Hydrological extremes and feedbacks in the changing water cycle (HydEF)
PROGRESS REPORT
Feb 2011 – Aug 2011

Background

Guidance to support adaptation to the changing water cycle and development of mitigation strategies to combat climate change is urgently required, yet the ability of water cycle models to represent the hydrological impacts of climate change is limited in several important respects. Climate models are an essential tool in scenario development, but suffer from key limitations in accuracy and resolution and fundamental weaknesses in the simulation of hydrology. This project will produce the underlying science and models needed to address these current limitations, integrating climate and hydrological science to take impact modelling beyond current state of the art. Specifically, the project will:

a) exploit current generation climate science and advanced statistical methods to improve and enhance projections of potential change in hydrologically-relevant variables and metrics over a time-scale of 10 to 60 years, in particular extremes of heavy precipitation and drought;

b) build on the analysis of historical meteorological and hydrological data, drawn from NERC and Defra/EA observational programmes, to improve scientific understanding and develop innovative methods for the modelling of the hydrological response to climate variability;

c) seek to improve the representation of hydrological processes in land surface models, in particular, the enhanced modelling of unsaturated zone and groundwater processes and associated land-atmosphere feedbacks.

Summary of progress

All the project research staff and students were in place by end of February (see list of project team in App 1), with the exception of the BGS post-doc. An inception report was produced and the project website set up. Two field trips, two project meetings, one steering group meeting, one CWC programme meeting, and various sub-project meetings have been held, as well as meetings with scientific collaborators and stakeholders. Progress with work programme has included

- data collection and formatting,
- literature review,
- model sensitivity and performance analysis to identify issues with JULES,
- initial insights into synoptic climate controls on hydrology,
- development of understanding and initial conceptual models of Thames and Eden hydrogeology,
- local scale borehole modelling methodology development,
- initiation of Isle of Wight case study.

Project Meetings

A Project kick-off meeting was held at Imperial on 19th November 2010. A Project and Steering Group meeting (see list of members in App 1) was held at Imperial on 14th February 2011, a field trip to the Eden on 5-6th May, a field trip to the Thames/Cotswolds on 9th June, and a Project meeting at Wallingford on 3rd August. The project was represented at a user forum meeting on 23rd June and at a groundwater-in-JULES meeting run by BGS on 16th

March. Imperial hosted a CWC programme meeting on 23rd Feb. Additionally, various intra-project meetings and meetings with CEH staff and partners have been held.
The project will be represented at the CWC programme annual meeting on 29-30 Sept 2011.
The next full project meeting will be at Reading on 18th January 2012, and the next Steering Group meeting will be on 15th Feb 2012, venue TBD.

Work package reports

Work package 1: Exploiting current generation climate science (Reading University, University College London, Imperial College London)
Dr David A. Lavers, Prof Andrew J. Wade, Dr David Brayshaw, Dr Richard Allan, Prof Nigel Arnell
Dr Richard Chandler, Dr Chiara Ambrosino
Dr Christian Onof

The primary aim of the research at Reading is to improve understanding of the atmospheric processes that generate flooding and drought in Great Britain (GB). To date on the project, the research has used 20 river basins across Britain (including the Eden and Thames basins); the catchments have different geologies and capture the precipitation gradient across mainland GB. Initially the focus has been on floods and a new pragmatic method for approximating catchment rainfall-runoff response times has been developed. The estimation of the catchment response time provides an estimate of the most appropriate time period over which to analyse the atmospheric processes that occurred concurrently with a particular flood. The Block Maxima method was used to extract the highest mean daily river flow in the winter and summer seasons in each of the 20 catchments. At each site, the Spearman rank correlation was calculated using the resultant high flow series and cumulative precipitation sums on each day prior to the high flow events. The lag-time between rainfall and runoff for which the highest correlation occurred was taken as an estimate of the general response time of the basin.

With the response times identified for the catchments, the mean sea level pressure (MSLP) fields from the Twentieth Century reanalysis were analysed over the response period. Here we use the Eden at Temple Sowerby to exemplify the method. In the Eden catchment the response time was two days, so the MSLP fields were averaged over two days (the day of the flood and one day prior to the flood). A hierarchical cluster analysis was employed on the MSLP anomaly fields to determine if there were particular pressure patterns causing the flood events. Figure 1 shows the resultant three clusters and the composite mean of all MSLP anomaly fields. In general a lower pressure (than average) is located to the north/north-west of the British Isles and a higher pressure (than average) is situated to the south/south-west of the British Isles. This causes a south-westerly air stream transporting moisture and rainfall over the Eden catchment, which in turn causes the flood events.

The next stage of research will consider other atmospheric variables, such as the winds and specific humidity, and will investigate the evolution of these variables over the river response time.

