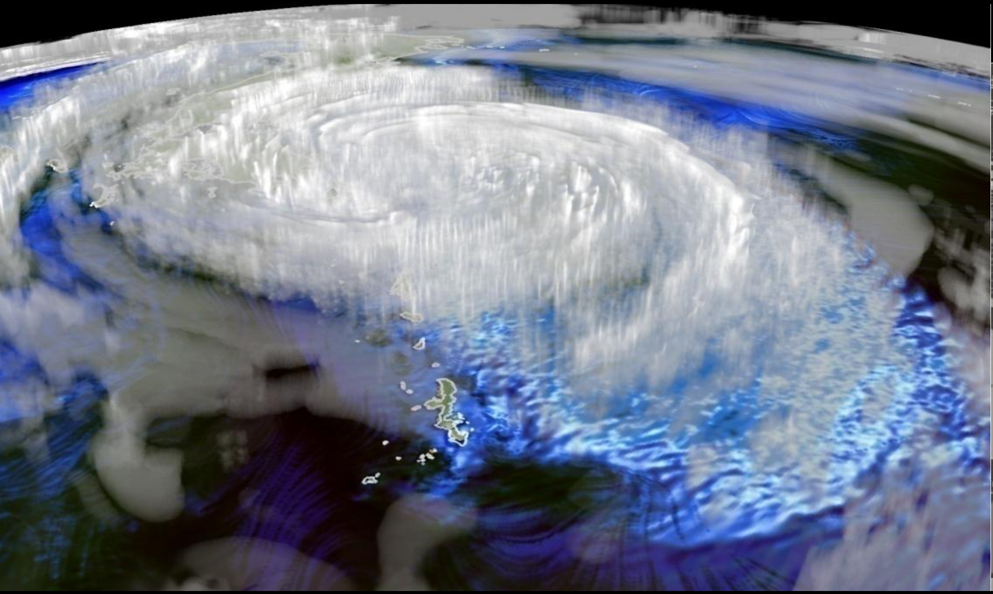
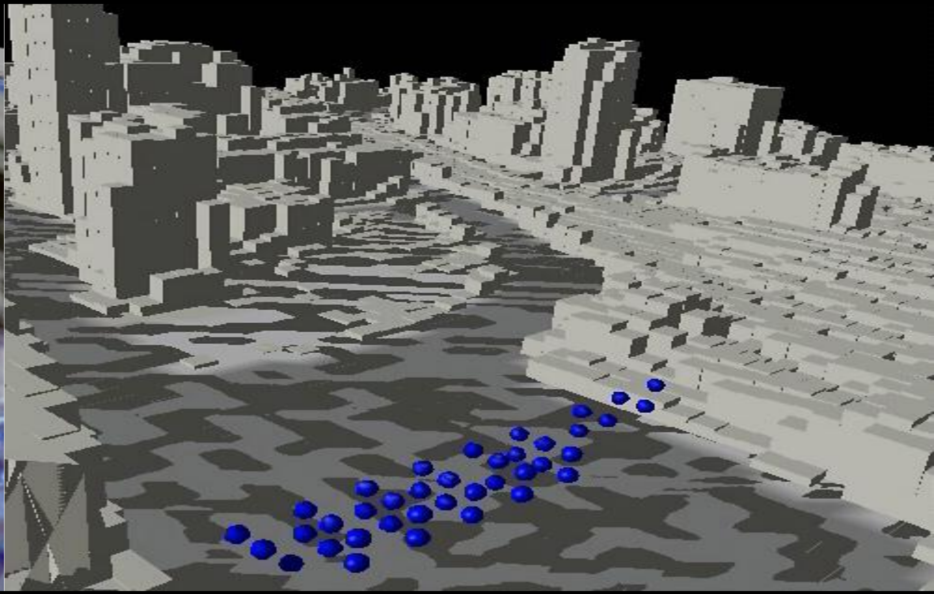
High Performance Computing of MSSG and its Physical Performance



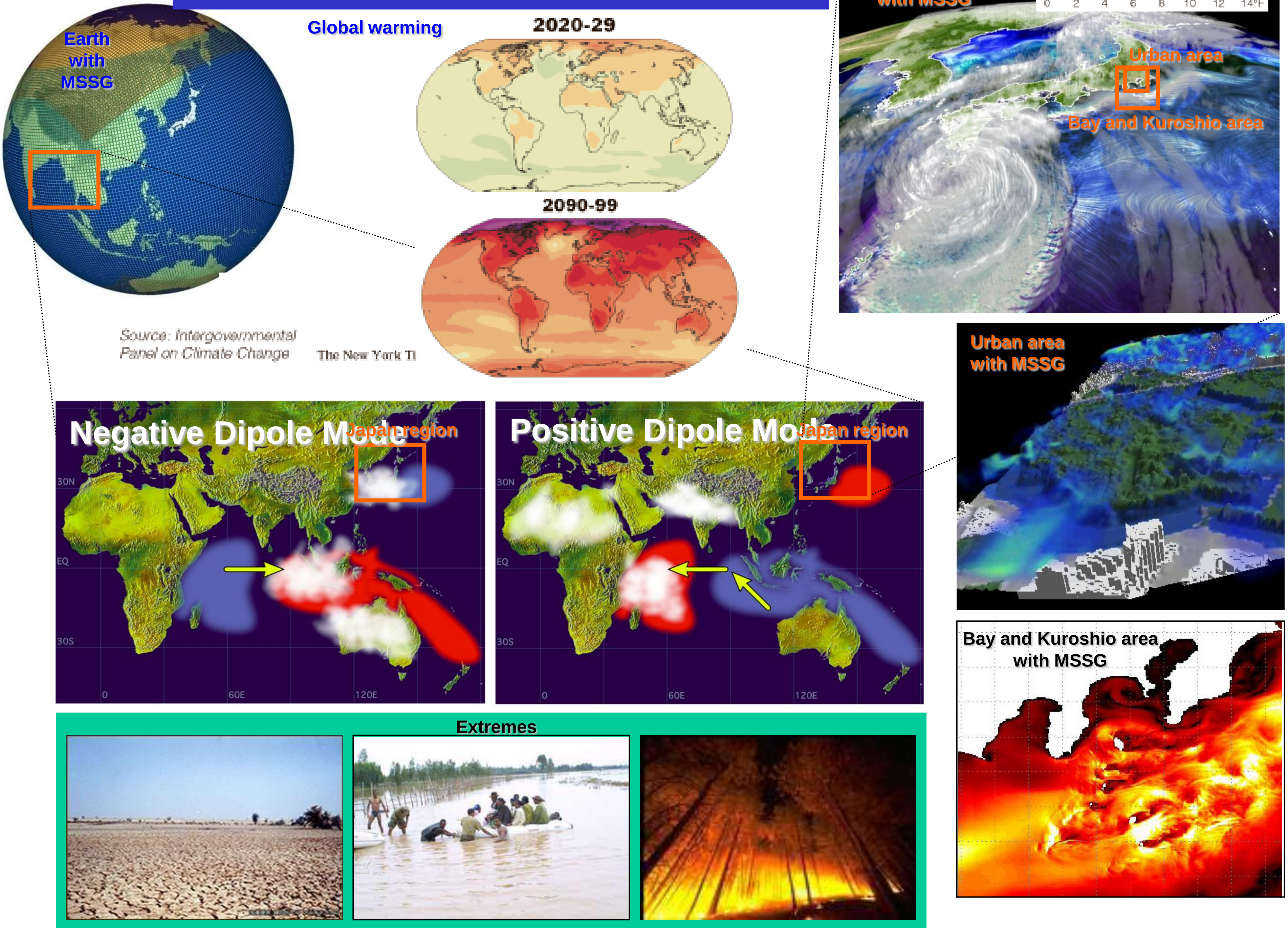


Keiko Takahashi, Ryo Onishi, Takeshi Sugimura, Yuya Baba, Shinichiro Kida, Koji Goto and Hiromitsu Fuchigami

Earth Simulator Center, Japan Agency of Marine-Earth Science and Technology (JAMSTEC)

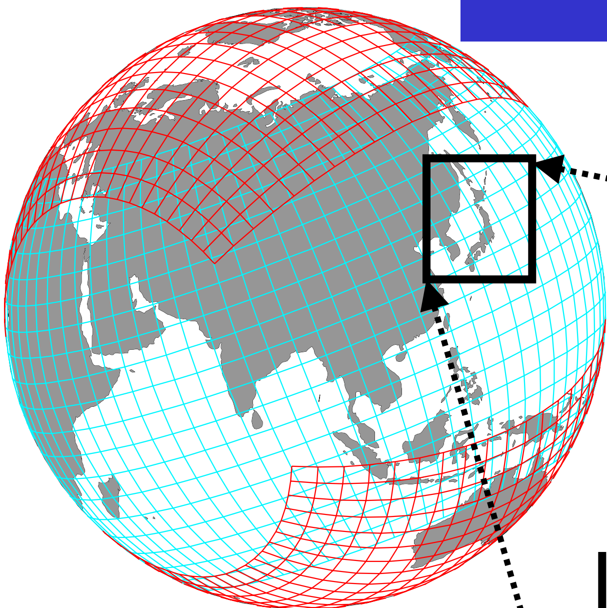
NEC Cooperation, NEC Informatec Systems LTD

Outline of Seamless Simulations with MSSG



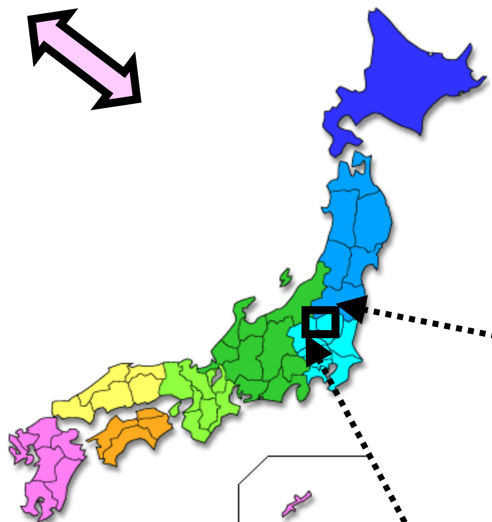
Multi-Scale Simulator for the Geoenvironment (MSSG)

Scalability



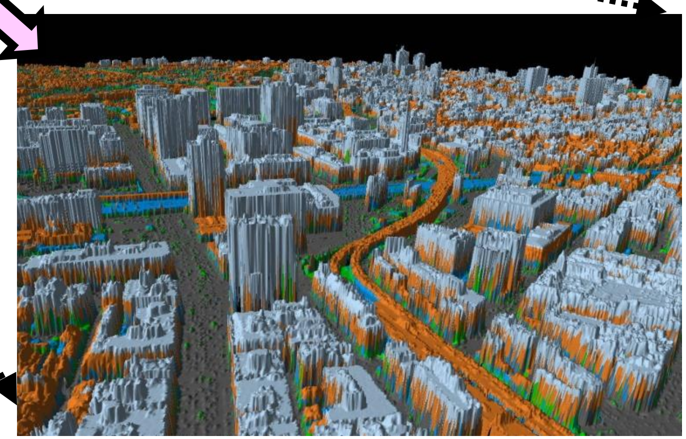
Seasonal ～Annual Projection

2- 40 km for horizontal, 100 vertical layers



Days ～Weeks forecasting Typhoon, Baiu rain etc.

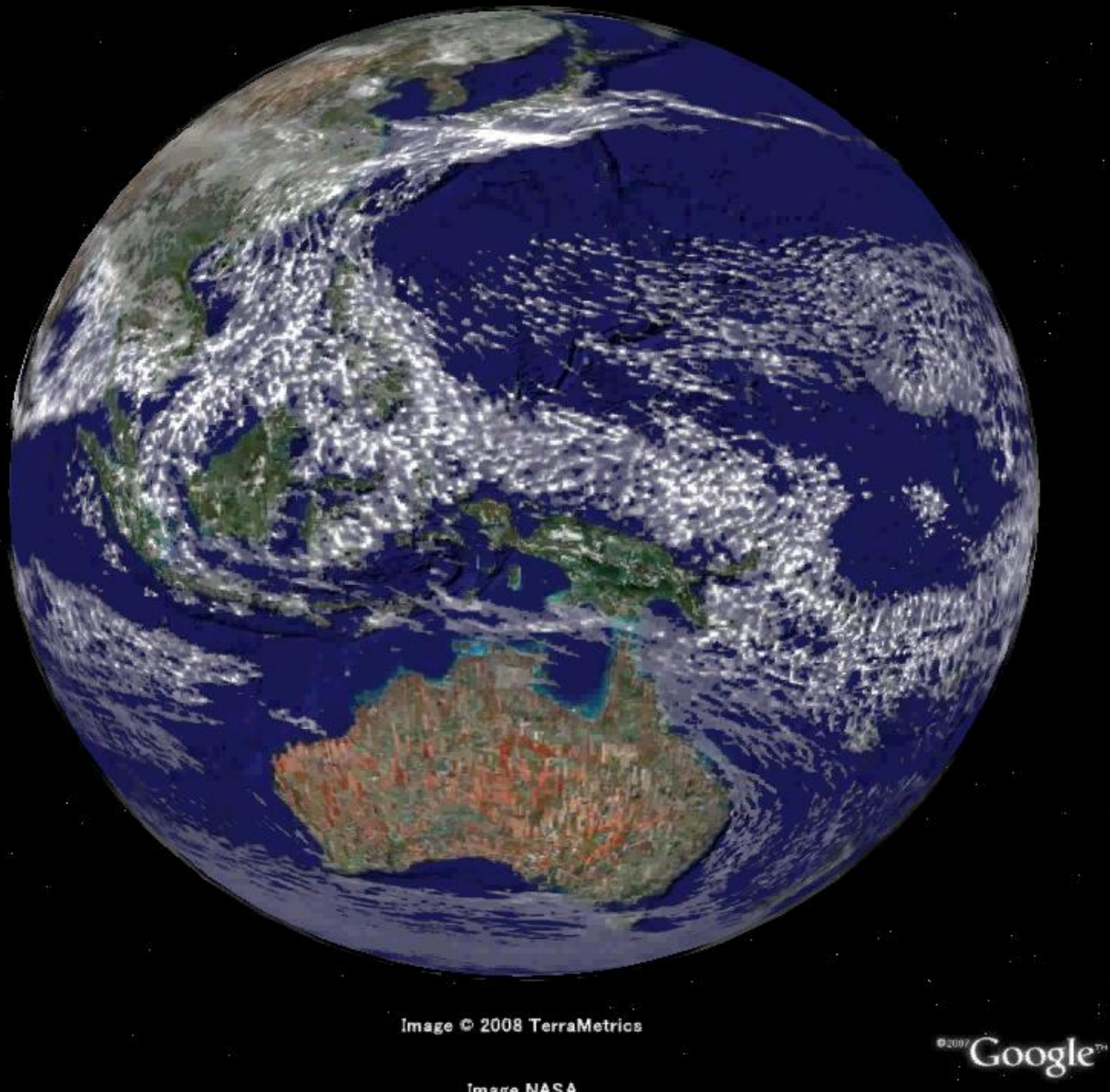
O(100) m - 2km for horizontal 100 vertical layers



