Overview of NICAM: global cloud-resolving simulations and development

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Refer to K. Oouchi’s talk on Tuesday

Workshop on “High-Resolution Climate Modeling”
August 10 - 14, 2009
Adriatico Guesthouse - Kastler Lecture Hall
The Abdus Salam International Center for Theoretical Physics
Trieste, Italy
Outlines

• Overview of NICAM
  Nonhydrostatic ICosahedral Atmospheric Model
  for Global Cloud-Resolving Simulations

• NICAM simulations
  – MJO, TCs, monsoons, precipitation, diurnal variations & cloud properties

• Summary and Future plans

Miura et al. (2007, Science)
Ice cloud evaluation by split windows

NICAM

• Nonhydrostatic Icosahedral Atmospheric Model
  
  Development since 2000
  
  
  Satoh et al. (2008, *J. Comp. Phys.*)
  
  First global dx=3.5km run in 2004
  
  
• Icosahedral grid
  
  Spring dynamics smoothing
  
  Second order accuracy
  
  
• Flux-form conservative nonhydrostatic scheme
  
  Split-explicit time integration
  
  Mass, total energy & momentum conserving
  
  
## Model description

### Dynamics

<table>
<thead>
<tr>
<th>Governing Equations</th>
<th>Fully compressible non-hydrostatic system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Discretization</td>
<td>Finite Volume Method</td>
</tr>
<tr>
<td>Horizontal Grid Configuration</td>
<td>Icosahedral grid</td>
</tr>
<tr>
<td>Vertical Grid Configuration</td>
<td>Lorenz grid</td>
</tr>
<tr>
<td>Topography</td>
<td>Terrain-following coordinate</td>
</tr>
<tr>
<td>Conservation</td>
<td>Total mass, total energy</td>
</tr>
<tr>
<td>Temporal Scheme</td>
<td>Slow mode - explicit scheme (RK2, RK3) \ Fast mode - Horizontal Explicit Vertical Implicit scheme</td>
</tr>
</tbody>
</table>

### Physics

<table>
<thead>
<tr>
<th>Radiation</th>
<th>MSTRNX / MSTRNX-AR5 (Sekiguchi and Nakajima, 2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud Physics</td>
<td>Grabowski(1998); NSW6(Tomita 2008); NDW6(Seiki 2009)</td>
</tr>
<tr>
<td>Shallow Clouds Boundary Layer</td>
<td>MYNN2, 2.5 or 3 (Nakanishi and Niino 2004)</td>
</tr>
<tr>
<td>Surface Flux</td>
<td>Louis(1979), Uno et al.(1995)</td>
</tr>
<tr>
<td>Surface Processes</td>
<td>SST specified &amp; bucket / slab ocean &amp; MATSIRO</td>
</tr>
</tbody>
</table>
NICAM simulations

• Boreal winter, 2006, 3.5km a week, 7km a month
  – H. Miura

• Boreal summer, 2004; 7km 3months, 14km 5months
  – K. Oouchi, A. Noda

• Ensemble exp. for TC cyclogenesis
  – H. Taniguchi, W. Yanase

• Aerosol coupling exp. (Jul 2006; Nov 2006)
  – K. Suzuki, T. Seiki

• APE, Global Warming-conditions
  – H. Tomita, S. Iga; K. Oouchi, Y. Yamada; Y. Tsushima

• Regional NICAM using coordinate transformation
NICAM SIMULATIONS

• MJO simulations
• Tropical cyclones
• Monsoon simulations, ISVs and TCs
• Diurnal variability, cloud properties
NICAM simulation: MJO Experiment

Horizontal grid spacing:
- 14 km, 7 km, 3.5 km

Vertical domain:
- 0 m ~ 38,000 m
- 40-levels (stretching grid)

Integration:
- 7km, 14km runs: 30 days from 15 Dec 2006
- 7km, 14km runs: 30 days from 1 Nov 2006
- 3.5km run: 7 days from 25 Dec 2006

Initial conditions:
- Interpolated from NCEP tropospheric analyses
  (6 hourly, 1.0x1.0 degree grids)

Boundary conditions:
- Reynolds SST, Sea ICE (weekly data)
- ETOPO-5 topography, Matthews vegetation
- UGAMP ozone climatology (for AMPI2)

