Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling

Seminar on Climate Change Impacts on Water Resources, Copenhagen, 23rd September 2008

Dr Hayley Fowler
*Reader in Climate Change Impacts and NERC Research Fellow, Newcastle University, UK*
Overview

- Why do we need downscaling methods?
- Types of downscaling methods
- Recent developments in downscaling methods
- Moving towards probabilistic projections
  - UKCIP08
  - Case study
General Circulation Models

- Based on well-established physical principles
- Reproduce observed features of recent climate and past climate changes
- Considerable confidence that GCMs provide credible quantitative estimates of future climate change particularly at the continental and larger scales – IPCC 2007 report
- Confidence in estimates is higher for some climate variables (e.g. temperature) than for others (e.g. precipitation)
Downscaling

General Circulation Models (GCMs)
- e.g. HadAM3H, ECHAM4

Dynamical Downscaling

Regional Climate Models (RCMs)
- e.g. HIRHAM, RCAO

Statistical / Empirical Downscaling
- Change Factors
- Regression methods
- Weather/circulation classification
- Stochastic weather generators

Climate outputs
Dynamical Downscaling

- Nested limited area models
  - Regional Climate Models (RCMs)
  - Resolution: 50 km / 25 km
  - Domain: size of Europe or India
  - Physical basis
  - Computationally expensive
  - But provides added value as regional climate change signals can be very different at the regional scale e.g. orographic forcing, extremes
  - Multiple GCM-RCM ensembles
Assessment of Climatology

- Regional Climate Models simulate mean climate adequately but not in all regions
- Mean temperature (left) and mean rainfall (right) simulated for UK, Scandinavia and Eurasia
Assessment of Climatology

- However, even Regional Climate Models find it hard to accurately simulate extreme events.

- Frequency of three month drought events in observed record (1961-1990) and six regional climate models – all models underestimate observed frequencies.
Downscaling

General Circulation Models (GCMs)
e.g. HadAM3H, ECHAM4

Dynamical Downscaling

Regional Climate Models (RCMs)
e.g. HIRHAM, RCAO

Statistical / Empirical Downscaling
Change Factors
Regression methods
Weather/circulation classification
Stochastic weather generators

Climate outputs
Statistical Downscaling Methods

- **Select predictor variables**
- **Calibrate and verify model**
- **Extract predictor variables from GCM output**
- **Drive model**

**Area**

**Grid Box**

**Predictor variables**
- e.g., MSLP, 500, 700 hPa geopotential heights, zonal/meridional components of flow, areal T&P

**Transfer function**
- e.g., Multiple linear regression, principal components analysis, canonical correlation analysis, artificial neural networks

**Observed station data for predictand, e.g., temperature, precipitation**

**Site variables, e.g., temperature and precipitation for future, e.g., 2050**
EA Weather Impacts and Rainfall Generator

- Generates series of daily rainfall, T, RH, wind, sunshine and PET on 5km UK grid for baseline (observations) and scenarios
- Change factor fields are applied to rainfall statistics: Mean, Variance, PD, Skewness Coefficient, Lag 1 Autocorrelation
- Change factor fields are applied to temperature statistics: Mean temperature, Temperature SD
Statistical Downscaling

**Advantages**
- Not computationally intensive
- Applicable to GCM and RCM output
- Provide station/point values

**Disadvantages**
- Require long/reliable observed series
- Affected by biases in the GCM
- Not physically based
- Non-stationarity in predictor-predictand relationship
Which downscaling method?

- Advantages/disadvantages of different methods known
- Temperature is downscaled with more skill than precipitation; winter downscaled better than summer; wetter climates better than drier
- Systematic intercomparisons, e.g. STARDEX, do not identify a ‘best’ method
- Selection of method should be based on need for downscaled variables in impact study
- Downscaling of multiple climate variables: RCMs, weather generators, statistical methods
Probabilistic Climate Projections

- Can provide a probabilistic basis for distinguishing projections of climate change for different emission scenarios
- Able to capture to some degree other uncertainties arising from model structure and natural variability

**Multi-model ensembles – models of opportunity (availability)**
- Allows consideration of implications of alternative model structures
- But not designed to sample modelling uncertainties in a systematic fashion

**Multi-member ensembles from a single model (perturbed physics)**
- Systematic sampling of modelling uncertainty within a single model framework
- Subjective (experts) estimate prior distributions for the set of model parameters to be perturbed – key physical and biogeochemical processes
Case Study 1: UKCIP08

Thanks to:

Roger Street (UK Climate Impacts Programme, UKCIP)

See www.ukcip.org.uk for more details
Address the limitations of previous UK climate scenarios

Improved spatial and temporal details

25km grid

Seven overlapping 30-year time periods
Consideration and Quantification of Uncertainties

Natural Variability (esp. at regional scales)

Emissions Scenario (esp. after mid-Century)

The way earth system processes are represented in the model - esp. at larger scales
Probabilistic Projections - Uncertainty

- Probabilities of projected climate change - dependent on approach used to develop the projections
- Informs the identification of projected likelihoods associated with exceeding (or not reaching) thresholds and tolerance limits
- Informs consideration of level of risk that can be weighed against the risk you are willing to assume
- Supports identification of response options but also identification of decision points, both in time and space - sequencing introduction of responsive adaptation options

Provides quantitative information on the likelihood of various projected outcomes.
The UKCIP08 package

Headline messages

A set of high-level headline messages will give a national overview of the main changes described by UKCIP08, plus region-specific headline messages. Focus will be on commonly used climate variable such as projected changes in rainfall, temperature and sea-level.

