Multi-scale coupled atmosphere-ocean GCM and simulations

Keiko Takahashi, Xindong Peng, Ryo Onishi , Mitsuru Ohdaira, Koji Goto, Hiromitsu Fuchigami, Takeshi Sugimura

Earth Simulator Center
JAMSTEC

Time/Space scale

Minutes ~ Hours, Days

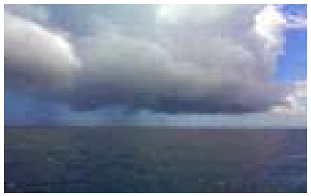
Atmosphere

Days ~ Months

Months ~ Years，Decadal

Cumulus

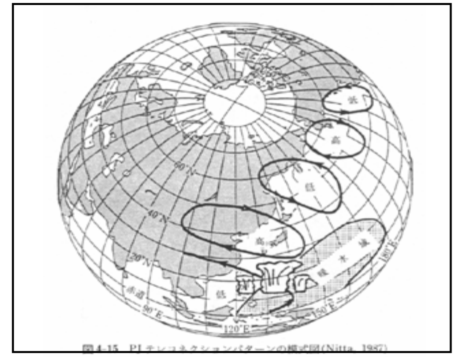
Heavy rain



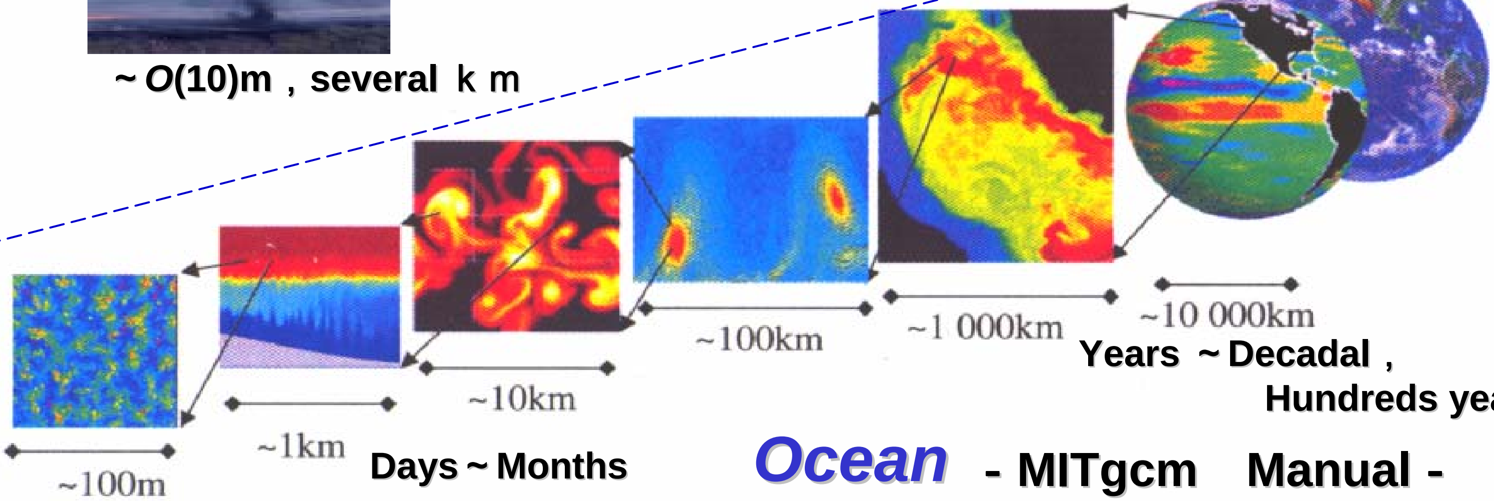
Tornado

~ *O*(10)m，several ｋｍ

~ 1000s　ｋｍ



[Nitta, 1987]　~ 10000s　ｋｍ

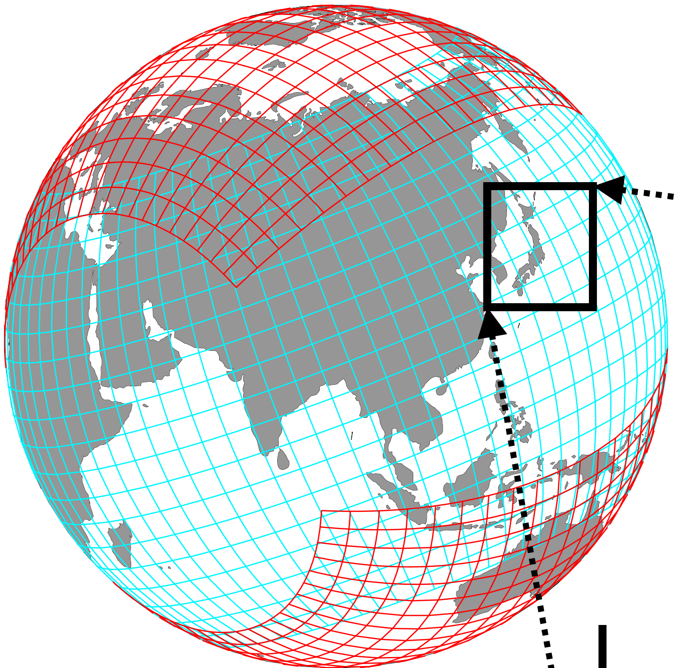


Days ~ Months

Years ~ Decadal，Hundreds years

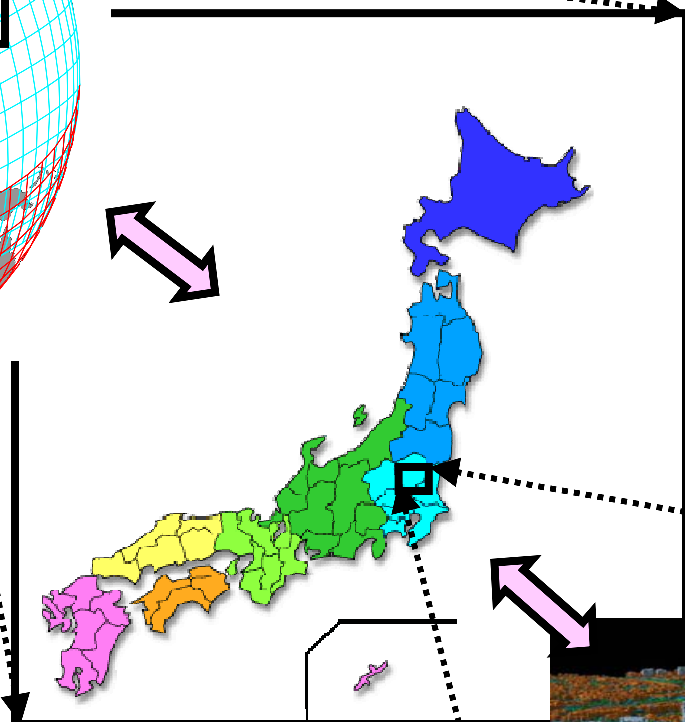
Ocean - MITgcm　Manual -

Scalability



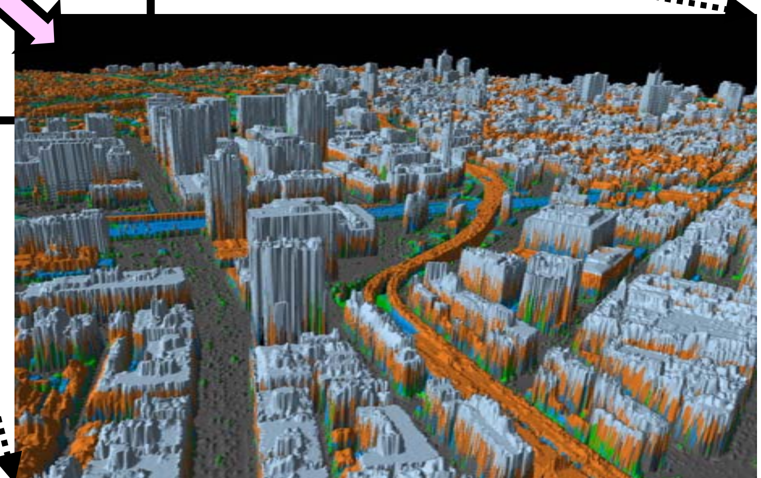
Seasonal ~ Annual Prediction

2 ~ 10 km for horizontal,
100 vertical layers



Days ~ Weeks Prediction
Local heavy Rain Prediction, etc.

100m ~ 2km for horizontal
100 vertical layers



Urban Weather /Climate Prediction

1m ~ 100m for horizontal,
200 vertical layers

(Data: Geographical Survey Institute)

Dynamical Core Framework
- Atmosphere -

- **Atmosphere: Fully compressible, non-hydrostatic equation set**

Continuity equation
$$\frac{\partial \rho'}{\partial t}+\frac{1}{G^{\frac{1}{2}}a\cos\varphi}\frac{\partial (G^{\frac{1}{2}}\rho u)}{\partial \lambda}+\frac{1}{G^{\frac{1}{2}}a\cos\varphi}\frac{\partial (G^{\frac{1}{2}}\cos\varphi\rho v)}{\partial \varphi}\frac{1}{G^{\frac{1}{2}}}\frac{\partial (\rho w^{*})}{\partial z^{*}}=0$$

Momentum equation
$$\frac{\partial \rho u}{\partial t}+\frac{1}{G^{\frac{1}{2}}a\cos\varphi}\frac{\partial (G^{\frac{1}{2}}p')}{\partial \lambda}=-\nabla\bullet(\rho u\vec{\mathbf{v}})+2f_{\mathrm{r}}\rho v-2f_{\varphi}\rho w+\frac{\rho vu\tan\varphi}{a}-\frac{\rho wu}{a}+F_{\lambda}$$

$$\frac{\partial \rho v}{\partial t}+\frac{1}{G^{\frac{1}{2}}a}\frac{\partial (G^{\frac{1}{2}}p')}{\partial \varphi}=-\nabla\bullet(\rho v\vec{\mathbf{v}})+2f_{\lambda}\rho w-2f_{r}\rho u-\frac{\rho uu\tan\varphi}{a}-\frac{\rho wv}{a}+F_{\varphi}$$

$$\frac{\partial \rho w}{\partial t}+\frac{1}{G^{\frac{1}{2}}}\frac{\partial p'}{\partial z^{*}}+\rho'\mathbf{g}=-\nabla\bullet(\rho w\vec{\mathbf{v}})+2f_{\varphi}\rho u-2f_{\lambda}\rho v+\frac{\rho uu}{a}+\frac{\rho vv}{a}+F_{r}$$

Pressure equation
$$\frac{\partial p'}{\partial t}+\nabla\bullet(p\vec{\mathbf{v}})+(\gamma-1)p\nabla\bullet\vec{\mathbf{v}}=(\gamma-1)\kappa\nabla^{2}T+(\gamma-1)\Phi$$

State equation
$$p=\rho RT$$

$$G^{\frac{1}{2}}=\frac{\partial z}{\partial z^{*}}=1-\frac{z^{*}}{H}$$ is a metric term.

Framework (2)

- **Ocean: in-compressive and hydrostatic equations with the Boussinesq approximation**

$$\frac{\partial c}{\partial t} = -\mathbf{v} grad c + F_c \qquad \frac{\partial T}{\partial t} = -\mathbf{v} grad T + F_T$$

$$0 = \nabla \bullet \mathbf{v} = \left(\frac{1}{r\cos\varphi}\frac{\partial u}{\partial \lambda} + \frac{1}{r\cos\varphi}\frac{\partial(\cos\varphi v)}{\partial \varphi} + \frac{1}{r^2}\frac{\partial(r^2 w)}{\partial r} \right)$$

$$\frac{\partial u}{\partial t} = -\mathbf{v} grad u + 2 f_{\mathrm{r}} v - 2 f_{\varphi} w + \frac{vu\tan\varphi}{r} - \frac{wu}{r} - \frac{1}{\rho_0 r\cos\varphi}\frac{\partial P'}{\partial \lambda} + F_{\lambda}$$

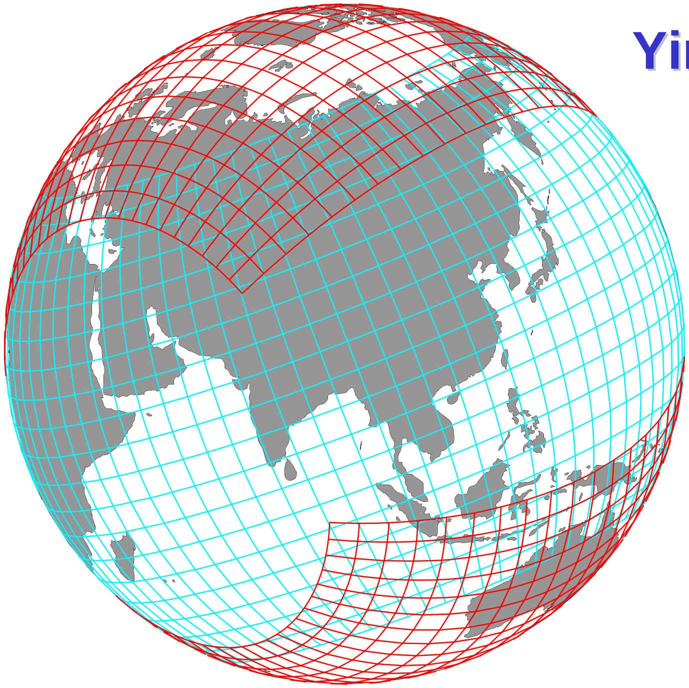
$$\frac{\partial v}{\partial t} = -\mathbf{v} grad v + 2 f_{\lambda} w - 2 f_r u - \frac{uu\tan\varphi}{r} - \frac{wv}{r} - \frac{1}{\rho_0 r}\frac{\partial P'}{\partial \varphi} = +F_{\varphi}$$

$$\frac{\partial w}{\partial t} = -\mathbf{v} grad w + 2 f_{\varphi} u - 2 f_{\lambda} v + \frac{uu}{r} + \frac{vv}{r} - \frac{1}{\rho_0}\frac{\partial P'}{\partial r} - \frac{\rho'}{\rho_0}\mathbf{g} + F_r$$

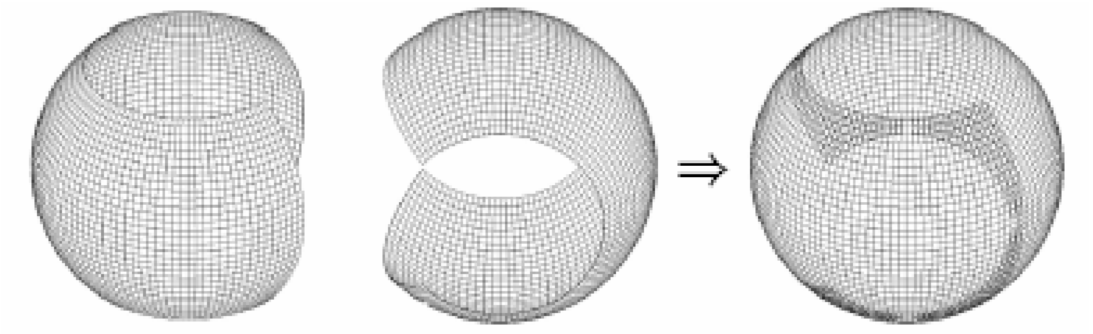
$$\frac{d}{dr} P_0 = -\rho_0 g(r)$$

$$\rho = \rho(T, c, P_0)$$ (: UNESCO scheme)

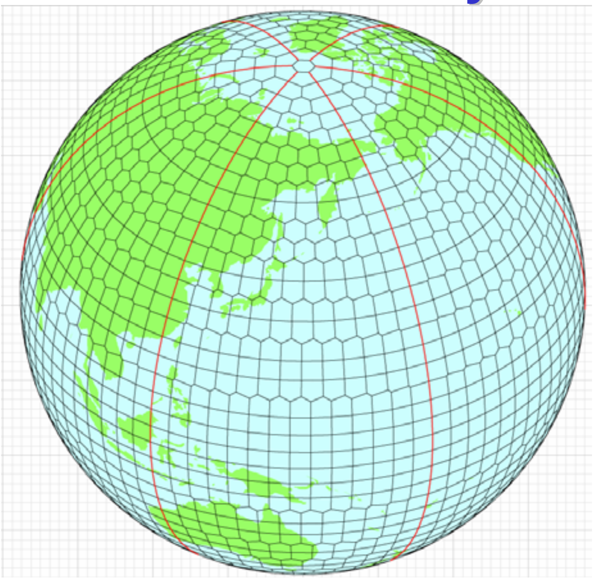
Grid System



Yin-Yang Grid System



New Reduced Grid System



- Orthogonal coordinates.
  (same as the lat-lon geometry)
- No polar singularity.
- Relax of CFL condition.
- The same grid structure of N and E component.
- Easy to nest.
- High parallelization.
- But need to take care of conservation law.

