Hydrological extremes and feedbacks in the changing water cycle (HydEF)
PROGRESS REPORT
Aug 2011 – Feb 2012

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 is producing 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 is:

a) exploiting 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) building 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) seeking 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 (more detail is given in work package reports below)

All the project research staff and students were in place by August 2011 (see list of project team in App 1), with the exception of the BGS post-doc, who, all going well, will be appointed in March 2012.

One project meeting has been held in this 6-month period (January 2012), as well as multiple sub-project meetings and meetings with scientific collaborators and stakeholders. One steering group meeting was held, in Feb 2012. One CWC programme meeting was attended by various project members in Sept 2011.

Additional dissemination work has included various abstract submissions and attendances at conferences, convening of one conference session, a journal paper submitted (Reading?), and relevant contribution to a water industry project.

Elements of the work that have continued from the previous period are:

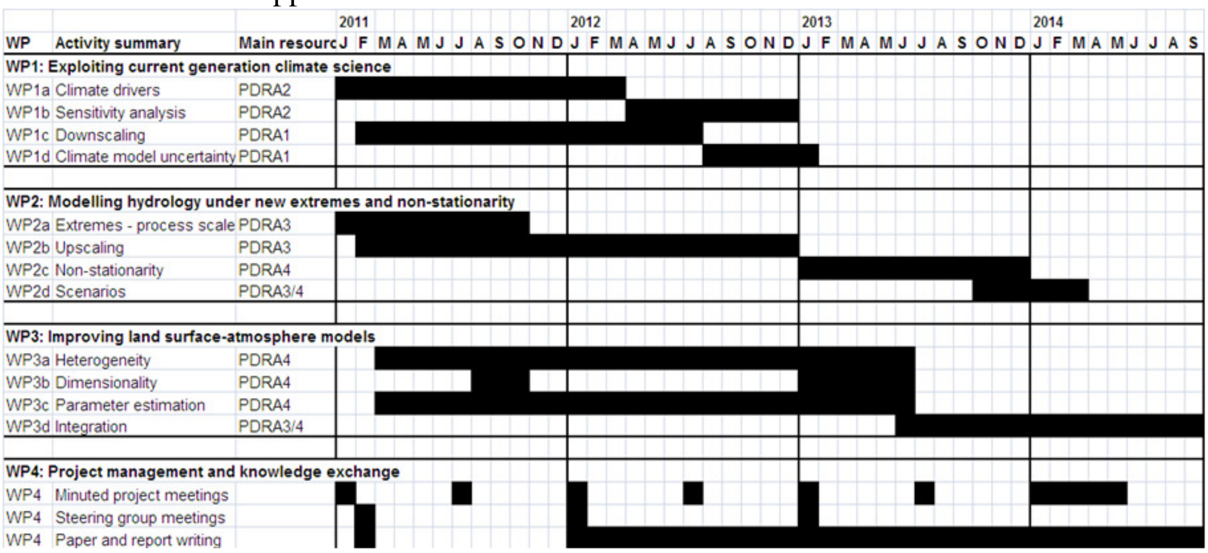
- data collection and formatting for the Thames and Eden, in particular hourly BADC climate data, land cover, HOST and soil property data sets.
- model sensitivity and performance analysis to identify issues with JULES at point and hill-slope scales,
- insights into synoptic climate controls on hydrology,
- development of understanding and initial conceptual models of Thames and Eden hydrogeology, in particular the Cotswolds.
- local scale borehole modelling methodology development,

- project management,
- website upkeep.

New items of progress are:
- data collection and field visit for the of Isle of Wight case study, and initial analysis,
- application of JULES to the Kennet catchment and result evaluation,
- initiation of linking JULES to the groundwater model, ZOOM,
- results and publication showing links between ‘atmospheric rivers’ and UK winter floods and initial development of indices for downscaling.
- pre-processing of hourly data from the MIDAS dataset.
- creating an interface to the GLIMCLIM (UCL climate downscaling software) from the freely-available R environment.

