Understanding the main uncertainties in hydrological ensembles of future climate change predictions

Jim Freer
Talk outline

- An overview of the Environmental Virtual Observatory pilot project
- The rationale of how I think about environmental systems – models, data, hypothesis testing under uncertainty…
- Results from recent research using FUSE, HBV and RCM’s
- Final comments
EVOp – The Consortium

- Leadership and Management team
  - Adrian McDonald (Leeds)
  - Robert Gurney (Reading)
  - Bridget Emmett (CEH)

- WP leaders
  - Phil Haygarth (Lancaster)
  - Jim Freer (Bristol)
  - Wouter Buytaert (Imperial)
  - Gordon Blair (Lancaster) & Gwyn Rees (CEH)
  - Doerthe Tetzlaff (Aberdeen)

Full team
- Keith Beven (Lancaster)
- Gordon Blair (Lancaster)
- John Bloomfield (BGS)
- Roland Bol (Rothamsted)
- Wouter Buytaert (Imperial)
- Bridget Emmett (CEH)
- Jim Freer (Bristol)
- Robert Gurney (Reading)
- Phil Haygarth (Lancaster)
- Penny Johnes (Reading)
- Paul Quinn (Newcastle)
- Mark Macklin (Aberystwyth)
- Christopher Macleod (Macaulay)
- Adrian McDonald (Leeds)
- Sim Reaney (Durham)
- Gwyn Rees (CEH)
- Marc Stutter (Macaulay)
- Doerthe Tetzlaff (Aberdeen)
“If you have ever faced the challenge of finding and making sense of environmental data, predictions and knowledge then you will understand the need for the Environmental Virtual Observatory”

The Vision

• To make environmental data more visible and accessible to a wide range of potential users and free to use for ‘public good’ applications;

• To provide tools to facilitate the integrated analysis of data, greater access to added knowledge and expert analysis, and visualisation of the results;

• To develop new, added-value knowledge from public and private sector data assets to help tackle environmental challenges.
EVOp and national modelling

National Scale objectives

The EVOp team is challenged over a 2 year program to demonstrate the benefits of a future EVO platform for integrated catchment science. At the national scale (one of 6 research themes) we focus on the following overarching questions:

- What happens when we join up data nationally?
- What happens when we join up modelling nationally?
- What would this deliver in terms of national capability?

Our approach is to bring together, for the first time, national datasets, models and uncertainty analysis approaches into cloud computing environments to explore and benchmark our current predictive capability for hydrology and biogeochemistry nationally. We shall explore how to manage and visualise these complex results to synthesise and improve our scientific understanding and to support policy/operational needs.

http://www.environmentalvirtualobservatory.org

A pilot Virtual Observatory (EVOp) for integrated catchment science – Demonstration of national scale modelling of hydrology and biogeochemistry

Jim Freer, John Bloomfield, Penny Johnes, Christopher (Kit) MacLeod, and Sim Reaney
**EVO Clouds of models and data**

Linking Cloud enabled resources to predictions at catchments

Models:
- PRMS
- SACRAMENTO
- TOPMODEL
- ARNO/VIC

Data:
- Water Quality
- Evaporation
- Discharge
- Precipitation
- Water Table
- Spatial soil moisture
- Discharge streams
EVO Running multiple models of hydrology and biogeochemistry nationally

Linking Cloud enabled resources to predictions at catchments

Uncertainty Analysis of models

Simulations applied nationally
Models and Data – The real world ‘lens’…

- Models and Data
- The real world ‘lens’
- Monitored World
- Natural Variability
- Failures
- Limitations
- Errors
- Perceptual Understanding
- Model Development
- Model evaluation
- Predictions
- ‘Real World’

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Northwatch workshop May 2012 - 8
Model development, prediction and evaluation – a learning framework?

- **Monitor Environment** incl. V(R, Q, P, S)
- **Perceptual Understanding** (P processes)
- **Develop Multiple Feasible Models**
- **Run Multiple Feasible Model Simulations**
- **Evaluate Observational Scenarios**
- **INPUT Observational Scenarios**
- **OUTPUT Observational Ranges**
- **Evaluate Observations** (limitations/uncertainties)
- **FEED BACK INTO MODEL DEVELOPMENT AND MONITORING**
- **Strategic Learning**
- **Evaluate Model Predictions**
- **Retain ‘good’ Simulations**
- **Reject ‘poor’ Simulations**
- **Evaluate Prediction Uncertainties**
- **Understanding**
Different observations have clearly different error structures – the information content of data
Example limits of acceptability

Unsure Observation

Time step based performance measure that includes data uncertainties

Performance Measure

?
Spaced Out: Linking model space to catchment space in an uncertainty analysis framework

Gemma Coxon, Jim Freer, Martyn Clark, Nick Odoni and Thorsten Wagener
Spaced Out

Research Question:
How can we better understand the dissimilarities and similarities of catchment behaviour and then link these to model predictions?