Urban Weather/Climate Forecasting

O(1)m～*O*(100)m for horizontal, 200 vertical layers （Data: Geographical Survey Institute）

Results from MSSG on Google Earth

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Our Grand Challenge

Prediction/Forecasting

Unser the Global Warming
Under the IOD/ El Nino
⇔ Seasonal Forecasting,
Regional Climate
Urban Climate

Impact of
Cloud Scale ⇔ Synoptic Scale
Weather ⇔ Climate Change

For Seamless Simulation between Weather and Climate

MSSG
(Multi-Scale Simulator for the Geoenvironment)
Coupled Atmosphere-Ocean-Land Model
as "Google Earth Model"

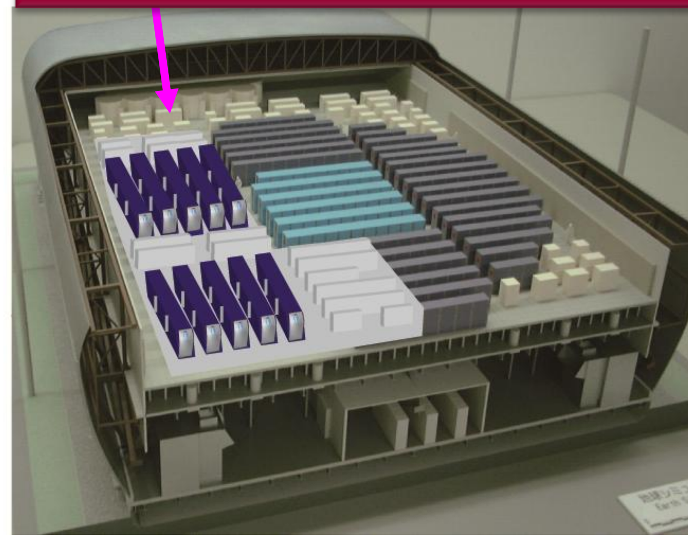
- Key words:
  - Down-scaling & Up-scaling
  - Climate/Seasonal Variability
  - Atmosphere-Ocean Interactions
  - Urban weather/climate

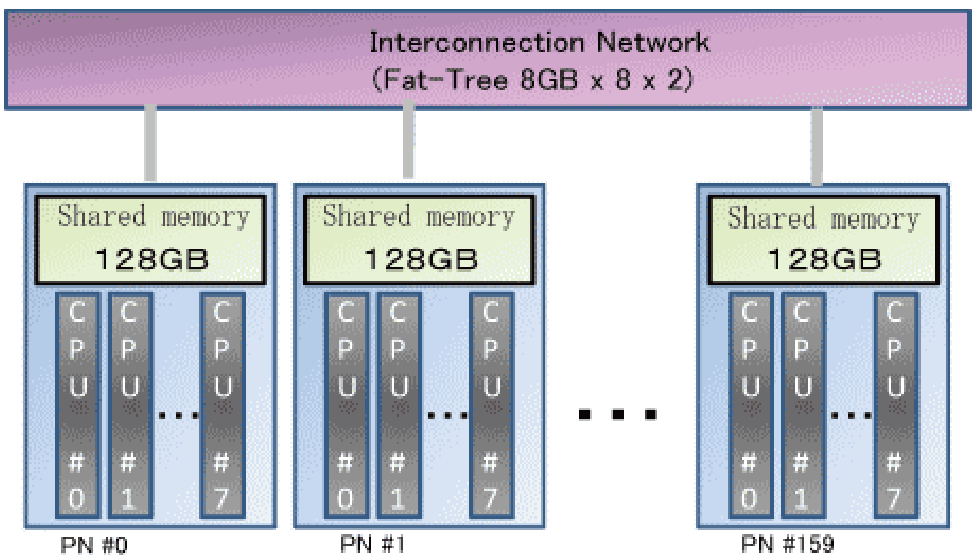
Earth Simulator (ES2)

Hardware

Peak performance/CPU	102.4Gflops	Total number of CPUs	1280
Peak performance/PN	819.2Gflops	Total number of PNs	160
Shared memory/PN	128GByte	Total peak performance	131Tflops
CPUs/PN	8	Total main memory	20TByte

ES2 LAYOUT





Ultra High Resolution Simulation

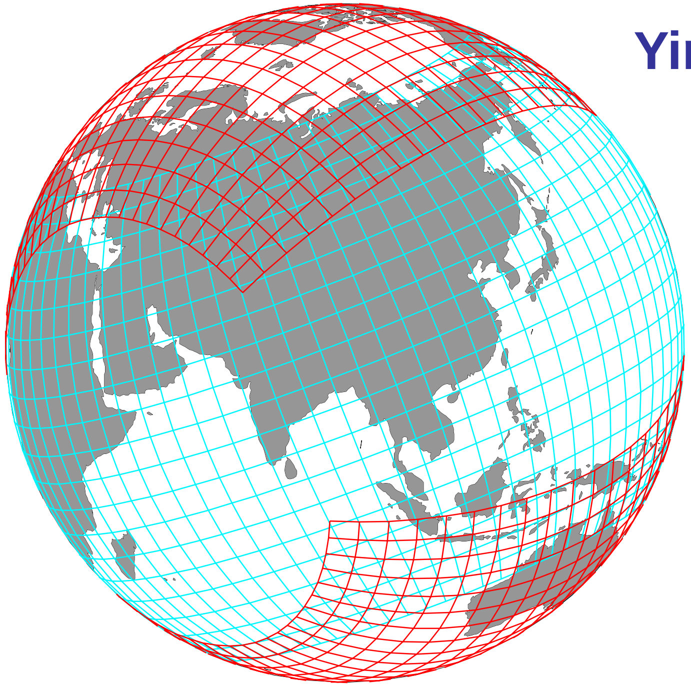
Global Simulation

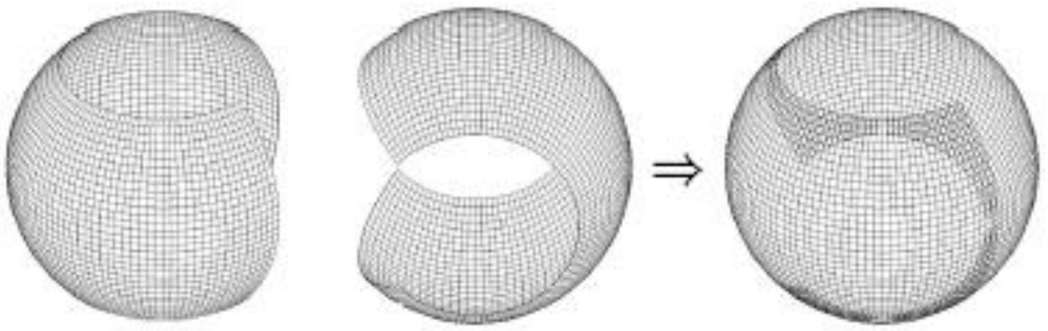
Regional Simulation

Up to the Limitation of Computational Power
of he Earth Simulator

Grid System

Yin-Yang Grid System

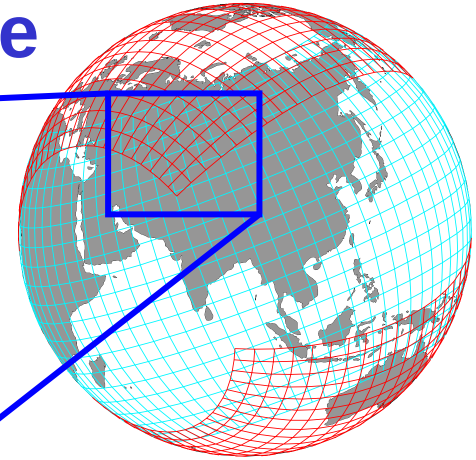


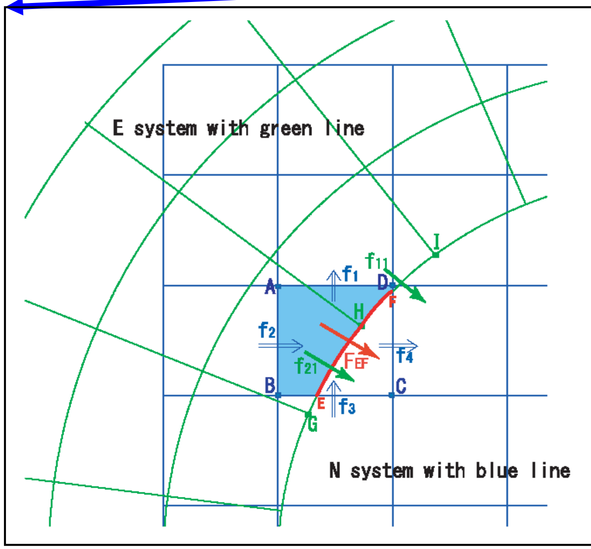


- Orthogonal coordinates. （same as the lat-lon geometry）
- No polar singularity.
- Relax of CFL condition.
- The same grid structure of N and E component.
- Easy to nest.
- High parallelization.
- But need to take care of conservation law.

Y. Baba, K. Takahashi, T. Sugimura, K.Goto, Dynamical Core of an Atmospheric General Circulation Model on a Yin–Yang Grid, Monthly Wearther Review, 138, 3988-4005 (2010).

Mass conserving numerical scheme



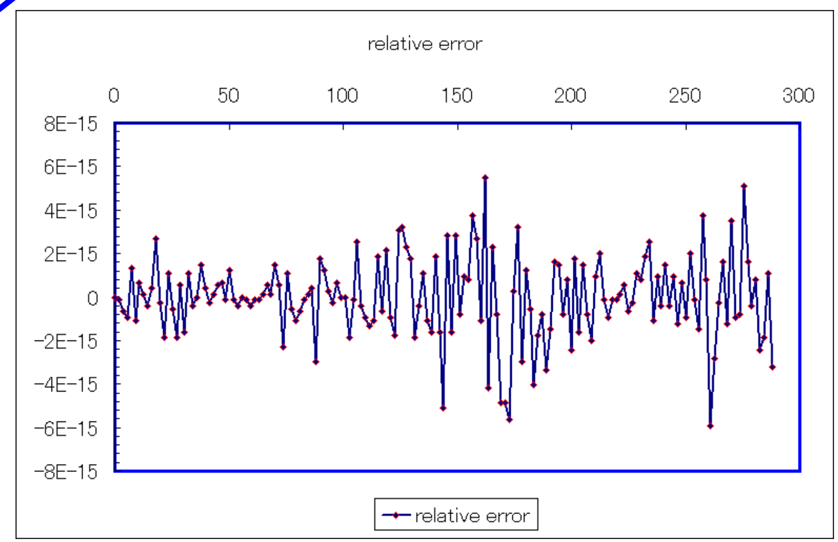


For flux F_{EF} on a circular arc EFshown as red circle is computed by the budget of fluxes f_N by on grid ABCD of N system and flux f_E estimated on a circular arc GHI of E system.

Computation all of fluxes on computational grids

↓

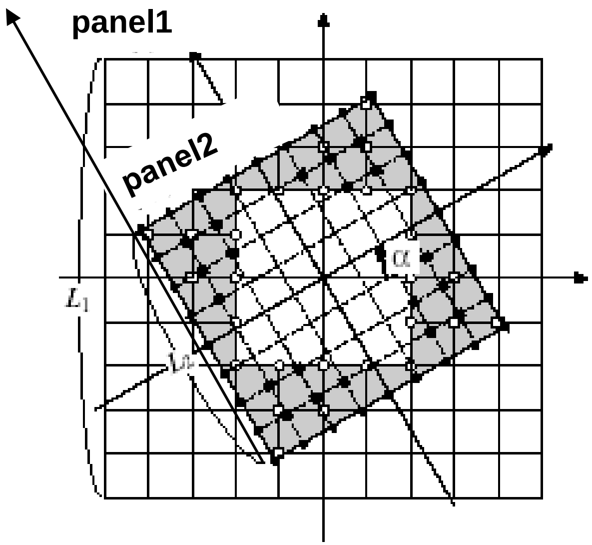
Correction for conserving

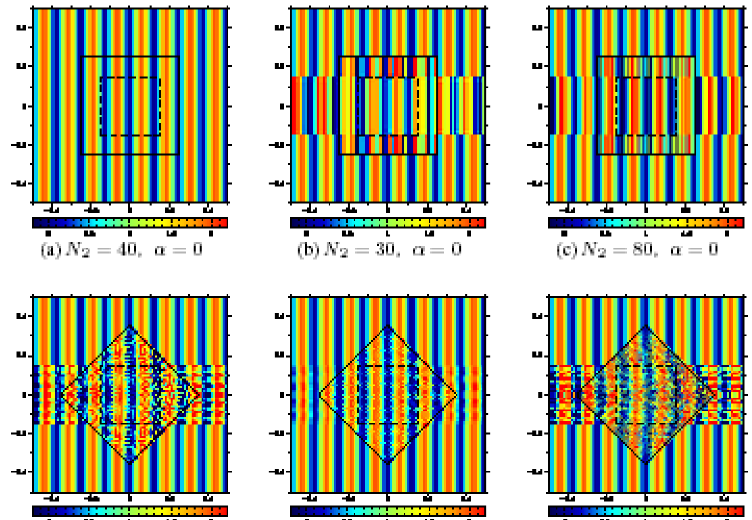


This conservative scheme, we have evaluated that time evolution of relative error of the mass has changed within the limit of rounding error.

