Joint Centre for Hydro-Meteorological Research

Report on research activities: 24 March to 9 October 2009

1. Short Term Ensemble Prediction System (STEPS)

Work during this period has focused on three areas: improving the execution speed of STEPS on the IBM supercomputer, improving model performance and investigating cases of apparent poor performance reported by the Environment Agency.

The migration of STEPS to the IBM supercomputer from the NEC SX8 was completed successfully in May 2009. STEPS has been configured to run simultaneously on 6 processors allowing an ensemble of 30 members (5 members per processor) to be generated every hour within 15 minutes of data time. Tests showed little change in execution times between the two platforms despite a change in the processor architecture from vector to scalar. Nonetheless, improvements in the execution efficiency of STEPS have been sought to facilitate the generation of larger ensembles. In September 2009, a 6-level cascade decomposition based upon a scale ratio of 0.3 was introduced. This replaces the 8-level decomposition used prior to this. Comparative verification and case study analyses of the two configurations have shown no loss of model performance but significant improvements in execution times (~20%) when using 6 cascade levels.

Case studies have demonstrated occasional problems with managing the mean and variance of the STEPS nowcasts of precipitation rate. A new probability matching technique has been developed, tested and implemented to address this issue. The target probability distribution at each nowcast step is created by sampling the extrapolation (radar) and MetUM-4km model forecast fields of instantaneous precipitation rate in proportion to their assigned weight in the control and ensemble nowcasts. Tests have shown that this technique reduces the forecast bias and ensures that the target nowcast distribution of precipitation rate tends from the radar-inferred distribution towards that of the MetUM-4km forecast with advancing lead time. In the control nowcast, this ensures that the nowcast evolution moves seamlessly from the extrapolated radar to the most recent MetUM-4km model forecast by T+6 h.

Over the summer of 2009, flood forecasting duty officers using STEPS accumulation nowcasts in the Environment Agency reported several occasions when STEPS appeared to provide poor guidance during significant precipitation events. These cases were investigated thoroughly. On one occasion, the cause of a poor advection nowcast was traced to the failure of a radar data feed from the Met Office's radar data processing system (Radarnet-IV) to the UKPP suite. On another occasion, errors in a MetUM-4km model forecast of a frontal wave development led to marked changes in nowcast precipitation accumulations over a small catchment in the Midlands during the course of an afternoon. It was concluded that the provision of an ensemble of nowcast solutions would have provided useful guidance on the uncertainty in the STEPS control nowcast. A presentation summarising these findings was made to an Environment Agency user group meeting involving representatives from each of the Agency's eight regions on 29 September 2009.

2. Use of probability forecasts

This jointly funded Met Office and Environment Agency project began in May 2006. The first phase of this project (financial year 2006/07) established an initial Environment Agency user requirement for probabilistic precipitation forecasts in relation to fluvial flood forecasting and warning.

In 2007/08, a second phase of the project implemented a web-based operational trial of probabilistic precipitation forecasts for the Environment Agency. This trial included the provision of MOGREPS NAE (North Atlantic and European configuration of the Met Office Global and Regional Ensemble Prediction System) based probability of exceedence maps and stacked probability charts for predefined areas and rain accumulation thresholds. Following completion of the trial in December 2007, a workshop was held to review feedback and clarify aspects of the user requirement.

A third phase of the project commenced in July 2008. This has overseen the launch of an operational, interactive web service hosting a range of probabilistic precipitation nowcast and forecast products tailored to the flood forecasting requirements of the Environment Agency. At present, the products generated for the web site are confined to Heavy Rainfall Warning area based stacked probability charts based upon MOGREPS-R forecast ensembles and STEPS nowcast ensembles. The service started in April 2009.

3. Blending convective scale NWP with ensemble nowcasts

This Met Office and Environment Agency jointly funded project aims to integrate precipitation forecasts generated by MOGREPS, STEPS and a high resolution (1.5 km) configuration of the Unified Model to produce a seamless, high-resolution ensemble precipitation forecast, suitable for driving hydrological models and for use by forecasters.

The proposed blending algorithm will exploit the STEPS cascade model framework to allow the scale selective combination of the various model forecasts. The resultant, blended ensemble forecast will have a horizontal resolution of $\leq$ 2 km and a forecast range of several days.

A paper proposing several possible blending formulations was circulated in autumn 2007. A report reviewing the comparative performance of the models on eight precipitation case studies from 2007 was prepared in January 2008. Following completion of this report, work was suspended as a result of staff shortages. The project re-commenced in November 2008 with the completion of a detailed software design for the blending algorithm. Coding of the algorithm started in May 2009 and is nearing completion.

A 24 member MetUM-1.5 km ensemble precipitation forecast has been run for the Ottery St Mary storm of 29 October 2008. Boundary conditions and initial condition perturbations from a 24 km resolution MOGREPS-R ensemble were used. These data will be employed to test variants of the blending algorithm formulation during autumn 2009.

4. First guess extreme rainfall alerts

Following the joint development by Met Office staff at the JCHMR (Wallingford), JCMM (Reading) and the Mesoscale Model Development & Diagnostics group (Exeter) of an automated, first guess extreme rainfall alert capability in support of an Extreme Rainfall Alert pilot service (launched in July 2008), an evaluation of this service was undertaken in December 2008 and a report written including a performance summary and recommendations for operational implementation.

The pilot service was deemed to have been a success, although some enhancements were recommended prior to the launch of an equivalent operational service in June 2009. These enhancements were implemented in May 2009. They include calibrated probabilities of exceedence inferred from time-lagged, MetUM-4km ensemble precipitation forecasts, the generation of these probabilities of exceedence on a regular, square grid across the UK and the visualisation of probability of exceedence fields for use by forecasters and flood warning officers in the joint Met Office and Environment Agency Flood Forecasting Centre. A parallel trial of an equivalent service based upon MetUM-1.5km ensemble precipitation forecasts is planned for autumn 2009.

5. Development of MOSES-PDM within the UKPP system

The current implementation of MOSES-PDM within the UK NWP Post-Processing (UKPP) system, which provides diagnoses of surface and sub-surface hydrological variables, has its soil property ancillary fields (including the van Genuchten parameters) based on the IGBP soils database. The resolution and accuracy of the IGBP data are no longer thought to be the best available.