Updated work programme

The updated programme is below. Significant changes to the original work programme are: The UCL programme is moved forward because of the early appointment of Chiara Ambrosino. The Imperial programme is 7 months behind schedule due to the initial part-time effort and current maternity leave of Nataliya Bulygina. The BGS programme is behind schedule due to late appointment of PDRA3.



Project Meetings

A Project and Steering Group meeting (see list of members in App 1) was held at Reading on 18th January 2012. The project was represented by 8 members at the CWC programme meeting on 29-30 Sept 2011. Additionally, various intra-project meetings and meetings with CEH staff and other partners have been held. The project will be represented at the CWC/Storm Risk programme meeting on 1-2 May 2011. The next full project meeting will be at Wallingford on 27th June 2012, followed by a field trip to the Cotswolds on the 28th.

Presentations from all meetings are available from the project website
http://www3.imperial.ac.uk/ewre/research/currentresearch/hydrology/changingwatercycles

Knowledge exchange activities

The project co-convened a session at the AGU meeting in San Francisco in Dec 2011 "Developing the Science for High Resolution Water-Energy-Biogeochemical Cycle Modeling" with Eric Wood of Princeton, James Famiglietti of UC Irvine, and Eleanor Blyth of CEH.

Meetings: Project steering group meeting Feb 2012 and CWC programme meeting Sept 2012.

Intra-CWC and JULES working group collaboration.

Collaboration with EPSRC's FRMRC2, NERC/DFID's ESPA, NERC's VO, DEFRA/EA's DTC programmes.

Submission of conference abstracts for BHS 2012 and EGU 2012
"Sensitivity Analysis and Parameter Identifiability of the Land Surface Model JULES at the point scale in the Pang and Lambourn catchments' by Bakopoulou, Bulygina, Mcintyre and Butler

Project website upkeep.

Dr McIntyre and Dr Butler are part of a UK Water Industry Research project (UKWR27) led by consultant Halcrow. Ideas developed from the research for improved estimation of groundwater yields have been fed into the final report from that project.

Press interviews: Dr McIntyre provide "Le Monde" newspaper about the current drought in England and impacts of climate change.

Publications

Lavers, D. A., R. P. Allan, E. F. Wood, G. Villarini, D. J. Brayshaw, and A. J. Wade (2011), Winter floods in Britain are connected to atmospheric rivers, Geophys. Res. Lett., 38, L23803, doi:10.1029/2011GL049783.

Other outputs and achievements

N/A

Related funding

The project has been used to leverage European funding (Climate Knowledge and Innovation Community project) at Imperial.

Additional funding has been provided by the Grantham Institute for Climate Change, fully funding a PhD to extend the Isle of Wight case study to agro-economics.

A sister CWC project has been funded “Hydrometeorological feedbacks and changes in water storage and fluxes in northern India” led by Wouter Buytaert at Imperial.

The project has input into the EU COST action VALUE (http://www.cost.eu/domains_actions/essem/Actions/ES1102) which seeks to improve collaboration and transfer expertise between different communities with interests in the impacts of regional climate change.

An EPSRC-funded PhD student at UCL is working on climate simulator uncertainty; this work will feed directly into Work Package 1d of the present project.

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

This report is a brief summary of: Lavers, D. A., R. P. Allan, E. F. Wood, G. Villarini, D. J. Brayshaw, and A. J. Wade (2011), Winter floods in Britain are connected to atmospheric rivers, *Geophys. Res. Lett.*, 38, L23803, doi:10.1029/2011GL049783.

Damage from flooding in the winter and autumn seasons has been widespread in the United Kingdom (UK) and Western Europe over recent decades. Due to the prevalence of winter flooding, our research at Reading has focused on understanding the hydrometeorological processes responsible for flooding in UK river basins, as this is an important step in assessing the future risks of flooding in the UK.