Peng, X., Xiao, F. and Takahashi, K., Global conservation constraint for a quasi-uniform overset grid on sphere, *Quart. J. Roy. Meteor. Soc.*, 132, 979-996 (2006).

Wave propagation characteristics on overset grid system



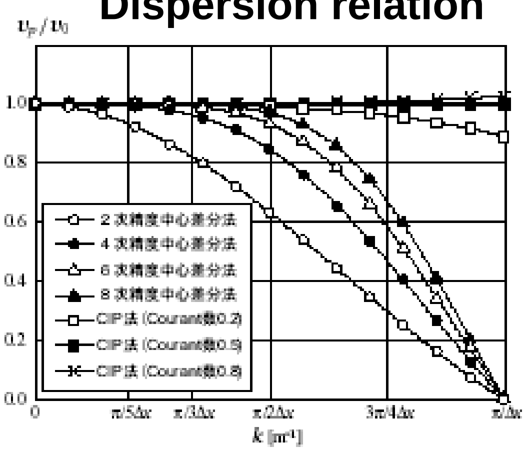


(a) $N_2 = 40, \ \alpha = 0$ (b) $N_2 = 30, \ \alpha = 0$ (c) $N_2 = 80, \ \alpha = 0$

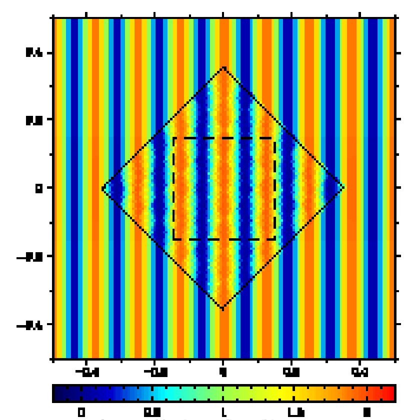
(d) $N_2 = 40, \ \alpha = \pi/4$ (e) $N_2 = 30, \ \alpha = \pi/4$ (f) $N_2 = 80, \ \alpha = \pi/4$

High order computational schemes and interpolation are required.

Dispersion relation



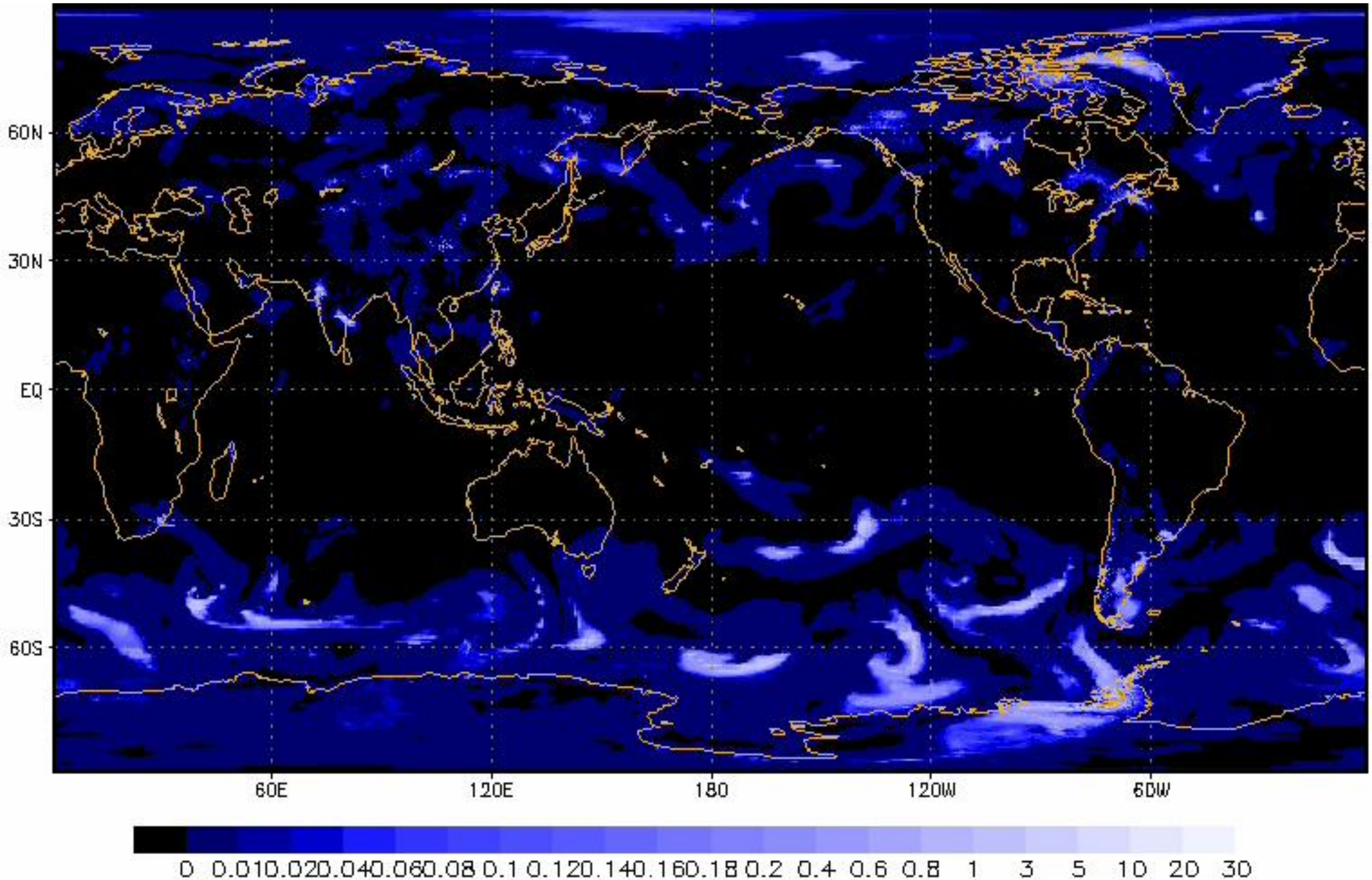
Dispersion relation is important to avoid errors on interface of overset grid system.



(a) 境界交換法． 波の数 $m = 8$.

Global Atmosphere Simulation with MSSG-A

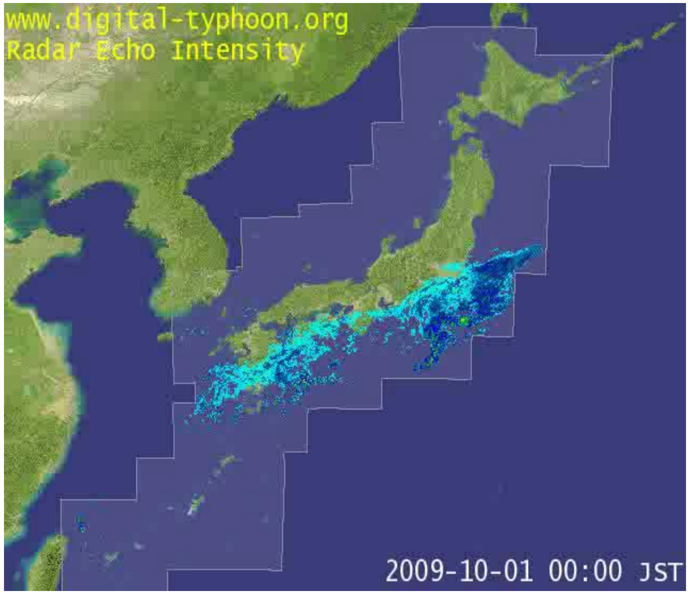
03-08AUG2003, Horizontal resolution: 1.9 km, 32 vertical layers

