Regional climate-change downscaling for hydrological applications using a nonhomogeneous hidden Markov model

Steve Charles
IRI Seminar, September 30, 2010
Talk outline

- Current Australian trends and climate change
- Downscaling overview
- Hydrological projections
- Future research and summary
CSIRO’s role

• CSIRO responding to the Federal Government’s National Innovation System and current National Research Priorities

• Unique capacity of CSIRO to help resolve Australia’s major challenges due to our size, geographic distribution and diversity of skills

• Developing better ways for CSIRO to deliver commercial, social and environmental outcomes from science

• Tackling Australia’s biggest challenges

• High impact, high quality, multidisciplinary science

• Focus on outcomes
“Provide Australia with solutions for water resource management, creating economic gains of $3 billion per annum by 2030, while protecting or restoring our major water ecosystems”
Drying trend across most of Australia

Annual rainfall trend from 1950 to 2009

1997–2009 rainfall decile (relative to 1900–2009 climatology)
Unprecedented low streamflow

Annual inflow to River Murray (SE Aus)

Annual inflow to Perth Dams (SW Aus)
Total volume Perth Dams (2003 to yesterday)
### Australia by Drainage Divisions

**Capacity (ML):** 25,209,825  
**Volume (ML):** 16,813,258

66.7% Up 39.9% from same time last year

#### Graph Details

<table>
<thead>
<tr>
<th>Drainage Divisions (12 available)</th>
<th>Capacity (ML)</th>
<th>Volume (ML)</th>
<th>% Full</th>
<th>Date Reported</th>
<th>Previous Year</th>
<th>Volume (ML)</th>
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**Latest Volume:** 50,517,881 ML  
**Accessible Capacity:** 78,425,731 ML

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**Snapshot**

- Latest: 28 Sep 10
- Last Year: 28 Sep 09

**Summary**

- 100%
- 80%
- 60%
- 40%
- 20%
- 0%

**Changes**

- 64.4%
- 51.8%
Overallocation and increasing demand for water

Many surface water systems are over-allocated

Increasing demand from cities, industries, irrigation and the environment
Australian hydroclimates are different

- Australia is drier and less of its rainfall becomes runoff.
- Australian river flows are more variable than elsewhere in the world.
- ENSO-streamflow teleconnection in Australia is amongst the strongest in the world.

- low variability
- medium variability
- high variability

- little ENSO-runoff teleconnection
- significant ENSO-runoff teleconnection
The rainfall elasticity of streamflow in Australia (2–3) is highest in the world.

A ten percent change in mean annual rainfall is amplified as a 20–30 percent change in mean annual streamflow.
What will the future look like?

- Some evidence linking part of the current drought to high global temperatures (intensification of STR, decreased La Nina events, high frequency of positive IOD, more frequent El Nino in combination with positive SAM).

- However, it is difficult to separate a global warming signal from the high natural climate variability.
Climate change projections

- Large uncertainties in global warming projections – dependent on (i) greenhouse gas emission and (ii) global climate sensitivity to increased greenhouse gas concentrations.

- Large uncertainties in GCM modelling of local/regional rainfall response to global warming.
Modelling climate impact on water

Global climate models (GCMs)

Hydrological modelling

Downscaling

Dynamic downscaling

Statistical downscaling
Downscaling GCM simulations to obtain catchment-scale climate series

- **Simple scaling methods** scale the entire historical daily rainfall series to obtain a future daily rainfall series, informed by GCM simulations for a future climate and a historical ‘baseline’ climate.

- **Statistical downscaling methods** relate synoptic large-scale atmospheric predictors to catchment-scale rainfall, and the relationship is used to downscale atmospheric predictors from GCMs to obtain catchment scale-rainfall.

- **Dynamic downscaling method** uses a high resolution regional climate model with boundary conditions provided by large-scale GCM simulations.
Relationships between larger-scale climate variables & local surface climate variables, derived from observed data, are applied to climate model output based on the two assumptions that:

- larger-scale variables are more reliably simulated
- relationships remain valid in a changed climate
Why do we need to statistically downscale?

GCM grid cell rainfall not representative of site rainfall
Why do we need to statistically downscale?

