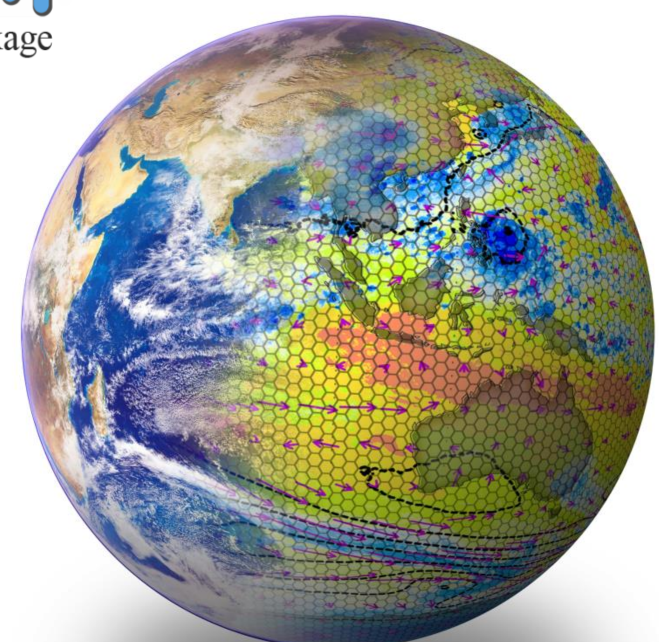
Global convection permitting/resolving model
--- Towards the Global LES ---

RIKEN/AICS Hirofumi Tomita
NICAM working team
&
Team SCALE

NICAM Dynamical Core Package



SCALE
Scalable Computing for Advanced Library and Environment

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Contents

- Terminology & definition
  - Cloud permitting? Cloud resolving?
- Historical view of NICAM project
  - Numerical method
  - Milestone simulation
    - APE
    - MJO,TC
    - Athena project
    - Ongoing project(>1km resolution run)
- Where are we going with HPC?
  - Towards the GLES
    - Understanding mechanism of our atmosphere by the first principle of physics and dynamics
  - SCALE project in RIKEN/AICS
    - Preparation for the future HPC use for meteorology

Terminology : Convection permitting model/cloud resolving model? / convection system resolving model

- Many terms exist! : (in my sense, debatable?.....)
  - Convection resolving?
    - Convection core and subsidence are well captured by multiple grids. (several 100m grid?)
  - Co vection system-resolving?
    - ection core is expressed by a single gri ection cell are aptured by multipl gr ds (a few km gri
  - Co v ti on permittin
    - Convections are ex p icitly, but are unrealistic for spatial and temporal structu ve dynamics such as cold pool dynamics are expressed? (5km~15k m) grey zone

No!

No!

No!

No!

No!

No!

In the terms of num ethodology a
If cu zation is not us hysics ed,
We call i ving model?

The examination of impact without CP is very important for mechanism of cloud physics!

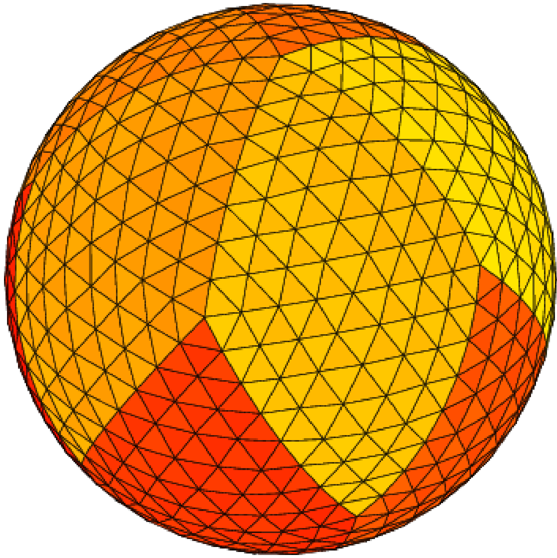
What is NICAM?

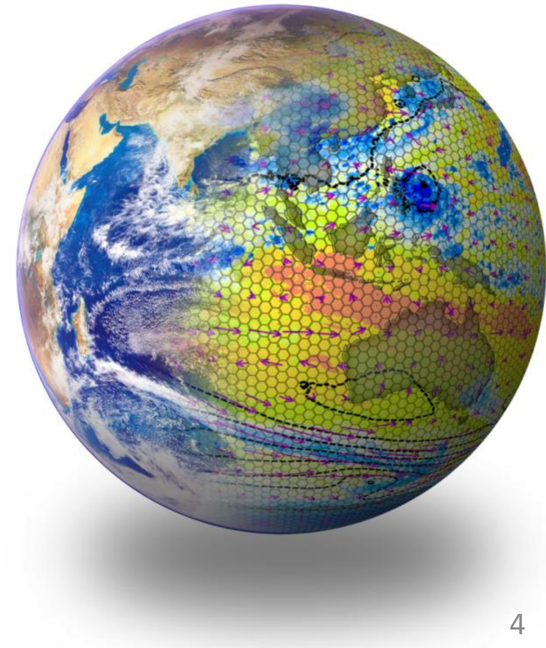
<u>NICAM development : ~2000</u>

<u>still development is continuing!</u>

Conceptual development philosophy

- **<u>Explicit resolving the cloud itself</u>**
  - Inevitably, we should go directly to the higher resolution model with sophistication of physics
    - Use of Icosahedral grid
      - To get a quasi-homogeneous grid for computational efficiency
    - nohydrostatic DC
      - To resolve cloud scale (deep convection, shallow cloud etc.)
    - explicit cloud expression:
      - To avoid the ambiguity of cumulus parameterization and understand the cloud dynamics





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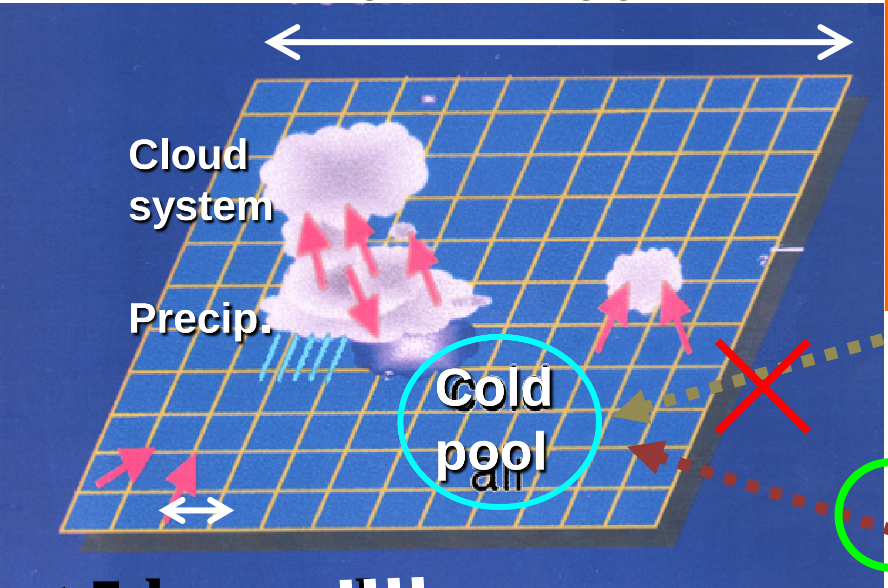
NICAM modeling strategy(from initial developmet stage)

Resolve the cloud system & related process over the globe

20km~100 km



< 5 km or les

Traditional GCM(horizontal 100km or less)

→ **Use "cloud parameterization"**

→ **Limit the representation of**

- **spatial structure hierarchy of cloud system**
- **lifetime of cloud system**

New GCM:aim to express the basic cloud physics explicitly
Increasing resolution drastically

→ **Avoid ambiguous "cloud parameterization"**

→ **Resolve the cloud system explicitly**

→ **Represent**

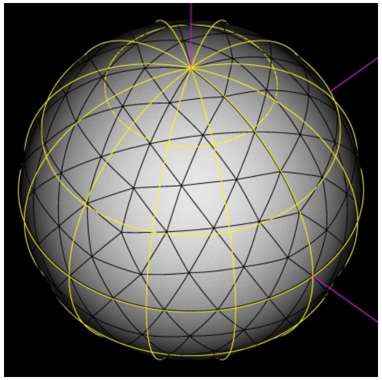
- **multi-scale cloud phenomena**
- **lifecycle of individual clouds**

Dynamical core should be changed, suitable for HPC trends

Strategy of NICAM dycore development

1. **Quasi-uniform grid is suitable!** **: we believed at the 2000(^^)**
   - *Spectral method* : not efficient in high resolution simulations.
     - Legendre transformation
     - Massive data transfer between computer nodes
   - *Latitude-longitude grid* : the pole problem.
     - Severe limitation of time interval by the CFL condition.
   - **The icosahedral grid: homogeneous grid over the sphere**
     - **To avoid the pole problem.**

   c.f. Cubed sphere and Ying-Yang grid are also promising



NOW, many techniques for spectral model is available and the above statements may not be necessarily true!
=> We have to trace the Computer trend and numerical technique
Sometimes, a breakthrough will be born!

2. **Non-hydrostatic equations system is neccesary!**
   - with full compressible system (no approximation in the continuous form)
   - conservation of mass and energy should be satisfied if possible for climate run.

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History of NICAM DC development

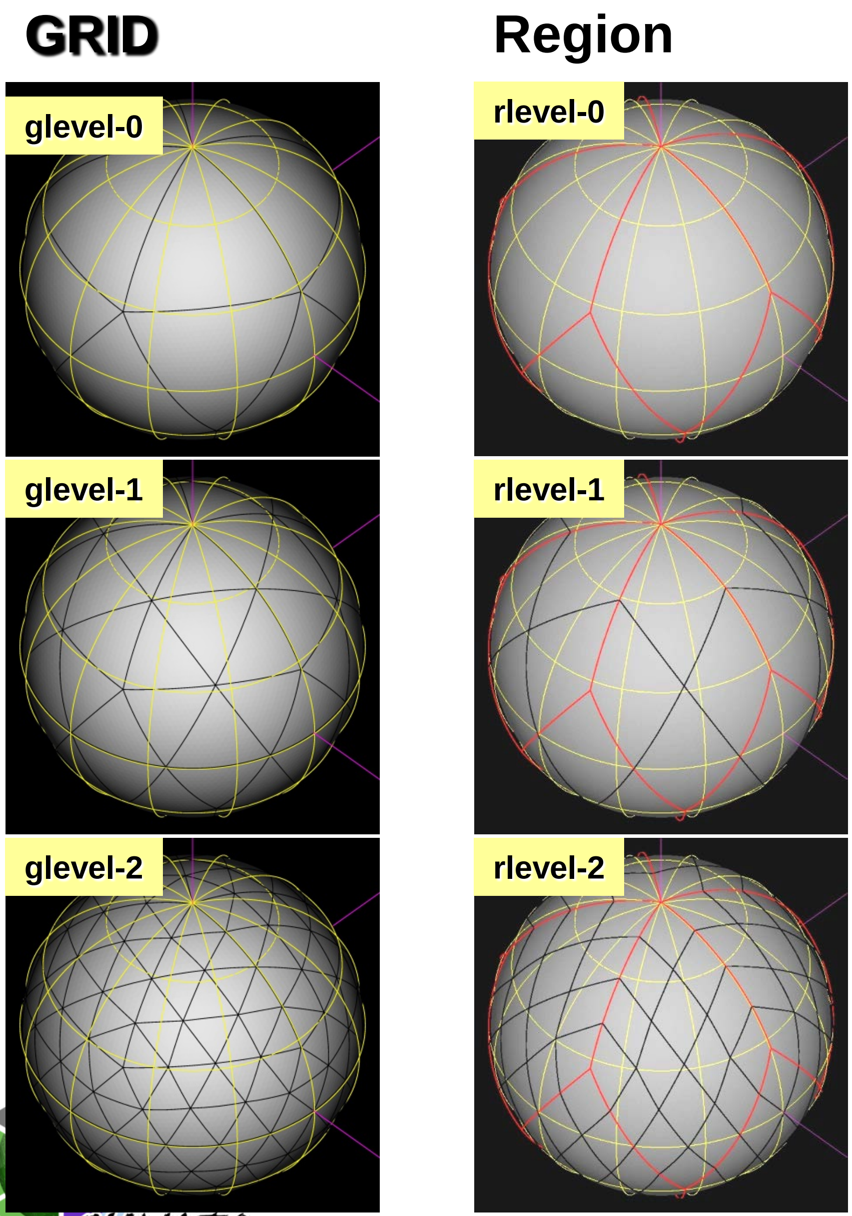
- NICAM DC development (~2000)
  - Horizontal grid : icosahedral grid with spring dynamics modification(Tomita et al. 2001, 2002 JCP)
  - Dynamics : Non-hydrostatic equation with conservation of total energy (Satoh 2002, 2003 MWR)

  → 3D DC (Tomita and Satoh 2004 FDR)

  – **First version completed by 2004 with full physics**

- 2004~
  - High order advection scheme with monotonicity(Miura 2007)
  - Consistency With Continuity(Niwa et al. 2011)
  - Grid arrangement (stretched grid, Tomita 2008, Iga and Tomita 2013)
  - Now, NICAM-DC is freely available with BSD2 license.
    – http://scale.aics.riken.jp/nicamdc/

Grid, domain, parallelization in NICAM



- Grid generation
  - Glevel0
    - Original icosahedron
  - Glevel1
    - Divide each triangle to 4 sub-triangle
  - Glevel2~
    - Iterate the same process
- Region generation
  - Rlevel0
    - Connection of two neighboring diamonds
  - Rlevel1
    - Divide each rectangle to 4 sub-rectangle
  - Rlevel2
    - Iterate this process
- Parallelization
  - 2D-domain decomposition with MPI

NICAM Dynamical core(1)

Governing eqns.: Non-hydrostatic equationwith deep atmosphere

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

Continuity eq.

$$\frac{\partial}{\partial t}\mathbf{V}_h + \nabla_h \frac{P}{\gamma} + \frac{\partial}{\partial \xi}\left(\mathbf{G}^3 \frac{P}{\gamma}\right) = \mathbf{ADV}_h + \mathbf{F}_{Coriolis}$$

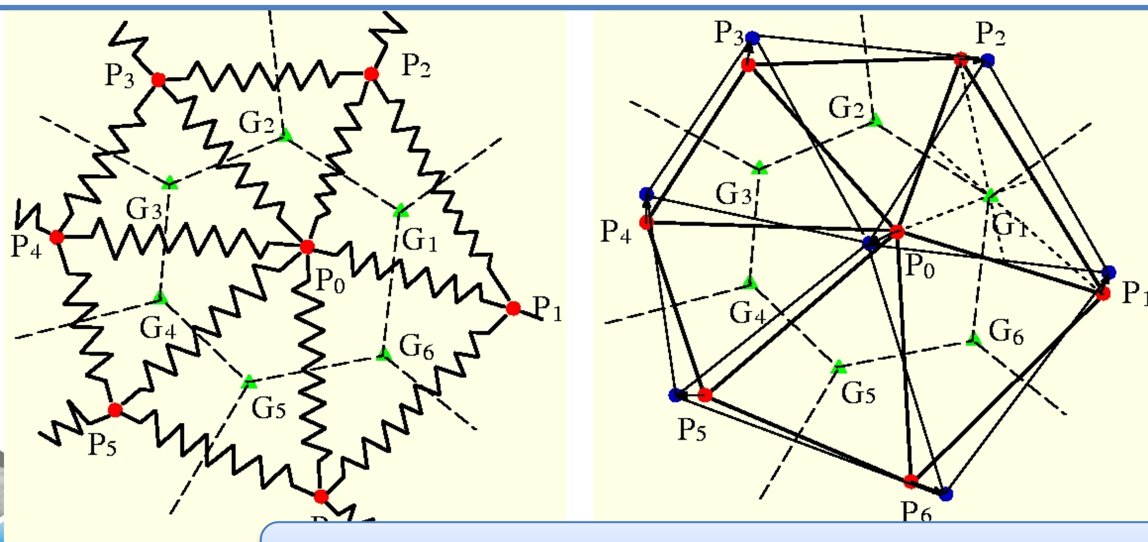
Horiz. ,mom. eq.

$$\frac{\partial}{\partial t}W + \gamma^2 \frac{\partial}{\partial \xi}\left(\frac{P}{G^{1/2}\gamma^2}\right) + Rg = ADV_z + F_{Coriollis}$$

Vert. ,mom. eq.

$$\frac{\partial}{\partial t}E + \nabla_h \cdot \left(h\frac{\mathbf{V}_h}{\gamma}\right) + \frac{\partial}{\partial \xi}\left[h\left(\frac{W}{G^{1/2}} + \mathbf{G}^3 \cdot \frac{\mathbf{V}_h}{\gamma}\right)\right]$$
$$-\frac{\mathbf{V}_h}{R} \cdot \left[\nabla_h \frac{P}{\gamma} + \frac{\partial}{\partial \xi}\left(\mathbf{G}^3 \frac{P}{\gamma}\right)\right] - \frac{W}{R}\gamma^2 \frac{\partial}{\partial \xi}\left(\frac{P}{G^{1/2}\gamma^2}\right) + Wg = Q_{heat}$$

Energy. eq.

