30-years of regional climate modeling: Where are we, how did we get there and where are we going?

Giorgi, JGR 2019, Grand Challenge paper.

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Outline

Basic principles

Historical overview

Key achievements

Outstanding issues

Future directions
After the first RCM papers came out (1989) I was interviewed for the NCAR newsletter and was asked the following question:

What will happen to regional climate modeling in 5 years time when GCMs will reach the same resolution?
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The “one-way nested” regional climate modeling technique

GCM

RCM

Inner Domain

Buffer Zone (LBC Relaxation)

Impacts

Water, food, energy, ecosystem services, biodiversity, migration, coastal areas, tourism
The sense of dynamical downscaling

(a) GCM (MPI)

(b) RCM (RegCM4)

(c) West Africa – Land only

Frequency

Intensity (mm/day)
The beginning of regional climate modeling
The Yucca Mountain Project (1987)
R. Dickinson, R. Anthes, B. Kuo, R. Errico, F. Giorgi, G. Bates
Representation of western U.S. topography at different resolutions

(a) 500 km

(b) 50 km

(c) 10 km
Reanalysis-driven simulations:
Giorgi and Bates (1989): “Climate mode” (1 month)
First ensemble of GCM driven month-long simulations (Giorgi 1990)
Winter Precipitation Present Day (Giorgi, Shields, Bates 1994)

Observations

RegCM

CCM1
Winter Precipitation Change 2CO2-Control

RegCM

CCM1
Other early RCM activities (nineties)

- **Europe**: Giorgi et al. (1990); Jones et al. (1995, 1997); Christensen et al. (1997, 1998); Machenauer et al. (1998)
- **East Asia**: Kida et al. (1991); Hirakuchi et al. (1995); Fu and collaborators
- **Arctic**: Lynch et al. (1995)
- **Australia**: McGregor and collaborators
- **North America**: Laprise and collaborators, Arritt-Gutowski and collaborators
- **Africa**: Semazzi and collaborators
Some key intercomparison projects

- **European projects**: MERCURE, PRUDENCE, AMMA, ENSEMBLES, CECILIA, CLARIS, ACQWA

- **Intercomparison projects**:
  - PIRCS (N. America)
  - RMIP (East Asia)
  - CLARIS (S. America)
  - AMMA (W. Africa)
  - NARCCAP (N. America)
  - BALTEX (Baltic region)
  - ARCMIP (Arctic)

- **CORDEX (Universe)**
PIRCS: Summers 1988 and 1993 (Takle et al. 1999)

Figure 7. Spatial pattern of model bias (mm) for 60-day total precipitation.
Uncertainties in regional climate change projections: The PRUDENCE strategy

Scenarios

A2
B2

GCMs

HADAM3H
ECHAM5
ARPEGE
FVGCM

RCMs

Hadley
Rossby
DMI
UCM
ETH
ICTP
MPI
GKSS

Impacts

Storm Surge
Agriculture
Hydrology
Ecosystems
Health
Water Res.
Tourism
Droughts
Floods
Sources of uncertainty in the simulation of temperature and precipitation change (2071-2100 minus 1961-1990) by the ensemble of PRUDENCE simulations (whole Europe) (Note: the scenario range is about half of the full IPCC range, the GCM range does not cover the full IPCC range) (Adapted from Deque et al. 2006)
Some key literature

- **Review papers:** Giorgi and Mearns (1991, 1999), McGregor (1997), Giorgi et al. (IPCC 2001), Leung et al. (2003), Mearns et al. (2003), Wang et al. (2004), Giorgi (2006); Laprise (2008); Laprise et al. (2008); Rummukainen (2010); Foley (2010); Arritt and Rummukainen (2011); Solman (2013); Rummukainen et al. (2015); Rockel (2015); Giorgi and Gutowski (2015); Giorgi (2019)

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Key achievements in RCM research