Issues on overset grid systems

1. How are wave propagation characteristics
   on Yin-Yang grid system?

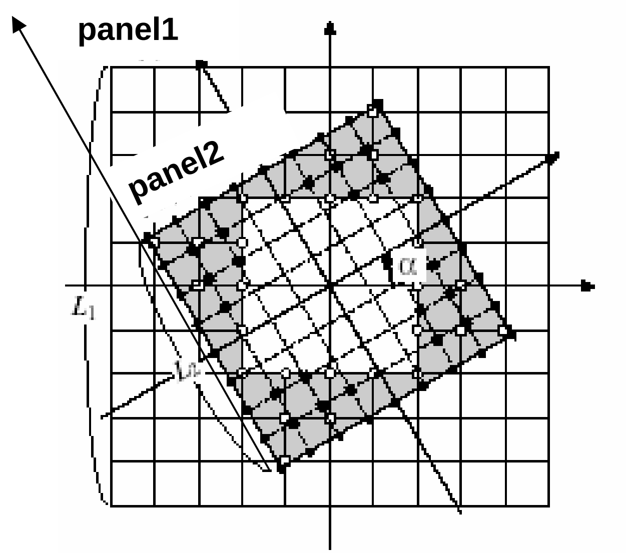
2. Is it necessary to high ordered computational schemes?

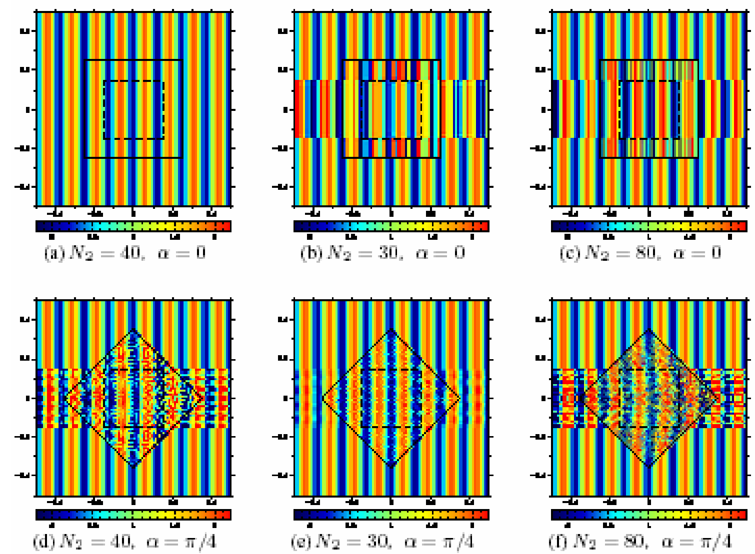
3. How long is integration possible on Yin-Yang grid system?

4. Which conservation scheme is suitable
   on Yin-Yang grid system?

Wave propagation characteristics on overset grid system

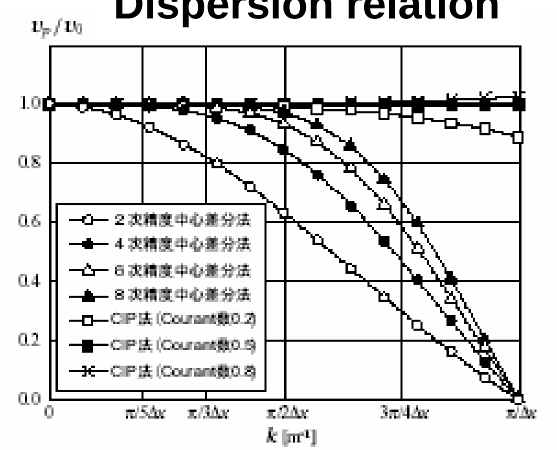
(Takeshi Sugimura)



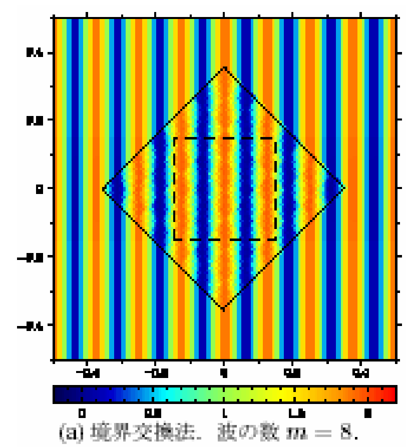


High order computational schemes and interpolation are required.

Dispersion relation



Dispersion relation is important to avoid errors on interface of overset grid system.

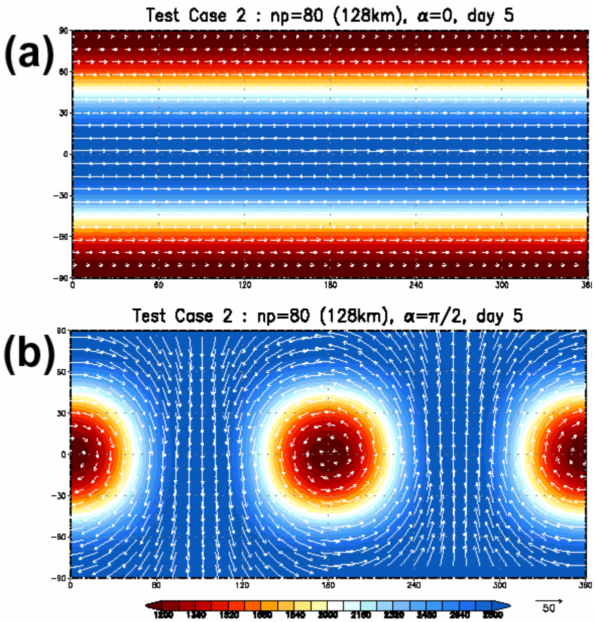


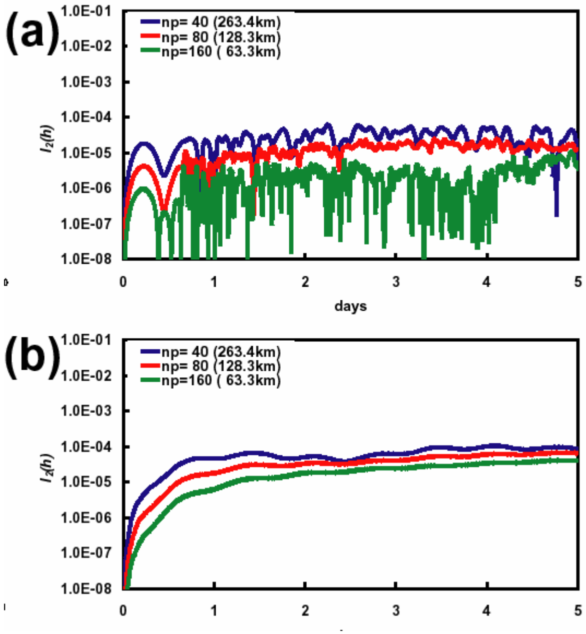
How long is integration possible ?

(Mitsuru Ohdaira, ESC)

(Kenji Komine, ESC)

Test Case 2 : Global Steady State Nonlinear Zonal Geostropic Flow



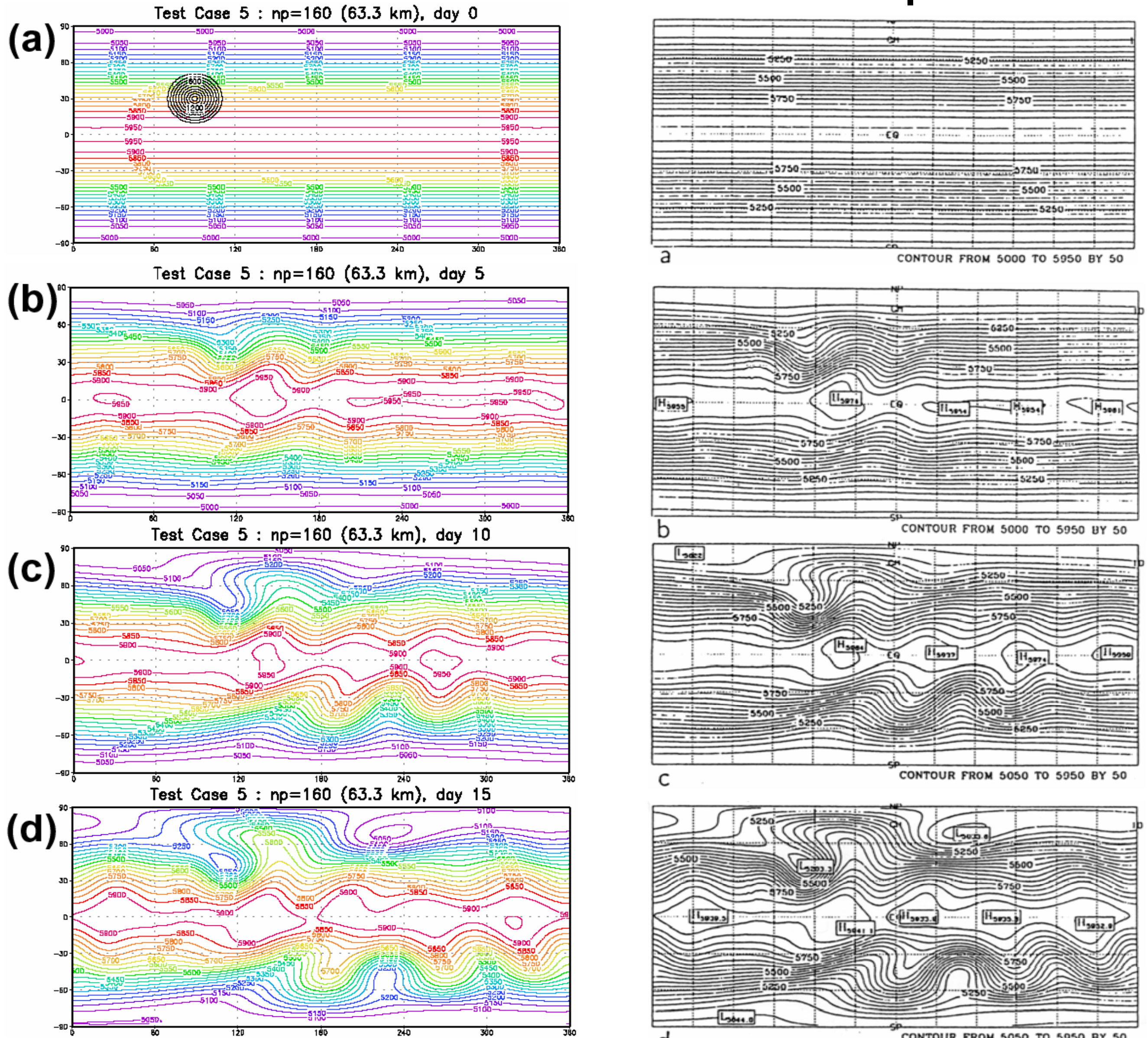


The solid body rotation field is maintained. The 2nd-orderaccuracy is maintained.

・ At least 3 years integration with the 2nd-orderaccuracy is maintained.

Test Case 5 : Zonal Flow over an Isolated Mountain

Simulation Results | **Results with spectral scheme**



R. Jakob, J. J. Hack and D. L. Williamson, Solutions to the Shallow Water Test Set Using the Spectral Transform Method., NCAR/TN-388+STR, 1993

Field at (a) day 0, (b) day 5, (c) day10, and (d) day 15.

Test Case 6 : Rossby-Haurwitz Wave

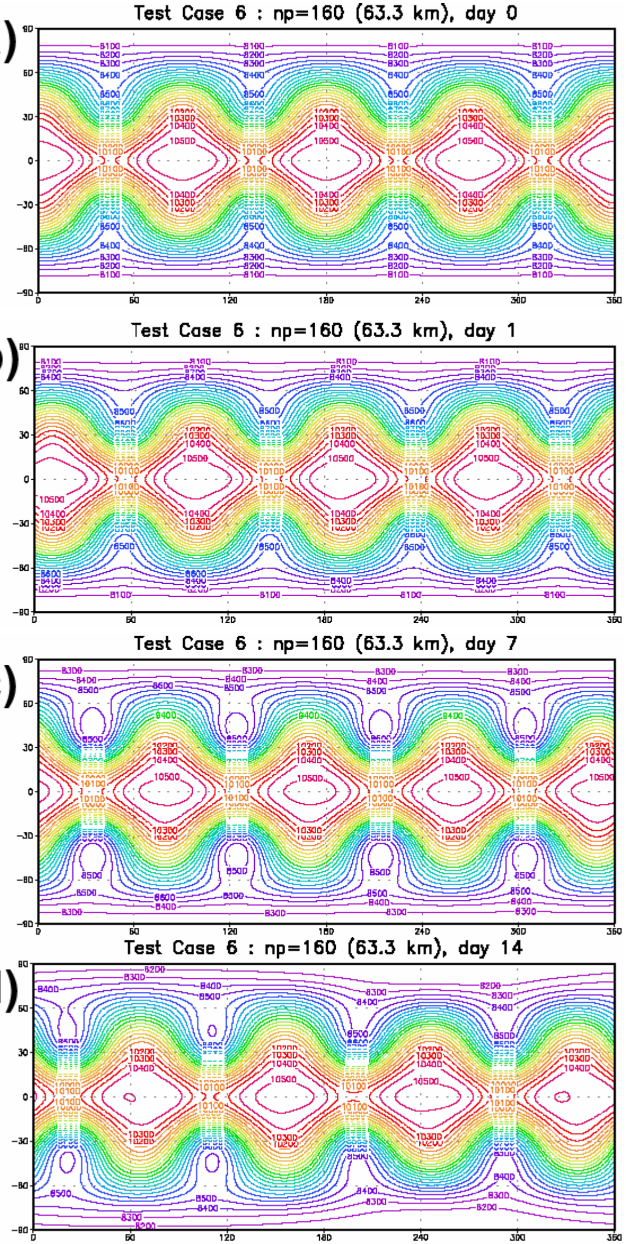
Simulation Results

(a)

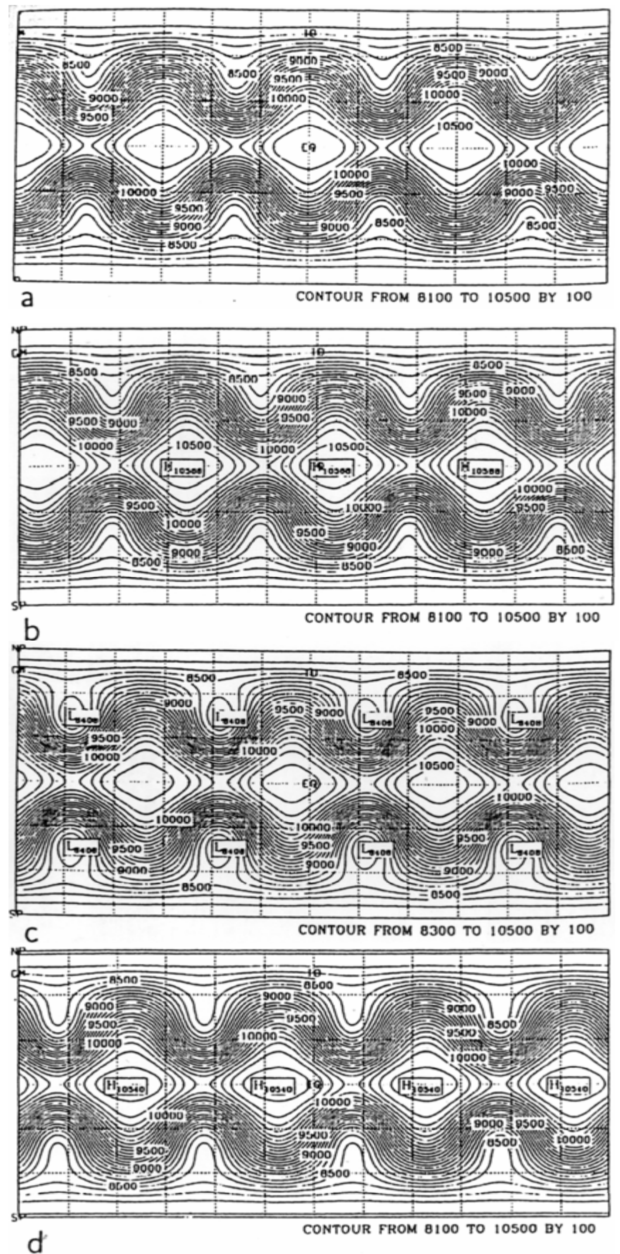
(b)