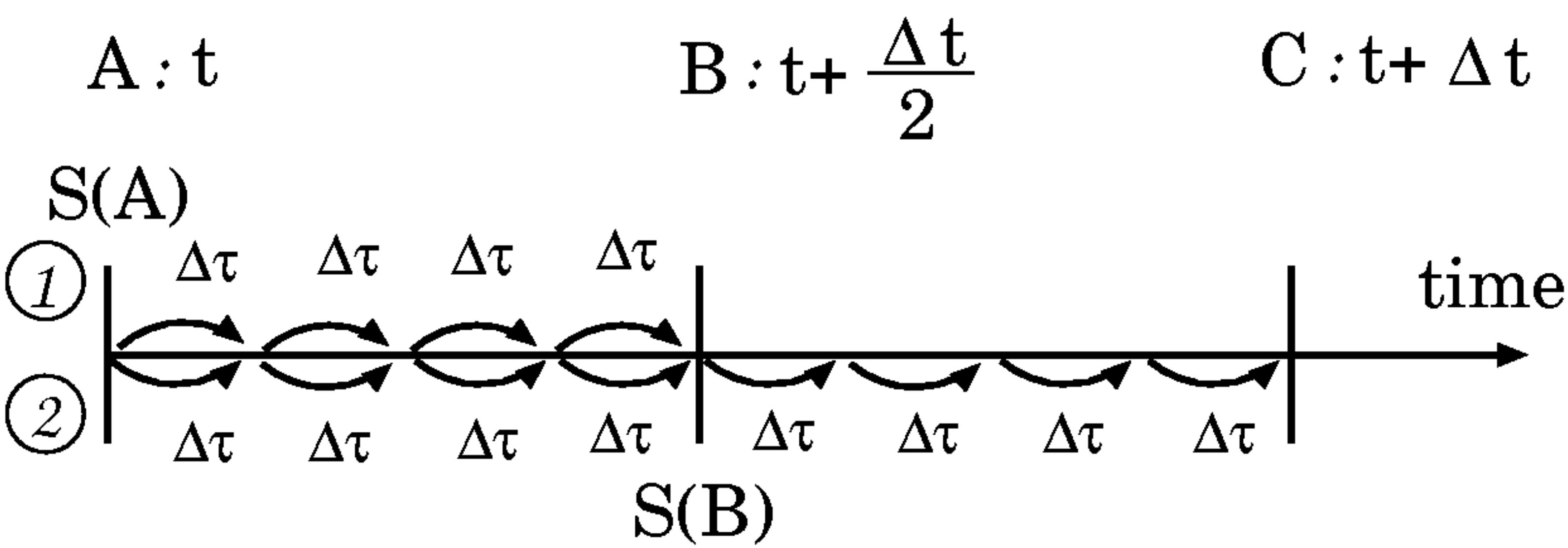


- **Horizontal grid**
  - Icosahedral grid with
  - modification by spring dynamics
  - Reallocation of grid to gravitational center of control volume

Guarantee the 2nd order differnce anywhere in the horizontal

NICAM Dynamical core(2)

- Vertical grid:
  - Terrain-following coordinate with Lorentz grid
    - Future improvement is necessary(Zangl's technique / Yamazaki' cut cell method)
- Time Solver
  - Split explicit method
    - Fast mode (e.g. acoustic wave, gravity wave)
      - Small time step (forward-backward)
  - Slow mode (e.g. advection term)
    - Large time step (by RK2 or RK3)
    - In slow mode
      - Horizontal explicit / vertical implicit scheme



NICAM Dynamical core(3)

Consistency with Continuity: very important issue for tracer advection

- Flux form of tracer advection equation

$$\frac{\partial}{\partial t}(\rho q) + \nabla_h \cdot (\rho q \mathbf{v}_h) + \frac{\partial}{\partial z}(\rho q w) = 0$$

Euler sense

  - If we use FVM, the total mass always conserves.
- Advection form

$$\frac{\partial q}{\partial t} + \mathbf{v}_h \cdot \nabla_h q + w \frac{\partial q}{\partial z} = 0$$

Lagrangean sense

  - If we discretize it, the total mass does not conserves in euler sense
  - However,.....
    - Lagrange conservation requres:
      - q should stay constant along trajectory!
        - » At least, if q=const over the domain,
          q must be constant at any dynamical step.
- When the tracer equation is discretized in the same manner as the continuity equation, the Lagrange conservation can be achieved.
  - CWC(suggested by Gross et al. 2002)

NICAM Dynamical core(3-2)

- We can do it easily!! : CWC scheme by the straightforward way

$$\rho^{t+1} = \rho^t - \frac{\Delta t}{A}\sum_i^6 \left(l_i \hat{\rho}_i \hat{\mathbf{v}}_i \cdot \mathbf{n}_i\right) - \frac{\Delta t}{\Delta z_k}\left(\tilde{\rho}_{k+1/2}\tilde{w}_{k+1/2} - \tilde{\rho}_{k-1/2}\tilde{w}_{k-1/2}\right),$$

$$Q^{t+1} = Q^t - \frac{\Delta t}{A}\sum_i^6 \left(l_i \hat{\rho}_i^t \hat{q}_i^t \hat{\mathbf{v}}_i^t \cdot \mathbf{n}_i\right) - \frac{\Delta t}{\Delta z_k}\left(\tilde{\rho}_{k+1/2}^t \tilde{q}_{k+1/2}^t \tilde{w}_{k+1/2}^t - \tilde{\rho}_{k-1/2}^t \tilde{q}_{k-1/2}^t \tilde{w}_{k-1/2}^t\right),$$

^ : horizontal cell wall values

~ : vertical cell wall values

- The density and tracers is updated at the small step.

However, we want to integrate the tracer equations at the large time step for efficiency!

NICAM Dynamical core(3-3)

- We use of time average mass flux for efficient way:
  - In the small time step, update of continuity equation:

$$\rho^{t+(n+1)\tau} = \rho^{t+n\tau} - \frac{\Delta\tau}{A}\sum_i^6 \left(l_i \hat{\mathbf{v}}_i^{t+n\tau}\hat{\rho}^{t+n\tau}\cdot\mathbf{n}_i\right) - \frac{\Delta\tau}{\Delta z_k}\left(\tilde{\rho}_{k+1/2}^{t+n\tau}\tilde{w}_{k+1/2}^{t+n\tau} - \tilde{\rho}_{k-1/2}^{t+n\tau}\tilde{w}_{k-1/2}^{t+n\tau}\right).$$

  - We introduce the time average mass flux,

$$\hat{\mathbf{V}}_i^* \equiv \frac{1}{\Delta t}\sum_{n=1}^{N_s}\left(\hat{\rho}_i^{t+n\Delta\tau}\hat{\mathbf{v}}_i^{t+n\Delta\tau}\Delta\tau\right),$$

$$\tilde{W}_{k\pm1/2}^* \equiv \frac{1}{\Delta t}\sum_{n=1}^{N_s}\left(\tilde{\rho}_{k\pm1/2}^{t+n\Delta\tau}\tilde{w}_{k\pm1/2}^{t+n\Delta\tau}\Delta\tau\right),$$

Sum of mass flux at the small step with weight of dtau/dt

  - The density update can be written in the large step and also q tracer update is done by the same manner.

$$\rho^{t+1} = \rho^t - \sum_{n=1}^{N_s}\left[\frac{\Delta\tau}{A}\sum_i^6\left(l_i\hat{\mathbf{v}}_i^{t+n\tau}\hat{\rho}^{t+n\tau}\cdot\mathbf{n}_i\right) - \frac{\Delta\tau}{\Delta z_k}\left(\tilde{\rho}_{k+1/2}^{t+n\tau}\tilde{w}_{k+1/2}^{t+n\tau} - \tilde{\rho}_{k-1/2}^{t+n\tau}\tilde{w}_{k-1/2}^{t+n\tau}\right)\right].$$

$$= \rho^t - \frac{\Delta t}{A}\sum_i^6\left(l_i\hat{\mathbf{V}}_i^*\cdot\mathbf{n}_i\right) - \frac{\Delta t}{\Delta z_k}\left(\tilde{W}_{k+1/2}^* - \tilde{W}_{k-1/2}^*\right) \quad ($$

$$Q^{t+1} = Q^t - \frac{\Delta t}{A}\sum_i^6\left(l_i\hat{q}_i^t\hat{\mathbf{V}}_i^*\cdot\mathbf{n}_i\right) - \frac{\Delta t}{\Delta z_k}\left(\tilde{q}_{k+1/2}^t\tilde{W}_{k+1/2}^* - \tilde{q}_{k-1/2}^t\tilde{W}_{k-1/2}^*\right).$$

We discretize the tracer equation in the large time step so as to keep the consistency with this formulation

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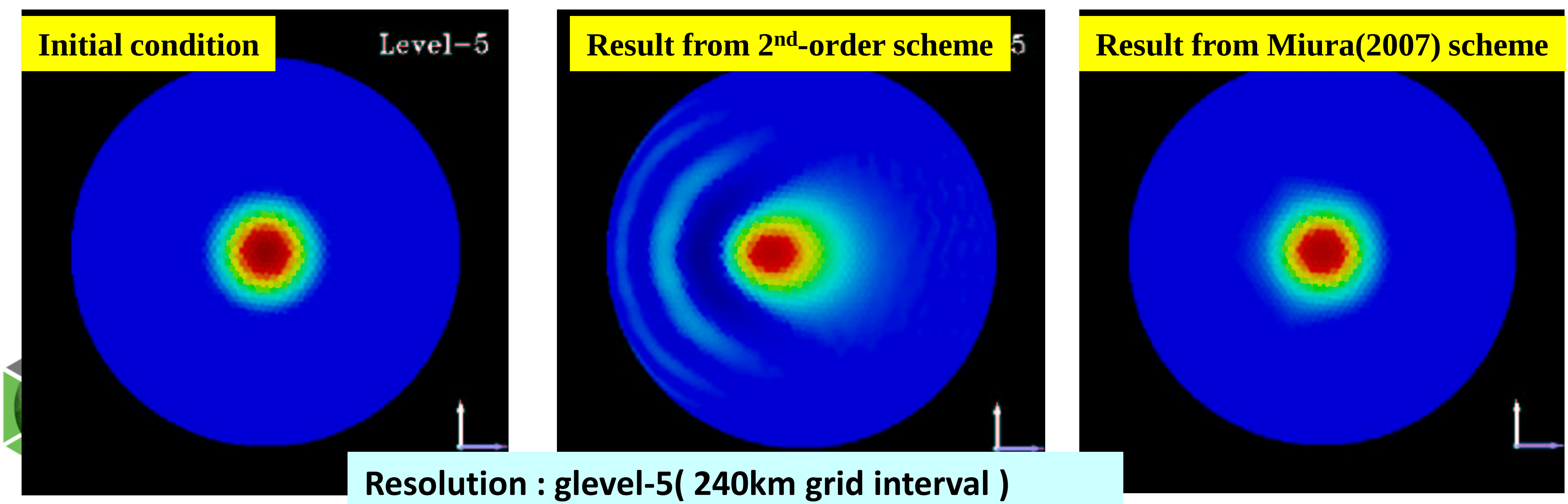
Determination of q at the cell wall

- Determination of q at the cell wall : the next subject
  - Based on Miura (2007,MWR) scheme
    - Very simple way of upstream bias flux calculation
    - With an appropriate filter (Thuburn 1996)

Williamson test case 1

- Original:
  - 2nd-order central scheme
    - Not guarantee the monotonicity!
    - Many ripple and negative value!
- New scheme (currently, default scheme in NICAM):
  - Miura(2007) + Thurburn(1996) limiter



Summary of NICAM current status

Ref. Satoh et al. 2008 *J. Comput. Phys.* ***/*** Tomita & Satoh 2004 *Fluid Dyn. Res.*
Recent DC description paper : Tomita et al. 2011, *ECMWF workshop proceeding*

■ Dynamics	
Governing equations	Fully compressible non-hydrostatic system
Spatial discretization Horizontal grid configuration Vertical grid configuration Topography	Finite Volume Method Icosahedral grid with spring dynamics smoothing (Tomita et al. 2001/2002) Lorenz grid Terrain-following coordinate
Conservation	Total mass, total energy (Satoh 2002, 2003)
Temporal scheme	Slow mode ー explicit scheme （RK2, RK3） Fast mode ー Horizontal Explicit Vertical Implicit scheme
■ Physics	
Turbulence/shallow clouds	MYNN 2.0,2.5(Nakanishi and Niino 2004) modified by Noda(2009)
Surface flux	Louis (1979), Uno et al. (1995)
Radiation	MSTRNX (Sekiguchi and Nakajima, 2005)
Cloud microphysics	NSW6 (Tomita 2008) --- 6 caegories of water (1moment-bulk) **NDW6(Seiki et al.2013)** --- 6 caegories of water (2moment-bulk)
Cloud parameterization	NONE
Surface process	MATSIRO(Takata et al.)