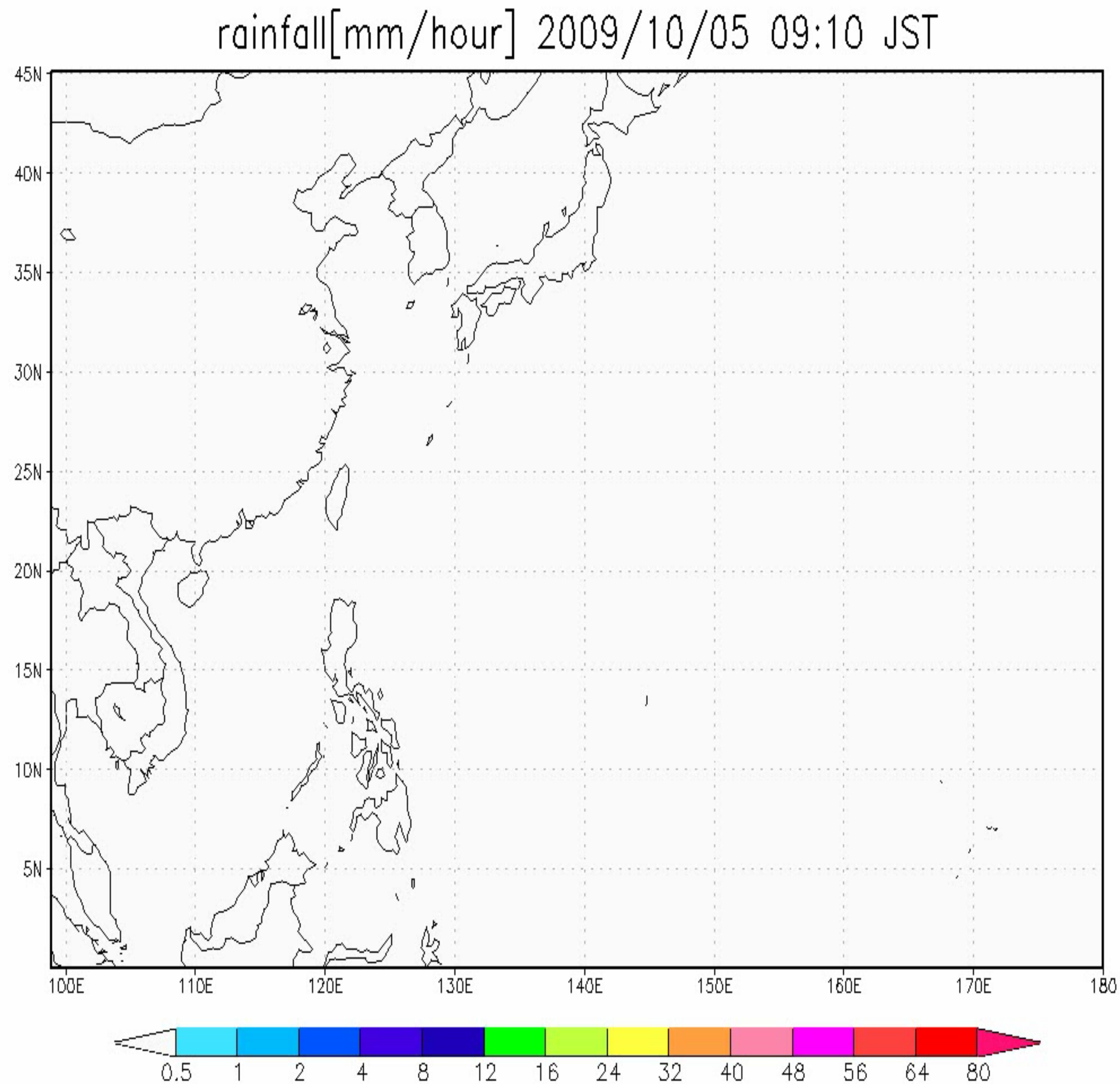


05 Oct 2009

Horizontal resolution: 2.6 km for global

32 vertical layers

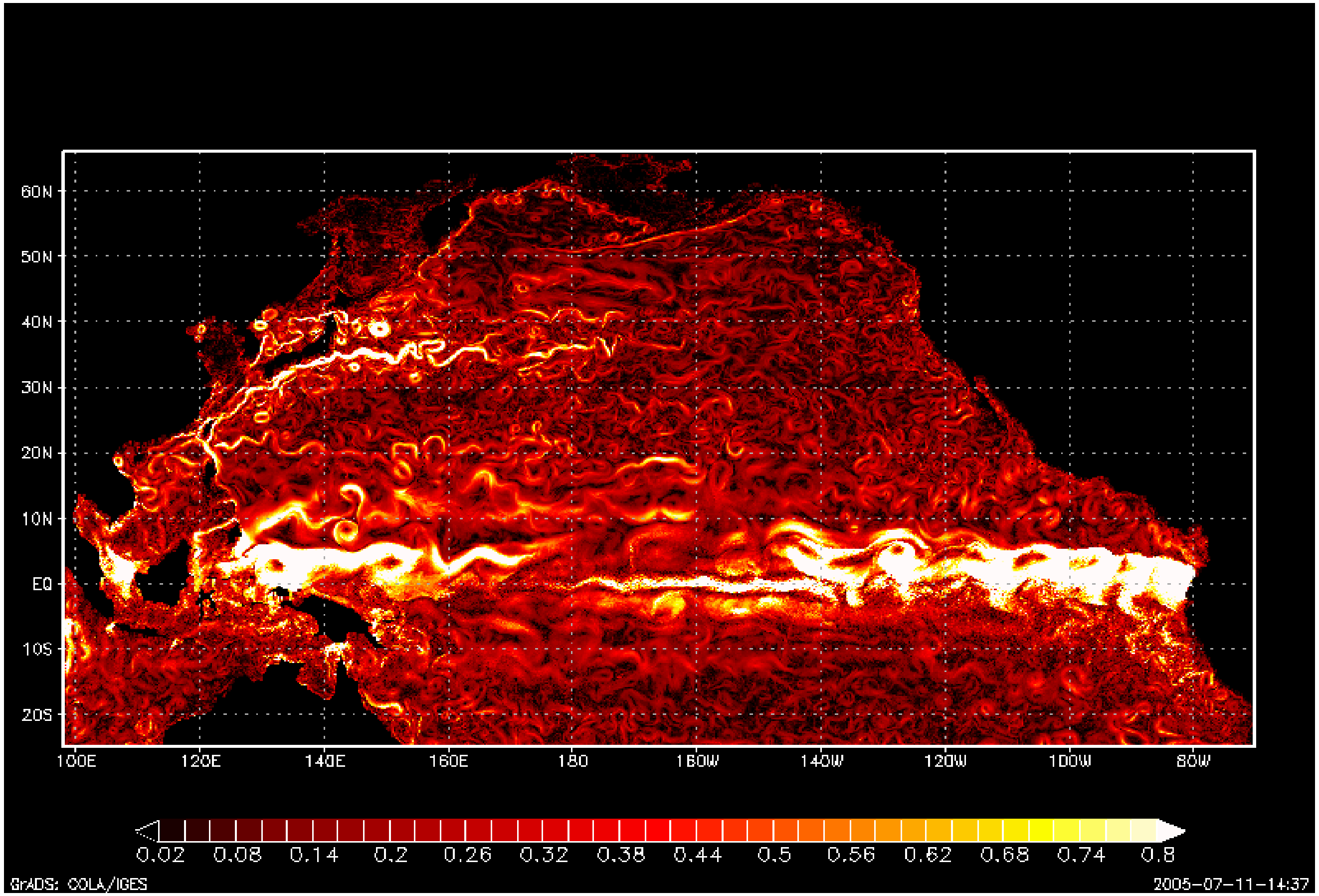




Ocean Component of Multi-Scale Simulator for the Geoenvironment: MSSG-O

The Northern Pacific Ocean

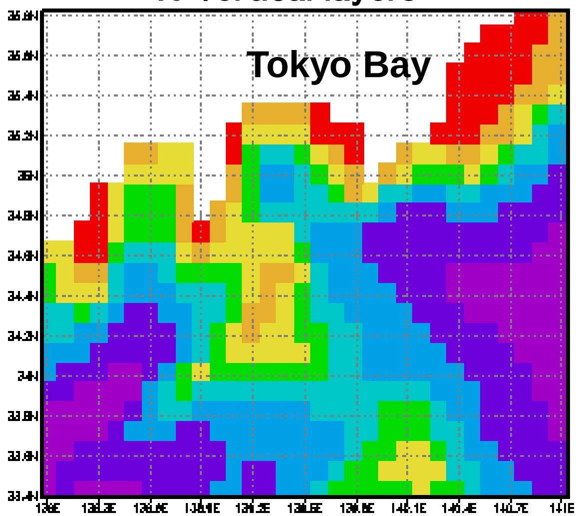
Horizontal Resolution: 2.78km, Vertical Layers: 40 layers, 15 years integration
Boundary condition: monthly data from NCAR
monthly data from OFES simulation(10km global simulation)



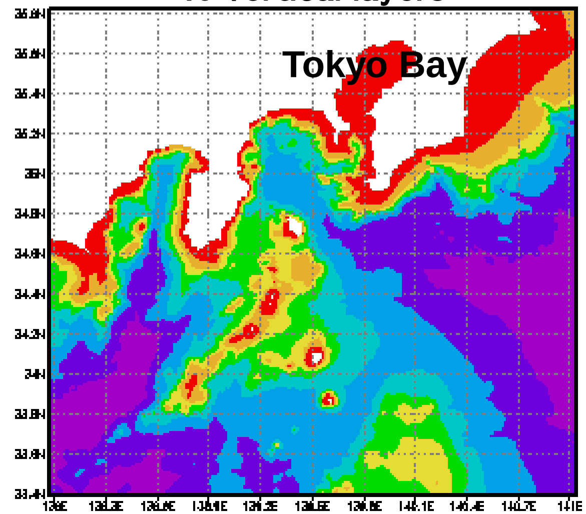
Simulation Results in Coastal Regeon with MSSG-O

The Northern Pacific Ocean nesting to Japan region

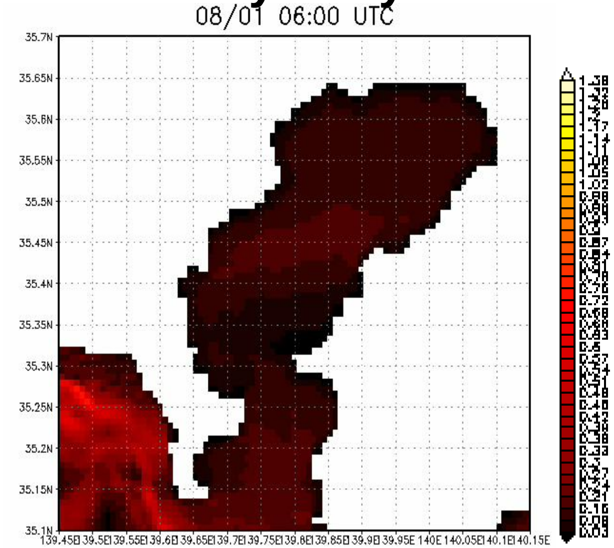
Horizontal : 11km,
40 vertical layers

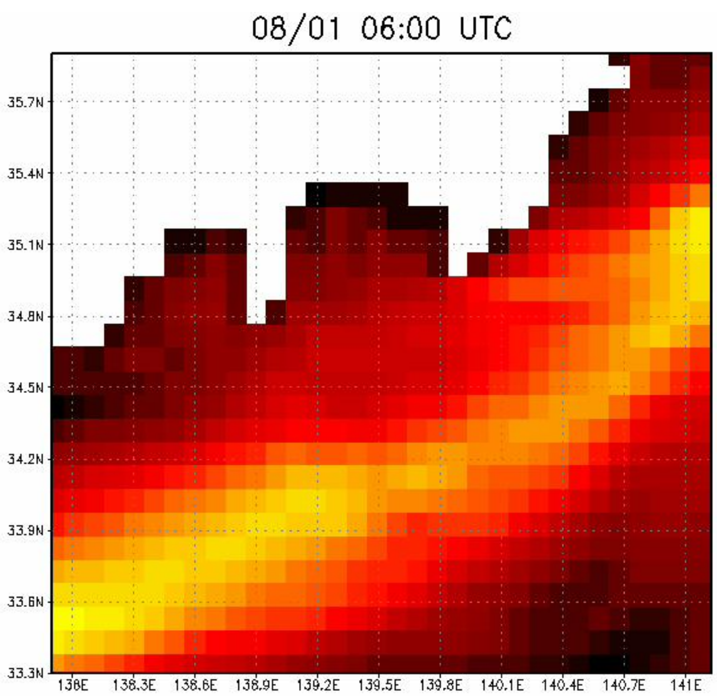


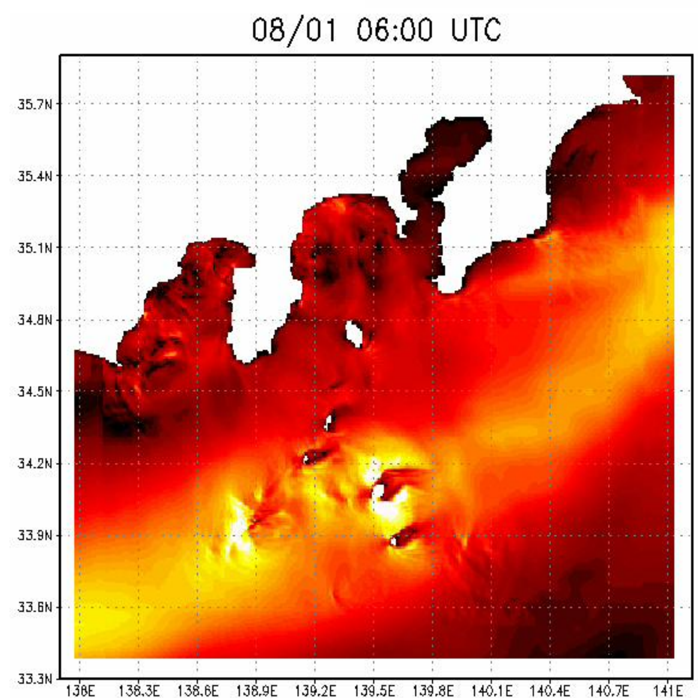
Horizontal : 850m,
40 vertical layers



Tokyo Bay







Outline of MSSG

		MSSG-A	MSSG-O
		Non-hydrostatic AGCM	Non-hydrostatic /hydrostatic OGCM
governing eqs.		Fully compressive N-S eqs.	incompressive N-S eqs.
grid system		Yin-Yang grid (overlapped 2 lat-lon)	Yin-Yang grid (overlapped 2 lat-lon)
discritization	space	Arakawa-C grid (horizontal), Z* (vertical)	Arakawa-C grid (horizontal), Z* (vertical)
	time	3rd/4th Runge-Kutta	3rd/4th Runge-Kutta
adv. schemes		5th flux form, WAF, CIP-CSLR	5th flux form
non-adv. schemes		4th flux form	4th flux form
sound wave		HEVI, HIVI	Implicit methods (2D, 3D)
microphysics		Bulk method (Qc,Qr,Qi,Qs,Qg)/ hybrid-Bin method	-
turbulence model		static Smagorinsky scheme	static Smagorinsky model
other models		cloud radiation model, backet land model, UCSS urban canopy model	sea-ice model
parallelization		horizontal 2D decomposition by MPI/ vertical decomposition by micro-task	horizontal 2D decomposition by MPI/ vertical decomposition by micro-task

Dynamical Framework (1)

- **Atmosphere: Fully compressible, non-hydrostatic equations**

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

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

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

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

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

$$p = \rho R T$$

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

Dynamical Framework (2)

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

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

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

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

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

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

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

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

MSSG as a Multi-Scale Coupled Model with nesting schemes

MSSG is available for the hierarchy of broad range of space and time scales of weather/climate phenomena as follows,

- **Global non-hydrostatic atmospheric circulation model: Global MSSG-A**
- **Regional non-hydrostatic atmospheric model: Regional MSSG-A**

- **Global non-hydrostatic/hydrostatic ocean model: Global MSSG-O**
- **Regional non-hydrostatic/hydrostatic ocean model: Regional MSSG-O**

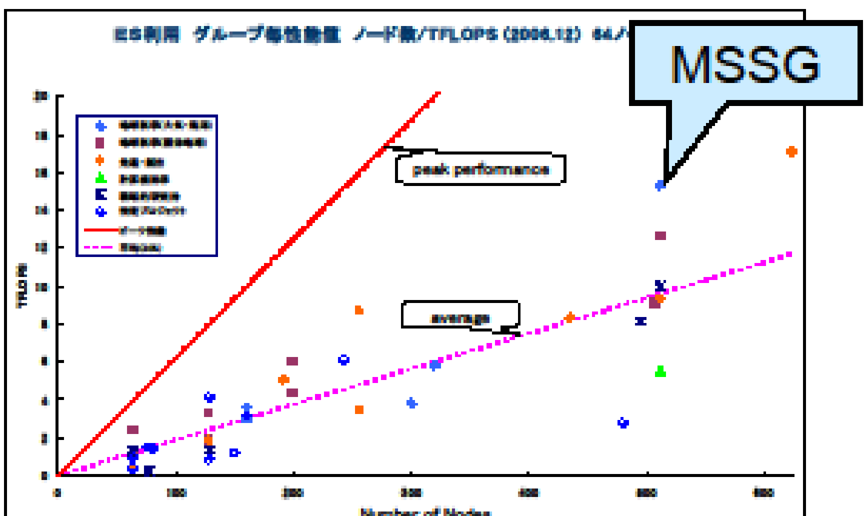
- **Coupled Global MSSG-A Global MSSG-O: MSSG**
- **Coupled Regional MSSG-A Regional MSSG-O: Regional MSSG**

- **MSSG (global) coupled with Regional MSSG using nesting schemes**

Computational Performance of MSSG 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%	11.35	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; A: Atmos.; RA: regional Atmos.; O: Ocean



Simple linearity will be kept until 2 PFLOPS

MSSG is selected as a core application for the next Japanese flagship supercomputer with 10PFLOPS

Computational Performance of MSSG on the Earth Simulator

EXCLUSIVE TIME[sec]	%	MFLOPS	V.OP RATIO	AVER. V.LEN	I-CACHE MISS	O-CACHE MISS	BANK CONFLICT		PROC.NAME
							CPU PORT	NETWORK	
19777.543	99.7	18592.9	99.54	236.1	256.595	772.348	262.653	6554.572	(A1) main loop
4479.512	22.6	22277.2	99.51	239.2	90.681	198.871	74.955	1697.248	(A2) N-S HEVI
2632.633	13.3	24765.7	99.50	238.7	26.207	71.759	52.430	821.099	(A2) N-S eq.(large)
4649.974	23.4	34140.6	99.80	238.7	16.851	60.720	20.966	566.511	(A2) tracer eq.
3996.377	20.1	7798.0	99.20	213.7	87.334	272.048	57.238	1878.027	(A2) physics
285.278	1.4	1471.8	99.36	230.4	8.858	15.927	10.138	198.995	(A2) boundary
596.373	3.0	584.6	99.40	224.2	5.130	8.725	13.396	445.971	(A2) boundary (side)
235.785	1.2	6361.6	99.11	239.6	0.385	1.991	5.099	93.416	(A2) z2ps
1073.107	5.4	305.1	81.38	172.9	1.550	3.569	1.977	218.644	(A2) output
130.365	0.7	23363.6	99.42	238.4	0.399	1.103	22.172	65.026	(A2) RKG
504.566	2.5	646.3	98.62	239.8	0.295	0.326	0.012	352.960	(A2) diagno
448.958	2.3	13480.8	99.24	227.6	16.439	33.263	4.128	192.399	(A2) subfield
734.071	3.7	1083.8	79.70	236.7	0.406	99.532	0.134	23.240	(A2) recalc dt
0.317	0.0	2.1	90.13	236.1	0.037	0.091	0.001	0.013	(A2) restart