(c)

(d)

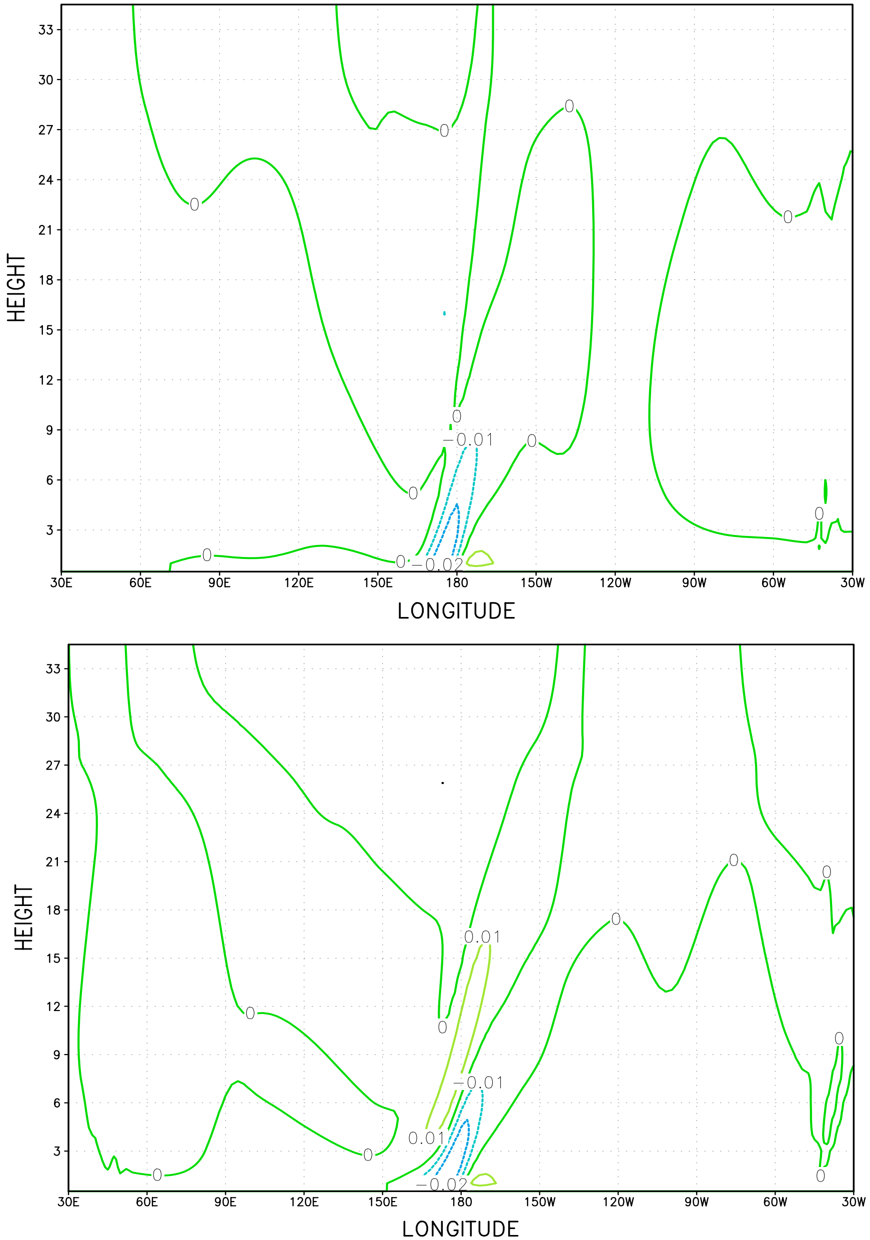


Results with spectral scheme

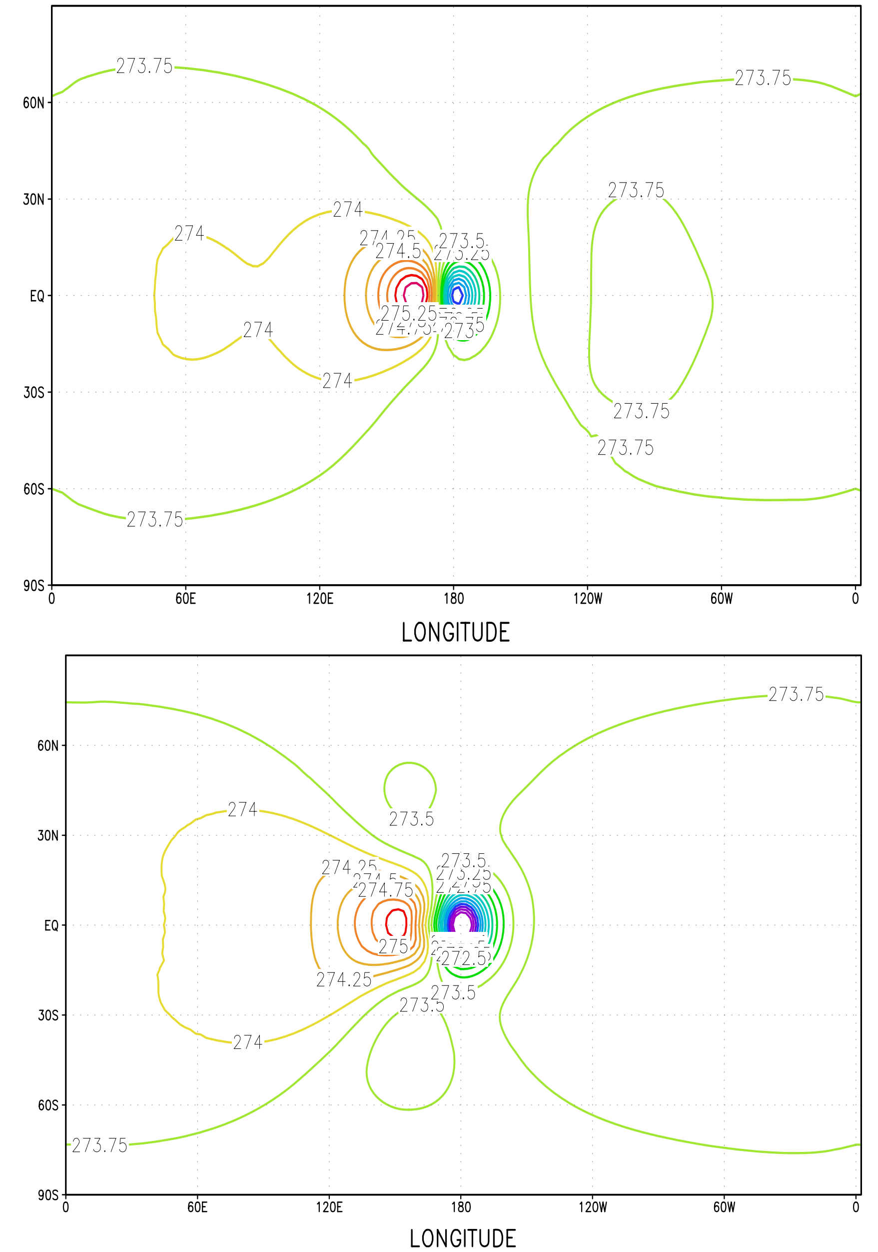


Rossby-Haurwitz wave shape has been propagated from the west to the east without change from initial field after 14 days integration.

R. Jakob, J. J. Hack and D. L. Williamson, Solutions to the Shallow Water Test Set Using the Spectral Transform Method., NCAR/TN-388+STR, 1993



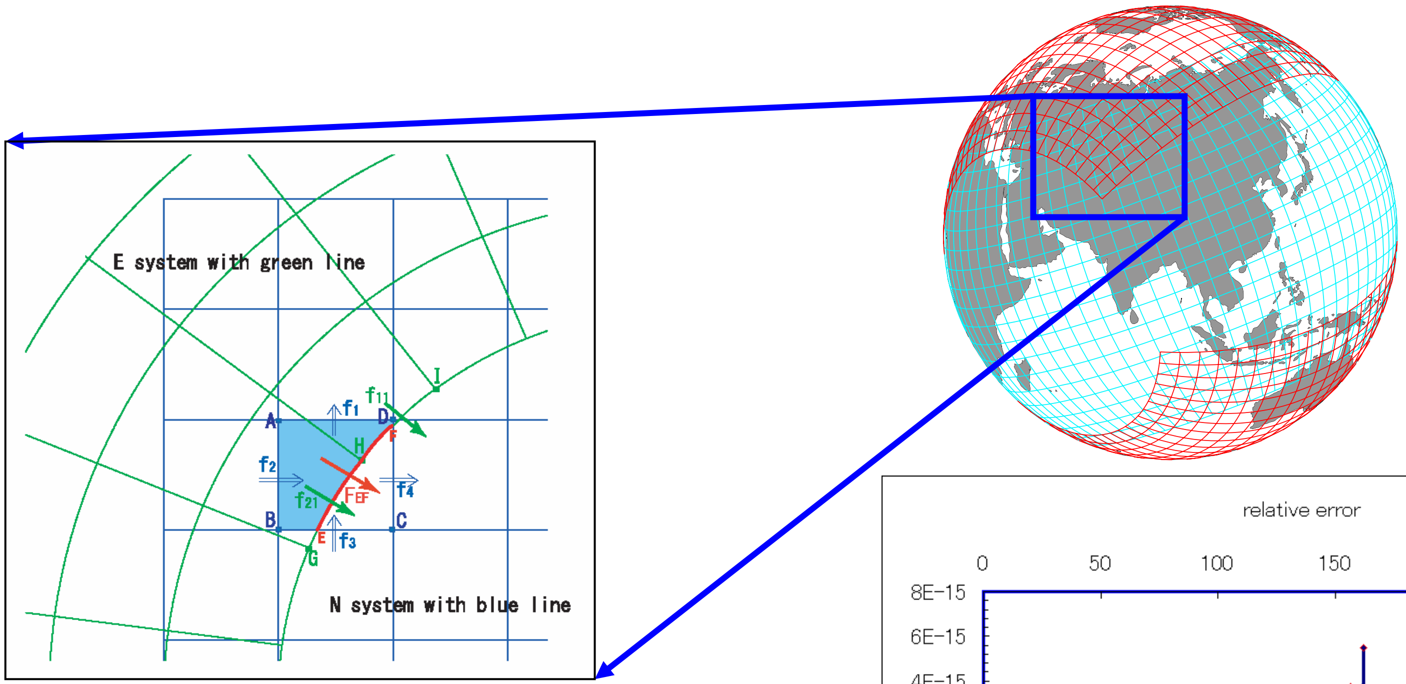
The λ-*z* cross section of vertical wind speed *w* (m s-1) along the equator after 12, 24hours.



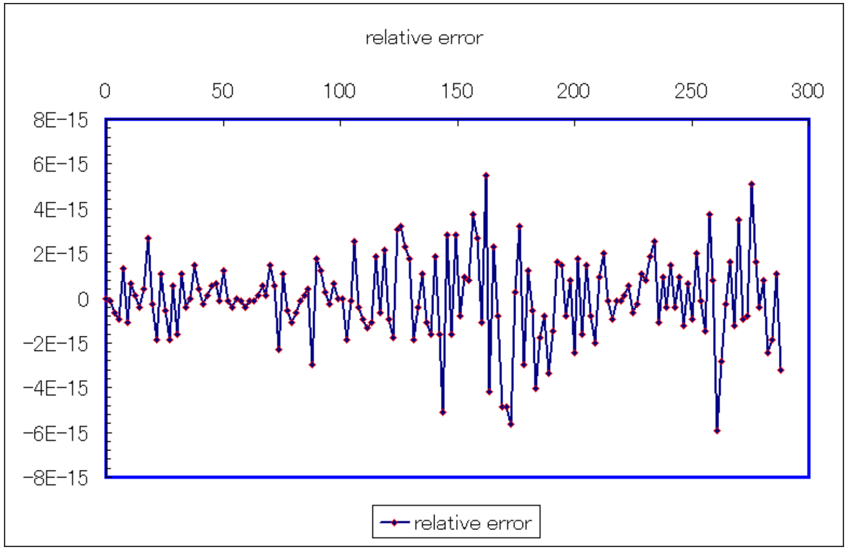
Temperature (K) at 0km (bottom) levels after 12, 24hours.

Mass conserving numerical scheme

(Xindong Peng)



For flux F_{EF} on a circular arc EFshown as red circle is computed by the budget of fluxes f_N by on grid ABCD of N system and flux f_E estimated on a circular arc GHI of E system.



This conservative scheme, we have evaluated that time evolution of relative error of the mass has changed within the limit of rounding error.

Computation all of fluxes on computational grids

↓

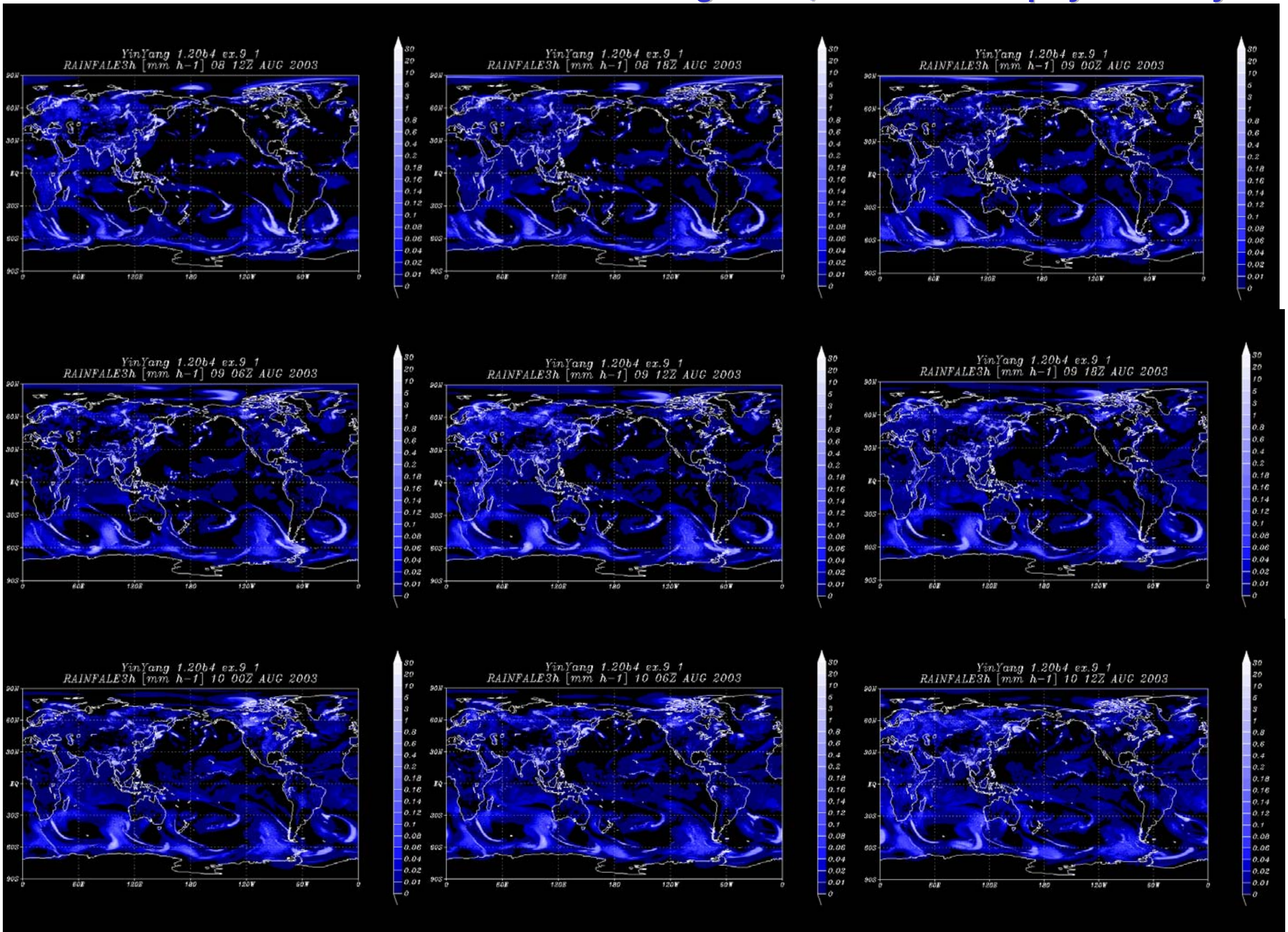
Correction for conserving

Implementation
Non-hydrostatic AGCM and OGCM

		Non-hydrostatic AGCM	Non-hydrostatic OGCM
Equations System		Fully compressive N-S equations	non-hydrostatic· incompressive N-S equations
Grid System		Yin-Yang grid system	Yin-Yang grid system
Discrimination	Space	Arakawa-C grid(horizontal), z*(vertical)	Arakawa-C grid(horizontal), z(vertical)
	Time	4th order Runge-Kutta	4th order Runge-Kutta
Advection terms		5th order flux form, CIP-CSLR	5th order flux form
not Advection terms		4th order flux form	4th order flux form
Sound wave		HEVI, HIVI	Implicit methods(2-dimensional, 3-dimensional)
Gravity wave		–	
Microphysics		Qc, Qci, Qr, Qs, Qg	–
Cumulus Param.		Kain-Fritsch scheme	–
Turburance		Smagorinsky scheme (static), dynamic Smagorinsky[LES]	Smagorinsky scheme (static), dynamic Smagorinsky[LES]
		Nesting systems(1way,2way)	Nnesting systems(1way,2way)
			Tide, Multi-grid Methods(Poison eq)
Parallelization		2-dim. decomposiotion, inter nodes:MPI, intra nodes:micro-task	2-dim. decomposiotion, inter nodes:MPI, intra nodes:micro-task

