Joint Centre for Hydro-Meteorological Research

Report on Research Activities 13 October 2005 to 27 April 2006

1. Short-Range Precipitation Forecasting R&D

1.1 Trial of the Short-Term Ensemble Prediction System (STEPS)

A trial of the STEPS commenced on 5 December 2005. This involved the routine running of a control member forecast and small ensemble (initially 5 members) on the Met Office's NEC supercomputer, and the production of a range of continuous and categorical verification statistics. Although the winter was drier than average, model performance during precipitation events in December 2005 and January 2006 revealed some deficiencies in the model formulation. These were the focus of investigation during March and April 2006 (see below).

1.2 Improvements to the formulation of the STEPS

a. Tuning of the control member

During the winter trial of STEPS, weaknesses in the generation of the stochastic noise fields were identified and subsequently confirmed by comparing STEPS power spectra with equivalent spectra derived from UK weather radar composites. Cases studies showed that the scaling model used to generate the noise fields was unable to capture the dynamic properties of the radar-derived power spectra; nor was it able to model the steepness of these spectra during convective weather events. This resulted in the rapid decay of showers, the under-prediction of peak rain rates in showers, and the over-prediction of light rain. A dynamic scaling model for the noise power spectrum has now been implemented using information from the radar power spectrum at scales below 32 km. A trial of the revised model formulation will commence in May 2006.

b. Development and calibration of an observation uncertainty algorithm

An initial version of an observation uncertainty algorithm for integration within the STEPS has been developed by the Bureau of Meteorology in Melbourne, Australia. This algorithm seeks to represent the uncertainty in radar-inferred surface rain rate by adding stochastic perturbations to a best guess field of rain rate. The principle challenge lies in representing the complex spatial and temporal variations in uncertainty arising from numerous sources including the drop size distribution, radar wave propagation, and variations in the vertical profile of reflectivity. In the initial version of the algorithm only uncertainties arising from variations in the drop size distribution are considered. The algorithm formulation is based upon the space-time model developed by Seed *et al.* (1999) and the radar measurement model of Jordan *et al.* (2003) and uses a multiplicative bounded log-normal cascade model to represent the uncertainty in space, and an auto-regressive model for the evolution of the temporal uncertainty in Lagrangian coordinates. A trial of the algorithm within the STEPS will commence in June 2006.

c. Development of algorithm for quantifying uncertainty in NWP forecasts of convective precipitation

A Numerical Weather Prediction (NWP) based post-processing algorithm for modelling the uncertainties in forecast convective precipitation has been developed for integration within the STEPS. Based upon a similar algorithm developed by Hand (2000), this attempts to model uncertainties in the NWP predicted evolution of convective precipitation fields by considering the impact of model errors and unresolved sub-grid scale processes on the probability of triggering free convection. Unlike its predecessor which produced a suite of probabilistic forecast products for predefined probability thresholds, this model seeks to convey the uncertainty through the generation of an ensemble of forecast scenarios. A trial of the algorithm will follow integration within the STEPS, due for completion by the end of April 2006.

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2. Development of a post-processing system for high resolution UK NWP models

An initial version of a post-processing system for the ~4km resolution UK NWP model has been completed and is running as an operational trial on the Met Office's NEC supercomputer. The system incorporates algorithms for the interpolation of UK NWP model fields to a 2 km resolution, horizontal grid, and the generation of analysis fields and nowcasts for the following variables: screen level visibility, temperature and dew-point temperature, cloud, wind and pressure, surface precipitation rate, accumulation and type. The system also includes algorithms for the extraction of forecast data for specific locations in contribution to a UK NWP-based winter trial of the Met Office's OpenRoad service.

The MOSES-PDM-RFM surface hydrology modules, which have been running within the Nimrod nowcast system at 5km resolution, have now been implemented at 2 km resolution within the UK NWP Post-Processing (UKPP) system. The required 2km resolution land-sea mask, land use fraction and soil property ancillary fields were created with care taken to ensure that each coastal 1km grid square of the River Flow Model (RFM) is within a land grid square of the UKPP system (i.e. that the 1 and 2 km resolution land-sea masks are consistent).

An algorithm has been devised to determine the Leaf Area Index (LAI) for each vegetated land surface type within each UKPP grid square from observed MODIS satellite data. This will be evaluated using test data when available and the LAI ancillary fields for each land use type will be used by MOSES-PDM within the UKPP system. Snow cover from Meteosat Second Generation will also be used to correct the MOSES-PDM snow amount.