Our work has shown that the 10 largest winter flood events since 1970 in a range of British river basins are connected to Atmospheric Rivers (ARs), narrow regions of high atmospheric water vapour content associated with large transports of moisture from the subtropics into the mid-latitudes. ARs are located in the lower troposphere within the warm sector of extra-tropical cyclones and are defined as areas of high water vapour content and strong winds. The large water vapour transport in ARs can lead to heavy precipitation and flooding when an AR makes landfall.

In November 2009 there was severe and devastating flooding in Northwest England. On 19th November the River Eden at Temple Sowerby experienced flood conditions following a three day rainfall total of 164.5 mm (Figure 1a). A deep low pressure (957 hPa) was situated to the south of Iceland and high pressure (1029 hPa) was located over southern Europe (Figure 1b). This circulation pattern led to a south-westerly air flow over the British Isles (Figure 1c), which was associated with an AR extending north-eastwards from the subtropics as shown in the 900 hPa specific humidity field at 0600UTC on 19th November (Figure 1d). As this moisture ascended in the warm sector of the extra-tropical cyclone and was then forced to rise over the Cumbrian Mountains, it was precipitated out, thus producing the high rainfall totals and flooding observed.

The role that ARs have in the occurrence of winter floods in the UK is highlighted by analysing the 900 hPa specific humidity field at 0600UTC on the day of the 10 largest winter flood events measured in the River Eden at Temple Sowerby basin since 1970 (Figure 2). Strikingly the top 10 winter floods are all accompanied by an AR with a similar southwest-northeast (SW–NE) orientation. This moisture is transported towards the UK by a south-westerly wind (e.g. Figure 1c) with both the large-scale ascent (in the warm sector) and orographic uplift leading to the water vapour being precipitated out, and in turn producing high rainfall totals and floods. Interestingly smaller winter floods are not necessarily associated with an AR over the river basin indicating that ARs are a characteristic of the biggest winter flood events in relatively flashy catchments.

In the future a change in frequency of AR occurrence is likely to affect the frequency of extreme winter flood events (especially in fast-responding basins). Furthermore the atmospheric water vapour content in a warmer climate is likely to rise, which is expected to lead to an enhancement of precipitation extremes. Therefore, our future research will assess AR occurrence under current projections of climate change.