The land surface ancillary fields and data assimilation group at the Met Office in Exeter has derived new soil property ancillary fields for the various NWP configurations of the MetUM from the Harmonised World Soil Database (HWSD). UKPP-MOSES-PDM currently supplies the UK soil moisture analyses for the operational high-resolution NWP models. It is desirable that the analyses and forecast models use consistent soil (and land use) ancillaries. Work has therefore started to make soil property ancillaries based on the HWSD for UKPP-MOSES-PDM. These will be tested in a version of the UKPP-MOSES-PDM, running in parallel to the operational version, to determine the impact on hydrological variables.

6. Flood modelling and forecasting

6.1 Weather Radar and Flood Forecasting System Developments

CEH's Hyrad system supports the real-time receipt, processing and display of weather radar and hydro-meteorological space-time images, especially for use in flood and water resource management. It is being used by the Environment Agency across England and Wales and by SEPA in Scotland to display Met Office hydrometeorological products and to support interfaces to their flood forecasting systems.

RFFS Developments

CEH's RFFS (River Flow Forecasting System) suite of modelling software encompasses both Model Calibration tools for application off-line and Model Algorithms streamlined for real-time use. The Model Calibration suite includes: "PDM for PCs" rainfall-runoff model, "KW for PCs" channel flow routing model. "PSM for PCs" rainfall-runoff model (encompassing the TCM and IEM models) and the PACK snowmelt model. These are in use by the Environment Agency as part of their NFFS (National Flood Forecasting System) deployment throughout England and Wales. The real-time Model Algorithms PDM (including data assimilation by state correction), KW and ARMA error predictor are being used within flood forecasting systems operated by SEPA in Scotland.

An extension has been made to the PACK snowmelt model adapter to output time-series of model state variables on the water content of the snowpack. These will then be available for inspection in real-time to support understanding of the depletion of the pack during snowmelt flood events. A guide to the PACK snowmelt model has been prepared in support of this new release to the Environment Agency and SEPA.

Hyrad Developments

With the above developments, the EA and SEPA have the capability to use Met Office hydrometeorological products (radar, NWP and MOSES), via CEH's Hyrad system, for use in flood warning and water resource management throughout England, Wales and Scotland. Hyrad is also being used to support RFFS-FloodWorks applications in Dender, Centrale, Demer and Dijle catchments in Belgium. The new release of Hyrad, outlined in the previous report and supplied to the EA and SEPA, is currently being prepared for use across Belgium. There have been modest support and maintenance activities relating to the Hyrad operational systems in the reporting period.

Rainfall-runoff models extended for groundwater catchments

The PDM rainfall-runoff model formulation had been previously extended to accommodate groundwater pumping, external springs and underflows: these influences can lead to ephemeral flow in chalk streams. The Environment Agency Southern Region have contracted CEH to evaluate the model on the rivers Lavant and Ems, with the eventual aim of including the extensions in the PDM model used operationally within the NFFS if successful. The Final Report was completed in September 2009. This reported on data collection and quality control, developed a strategy for modelling and implemented this for the rivers Lavant and Ems. Model calibration and assessment demonstrated good performance supporting a recommendation for future operational deployment. Sensitivity analyses on the forms of model input to use operationally supported recommendations on the combinations of raingauges to use, the value of radar rainfall, and the profiles of potential evaporation and abstractions to employ. An emulation of the real-time application of the models in forecast-mode demonstrated their potential to forewarn of rapid rises in river flow during the onset of major flood events, such as that affecting Chichester in January 1994.

Of hydrometeorological interest is a comparison of the operational MOSES and MORECS products over these catchments. In contrast to the comparison by Hough (2003), which used MORECS-based input data to MOSES, MOSES was found to consistently estimate more PE than MORECS when monthly totals were compared from July 2005 to August 2008; the relative difference increases with increasing PE. Modelled river flow is therefore likely to be reduced if MORECS is simply swapped for MOSES in existing rainfall-runoff models calibrated using MORECS PE as input. A MORECS long-term annual average profile is recommended for operational use as consistent with the model calibration, subject to tactical review in unusual years. A future trial of MOSES is recommended when sufficient records and flood events are to hand.

6.2 Flood modelling for ungauged basins

The Environment Agency are seeking improved ways of providing warnings for ungauged and low benefit locations that presently receive only a general Flood Watch service. CEH was commissioned, under the EA/Defra National R&D Programme, to develop and evaluate improved techniques for flood forecasting at such locations with the eventual aim of the Agency offering a more targeted and technically sound flood warning service. The final reports are now freely available on the web (see Publications list on the JCHMR web site), whilst highlights are contained in IAHS Publication 305.

Ongoing developments under this theme, now funded under the CEH Science Budget, are focussed on the Grid-to-Grid Model for area-wide forecasting. Improved formulations for runoff-production, utilising terrain/soil/geology/land-cover spatial datasets, and for flow routing are being explored through regional and nationwide case-studies.

A paper on “Distributed hydrological modelling using weather radar in gauged and ungauged basins” has been published in “Advances in Water Resources”.

6.3 Flood forecasting using NWP model rainfalls in deterministic and ensemble forms

The NERC FREE (Flood Risk from Extreme Events) programme is funding a three year project, that started in January 2007, entitled “Exploitation of new data sources, data assimilation and ensemble techniques for storm and flood forecasting”. This project provides an important opportunity for collaboration between meteorologists at Reading (the University and Met Office JCMM) and CEH hydrological modellers at the JCHMR, Wallingford. The aim is to obtain probabilistic flood forecasts through using ensembles of high-resolution NWP rainfalls as input to hydrological models, using data assimilation to improve the initialisation of the models. CEH's component of the project is concerned with research on initialisation, data assimilation and uncertainty for hydrological flood models.

Work in the present reporting period has continued to work on initialisation and state-correction for an extended form of the G2G Model (this employs spatial data on soil properties as a control on runoff production and alternative routing functions). Experience is being gained on the use of different schemes that is supporting decisions on operational deployment across England and Wales.