• Development of flexible and portable RCM systems used by large communities (at least 10)
• Increase in simulation length and resolution to centennial scale and ~ 10 km grid spacings (even less with convection permitting models).
• Application of RCMs to a wide variety of scientific problems (process studies, paleo, projections etc.)
• Development of fully coupled regional Earth System Models (RESMs, at least 10)
• Increasing use of RCM output for VIA-CS applications
• Involvement of community of scientists from developing countries
• CORDEX !!!
COordinated Regional Downscaling EXperiment (CORDEX) – Some history

- Initial discussions across the downscaling community (mostly RCM)
  - Toulouse 2009
- Establishment by the WCRP of the Task Force on Regional Climate Downscaling, TFRCD (2010)
- Design of Phase I CORDEX framework (Giorgi et al. 2009; Jones et al. 2011)
- Establishment by the WCRP of the Science Advisory Team, SAT (2012)
CORDEX Vision and Goals

The CORDEX vision is to advance and coordinate the science and application of regional climate downscaling through global partnerships.

- To better understand relevant regional/local climate phenomena, their variability and changes through downscaling.
- To evaluate and improve regional climate downscaling models and techniques (RCM, ESD, VAR-AGCM, HIR-AGCM).
- To produce large coordinated sets of regional downscaled projections worldwide.
- To foster communication and knowledge exchange with users of regional climate information.
• CORDEX Science advisory team (SAT), 12 members

SAT-2 meeting
SMHI (Sweden)
25-27 Feb., 2015

• International Project Office for CORDEX (IPOC) hosted at SMHI since January 2015 (E. O’Rourke, I. Lake Head).

• Regional points of contact (POCs), 2-3 per region
CORDEX Phase I experiment design

**Model Evaluation Framework**

**Climate Projection Framework**

**Multiple regions at 50 km grid spacing**
Higher for some regions (Europe – 12 km)

**AMIP like**

ERA-Interim LBC 1989-2007

**CMIP like**

Evaluation of present day GCM-driven climate runs

Scenarios (1951-2100) RCP4.5, RCP8.5

Regional Analysis Regional Databanks

Multiple driving AOGCMs
CORDEX domains
Ensembles of projections were produced for most domains.

**CORDEX-S. ASIA**

**EURO-CORDEX**

**CORDEX-AFRICA**

**RCP4.5**

**RCP8.5**

Ensembles of projections were produced for most domains.
EURO-CORDEX: unprecedented set of ~50 projections at ~12 km grid size

Jacob et al. (2013)

Fig. 2. Projected seasonal changes of heavy precipitation [%] based on the RCP 8.5 scenario for 2071-2100 compared to 1971-2000. Hatched areas indicate regions with robust changes. Changes are not significantly due to only three model simulations.
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Outstanding issues in RCM research

• **ADDED VALUE !!!** (There are many papers identifying the added value of RCMs in individual experiments or regions, but a fully comprehensive paper is still not there)
The case of summer precipitation over the Alpine region
Torma et al. (2015), Giorgi et al. (2016)

Reference period: 1975-2004
Future period: 2070-2099

Observational data: EURO4M-APGD (Isotta et al., 2014)

Horizontal resolutions: 1.32°, 0.44° and 0.11°
Added value: Simulation of spatial patterns of summer precipitation

Higher resolution

Increasing details in precipitation spatial distribution

Fine scale AV
Summer precipitation change

GCMs

RCMs

0.11°

Observed summer precipitation change (1975-2004)

RCM – GCM Anomaly

mm/day/century
Summer precipitation change

Convective

Non-Convective

Evaporation

Potential Instability Index
Outstanding issues in RCM research

- **ADDED VALUE !!!**
- **Garbage in – Garbage out**
- **Configuration of model simulations**
  - Internal variability
  - Dependency on domain size
  - Dependency on domain placement
  - Dependency on model physics schemes
  - Dependency on LBC technique (e.g. relaxation vs. nudging)
Domain Choice
The choice of domain needs to be done very carefully, possibly with testing of different domain sizes
Gao et al. (2001)
Outstanding issues in RCM research

- **ADDED VALUE !!!**
- **Garbage in – Garbage out**
- Configuration of model simulations
  - Internal variability
  - Dependency on domain size
  - Dependency on domain placement
  - Dependency on model physics schemes
  - Dependency on LBC technique (e.g. relaxation vs. nudging)
- **Uncertainty in regional projections**
  - The use of RCMs or different downscaling approaches adds a further level of uncertainty
Precipitation trend 1990-2050
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Future directions in RCM research: Convection-permitting modeling

Convection permitting models can improve the simulation of precipitation at sub-daily scales and of convective systems. Courtesy of N. Ban and A. Prein.