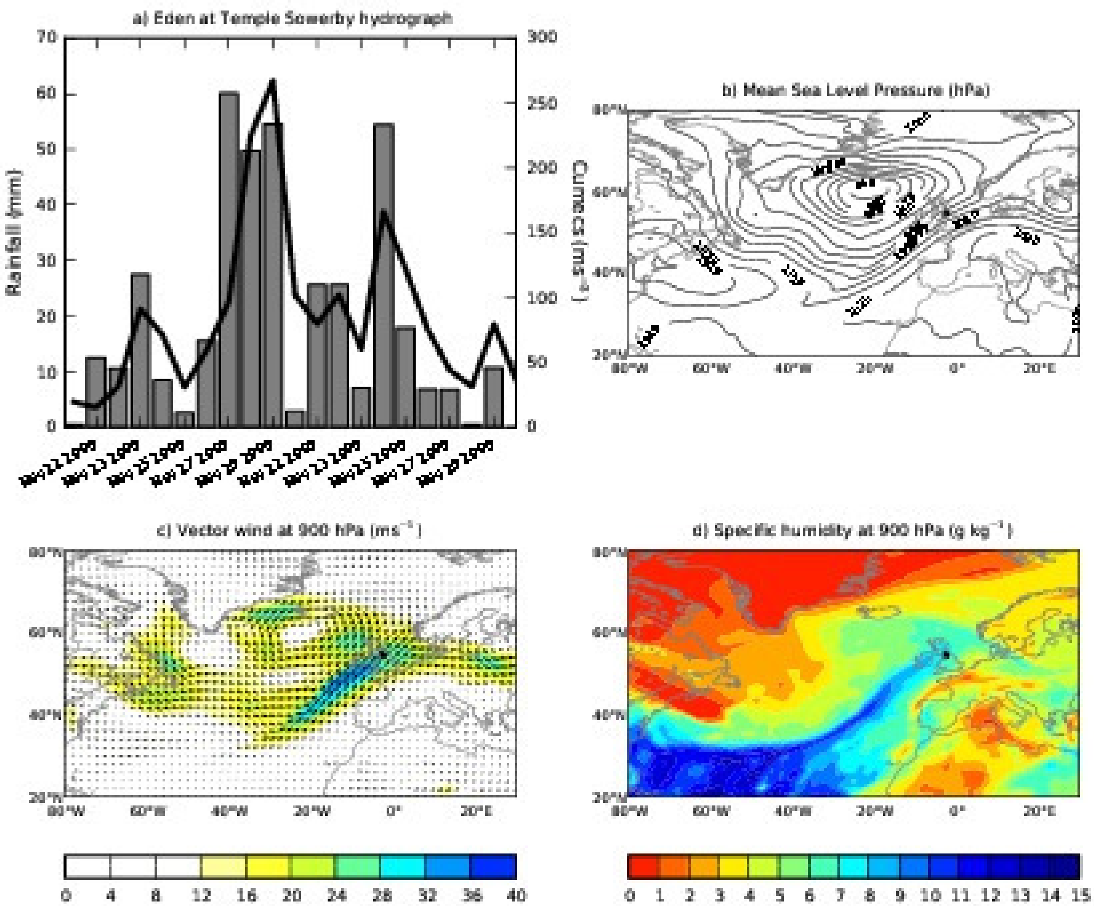


Figure 1: The 19th November 2009 flood event on the River Eden at Temple Sowerby (Cumbria): (a) the hydrograph of mean daily river flow (black line) and rainfall totals (grey bars); (b) the Mean Sea Level Pressure (MSLP) field (in hPa) at 0600UTC on 19th November 2009; (c) the vector wind at 900 hPa (in ms^{-1}) at 0600UTC on 19th November 2009; (d) the

specific humidity at 900 hPa (in g kg^{-1}) at 0600UTC on 19th November 2009. The black circle in Figure 1b–d marks the location of the River Eden at Temple Sowerby gauging station.