Ongoing collaboration with Reading University on the use of physically-based ensembles of NWP rainfall in probabilistic flood modelling is developing a case study around the Boscastle convective storm. Ensembles are being generated by perturbing the potential temperature in the NWP model which impacts on the buoyancy of the atmosphere and the initiation of convective storm cells. The first set of ensembles have been received at Wallingford and work is ongoing concerning there use in the G2G Model to produce ensemble flood forecasts and real-time flood risk maps.

CEH convened a session at EGU2009 (20 April 2009) on "Uncertainty and data assimilation in hydrological forecasting" and presented a paper entitled "Model initialisation, data assimilation and probabilistic flood forecasting for distributed hydrological models". The paper presented first results on probabilistic flood forecasting in spatial form: flood risk maps of flood exceedance were obtained using pseudo-ensemble NWP rainfalls as input to the G2G Model.

An invited paper entitled "Challenges in data assimilation for hydrological forecasting" was presented at the workshop on "Data assimilation for hydro-meteorological hazard forecasting" within the Royal Meteorological Society Conference (University of Reading, 1 July 2009).

A keynote paper was presented at the 3rd FREE Science Meeting (University of Plymouth, 10 September 2009) entitled "Initialisation, data assimilation and uncertainty for hydrological flood models".

A poster entitled "Ensemble Flood Forecasting" was presented at the NERC FREE Ensemble Workshop (Wokefield Park, Reading, 23-24 September 2009). CEH scientists also served as chair and rapporteur of a Breakout Group on "Propagation of uncertainty between models". A "white paper" is being prepared for the Natural Hazards theme leader and a discussion journal article (for HESS Discussions) on the potential future research directions is planned.

6.4 Hydrological modelling using convective scale rainfall modelling

The EA/Defra Project 'Hydrological Modelling using Convective Scale Rainfall Modelling' is a collaboration between Deltares and CEH that began in January 2007 and ends in Autumn 2009. This Environment Agency led project is a response to ongoing enhancements in the Met Office to its numerical weather prediction capability, including its nowcasting STEPS (2km out to 6hours) and MOGREPS (24km out to 2 to 3 days) systems both providing ensemble rainfall forecasts. These developments offer interesting opportunities for the Agency and help prepare for using a probabilistic approach to flood forecasting in operational practice. Operational research is required to realise the potential benefits of these developments to the flood warning service of the Agency.

In addition, Met Office research is aiming to improve the prediction of convective events by using much finer grid sizes, moving from 12km to 4 (now operationally available) and 1.5km models. With such data available as input to hydrological models, it should be possible to predict the risk of flooding more accurately and with longer lead times. However, the potential benefits for operational flood warning will only be fully realised if appropriate hydrological modelling concepts are applied. The project aims to investigate what hydrological model concepts and associated computational methods allow for making best use of the latest Met Office developments in NWP. A focussed aim is to make operational the use of ensemble data generated by the Met Office's regular weather models as well as considering the future potential of convective-scale rainfall predictions. The project aims to employ both operational lumped rainfall-runoff models and new distributed hydrological models as part of the investigation.

CEH is responsible for the application of the lumped PDM rainfall-runoff model and the G2G area-wide hydrological model within the project; the latter model is especially relevant for flood forecasting and warning at ungauged locations. The NFFS, based on Delft-FEWS system environment, is being used to trial the use of these models in an historical emulation of the operational system.

Phase 1 of the Project was concerned with "inventory and data collection". The Grid-to-Grid (G2G) Model was developed in Module Adapter form, allowing the model to be used in the Project to emulate operational use within the NFFS environment. Because the G2G Model employs gridded rainfalls as input, a Module Adapter form of HyradK was developed to calculate gridded rainfalls from either raingauge data or raingauge-adjusted radar data. To facilitate efficient transfer of space-time data in and out of the Grid-to-Grid Module Adapter, use was made of Hyrad's Spatial Image DataBase, SIDB, as part of the Module Adapter software. Note also that CatAvg had previously been developed as a Module Adapter for the EA to calculate catchment average rainfall from gridded rainfall data. These integrated developments culminated in the 'CEH Spatial Hydrology Module Adapter'. This brings together CEH's spatial hydrology processing applications and models under one umbrella providing a harmonised interface to facilitate integration with the NFFS.

A large case study area over Southwest England, encompassing Boscastle, was chosen under Phase 1 as the focus of the Phase 2 'Pilot' work. This was used to assess the performance of lumped and distributed models for a variety of catchments, some treated as ungauged, and also investigated their suitability for use in producing probabilistic flood forecasts. A collaboration between CEH and the JCMM (Met Office) employed high-resolution NWP model rainfalls for the Boscastle storm to generate pseudo-ensemble NWP rainfall forecasts. These emulate (at a functional level) NWP ensemble rainfall products that will become available in the future. A Feedback Workshop with the Agency was convened on 1-2 April 2008 and an internal report on the Phase 2 work completed in July. Phase 2 of the project demonstrated that the G2G distributed hydrological model, set up using a digital terrain model, can be operated on the Environment Agency's National Flood Forecasting System (NFFS) platform, with short enough run-times for use in real-time forecasting. The distributed nature of the G2G Model means that it is sensitive to the position of the forecast rainfall and thus to the positional uncertainty of NWP rainfalls. It is thus well suited for interfacing to NWP rainfall ensembles for propagating this source of uncertainty, as part of a procedure aimed at providing probabilistic flood forecasts.

Phase 3, concerned with verification and synthesis, has employed two further case studies: (i) a national case study involving configuration and assessment of the G2G Model across England and Wales, and (ii) a more detailed regional case study (the Summer 2007 floods over the Avon and Tame catchments in the Midlands). High-resolution NWP rainfall forecasts from the 1.5km model for two storms with embedded convection have been produced by the JCMM Reading and CEH have generated pseudo-ensemble forms of them to trial probabilistic flood forecasting. STEPS ensemble rainfall forecasts, on a 2km grid and out to 6 hours, have also been generated for these storms for use as input to the flood forecasting models. Lumped hydrological models have also been used in the assessments to mirror current operational practice, but extended to provide flood forecasts in probabilistic form. National and Midlands Region datasets for hydrological model calibration, assessment and emulated real-time trial within the NFFS have been collated for project use. Gridded rainfall datasets (using radar and raingauge data with HyradK) with England and Wales coverage on a 1 km grid at 15 minute intervals, for input to the G2G Model, have been developed. Rainfall data from circa 750 telemetry tipping-bucket raingauges along with the national radar composite have been used. An initial England and Wales configuration of the G2G Model with multi-site data assimilation has been transferred to the test NFFS system for trials operated by Deltares on behalf of the EA. A closing project workshop and Final Report for review is planned in October 2009.