NICAM milestone simulations : Cloud resolving/permitting NICAM output

- 2005: The 1st global cloud resolving simulation
  - Aqua-planet experiment (Tomita et al. 2005)
- 2007: Successful simulation of MJO
  - 2006 boreal winter (Miura et al. 2007)
- 2010: TC changes at future warming climates
  - Yamada et al. 2011

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- International collaborations
  - JAMSTEC-IPRC Initiative (JII)
  - Athena project (2009-10): COLA, NICS, ECMWF, JAMSTEC, Univ. of Tokyo
  - G8 ICOMEX (2011-): Germany, UK, France, US, Japan

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- Ongoing project:
  - SPIRE project (2011-) : official
  - SNIPER project (sub km horizontal resolution) (2012-) : unofficial

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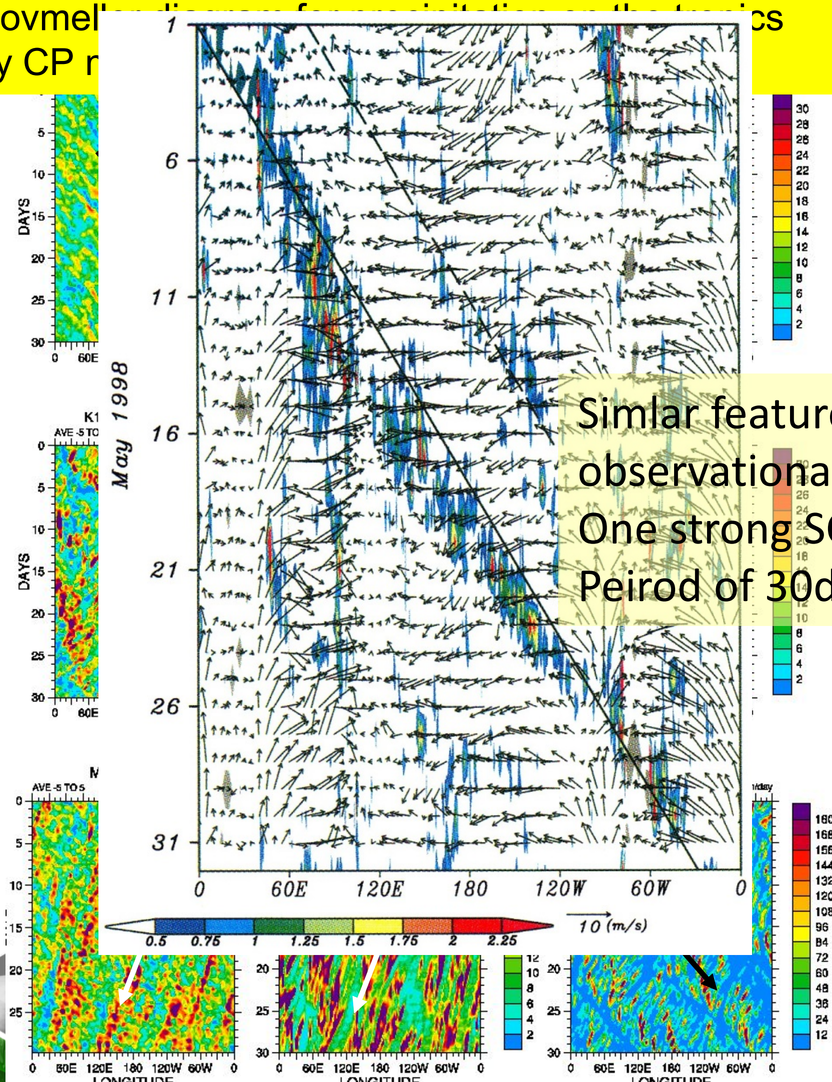
Aqua Planet Experiment(Tomita et al. 2005)

- Experimental setup
  - follow the CONTROL RUN of Neal & Hoskins(2000)

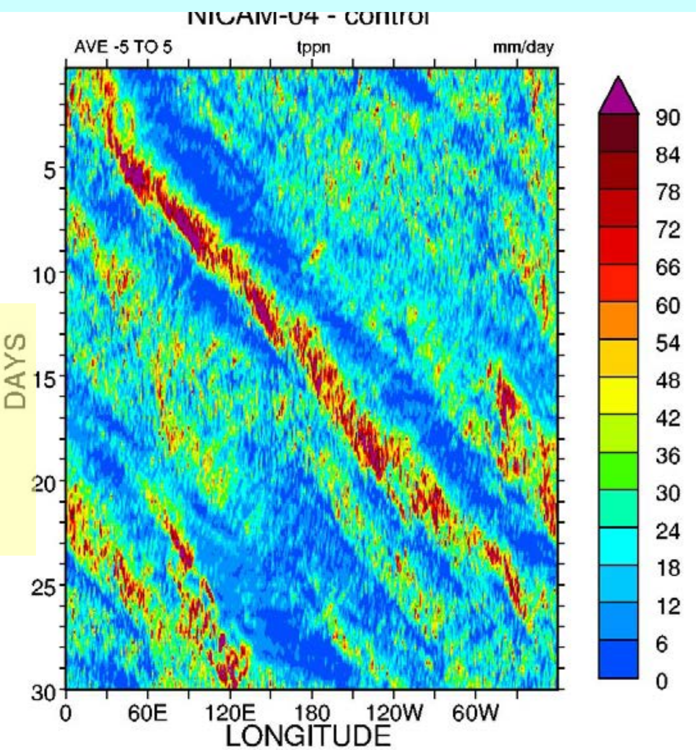
Hovmeller diagram for precipitation on the tropics by CP r



Simlar feature with observational result:
One strong SCC
Peirod of 30days

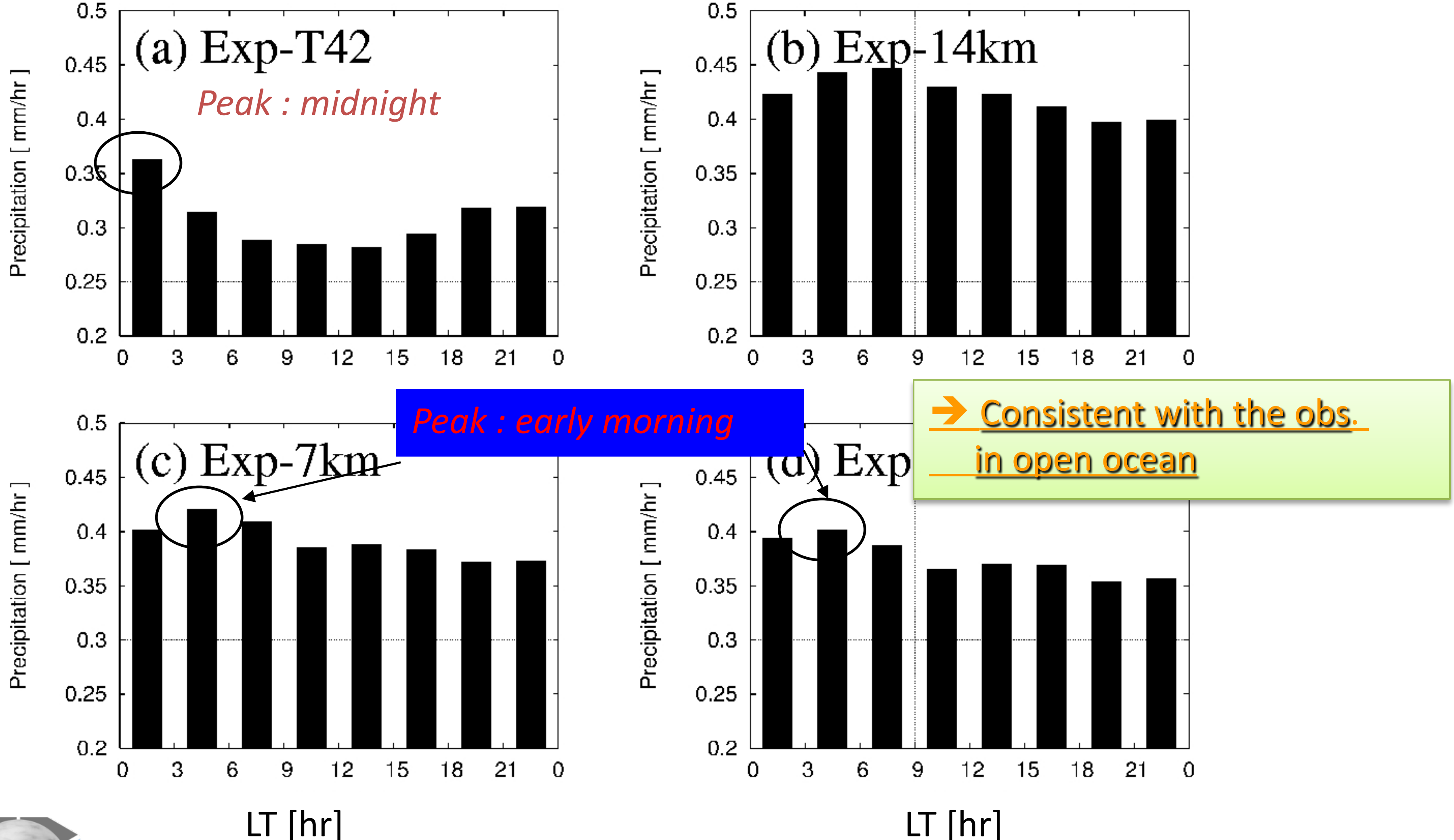
Produced by Dr. Williamson

Hireso without CP-results: NICAM



- 2 or 3 convective regions
- Eastward propagation with 30-days period
- One strong convective region

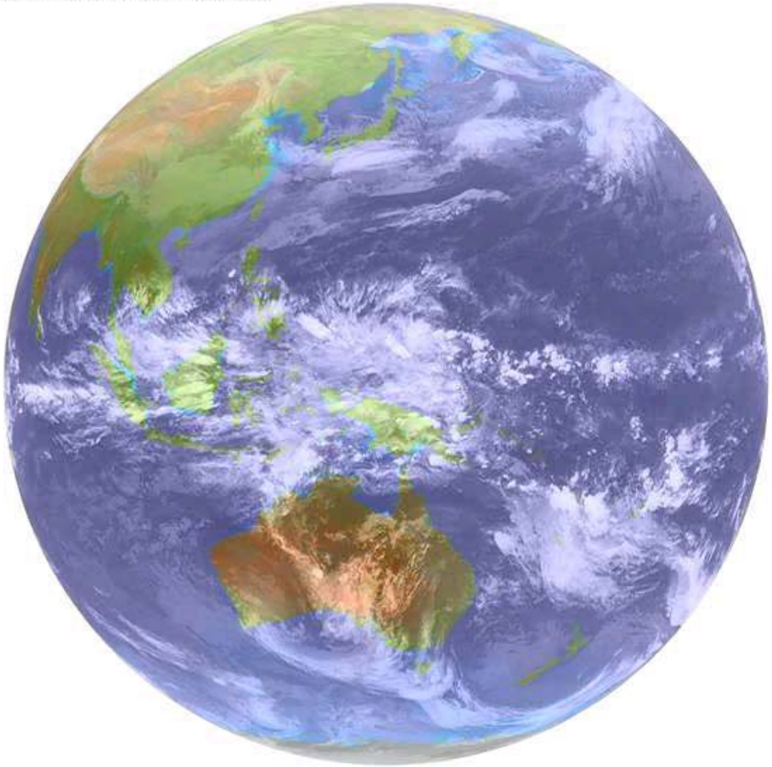
Histograms of diurnal cycle for precipitation



A Simulation of Madden-Julian Oscillation(1)

A large MJO on Dec. 2006.
→ Heavy rainfall event at Malaysia

Miura et al.(2007)



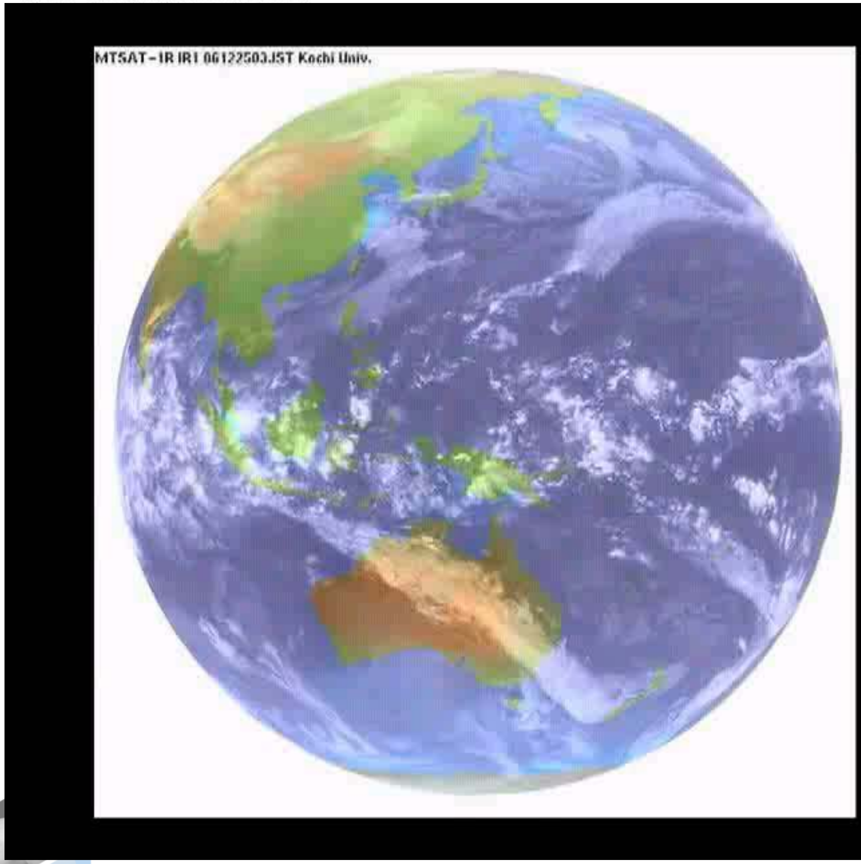
A Simulation of Madden-Julian Oscillation(2)