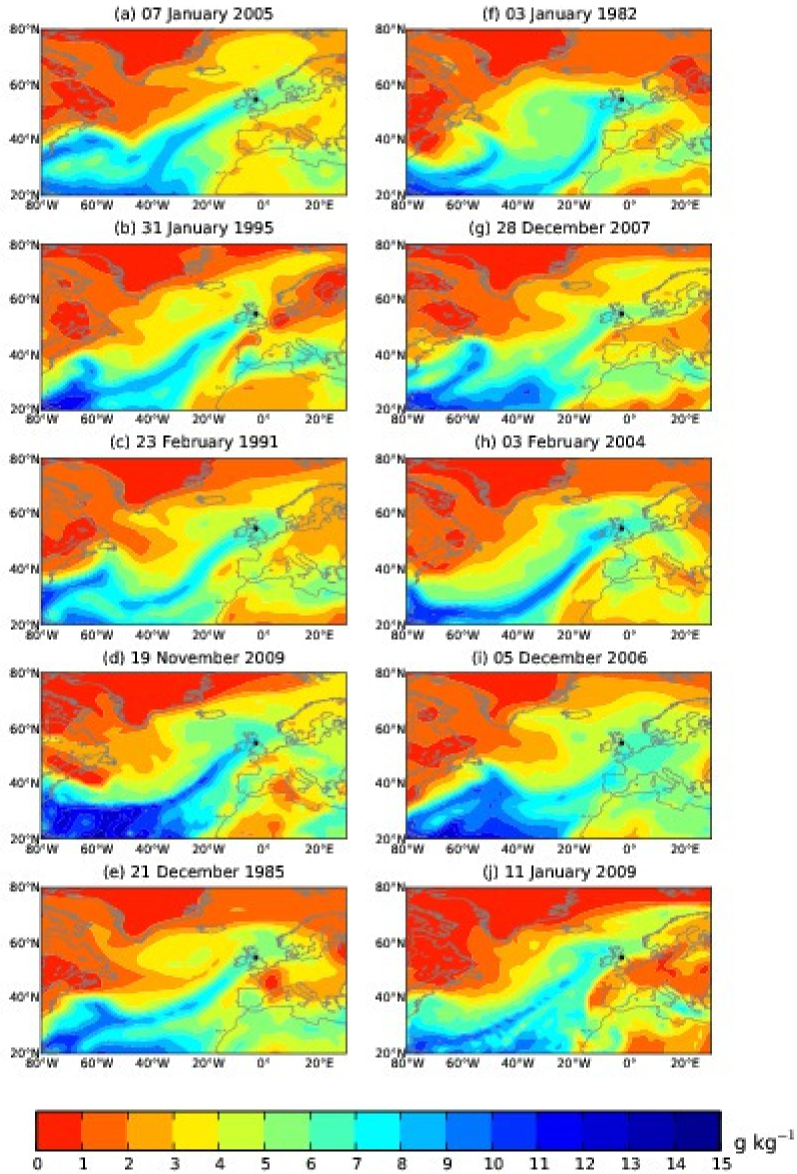


Figure 2: The 900 hPa specific humidity fields at 0600UTC for the top 10 (a to j) winter flood events on the River Eden at Temple Sowerby. The black circle marks the location of the River Eden at Temple Sowerby gauging station.

At the time of the last progress report, to support Work Package 1c the pre-processing of hourly data from the MIDAS dataset was almost finished. This has now completed and some preliminary analyses have been carried out. These analyses revealed that data for some of the required variables were missing from many of the stations where they were nominally available; and that record lengths at other stations were often short (see Table 1)

Table 1 Numbers of stations in the MIDAS dataset with hourly data for selected variables in the Thames and Eden catchments. There are 157 stations in total for the Thames, and 35 for the Eden.

	Stations with data	
	Thames	**Eden**
Precipitation	71	16
Pressure	52	7
Temperature	140	28
Wind speed	135	28
Short-wave radiation	22	2

We have explored the possibility of using additional daily data from the MIDAS dataset; however, following more extensive processing it has been found that daily data are available only for a couple of variables and that the additional benefit from their inclusion will be limited.

The shortage of data for some variables poses additional challenges for the modelling, since there is potentially large uncertainty in these variables. One possibility would be to move away from station records for model development and calibration, and to work with gridded data products instead; however, these products themselves rely on observations such as those in the MIDAS dataset and hence there may be large uncertainties in the supplied values here. Neglecting these uncertainties could have serious implications for hydrological impacts. We therefore propose to use multiple imputation to account for these uncertainties, by sampling the "missing" data from conditional distributions that are conditioned on all available observations. The GLIMCLIM software package provides this facility already for single variables; it will be necessary to build some imputation facility into the model calibration procedure in the multivariate case, however, so as to allow models to be fitted to data from sites where not all variables are available.

Elsewhere in Work Package 1c, the UCL and Reading teams are in continuing dialogue with a view to defining climate indices, informed by the Reading work in Work Packages 1a and 1b, that can be used to drive the weather generator development. The conceptual framework for the weather generator is in place, following the review of numerical weather prediction models discussed in the last project report; and some preliminary results have been obtained for the downscaling of sea level pressure in the Thames catchment. A considerable amount of effort has also been expended on the creation of a user-friendly software tool: this is being done by creating an interface to GLIMCLIM from the freely-available R environment (www.R-project.org). Unfortunately, progress here is slower than anticipated, due to unexpected constraints in the interface between R and the underlying Fortran code for GLIMCLIM. These difficulties have now been largely overcome, and we anticipate having some concrete results from the new software tool within the next three months.

Work on Work Package 1d is ongoing, with methodological development currently being undertaken by an EPSRC-funded PhD student at UCL. This will free up some more time for the UCL PDRA to concentrate on the weather generator development, which will be harder than originally envisaged due to the data availability and software challenges outlined above.