6.5 Probabilistic Flood Forecasting

CEH are supporting an Environment Agency funded science project entitled "Risk-based probabilistic fluvial flood forecasting for integrated catchment models" led by Atkins and involving Deltares, the University of Lancaster and EdenVale Young. The aim is to develop a framework for probabilistic flood forecasting and employ case studies to illustrate use of this framework, such that the outcomes are immediately accessible for real-time use within the NFFS (National Flood Forecasting System). A Phase 1 Science Report has been produced for formal publication. This reviews the main sources of uncertainty in flood forecasts along with available techniques for reducing uncertainty, through data assimilation, and for representing uncertainty of flood forecasts. Ongoing work under Phase 2 concerns developing the case study applications. CEH is leading the Upper Calder rapid response catchment case study involving use of the PDM rainfall-runoff model and STEPS ensemble rainfall forecasts from the Met Office JCHMR.

6.6 River flow and flooding forecasts for military deployed areas

CEH has worked with the Met Office and the Ministry of Defence (MOD) to further develop the Crisis Area Model (CAM) to provide a demonstration system for forecasting river flow and flooding in military deployed areas. The CAM will use MOSES-PDM (or MOSES-LSH) to estimate surface and sub-surface runoff which will be routed via the River Flow Model (RFM), the routing component of the Grid-to-Grid (G2G) Model to produce estimates of river flows on a grid covering the areas of military deployment.

In support of these objectives CEH has delivered high-resolution (0.01˚) datasets required by the River Flow Model (RFM) for two separate regions around military deployed areas. The high-resolution (0.01˚) datasets required by the RFM consist of flow directions (with values from 1-8), accumulated area (number of ~1km^2 pixels) and slope (%). Special consideration has been paid to closed (endorheic) drainage basins. Basins of this type drain to evaporating lakes and form internal drainage basins with no outlet.

The final report describes the methods used to derive the RFM input datasets (ancillary files) and discusses further work that might improve river flow and flooding forecasts for the military in deployed areas. An important aspect of modelling river flows in ungauged or remote terrain is the ability to utilise digital spatial datasets on properties of the terrain, land cover and soil that will influence the hydrological response. At the outset of this project there was little known hydrological information available for case study areas, other than the 30 or 90m resolution digital elevation data. Digital datasets from the MOD and the recent availability of USGS hydrological studies now provide some of the information required to undertake a remote hydrological analysis. An annex to the final report provides a detailed survey of available literature, investigation of available river gauging data and recommended geomorphological equations for the case study areas. These equations are used in the RFM to compare real-time estimates of river flows with estimates of bankfull capacity of the river. River flows which exceed bankfull capacity can be taken as indicative of localised flooding, and for flows within bankfull capacity, localised "at-a-station" relationships between river flows and width/depth can provide an indication of the river dimensions. The report also indicates where the updated equations suitable for the military deployed areas should be introduced in the RFM model code.

7. JULES modelling

7.1 JULES v2.1

JULES v2.1 (Joint UK Land Environment Simulator) has now been released following a bug-fixing and testing stage. This version will be almost identical to the JULES code that is being implemented within the Unified Model. The only differences will be due to bug fixes that are required to get the JULES code working fully within the UM (including bit comparison over various PE configurations). This version will therefore form the basic version of JULES upon which all future developments will build.

In order to maintain the functionality of the stand-alone code and the requirements of the Met Office Unified Model requirements whilst keeping one code version, the source code for JULES now requires a pre-processing stage before being released as a standalone code to the community.

The JULES code has now been set up within a formal FCM repository. This means that the FCM development tools can be used to implement future physics changes from the community. In addition, this moves towards the final goal of having Unified Model jobs built from this separate JULES code repository, removing the need to have mirrored code.

Provision for netCDF output has been added in this version and both diagnostic and restart files can be written in netCDF.

7.2 Benchmarking of JULES

The assessment of JULES against the evaporation fluxes measured at 10 FLUXNET sites has been documented and a paper describing the results has been accepted by the Journal of Hydrometeorology. The results were presented at the GEWEX International Symposium on Global Land-surface Evaporation and Climate.

The further assessment of the performance of JULES against the 5 sets of data (river flow, NDVI, atmospheric concentration of CO_2, fluxnet data on evaporation and carbon dioxide fluxes and potential land cover) is being been carried out. The analysis focuses on 8 regions. The initial results of this work were presented at the GEWEX-iLEAPS conference in Melbourne (August 2009) and the GEWEX Benchmarking Meeting held in Exeter in June 2009. A paper is being prepared.

In parallel to the JULES-benchmarking, a project in which 5 land surface models are compared to the same benchmark datasets with the same tests and modelling protocols is underway. This comparison includes JULES and 4 other European models (Orchidee, LPJ-mL, LPJ-GUESS and LPX). The project (ILAMB) is due to merge with a similar initiative in the USA (C-LAMP) to generate an international standard in benchmarking land-surface models. The GEWEX Benchmarking Meeting in Exeter was held to discuss this and further meetings are planned.

The automated benchmarking tool for the FLUXNET tests is now close to completion, requiring only some more robust error handling and some documentation. The entire system is written in IDL (both running the model and the post-processing - no Python components anymore), and has basic tests for evaporation and carbon based on the FLUXNET data that compare output from runs using the user's JULES executable to 'official' baseline model runs and observations. These tests consist of a combination of plots and basic statistical tests (correlation coefficient, RMSE). Each statistic is tested for statistically significant change to determine whether the user's version of the model does 'better' for that statistic than the 'official' model. This is indicated using a 'traffic light' system, where green indicates an improvement for the statistic, yellow indicates a degradation that is not statistically significant and red indicates a statistically significant degradation.