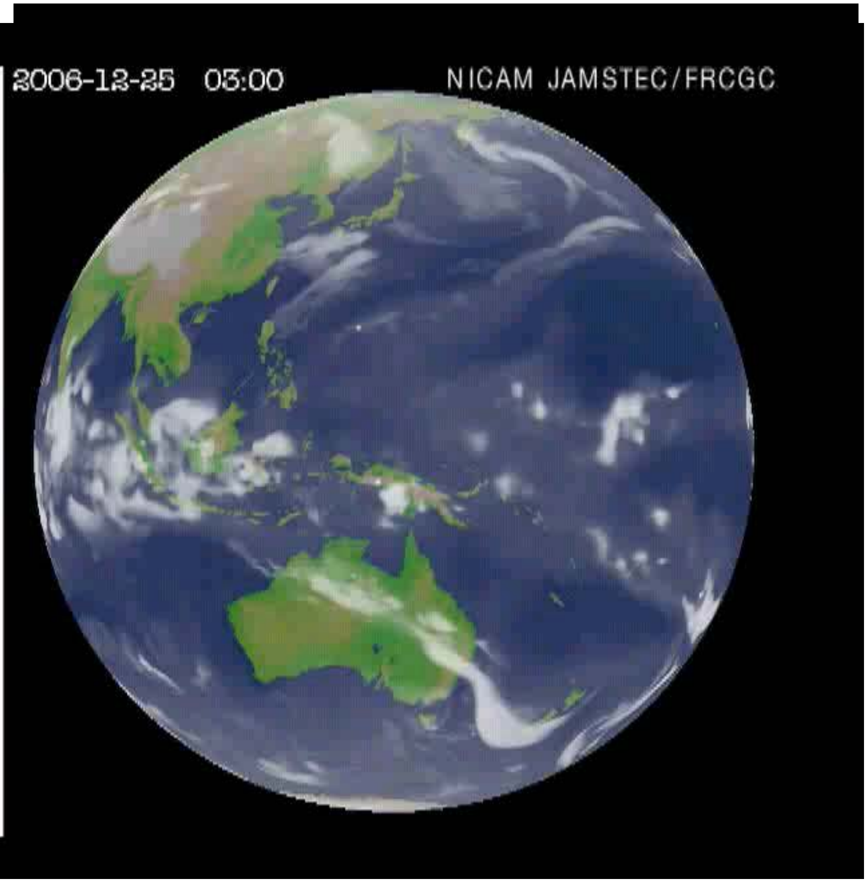
3.5km simulation of an MJO event

MTSAT cloud image
http://weather.is.kochi-u.ac.jp

NICAM 3.5km simulation (OLR)

Miura et al.(2007)



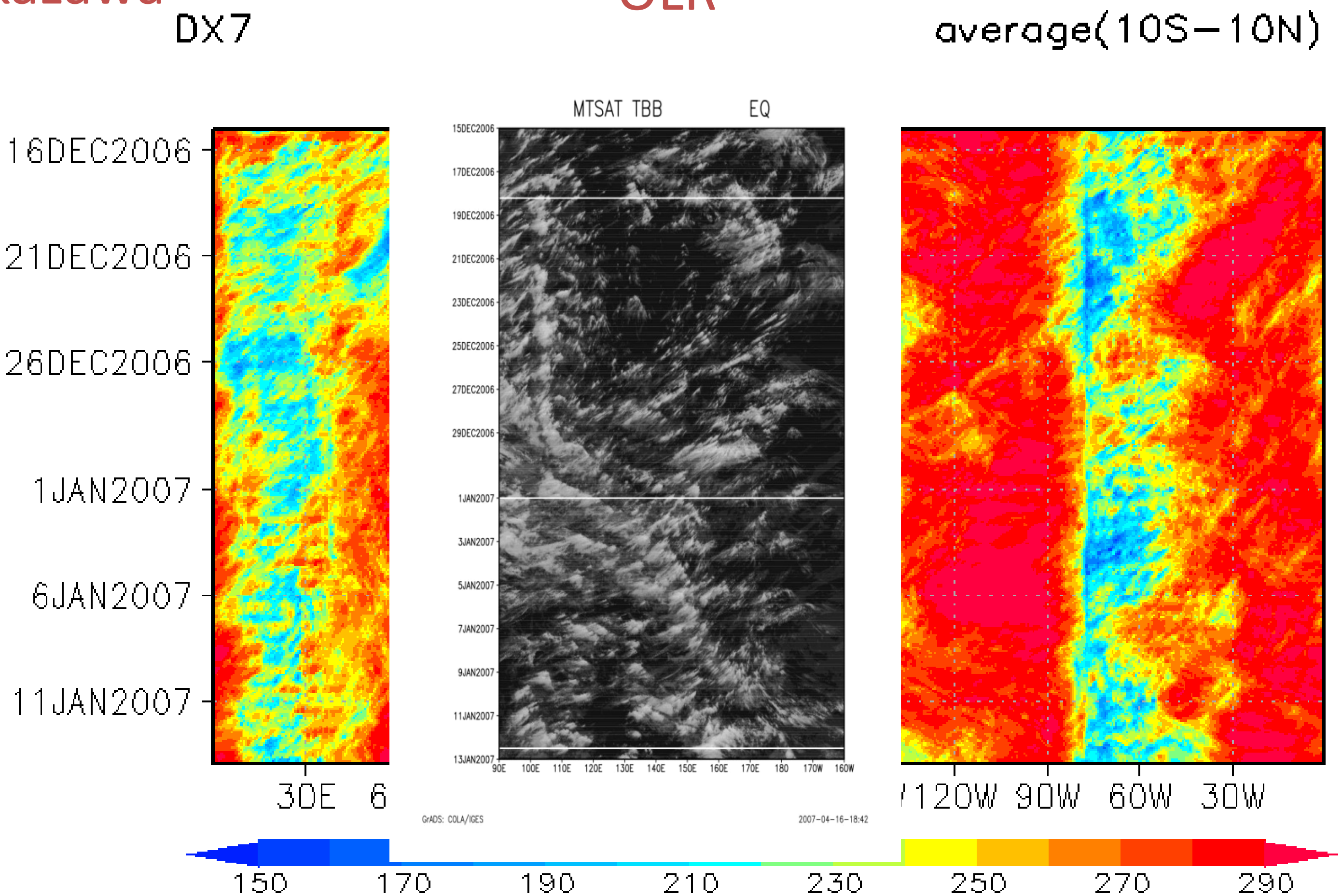


A Simulation of Madden-Julian Oscillation(3)

Hovmoller diagram of OLR along equator

MTSAT-1R TBB
by T.Nakazawa

NICAM dx=7km
OLR



The Athena Project(Kinter et al.(2013,BAMS)

Collaborating Groups

- **COLA** - Center for Ocean-Land-Atmosphere Studies, USA
- **ECMWF** - European Center for Medium-range Weather Forecasts, UK
- **JAMSTEC** - Japan Agency for Marine-Earth Science and Technology, Research Institute for Global Change, Japan
- **University of Tokyo**, Japan
- **NICS** - National Institute for Computational Sciences, USA
- **Cray** Inc.
- **RIKEN/AICS**

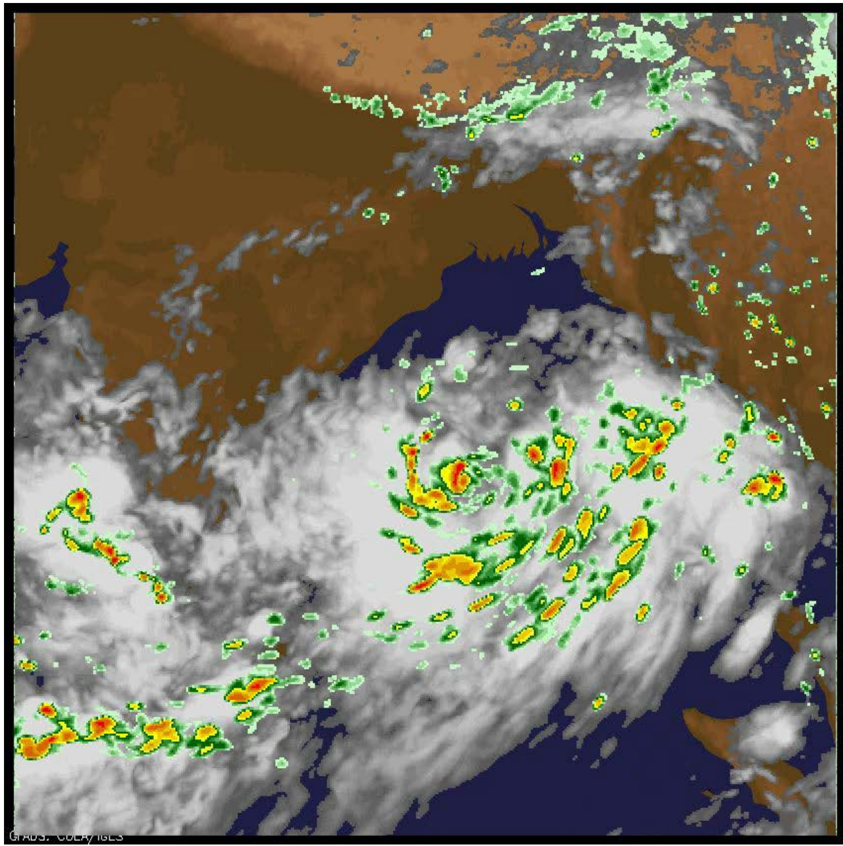
Codes

- **NICAM**: Nonhydrostatic Icosahedral Atmospheric Model (7km)
- **IFS**: ECMWF Integrated Forecast System (TL2047)

Super-computers

- **Athena**: Cray XT4 - 4512 quad-core Opteron nodes (18048)
  - #30 on Top500 list (at November 2009)
- **Kraken**: Cray XT5 - 8256 dual hex-core Opteron nodes (99072)

NICAM7km 6month run



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Statistical results of # of TC over 8 years(JJA)

IFS T2047: 10-m wind speed (7.5-min ave), JJA season, 2001-2002 & 2004-2009, tracks with wind speeds ≥ 15.4 m/s are retained, TC criteria of (1/1) is applied

NICAM gl10: 10-m wind speed (30-sec ave), JJA season, 2001-2002 & 2004-2009, tracks with wind speeds ≥ 17 m/s are retained, TC criteria of (1/1) is applied

CASE	In.	W.P.	E.P.	At.	Gl.
IBTrACs / JJA	2	78	69	39	188
JUNE	1	12	7	1	21
JULY	1	25	27	10	63
AUGUST	0	[illegible]	[illegible]	28	104
NICAM / JJA	8	[illegible]	[illegible]	[illegible]	196
JUNE	5	[illegible]	[illegible]	8	56
JULY	1	19	45	5	70
AUGUST	2	[illegible]	[illegible]	12	70
IFS 17.5 / JJA	9	[illegible]	[illegible]	[illegible]	84
JUNE	4	[illegible]	[illegible]	1	22
JULY	3	[illegible]	[illegible]	5	42
AUGUST	2	[illegible]	[illegible]	4	44
IFS 15.4 / JJA	15	[illegible]	[illegible]	[illegible]	145
JUNE	5	[illegible]	[illegible]	1	29
JULY	6	[illegible]	[illegible]	5	55
AUGUST	4	[illegible]	[illegible]	5	61

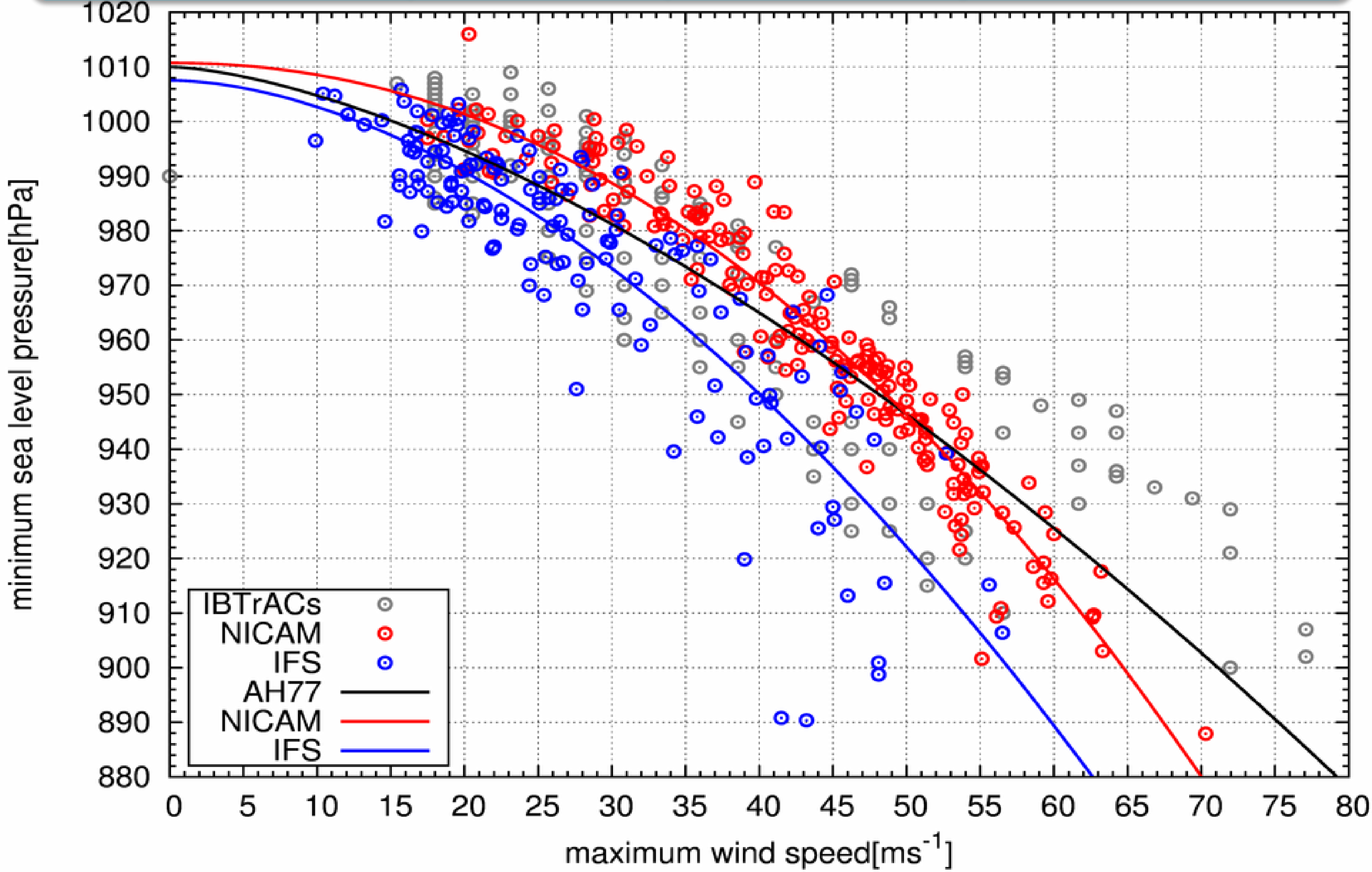
# of TC is reasonable in NICAM

On the same criterion, IFS has a little bit small

If threshold values be high, IFS has a reasonalbel number

TC intensities: SLP vs. MWS

NICAM well captured the TC structure, comparing with theory and observation.
Why? => CRM?Nonhydro? : => Todo subjects