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

Three MSc projects were supported over the summer: understanding and simulation of flows at the Blue Pool springs in the Pang catchment, Berkshire; simulation of groundwater flooding in the Pang and Lambourn; and further conceptualisation of groundwater flow in the Cotswolds aquifers. A modelling system of the Blue Pool, including conduit and continuum models, was developed. Extra runs were undertaken of MaBSWeC to assess groundwater flooding under conditions of climate change. The conceptualisation of groundwater in the Cotswolds (Figure 3) was improved by undertaking a water balance and an attempt at using Artifical Neural Networks to simulate baseflow in the rivers Churn and Colne. The latter was supported by a field trip visit. As well as the MSc students, a MEng student project on the Eden catchment was started, supported by the development of a preliminary recharge model for the catchment.

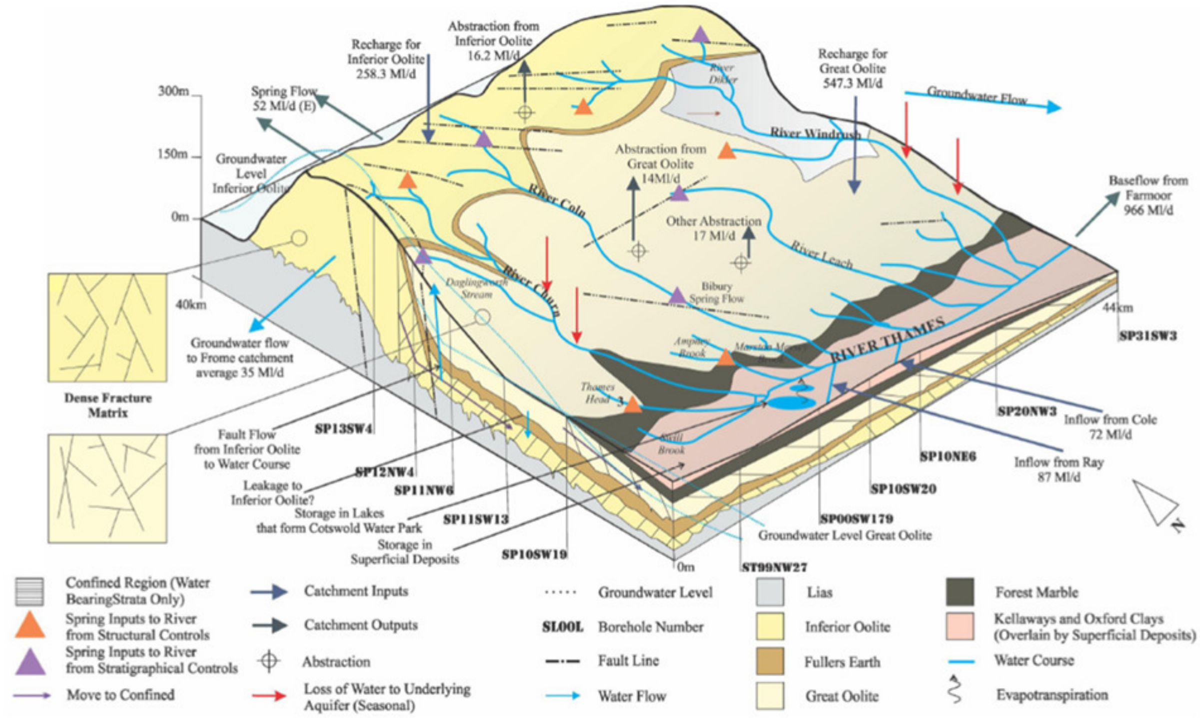


Figure 3. Conceptual model of the Cotswold hydrological system developed by BGS

An abstract on the proposed Thames basin modelling system was accepted as a poster for the Planet Under Pressure conference, to be held in March 2012. To complement this, a paper on the proposed modelling system has been drafted. An abstract was accepted for an oral presentation in the IAH Fractured Rock conference in Prague, May 2012.