• EXP. Nov. 2006 (MISMO): Miura et al. (2009, GRL)
Realistic MJO simulation

Miura et al. (2007, Science), Nasuno et al. (2009, JMSJ), Fudeyasu et al. (2009, GRL), Liu et al. (2009, MWR)

NCEP/CPC IR  NICAM 7km, OLR
Hovmöller diagrams: precipitation, temperature

Role of cold pools

Precipitation (10S-5N)  TRMM PR

NICAM  dx=7 km

T (975 hPa)  NCEP

Eastward 10-15 m/s
1000-2000 km
(1-2 day)

NICAM  dx=7 km
Hovmöller diagrams: zonal winds & vertical cross section (composite)
Westward Rossby waves & Eastward Kelvin waves or squall type rain bands
Zonal wind (4-day running mean subtracted)

NCEP

U(850 hPa), IR NCEP

NICAM dx=7 km

3N-3S average

(a) U(z=1.5km), OLR, precipitation DX7

Black lines: IR TBB

Black lines: OLR, white: precipitation

Nasuno et al. (2009)
NICAM (dx=7km)

Similar feature in observations
(Dr. H. Yamada)

precipitation dx=7km 12:00  6 jan 2007
Vertical structure; composite along gust front

Rainband B

Squall-type cluster

NICAM (dx=7km)

Zonal velocity contour:
Vertical velocity

Temperature contour:
Condensate

125-155E background

120-130E front

117-119.5E rear

3N-3S average

120-130E front

120-130E rear

120-155E background

Nasuno et al. (2009)
MISMO

Convections  Maldives  Mirai

10 Nov.

20 Nov.

30 Nov.

3 Dec.

7 Nov.

6 Dec. 2006 07UTC

Range Circle of Mirai Doppler Radar

Leading Edge of a Convective System

90E

500km

Roles of squall line types clusters on MJO

Precipitable water

Column integrated cloud water

2 Jan 2007

rainband

6 Jan 2007

Miura et al. (2007)
• Rossby waves: accumulation of water vapor on the front of MJOs. from eastward
• Moist Kelvin waves become active when MJOs are active.
• Multiscale interactions of Rossby/Kelvin waves and MJOs.

Ichikawa and Yasunari, 2007

Nakazawa 1988
NICAM SIMULATIONS

• MJO simulations
• Tropical cyclones
• Monsoon simulations, ISVs and TCs
• Diurnal variability, cloud properties
NICAM reasonably produced not only the large-scale circulation, such as the MJO, but also the embedded mesoscale features, such as TC rainbands.

NICAM reasonably captured Isobel’s motions, timing, and intensity changes.

Fudeyasu et al. (2008, GRL)
TC genesis in MJO

Front of WV

Returned disturbance

TC development due to cyclonic shear
<table>
<thead>
<tr>
<th>Date</th>
<th>Stage</th>
<th>Synoptic scale 1000km</th>
<th>TC scale 300km</th>
<th>Convective scale in core region 50km</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>Pre-conditioning</td>
<td>MJO-WWB</td>
<td>preconditioning /cycclonic shear convergence</td>
<td>Vortex enhancement</td>
</tr>
<tr>
<td>IE</td>
<td>Intensifying</td>
<td>WWB extension</td>
<td>Concentric MCV with PV monopole formation</td>
<td>Vortex upscale cascade/Warm-core formation/symmetrization</td>
</tr>
<tr>
<td>29</td>
<td>Sub-tropical high</td>
<td>Stretching deformation</td>
<td>PV redistribution</td>
<td>CISK/WISHE/SSI</td>
</tr>
<tr>
<td>30</td>
<td>Northwesterly vertical shear</td>
<td>Downshear-side convection</td>
<td>Asymmetric MCV</td>
<td>Decaying symmetric MCV</td>
</tr>
<tr>
<td>31</td>
<td>Landfall</td>
<td>Less-LHF/SHF/Friction</td>
<td>Large outer rainband formation</td>
<td>Eye-wall Reformation</td>
</tr>
<tr>
<td>1</td>
<td>Break</td>
<td>Stretching deformation</td>
<td>Convective heating off</td>
<td>Convective heating</td>
</tr>
<tr>
<td>2</td>
<td>Re-intensifying</td>
<td>Downshear-side convection</td>
<td>MCV weakening</td>
<td>SSI</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>MCV transport</td>
<td>SSI</td>
</tr>
<tr>
<td>4</td>
<td>Decaying</td>
<td>Landfall</td>
<td>MCV decaying</td>
<td>TC-scale MCV development</td>
</tr>
</tbody>
</table>