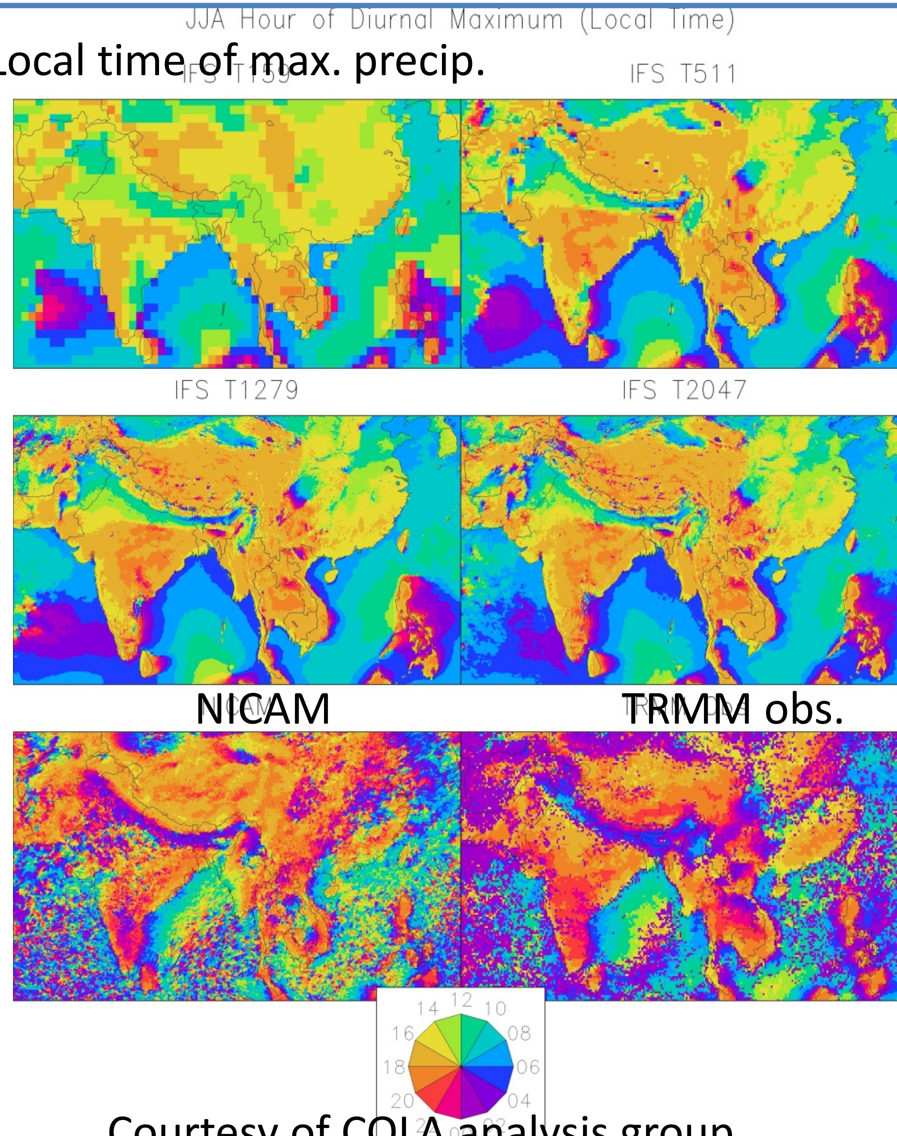
Dirurnal cycle of precipitatiaon

Diurnal cycle in GCRM is a typical advantage over the convectional GCM

- Diurnal cycles of precipitation : tremendously improved both in ocean and land.

=> Importance of explicit expression of cloud (not CP)

Local time of max. precip.



IFS

NICAM

TRMM obs.

Courtesy of COLA analysis group

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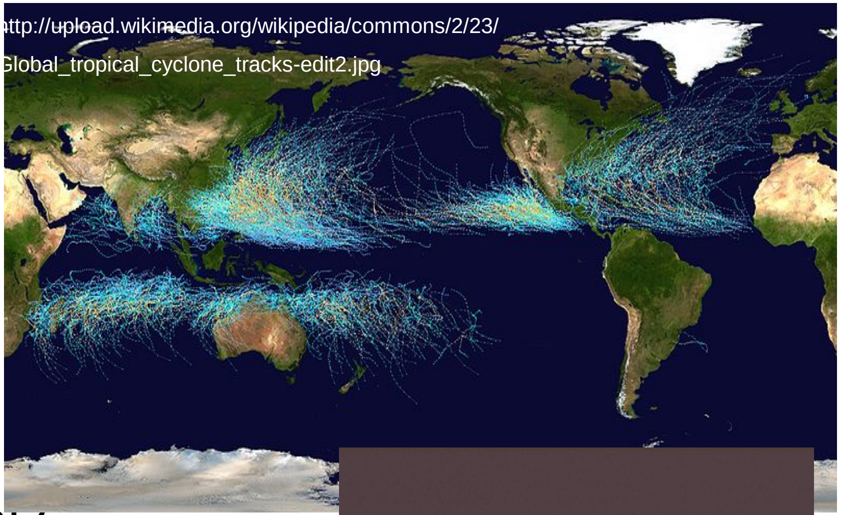
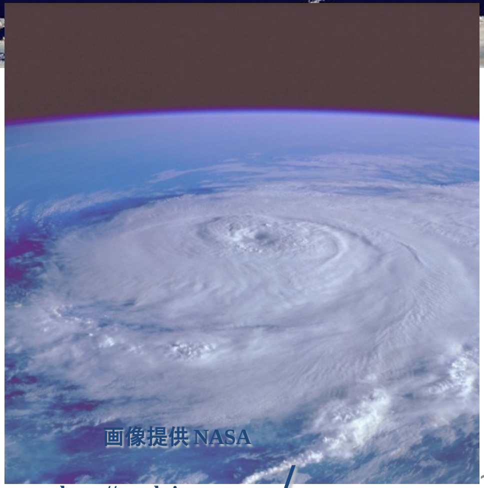
Ongoing projects on the K-computer using NICAM

- HPCI strategic project #3
  - The tropical cyclone in the GW climate:
    - How does the tropical cyclone change from the current climate to future warmed climate?
  - The possibility of extended prediction in the tropics:
    - How long can we expect to predict the tropical disturbances by the global cloud-system resolving model?
  - Target resolution:
    3.5km, 7km horizontal resolution
    - 7km ~ 20 year s X 2
    - 3.5km ~ 10 years





http://earth.jsc.nasa.gov/

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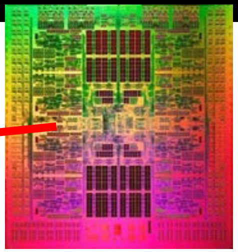
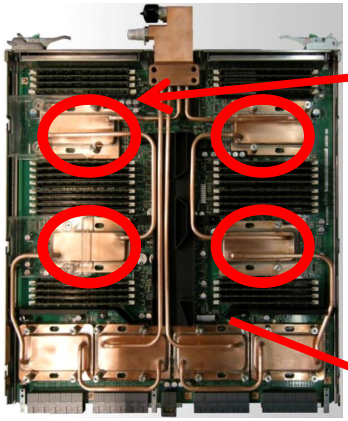
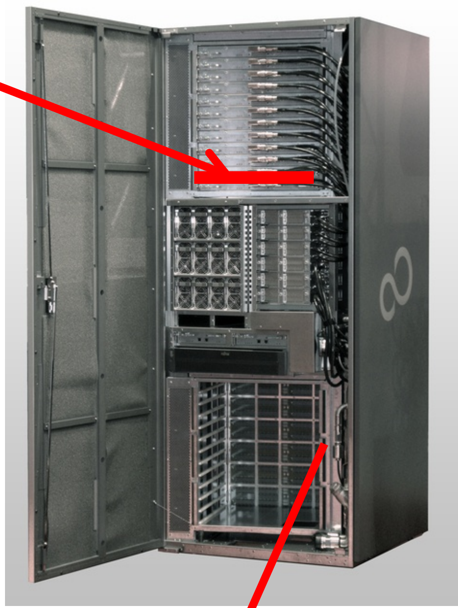
K Computer : System configuration

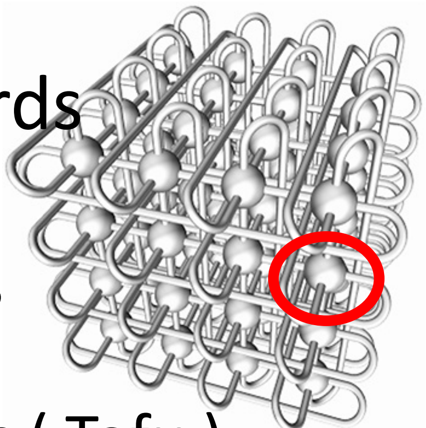


Courtesy of Fujitsu Ltd.

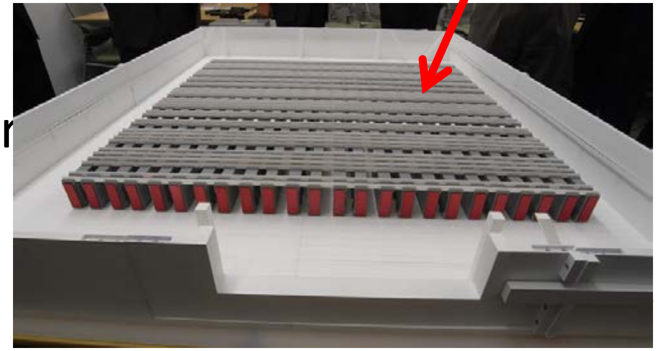




- CPU : SPARC 64 VIIIfx
  - 8core， 128GFLOPS
- Memory : 16GB/CPU
  - B/F : 0.5
- System board : 4 CPUs
- Cabinet : 24 system boards
  - 12.3 TFLOPS
- Network: 6D mesh torus
  - 3D torus connection between 12nodes-groups (Tofu)
  - 3D network in Tofu
    - Set up 3 paths from one node to another
      - Support fault tolerance
- Total cabinets: > 800



Courtesy of Fujitsu Ltd.



Higher resolution simulation is needed?

- Grand Challenge!
  - Horizontally 860m resolution, vertically 100 levels
    - Use of whole system of K-computer
  - Purpose
    - One reference solution to coarser grid simulation.
      - Definitely global cloud-system resolving!
    - Computationally, check the scalability at the use of full resource.
- Toward exa-scale computing, the GLES may be a next milestone!

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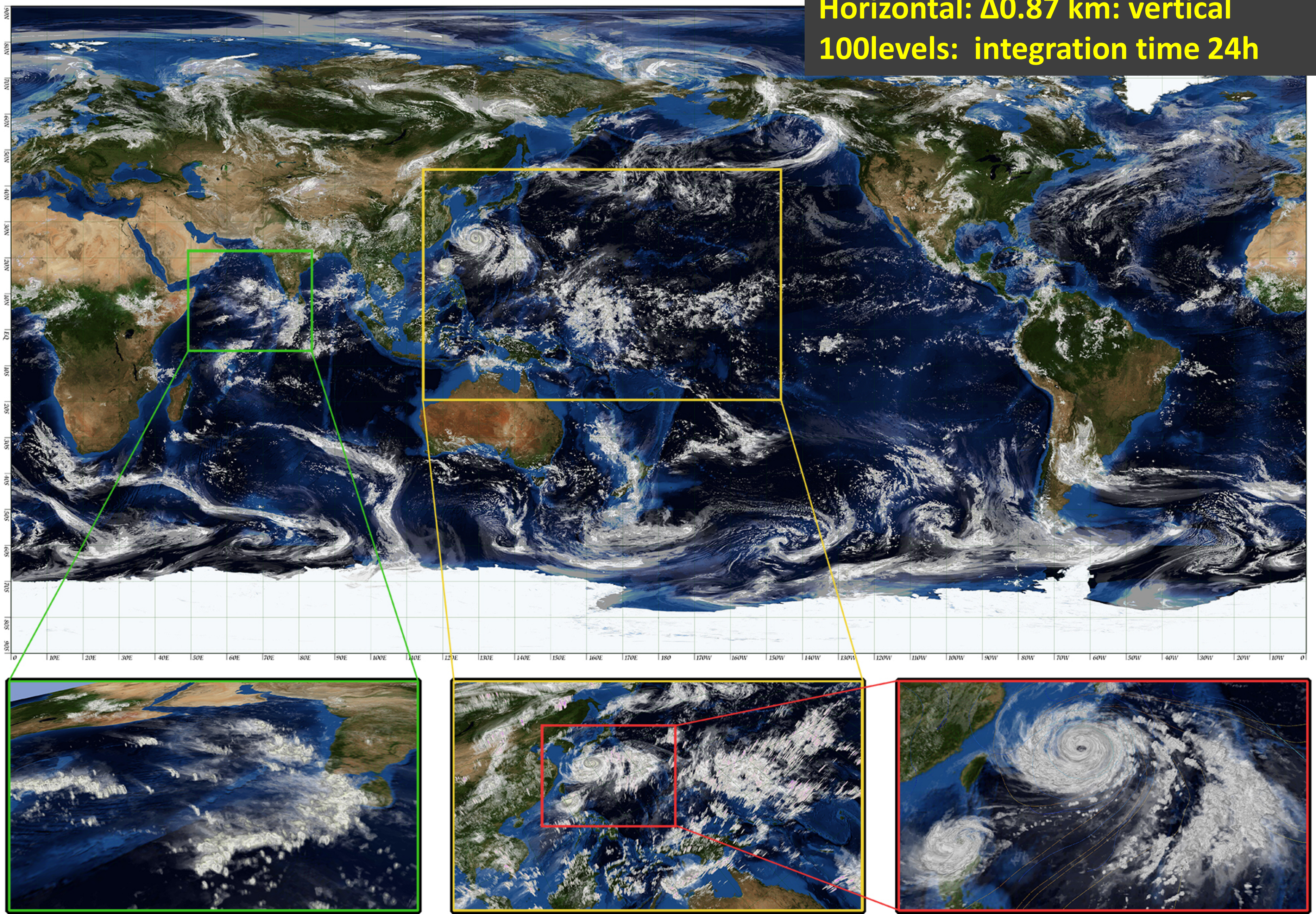
A sub-km AGCM starts!

Horizontal: Δ0.87 km: vertical 100levels: integration time 24h



How can we pull the scientific outcome?

- Even current High-end machine, sub-km GCM is like a demonstration:
  - However, next genration HPC enable us to integrate the long time simulation.

==================================

- Current analysis: *submitted to GRL(Miyamoto et al.*
  - Global statistical convection feature by a snapshot
    - Convergence
      - Number of convection
      - Distance of neighboring convection cells
      - Etc.