- Over 30% computational performance to theoretical peak performance of ES
- Computational cost of main loop: 18GFLOPS/1CPU
- Dynamical core (N-S eq., HEVI, tracer eq.): 60%
- Physics: 20%
- Communications: (boundary, boundary(side)): 5%
- Others: 15%

MSSG:

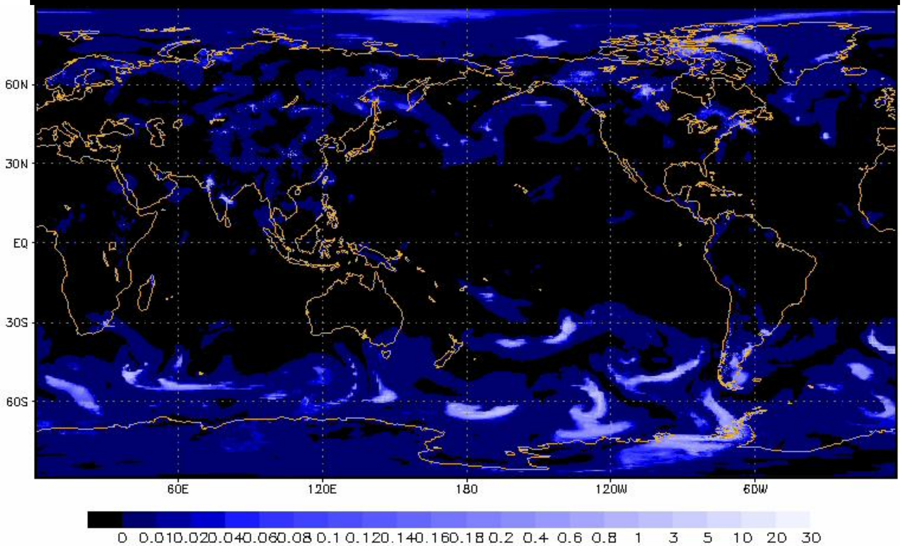
global forecasting with 11km horizontal, 40 vertical layers

5 days (120 hours) integration → about 5 hours on 48 nodes of ES2

3 month integration → about 2.5 days on 80 nodes (1/2) of ES2

MSSG-A

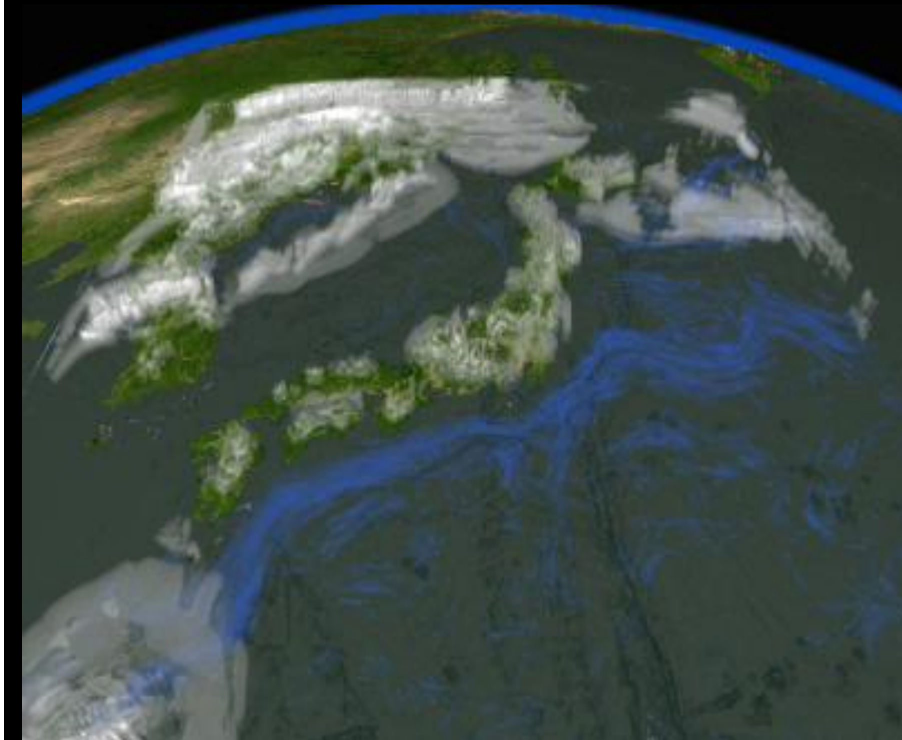
Horizontal:1.9km, Vertical:32layers, 14 days integration



SST

Heat, Flesh water, Momentum fluxes

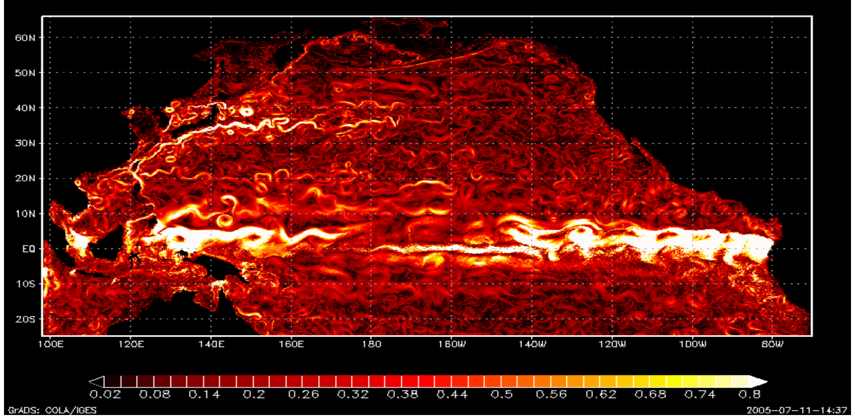
MSSG



Typhoon ETAU in 2003

MSSG-O

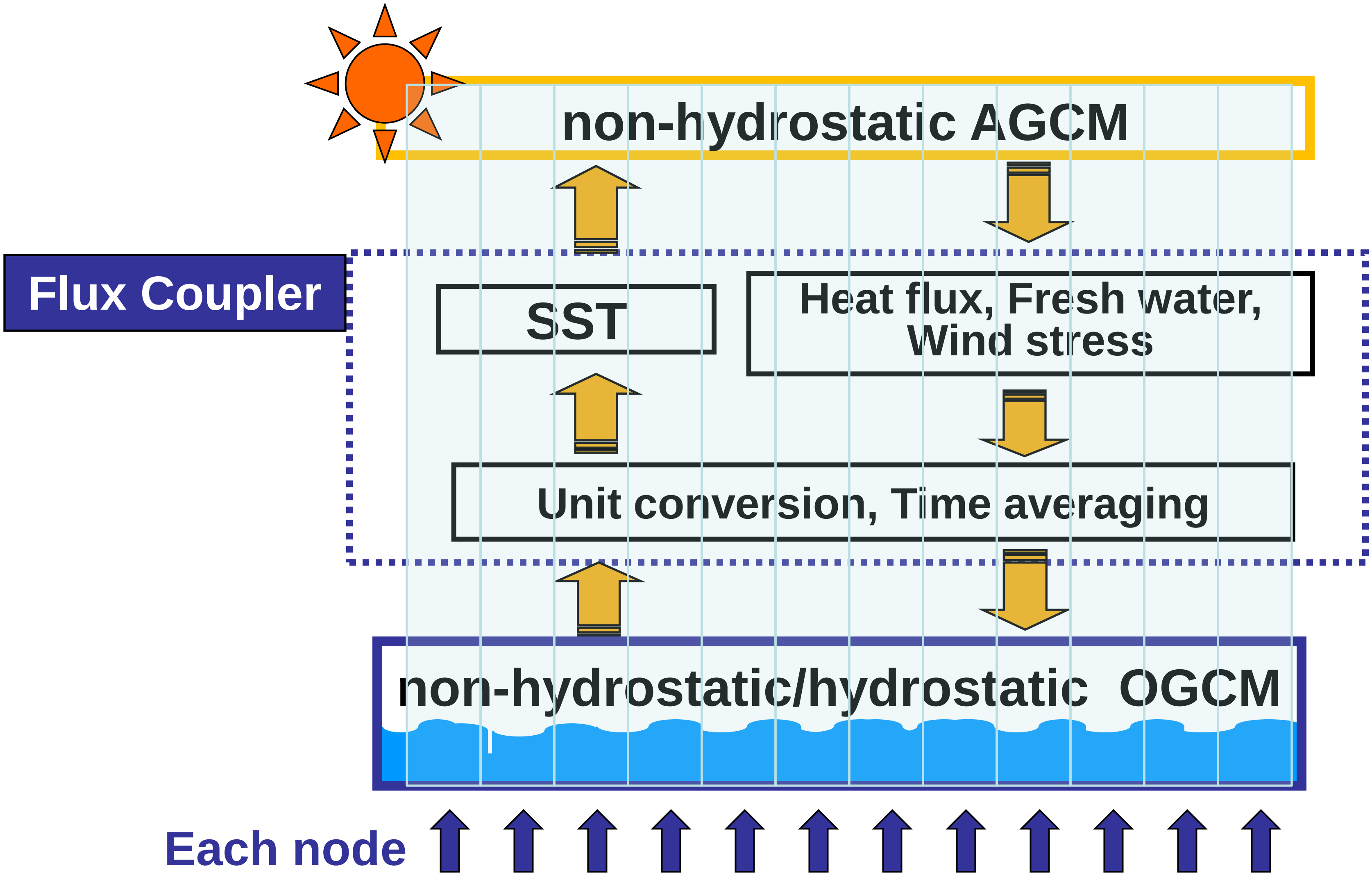
Horizontal: 2.78 km, vertical: 40 layer, 15 years integration



Sea Ice

Okhotsk-sea (1/12deg.)

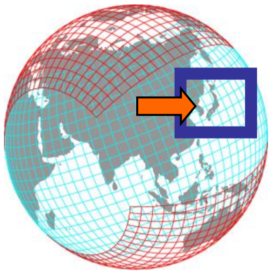
MSSG: Coupled Atmosphere-Ocean Model



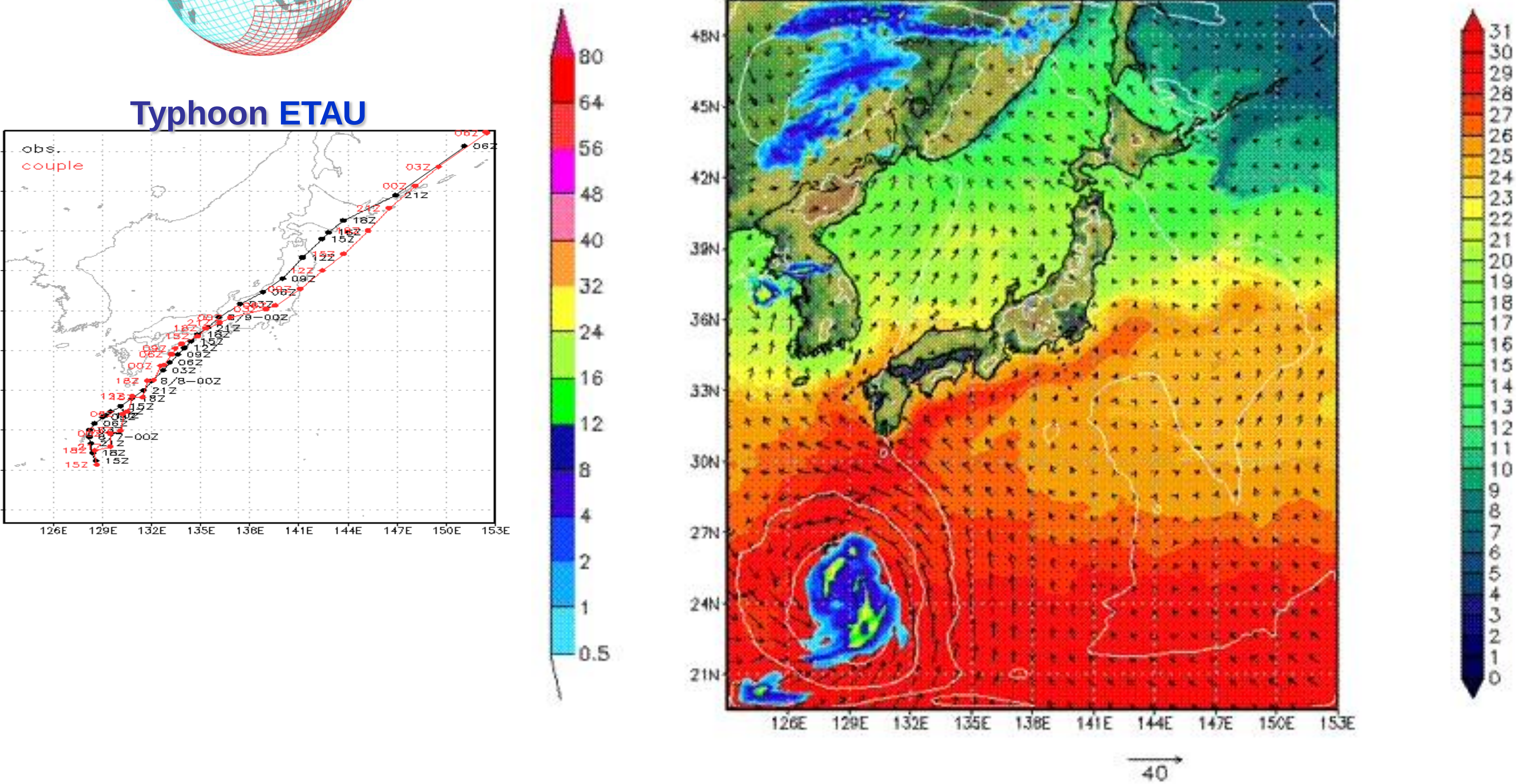
5 Days Forecasting of Typhoon 10 of 2003