Fudeyasu et al. (2009, in prep)
NICAM SIMULATIONS

• MJO simulations
• Tropical cyclones
• Monsoon simulations, ISVs and TCs
• Diurnal variability, cloud properties
Monsoon simulations


• Boreal Summer experiments:
  • 14km: June-Oct. 2006
  • 7km: June-Aug. 2006
Precipitation distribution over south Asia average, June-Aug., 2004

TRMM observation  NICAM 7km-grid exp.

Oouchi et al. (2009, Geophys. Res. Lett.)
Intra-Seasonal variabilities

**Indian Ocean**

- Northward propagation in the Indian Ocean
- Monsoon index
- Boreal summer MJOs and TC activities

**Western Pacific**

- Precipitation rate
- Relative vorticity


Oouchi et al. (2009, SOLA)
The Myanmar cyclone simulations


• The Myanmar cyclone Nargis
  • 14km: Apr. 2008, Ensembles
  • Regional NICAM exp.
Myanmar cyclone Nargis (2008) ensemble simulations
TC genesis captured with ISV and MJO
26 Apr. – 26 May 2008

Taniguchi et al. (2009, JMSJ, submitted)
TC cyclogenesis in Indian Ocean is generally captured with ISV using stretch-NICAM. Yanase et al. (2009, JMSJ, submitted)
Number and intensities of tropical cyclones
Yamada et al. (2009, in prep.) & K. Oouchi’s talk on Tuesday

- TC threshold 17 m/s
- TC activities with ISVs, easterly
Change in Tropical cyclone intensities

CTL : JJA, 2004
GW: JJA, average of 2070-99

Consistent with other studies:
less number and stronger TCs

Cloud height vs MSLP

Figure 3.

Figure 4.
NICAM SIMULATIONS

• MJO simulations
• Tropical cyclones
• Monsoon simulations, ISVs and TCs
• Diurnal variability, cloud properties
Diurnal variation of precipitation

Phase

NICAM 7km vs TRMM 3B42
15 Dec 2006-15 Jan 2007
Improvement of phase and amplitudes from 14km-mesh to 7km-mesh
Cloud clusters: NICAM 3.5km at 00UTC 26 Dec 2006

MTSAT-1R TBB 00UTC 26 Dec 2006

NICAM 3.5km OLR

MTSAT-1R TBB

NICAM DX3.5km


Diurnal variations of OLR
Ice cloud evaluation by split windows

Calipso/CloudSat simulated reflectivities by COSP

532nm (1/km/sr) 00 UTC 26 Dec, 2006

NICAM ICE PROFILE 26 Dec

NICAM SNOW PROFILE 26 Dec

Cloud ice

Snow

Calipso

CloudSat
Ice clouds

NICAM IWP is larger than the observed range of IWP.

Waliser et al. (2009)
Ice Water Contents

NICAM IWC is larger in the tropics

Waliser et al. (2009)
Iga et al. (2009, in prep.)
Cloud Microphysics Schemes of NICAM

- Grabowski (1998)
- NSW6 (Tomita 2008, JMSJ)
  - Single-moment 6-categories of water
- NDW6 (Seiki)
  - Double-moment 6-categories of water

After Seifert and Beheng (2006)
Sensitivity to cloud microphysics schemes: CFADS - maritime continent region in the tropics
use of the satellite simulator COSP

CloudSat/CALIPSO

NICAM-GCRM 3.5km, Grabowski (1998)

NSW6 (Tomita 2008), stretched-NICAM <5km

Satoh et al. (2009, JGR, submitted)
Pilot simulations of 2-moment cloud model with Global 7km resolution.
Comparisons with satellites and further challenges.
(Validation of 2-moment cloud model
Seiki Tatsuya. (CCSR, Univ. of Tokyo)

MODIS/Aqua Level2
COT(all clouds), 2006/11/19

NICAM gl10(SB06+CCNMAP)
COT(cloud, rain, ice, snow, graupel), 2006/11/19
Aerosols interactions