A web-based interactive display system and verification software for the UKPP system have been implemented on the Nimrod hardware as a temporary measure until the introduction of a new centralised data repository, planned for later this year.

3. Evaluation of river flow diagnosed by the Nimrod-MOSES-PDM-RFM

River flow data from Nimrod-MOSES-PDM-RFM for 20 gauging stations has been extracted from the Nimrod archive for the period August 2004-January 2006. Daily mean river flow observations for the same period and gauging stations have been obtained from the National River Flow Archive, maintained by CEH, for validation of the model. This is the first such validation since Nimrod-MOSES-PDM was changed to use the van Genuchten soil hydraulics formulation and parameters and the reduction in the PDM's soil heterogeneity parameter, B, to 0.5. The validation suggests that the lower soil heterogeneity parameter is too low in upland catchments, leading to insufficient surface runoff and river flow, and that kinematic wave speed for the river flow model is too large for 'normal' (i.e. lower than bankfull) river flows.

4. Development of MOSES-PDM for chalk soils

All the relevant measurements from the two sites, Sheepdrove Farm and Bridgets Farm, were brought together, quality controlled and, in the case of the soil water contents and matrix potentials, aggregated to the MOSES soil model layers.

The code for the soil water model was extracted from MOSES and additional code written to allow it to be run as a separate entity, driven by observed evaporation and rainfall. The soil water model has been run with the parameter values used with Nimrod and the outputs compared with the measurements. This showed up a discrepancy between the measured soil water contents and matrix potentials, probably due to hysteresis effects, and so further analysis focussed solely on the soil water contents. A Monte Carlo run was carried out, with 5000 parameter sets, to optimise the parameters.

Code was added to the model that allowed a simple representation of dual permeability in the soils. The parameters for this model were then optimised using the same Monte Carlo procedure. The three parameter sets were then used with the data from Bridgets Farm. A full report is currently being written.

5. Hyrad and RFFS

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. A new release of Hyrad to the Environment Agency (EA) will be made in April 2006 supporting three new enhancements: (i) display of averages and totals for rainfall forecasts within a user-specified time window, (ii) support to ESRI Shapefile import of overlays to the Display Client and catchment boundaries to the Server (for catchment average rainfall estimation for onward transmission to Flood Forecasting Systems), and (iii) export of image data as CSV files from the Display Client.

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 include: "PDM for PCs" rainfall-runoff model, "KW for PCs" channel flow routing model and "PSM for PCs" rainfall-runoff model (encompassing the TCM and IEM models). A new release of the Model Calibration suite, planned as part of the EA's Enterprise Licence procurement, was made in December 2005 and used as the basis of a Modelling Training Course to the EA in March 2006. The real-time Model Algorithms PDM (including data assimilation by state correction), KW and ARMA error predictor were supplied to SEPA (Scottish Environment Protection Agency) in March 2006 in support of their roll-out of new flood forecasting systems across Scotland.

With the above developments, the EA and SEPA will have the capability to use Met Office Nimrod products (radar, NWP and MOSES), via CEH's Hyrad system, for use in flood warning and water resource management throughout England, Wales and Scotland.

6. Extreme Event Recognition

This Defra R&D Project involves a Met Office lead consortium encompassing inputs from CEH and the University of Salford. The overall objective is to improve the capability to provide warnings of extreme flood events via improving rainfall forecasts and flood forecasting models/procedures (including decision-support). CEH is developing spatio-temporal rainfall datasets, using radar and raingauge data from historical heavy rainfall events, enhanced to represent extreme events. These datasets are being used to evaluate and improve the performance of hydrological models under such extreme event conditions. They are also to be used for model destruction testing.