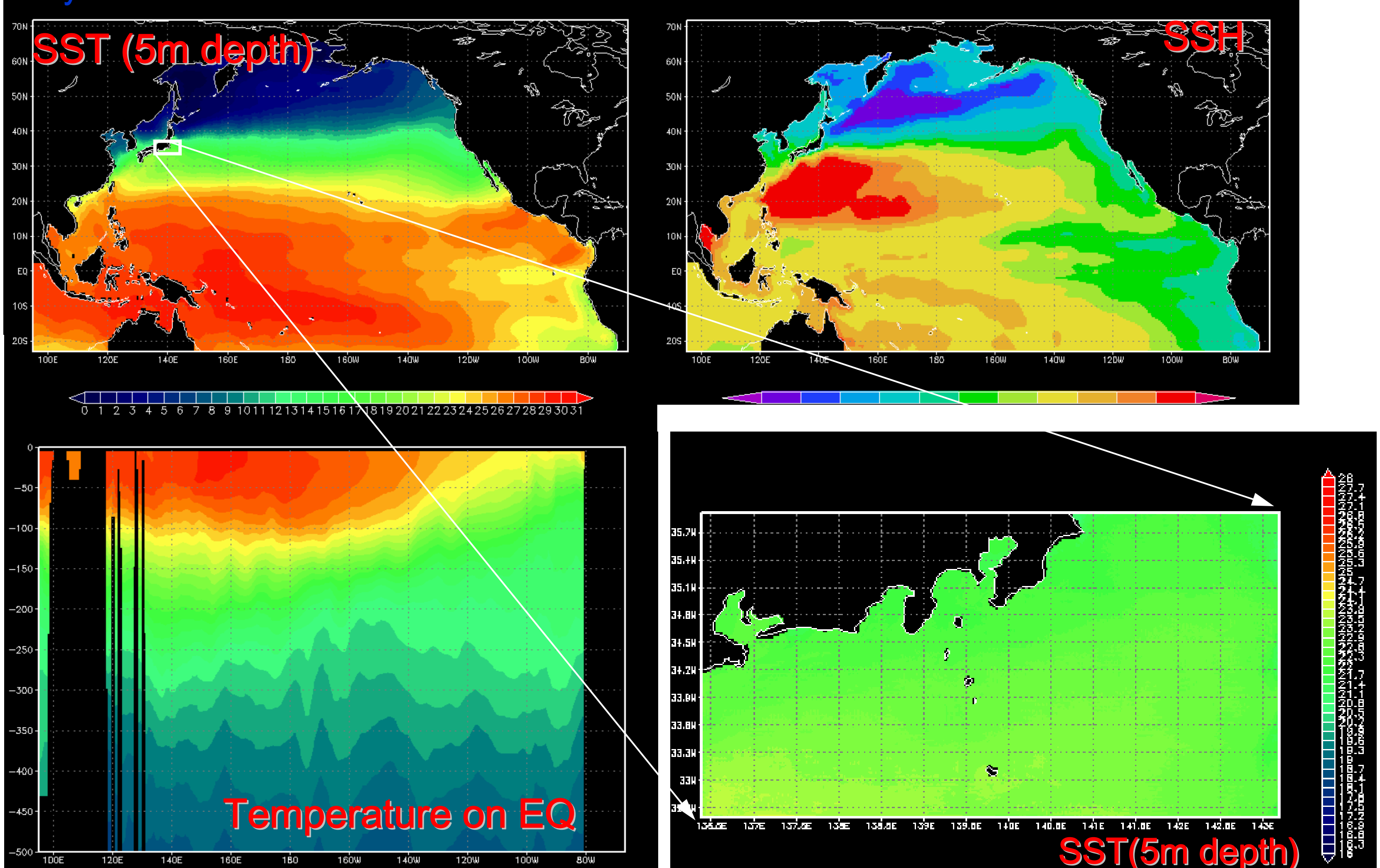
- **Kain-Fritsch cumulus parameterization ← more than 10km horizontal resolution**
- **Reisner et al. (1998) cloud microphysics ← less than 10km horizontal resolution**
- **Smagorinsky (1965) turbulence closure scheme ← for both atmosphere and Ocean components**
- **Monin-Obukhov similarity theory (Zhang and Anthes, 1982)**
- **Simple short and long-wave radiation scheme**
- **0-D bucket model for land surface process**
- **Multi-grid methods for Poison equation (Ocean)**

Atmospheric Global Circulation (5.5km horizontal and 32 vertical)
48hours integration, micro cloud physics only



North Pacific Ocean and Japan Region

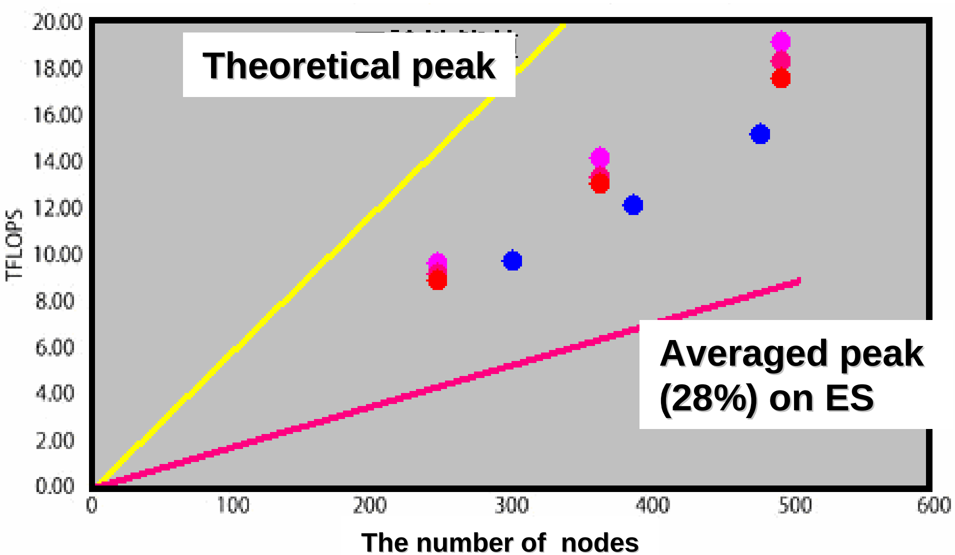
- North Pacific Ocean：50km(horizontal)，40layers (vertical)。
  January monthly data as initial data，surface boundary condition：NCEP re-analysis data, 25 years integration without motion as initial condition.
- Japan Region：2.5km (horizontal)，40layers (vertical)。
  Initial data: 1st Jan of the above results from North Pacific Ocean.
  boundary condition：above results from North Pacific Ocean、surface boundary：NCEP re-analysis data.



Computational performance on the Earth Simulator

CASE	TPN	TAP	grid pts	Mflops/AP	Vector Length	V.OP ratio	Tflops	Peak ratio	Parallel efficiency	Speed up
C	512	4096	3,866,296,320	4166.7	229	99.3%	17.07	52.1%	90.0%	461.0
	384	3072		4273.8	229	99.3%	13.13	53.4%	92.3%	354.6
	256	2048		4401.9	229	99.3%	9.02	55.0%	94.8%	242.6
A	512	4096	2,882,764,800	4575.2	228	99.5%	18.74	57.2%	93.6%	479.1
	384	3072		4606.1	228	99.5%	14.15	57.6%	95.1%	365.2
	256	2048		4692.4	228	99.5%	9.61	58.7%	96.7%	247.5
RA	512	4096	2,882,764,800	4340.8	229	99.4%	17.78	54.3%	90.7%	464.4
	384	3072		4401.0	229	99.4%	13.52	55.0%	92.9%	356.6
	256	2048		4560.5	229	99.4%	9.34	57.0%	95.1%	243.5
O	498	3984	4,954,521,600	3629.3	240	99.3%	14.46	45.4%	80.6%	401.3
	398	3184		3568.5	240	99.3%	11.36	44.6%	83.8%	333.7
	303	2424		3986.8	240	99.3%	9.66	49.8%	87.2%	264.2
	207	1656		4234.3	240	99.3%	7.01	52.9%	90.9%	188.2

C: Coupled AOGCM, A: AGCM, RA: regional Atmos. O: OGCM

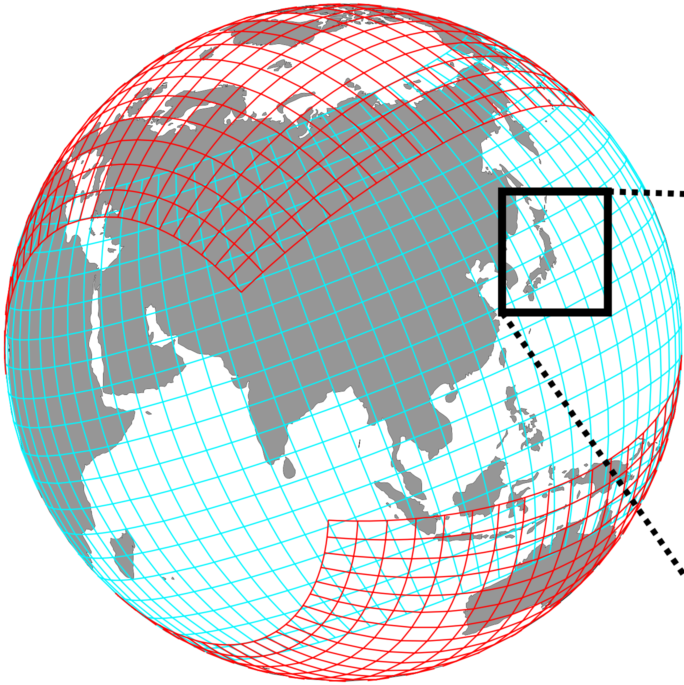


Global atmosphere: 5.5km for horizontal
32 vertical layers
⇒ 3.0 hrs on 512 nodes
for 72 hrs integration

Regional Coupled A-O model:
Global atmosphere:11km for horizontal
32 vertical layers
+Coupled: 2.78 km Japanese region
⇒ 1.5 hrs on 512 nodes
for 120 hrs integration