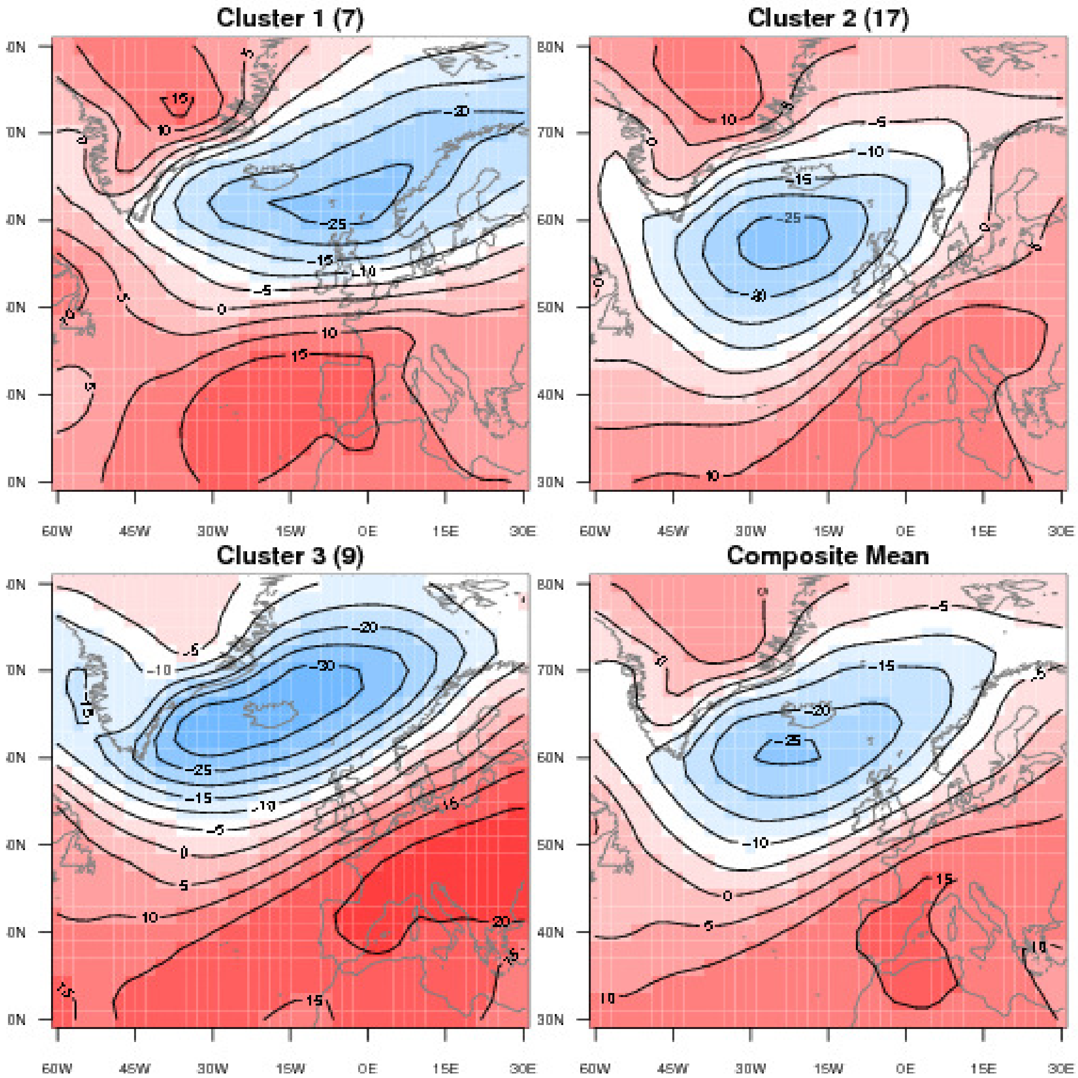

Figure 1: Hierarchical cluster analysis of the MSLP anomaly fields over the response time of the Eden at Temple Sowerby.

The primary role of the UCL team is to take responsibility for Work Packages 1c) (statistical downscaling and weather generator development) and 1d) (climate uncertainty analysis); and to contribute to Work Package 4 (project management including data management and knowledge exchange). Work Packages 1c) and 1d) are being carried out in close collaboration with the work being done at Reading on Work Packages 1a) (climate model performance) and 1b) (sensitivity of hydrological systems to climate inputs).

Most of the UCL progress to date has been in relation to Work Packages 1c) and 1d). Details are as follows:

Work Package 1c): The first task here was to establish the precise requirements of the other project teams, in terms of downscaling and weather generator outputs for use in Work Packages 2 and 3. It has been established that the weather generator will need to provide hourly, multi-site sequences of eight different weather variables (rainfall rate, air pressure, snowfall rate, air temperature, wind speed, specific humidity, downward short wave radiation and downward long wave radiation).