The CEH project addresses the question "What makes an extreme storm an extreme flood?" A methodological framework has been developed for investigating the shaping mechanisms of an extreme flood from storms of differing kind and catchments of varying form. Extreme storms of frontal, orographic and frontal origin have been chosen from historical records and characterised in terms of return period for their critical rainfall depth and duration and other storm properties. The flood response over a catchment has been assessed for flood peak return period and modelled using lumped and distributed approaches. Areal rainfall estimates for catchment and grid-square areas, used as model input, have been obtained by multiquadric interpolation methods applied to raingauge data alone and in combination with weather radar data. Shortcomings of stage-discharge ratings affecting implied model performance have been taken into account when assessing the results. A rainfall transformation tool has been developed and applied to historical storms to change their speed and direction of movement and their magnitude and shape to create artificial storms of greater return period. The flood response has been investigated for catchments co-located with the storm and, by invoking storm transposition, to other catchments of different form. One model experiment has taken a fast-moving extreme convective storm that failed to produce an extreme flash flood. When transposed to another catchment, reduced in speed and re-orientated to align with the river network, a modelled extreme flood response was found to be produced. The more extreme response obtained from the distributed rainfall-runoff model, relative to the lumped one, served to highlight the potential value of distributed models in forecasting unusual extreme storms. Animated images of flood forecasts with area-wide coverage, obtained from the distributed model, have provided fresh insight into the space-time shaping of the flood by the catchment form. The results of the project have particular relevance to flood warning for ungauged locations. The Final Report is scheduled for publication in 2006.

7. 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 has been 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.

A review of best practice has been carried out along with proposing, investigating and prototyping some new improved methods. Seeking physically-based methods of applying conceptual hydrological models to ungauged catchments using digital datasets on basic properties, as opposed to employing empirical relations between model parameters and catchment characteristics, is seen as a way forward. A new method of representing runoff production under the control of soil properties and topography, with an emphasis on lateral water transfers, has been developed in prototype form and used to illustrate the benefits of area-wide grid-based modelling. Also, a variable time-step Muskingum-type flow routing methodology with links, via the St Venant equations, to channel properties has been identified as deserving further investigation for application to ungauged areas. A range of options for data assimilation to support forecast updating, depending on the level of data availability and model structure, have been set down. A Report on the work is to be published in 2006.

8. Global water and carbon cycles

8.1 Development of a community land surface model

The prototype version of JULES now has 20 registered users. There has been little feedback on the model to date, but this can be seen as a positive. It demonstrates that the user interface and documentation are sufficient for users to be able to actively use the model.

The management committee for JULES has now been established. Its membership consists of 2 people from the Met Office (Olivier Boucher and Martin Best), two people from CEH (Richard Harding and Eleanor Blyth) and four people from the community outside of the JCHMR (Colin Prentice, Piere-Luigi, Ian Woodward and Richard Essery). The first meeting of the management committee is currently being arranged.

The second version of JULES is also currently being developed. The new version will be able to run at multiple points and will be able to deal with a number of data formats. In addition, the code is being re-written so that it is more modular. This includes changes to areas of the code where separate routines are required for land, sea and sea-ice points. These routines are being consolidated into single routines that can deal with any surface as part of the generic surface exchange module.

The main differences between land, sea and sea-ice will then be through different sub-surface modules. This will introduce the flexibility of having more that one soil column (although they will not have to be aligned with the surface tiles), having a sea-ice module that is separated from the land surface scheme and can therefore be passed back to the ocean modellers, having a surface temperature over oceans that is distinct from the SST (allowing difference between surface temperature as observed by satellite and that measured using the bucket method), and enabling the possibility of a full lake model that is not constrained by the current code structure.

As part of the restructuring, more flexibility will be introduced with respect to the land surface tiles. At present there are only two options: 9 tiles or an aggregate scheme of 1 tile. In addition, the specification of the 9 tiles is fixed. So the aim is to enable the user to define not only the number of tiles to be used, but also the specification of the tiles (e.g. for climate applications there could be 4 tiles for trees: evergreen broadleaf trees, deciduous broadleaf trees, evergreen needleleaf trees and deciduous needleleaf trees, whist for NWP applications, this equivalent could be just one tile representing tall vegetation).

As part of the flexible tile definitions, elevation bands will be introduced into the tile specifications. This will be done by specifying the height of the tile above the surface and will have the effect of changing the forcing temperature for the surface scheme by a lapse rate. This is particularly important for snow melt and sublimation, with the resultant impact on the timing or runoff and river flow.

8.2 Hydrological dynamics within MOSES

Whilst undertaking analysis of the warm bias within HadGEM, it was discovered that there were significant differences in the hydrological components of HadGAM compared to HadAM3. In the region of the Asian warm bias, the snowmelt goes directly into surface runoff within HadGAM, whilst in HadAM3 there was no surface runoff and very little sub-surface runoff.