An easy-to-use version of the regional benchmarking system is being considered whereby single point runs representing the 8 regions can be run, without running the full distributed version of JULES. This will provide JULES users good access to the benchmarking data and tests. The GLASS (GEWEX Land Atmosphere System Study) committee considered these plans to be important and have endorsed this activity (GLASS committee meeting at Melbourne).

7.3 JULES within the QUEST Earth System Model (QESM)

There has been further work on developing the FLUME-compliant version of JULES that is required by the QESM. The new components were developed in a variety of environments (IMOGEN-MOSES, JULES1, JULES2.0) and these have had to be reconciled with the FLUME-JULES framework. Work is ongoing to ensure that these new science components can be supported alongside the existing options - in particular that the Ecosystem Demographics (ED) vegetation model fits into the existing tile structure.

7.4 New processes in JULES

(i) **Crop modelling and plant growth**
Adaptations to the way the carbon allocation takes place need to be made in order that the model can reproduce the observed growth of crops and energy crops.

(ii) **Carbon balance of Northern Latitudes**
Discussions with Met Office and CEH modellers are taking place to ensure best-practice. Issues include: representation of permafrost, organic soils, wetlands, snow cover, soil freezing. All of these are being developed and researched in universities and at the Met Office and CEH.

(iii) **Irrigation**
Irrigation can be modelled in JULES in two possible modes. The first method, only available in offline runs, involves running the model twice, once for the irrigated area of

each grid box and once for the non-irrigated area. The second method, which incorporates the moisture transfer in the soil and its extraction due to evapotranspiration for both the non-irrigated and irrigated areas of each grid box, is in its final development stage. The former has been tested against FAO AQUASTAT estimates of irrigation water requirements. The model produces an annual mean value of 455km^3/yr for India, Pakistan and Bangladesh which compares well to the FAO estimate of 394km^3/yr.

(iv) **Wetland inundation dynamics**
This work is based on the fact that observed river gauging data show significant evaporative losses from the land and water surface in the Niger Inland delta. These losses indicate an important potential feedback between the land-surface and atmosphere. Moreover, the reduction in river flow downstream of the wetland has clear implications for water management in the region and beyond. In this work, evaporative losses that occur over the Niger Inland Delta have been modelled by adding an overbank flow parameterisation to the JULES land-surface model. The hydrological component of this model comprises a probability-distributed model (PDM) of soil moisture and runoff production coupled with a discrete approximation to the 1-D kinematic wave equation to route river water downslope (G2G routing). Sub-grid-resolution topographic data are used to derive a two-parameter frequency distribution of inundated areas for each grid-box which is then employed to represent overbank inundation in the model. The model was driven using data from the ALMIP experiment (ALMIP stands for AMMA Land-surface Model Inter-comparison Project, wherein AMMA stands for African Monsoon Multidisciplinary Analyses). The model reproduces the salient features of the observed river flow and inundation patterns; these include significant evaporative losses from the inundated region accounting for doubling of the total land-atmosphere water flux during periods of greatest flooding. Predictions of inundated area are in good agreement with observed estimates of the extent of inundation obtained using satellite infra-red and microwave remote sensing. A paper on this work, which was funded by the WATCH project, is in preparation and will be submitted in October 2009. Discussions are ongoing with the Met Office to perform a fully-coupled simulation, and plans to run the model in other basins with significant wetland evaporation are under discussion.

7.5 Model evaluation

There are currently 3 strands of work evaluating the seasonality of soil moisture with observations:

(i) Analysis of daily mean river flow at the catchment scale is being extended by using GRACE (gravity recovery and climate experiment) data to further validate the soil moisture seasonal cycle.

(ii) Methodology developed to evaluate the simulated seasonality of soil moisture globally with NDVI (Normalized Difference Vegetation Index) has been applied to test alternative global soil parameter datasets provided by the Met Office (including the Harmonised World Soil Database) using both the existing and van Genuchten formulations. The new datasets resulted in an improvement in the seasonality of the soil moisture stress in the tropics.

(iii) Offline JULES simulations have been compared with MODIS Land Surface Temperature data to assess the simulation of summertime drought stress across Western Europe. The results showed that the simulated amplitude of summertime warming was up to 8°C too large in some regions, consistent with the soils drying out too rapidly. This work has been submitted in a PhD thesis (Heather Ashton) and ongoing work at CEH will further explore the reasons for the bias, and their consequences in coupled simulations. The methodology will also be applied to examine in more detail the representation of soil moisture in the CEH CHESS implementation of JULES over the UK.

The simulation of snow cover in a mountainous region is the focus of work for Dr. Juraj Parajka, holder of a JCHMR Visiting Research Fellowship between August 2009 and April 2010. Whilst at CEH, Juraj plans to evaluate the accuracy with which JULES is able to reproduce snow cover and snow depth observations over the European Alps. This project involves the use of a detailed archive of observed data on snow depth and cover which Juraj has assembled for Austria, and which covers the period 1975-2002. Evaluation of the performance of JULES will also employ remotely-sensed snow cover data from the MODIS satellite. Initial results indicate that JULES calculates the timing of the onset and decay of snow cover in the Austrian Alps with reasonable accuracy, but that accurate simulation of snow depth is not yet achieved. Work to improve the model's performance is ongoing, in collaboration with Richard Essery at the University of Edinburgh. A research visit to Edinburgh is planned for October 2009. Results from this work will be submitted for presentation at the JULES science meeting in Leeds in January 2010.

7.6 Forcing datasets

The WATCH Forcing Data for 1958-2001 was revised to remove outliers and re-released in July 2009. In September, code for temporal interpolation of these data - based on procedures used in GSWP2 - was provided in association with the University of Lisbon. The data are currently being used within WATCH for WaterMIP (see below). Additionally, in association with Jim Shuttleworth (University of Arizona), the WATCH Forcing Data are being used to examine global changes in potential evaporation (via the Penman-Monteith equation) and aridity (climatological resistance) from 1958 to 2001. These model-independent results will provide a context for the WaterMIP model calculations of actual evaporation.

Land surface ancillaries for WATCH have been produced including soil ancillaries from the recently published global dataset (Harmonised World Soils Database). The impact of these soil ancillaries on soil moisture seasonality have been assessed, as mentioned above.