NICAM development

- On going & near future
  - Cloud microphysics scheme: single moment bulk, NSW6, double moment bulk, NDW6
  - Aerosols coupling (SPRINTARS)
  - Boundary layer scheme: MYNN2.5, 3
  - Dynamics: step mountains
  - Coupling to ocean models (COCO)
  - Assimilation LETKF (Kondo and Tanaka 2009, SOLA)
  - 3D radiation (Iwabuchi 2006, JAS)
    & bin microphysics (Iguchi) for references

- Use of 10PF super computer in Kobe (2012-)
  - 10 years time slice exp.
    - AMIP-type, future time slice exp
  - 400m-mesh global runs
  - AO-coupled model; climate simulations
Summary and final remarks

• NICAM simulates
  – good ISVs, TCs, and diurnal variations
  – multiscale structures of tropical convection
  – good cloud properties (high/low) with improved schemes

• Known biases
  – Stronger precipitation
  – TC numbers, depend on physics and resolutions

• Development on going

• Data and model available for collaborations
  – Further information http://nicam.jp
Stretch-NICAM exp.

- Use of NICAM as a regional model: local-CRM
  Tomita (2008, JMSJ)
- \( dx = 2.5\text{km} - 250\text{km} \)
  Stretch factor = 10, Glevel8
- Integration: 2007.1.1.12-1.5.12
- Sensitivity to cloud microphysics scheme: NSW6

Satoh et al. (2009, JGR, submitted)
Nonhydrostatic scheme

$$\frac{\partial}{\partial t} R + \nabla_h \cdot V_h + \frac{\partial}{\partial \xi} \left( \frac{W}{G^{1/2}} + G^3 \cdot V_h \right) = 0$$

$$\frac{\partial}{\partial t} V_h + \nabla_h P + \frac{\partial}{\partial \xi} \left( \frac{G^3 P}{G^{1/2}} \right) = \text{ADV}_h + \text{F}_{Coriolis}$$

$$\frac{\partial}{\partial t} W + \frac{\partial}{\partial \xi} \left( \frac{P}{G^{1/2}} \right) + Rg = \text{ADV}_z + \text{F}_{z,Coriolis}$$

$$\frac{\partial}{\partial t} E_{total} + \nabla_h \cdot [h + k + \Phi \nabla_h - \frac{\partial}{\partial \xi} \left( \Phi + k + \Phi \left( \frac{W}{G^{1/2}} + G^3 \cdot V_h \right) \right)] = 0$$

**Prognostic variables**
- density
- horizontal momentum
- vertical momentum
- total energy

**Metrics**
- \( R = G^{1/2} \rho \)
- \( V_h = G^{1/2} \rho \mathbf{v}_h \)
- \( W = G^{1/2} \rho w \)
- \( E_{total} = \rho G^{1/2} e_{in} + k + \Phi \)
- \( G^{1/2} = \left( \frac{\partial z}{\partial \xi} \right)_{x,y} \)
- \( G^3 = \Phi_h \xi \)
- \( \xi = \frac{H(z - z_s)}{H - z_s} \)
Computational Performance

Table 2: Computational performance of the aqua planet experiments with NICAM.

<table>
<thead>
<tr>
<th>NICAM</th>
<th>glevel 9</th>
<th>glevel 10</th>
<th>glevel 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta x$</td>
<td>14 km</td>
<td>7 km</td>
<td>3.5 km</td>
</tr>
<tr>
<td>$\Delta t$ [sec]</td>
<td>30</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>nodes</td>
<td>80</td>
<td>320</td>
<td>320</td>
</tr>
<tr>
<td>1 day time [hr]</td>
<td>0.64</td>
<td>0.81</td>
<td>5.28</td>
</tr>
<tr>
<td>GFLOPS</td>
<td>1911.8</td>
<td>7607.6</td>
<td>7701.5</td>
</tr>
<tr>
<td>sustained performance [%]</td>
<td>37.3</td>
<td>37.1</td>
<td>37.6</td>
</tr>
</tbody>
</table>

Satoh et al. (2005, *J. Earth Simulator*)
The spatial structure was reproduced reasonably.
Precipitation rate was overestimated in the tropics.
Temperature and precipitation change for global change time slice JJA GW condition - present, dx~14km

Concentration of ITCZ
More precipitation in South Asia
Geo-stationary satellite (MTSAT-1R) Infrared image

NICAM 3.5km-grid mesh Simulation Outgoing Longwave Radiation (OLR)