Running JULES with data extracted from HadGAM has shown that the cause of these differences is the way in which MOSES 2.2 deals with super-saturation in a soil layer compared to MOSES I. Within the MOSES I code, if a layer becomes super-saturated the excess water is added to the water flux out of the bottom of the layer, and if this layer is the bottom one, then the excess water is added to the sub-surface runoff. However, in the MOSES 2.2 code when a layer is saturated the excess water is subtracted from the flux into the top of that layer. This has the impact of increasing the moisture convergence in the layer above. If the layer is then the top soil layer, the net impact is to increase the surface runoff.

For the case of the warm bias regions, it would appear that the soil is saturated in the top layer (with only a fraction of this moisture being un-frozen). The layers below are not saturated and can be quite dry. Hence the MOSES I scheme will increase the soil moisture in the lower levels during snowmelt, whilst the MOSES 2.2 scheme will put all of the snowmelt into surface runoff. The net impact is that after the spring thaw, there is less soil moisture in HadGAM which leads to soil moisture stress on the vegetation at an earlier time of the year and hence warmer temperatures.

However, changing back to the MOSES I scheme is not necessarily the solution as it could have a detrimental impact on surface runoff during large convective storms in the tropical regions. Hence more analysis is required to find a solution. As part of this, the NERC EO Centre of Excellence CLASSIC, which has involvement from both CEH and the Met Office, has a member of staff working at Wallingford and looking into the problem of snowmelt and infiltration into frozen soils.

8.3 Dynamic Global Vegetation Model Intercomparison

Five Dynamical Global Vegetation Models (DGVMs) have been used within the GCM analogue climate model IMOGEN. These models have been run with four SRES (Special

Report on Emission Scenarios, IPCC) emission scenarios to help address the following research questions: What is the uncertainty in the future atmospheric CO_2 concentration associated with choice of DGVM (Dynamic Global Vegetation Model) and SRES emission scenario? Do DGVMs agree on their global and regional responses to changes in climate and atmospheric composition? Which key ecological processes are poorly represented in the DGVMs?

Results indicate large uncertainties in future atmospheric CO_2 concentrations associated with uncertainties in the terrestrial biosphere response to changing climatic conditions. By 2100, atmospheric CO_2 concentrations differ by up to 285 ppm among DGVMs, equivalent to about half the uncertainty associated with choice of SRES emission scenario.

The regional response of the DGVMs is less robust than their global response. All models simulate a release of land carbon in response to climate forcing, implying a positive terrestrial climate-carbon cycle feedback. DGVMs agree on a reduction in NPP and a decrease in soil residence time in the tropics and extra-tropics respectively, although large uncertainties among DGVMs are associated with the magnitude of these responses. Major uncertainties relate to the response of tropical vegetation to drought and boreal ecosystems to elevated temperatures and changing soil moisture status, the treatment of which differs among DGVMs.

The maximum uncertainty in future cumulative land uptake (485 PgC) associated with the response of land processes to elevated atmospheric CO_2 concentrations and climate is equivalent to ~56 years of anthropogenic emissions at the 2000 levels. Improving our understanding of and ability to model terrestrial biosphere processes is therefore paramount to enhance our ability to predict the future development of the Earth system.

8.4 Impact of Ozone on land atmosphere carbon exchange

Plants are known to suffer ozone damage, which reduces both stomatal conductance and photosynthesis rates. O_3 causes cellular damage inside the leaves which adversely affects plant production, and thus reduces crop yields.

These effects of O_3 exposure on plants have been parameterised within MOSES. The model of O_3 effects on photosynthesis has been calibrated against experimental data from different plant functional types, for both high- and low-ozone sensitivity plants. This model has then been coupled to the IMOGEN climate analogue model and driven with fields from the STOCHEM tropospheric chemistry model to investigate the impact of O_3 on present and future land atmosphere carbon exchange and its uncertainty.

The simulated present-day O_3 are high over many regions during the northern hemisphere summer. In Eurasia and eastern North America high O_3 coincide with the peak in growing season, and is likely to cause maximum effects on plant production.

Future levels of tropospheric O_3 are projected to increase further, exceeding 60 ppb in some regions. Of particular concern are the projected large concentrations across Eurasia, North America and East Asia during the northern hemisphere growing season. The densely populated areas of these regions rely heavily on their agricultural production for supplying their nutritional requirements.

