Regional Climate Modeling Using
the Weather Research and
Forecasting (WRF) Model:
Applications in the Tropics and the
Western U.S.

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Findings from the NRC Report (2007)

- Discovery science and understanding of the climate system are proceeding well, but use of that knowledge to support decision making and to manage risks and opportunities of climate change is proceeding slowly.
- Progress in understanding and predicting climate change has improved more at global, continental, and ocean basin scales than at regional and local scales.
- Our understanding of the impact of climate change on human well-being and vulnerabilities is much less developed than our understanding of the natural climate system.
- Could the lack of an attempt to understand and provide regional climate predictions or projections be an underlying problem for all these symptoms?
Why Regional Scale is Important: The Southwest Drought Example

Changes in annual runoff based on GCMs, 2041-2060 (~ 20% reduction)

Milly et al. (2005)

Changes in annual runoff based on offline hydrologic model driven by downscaled GCMs outputs (~ 6 - 10% reduction)

Christensen and Lettenmaier (2007)
Reconciling the Differences Between the Drying Trends

- GCMs coarse resolution precludes negative feedback in the small high elevation headwater areas

Coarse scale models

- Warmer Temperature
- Higher Evaporative Demand
- Reduced Runoff

High resolution models

- Warmer Temperature
- Earlier Snowmelt
- Wetter Soil
- Less Evaporative Demand
- Reduce Runoff and ET Sensitivity to Temperature
Regional Scale is Important When it Comes to Water and its Phase Changes

- Large uncertainty in projecting future climate is related to the complexity of feedback processes associated with water and its phase changes (e.g., water vapor feedback, cloud/aerosol feedbacks, snow albedo feedback)
- Latent heat is a major driver of tropical and extratropical circulation and severe storms such as hurricanes
- Precipitation is a key variable linking the physical, chemical, and biological processes – important for earth system prediction
- Precipitation is a key driver of environmental impacts (e.g., natural resources, human health) – important for assessing climate change impacts
A Global Climate Modeling Dilemma

- Complexity vs Resolution
- Computing resources are not enough to support significant advancement in both

IPCC AR4
What Values Have Been Demonstrated with regional modeling?

- Topographic effects – more realistic topographic response in precipitation, snowpack, glaciers, snowmelt runoff
- Regional circulation – the Low Level Jet, diurnal wind systems (e.g., land-sea breeze, mountain-valley circulation)
- Extreme events – simulate more realistic intense precipitation rates, extreme temperature, hurricane statistics
RCM Research Using MM5/WRF

- Climate change impacts on water resources (e.g., snowpack, streamflow, extreme events)
- Climate change impacts on air quality (e.g., ozone, PM2.5, visibility, biogenic emissions)
- Aerosol effects on hydrological cycle in Asia and western US (Atmospheric Brown Cloud, aerosols effects on orographic precipitation, and soot on snow)
- Downscaling seasonal climate forecasts for hydrologic predictions
- Development of regional climate change scenarios for impact assessments
- Investigate methods to address tropical biases in climate simulations
Analysis of Tropical Biases in the WRF Tropical Channel Simulations

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With NCAR MMM/CGD scientists, students, and visitors
Modeling the Tropics

- Most GCMs exhibit large tropical biases, including simulations of the ITCZ, tropical modes, and diurnal cycle.
- The lack of scale interactions in GCMs could be a critical factor responsible for the tropical biases.
- An example of scale interactions: Mid-level clouds undergo strong diurnal variations, and they provide moisture needed for deep convection (interaction between diurnal and intraseasonal time scales, and interactions between processes related to diurnal variations and MJO).

No GCM comes close to simulating the eastward propagating Madden-Julian Oscillation (MJO) – a dominant component of intraseasonal variability in the tropics that is linked to rainfall variability in the Pacific Islands, monsoon regions of Asia, and west coast of North and South America.
WRF Tropical Channel Simulations

- To explore ways to represent scale interactions, we use a limited area model, the Weather Research and Forecasting (WRF) model, configured as a tropical channel at 36 km resolution to simulate tropical phenomena; observations for 1996 - 2005 are used to specify the north/south boundaries and lower boundary.