The next step was to acquire and pre-process the necessary data for weather generator development and calibration in the project case study areas (i.e. the Thames and Eden catchments). All available hourly data from both catchments, for the period 1950-2011, have been extracted from the Met Office MIDAS data set. The data were obtained from the British Atmospheric Data Centre. There are 157 stations contributing hourly data in the Thames catchment area, and 35 in the Eden. A substantial amount of effort has been expended in pre-processing the data, dealing with data quality problems such as (conflicting) duplicate observations, and creating a clean archive of hourly data that is suitable for model development. This pre-processing is now almost complete.

The development of a multisite, multivariate, subdaily weather generator is a nontrivial task. As far as we are aware, there are no existing generators in existence that meet all of these requirements (UKCP09 provides only a single-site generator, for example). To achieve this within the time scale of the project it will be necessary to take some short cuts. We have completed some preliminary analysis of hourly data from both the Thames and Eden catchments, which suggests that adequate performance can be obtained by focusing most attention on the generation of multisite daily sequences and then using a relatively simple procedure to disaggregate these to an hourly resolution. The development of the daily generator, using generalised linear models (GLMs), is now starting.

A review of weather generators has been carried out. All existing daily weather generators start by producing precipitation sequences; other variables are then generated conditional on the precipitation. This approach is slightly non-physical however: on the advice of the Reading team, we have also carried out a review of the structure of numerical weather prediction (NWP) models from which it is clear that in physical terms it is the pressure field that controls the other variables. To maintain consistency with the underlying physics as far as possible, we propose to mimic the ordering of the variables in NWP models as we develop our weather generator. The GLM-based approach makes this feasible.

Over the next three months, we aim to produce a preliminary framework for generating two or three of the primary variables in the weather generator. Many of the challenges here relate to the creation of a software environment that is relatively easy to use and does not involve the user in cumbersome manipulations of multiple data files. We aim to build on the existing GLIMCLIM platform to achieve this.

Work Package 1d): In this work package, we are committed to building on the methodology of Leith and Chandler (2010, *Applied Statistics*) as a way to handle uncertainty in projections of future climate. This methodology has now been extended to the point where it can now be used to make probabilistic statements about future climate, taking account of features such as shared discrepancies and biases in climate models. A paper is currently under revision for *Climatic Change*.

The UCL and Reading teams have been working closely together to ensure that the contributions to Work Package 1 form an integrated whole. The teams will continue to work closely during the development of the daily weather generator.

Work package 2: Prediction under new extremes and non-stationarity (British Geological Survey and Imperial College London)

Prof Denis Peach, Dr Andrew Hughes, Dr Chris Jackson, Mr David Macdonald, Ms Stephanie Bricker
Dr Neil McIntyre, Dr Adrian Butler, Dr Nataliya Bulygina, Mr James (Mike) Simpson, Ms Christina Bakopoulou, Prof Howard Wheater, Ms Kirsty Upton

The first attempt at appointing a BGS post-doc failed and BGS are in the process of re-advertisement with a closing date at the end of September. Study areas and workscope have been identified as:

Thames Basin	Oxford – role of groundwater flooding.
	Colne Valley – impact of drought on Chalk adited abstraction sources

Pang/Lambourne – impacts of extreme event on Groundwater flooding and in droughts on groundwater resources and stream flow
Jurassic Limestones – baseflow and abstraction under drought conditions

Eden Valley	Recharge and security of groundwater abstraction

Role of hydrogeology in flooding

Isle of Wight	Support for development of conceptual models

Work has included linking ZOOM3QD and Infoworks RS (Fluid Earth) models for Oxford. In Pang/Lambourn, understanding of karst, sub-karst and Palaeogene deposits in supporting baseflow in Chalk is being developed using River Pang and Lambourn as examples. In particular, the model behaviour of Blue Pool as perennial head of Pang under drought conditions – model development underway with a Masters student project. A field trip was undertaken to examine sinking streams and karst structures in the Palaeogene.

Jurassic Limestone of Cotswolds: conceptual understandings of the groundwater flow regime, interconnections between Inferior and Greater Oolite, and the role of the outcrop in groundwater storage are being developed. Also the role of the large tract of Thames gravels at the down dip edge of the Jurassic in supporting baseflow in Thames and providing groundwater storage is being investigated. Work on a conceptual model and water balance is well underway, a 3D geological model is being dveloped, and data collection more or less complete. Three field trips have been undertaken.
Thames Valley (as a whole): a preliminary understanding of the relationship between the several aquifer systems has been developed, as has an approach for modelling the whole groundwater and surface water system by linking a variety of. An initial generic paper in preparation. A talk for Geological Society of America Conference (October) is in preparation.