7.7 Offline applications of JULES

(i) **Water Model Intercomparison Project (WaterMIP)**
A workshop on this WATCH-GWSP global model intercomparison project was held in Wallingford on 27-28 May 2009 and was attended by representatives of around a dozen modelling groups from around the world. Results using a prototype of the WATCH forcing data were presented and plans laid for work for the rest of the year. Subsequently further problems with the forcing data have been ironed out and another round of "naturalised" simulations for the late twentieth century is underway, including runs with JULES.

(ii) **Sensitivity of simulated hydrological cycle to resolution**
The sensitivity of the global hydrological cycle to different temporal and spatial resolutions of the WATCH forcing data is being analysed. JULES is being run with a 1 hour time-step and 0.5, 1 and 2° resolution. Also at 0.5° resolution a run with 3 and 6 hour time-steps will be run for two decades during the last century (1960s and 1990s). Ancillary files and forcing data have been provided for this period for these time and space scales.

(iii) **Soil moisture analysis over West Africa in the AMMA project**
Early results from a scheme that assimilated land surface temperature from Meteosat Second Generation into JULES were presented at the AMMA Science conference in Ouagadougou, Burkina Faso and at the GEWEX/iLeaps conference in Melbourne, Australia. There are plans in 2010 for the Met Office to re-run the forecast model for the AMMA Special Observing Period (summer 2006) with alternative soil moisture initialisations provided by CEH. Results from the AMMA Land Model Intercomparison Project (ALMIP), in which JULES participated, were published in the Bulletin of the American Meteorological Society in September. A further analysis of the ALMIP simulations, comparing model-derived top-of-atmosphere radiances with C-band radiances observed by the AMSR-E satellite sensor, was also published.

(iv) **Urban model comparison**
Results from the urban model comparison are now being analysed. The initial conclusions are that simple models do as well as the more physically complex models in reproducing the net radiation, sensible and latent heat fluxes and the heat storage flux. This means that for weather forecasting and climate predictions, a simple representation of urban areas may well be sufficient.

Two interesting conclusions have come from the comparison. Firstly, it is important to include a representation of vegetation within the urban footprint area, even if the total fraction of vegetation is very small. Secondly, models that do not include the anthropogenic heat source do as well in predicting the turbulent heat and moisture fluxes as models that include this term. Both of these results require further investigation to understand the physics behind these results.

A number of papers on the results of the comparison are being planned. These papers will include aspects on the seasonality of the model results, the impact of initialisation, the use of parameter information and the impact of including both vegetation and anthropogenic heat flux within the models.

8. Feedbacks via the water, energy and carbon cycles

8.1 Global Evaporation Assessment

The GEWEX International Symposium on Global Land-surface Evaporation and Climate was hosted at CEH in Wallingford in July 2009. This brought together scientists from around the world with expertise in global evaporation processes and relevant models, satellite data and field data. The meeting has been reported in several places (HPToday commentary, Planet Earth article, as well as a film on the WATCH website: www.eu-watch.org). It was also reported at the LandFlux meeting in Melbourne (August 2009) and the GEWEX-iLEAPS conference in Melbourne (August 2009).

Several of the products are funded/generated under the WATCH project and extra meetings are being held with the WATCH community to address the issues raised. This dataset is not yet part of the Benchmarking datasets as it is a model-derived product. However, it is envisaged that in the next 18 months, an ensemble of the satellite products will become available to land surface modellers for testing their models. These data will then be included in the benchmarking system being built.

8.2 Feedbacks in WATCH

The issue of the impact of atmospheric feedbacks on water resources is being developed in partnership with European partners in WATCH. A regional study of India is underway, with the Met Office running the RCM with and without irrigation for that region. A comparison with other RCMs will take place in parallel to a desk study of feedbacks analysed from Atmospheric Profiles (Wageningen researcher).

In addition to this regional study, a desk study of the likelihood of feedbacks across the globe is being carried out using atmospheric profiles and defining feedback-strength diagnostics. This study will be used to define areas where feedbacks need to be assessed by the water-resources community.

8.3 Feedbacks in West Africa

Work focusing on the Mali wetlands has developed along several axes. A study using satellite data to identify the impact of the wetland on precipitation has been submitted. A paper describing the development of a flood inundation model within JULES for this wetland will shortly be submitted (see section 7.4). As mentioned above, there are plans to simulate this region using the RCM to further explore this feedback. In addition, a new project is starting at CEH looking at the impact of the wetland on atmospheric methane, as monitored by SCIAMACHY.

Earlier observational work looking at soil moisture feedbacks on intra-seasonal variability in the monsoon circulation has been advanced through simulations with HadAM3. The model captures this mode of variability well, and sensitivity runs indicate that soil moisture plays an important role. The results form part of a PhD thesis (Sally Lavender) and have been submitted in a paper.

An AMMA continuation project on land-surface influences on convection, led by Leeds and involving CEH and the Met Office, has been funded. This will provide the framework for the soil moisture sensitivity runs of the global forecast model described under 7.7(iii).

8.4 Feedbacks in the Arctic

A CEH research project, funded by NERC entitled ‘The response of Arctic regions to changing climate’ will start in Spring 2010. The project’s overarching aim is to answer the question: "How will the terrestrial Arctic physical and ecological response to climate change feed-back on the global climate-carbon cycle system in the 21st Century?" New parameterisations for JULES will be trialled and validated against data and then feedbacks will be studied with the IMOGEN modelling system

The IMOGEN system is not currently capable of capturing local adjustments to surface climate when the land-surface is predicted to change markedly from that in the original GCM, against which the “pattern scaling” is calibrated. Some large changes to the surface energy balance (affecting near-ground temperature and humidity) can be expected, especially when changes in snow cover are predicted. To capture these feedbacks, it is necessary to run a model with full land-atmosphere interactions i.e. a GCM. Through JCHMR collaborations with the Hadley Centre, such simulations will be undertaken. In the event of IMOGEN determining “tipping points” in net Arctic land-atmosphere fluxes, the GCM will inform on whether atmospheric feedbacks bring forward (or otherwise) their expected timing.

