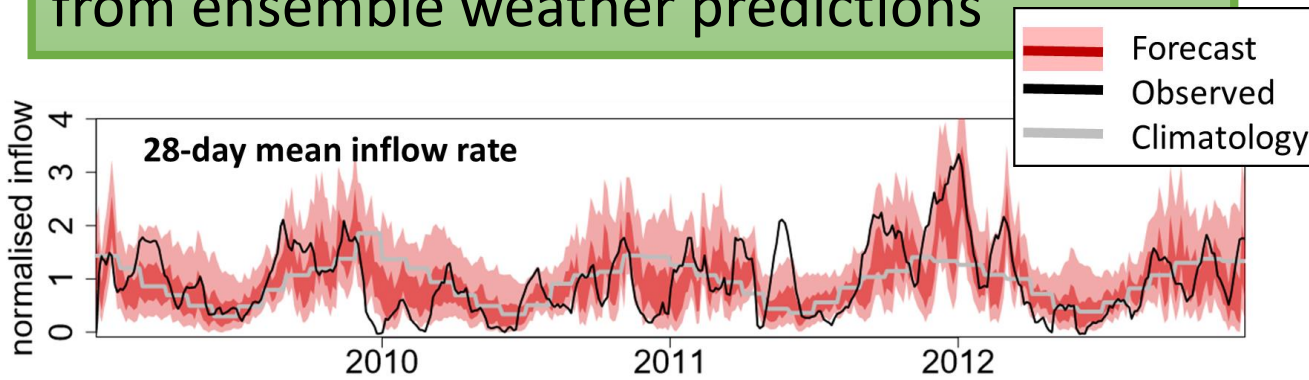


Developing a sub-seasonal to seasonal (S2S) forecasting system for hydropower reservoirs in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Goal:

Derive S2S probabilistic inflow forecasts from ensemble weather predictions



Data:

- Historical inflow record (2009-2019)
- ECMWF extended-range hindcasts (2009-2019)

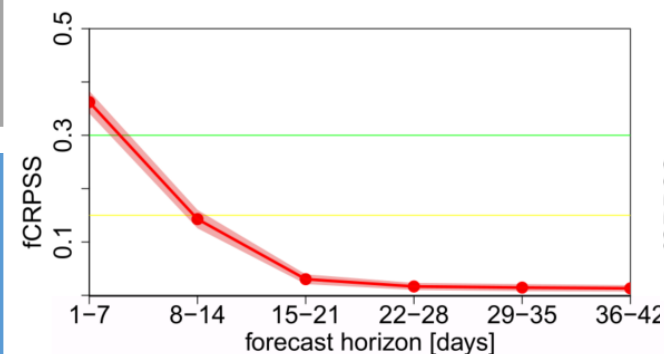
Methods:

- Regression model: historical inflow $\sim$ NWP precipitation
- EMOS post-processing and calibration [Scheuerer, 2014]

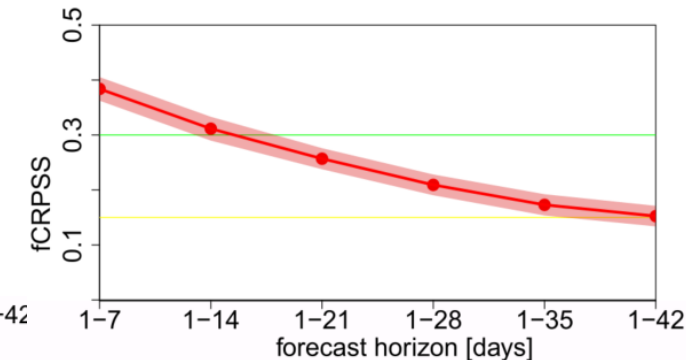
Results:

- Forecasts hold skill up to six weeks ahead
- Greater skill in winter than summer
- Cost model used to explore value of forecasts
- Probabilistic forecasts consistently add value relative to climatological or deterministic forecasts

7-day mean inflow forecasts skill



Cumulative inflow forecasts skill



S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

The problem:

- Hydropower operators require forecasts to schedule power generation in advance
- S2S forecasts could inform precautionary actions to mitigate impact of high and low inflow events, improving water-management and increasing revenues
- Inflow forecasts in Scotland are highly dependent on weather predictions rather than initial hydrological conditions, due to low soil-water storage capacity



S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Project aims:

- Develop method of deriving S2S probabilistic inflow forecasts for hydropower reservoirs in Scotland
- Evaluate potential economic value of the S2S inflow forecasts through improved operational decisions