Experiments of Atmosphere Component

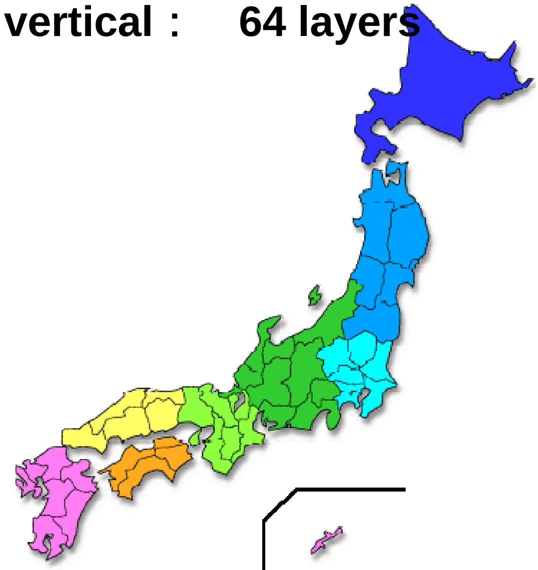
（with only cloud micro-physics）



horizontal：11km
vertical： 32 layers

1 way
2 way
nesting

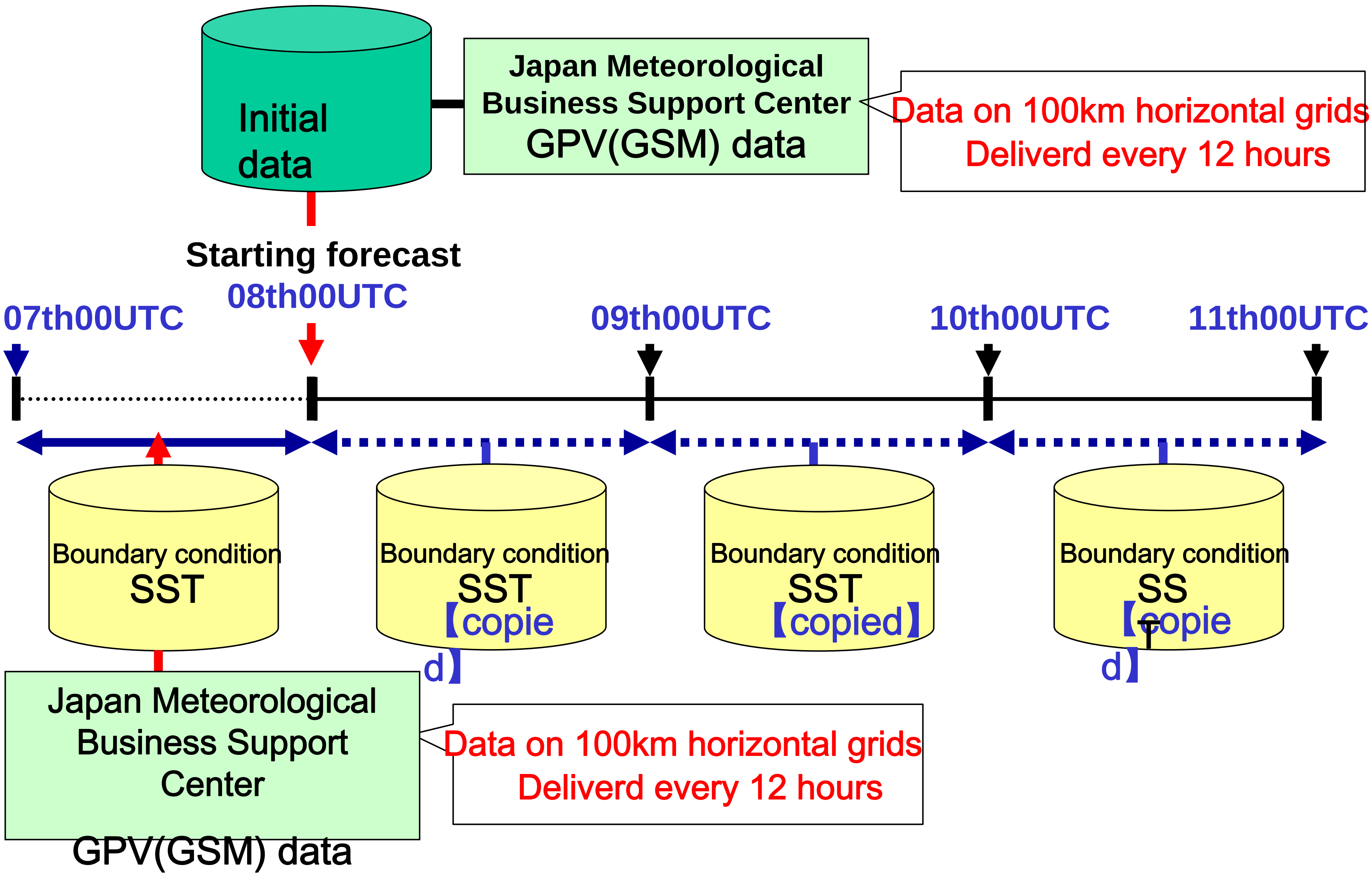
horizontal：1.13km
vertical： 64 layers



Global Simulations → Online 1way, 2way nesting → Japanese region Simulations

AGCM simulations：initial and boundary data

2003/8/8/00UTC～11/8/00UTC: 72 hours forecasting

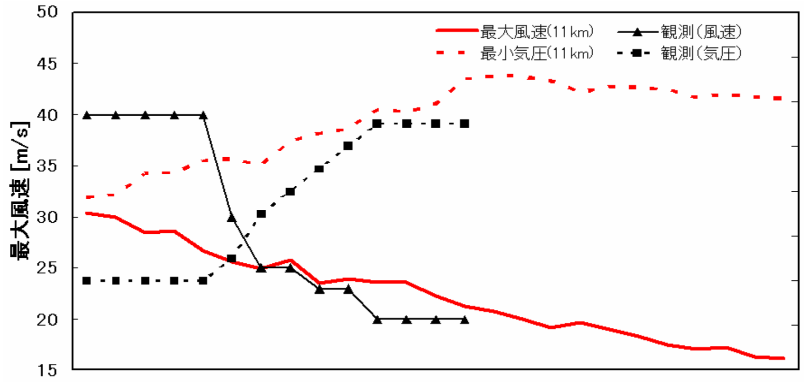


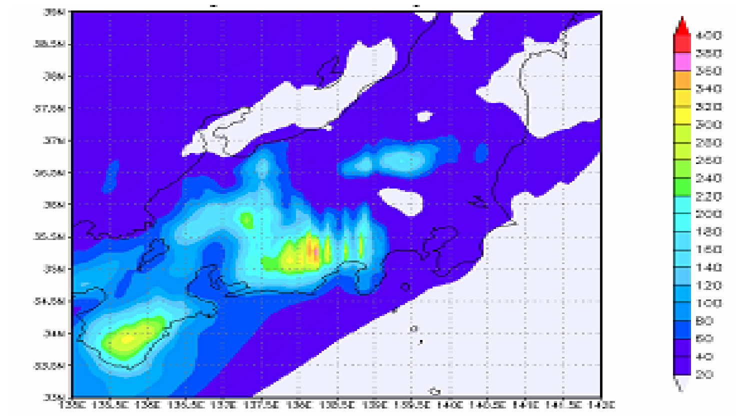
Typhoon ETAU(2003) Intensity

Atmosphere component, 1way nesting

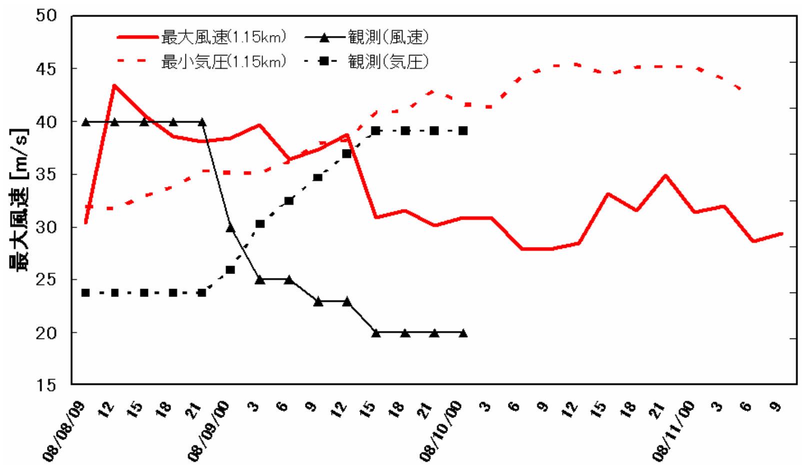
00UTC 08 Aug – 00UTC 11 Aug, 2003

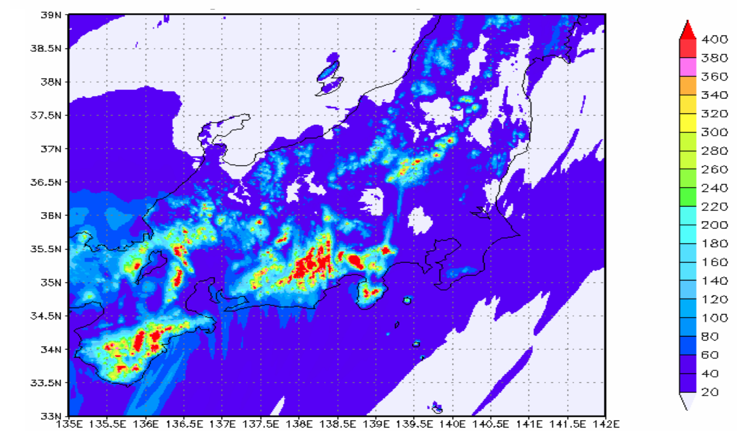
Global 11km

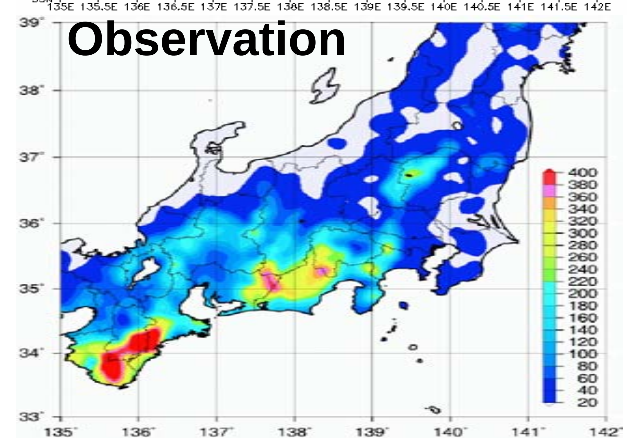




Nested Japanese Region 1.13km







Black: observation

dot line: min. surface pressure (hPa)

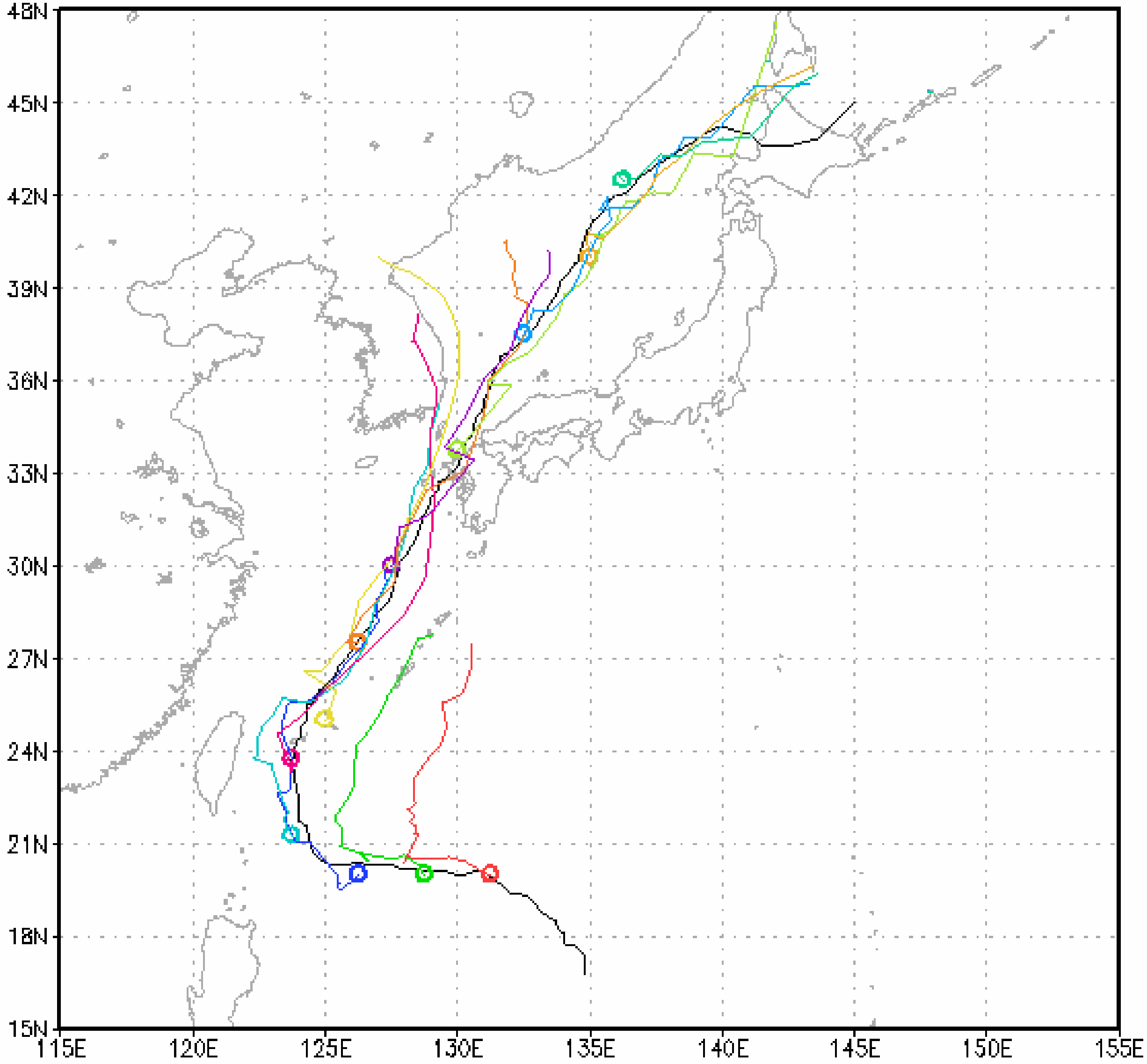
solid line: max. wind speed (m/s)

Red: simulation results

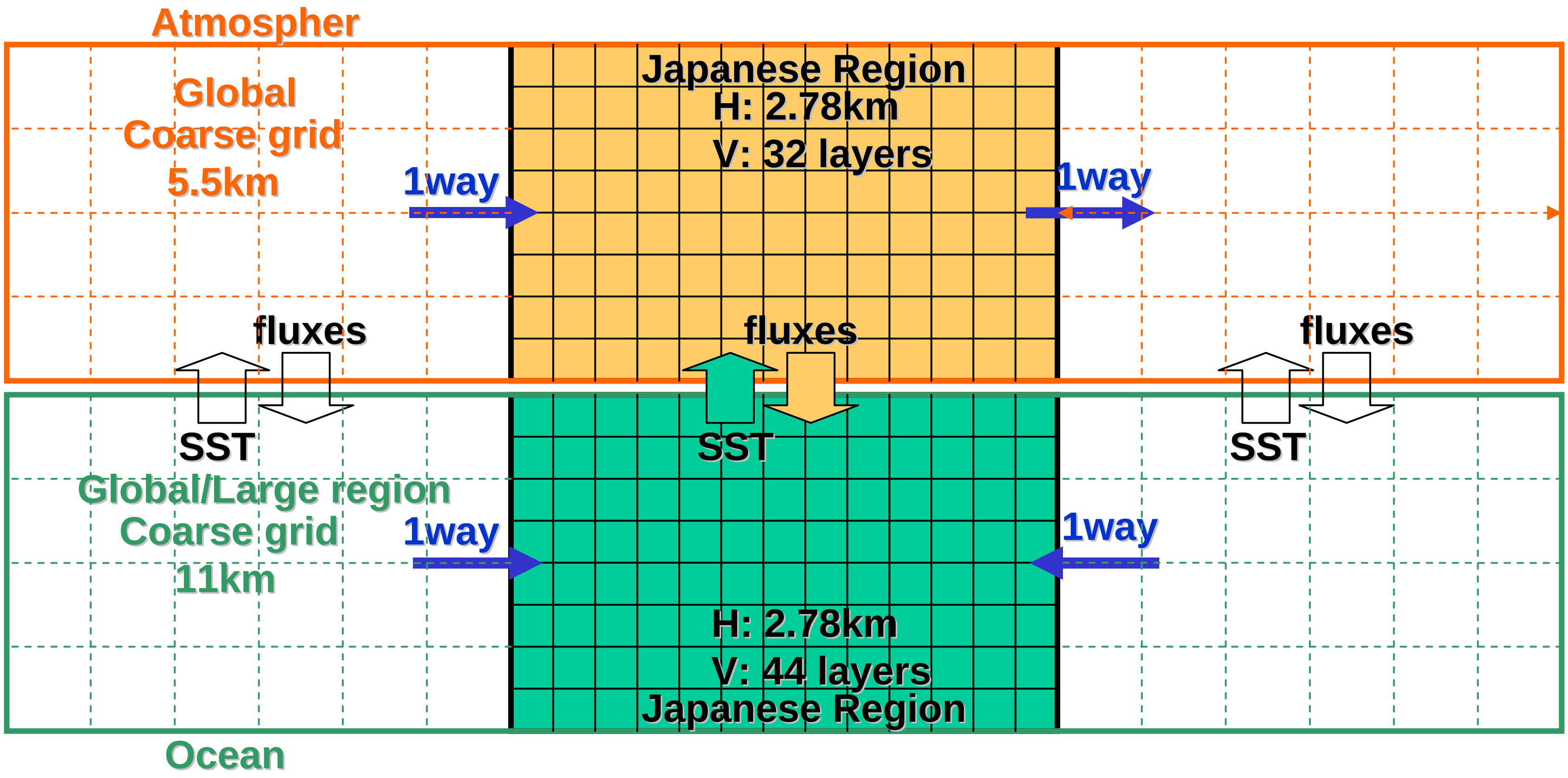
dot line: min. SLP (hPa)

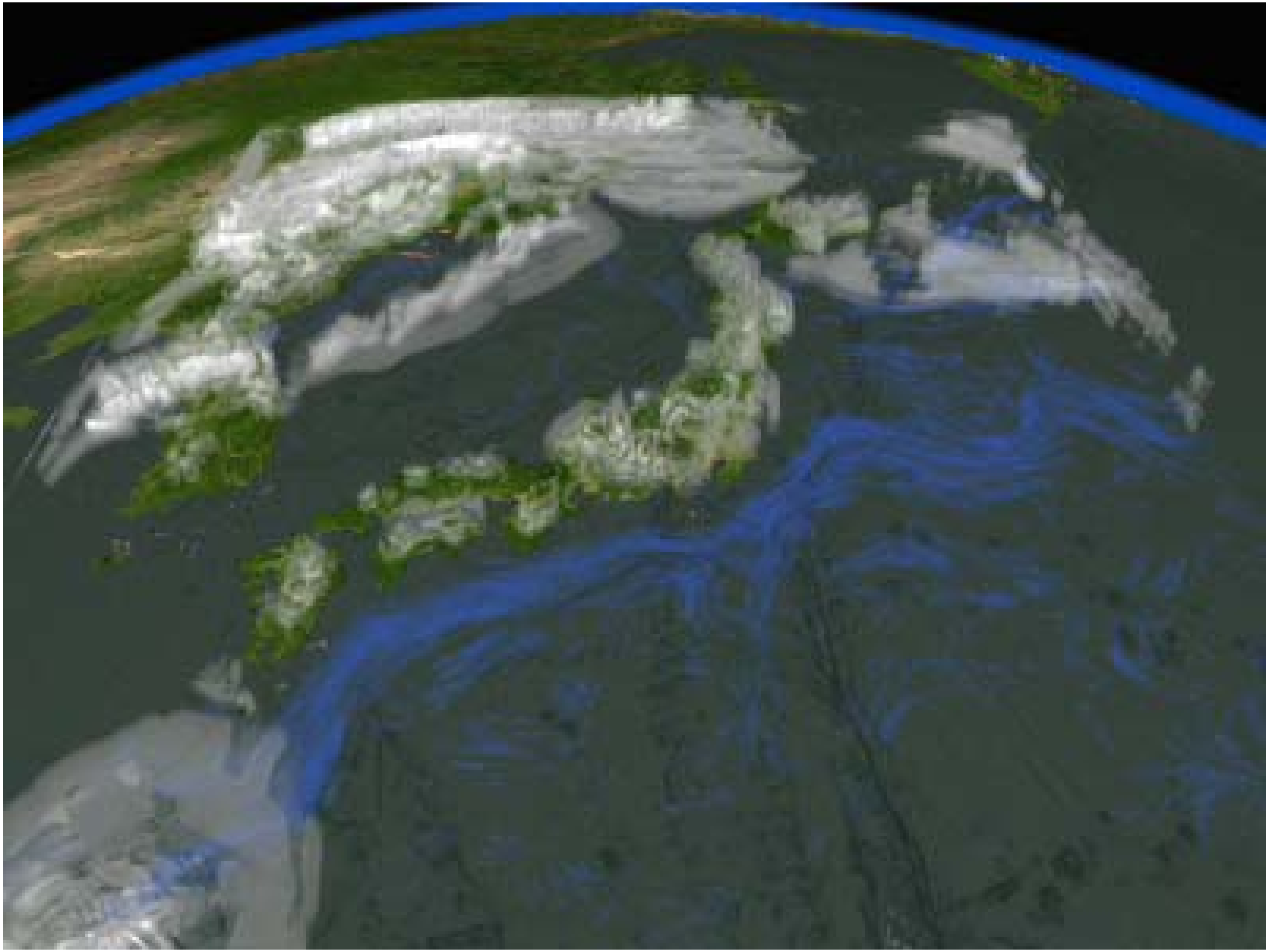
solid line: max. wind speed (m/s)

