Introduction to Climate Modeling: GCMs and RCMs

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1. Global and regional processes, climate mechanisms
1. Environmental impacts, assessments and mechanisms
1. Climate and climate system, mathematical model
1. Climate downscaling with nested and global models
1. HPC – High Performance Computing
King Abdullah University of Science and Technology
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Simulating the Global Earth System

Atmosphere  Hydrosphere  Cryosphere  Biosphere
\[ dx = r \, d\lambda \cos \phi \]
\[ dy = r \, d\phi \]

\[ u = \frac{dx}{dt} = R_E \cos \phi \frac{d\lambda}{dt} \quad \text{zonal velocity} \]

\[ v = \frac{dy}{dt} = R_E \frac{d\phi}{dt} \quad \text{meridional velocity} \]

\[ w = \frac{dz}{dt} = \frac{dr}{dt} \]
Continuity equation
\[
\frac{d\rho}{dt} = -\rho \text{div} V;
\]
\[
\frac{d}{dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial (a \cos \varphi)} \frac{\partial}{\partial \lambda} + v \frac{\partial}{\partial \varphi}
\]

Momentum equation
\[
\frac{dV}{dt} = -2\omega \mathbf{k} \times V - \frac{1}{\rho} \text{grad} P + g + F; \quad \omega = \Omega \sin \varphi
\]

Energy equation
\[
C_p \frac{dT}{dt} = Q + \frac{1}{\rho} \frac{dP}{dt}; \quad \text{Radiative Transport} \quad \frac{\partial I_v}{\partial s} = -\kappa \nu \rho [I_v - J_v]
\]
\[
\frac{dq}{dt} = S(q) \quad \text{— Water vapor transport and transformations}
\]
\[
P = \rho RT \quad \text{— Equation of state}
\]

Spatial domain: \(0 < \lambda < 2\pi; \quad -\pi/2 < \varphi < \pi/2; \quad z_s < z < z_{top}\)

Boundary conditions: \(z = z_s: \quad v_n = 0; \quad F^\uparrow = F_s\)
\[
z = z_{top}: \quad w = \frac{\partial z_{top}}{\partial t} + u \frac{\partial z_{top}}{(a \cos \varphi) \partial \lambda} + v \frac{\partial z_{top}}{a \partial \varphi}; \quad F^\downarrow = S_0 \cos \varsigma
\]
ND storm of 1989

Deep convection plays a profoundly important role on atmospheric circulation and climate.

To be resolved requires grid spacing of 1 km.
Cubed Sphere Coordinates

a) Conformal
One-Way Boundary Conditions

Two-Way Boundary Conditions
Regional models require imposing lateral boundary conditions using meteorological fields calculated in a parent large-scale model.

The RCM domain has to be small enough to be computationally effective and allow to conduct fine-resolution calculations.

The RCM domain has to be big enough to let the RCM to develop a fine scale starting from coarse initial and boundary conditions.

The RCM physics has to be consistent with the physics of the parent model to reduce disturbances near the lateral boundaries.
Figure 1. Domain utilized in the control experiment, with an outline of the extent of the buffer zone along the boundaries. See color version of this figure and access the enhanced image in the HTML.
Spectral nudging was originally introduced for a regional model by Waldron et al. [1996] and has also been applied for climate simulations by von Storch et al. [2000]. It consists of adding a new term to the tendencies of the variables that relaxes the selected part of the spectrum to the corresponding waves from reanalysis. The formula is:

\[
\frac{dQ}{dt} = L(Q) - \sum_{|n|\leq N} \sum_{|m|\leq M} K_{mn} \cdot (Q_{mn} - Q_{omn}) e^{ik_m x} e^{ik_n y}.
\]

Q is any of the prognostic variables to be nudged, L is the model operator, and Qo is the variable from the driving fields. Qmn and Qomn are the spectral coefficients of Q and Qo respectively. Kmn is the nudging coefficient, which can vary with m and n and also with height; m and n are the wave numbers in the x and y directions.

The wave vector components km and kn in the x and y directions depend on the domain size Dx and Dy in the corresponding direction and wave number.
Dust Storm Front Affecting the Saudi capital of Riyadh, Saudi Arabia, Tuesday, March 10, 2009
Aerosol Optical Depth at 600 nm, 800-1400 UTC

Comparison with Aeronet at Solar Village
Accumulation mode

Coarse mode

Total

Day-time aerosol concentration (ug/m³) in the lower atmosphere

Dust emission

Ug/m²/s

Source function

Daily emissions

Day-time aerosol concentration (ug/m³) in the lower atmosphere

Accumulation mode

Coarse mode

Total
MODIS 550 nm AOD, 1055 UTC
Jan 14, 2009

Simulated 600 nm AOD, 1000 UTC
Deposition rate (g/m²/a)

AOD and SW forcing, 11UTC, Jan 14, 2009

Daily area average deposition
Global stretched-grid models allow effective fine resolution calculations in the area of interest and do not require lateral boundary conditions and parent driving GCM output.

There is a restriction to the rate of stretching. It should not exceed 10%.
Stretched Grid and Land Elevation
Inter-tropical Convergence Zone (ITCZ)
Recent Surface Air Temperature Change in Middle East and North Africa – MENA Region
Red Sea SST monthly anomaly from AVHRR/base-period 1985-1990
Genin et al. (1995) found coral death in the Red Sea in the winter following the Pinatubo eruption.

Cooling induced mixing, bringing nutrients which produced an algae bloom, which smothered the coral.

a. Dec. 15, 1994 (normal)
b. April 6, 1992 (after Pinatubo)
Conclusions

• Regional climate change in Middle East is closely linked to global circulation processes

• Middle East experiences strong regional climate variations

• Because of dry conditions surface temperature response in this region is especially strong

• Dust aerosol is a predominant air-pollutant with strong effect on radiative transport, cloud formation, and precipitation

• Regional climate prediction has to be accompanied by comprehensive studies of fundamental physical processes in the region

• Combination of the regional nested model projections with high-resolution global calculations is a fruitful approach that could help to better understand climate change processes in the Arab Region
Simulated and observed (MODIS)dust plumes at 1100 UTC on January 14, 2009