- A cloud resolving nest at 4 km resolution is embedded over the Pacific warm pool - the heat engine of the tropics - to investigate tropical convection and its upscaled effects.
Large Scale Circulation Features

OLR
Domain Mean = 275.1

Upward SW
Domain Mean = 96.8

Upward motion

OBS

NRCM
Tropical Modes

- WRF reasonably captured various tropical modes, including the eastward traveling Kelvin waves and MJO

Source: Julie Caron
Tropical Modes

- More organized eastward propagating tropical waves in the observations over the India Ocean, South America, and West Africa

Source: Stefan Tulich
Kelvin Wave Variance and Structure

- Low Kelvin wave variance in the deep tropics
- Simulated realistic structures of Kelvin waves

Source: Stefan Tulich
MJO Variance

- Insufficient TIV (total intraseasonal variance) and MJO variance in the deep tropics, particularly over the Indian Ocean.

MJO variance and Total Intraseasonal Variance (TIV) of precipitation

Source: Ray Pallav
MJO Propagation

- MJO propagation speed fairly well captured by model

Lag-correlation of 20-90 day precipitation

Source: Ray Pallav
The May 1997 MJO Event

- The model is able to carry the MJO signal or pre-conditions in the initial conditions forward within the MJO predictability limit (20 days)

Source: Ray Pallav and Chidong Zhang
East Asian Monsoon

- Generally there are dry biases in the summer monsoon rainfall in East Asia, except for 1998.
East Asian Monsoon

- 1997: West Pacific Subtropical High pushed further east, low pressure in the South China Sea, northeasterly flow in eastern China, southwesterly monsoonal flow never reaches China.
East Asian Monsoon

- 1998: West Pacific Subtropical High has reasonable strength and location, southwesterly monsoonal flow brings abundant moisture to China
Dynamical Response to Diabatic Heating

- The low pressure at 850 mb west of the intense convective center is likely a dynamical response to the convective heating that maximizes near 400 – 500 mb

Liu et al. 2001; 2003
Sensitivity Experiments

• The 98SST experiment has the largest impacts, reducing wet biases in the western Pacific, and improving monsoon rainfall in China.
Sensitivity Experiments

• The 98SST experiment has better simulation of the monsoon circulation
Implications

• In the large tropical channel domain, SST exerts stronger influence than lateral boundary conditions

• Change in convection schemes (KF, BM) has little impacts

• The model is over-sensitive to SST forcing in the tropical Pacific, leading to much larger monsoon response to ENSO SST changes than is observed

• Previous studies suggest that air-sea interactions in the Arabian Sea and Bay of Bengal may provide a negative feedback loop to counteract the monsoon weakening associated with warm ENSO events

• Further sensitivity experiments using daily SST and a skin sea surface temperature scheme produced insignificant change - need a mixed layer ocean to capture such effects

Lau and Nath (2000)
What Have We Learned?

• WRF captured some basic large scale circulation features in the tropics such as the seasonal migration of ITCZ, TOA cloud forcing, and transition from stratocumulus to deep convection in the East Pacific transect

• In the large tropical channel, the simulation is more strongly controlled by SST than lateral boundary conditions, though results show some sensitivity to the location of the southern boundary, particularly over the South Indian Ocean

• Some features of MJO and Kelvin waves are well simulated, but the simulation generally lacks intraseasonal variability in the deep tropics, with less organized eastward propagation

• Larger biases are found over the Indian Ocean and western Pacific where convection responds too strongly to warm SST; biases in diabatic heating have negative impacts on the monsoon circulation, which also correlates with poor simulation of tropical cyclones in northwestern Pacific during some years
What Have We Learned?

• In the tropical channel at 36 km spatial resolution, parameterized convection continues to present challenge in simulating tropical convection; what further improvement can we make using parameterized convection between 10 – 100 km resolution?

• Lack of air-sea interactions could also be an important factor contributing to the biases in tropical convection and tropical modes?

• The impacts of the cloud resolving (4 km) nest over the warm pool have not been addressed

• Large tropical biases have serious implications to climate predictions at the (1) intraseasonal time scale as tropical modes strongly influence variations in large scale circulation and hydrological cycle (2) interannual time scale as tropical modes are linked to ENSO, and (3) decadal to century time scale as they present a fundamental test of our understanding of clouds and various feedback processes critical to determining climate sensitivity to greenhouse forcing
The North American Regional Climate Change Assessment Program (NARCCAP):
A Multiple AOGCM and RCM Climate Scenario Project over North America

Linda O. Mearns, NCAR
NARCCAP Goals

1. Quantify multiple uncertainties in regional and global climate model projections of regional climate in North America

2. Develop multiple high resolution regional climate change scenarios for use in impacts and risk assessments

3. Evaluate regional model performance over North America by nesting the RCMs in reanalyses

4. Understand critical regional climate change issues (e.g., effects of increased GHGs on the frequency of extreme weather events)