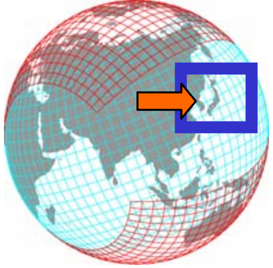
Real time forecasting ShanShan, 12th Aug.-19th Aug. in 2006



Regional Coupled Model



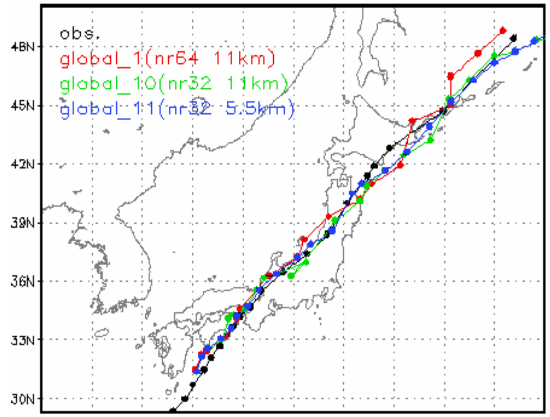


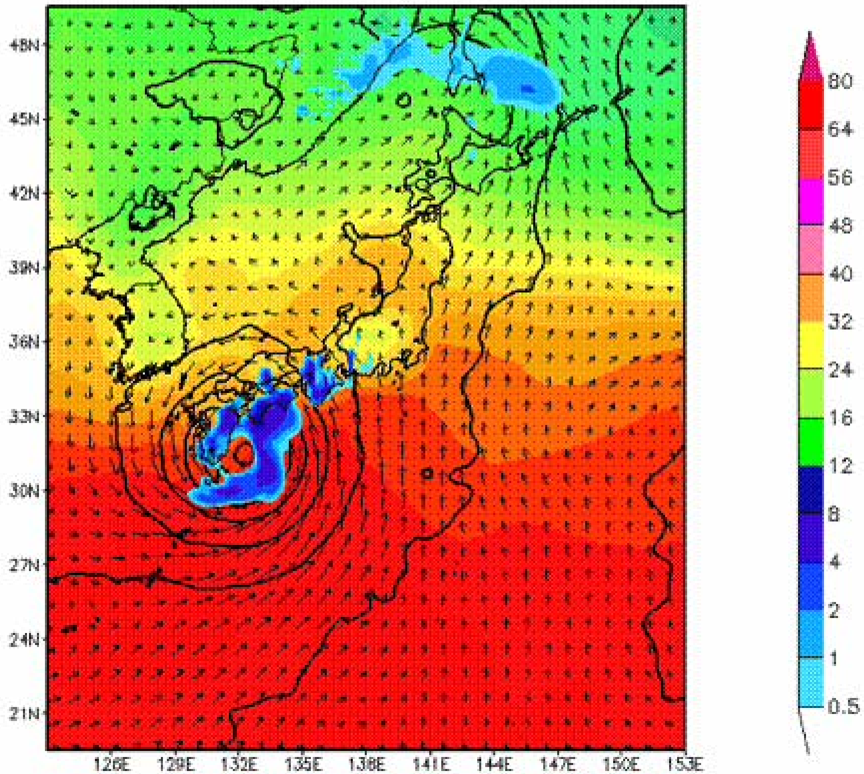


Typhoon ETAU

Atmosphere Model

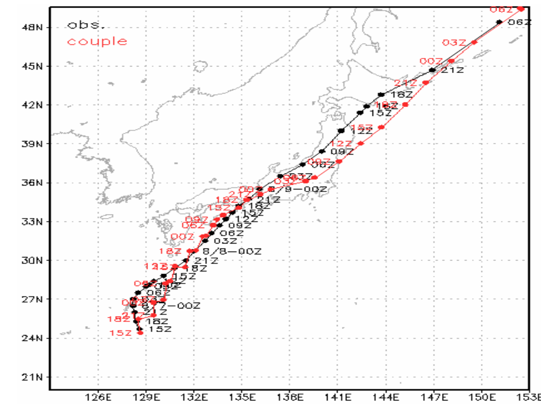
72hours forecast

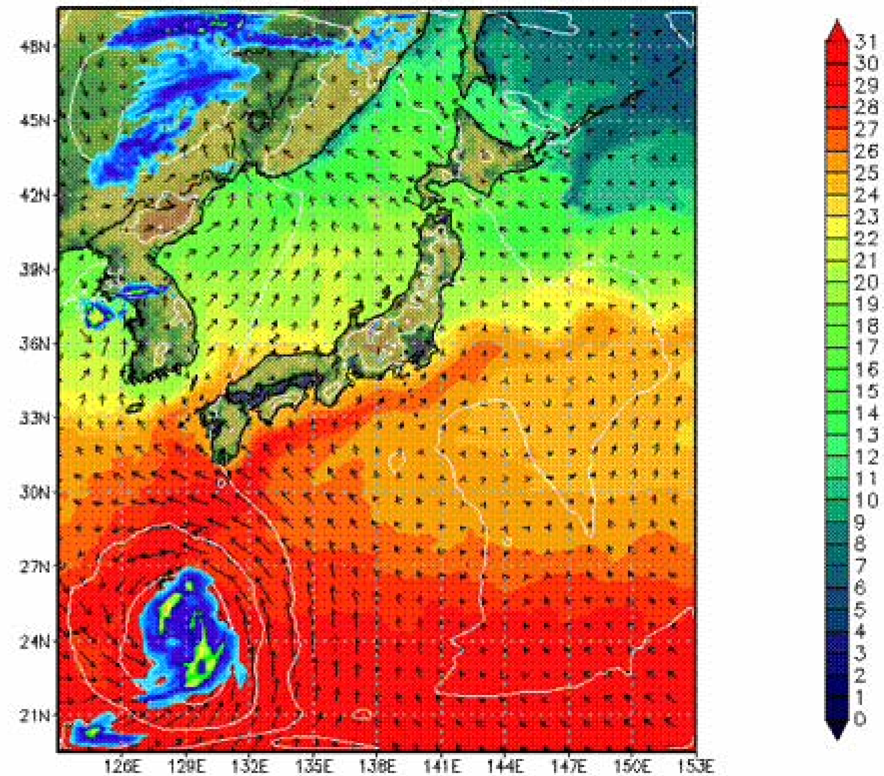




Coupled Atmosphere-Ocean Model

120 hours forecast

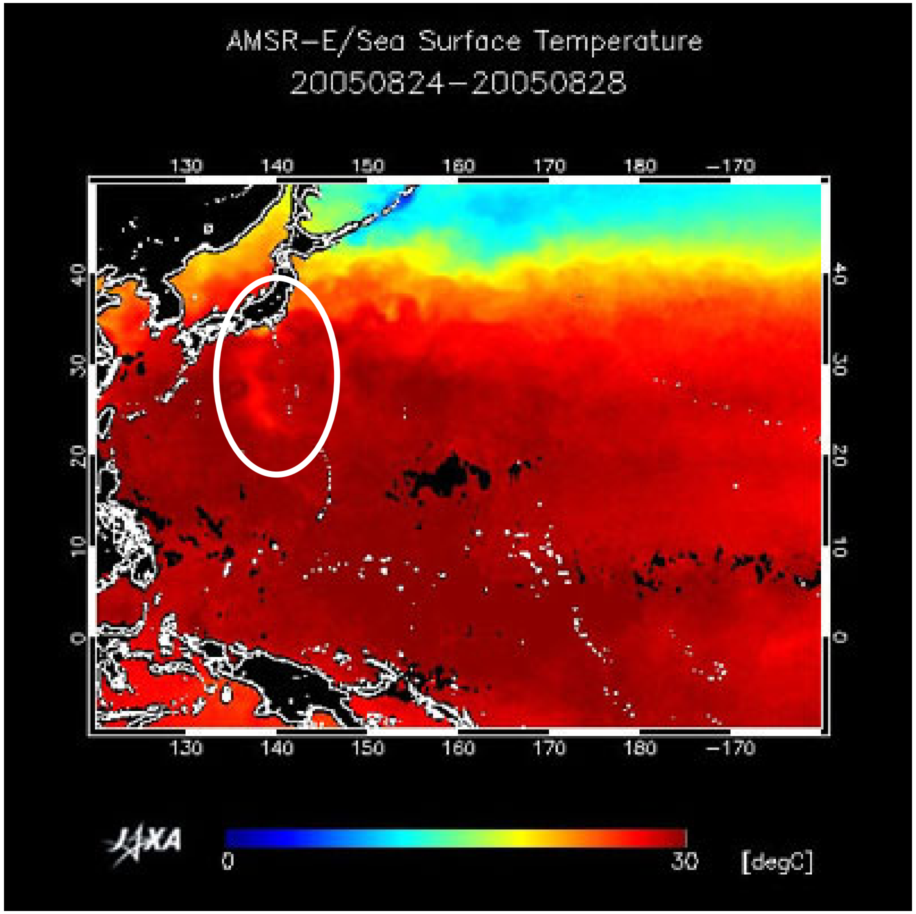




Footmark of Typhoon 11

JAXA，http://www.eorc.nasda.go.jp/imgdata/topics/2005/tp050922.html

Obseravation data by AMSR-E in Aqua (NASA)
SST distribution averaged during 5 days
from 24th August to 28th August in 2005



Tracking of typhoon 11
From database in JAXA/EORC

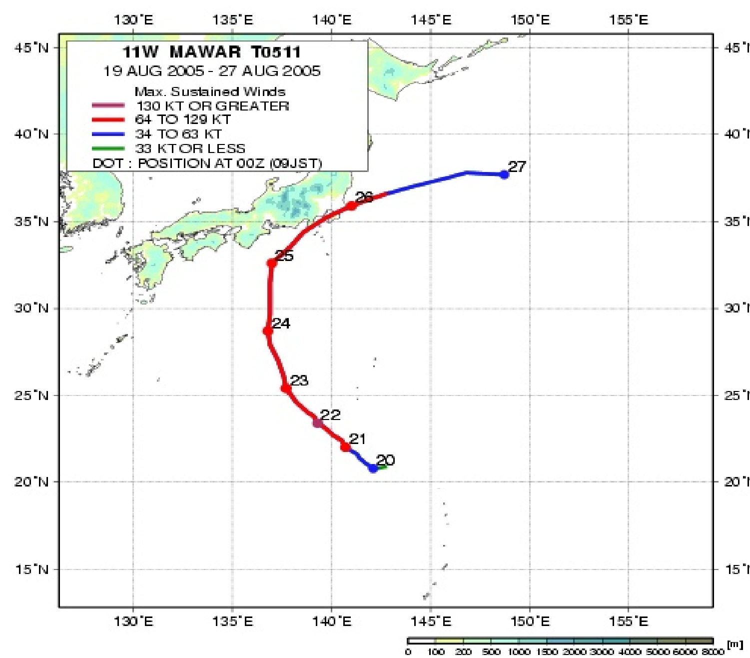
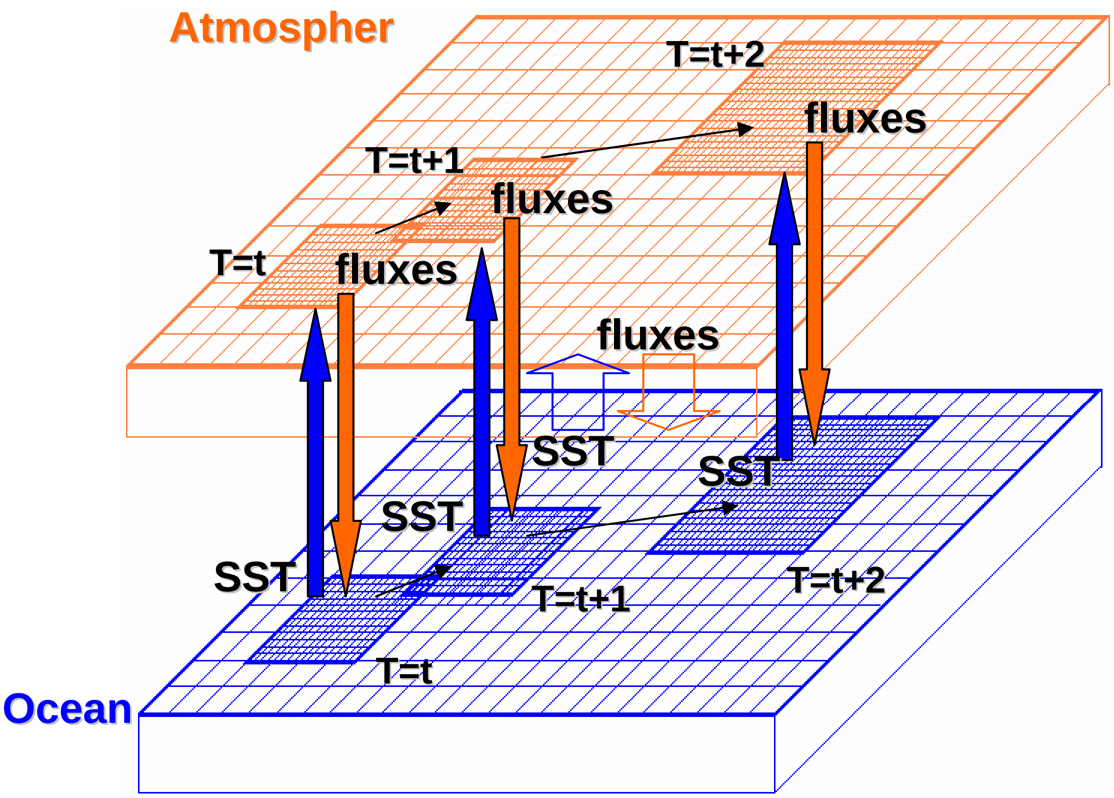


Photo by Prof. Hasegawa in 1955

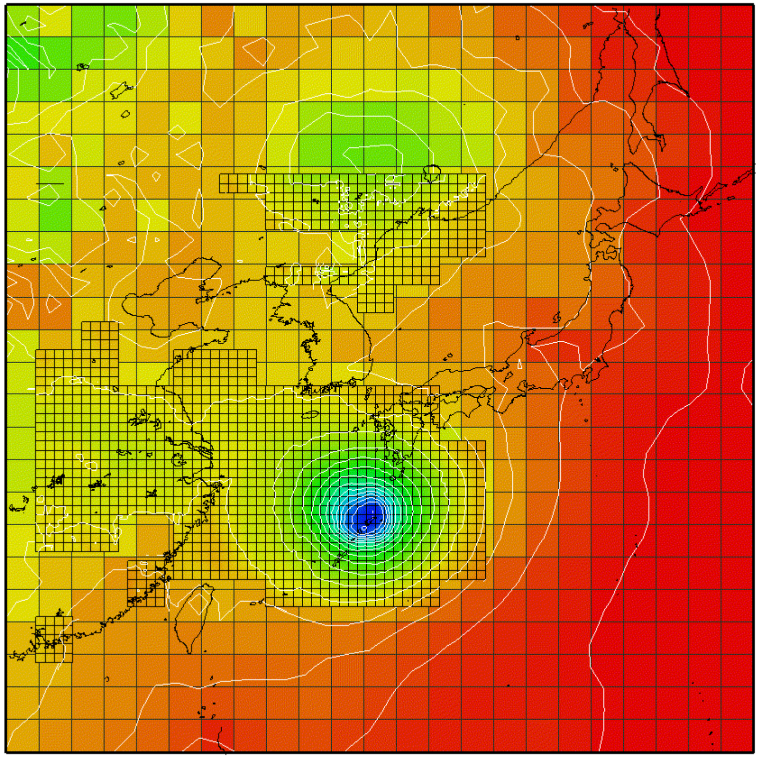
Improvements in Model Development

Adaptive Mesh Refinement (AMR) for both Atmosphere and Ocean components



Characteristics:

- High Performance Computing
  - No Overhead Computation for Moving Grid
  - Ultra High Parallelization
- Multiple fine meshed regions are available
- Only Horizontal Refinement
- Refinement Criterion:
    - low surface layer pressure
    - vorticity
    - gradient of physical parameters



Near Future Work

- **Much more validation experiments for short term severe events.**

- **Further accurate descritization schemes**
  - **Cost tuning with CIP-CSLR.**

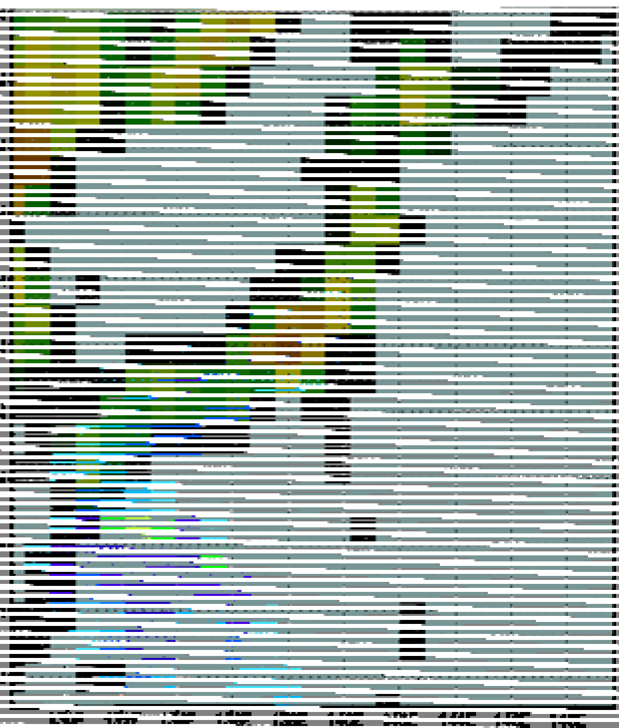
- **Progress of cloud micro-physics, radiation, interfaces**
  - **Effect of turbulence**

- **Further longer integration validation experiments**
  - **Seasonal forecasting with ensemble methods**

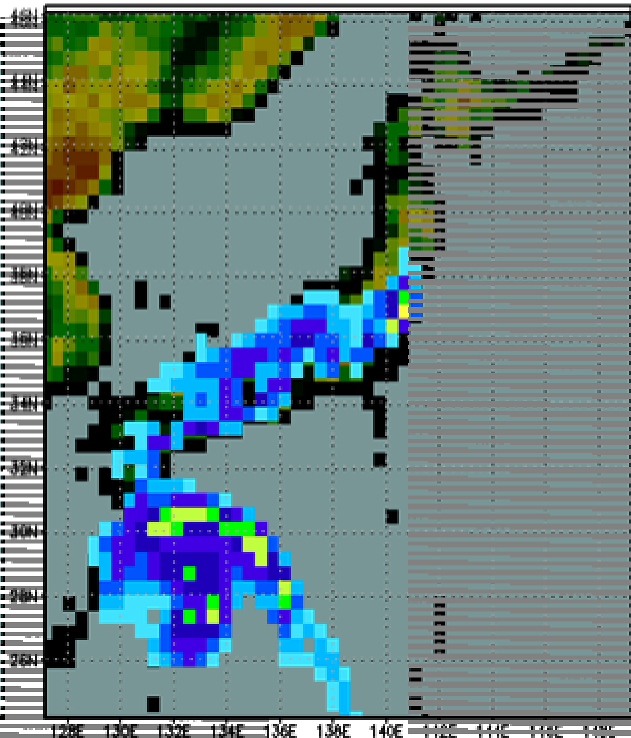
- **How to exchange information among different scale/physics phenomena ?**

Thank you.

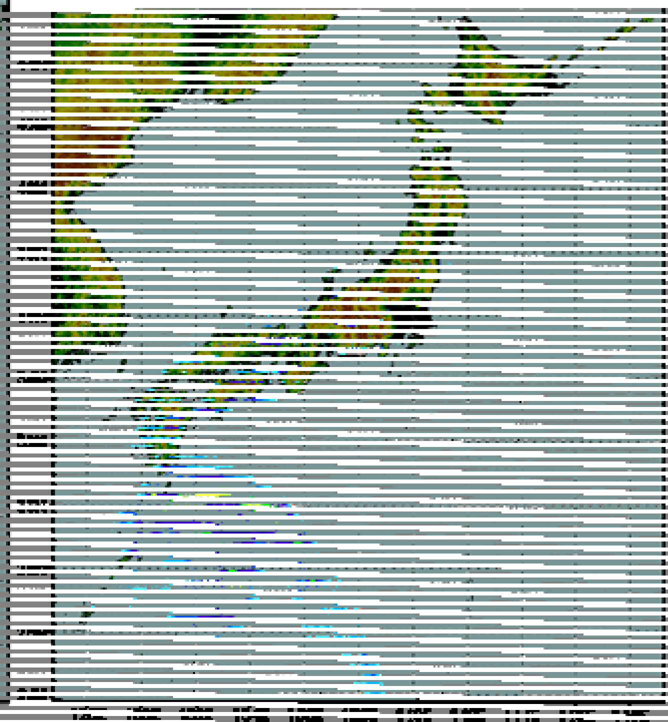
High resolution and Precipitation distribution



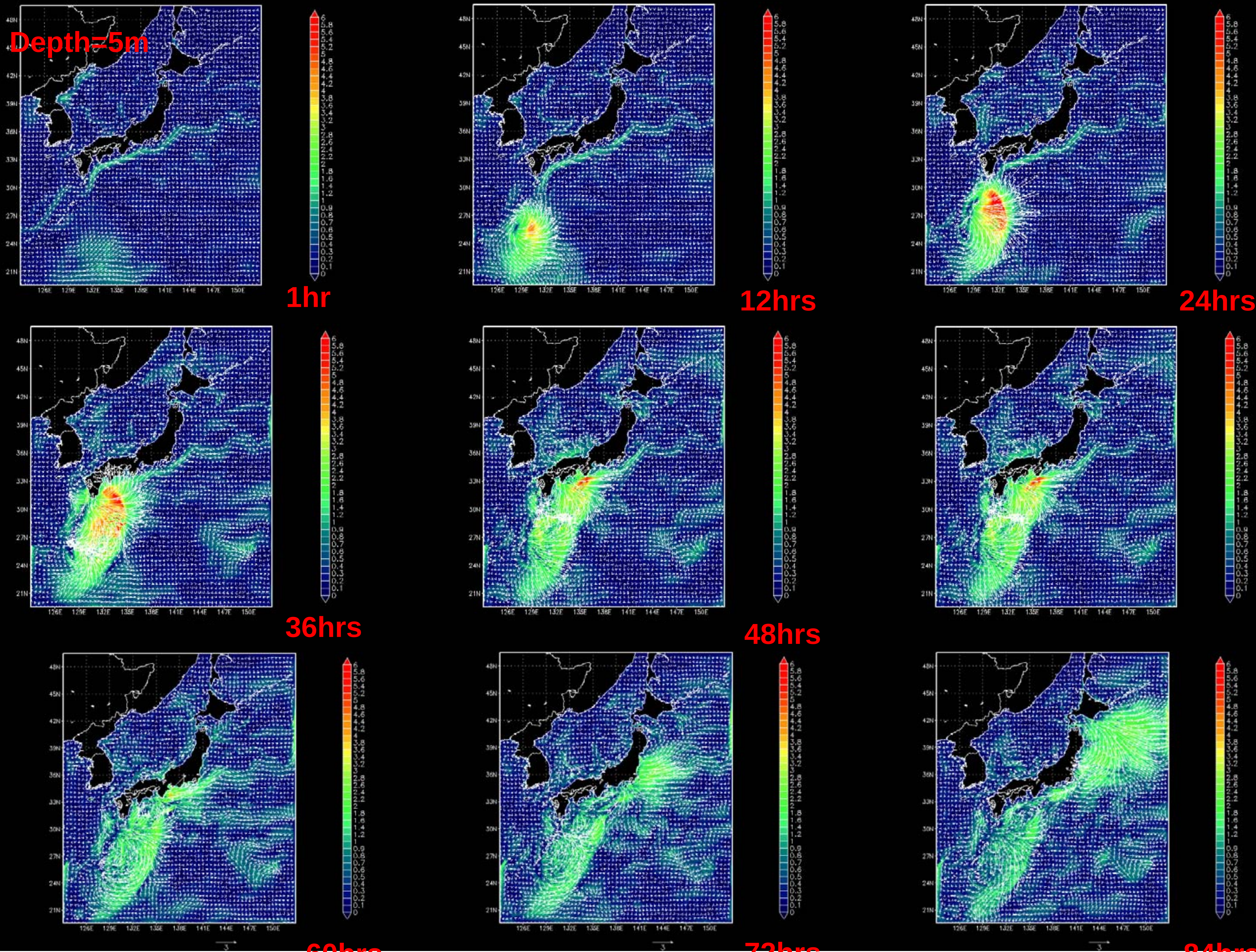
100km resolution

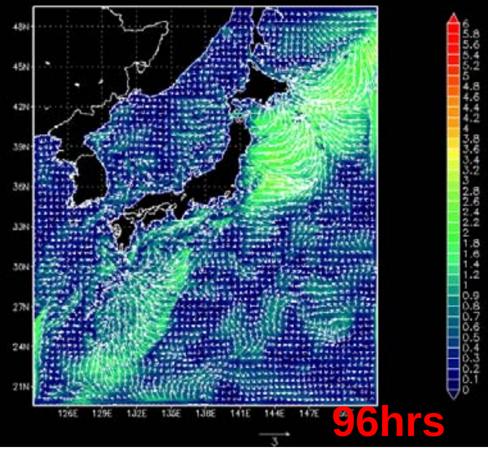


50km resolution

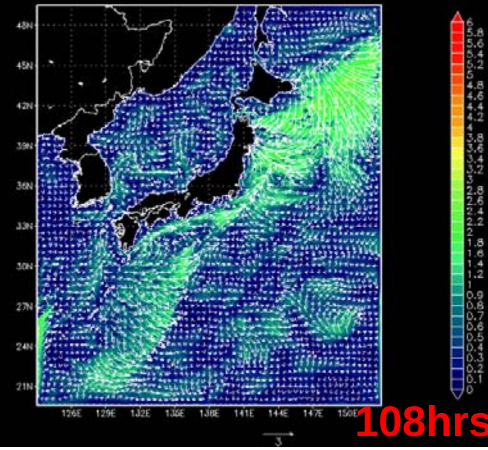


5km resolution

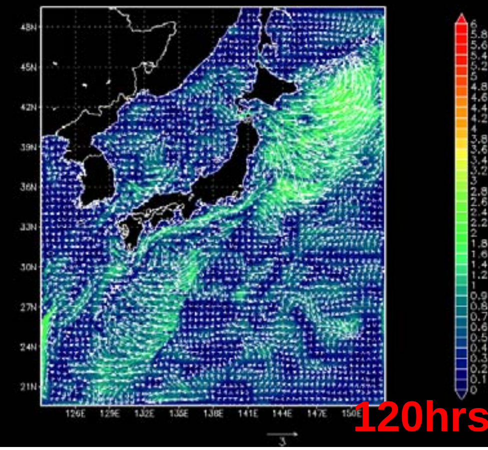

Depth=5m
1hr
12hrs
24hrs
36hrs
48hrs



96hrs



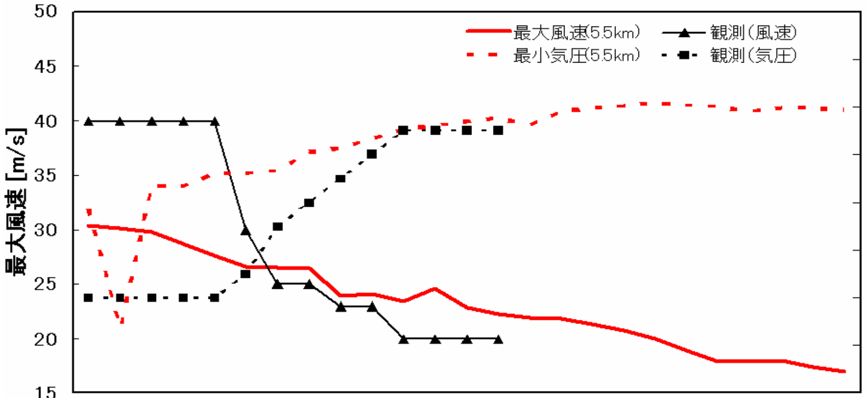
108hrs

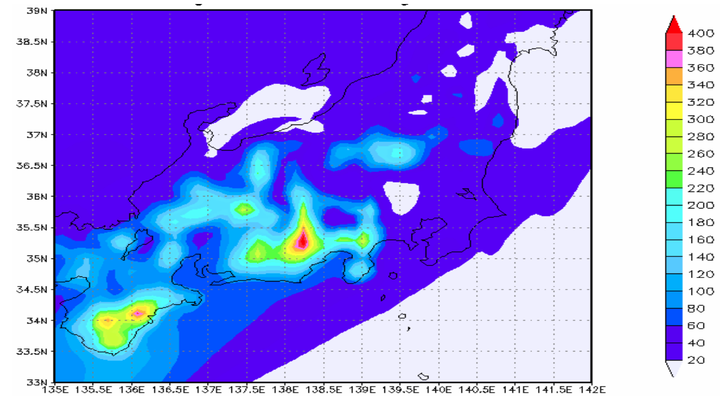


120hrs

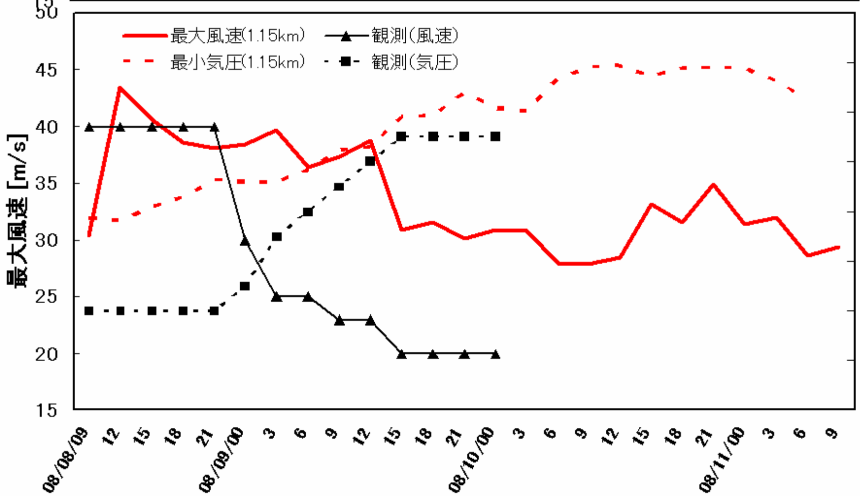
台風強度予測シミュレーション　- 解像度による違い -

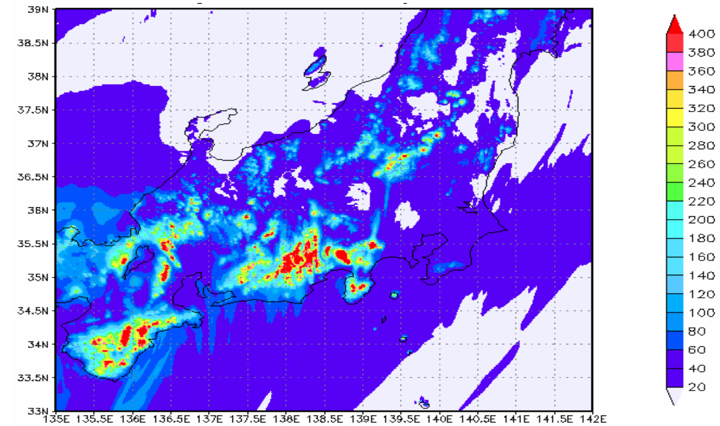
全球大気
5.5km



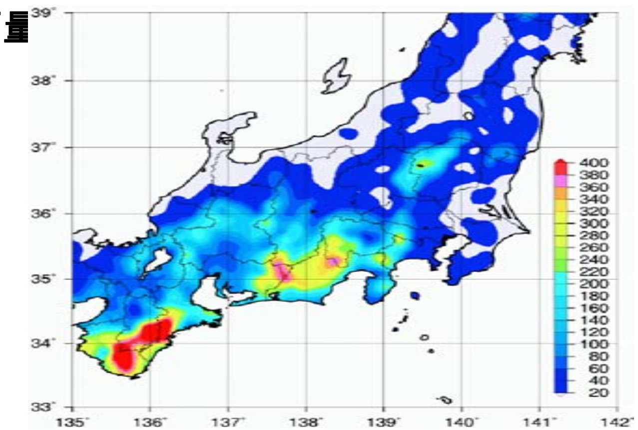


領域大気
1.15km
(ネスト)