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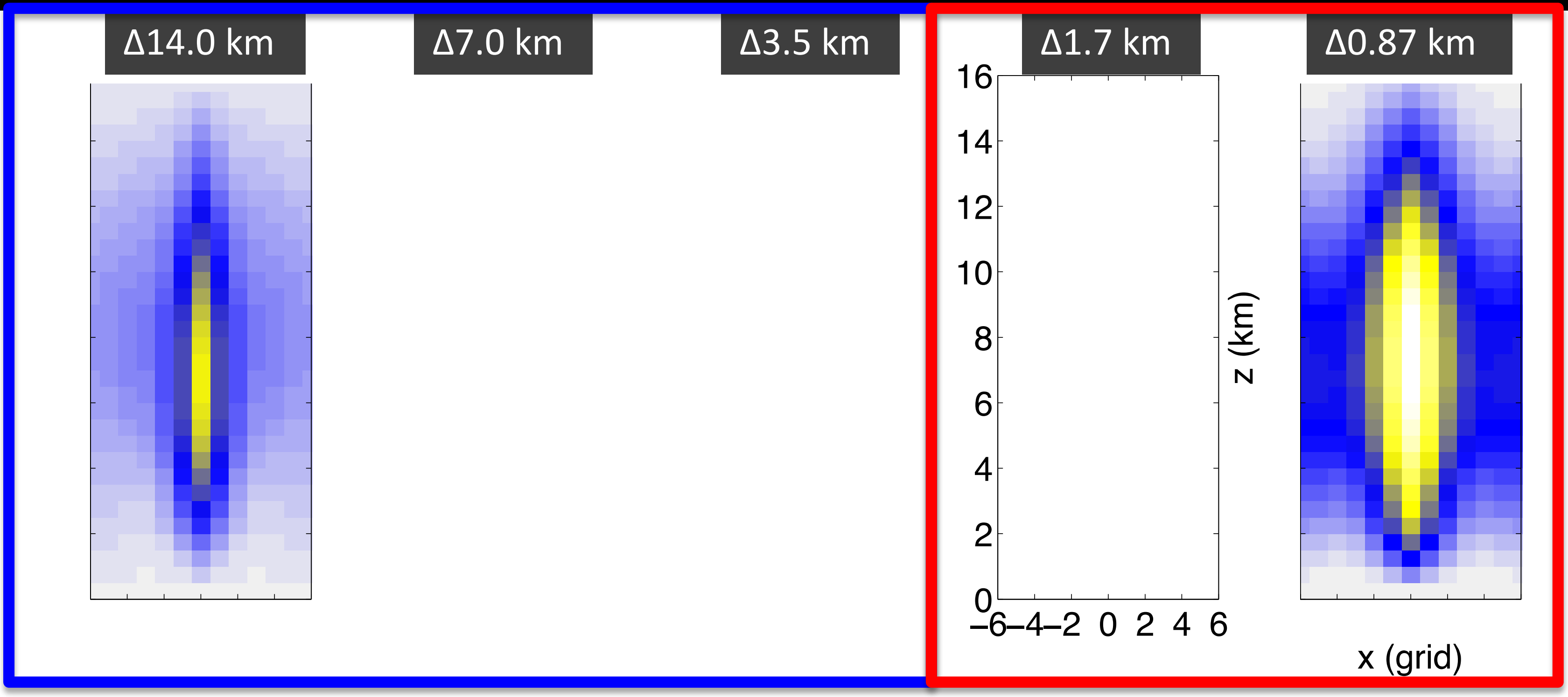
Composite of convection (vertical velocity)



Δx ≧ 3.5 km:

- Convection is represented at 1 grid
- Little dependence on resolution

Δx ≦ 1.7 km:

- Convection is represented at multiple grids
- Intensify w/ resolution

※transform the coordinate into the cylindrical around the core grid
mean of all the detected convection
symmetric around the x axis

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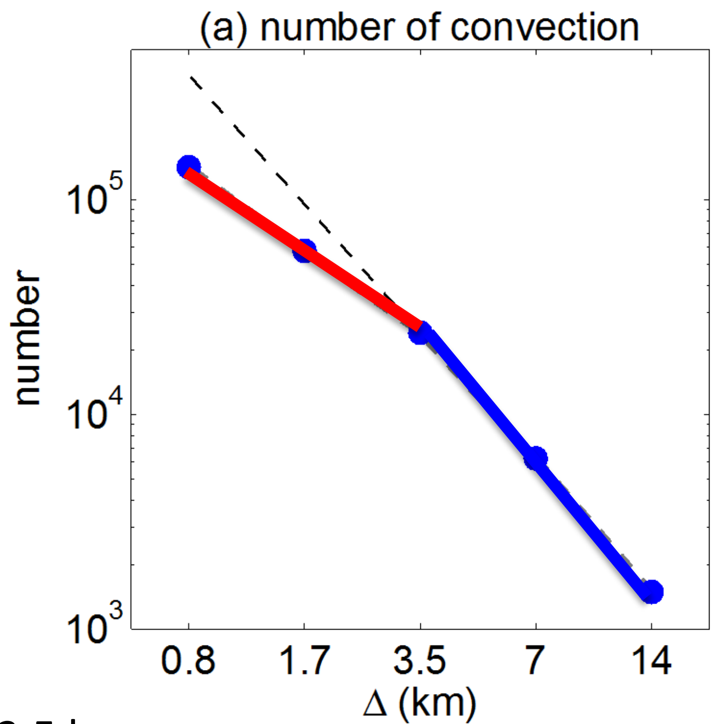
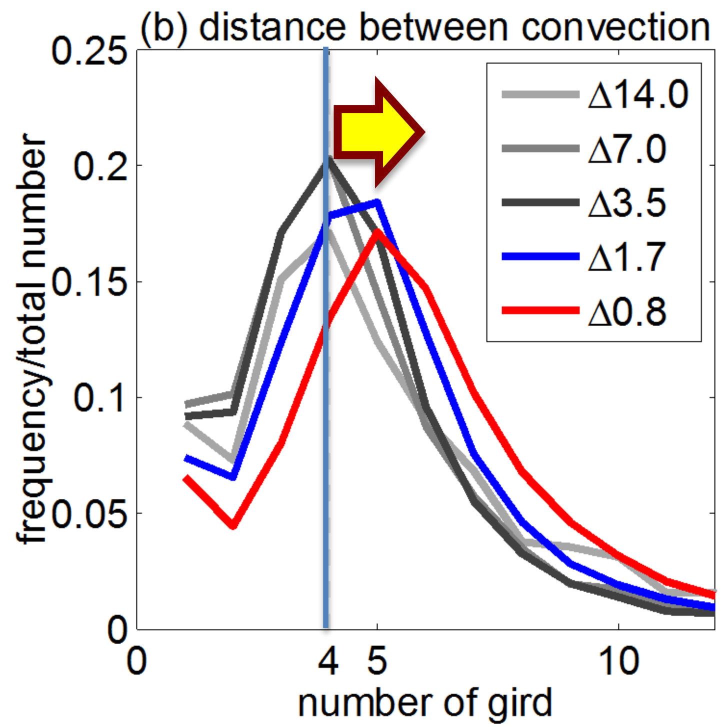
Number and distance of convection





Δx ≧ 3.5 km:

- number: increase by factor of 4
- Distance between convection: 4 grids => unphysical?

Δx ≦ 1.7 km:

- number: decrease in increasing rate
- distance: >5 grids => close to the nature

conclusion

Convection features (structure, number, distance

change between Δ3.5 km ⬄ Δ1.7 km

- Δx should be 2.0〜3.0 km to resolve convection in global models

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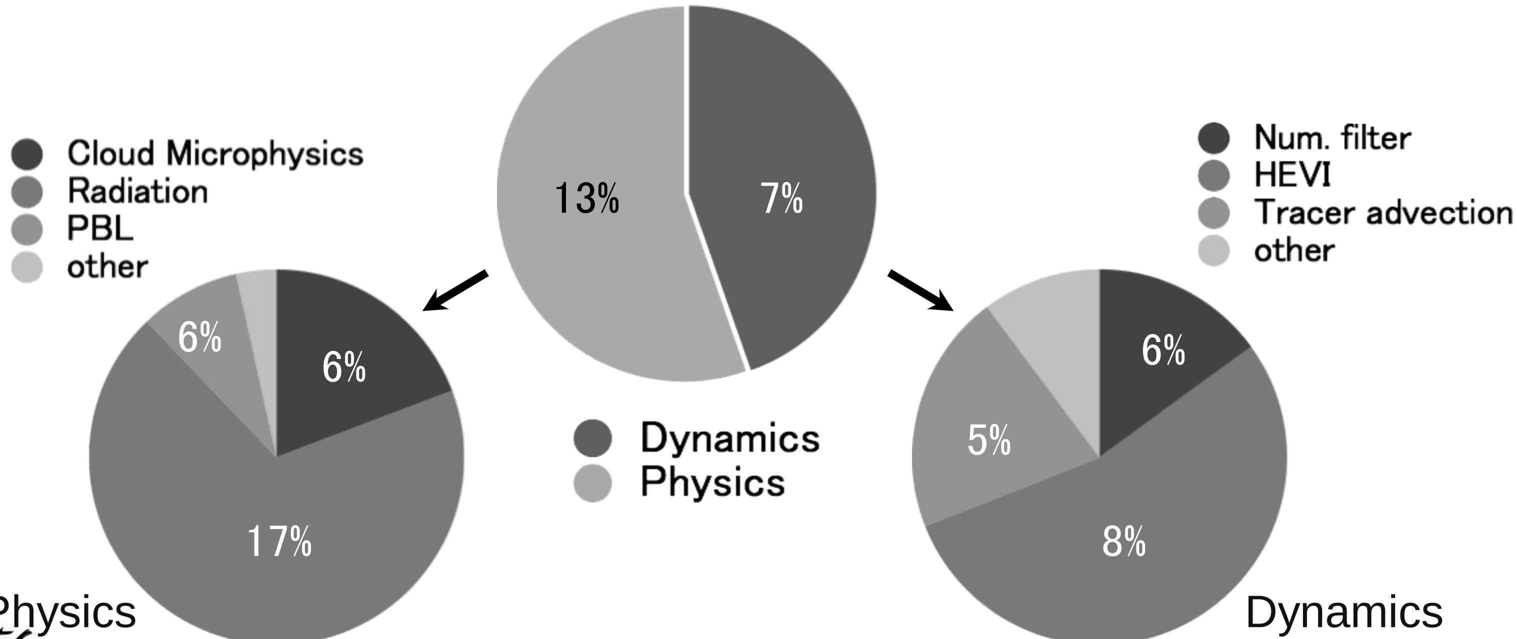
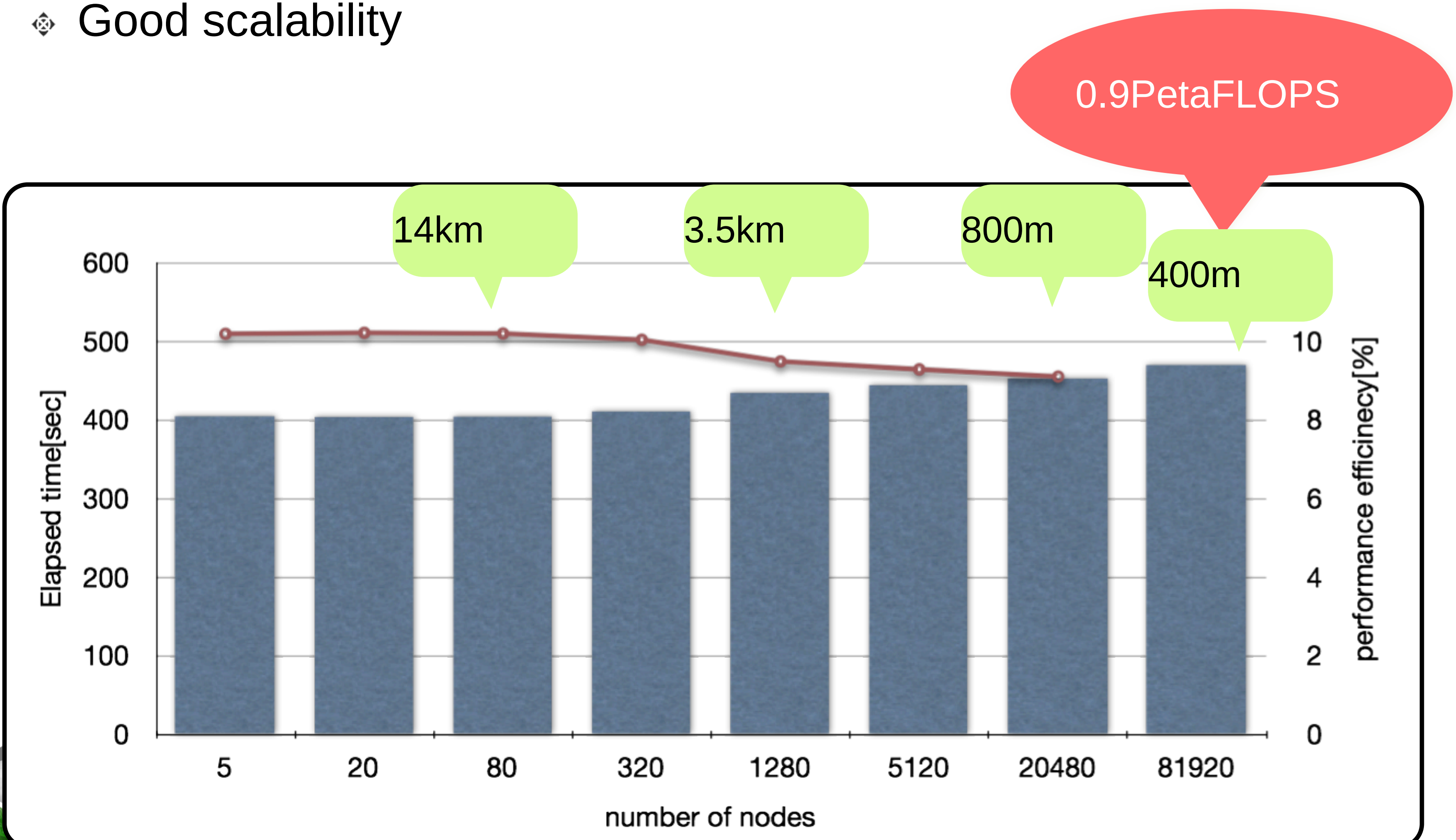
Efficiency of NICAM on K Computer

- Performance efficiency
  - Just after porting from ES : ~4%
  - Cache optimization to stencil operators : ~5%
  - Cleaning the time-wasting codes : ~7%
  - Modify conditional branches, refactoring : **~10%**



Weak scaling test

- Same problem size per node, same steps
- Good scalability



GCRM => GLES?!

AGCM milestone from GCRM to GLES?!(roughly estimate)

Assumption: sustained peformance 10% (we wish)

Resolution Grid interval/ level	Total FLOP for 1day simulation	Machine	efficiency (%)	Elapse time for 1day simulation	Elapse time for 1 month simulation	What's resolved? What is meaningful for scientific advance?
3.5km/L40	220P	131TFLOPS (ES2)	15%	3.2hour	4day	Meso-scale convection system. Cold pool dynamics
800m/L100	36800P	10PFLOPS (K computer)	10%	10hours	12.5days	Convection resolving?
400m/L100	295000P	1EFLOPS	10%	50min	24days	Definitely convection resolving(expected)
200m/L100	2360E					Breakthrough does not exits. But good expression of deep cloud
100m/L100	18880E					Insufficient for LES
50m/L200	302Z	100EFLOPS	10%	50分	24hour	Global LES???