8.5 Land feedbacks on methane

A developing area of collaboration is on terrestrial emissions of methane. Both CEH and Hadley have collaborated with Edinburgh University to operate the atmospheric-chemistry model STOCHEM (pre-cursor to UKCA) to analyse global methane concentrations. A variety of land surface descriptions and meteorological drivers are being considered to analyse the largest contribution to atmospheric methane variability. A novel feature of this study is that Sciamachy Earth Observations of total column methane concentration were used for comparison. Initial discussions indicate that year-on-year variation in wetland emissions have a strong influence on global values. This global study is complemented by the regional work in Africa (see 8.3)

8.6 Other areas of collaboration

(i) **Land Use Change**:
As part of the WATCH project, CEH are participating in the LUCID modelling project. The aim of the project is to examine the impact of land use change on the climate system using runs from an ensemble of models. Contact was made with Pete Falloon, in the Hadley Centre, to try and extract output from UM runs looking at land use change.

(ii) **Carbon cycle**:
CEH and Hadley (and Leeds University) have collaborated with the French group LSCE, who made available a merged CRU-NCEP (1901-2008) set of driving data. CEH successfully translated this 6-hourly data into drivers for IMOGEN, and this has led to a paper submitted investigating recent past atmospheric CO_2 trajectory (i.e. right up to 2008) with an emphasis on land surface draw-down.

(iii) **Vegetation impacts on climate via isoprene**:
A new collaboration is developing between CEH and the Hadley Centre linking isoprene emissions, photosynthesis and diffuse radiation effects.

(iv) **Detection and attribution**:
CEH and Hadley have collaborated with Oxford University on building up the required datasets for an eventual detection and attribution study on global rainfall patterns.

(v) **Research Hotel:**
CEH Wallingford has set aside a room as a three month "research hotel" experiment, and where one focus for October to December will be to generate linkages between more immediate emission targets and long-term stabilisation goals. Hadley Centre staff (from Reading, Exeter and JCHMR) will meet regularly in this room. It is hoped to supply our findings to DECC in time for the December Copenhagen meeting. The room will also be used to discuss the methane modelling aspirations.

9. Flood risk assessment and climate change

9.1 FRACAS

FRACAS (Flood Risk Assessment under climate ChAnge Scenarios) is funded under the NERC FREE programme and will produce a linked system of rainfall, hydrological, defence performance and flood inundation models for strategic flood risk assessments. This framework will be capable of a full national assessment, and will be demonstrated through the application to a number of selected regions and large river basins in the UK. The consortium is made up of CEH (lead), the Met Office Hadley Centre, the University of Newcastle and HR Wallingford.

CEH's Grid-to-Grid (G2G) Model, incorporating variable soils data and lateral flows of soil moisture, has been implemented at the national scale and assessed using historical observations. Hadley Centre 25km RCM data have been used to provide rainfall and potential evaporation for current and future time-slices in support of a climate change impact assessment. Changes in flood frequency under a possible future climate have been estimated on a 1 km grid across the UK using the Grid-to-Grid Model. These maps indicate a high degree of spatial variability in the response of the UK landscape to projected climate change.

Stochastic rainfall estimates from Newcastle University's weather generator can provide an alternative source of gridded rainfall estimates for catchments up to 10,000km^2. The limited spatial coverage is counterbalanced by the longer time-series that can be produced using a stochastic model. Gridded data from both the RCM and the stochastic weather generator have been used as input to the G2G applied to the River Eden to Carlisle. Flood frequencies derived using both types of rainfall estimate have been produced on a 1km grid over the Eden catchment to Carlisle. Ongoing work is investigating the relative merits of the two rainfall sources when used as input to a gridded hydrological model. One benefit of the weather generator is that its long time-series rainfall estimates can extend the return period flow estimates to beyond 100 years.

Grid-to-Grid Model time-series estimates of river flow are also being used by HR Wallingford for input to their flood inundation models. A (semi-)continuous version of the RASP (Risk Analysis for Strategic Planning) tool has been used to estimate flood inundation and risk at a national scale from peak flows provided by the G2G Model. Another model, Infoworks RS, can be used to estimate the probability of various defence failure scenarios. Resulting economic damages are combined to derive flood risk at a catchment scale.

9.2 River flow modelling, flood frequency and climate change

The Met Office's Hadley Centre and CEH Wallingford are collaborating on developing methods to predict flood frequency over the UK in current and future climates. The main focus of this research is to provide national estimates of the impact of predicted future changes in the weather on flood frequency throughout the century. A grid-based methodology is used to translate Regional Climate Model (RCM) meteorological variables into gridded time-series estimates of river flow and fluvial discharges to the sea.

The performance of the G2G Model, used as the distributed hydrological model in this work, has been assessed using historical records from river gauging stations across the UK. A single area-wide model with one set of parameters is used to estimate river flows across the UK on a 1km grid. Use of RCM estimates of rainfall and potential evaporation (PE) as input to the G2G Model has enabled maps to be derived across the UK of estimated future percentage changes in flood frequency, including some quantification of uncertainty.

A paper describing the G2G model formulation, which now includes variable soil properties and lateral movement of soil moisture, is now published in the Journal of Hydrology (papers in press electronic form). Following an assessment using historical data for 43 UK catchments, observed precipitation and PE data used as input to the G2G Model were replaced by RCM estimates on a 25 km grid for a Current (1961 to 1990) and a Future (2071 to 2100) time-slice. Flood frequency curves derived from the flow simulations for the two time-slices were used to estimate, for the first time, maps of changes in flood magnitude for all river points on a 1 km grid across the UK. A high degree of spatial variability is seen in the estimated change in river flows, reflecting both projected climate change and the influences of landscape and climate variability.

- Use of the G2G Model with RCM estimates of rainfall and PE as inputs forms part of the guidance for UKCP09 on the use of climate model output for impact assessment. A worked example demonstrating the use of UKCP09 (UK Climate Impacts Programme) climate scenarios to estimate probabilistic change in flood frequency across the UK is now published on the UKCP09 website: http://ukclimateprojections.defra.gov.uk/content/view/2306/510/
- At the regional scale, an assessment has been made of the performance of the RCM coupled with the G2G Model implemented at a 25km resolution over a selected region of Europe.

Ongoing work is investigating how estimates of impact uncertainty and variability can be improved through the use of a weather generator to transform a limited number of climate model predictions into a large ensemble of localised weather estimates.