- RCM rainfall
- Occurrence Amounts
- Observed rainfall

![Graph showing the relationship between RCM rainfall and observed rainfall for occurrence and amounts.](image)
Rainfall

MSLP

25 IPCC AR4 GCMs; 110-122.5E and 37.5-27.5S; 1961-2000 Annual means
• Simulates stochastic local-scale daily time series based on a small set of “hidden” states defined from daily rainfall observations at a network of sites

• Provides a classification of the local rainfall patterns produced by regional-scale atmospheric variability

• Downscaling is achieved by allowing the Markovian transition probabilities between the states to vary “nonhomogeneously” over time according to a set of predictors
**Nonhomogeneous Hidden Markov Model (NHMM)**

*Observed process:* sequence of rainfall patterns across a region

*Hidden discrete-valued process:* sequence of weather states

Transition from state to state driven by atmospheric information

\[
P(R_t) \quad R_1 \quad R_2 \quad R_3 \quad R_4 \quad R_5 \quad R_6
\]

\[
P(R_t | S_t) \quad S_1 \quad S_2 \quad S_3 \quad S_4 \quad S_5 \quad S_6
\]

\[
P(S_t | S_{t-1}) \quad X_1 \quad X_2 \quad X_3 \quad X_4 \quad X_5 \quad X_6
\]

\[
P(S_t | S_{1:t-1}, X_{1:T}) = P(S_t | S_{t-1}, X_t)
\]
NHMM process

**Calibration process:**
- Selection of rainfall station network (quality control for daily data non-trivial!)
- Selection of candidate atmospheric predictors (variables and domain)
- Selection of # of states and optimum combination of predictors

**Validation process:**
Out-of-sample reproduction of rainfall statistics
- Wet-day occurrence frequencies
- Wet- and dry-spell length distributions
- Rainfall amount distributions and interannual variability
- Spatial correlation for occurrences and amounts

**Outputs:**
- NHMM is stochastic: multiple realisations of daily multi-site rainfall series
- Diagnosis of historical rainfall variability and atmospheric driver relationships
- Aids assessment of climate models: more confidence in SD projections
Examples of selected NHMMs

Kimberley Region of North-West Australia

- **Summer (Nov-Apr)**
  - 5 weather states, 3 atmospheric predictors
  - Northeast-Southwest gradient in MSLP
  - North-South gradient in 850hPa level Westerly wind speed
  - 850hPa level Specific humidity

- **Winter (May-Oct)**
  - 3 weather states, 4 atmospheric predictors
  - Northeast-Southwest gradient in MSLP
  - East-West gradient in 850hPa level Westerly wind speed
  - 700hPa level Specific humidity
  - Total-totals
NHMM Calibration Step 1: Determining number of states

Bayesian information criterion vs. number of states for two datasets:
- Blue line: kim9_all
- Pink line: kim_9hq
NHMM Calibration Step 2: Determining predictor set

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<th>Predictor combinations</th>
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<tr>
<td>1</td>
<td>slp</td>
</tr>
<tr>
<td>2</td>
<td>N-S slp</td>
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<td>24</td>
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Northeast-Southwest gradient in MSLP

North-South gradient in 850hPa level Westerly wind speed
Northeast-Southwest gradient in MSLP

North-South gradient in 850hPa level Westerly wind speed

850hPa level Specific humidity
NHMM Calibration Step 3: Assessment and validation
Downscaled NDJFMA precipitation for 3003 Broome Airport (Station 5)

Downscaled NDJFMA precipitation for 2016 Lissadell (Station 3)

Downscaled NDJFMA precipitation for 3030 Biddyadanga (Station 9)

Downscaled NDJFMA precipitation for 3017 Mount House Station (Station 6)
At-site interannual and out-of-sample validation
Diagnosing drivers of observed trends

State 1
State 1 of 5 46%

State 2
State 2 of 5 12%

Month 5 State 1
Month 5 State 2
Month 5 North-South MSLP

N-S MSLP
DTD700
DTD850
N-S Z700

1958 2007

May

June


700hPa Dew Point Depression
850hPa Dew Point Depression
North-South 700hPa Geopotential H
Climate change projection

Wet state

Dry state

Wet state

Dry state
SWWA Rainfall Changes

Occurrence: 1970

Occurrence: 2000

Amounts: 1970

Amounts: 2000
SWWA Atmospheric Predictor Changes

Bates et al. (2010) Assessment of apparent non-stationarity in time series of annual inflow, daily precipitation and atmospheric circulation indices: A case study from southwest Western Australia. Water Resources Research, accepted.
Statistical downscaling benefits