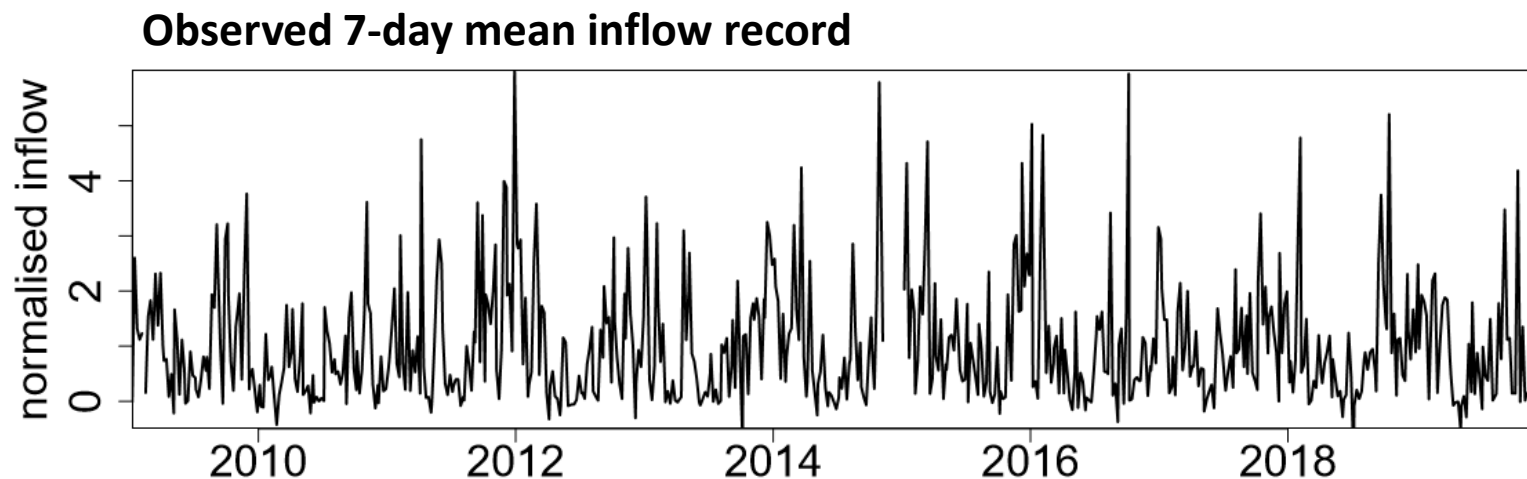


S2S forecasting system for hydro-resources in Scotland

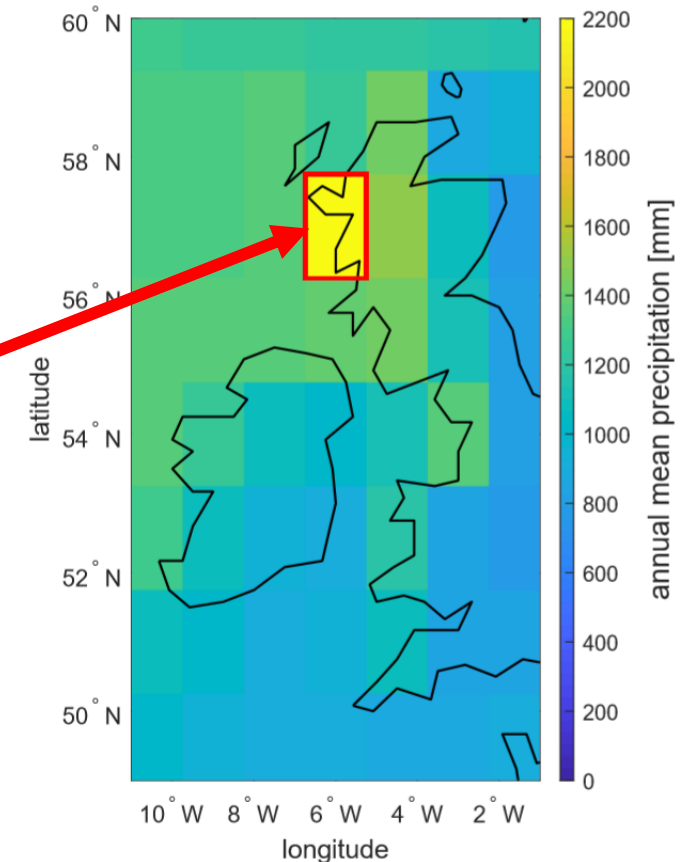
Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Data:

- Historical inflow record for case-study reservoir (2009-2019)
- ECMWF extended-range forecasts (Hindcast dataset 2009-2019, 2 x forecasts per week with 10 ensemble members)



**ECMWF extended-range forecast
Precipitation climatology**



S2S forecasting system for hydro-resources in Scotland

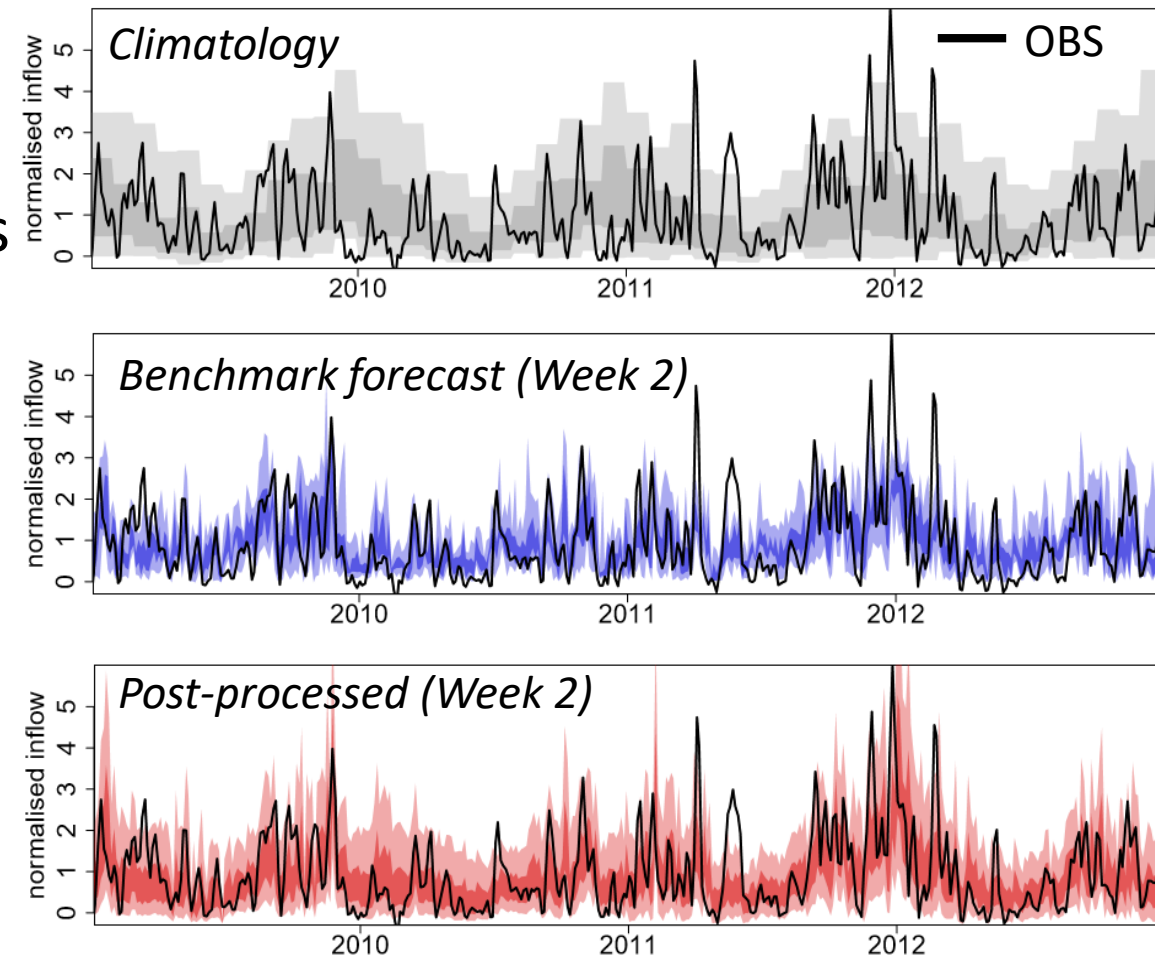
Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Methods:

- Extract S2S precipitation forecasts at site of case study reservoir
- Train linear regression model for observed inflow onto forecast precipitation (lead-times < 7days) → *benchmark inflow forecast*
- Post-processing following method of Scheuerer (2014) to produce calibrated probabilistic inflow forecasts

Cross validation: forecast year and subsequent year always excluded from training data (e.g. forecasts for 2015 use no data from 2015-16)

7-day mean inflow forecasts



Shaded areas: 50% and 90% prediction intervals

S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Methods: Forecast horizons evaluated

	Weekly average inflow rate forecasts	Extended average inflow rate forecasts
Week 1	days 1-7	
Week 2	days 8-14	days 1-14
Week 3	days 15-21	days 1-21
Week 4	days 22-28	days 1-28
Week 5	days 29-35	days 1-35
Week 6	days 36-42	days 1-42



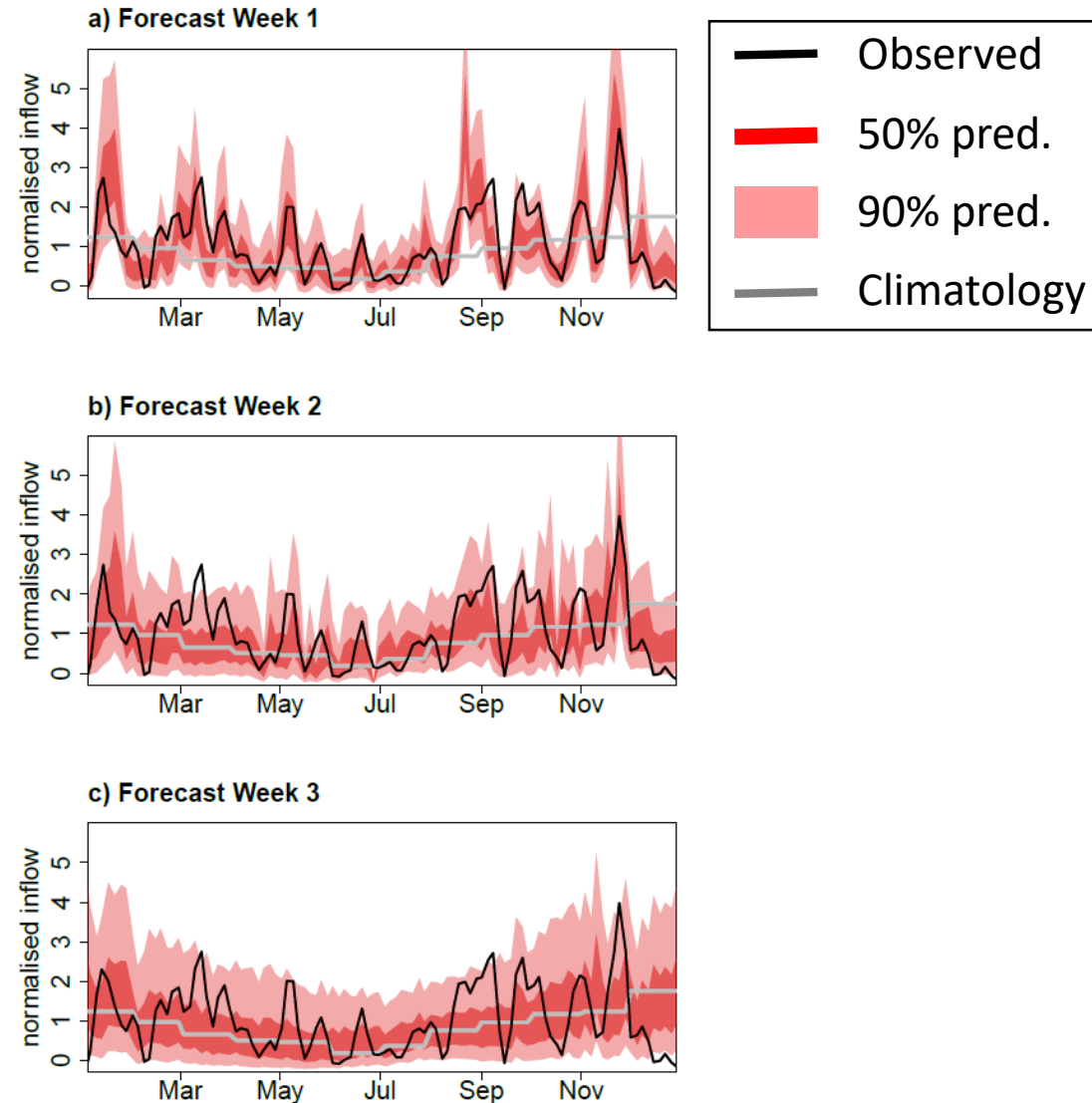
S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Results: S2S inflow forecasts

