teleconnections)
- Try something new every day & be brave!



Arnal et al (in review) EFAS seasonal outlook



Coproduction of ensemble forecasting systems

h.l.cloke@reading.ac.uk

Department of Geography and Environmental Science
Department of Meteorology

University of Reading

FLY ME TO THE MOON:
THANKS FOR LISTENING!

a BIG THANKYOU to Water@Reading, ECMWF, HEPEX community, partners

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@hancloke