- Spatial scale required by process models (rain gauge or grid)
- Daily, multi-site rainfall patterns – ‘weather states’
- Frequencies, amounts, wet & dry spell-length distributions
- Inter-site spatial correlations
- Stochastic simulations conditional on observed or modelled atmospheric predictors (climate variability & change)
- Allow analysis and diagnosis of the drivers of observed regional rainfall change (e.g., SW Western Australia)
- Other variables (e.g. T, Rad) generated using a weather generator conditional on weather states and rainfall
Statistical downscaling caveats

- Networks of individual stations, not national coverage
- Assumes relationships derived for current climate hold for future climate (can be tested to some extent)
- Projections limited to periods with GCM daily data availability
- Results are sensitive to the choice of GCM – thus GCM assessment and selection important
- GCM predictor biases degrade downscaled projections
Hydrological modelling Framework / Flowchart

Source Rivers

- Option 1 - sum runoff over area 5 km² runoff grids
- Option 2 - pre-calibrated parameters from 5 km²
- Option 3 – user calibration

Source Catchments

- Spatially explicit

Existing Inflows

File

Run model to generate runoff

Time series runoff

Parameter set

Calibration tools

Parameters

- Calibration and application guidelines
- Objective functions
- Regionalisation methods
- Spatial LAI

Climate dataset

CWYET Filters
- Climate change impacts
- Plantation impacts
(expressed as inflow scaling factors)

CWYET

Climate change impacts
Plantation impacts

Runoff over area 5 km² runoff grids

Pre-calibrated parameters from 5 km²

User calibration
Modelling climate impact on water (uncertainty in modelling components)

Global climate models (GCMs)

Range of future projections is more than 40%

Downscaling

Differences between downscaling methods/models are less than 20%

Hydrological modelling

Differences between hydrological models are less than 10%
Daily runoff (mm) that is exceeded 1 percent of the time
Mean summer runoff (mm)
Mean winter runoff (mm)
Cv of annual runoff
Number of days (per year) with daily runoff less than 0.1 mm

Modelled runoff using observed daily rainfall
Modelled runoff using daily rainfall from downscaling models
Analogue GLIMCLIM NHMM CCAM

Downscaling models
- Analogue
- GLIMCLIM
- NHMM
- CCAM

GFDL GCM
CSIRO GCM
MRI GCM
GCM assessment – MSLP predictor biases

- CCAM
- CSIRO Mk3.0
- ECHAM4
- HadAM3P
Effect of GCM bias on SD rainfall & runoff

**Rainfall**

- Observed 1975 - 2004
- Mk3 1975 - 2004
- Mk3 2035 - 2064

**Runoff**

- Observed 1975 - 2004
- Mk3 1975 - 2004
- Mk3 2035 - 2064
Effect of GCM bias on SD rainfall & runoff

![Rainfall](image1)

![Runoff](image2)
Accounting for GCM uncertainty

- Aim to establish a distribution for statistical parameters that describes ‘population’ of climate models
- Hierarchical model fitted in Bayesian framework using Markov Chain Monte Carlo methods
- Hierarchical model suggests pooling GCM results underestimates uncertainty, especially in lower extremes CAVEAT: results sensitive to choice of prior and emulator structure

Future research

• Statistical downscaled stochastic simulations of gridded daily precipitation suitable for input into hydrological prediction models

• Quantify the relative uncertainties due to
  • GCM climate projections
  • downscaling methods (statistical and dynamic)
  • different rainfall-runoff models

• Uncertainty framework to provide improved probabilistic projections of future runoff and water availability

• IPCC AR5
  • Near term – to 2035 (particularly the decade 2026-2035)
  • Long term – to 2100 and beyond
Summary

- South-east Australia has experienced a prolonged decadal drought with unprecedented decline in streamflow. In south-west Australia, the mean annual streamflow after the mid-1970s is less than half the earlier mean.

- Projections indicate that southern Australia is likely to be drier on average in the future. There are tools for estimating climate impact on water, using GCM projections, downscaling methods such as the NHMM, and hydrological models.

- Predictions of future water availability and runoff characteristics are improving rapidly with more data becoming available and with the rapid progress in climate and water science. However, the range of plausible future projections is likely to remain large.
Thank-you

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