Forecasts of 7-day mean inflow rate:

- Forecast probability distribution increases with lead time
- Week 1 and Week 2 forecasts capture temporal variability of inflow
- Forecast probability distribution is typically near climatology from Week 3 onwards

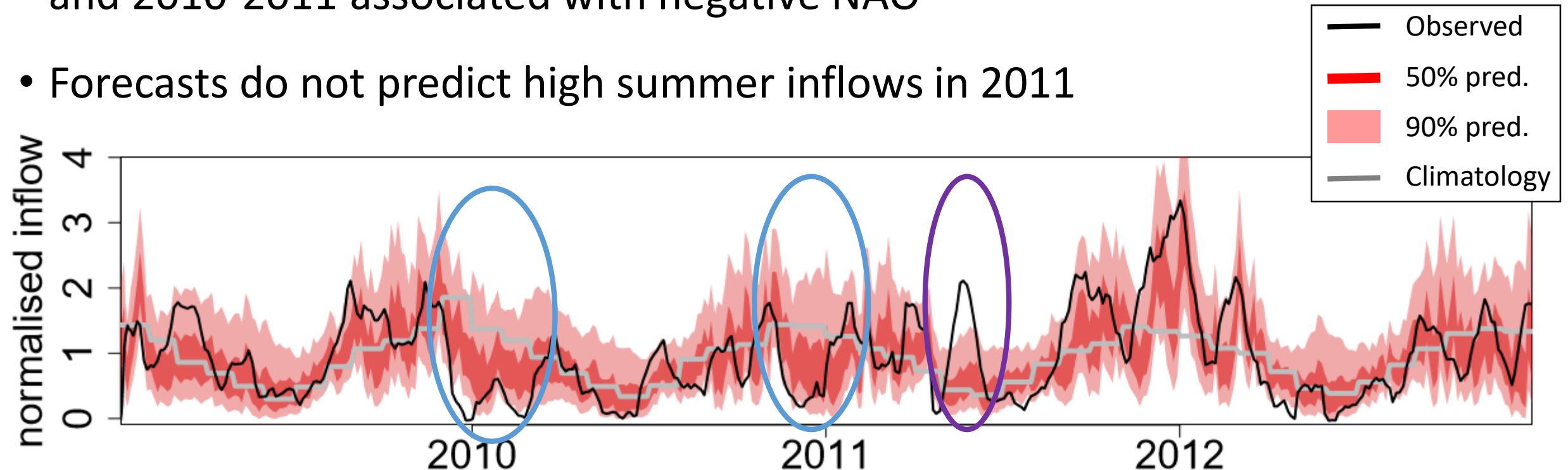


S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Results: S2S inflow forecasts

- 4-week average inflow forecasts largely capture temporal evolution of observed inflow.
- Forecasts clearly predict low inflows during winter 2009-2010 and 2010-2011 associated with negative NAO
- Forecasts do not predict high summer inflows in 2011