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SCALE project

- We have started the preparation towards the Global Large Eddy Simulation
- Co-design with computer science people in RIKE/AICS

http://scale.aics.riken.jp/

Team SCALE

Computational Climate Science Research Team

TL : H.Tomita

Software Research Team

TL : Y.Ishikawa

Programming Environment Research Team

TL : M.Sato

Programing Framework Research Team

TL : N.Maruyama

HPC Usability Research Team

TL : T.Maeda

Library, and Research for weather/climate research
With computer science people (SCALE library)

Background1: HPC trends / model R&D environment

- Two trends of HPC environment
  - VECTOR → SCALAR
    - e.g. ES2: 160 vector machine → K Computer : 80,000 scalar processor
  - General purpose machine → special purpose machine?
    - e.g. Anton(biophysics field), GRAPE(MD field), etc.
- We have to consider many things related to computer architecture.
  A) Low Byte/Flops ratio
  B) Massive inter-node communication frequency
  C) Heterogeneous architecture
  D) Deep Memory Hierarchies

Question

- Do we need the reconstruction of model concept?
- Which is the better/best computer system for Weather/Climate application?
- Which is the better/best numerical scheme?
- What can we say about an architecture design?

Example :One concerned issue
low B/F ratio

Dynamical core based on stencil calculation becomes fatal !?

- The model performance (stencil calculation) may be **limited** by memory bandwidth...
  - E.g. B/F: 0.5 in K Computer
    - Performance efficiency of typical FDM, FVM
      : 6-12% for double precision

- Estimated : B/F: 0.1~2? Exa scale machine?
  - A few %???

Background2:
Meteorological model development trends

- Shallow cumulus / stratocumulus
  - One of key issues for climate model
- LES is a vital tool.
  - However, current LES in the meteorological field is enough?
    - **Hypothesis of LES is based on the dry homogeneous fluid.**
      - *Moist process injects the energy at grid-scale.*
      - *Large aspect ratio of grid is not acceptable.*

Toward the Global LES

The basic study from the viewpoint of computational and computer sciences is needed!

Concepts of SCALE

- **<u>Our general concept to get high performance in SCALE</u>**
  - **Simpler method, Faster calculation, Reasonable accuracy**
    - We don't pursue the flops:
      - If we use higher order scheme, high flops can be easily achieved (<- owing to reusablity the cash memory) but,….2^{nd} order-4^{th} order maybe enough (<- due to physical parameterization)
- **<u>Current technical issue</u>**
  - **<u>Time integration method</u>**
    - Comparison between **HEVE(Full explicit), HEVI(usual method)**, **HIVI (Full implicit)** for the future high resolution runs.
      - Which is suitable for the LES scale simulation?
    - ***<u>Full explicit gives the reference solution.</u>***

<u>Final goal :</u>

- Develop the library & middleware based on the knowledge through the development
- Provide them to the community as the open source

Dynamics in SCALE-LES

Dynamics	
Governing equations	Compressive, non-hydrostatic system
Spatial scheme Spatial discretization Grid configuration	4th-order centered, Finite Volume 3D cartesian with isotropic resolution, no terrain, Arakawa-C grid (horizontal), Lorenz grid (vertical)
Prognostic variable	Density, mass flux, potential temperature
Temporal scheme	**3rd-order Runge-Kutta (full explicit scheme)**
Advection scheme	**4th-order Finite Volume** with Flux Correction Transport (FCT) limiter

Nishizawa et al. (2013)
in preparation

Why Full explicit?

- No divergence damping filer is needed.
- The memory load/store may be minimal
- If aspect ratio of grid becomes unity, HEVI is no longer meaningful.

Why 4th order of advection term is needed?

- The 2nd order advection term has implicit Laplacian-type diffusion term,which may be overlapped with the smagorinsky-diffusion.

Computational performance

Hisashi YASHIRO（AICS）

Δxyz=5m, Δt(dyn)=0.008sec, Δt(phy)=0.8sec, (k,i,j)=(1256,32,32)

[sec]	CTL	RDMA	w/ kessler	w/ NDW6 orig	w/ NDW6 tuning
Main loop	110.6	102.5	112.7	124.9	116.3
Dynamics	109.5	101.5	108.7	108.7	108.7
TB	0.0	0.0	0.8	1.0	0.9
Micro-physics	0.0	0.0	1.6	13.7	5.4
COMM	15.9	4.7	15.7	15.7	15.7

- Dynamics: 10%～12%　sustained performace
- If real8 is changed to real4, getting more performance?
- Communication : 16/110 = 15% in MPI case.

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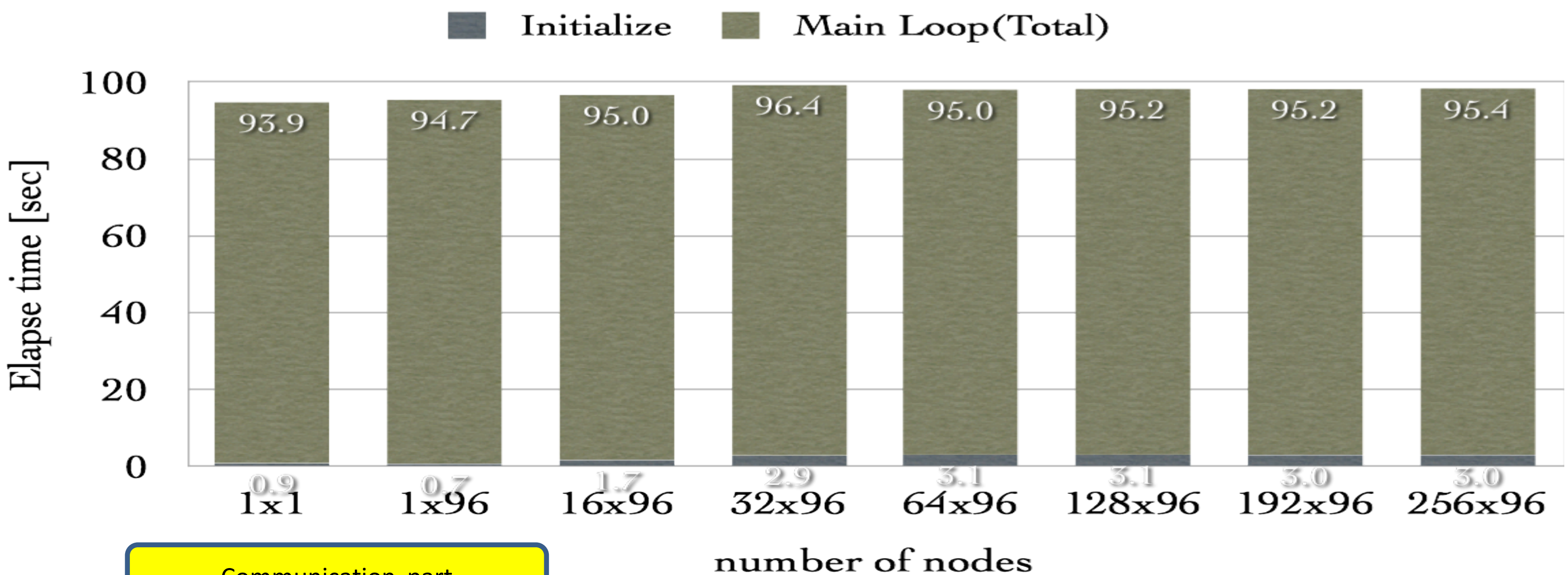
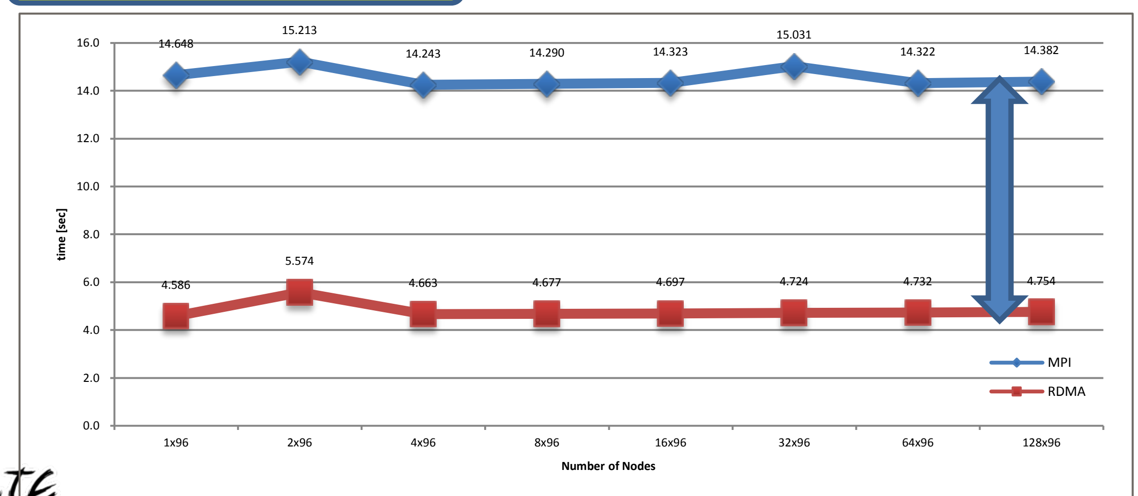
Weak scaling results

Hisashi YASHIRO,
Yoshiyuki OHNO（AICS）

Δxyz=5m, Δt(dyn)=0.008sec, Δt(phy)=0.8sec, (k,i,j)=(1256,32,32)



Communication part



The use of RDMA can enhance the communication speed.

3X

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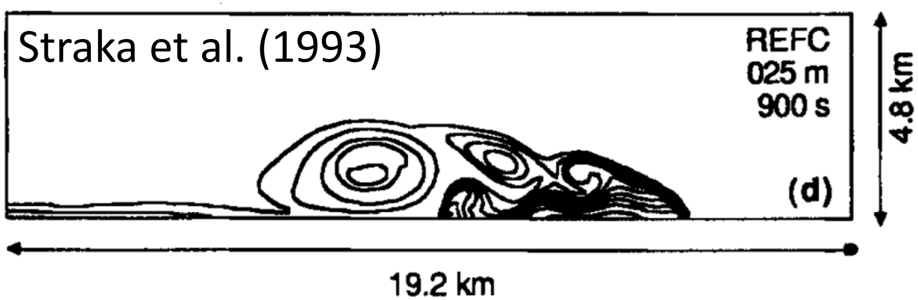
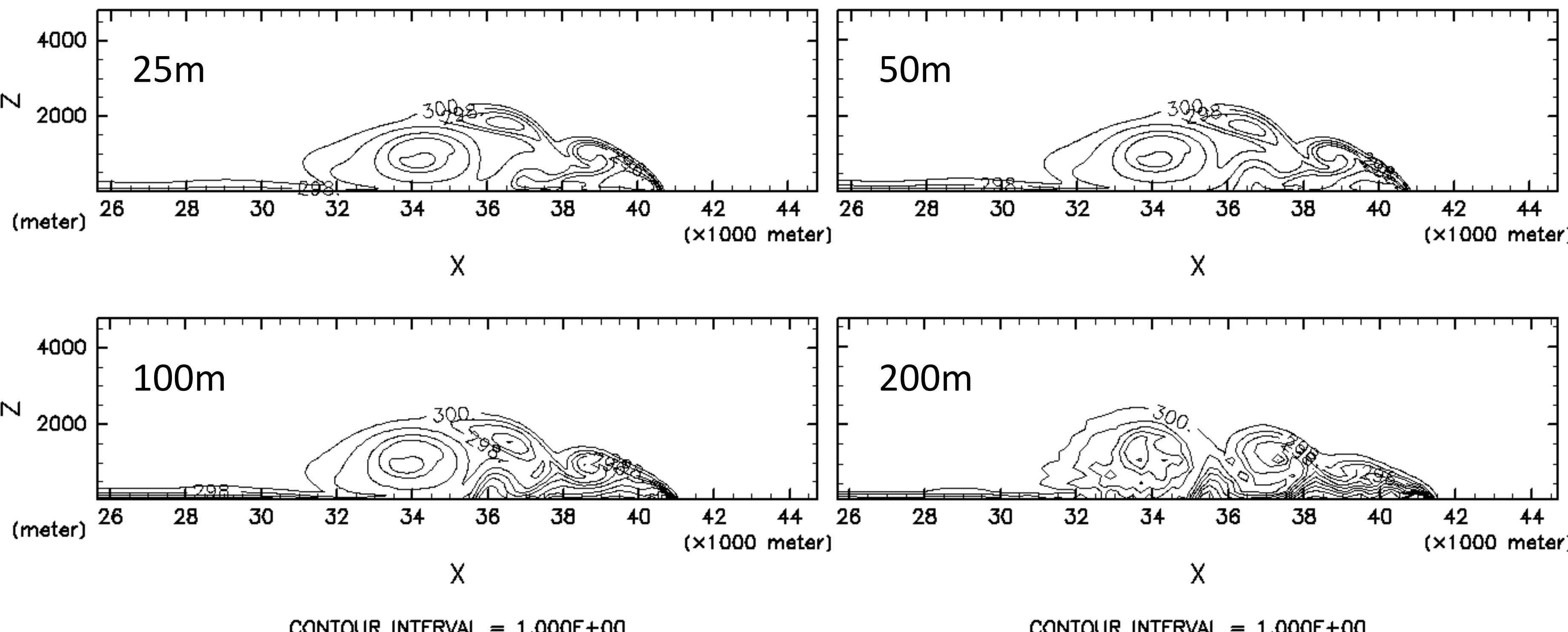
The first test case(NHM-DC check)

- Straska et al. (1993) cold bubble exper

NISHIZAWA（AICS）



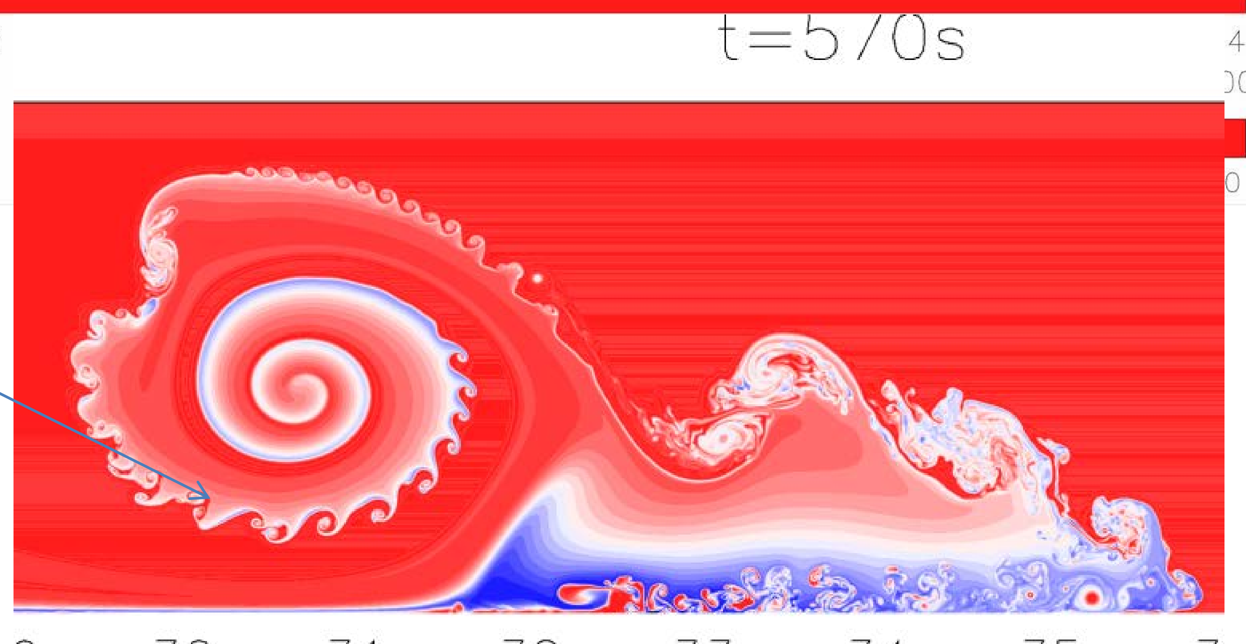
- Explicit viscousity and diffision: 75m^2/s
- Grid refiment test
- → Numerical accuracy



Another interesing test based on Straska et al.