References

Bell, V.A., Davies, H.N., Dadson, S.J. and Moore, R.J. 2009. River flow and flooding forecasts for military deployed areas. Final Report. Contract Report to the Met Office, Centre for Ecology & Hydrology, Wallingford, UK, 71pp.

Bell, V.A., Kay, A.L., Jones, R.G., Moore, R.J. and Reynard, N.S. 2009. Use of soil data in a grid-based hydrological model to estimate spatial variation in changing flood risk across the UK. *J. Hydrol.*, doi: 10.1016/j.jhydrol.2009.08.031, (in press).

Blyth, E.M., Clark, D.B., Sitch, S. and Pryor, M. 2009. Benchmarking the JULES model for use in a GCM. Presentation at the GEWEX/iLEAPS conference on Water in a Changing Climate.
http://www.gewex.org/2009Conf/2009gewex_ileaps_conf_program.pdf

Blyth, E.M., Gash, J.C.H., Lloyd, A., Pryor, M., Weedon, G.P. and Shuttleworth, W.J. 2009b. Evaluating the JULES land surface model using FLUXNET data. *J. Hydromet.* (in press).

Blyth, E.M., Harding, R.J. and Shuttleworth, W.J. 2009. Global land surface evaporation and climate. Presentation at the GEWEX/iLEAPS conference on Water in a Changing Climate. http://www.gewex.org/2009Conf/2009gewex_ileaps_conf_program.pdf.

Blyth, E.M., Shuttleworth, W.J. and Harding, R.J. 2009a. Summary of the GEWEX International Symposium on Global Land-surface Evaporation and Climate. HP Today Report. *Hydrological Processes* (in press).

Boone, A., de Rosnay, P., Balsamo, G., Beljaars, A., Chopin, F., Harris, P., Taylor, C.M. et al. 2009. The AMMA Land Surface Model intercomparison Project (ALMIP). *Bulletin of the American Meteorological Society* (in press).

CEH Wallingford 2009. A guide to the PACK snowmelt model. Centre for Ecology & Hydrology, Wallingford, UK, 10pp.

Cole, S.J., Howard, P.J. and Moore, R.J. 2009. Hydrological modelling for the rivers Lavant and Ems. Contract Report to the Environment Agency Southern Region, Centre for Ecology & Hydrology, Wallingford, UK, 109pp.

Cole, S.J. and Moore, R.J. 2009. Distributed hydrological modelling using weather radar in gauged and ungauged basins. *Advances in Water Resources*, **32**, 1107-1120.

Cole, S.J. and Moore, R.J. 2009. Hydrological modelling for the rivers Lavant and Ems: Interim Report. Centre for Ecology & Hydrology, Version 1.1, June 2009, 52pp.

de Rosnay, P., Drusch, M., Boone, A., Balsamo, G., Decharme, B., Harris, P., Kerr, Y., Pellarin, T., Polcher, J., Wigneron, J.-P. 2009. AMMA Land Surface Model Intercomparison experiment coupled to the Community Microwave Emission Model: ALMIP-MEM. *Journal of Geophysical Research*, **114** (D05108), 18 pp., 10.1029/2008JD010724

Ellis, R.J., Taylor, C.M., Weedon, G.P., Gedney, N., and Clark, D. B. 2009. Using earth observations and a land-surface model to better understand the constraints on transpiration, *J. Hydromet.* (in press).

Garcia-Carreras, L., Parker, D.J., Taylor, C.M., Reeves, C.E. and Murphy, J.G. 2009. The impact of mesoscale vegetation heterogeneities on the dynamical and thermodynamical properties of the planetary boundary layer. *J. Geophys. Res. – Atmospheres*, (in press).

Huntingford, C., Lowe, J.A., Booth, B.B.B., Jones, C.D., Harris, G.R., Gohar, L.K., Meir, P. 2009. Contributions of carbon cycle uncertainty to future climate projection spread. *Tellus B*, **61B**, 355-360. 10.1111/j.1600-0889.2009.00414.x

Kay, A.L., Davies, H.N., Bell, V.A. and Jones, R.G. 2009. Comparison of uncertainty sources for climate change impacts: flood frequency in England. *Climatic Change*, **92**(1-2), 41-63, doi: 10.1007/s10584-008-9471-4.

Lowe, J.A., Huntingford, C., Raper, S.C.B., Jones, C.D., Liddicoat, S. K., Gohar, L.K. 2009. How difficult is it to recover from dangerous levels of global warming? *Environmental Research Letters*, **4**, 014012. 9, pp. 10.1088/1748-9326/4/1/014012

Mercado, L.M. Lloyd, J., Dolman, A.J., Sitch, S. and Patiño, S. 2009. Modelling basin-wide variations in Amazon forest productivity – Part 1: Model calibration, evaluation and upscaling functions for canopy photosynthesis. *Biogeosciences*, **6**, 1247-1272.

Messager, C., Parker, D. J., Reitebuch, O., Agusti-Panareda, A., Taylor, C.M. and Cuesta, J. 2009. Structure and dynamics of the Saharan atmospheric boundary layer during the West African Monsoon onset: observations and analyses from the research flights of 14 and 17 July 2006. *Quart. J. Roy. Meteorol. Soc.* (in press).

Sene, K., Weerts, A., Beven, K., Moore, R.J., Whitlow, C. and Young, P. 2009. Risk-based probabilistic fluvial flood forecasting for integrated catchment models. Phase 1 Report. Environment Agency Science Report – SR SC080030, Research Contractors: Atkins Ltd, Deltares, Lancaster University, CEH Wallingford, Edenvale Young. Environment Agency, Bristol, UK, 181pp.

Taylor, C.M., Harris, P.P. and Parker, D.J. 2009. Impact of soil moisture on the development of a Sahelian mesoscale convective system: a case study from the AMMA Special Observing Period, *Quart. J. Roy. Meteorol. Soc.* (in press).

Timouk, F., Kergoat, L., Mougin, E., Lloyd, C.R., Ceschia, E. Cohard, J.-M., de Rosnay, P., Hiernaux, P., Demarez, V. and Taylor, C.M. 2009. Response of heat and radiation fluxes to water regime and vegetation development in a Sahelian landscape. *J. Hydrol.*, **375**, 178-189.