Results indicate the largest reductions in productivity and land carbon storage over temperate regions (N. America, Europe, China, India). In terms of carbon storage, plant O_3 exposure, reduces global land carbon storage by up to ~200Pg by 2100, equivalent to one quarter of the simulated CO_2 fertilisation effect over the same period. Uncertainty in the O_3 effect is large ranging from reductions of 80 to 200 PgC in global land carbon for the "low" and "high" O_3 sensitivity simulations, respectively. O_3 exposure may cause additional vulnerability to tropical forests.

8.5 GEMs: Evaluation of JULES with data from 20 Flux Tower Stations on the seasonal time scale

Latent and sensible heat fluxes modulate local climate and together with CO_2 exchange affect regional and global climate. The land surface description is an integral component of climate models. Given the large potential impact of land surface dynamics on future climate, and the policy relevance of such findings, there is an urgent need to evaluate the performance of land surface models against existing data.

In recent years eddy covariance measurements of water and carbon fluxes have been made at flux sites located in a variety of terrestrial ecosystems. Multi-year datasets of half hourly fluxes are now available for 20 sites, providing a suitable benchmark for land surface models.

JULES is evaluated using data of heat fluxes (sensible and latent) and CO_2 exchange from the 20 flux tower sites. The model is forced with site meteorology, and simulated fluxes are compared against observations on the seasonal time scale.

JULES is able to capture the seasonality in both sensible and latent heat exchange, as seen in the high correlation coefficients between data and model, at the 20 sites representative of northern hemisphere ecosystems. However the normalised RMSE are moderately high. Simulated latent heat fluxes are consistently higher than observation. Given the problem of energy closure at flux tower sites, the model-data bias may indeed be an artefact.

JULES is able to capture seasonality in NEP in forested ecosystems. Results are worse at sites representing water limited ecosystems, e.g. grasslands, Mediterranean ecosystems. This is in broad agreement with the findings of Morales *et al.* (2005) for other terrestrial biosphere models. The ability of JULES to simulate the correct amplitude of the seasonal NEP exchange improves with increasing latitude in forest ecosystems. NEP is the small net flux of two large opposing fluxes, GPP and RESP. As to be expected the performance of the model, in terms of correlation coefficient and RMSE, is better for these large fluxes than the small net flux, NEP. It is unclear as to whether the poor ability of JULES to simulate NEP at several sites is a result of an inherent problem with GPP or RESP. However results indicate JULES tends to overestimate peak growing season GPP.

8.6 Large scale runoff: detection and attribution

A paper has been published in Nature which explains the trends in climate, CO2 effects on stomata, aerosols and land use in changes in continental scale runoff. This received some publicity including a write-up in The Economist.

The analysis has now been extended to include best estimates of human water use.

8.7 Wetland methane emission feedback on climate change

Attended the first Workshop of Methane Working Group at the National Center for Ecological Analysis and Synthesis, Santa Barbara, USA in March 2006. The aim of this working group is to integrate multiple scale observations and modelling in order to reduce the uncertainty in emissions of methane from land. We plan to compare our simple modelling approach with much more complex models.

8.8 IMOGEN

Work has been carried out to ensure the IMOGEN system (an analogue to the GCM) is reproducing key elements of the original GCM from which it is calibrated. This work has shown that the results are sensitive to the way in which IMOGEN is coupled to the land surface scheme (MOSES + TRIFFID). Not all of the differences have been established yet, so work is ongoing.

8.9 Runoff generation

A paper has been submitted to the Journal of Hydrometeorology outlining the relative performance of the two runoff generation methods used within MOSES and JULES (the PDM and TOPMODEL). The models were compared using the Rhone_AGG dataset for the Rhone catchment in France. Improvements were made to both the PDM and TOPMODEL in this paper and after tuning both models, the results were similar. It was concluded that other areas should be studied. The method of study used should be repeated for other sites around the world.

8.10 Snow and soil freezing modelling in Northern Europe

The MOSES system was used, driven by meteorological data from the regional climate model, REMO, of MPI in Hamburg. The area where the simulations were made was northern Europe. Different ways of representing snow fractional cover were explored. In addition the soil moisture and fractional soil freezing from the MOSES model were transferred to a plant-growth modeller at Lund University and it was shown that there were considerable improvements to be made in predicting plant-response to climate change using the MOSES data rather than the in-house soil moisture availability (which did not include soil freezing).