Seiya NISHIZAWA
(AICS)

- Decrease of numerical diffusion (4^{th} order hyper diffusion) according to increasing resolution (up to 1.5625m)



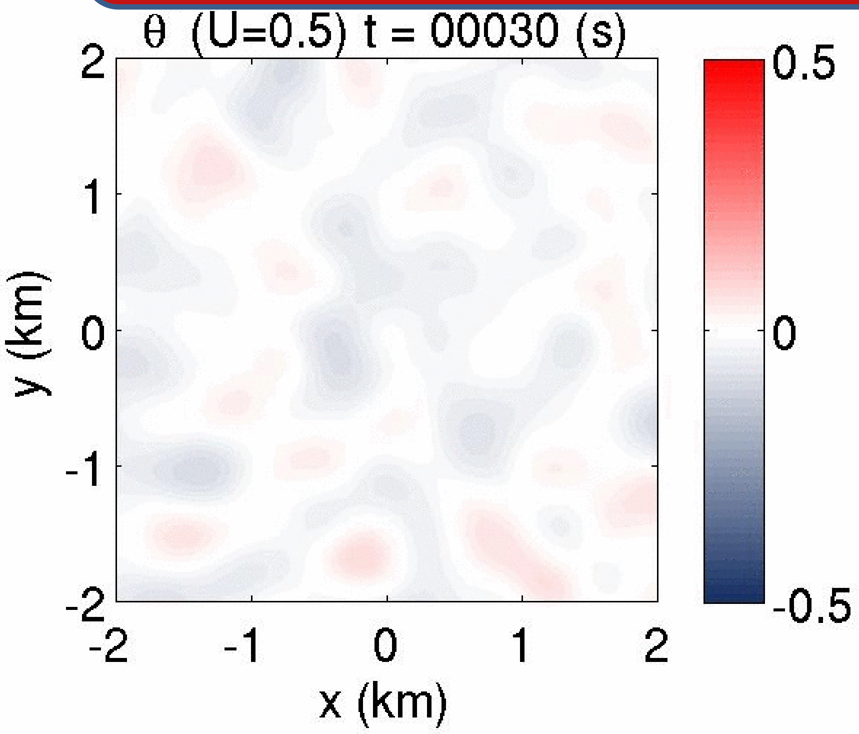
Explicit eddy-diffusion can be seen, increasing resolution.
→ Useful to validation of eddy-diffision estimation?

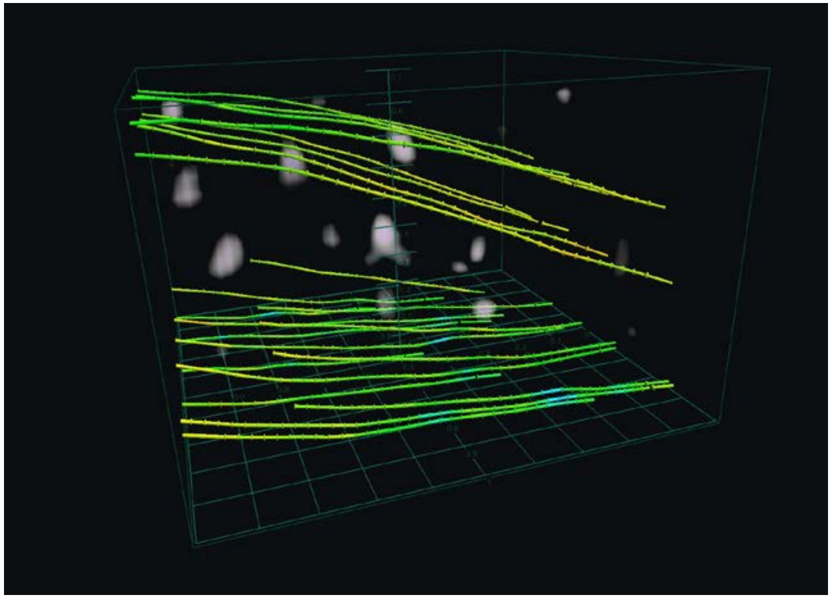
The test case : dry turbulence

Yoshiaki MIYAMOTO
Seiya NISHIZAWA（AICS）

Question:

If aspect ration becomes large,
the LES can produce the same result?





Target simulation plan

- **Very high resolution run for DYCOMS II RF01**
  - 5m cubic grid with 2nd moment / spectral bin model.
  - The database can be a reference solution to other model results.

- **Very wide domain, meso-scale LES run**
  - The transition from stratocumulus to shallow cumulus
  - The transition between open & close cells, and POCS.
    - aerosol interaction : key issue?
  - ~~5m cubic grid with 100km X 1000km~~
  - *5m v-grid & 50m h-grid with 100km X 1000km?*
    - *However, the enough validation of aspect ratio is needed!*

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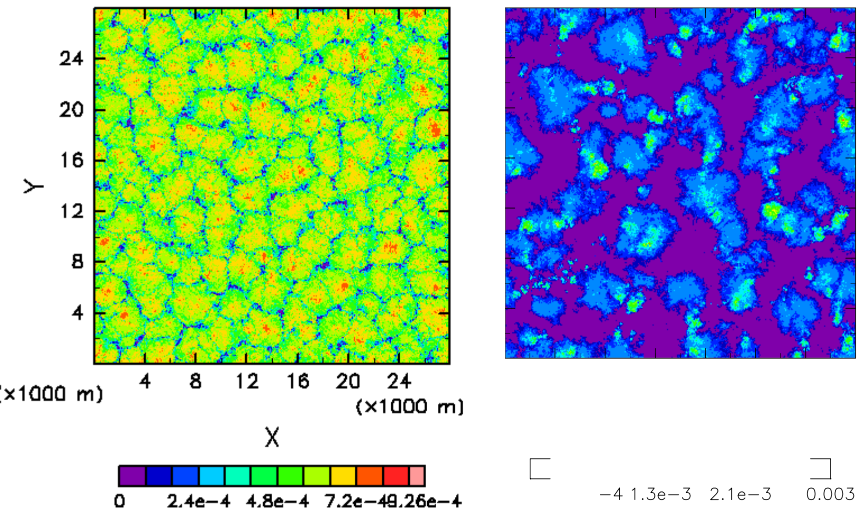
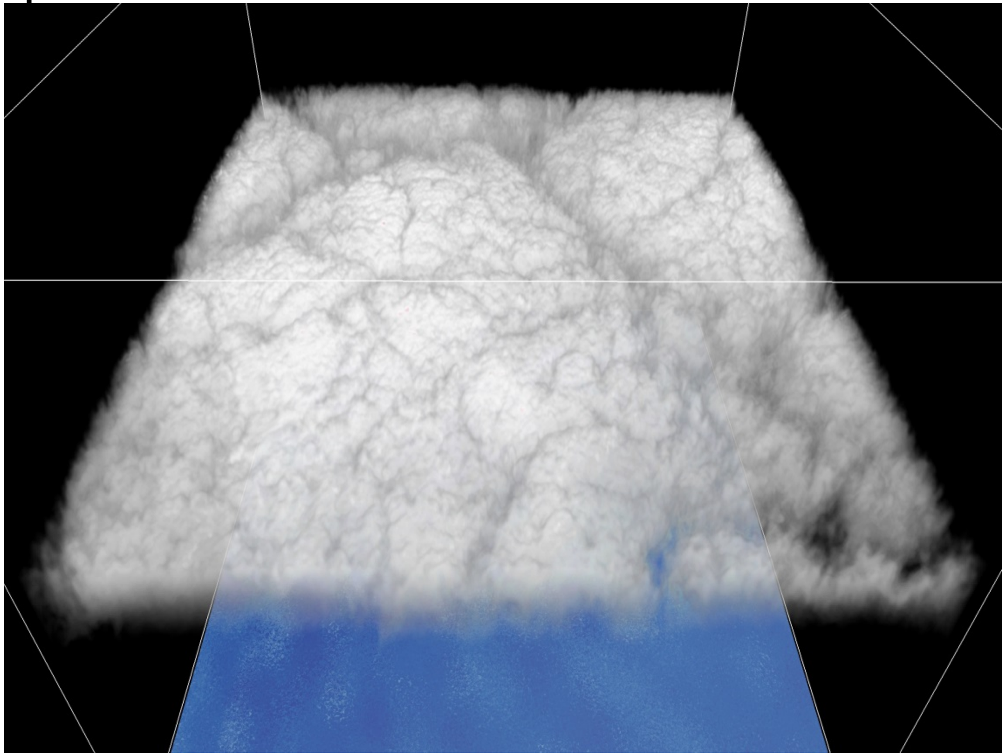
The first test to the target: DYCOMS-II RF01

Yosuke SATO
Yoshiaki MIYAMOTO（AICS）

- Resolution : dx=dy=dz=5m
- Integration time : 4hours
- Domain ：2.7km X 2.7km
  - turbulence：Smagorinsky
- Cloud microphysics ：2moment bulk（Seiki and Nakajima 2012）/ Spectral bin method (Suzuki et al.)
- Radiation ：Stevens et al. 2005' parameterization

Stratocumulus(Closed cell,Open cell)dx=35m）by SCALE-LES

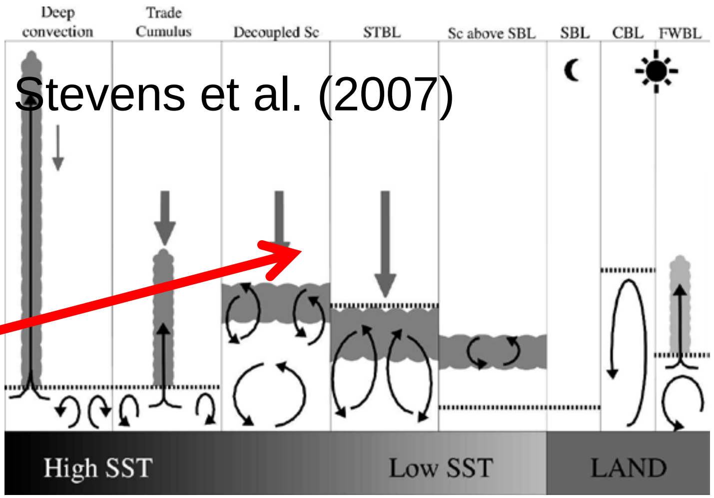




Current science target of SCALE-LES

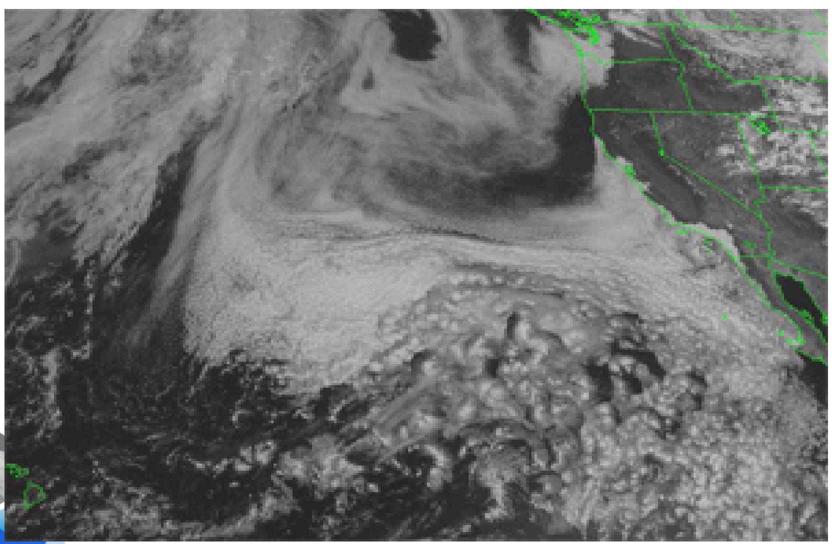
Simulation of ***transition process from Stratocumulus to Shallow Cumulus***

- We want to analyze the detail process such as decoupling process, cloud top entrainment process



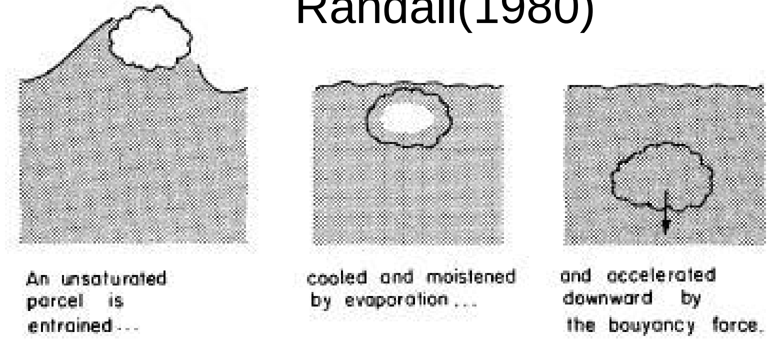
Stevens et al. (2007)

Which is the main process for collapse of Stratocumulus?



http://www.atmos.ucla.edu/~bstevens/Research/projects.html

Randall(1980)



Summary(1)

From our experience

- Quasi-homogenious grid (e.x. icosahedral grid) is a promising for future HPC.
  - Even in icosahedral grid, many schemes are proposed;
    - A-grid, triangle C-grid, Hexagonal C-grid
- "Cloud permitting model" without cumulus parameterization is useful in the context of explicit expression of mechanism of cloud physics.
- A sub-km model is deep-cloud system resolved?
  - Still not convergence, but convergence trend was found.

Summary(2)

FUTURE SCOPE:

- ***LES is a vital tool!***
  - However, we should overcome several issues.
    - I. **Validation of the aspect ratio of grid:**
      - Usually, very large aspect ratio is used in the meteorological application, although the theory has assumption of homogenous turbulence.
    - II. **Treatment of moist process:**
      - Moist process injects the grid-scale energy, so that the energy cascade theory in the inertia sub-range may be invalid in this case.
  - Dynamical core scheme should be reconsidered!
    - *HEVE, HEVI, HIVI, split explicit : which is the best?*
- ***Hardware & Software in HPC become changed now!***
    - Chip architecture, system software, programing environment.
  - *We should collaborate with computer scientists to build up the next-generation HPC.*

Final message :
Towards the further high resolution, we have to study the top-down approach(from GCM to LES) and bottom-up approach (from LES to GCM)

Thank you for your attention!!

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