SSG, non-hydrostatic Global Ocean-Atmosphere Coupled Simulation

Horizontal resolution : 2.7 km
Vertical resolution : 72 layers



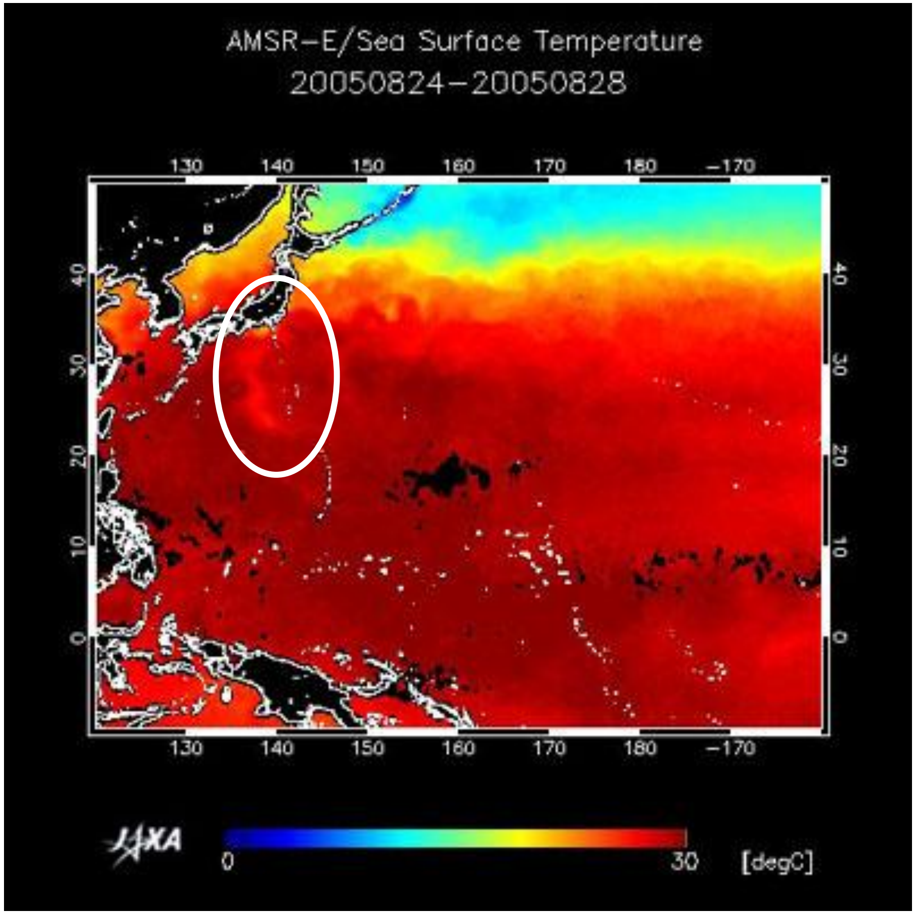
Typhoon ETAU

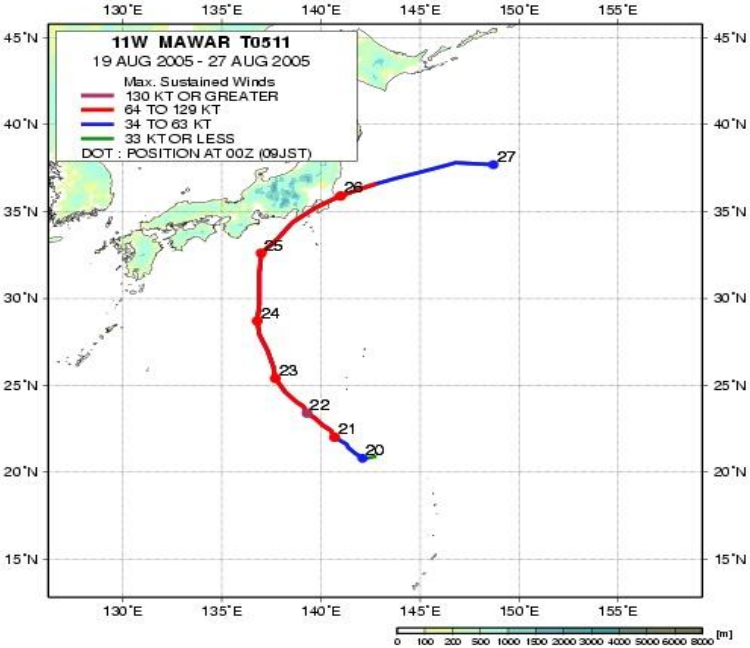


Sea Surface Temperature after Typhoon 11 tracking（2005）

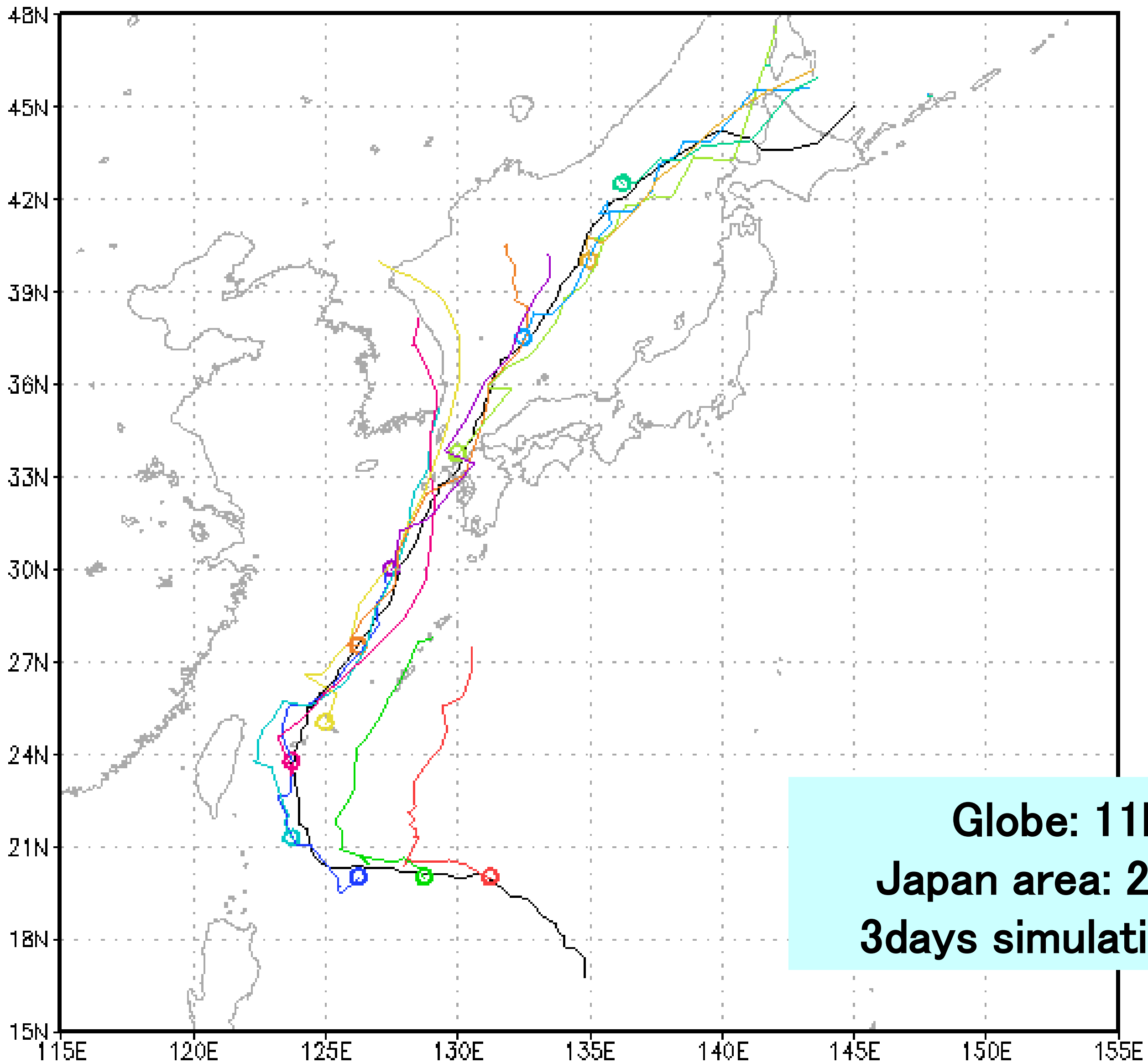
JAXA, http://www.eorc.nasda.go.jp/imgdata/topics/2005/tp050922.html

Aqua, NASA
Sea Surface temperature
averaged for 5 days(24th August～28th August)





Real time simulation for Typhoon T1306
（12-19, Sept 2006）



Globe: 11km, 32 layers
Japan area: 2.78km, 32 layers
3days simulation every 12 hours

Cumulus should be resolved,

and

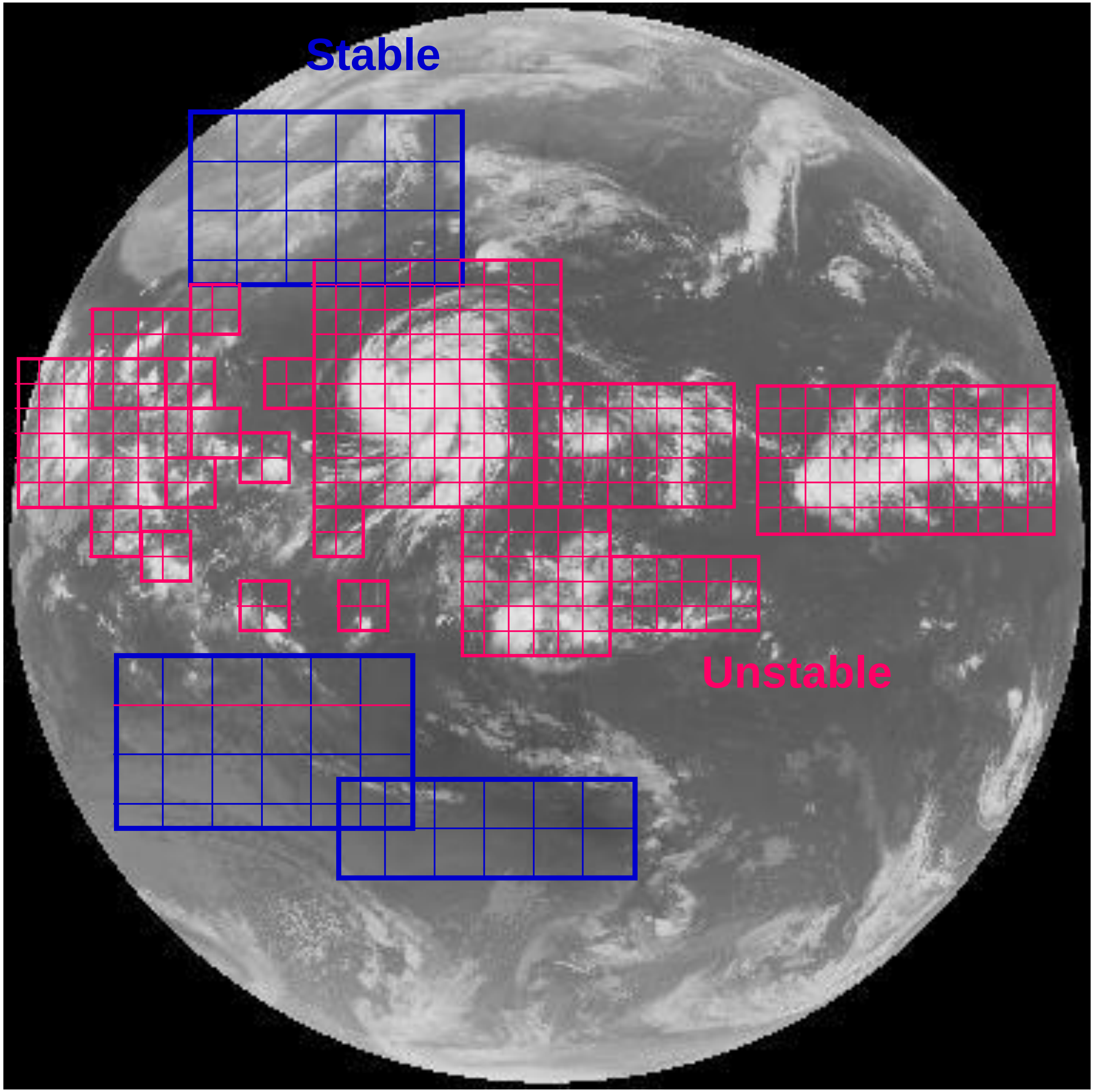
O(100)m horizontal resolution is required,