Special issue of Climate Dynamics (2019)
Future directions: Development of Regional Earth System Models
Future directions in RCM research

• Strengthening of some scientific areas of RCM application
  – Seasonal to decadal prediction
  – Paleoclimate simulation
  – Regional detection and attribution
  – Feedbacks to GCM modeling

• Increased use in VIA-CS studies
  – Necessity to develop guidelines
  – Greater interactions with the user communities
  – New breed of scientists at the interface between climate science and application
Future CORDEX directions: CORDEX CORE
Two groups have completed the CORDEX-CORE runs !!! (RegCM, REMO)

Model Evaluation Framework

Climate Projection Framework

Core number of RCMs run over all domains
25 km grid spacing

ERA-Interim LBC
1989-2007

Evaluation of present day GCM-driven climate runs

Scenarios (1970-2100)
RCP2.6, RCP8.5

Core set of driving AOGCMs

Regional Analysis
Regional Databanks
Focus on smaller regions to address specific science and VIA issues

Effects of regional forcings
Land-use change
Urbanization
Aerosols

Intercomparison of different downscaling techniques (e.g. RCM, ESD)

Interactions with other WCRP projects (e.g. GEWEX)

Modeling (Added Value) at multiple scales, down to cloud resolving. Model development

Availability/production of high quality, high resolution, multiple variable observations

Development of coupled Regional Earth System Models (RESMs)

Production of large ensembles for uncertainty characterization

Study of phenomena relevant for regional climate and impacts through targeted experiments (e.g. MCS, TC, extremes, monsoon)

Relevance for VIA and adaptation/policy applications
Distillation of actionable information

Future CORDEX Directions
Flagship Pilot Studies
Final considerations

- RCM research is still alive and kicking, even after 5 years of regional climate modeling (RCMs are not just downscaling tools !!!)
- The production of CP and RESM-based ensembles will pose tremendous technological challenges (computing time and storage)
- The increasing interaction with the stakeholder community will pose another formidable challenge (under various viewpoints)
- CORDEX has to remain the centerpiece of RCM research
Looking forward to the next 30 years of RCM research !!!

THANK YOU
The ESP RegCM and Regional Climate research NETwork, RegCNET

Regional Modeling

Collaborative research projects
Use of ICTP model tools and datasets
Workshops at ICTP and on-site

E-mail list (over 700 p.)
Interactions with other international programs
Visitor program

Storms  Flood  Drought  Water Resources  Energy  Agriculture  Landuse Change  Pollution  Health  Fisheries  Ecosystems
Effect of different LBC configurations

Giorgi et al. 1993b
Tip 3: RCM internal variability

The internal variability of RCMs may be misinterpreted as a real signal

Figure 10. Bottom model level temperature (K) and precipitation (mm/day) BIAS for the LBC and IC perturbation experiments (not including the first 15 days of simulation). Season is JJA. (a) Temperature BIAS, Exp. LBC; (b) temperature BIAS, Exp. IC; (c) precipitation BIAS, Exp. LBC; (d) precipitation BIAS, Exp. IC. Light shading is for negative values and dark shading is for positive values.

Giorgi and Bi (2000)
RCM internal variability
Figure 12. BIAS for precipitation ($P$) and wind speed ($U$), temperature ($T$), and water vapor mixing ratio ($Q$) at $\sigma = 0.995$ for different experiments. Only land points are used in the calculations. (a) $U$, (b) $T$, (c) $Q$, (d) $P$. Season is JJA.