S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

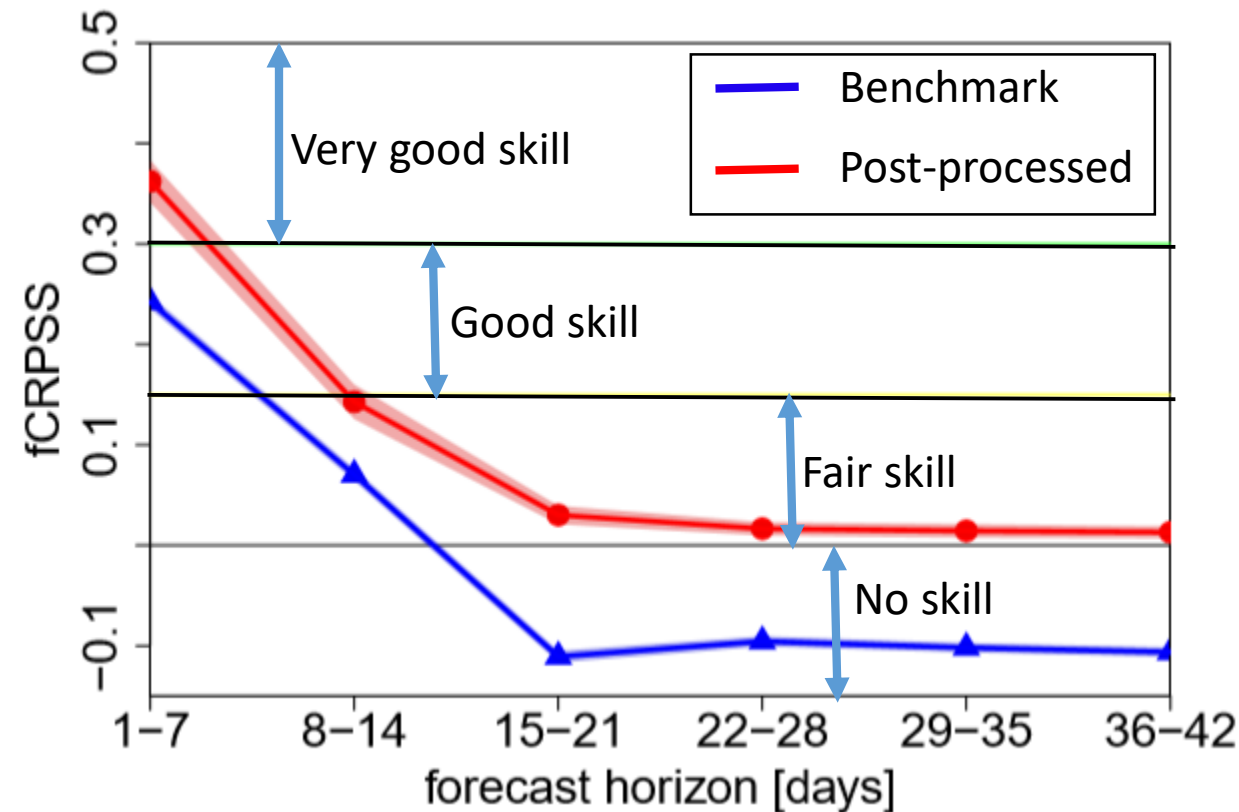
Results: Skill of S2S inflow forecasts

Forecasts of 7-day mean inflow rate:

- Post-processed forecasts demonstrate significant (although low) skill up to forecast week 6.
- Benchmark forecasts demonstrate skill up to forecast week 2

Skill evaluated using fair Continuous Rank Probability Skill Score relative to climatology (fCRPSS, SpecsVerification package R)

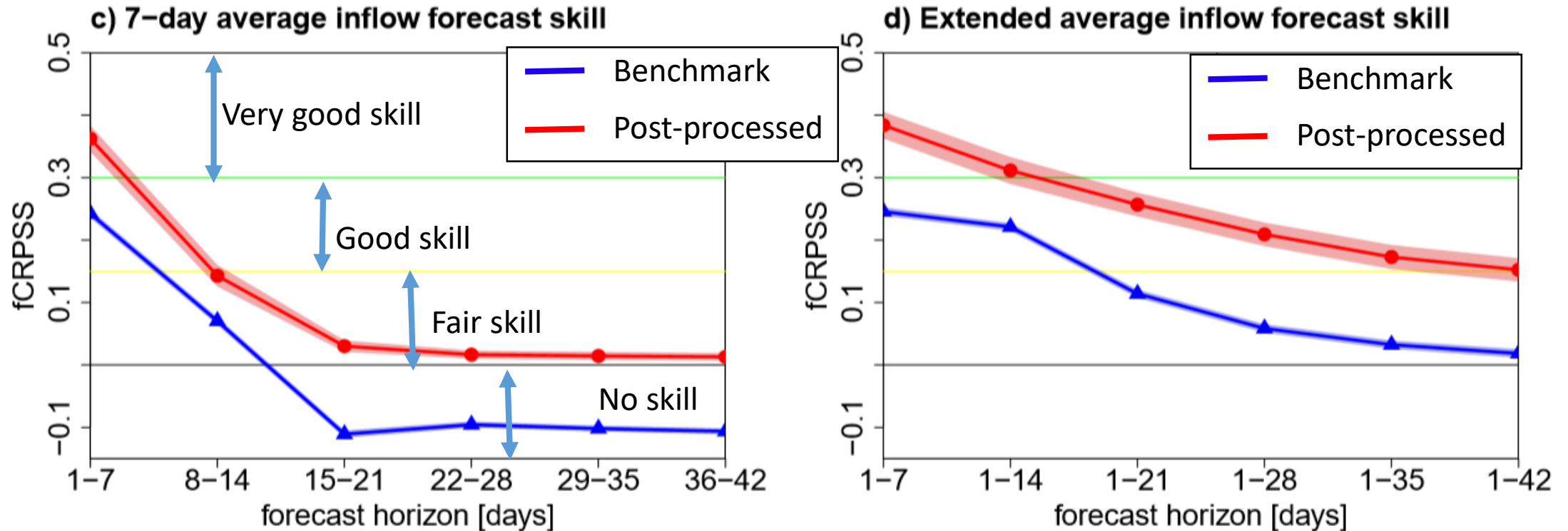
Classification of forecast skill scores follows system used in the S2S4E Decision Support Tool (<https://s2s4e.eu/>)



S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Results: Skill of S2S inflow forecasts