but

Even if Earth Simulator is used ,

it is impossible for the whole

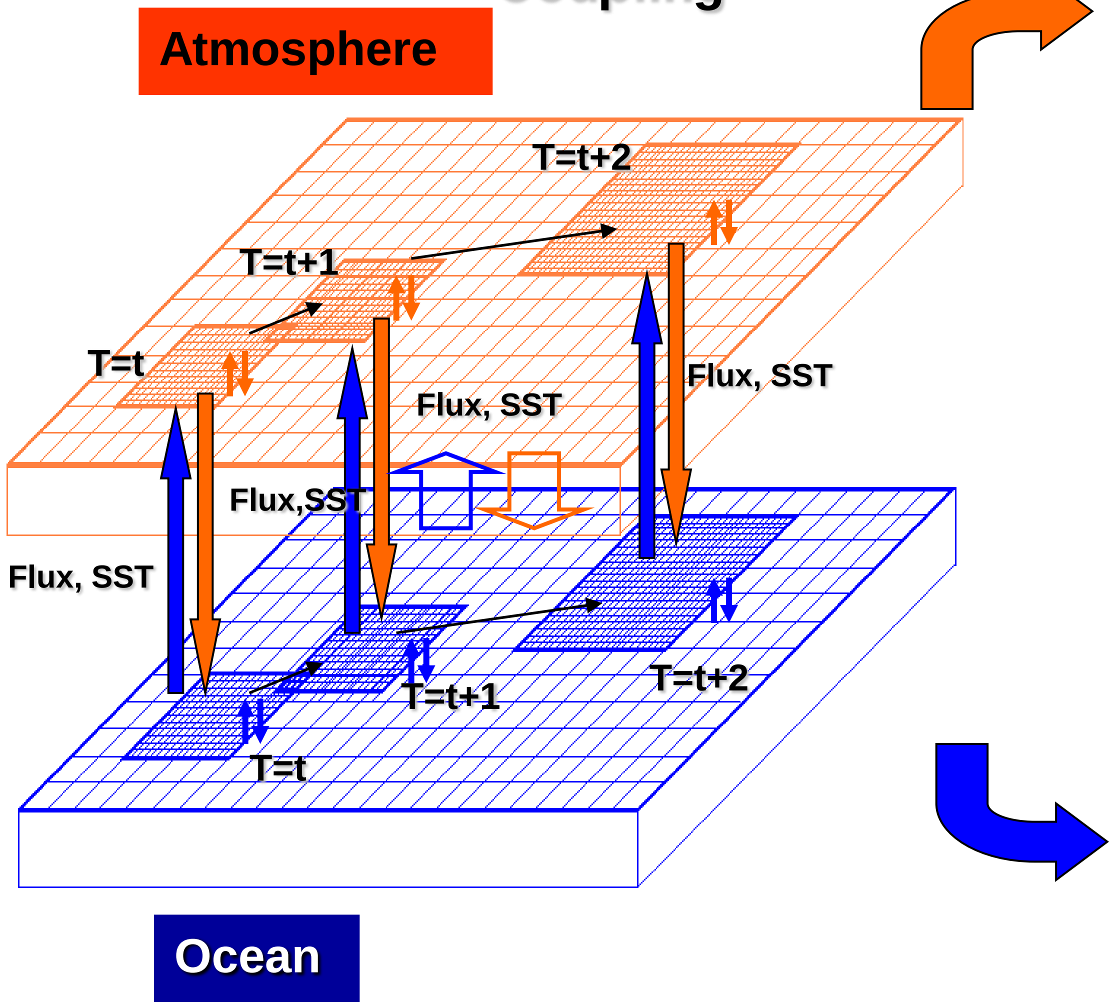
Downscaling & Upscaling !

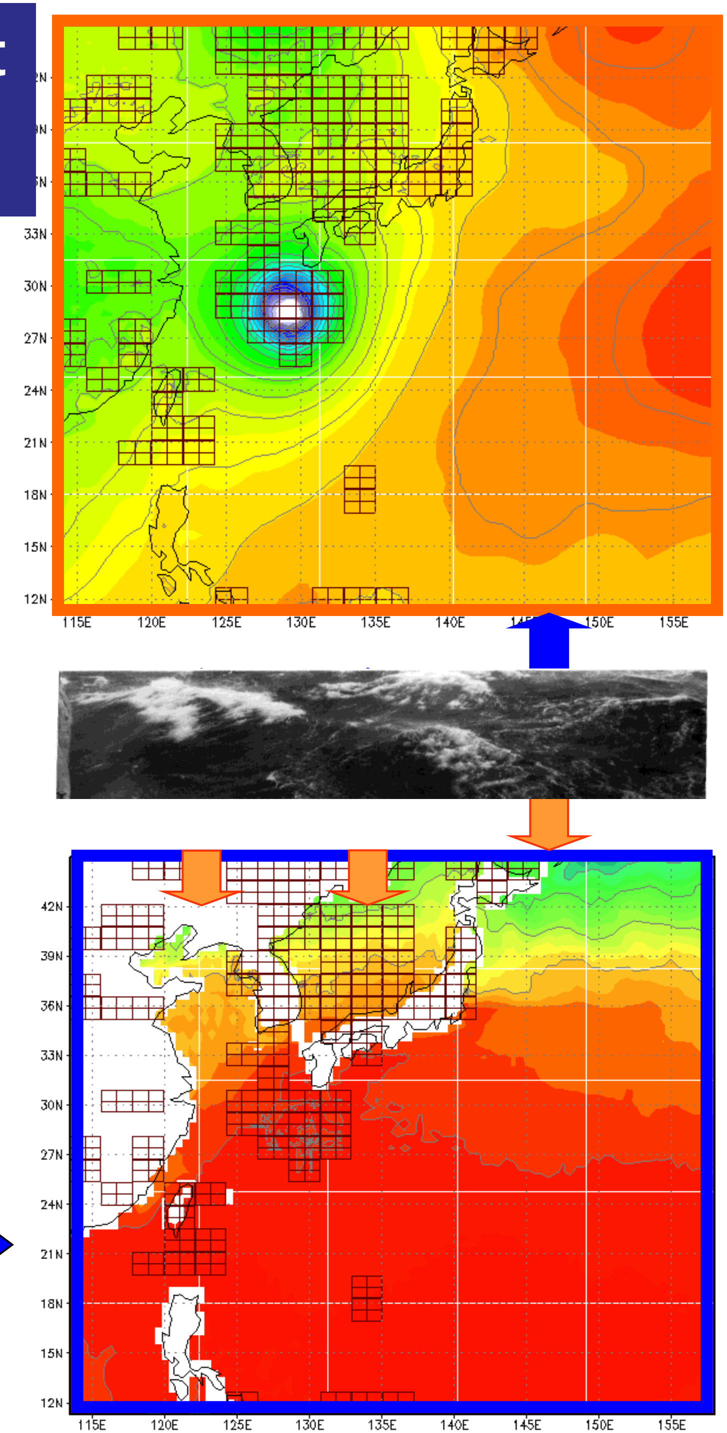


http://agora.ex.nii.ac.jp/~kitamoto/
research/rs/multi-spectrum.html.ja

Dynamic Adaptive Mesh Refinement In MSSG

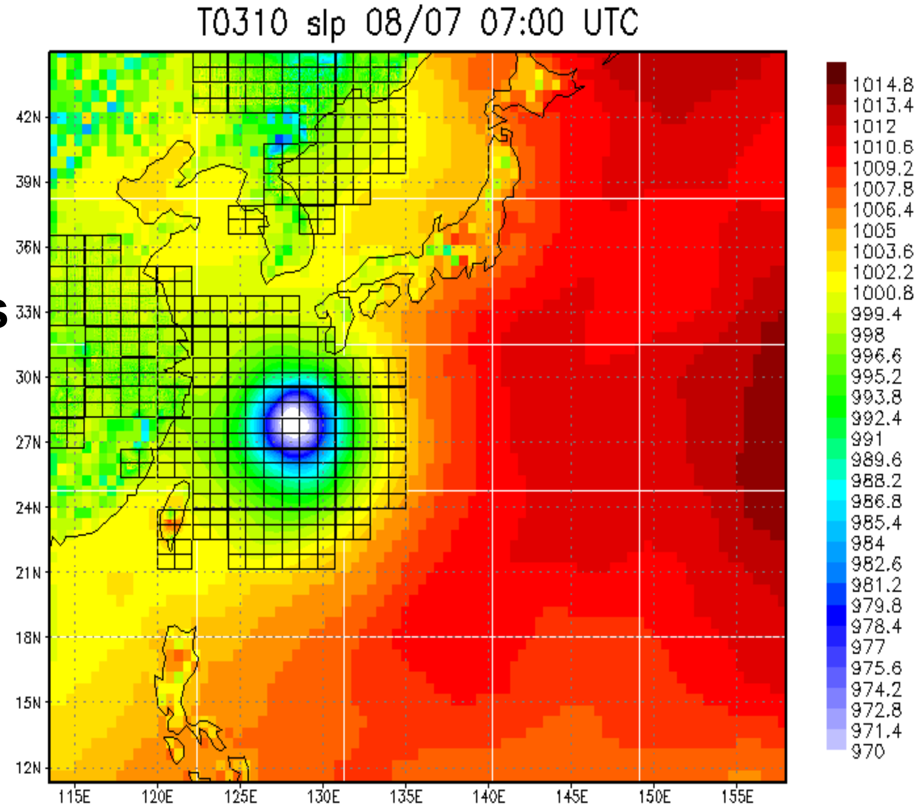
Dynamic Adaptive Mesh Refinement + 2-way nesting +Coupling



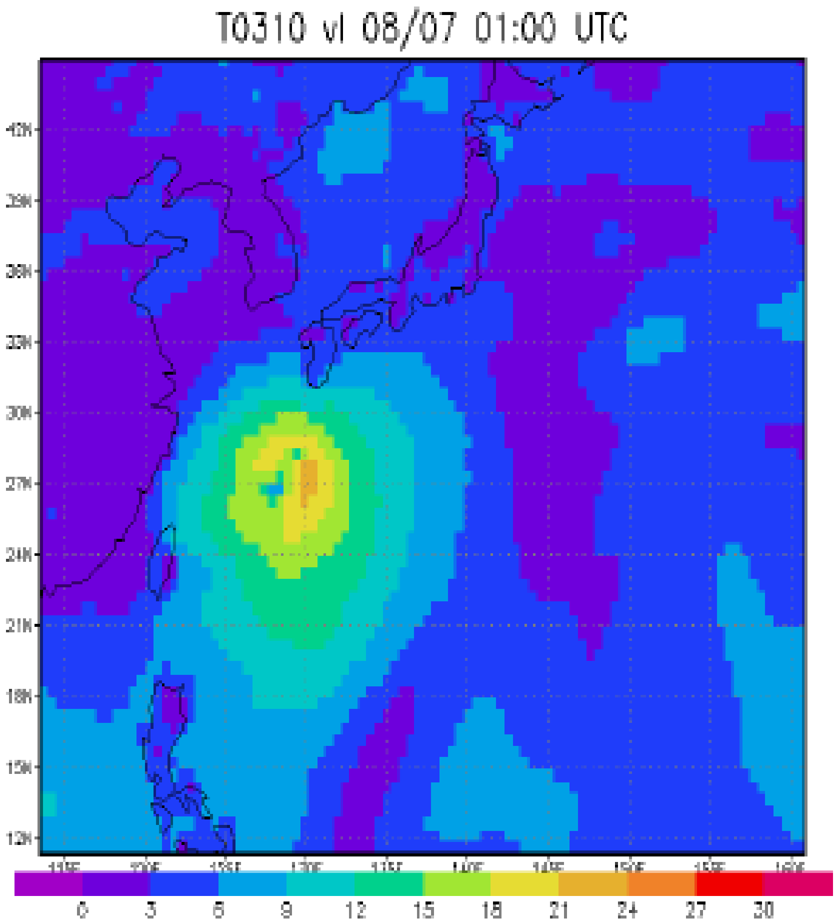


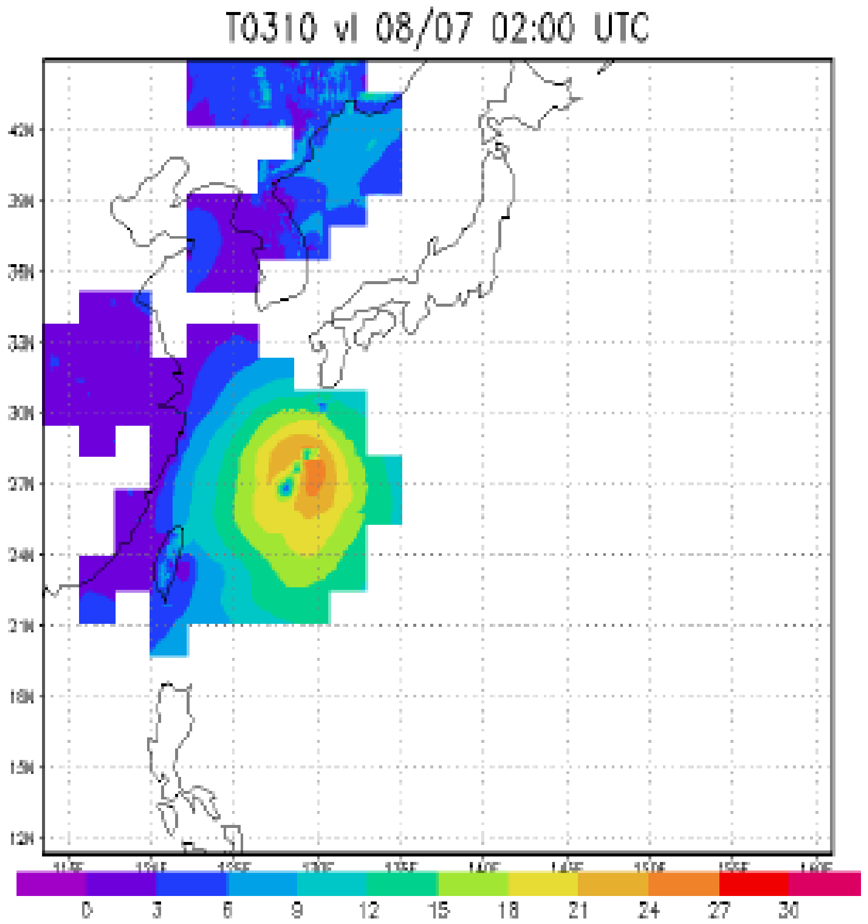
Dynamic Adaptive Mesh Refinement

- **High Performance Computing**
  - **No Overhead Computation for Moving Grid**
  - **Ultra High Parallelization**
- **Multiple fine meshed regions are available**
- **Not only Horizontal Refinement, but Vertical Mesh refinement**
- **Refinement Criterion:**
  - **low surface layer pressure**
  - **Vorticity**
  - **gradient of physical parameters**