Published material

Reports including:
- Observed UK climate trends
- Probabilistic climate projections
- Marine projections
- Summary report

Customisable output

The UKCIP08 user interface will allow users to create:
- Customised image products such as maps, probabilistic plots (PDFs, CDFs), plume diagrams and scatter graphs.
- Customised numerical products such as GIS format files and sampled model output
- Access to an integrated weather generator

A set of electronic pre-prepared maps & graphs
What are the UKCIP08 products?

- **Headline messages**
- **Published material**
  - 1 Headline messages
  - 2 Briefing report
  - 3 Observed trends
  - 4 Climate projections
  - 5 Marine projections
  - 6 Pre-prepared maps & graphs
- **Image products**
  - 7 Maps
  - 8 PDFs
  - 9 CDFs
  - 10 Plume diagrams
  - 11 Scatter plots
  - Under-water profiles
- **Numerical products**
  - 12 GIS-format files
  - 13 Underlying model output
  - 14 Weather Generator output
  - 15 Observed climate datasets

- **User Interface**
- **UKCIP08 website**

**User Guidance**
- Few studies have examined the uncertainties introduced by using multiple climate model outputs on the hydrological response to climate change

- Probabilistic scenarios have been produced for large regions or globally

- Applications in other fields have demonstrated that combining models through a multi-model ensemble increases skill and reliability of predictions

- How do we combine probabilistic & downscaling methods to study impacts at the catchment scale?
Case Study 2: Eden River

Contributions from:

Claudia Tebaldi (NCAR)
Stephen Blenkinsop (Newcastle)

Example of this approach in the review paper: Fowler, H.J., Blenkinsop, S. and Tebaldi, C. 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling, International Journal of Climatology, 27, 1547-1578, available from h.j.fowler@ncl.ac.uk
Full version in preparation for the Journal of Hydrometeorology
Eden Catchment

RCM data – 50km x 50km
Control 1961-90
Future SRES A2 2070-2100
Interpolated observations – 5km x 5km
Method

- **A. Bayesian weighting scheme using RCM regional means**
- **B. EARWIG Weather Generator**
- **C. Rainfall-Runoff model**
- **D. Monte-Carlo re-sampling of flow time series**

**Methodology Diagram:**

- **PRUDENCE RCMs**
- Extract CFs for catchment region
- **Mean Flow DJF**
  - black=2080s, red=2050s, green=2020s
  - % Change
  - PDF
- **λ**
**EA Weather Impacts and Rainfall Generator**

- Generates series of daily rainfall, T, RH, wind, sunshine and PET on 5km UK grid for baseline (observations) and scenarios
- Change factor fields are applied to rainfall statistics: Mean, Variance, PD, Skewness Coefficient, Lag 1 Autocorrelation
- Change factor fields are applied to temperature statistics: Mean temperature, Temperature SD
- For each RCM, 1000 x 30 year simulations produced for future climate; 1000 x 30 year for observed baseline
Rainfall-runoff model

- ADM model, simplified version of Arno
- Calibrated for Eden catchment on observed data
- $R^2 = 0.73, 0.78$

- Each simulated climate used to produce simulated future flow series (1000 x 30 years) for each climate model using P and PET
- 1000 x 30 year simulation also produced for observed baseline
Temperature

Q95 flow

2050s
Bayesian statistical model delivers a fully probabilistic assessment of the uncertainty of climate change projections at regional scales

Based on:

- Reliability Ensemble Average method (Giorgi and Mearns, 2002)
- Summary measures of regional climate change, based on a WEIGHTED AVERAGE of different climate model responses for BIAS and CONVERGENCE ($\lambda$ weights)
Monte Carlo re-sampling method

- Monte-Carlo technique used to weight models according to $\lambda$ values (from Bayesian weighting)
- Random numbers used to select control and future simulations for each RCM; seasonal statistics of change in mean flow, SD flow, 5th and 95th percentiles then calculated
- If seasonal $\lambda=0.14$ then random number generator selects 140 control/future 30 year runs for that particular RCM
- Generates total of 1000 change statistics for each season – pdf then fitted using kernel density
Change in 2050s flows

- Mean Flow
- Standard Deviation of Flow
- 5th Flow Percentile
- 95th Flow Percentile
A method has been developed to combine different projections of change in climate and flow statistics from multiple RCMs into single probabilistic estimates, shown here as pdfs. These estimates are conservative as the method omits investigation of uncertainties introduced by (1) GCM, (2) downscaling method, (3) impacts model.

BUT QUESTIONS REMAIN…
Big questions:

- How to handle outputs from different climate models?
- How to assess how different uncertainties contribute to overall uncertainty in hydrological impacts? – climate models may provide the largest uncertainties however
- How to combine pdfs of climate change with hydrological models to estimate impacts? – many hydrological models are very computationally expensive
- How do we make adaptation decisions given large uncertainties? – need to better communicate and understand uncertainties and limitations of model outputs
Overall Conclusions

- Very few downscaling studies consider impacts, and fewer consider ‘hydrological’ impacts
- Need to move away from comparison studies into the provision of robust downscaling methods to act as decision-making tools
- Probabilistic methods offer a way forward although it is uncertain how to apply such methods most robustly
- We need clear guidance on how to use probabilistic scenarios/uncertainties to assess impacts and, importantly, also on the physical limitations of model outputs
- It is a challenge to us all to use downscaling methods and will be an even greater challenge to use pdfs!
Thanks to:

NERC Research Fellowship Award (06-09)
NCAR Visiting Scientist Funding 06 and 08