Aim:
To quantify the amount of dissimilarity we can identify from multiple catchments by applying competing models of hydrological behaviour in an uncertainty framework.
**Study Site**

- 16 small UK catchments (100 – 250 km²)
- 11 year time series from 01/01/1998 to 31/12/2008 collected on a daily timestep
- Chosen to represent wide climatic and hydrologic diversity across the study site

- Precipitation (P)
- Potential Evapotranspiration (PE)
- Discharge (Q)
Results

Flow Duration Curve

Runoff Coefficient

Rising Limb Density

Runoff Coefficient - Winter

Runoff Coefficient - Summer

All Hydrologic Signatures
Model Structures

Catchment 39020, BFI = 0.93
Maximum Number of Behavioural Simulations per model structure = 340

Catchment 33063, BFI = 0.69
Maximum Number of Behavioural Simulations per model structure = 21

Catchment 42014, BFI = 0.49
Maximum Number of Behavioural Simulations per model structure = 19

Catchment 55026, BFI = 0.37
Maximum Number of Behavioural Simulations per model structure = 960
Understanding the main uncertainties in hydrological ensembles of future climate change predictions

Jim Freer, Martyn Clark, Nick Odoni, Gemma Coxon, Hillary McMillan, and Max Souvignet (with Hannah Cloke and Frederick Wetterhall)
Observed and RCM Simulations

Uncertainty in RCM and Impact modelling

“grand” ensemble:
1. multi-model RCMs (ENSEMBLES) cascaded directly into hydrology impact model (FUSE)
2. RCM rainfall overlain on impact model response surfaces and compared to Observed 1km\(^2\) product

3 RCMs KNMI, ICTP and SMHI
and 1km\(^2\) daily Observed (Met Office)
UK Catchments analysed

57 UK catchments >500km² (not nested)
Multiple model structures

Framework for Understanding Structural Errors (FUSE) – Applying competing models of hydrological behaviour.

Period used 1991-2000 (daily)

- 4 model structures
- Wide sampling ranges
- Model warm up of 1 year

Choice:

1: Upper Layer Architecture
   - A. Single State
   - B. Separate tension storage
   - C. Cascading buckets

2: Lower Layer Architecture and Baseflow
   - A. Single State - without evapotranspiration
   - B. Single State - with evapotranspiration
   - C. Parallel baseflow reservoirs - with evapotranspiration

3: Percolation
   - A. Single linear reservoir
   - B. Two parallel linear reservoirs
   - C. Single non-linear reservoir
   - D. Single non-linear reservoir, topographic index
   - A. Gravity Drainage
   - B. Drainage above field capacity
   - C. Saturated zone control

4: Surface Runoff
   - A. Unsaturated zone linear
   - B. Unsaturated zone Pareto
   - C. Saturated zone
Monte Carlo simulations - GLUE

1) 20,000 simulations (in total 18.2m simulations 57 catchments * 4 rainfall products * 4 models * MC simulations)

2) Uniform random sampling of parameters

3) Assessment is FDC

4) A 'limits of acceptability approach of +/- 10% of discharge for Q5, Q25, Q50, Q75, Q95 (1991-2000)
Rain Obs and KNMI-RCM Daily 1991-2000

\[ R(\text{mean}) = 0.51 \]
Rain Obs and KNMI-RCM Weekly 1991-2000

$R(\text{mean}) = 0.74$
FUSE FDC (Q5,25,50,75,95) rejection
FUSE FDC Q5 rejection
5-day precip cumulative distribution functions for 1961-2000 and 2071-2100 time slices
Model Output Statistics-corrected, performance measure-weighted

HBV parameter uncertainty

RCM uncorrected

RCM corrected

future change in **mean annual maximum** river discharge
The contours show the conditional probability of exceeding the warning threshold in any one year.

For the winter months (dec-feb)

The colour plot is the changes in precipitation and temperature calculated from the Perturbed physics experiment.

The black dots are the individual RCM runs from the UKCP09, and the blue dots are the RCMs from the ENSEMBLES project.

The thicker dots denote the mean of the groups of RCMs.
The contours show the conditional probability of exceeding the threshold for the winter months (Dec-Feb).

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Perturbed physics experiment for the conditional probability that the flood warning level is exceeded for the Montford catchment.

The contours show the conditional probability of exceeding the threshold and the colour plot the density of runs from the perturbed physics experiment.

The black dots are the individual RCM runs from the UKCP09, and the blue dots are the RCMs from the ENSEMBLES project.

The thicker dots denotes the mean of the groups of RCMs.

For the winter months (dec-feb)
2 year return period – 50% conditional probability of reaching flood warning threshold at Montford
Conclusions

• Bias correction or MOS is necessary to achieve good predictions for higher flows but it throws out the physics and is not a credible product.

• The quality of RCM rainfall inputs driven by ERA40 is variable by catchment and by RCM (much more work on this to be done to understand systematic behaviour across the UK and by season – NERC DEMON project).

• Impact decisions are best informed by an approach that considers uncertainty comprehensively.

• Different methods give different indications of future change, sometimes substantially so. Difficult to distinguish which may be more realistic.

Further work

• Continue our analysis for 1,400 UK catchments (now automated to run FUSE anywhere from various products).

• Explore the linkages between model structures (and responses) and catchment characteristics.

• Develop strategies for understanding weaknesses in RCM’s and NWP models to improve strategies for looking at future scenarios.