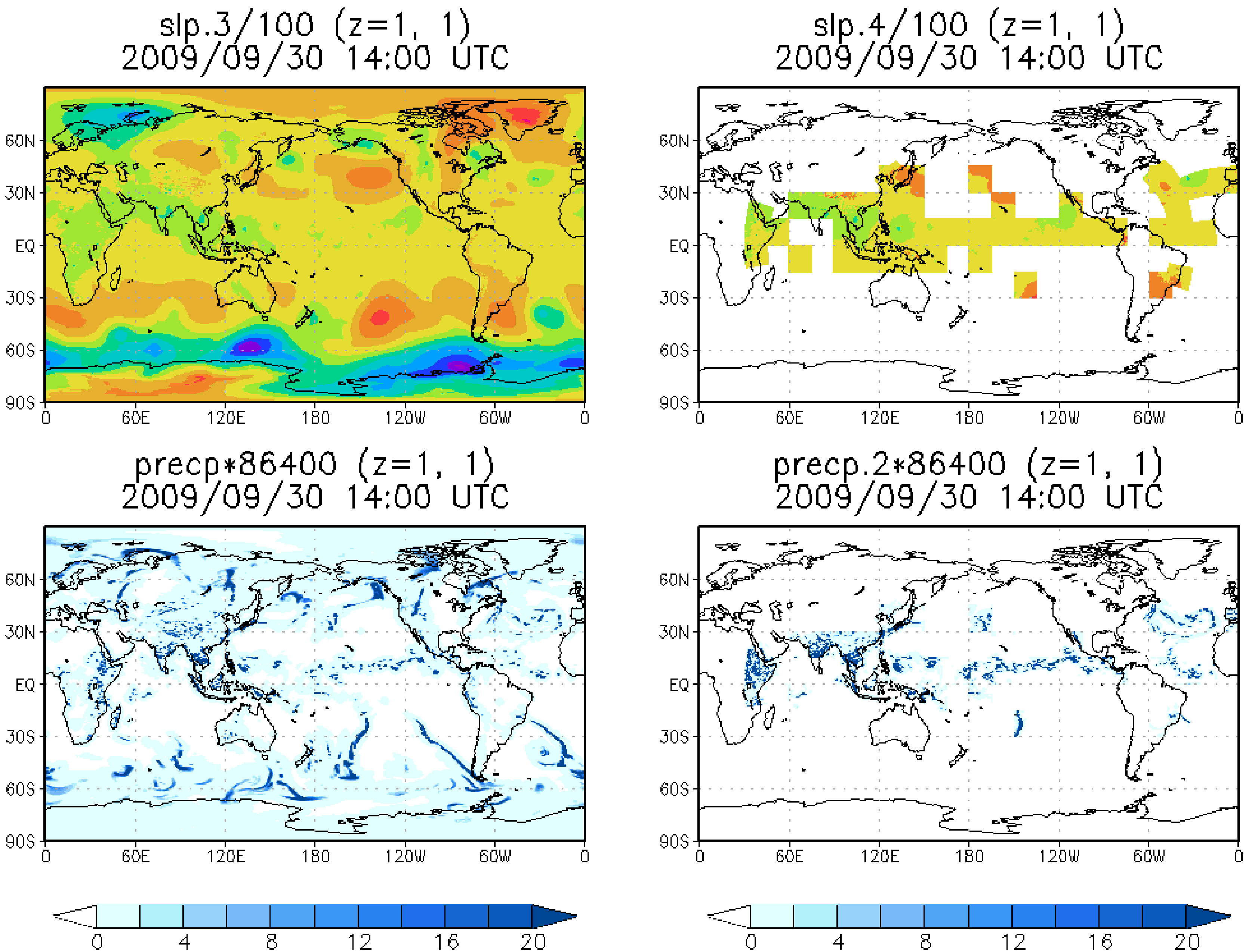


Physical performance
on coarse grid system v.s. fine grid system in AMR





AMR on Global Yin-Yang Grid System



Computational cost

										AMR	
	nest	Mgr ids	steps	Mgr ids*steps	%	elapse	%	nest	%	reinit	%
Atm	0, 0	181	17738	3210578	69%	15781.9					
	1, 1	34	17738	603092	13%	2964.6					
	2, 1	46	17670	812820	18%	3995.5					
				4626490		22742.0	90.9%	1028.7	5%	1.1	0.0%
Ocn	0, 0	77	22140	1704780	43%	964.3					
	1, 1	45	22140	996300	25%	563.5					
	2, 1	61	21280	1298080	32%	734.2					
				3999160		2262.0	9.0%	363.9	16%	1.4	0.1%
Cpl								0.7		0.0	
total						25015.2		1393.3	6%	2.5	0.0%

<u>Depth of Levels for AMR</u>

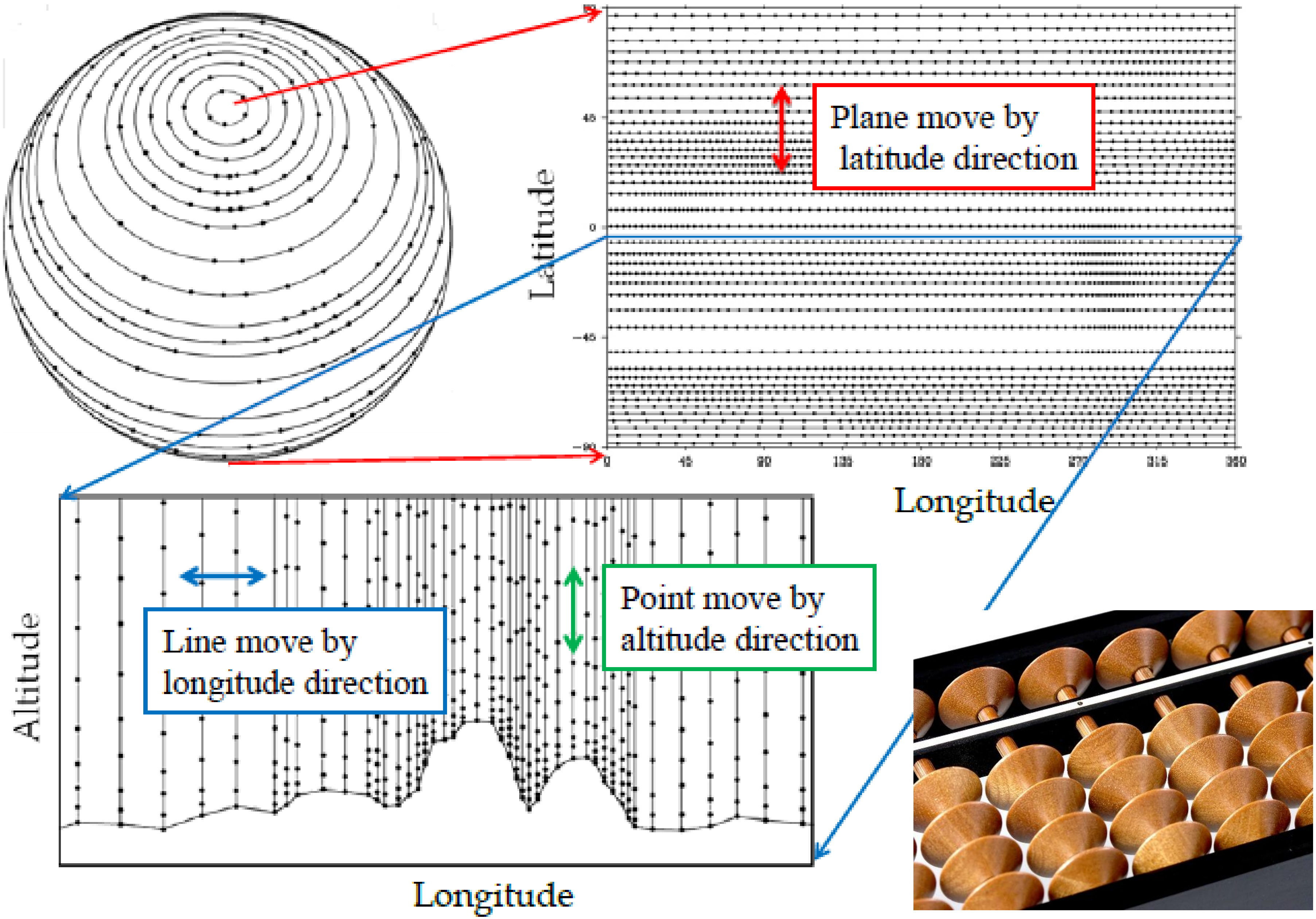
Is it efficient for the focused events?

Furthermore,

validate the conservation for loner integrations.

relax the length of time step for fine girds system.

Global Soroban Grid

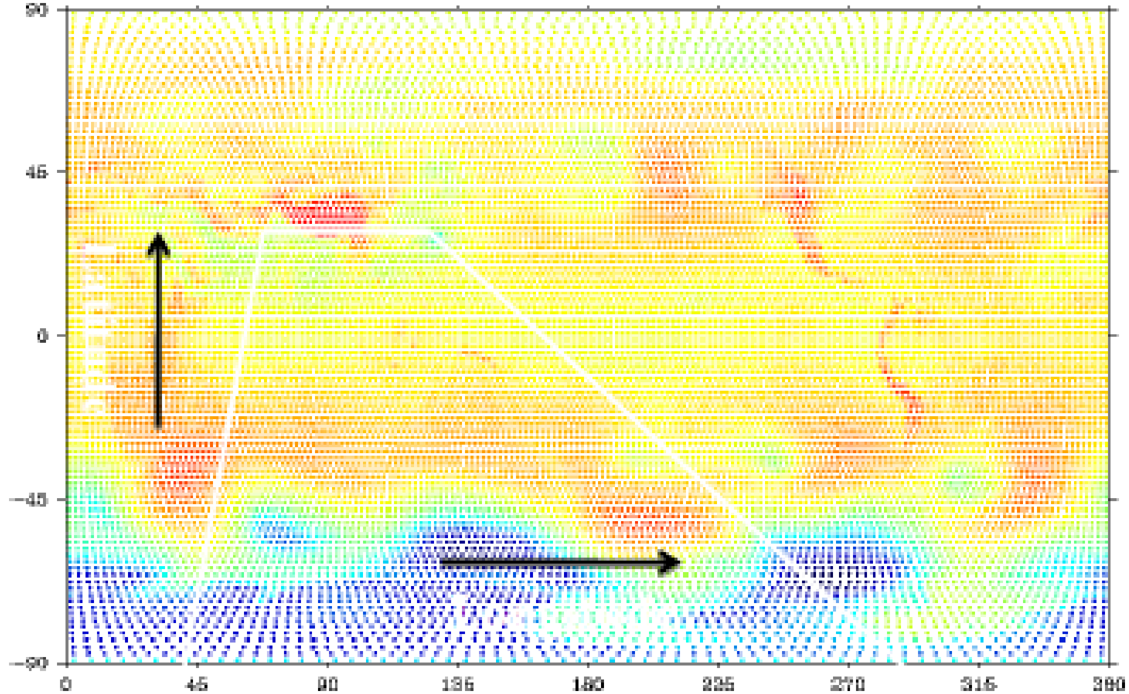


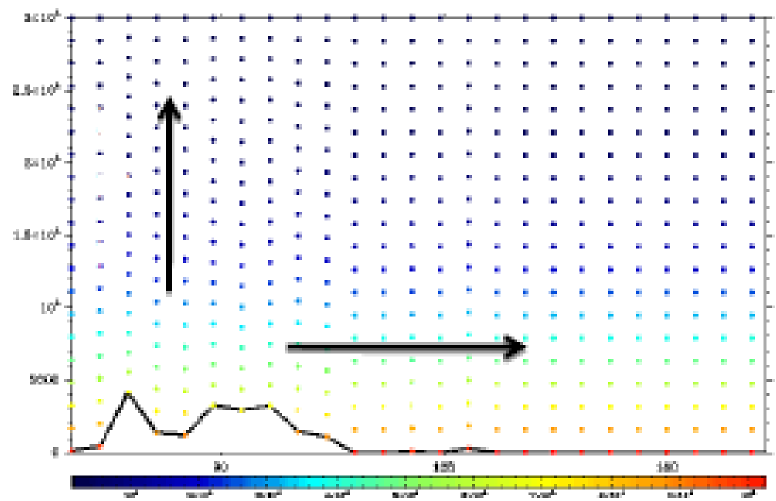
Grid Moving Tests

- Validate the grid moving scheme on the Global Soroban grid.
- Initial condition : realistic pressure state (2003/08/01).
- Criterion:

  gradient of pressure.

※No time integration





Initial grid position and pressure value

Near Future Plan:

- **Requirment:**
  - **Validation of multi-scale circulation in MSSG**
    - **Horizontal**
    - **Vertical**
    - **Extremes in IOD and Monsoon**
  - **Resolving urban canyon in MSSG**
    - **Heat-island phenomena , Heavy rain**

- **Computational Optimization for Multi-scale & Multi-physics simulations on the Peta-flops machine K-computer.**
  - **For the trend of many cores**
  - **To consider memory Band Width**
  - **To control hierarchy of memory ⇔ hierarchy of programming to keep the HPC**