Eden Valley: The project is in the data gathering phase. Until a post-doc is appointed, rapid progress will not be made. A field trip to examine geology and hydrogeology revealed great complexity in the catchment, ranging from lowland permeable granular aquifers, high level karst aquifers, variable till cover and hard-rock poorly permeable mountainous areas. Preliminary conceptual diagrams of hydrogeological systems have been prepared. Lack of physical property data is likely to be an issue.

Colne Valley: The conceptual / hydrogeological model development for the Colne is due to begin in Jan 2012

Under an associated PhD (Kirsty Upton), in collaboration with Thames Water, new methods for multi-scale groundwater yield modelling are under development, with a new approach to small-scale (single borehole and borehole cluster) modelling being tested.

The Isle of Wight case study (Imperial PhD, James Simpson) was initiated in Feb 2011. Historic environmental data from the Isle of Wight have been collected and examined, including rain gauges, groundwater level logs, river gauges and anthropogenic abstractions and discharges. A set of catchments and river gauge based watersheds for surface water has been developed, and continuous rainfall and evaporation datasets. Early conclusions are that the Isle of Wight has a very complicated groundwater system, presumably because of the steeply dipping and compressed geology along the Isle of Wight-Purbeck Monocline and the high volumes extracted from groundwater.

Work package 3: Improving land surface-atmosphere models (Imperial College London and British Geological Survey)
Dr Neil McIntyre, Dr Adrian Butler, Dr Nataliya Bulygina, Mr James (Mike) Simpson, Ms Christina Bakopoulou, Prof Howard Wheater
Prof Denis Peach, Dr Andrew Hughes, Dr Chris Jackson, Mr David Macdonald, Ms Stephanie Bricker

The Research Associate at Imperial, Nataliya Bulygina, has been working half-time on the project since Jan 2011 (will transfer to full-time on 12 Sept 2011).

Research at Imperial has included a literature review on land surface models (LSMs), presented in the inception report. In summary: Over the last four decades LSMs underwent through a variety of structural changes resulting in three model generations. The first generation models are often called "Manabe bucket models" and have the following distinctive features:

- Globally constant soil depth and soil properties,
- No heat conduction into the soil,
- Water content limited rate of ET,
- And saturation excess runoff generation.

A decade later, the second generation models were developed, so that the models got the following distinctive characteristics:

- Several soil layers (two or more) with location specific properties,
- Modelling of vegetation impacts on energy, water budgets, and momentum transfer,
- Soil type specific Richards' equation based subsurface water transfer,
- And saturation/infiltration excess surface runoff generation.

These models outperformed the first generation LSMs, and improved modelling of surface-atmosphere interactions on the time scale of days.
Carbon balance modelling and improved representation of vegetation conductance (to calculate ET) constitute the main advances in the third generation LSMs (which includes JULES).
There have been a number of projects comparing different LSMs. For example, the GWSP/EU-WATCH project applied 10 surface exchange schemes of various complexities to large catchments around the world, using the same driving data. The results show that there is a significant difference in inter-model simulated annual ET and runoff (±40-100%).
To conclude, structures of the state-of-the-art LSMs approximate large scale physical processes using point-scale laws, and rely on various system simplifications. The effects of such assumptions are not known, and the corresponding prediction uncertainty has not yet been properly evaluated.

Research at Imperial has also looked at sensitivity of soil moisture and evaporation flux estimations to the limitations of JULES associated with the lower boundary condition, 1-dimensional nature and the absence of groundwater. This was achieved by comparing JULES outputs for a Chalk hillslope with those of one and two-dimensional finite volume subsurface models previously developed under NERC's FREE programme. This demonstrated, as expected, the large effect on the time-distribution of runoff due to the lack of a groundwater component in JULES, and the large effect on soil moisture of the free drainage lower boundary at 3m depth. For the tested hill-slope, with a deep groundwater table, there was no significant error introduced into the evaporation estimate. Further sensitivity analyses on a wider range of hill-slopes will be conducted.

An associated PhD project (Christina Bakopoulou) is:
1. Testing performance of the Land Surface Model JULES at a range of spatial scales; point, small (1 km2), subcatchment (Pang/Lambourn) and catchment (Thames catchment).
2. In the case that model performance is found to be poor or unacceptable, the JULES parameter specification and, if appropriate, the model structure, will be revised.

A literature review has been conducted, including reviewing relevant calibration methods and previous point-scale studies with JULES. .
Data sets originating from NERC's LOCAR programme at Grimsbury Wood in the Pang catchment (Thames basin) have so far been used to test point-scale performance. The results revealed the model outputs are broadly representative of the observed hydrology, however parameter calibration is beneficial. The next step under the PhD will be the implementation of sensitivity analysis and parameter calibration techniques for the point scale.

Appendix A: project contacts and websites

NERC's CWC programme: http://www.nerc.ac.uk/research/programmes/cwc/facts.asp
HYDEF site:
http://www3.imperial.ac.uk/ewre/research/currentresearch/hydrology/changingwatercycles

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