8.11 Distributed JULES

The use of JULES in distributed mode driven by many data sources has been worked on in the last 6 months. The first application is to use it with GSWP data and to make comparisons with satellite observations. Many more applications are anticipated.

9. Coupling CEH hydrological models to Met Office regional climate models

As part of a Defra-funded project, the Met Office’s Hadley Centre and CEH Wallingford are collaborating on developing methods to predict flood frequencies over the UK in current and future climates. Regional Climate Models (RCMs) are being coupled to CEH hydrological models to predict fluvial flooding, and coastal flooding when coupled to a shelf-sea model.

Previous work has compared the use of ERA-15–driven RCM and observed rainfall as input to hydrological models for simulating river flows. The availability this year of ERA-40-driven RCM data, for 1961-2001, meant that an extended comparison has been possible, for a period including the Autumn 2000 floods in the UK. The parameter-generalised PDM (Probability-Distributed Model) was run for 16 catchments, with input data derived from an RCM driven by ERA-40 boundary conditions. A comparison with the use of observed data for the same period, in terms of flood frequency curves, showed that the flood frequencies derived using RCM input data were generally under-estimated; only one catchment shows significant over-estimation, with 13 showing significant under-estimation. This is relatively consistent with under-estimation of annual average rainfall, and explains why the under-estimation tends to be worse for larger catchments, due to the cumulative effect of spatial integration of rainfall errors. Applying a (catchment-specific) correction factor for errors in annual average rainfall improves the performance significantly, although it pushes some catchments into a significant over-estimation of flood frequency. The general under-estimation of flows is particularly evident in the flood peaks of Autumn/Winter 2000, even after the application of the correction factor. This is probably because of the sustained nature of the rainfall that caused those floods, and the cumulative effect of rainfall deficiencies on antecedent conditions.

Previous work has developed an initial system to predict changes in flooding for the UK. This system provides a grid-based methodology in the form of a grid-to-grid model for translating regional climate model (RCM) meteorological variables, such as rainfall and evaporation, into estimates of river flow and fluvial outflow to the sea. The initial development work used a simple runoff-production scheme, providing reasonable runoff estimates to allow testing of the routing component which transforms the runoff into river flow. This year the routing scheme, called the Grid-to-Grid model or G2G, has been linked to the Met Office land-surface scheme MOSES in the form of JULES. The combined MOSES-G2G model now provides a stand-alone platform to support research into broad-scale runoff-production and routing schemes. This supports the development and testing of a system for off-line assessment of the response of river flows over a whole region to changing meteorological drivers and the integration of this system as a component of the RCM. The latter then allows both the online calculation of the response of rivers flows and the use of this RCM as part of a coupled atmosphere-ocean RCM (which requires freshwater input into the regional ocean component).

The combined model is currently configured for use at two grid-resolutions: (i) on the UK National Grid used by the Met Office Nimrod nowcasting scheme with MOSES operating at a 5km resolution and 1km Grid-to-Grid routing, (ii) on the European RCM domain with both MOSES and G2G operating at a 25km resolution. Initially this required a set of hand-corrected flow-directions at the resolution of each domain (25 and 1km respectively). This gave reasonable river networks and catchment areas but was time-consuming: thus alternative methods for deriving river networks from higher resolution Digital Terrain Model (DTM) data were explored. New flow directions have now been developed for the G2G at both spatial scales, and have lead to improved accuracy in catchment area. Only a limited amount of hand-correction to overcome any residual errors is then required to obtain the final derived flow directions.

A comparison was performed of the effect of different sources of uncertainty on the impact of climate change on flood frequency. Seven different sources of uncertainty were included: Future greenhouse gas emissions; Global Climate Model (GCM) structure; GCM initial conditions; Downscaling from GCMs (including Regional Climate Model structure); Hydrological model structure; Hydrological model parameters; Impact definition (including natural variability). The results suggested that uncertainty from GCM structure is by far the largest source of uncertainty. However, this is due to the extremely large increases in winter rainfall predicted by one of the 5 GCMs used (CCSR). Omitting the results for this GCM meant other sources of uncertainty became more significant, although uncertainty from sources relating to modelling of the future climate is generally still larger than that relating to emissions or hydrological modelling. It was also shown that natural variability can play a significant role.

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