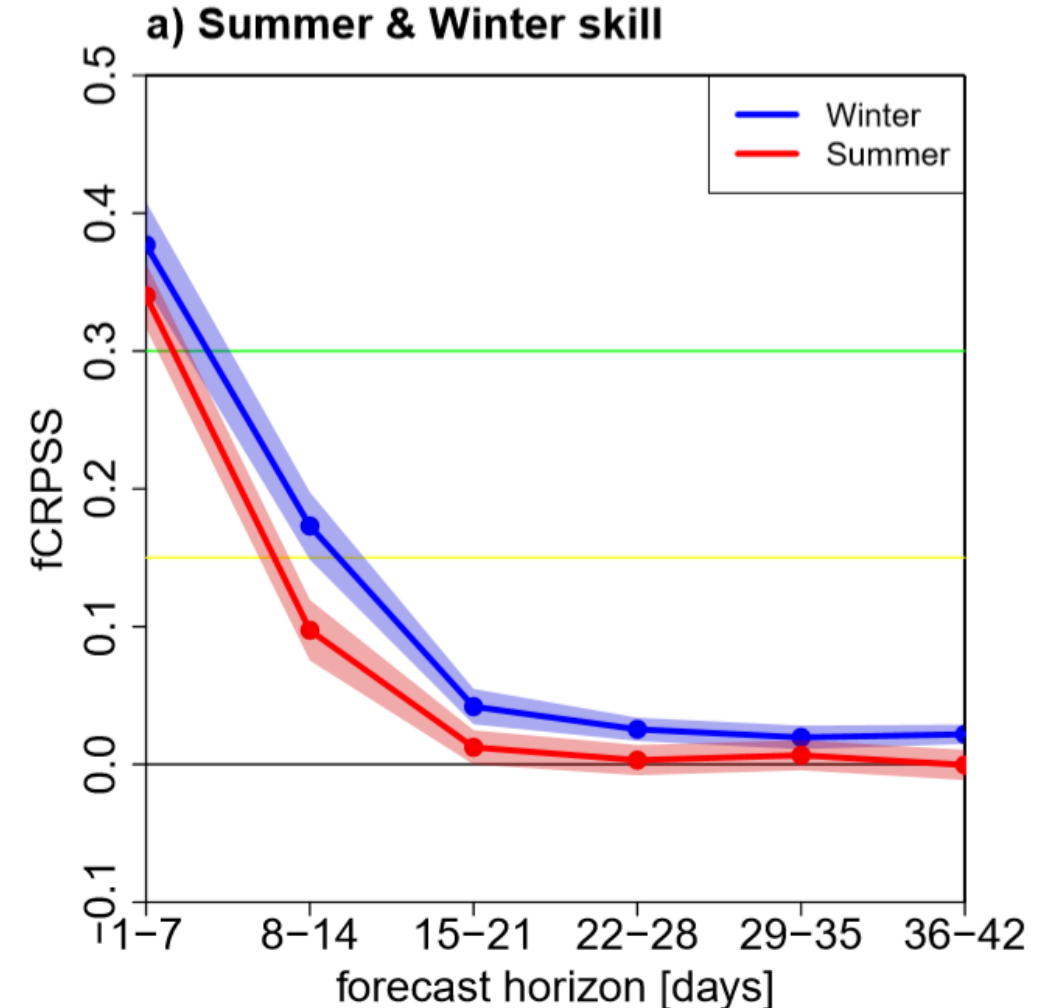
- 4 week average probabilistic inflow forecasts demonstrate good skill relative to climatology
- 6-week average probabilistic inflow forecasts hold comparable skill to 7-day average inflow forecasts for week 2 (8-14 days ahead)

S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Results: Skill of S2S inflow forecasts

- Inflow forecasts hold greater skill in winter than summer
 - Important for hydropower applications: Reservoir levels are higher during winter, meaning greater risk of spills
- Inflow forecasts during summer hold no significant skill beyond week 2

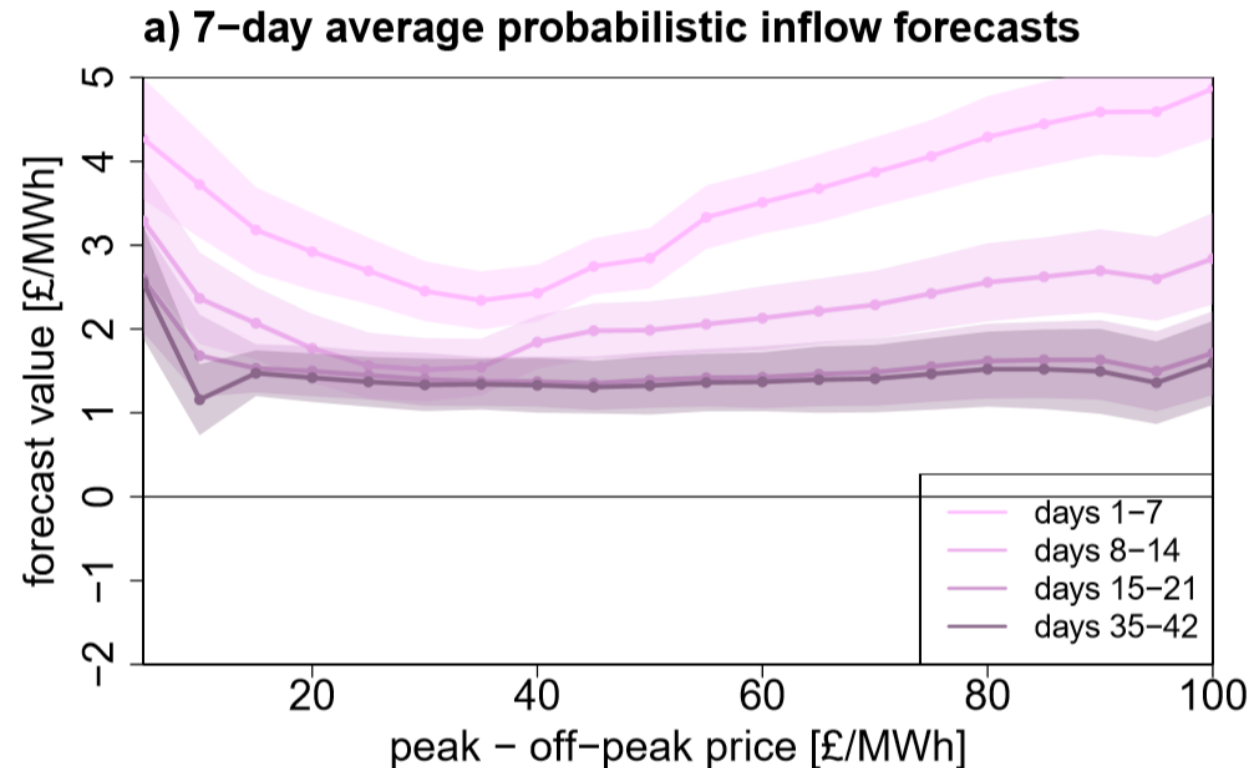


S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Value of inflow forecasts:

- Forecast value explored using stylised cost model based on “*News Vendor*” optimisation problem
- Probabilistic forecasts consistently deliver increased economic value relative to deterministic climatological forecast, up to 6 weeks ahead