To support the conceptualisation of groundwater flow to the Blue Pool, funding was sought and obtained to drill two piezometers in the Pang catchment. These were planned during this period and the drilling commenced later February. Assistence was provided to the PhD students working on the Isle of Wight by facilitating a meeting with the mapping geologists working on the island. Alongside these activities, the PDRA post was re-advertised and applicants sifted for an candidates to interview in early March.

The Isle of Wight case study is proceeding through the CWC-funded PhD studentship at Imperial (Mike Simpson). Following the development of the watershed-based subcatchments, water balance models of each catchment has been developed, based on historic data. These highlight areas where more data is required, specifically in streamflow and borehole records, which are being sought from the EA, Southern Water and the BGS. The existing borehole records have been used to identify coherent units within the groundwater through cluster analysis. These will form the basis of groundwater catchments in the conceptual model. A review of published models has allowed the development of basic conceptual model allowing calibration against borehole and streamflow records. This case study is being extended to hydro-economic modelling through a PhD funded by the Grantham Institute for Climate Change, which started in October 2011.

Kirsty Upton is in the second year of a PhD studentship, funded by EPSRC and supported by BGS and Thames Water Utilities Limited, to research and develop new methodologies for the evaluation of groundwater deployable output (GWDO). The subject matter is therefore of direct relevance to the Changing Water Cycle project and her work is regarded as an important component of the work at Imperial College. The aims of her research are to develop techniques for modelling pumped water levels at abstraction wells within regional groundwater models and thereby simulate constraints on abstraction rates due to the physical properties of the well (including the pump), the aquifer and the regional context. Such an approach would also enable historic droughts and climate change scenarios to be investigated, which is not possible using the current method for calculating GWDO. To date, she has developed a model of groundwater flow to a well using the Lattice Boltzmann Method (LBM). The LBM approach is based on a form of the Navier Stokes equation and can, therefore, represent the effects of turbulent flow, which is a key consideration when simulating abstraction wells in the Chalk. The results from the model are being compared with solutions derived based of the Forchheimer equation. The outcome from this analysis is being used to assess the most appropriate approach for the next stage of the work, which is to develop detailed well models that can be used to simulate abstraction water levels within BGS's regional groundwater model ZOOMQ3D.

<u>Work package 3: Improving land surface-atmosphere models</u> (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 transferred from part-time on the project to full-time on 12 Sept 2011, and has been on maternity leave from 1st January 2012 to date. An independently funded PhD student, Christina Bakopoulou, is also working on the JULES research.

Research into the evaluation and development of the JULES land surface model has continued. JULES has been included within a Monte Carlo framework to explore parameter uncertainty and sensitivity. Linking with NERC's Virtual Observatory programme, this has been set up to run on a server and is amenable to 'cloud' computing. Running on a parallel processing facility is envisaged. The Monte Carlo analysis has been applied to assess point scale performance and uncertainty of JULES at sites instrumented under NERC's LOCAR programme, with data provided by CEH. Results show reasonable performance for the upper soil layers especially after calibration of the key hydrology parameters, but reducing performance as depth increases, due to the simplistic lower boundary condition.

JULES has been applied to the Kennet catchment. Globally-available soils data was used, to represent the degree of spatial resolution used operationally in GCM runs. Different versions of JULES have been tested: the Topmodel, PDM, default and extended soil column versions. Results illustrate significant (up to 10%) differences in evapotranspiration fluxes depending on which version is assumed. None of the versions perform well when compared to streamflow data, and those that perform best don't have physically sensible model structures for this catchment (principally, no groundwater routing). Hypotheses for the poor performances are formulated and will be tested in the following 6 months. Work has begun recently on coupling JULEs with the ZOOM groundwater model. It was decided not to pursue the hill-slope modelling started in the previous period. This relied on good quality benchmark models, which could not easily be developed for the other hill-slopes of interest.

An updated version of the JULES in groundwater strategy has been written, reviewed and revised. Further work on this is necessary after discussion with CEH.

Data: Licenses have been obtained from CEH for the use of HOST and Landcover2000 data bases; and from NSRI for use of Natpmap1000, Soils Horizons and Soils Fundamentals databases.

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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