5. Create greater collaboration between US, Canadian, and European climate modeling groups to leverage the diverse modeling capability across the countries

6. Derive added value from diverse regional and global modeling projects and programs currently underway in the US, Canada, Europe and South America.
Organization of Program

Phase I: 25-year RCM simulations (50 km res.) using NCEP/DOE boundary conditions [6 RCMs]

Phase II:
- 30-year control/scenario RCM simulations (50 km res.) using AOGCM boundary conditions
- Time-slice AGCM simulations (50 km res.) [GFDL and NCAR CAM3]

Opportunity for double nesting to include participation of other RCM groups (over specific regions - e.g., for NOAA OGP RISAs, California Energy Commission, New York Climate and Health Project).

Formal statistical models for scenario formation and characterization of uncertainty.
NARCCAP PLAN

A2 Emissions Scenario

GFDL
CCSM
HADAM3
CGCM3

Provide boundary conditions

1970-2000 current
2040-2070 future

MM5
Iowa State/ PNNL

RegCM3
UC Santa Cruz ICTP

CRCM
Quebec, Ouranos

HADRM3
Hadley Centre

RSM
Scripps

WRF
PNNL/ NCAR
Global Time Slice / RCM Comparison
at same resolution (50km)

A2 Emissions Scenario

GFDL AOGCM

CCSM

Six RCMS
50 km

GFDL
Time slice
50 km

compare

compare

CAM3
Time slice
50 km
Domain Sensitivity Study
Each simulation lasts for one year (1979) using NCEP/DOE reanalysis b.c.
Phase 1 Simulation

• A WRF simulation driven by the NCEP/DOE reanalysis and AMIP SST has been completed for 1979/9 - 2004/12 using the NARCCAP domain

• Physics parameterizations: CAM radiation, KF convection, WSM5 mixed phase microphysics, YSU non-local PBL, Noah LSM

• Update of SST, sea ice, vegetation fraction, surface albedo; consistent treatment of snow emissivity in Noah LSM

• Model outputs have been archived at NERSC and NCAR and accessible from the Earth System Grid (ESG)
Cold Season Variability

WRF and MM5 have similar skill in capturing cold season variability

ACC ~ 0.90
Columbia River Basin

ACC ~ 0.94
California

ACC ~ 0.92
Great Basin

ACC ~ 0.30
Ohio Basin

ACC ~ 0.60 in NCEP
Warm Season Variability

Larger differences between WRF and MM5 year-to-year variability, but generally ACCs are similar.

**Columbia River Basin**

ACC ~ 0.80

**California**

ACC ~ 0.60

**Upper Mississippi Basin**

ACC ~ 0.3 - 0.8

ACC ~ 0.60 in NCEP

**Ohio Basin**

ACC ~ 0.3 - 0.4

ACC ~ 0.17 in NCEP
Mean Cold Season T and P
Impacts of ENSO in the Cold Season
ENSO Anomalies

• Regional details in the ENSO precipitation anomalies demonstrate the interactions between large scale circulation changes with the regional topography.

Composited El Nino Precipitation Anomaly

Leung et al. (2003)
Mean El Nino T and P Anomaly

Cool-Wet (Southwest) vs Warm-Dry (Northwest)
Mean La Nina T and P Anomaly

Cool-Wet (Northwest) vs Warm-Dry (Southwest)
Atmospheric Rivers and Floods

- An atmospheric river was present in all of the floods on the Russian River since 1997, though not all atmospheric rivers are flood producers.
- Main ingredients for heavy orographic precipitation: LLJ, large moisture content, neutral stability.
- Stratification with respect to unsaturated vs saturated conditions can produce drastically different orographic response.

Ralph et al. (2005)
Mean T and P Anomaly Averaged Over 143 Days During Pineapple Express Events (1980 - 1999)
The 1986 President Day Event (Anomaly)
The 1997 New Year Event (Anomaly)
Future Directions

• WRF has become a very flexible modeling framework - it can be configured as a limited area model, tropical channel model, and global model, with one-way and two-way nesting capability going down to the cloud resolving scale

• WRF/ROMS can be embedded 2-way within global modeling systems to simulate regional atmosphere-ocean-land processes

• WRF is a useful framework for downscaling, upscaling, and investigation of scale interactions

• WRF can be used to test and develop physics parameterizations for global cloud resolving models and assess potential impacts of global cloud resolving modeling

• With earth system components, WRF can be a useful tool to understand regional earth system processes, allowing model parameterizations to be evaluated using measurements highly influenced by local conditions