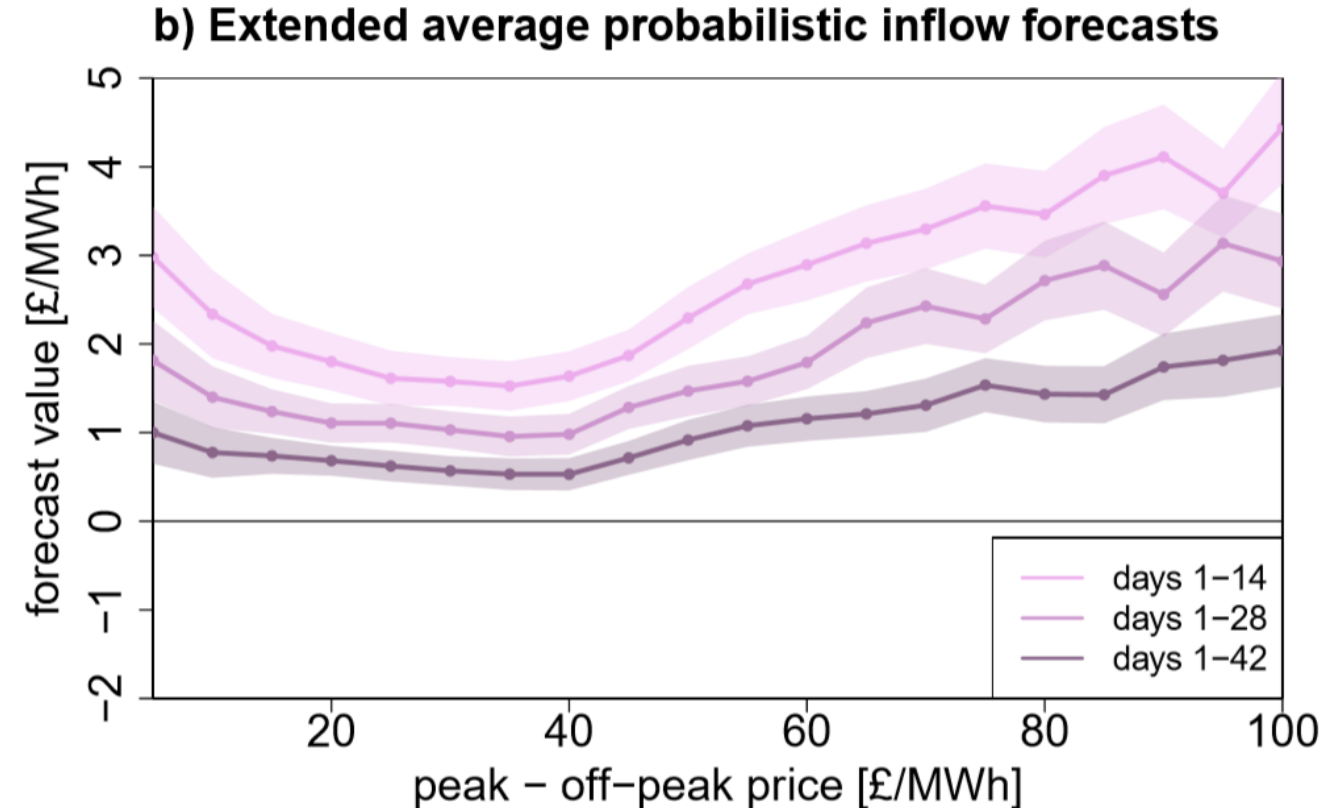


S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Value of inflow forecasts:

- Forecast value is non-linearly related to price differential between peak and off-peak energy prices
- Higher forecast value for larger price differentials
- Value of inflow forecasts could increase in future with more volatile energy prices



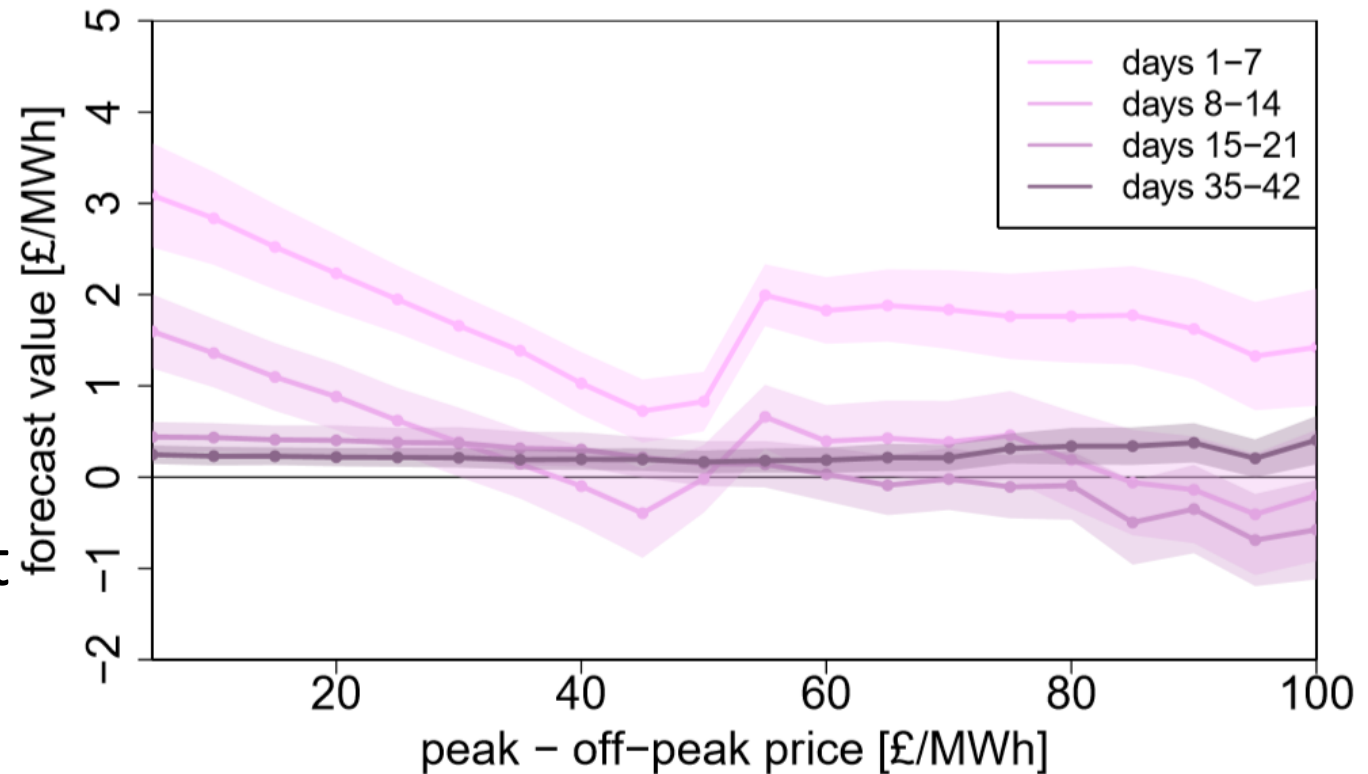
S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Value of inflow forecasts:

- Deterministic inflow forecasts can deliver negative economic value relative to climatological forecasts, even by forecast week 2.
- Hydropower operators require probabilistic forecasts for make informed decisions about high-cost – low-probability outcomes.

c) 7-day average deterministic inflow forecasts



S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Summary:

- Method of deriving skilful S2S probabilistic inflow forecasts from ensemble weather predictions
- S2S inflow forecasts demonstrate skill up to six weeks ahead
- Forecasts hold greater skill in winter than summer
- 4-week average inflow forecasts exhibit good skill relative to climatology and more reliable than 7-day average inflow forecast for week 2
- Forecasts consistently improve operational decisions up to six weeks ahead, increasing revenue

S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Next steps:

- Apply methodology to other reservoirs
- Evaluate forecasts over longer historical record
- Apply more advanced cost model

S2S forecasting system for hydro-resources in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White

Acknowledgements:

This research was funded through the University of Strathclyde's Low Carbon Power and Energy program, a strategic industrial collaboration between the University, Scottish and Southern Energy, Scottish Power and Wood. Jethro Browell is supported by EPSRC Innovation Fellowship (EP/R023484/1).

We thank Andrew F. Low and Richard Hearnden from SSE Renewables for their valuable input on this project and providing the historical inflow record for the case study reservoir.

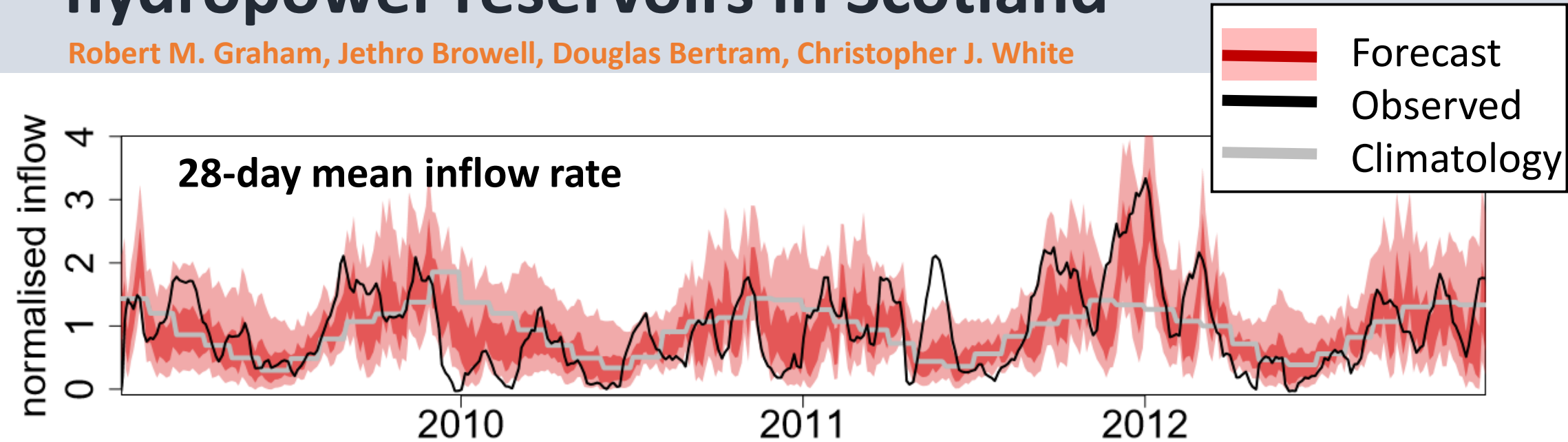
Thank you for reading!

Questions & further information: Robert.Graham.100@strath.ac.uk

Full results presented in forthcoming paper by R.M. Graham, J. Browell, D. Bertram and C.J. White, "The application of sub-seasonal to seasonal (S2S) predictions for hydropower forecasting"

Developing an S2S forecasting system for hydropower reservoirs in Scotland

Robert M. Graham, Jethro Browell, Douglas Bertram, Christopher J. White



- Method of deriving probabilistic inflow forecasts from S2S ensemble weather predictions without additional hydrological model
- Inflow forecasts demonstrate skill up to 6-weeks ahead
- Inflow forecasts hold greater skill in winter than summer
- Economic value of inflow forecasts explored using stylised cost model