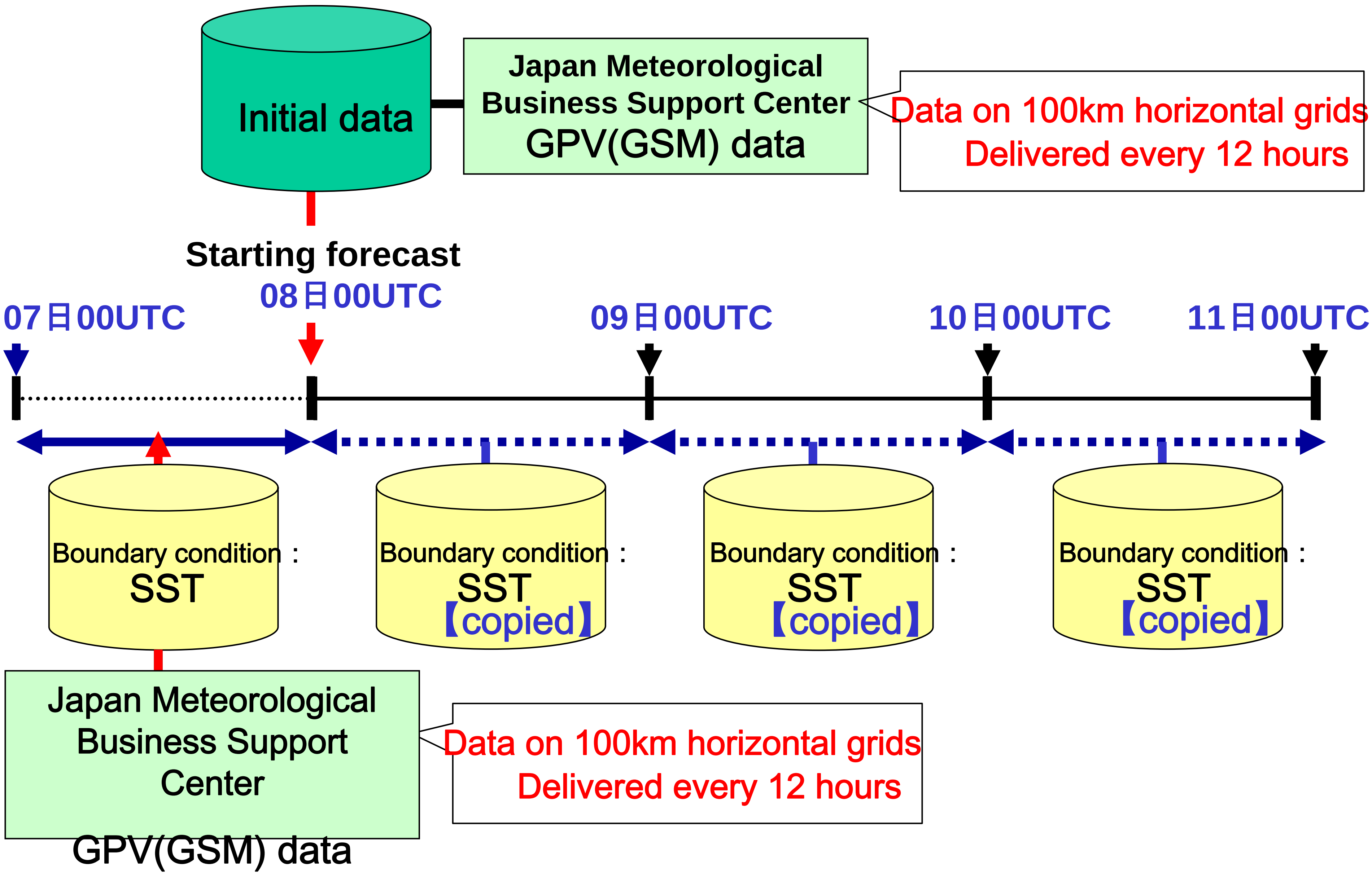
観測: 8月7日18：00～9日24時までの積算雨量



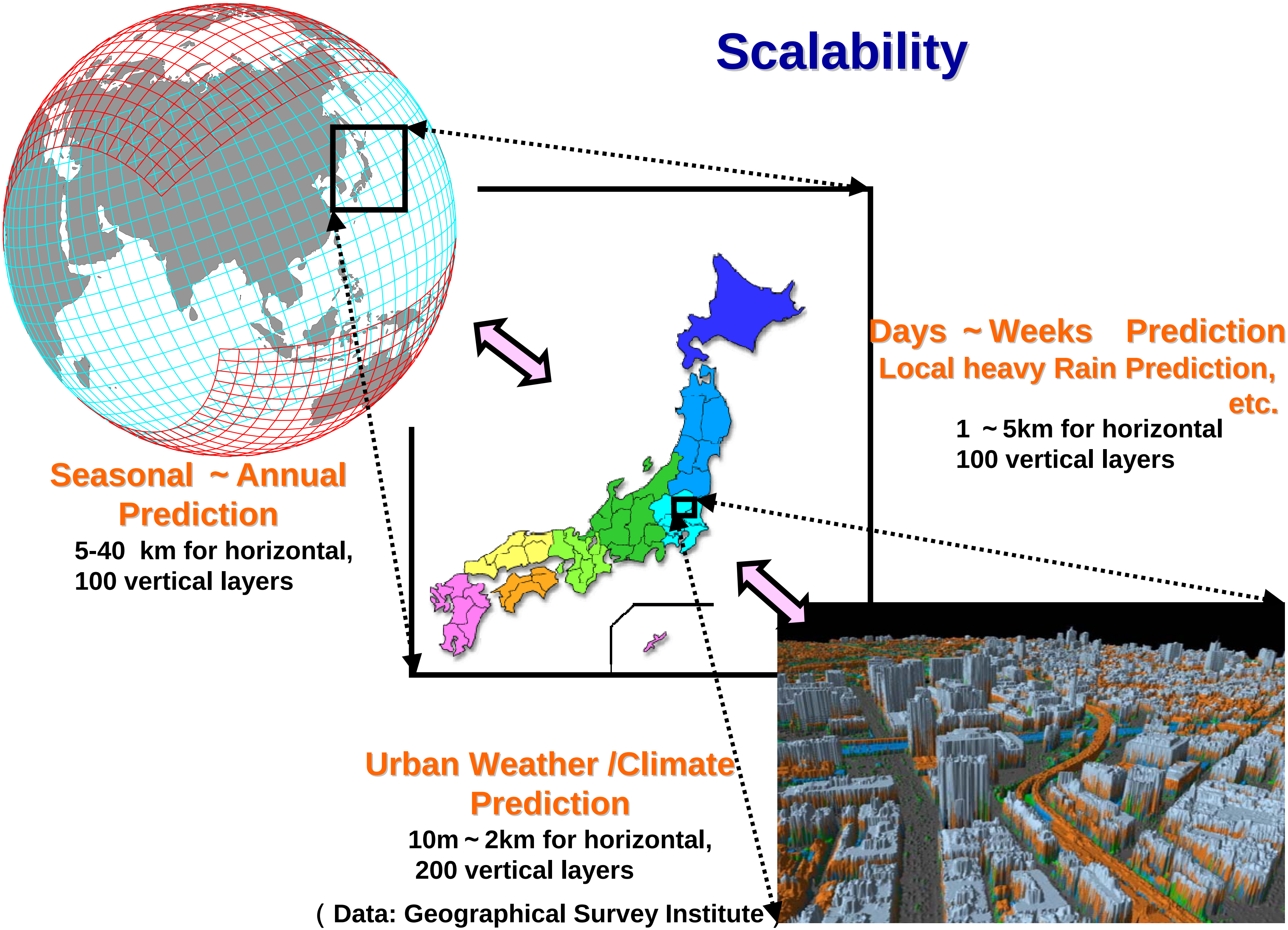
豪雨，風の強度についての予測精度向上を示唆

AGCM simulations：initial and boundary data

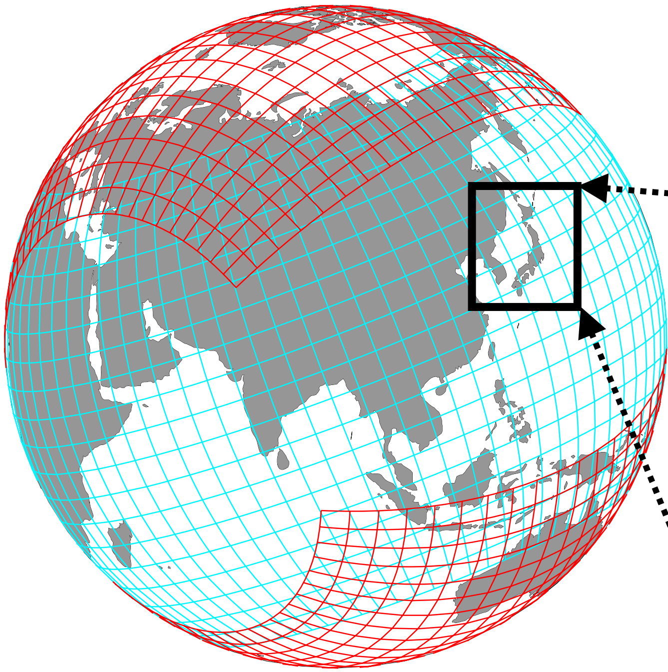
2003/8/8/00UTC～11/8/00UTC: ７２ hours forecasting



Scalability



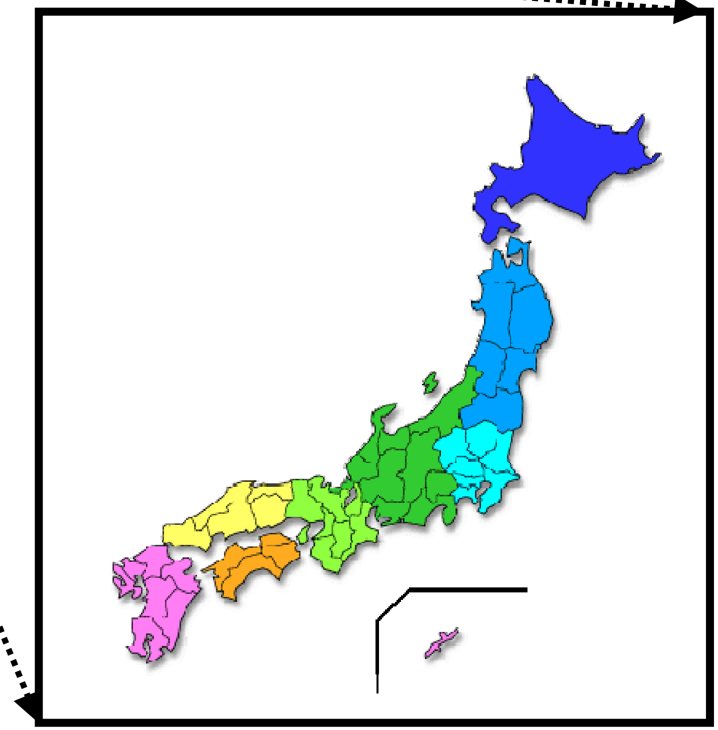
Scalability



Global

Months ~ Years Prediction

5-20 km for horizontal,
100 vertical layers



Reagional

on the sphere

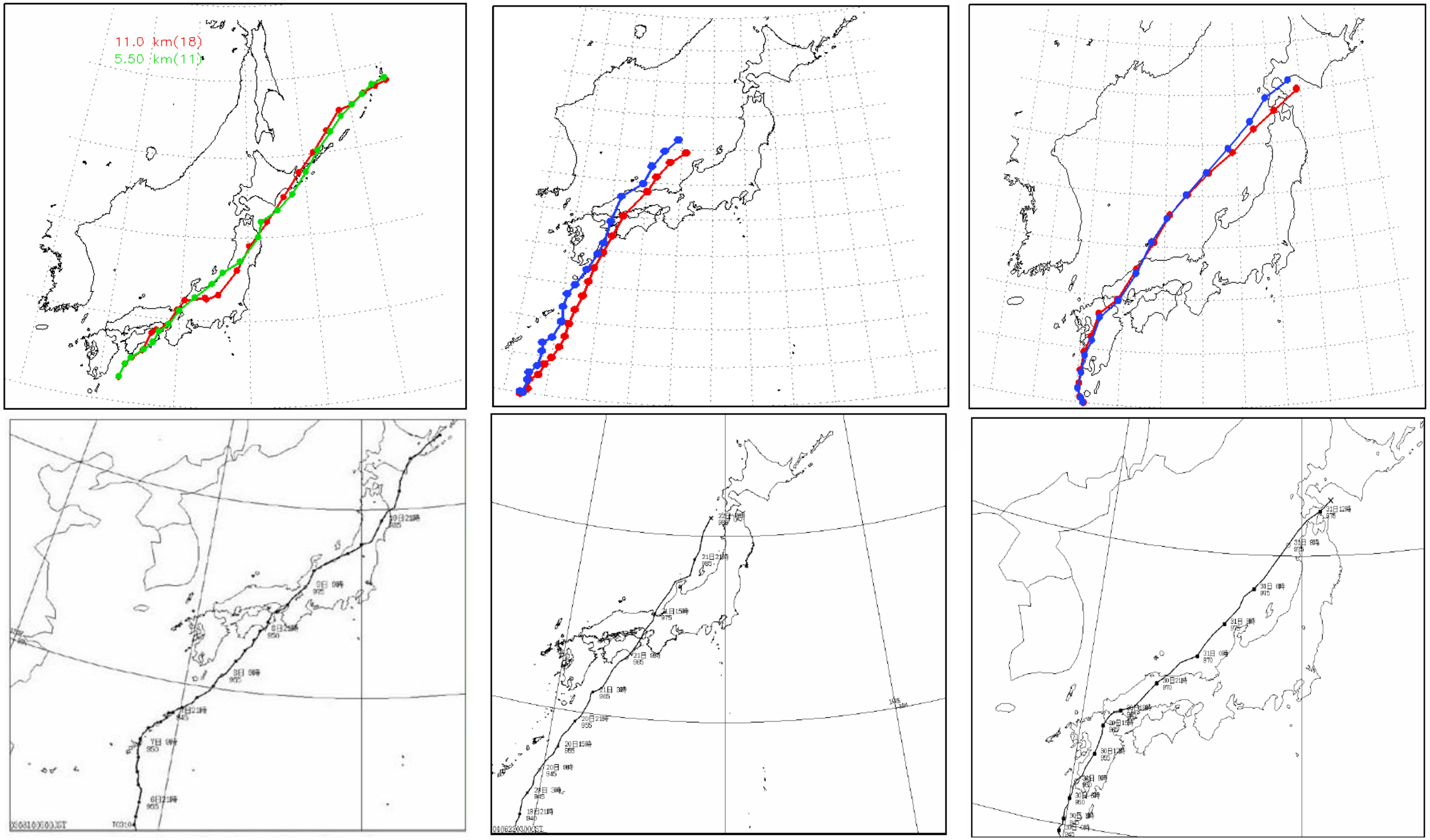
Days ~ Weeks Prediction

Local heavy Rain Prediction, etc.

1 ~ 5km for horizontal
100 vertical layers

Prediction of Typhoon tracking
- simulation results -

00UTC 08 Aug – 00UTC 11 Aug, 2003 | **00UTC 19 Jun – 00UTC 22 Jun, 2004** | **00UTC 29 Aug – 00UTC 01 Sep, 2004**



Global 11km for horizontal, Global 5.5km for horizontal

Model Evaluation by Case Study

Summer Case

- **48hr Global 60-km 32-lvls simulation**
- **Start at 00UTC Aug.8, 2003**
- **KF2 + large-scale condensation**

06UTC Aug.8 2003