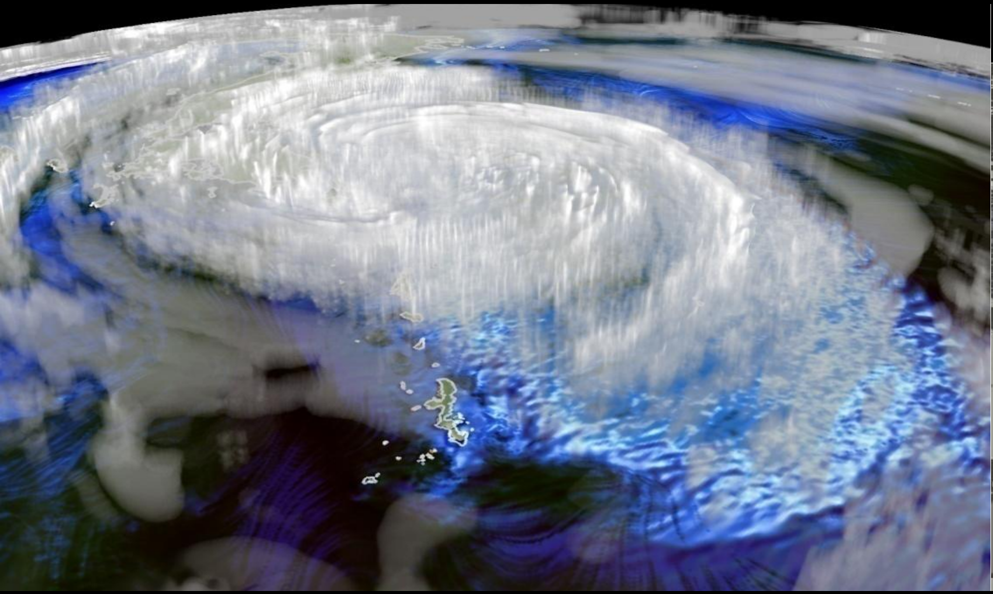
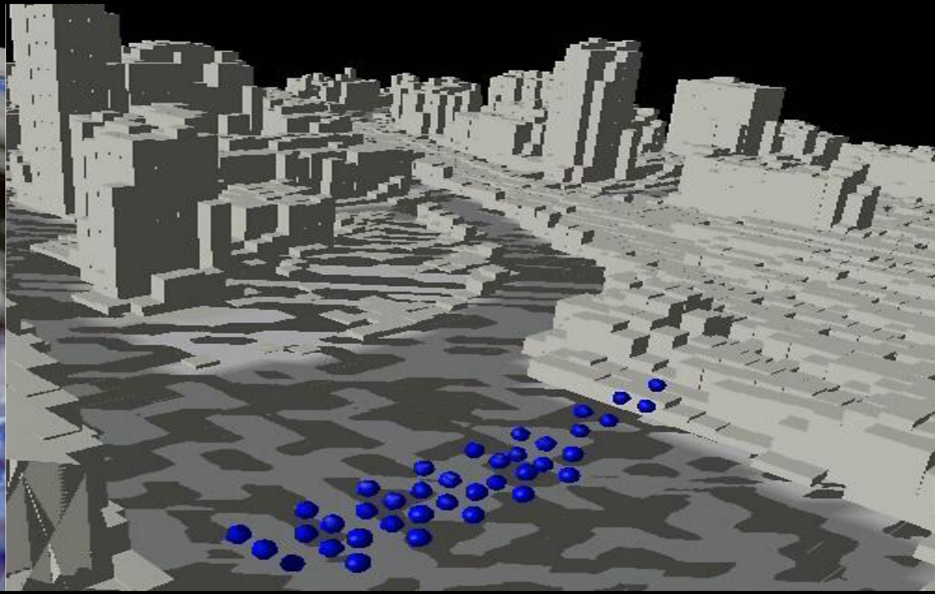
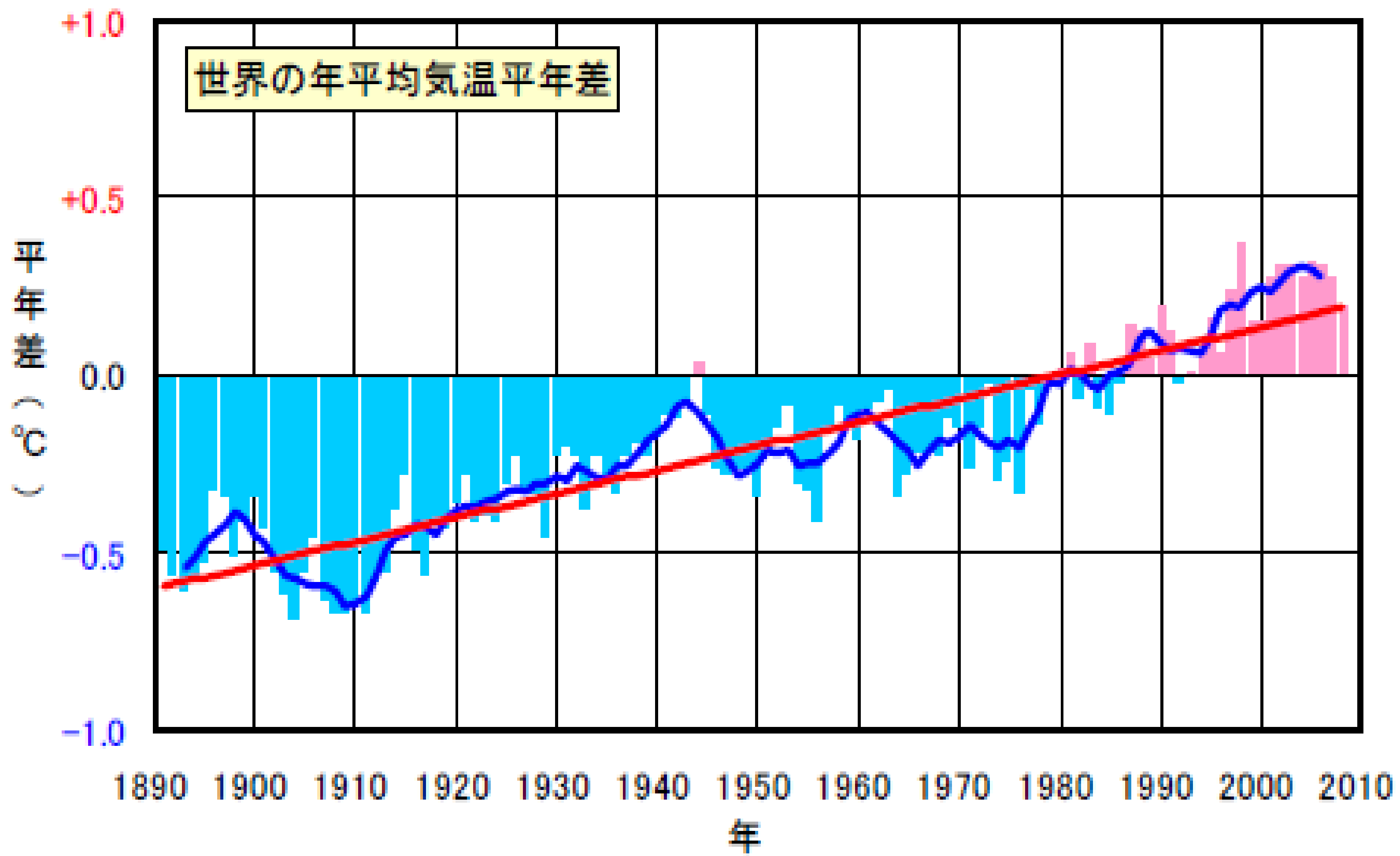
Multi-scale Multi-physics simulations and toward the next step on the Earth Simulator





Keiko Takahashi, Yuya Baba, Shinichiro Kida, Keigo Matsuda, Ryo Onishi
Earth Simulator Center, Japan Agency of Marine-Earth Science and Technology (JAMSTEC)



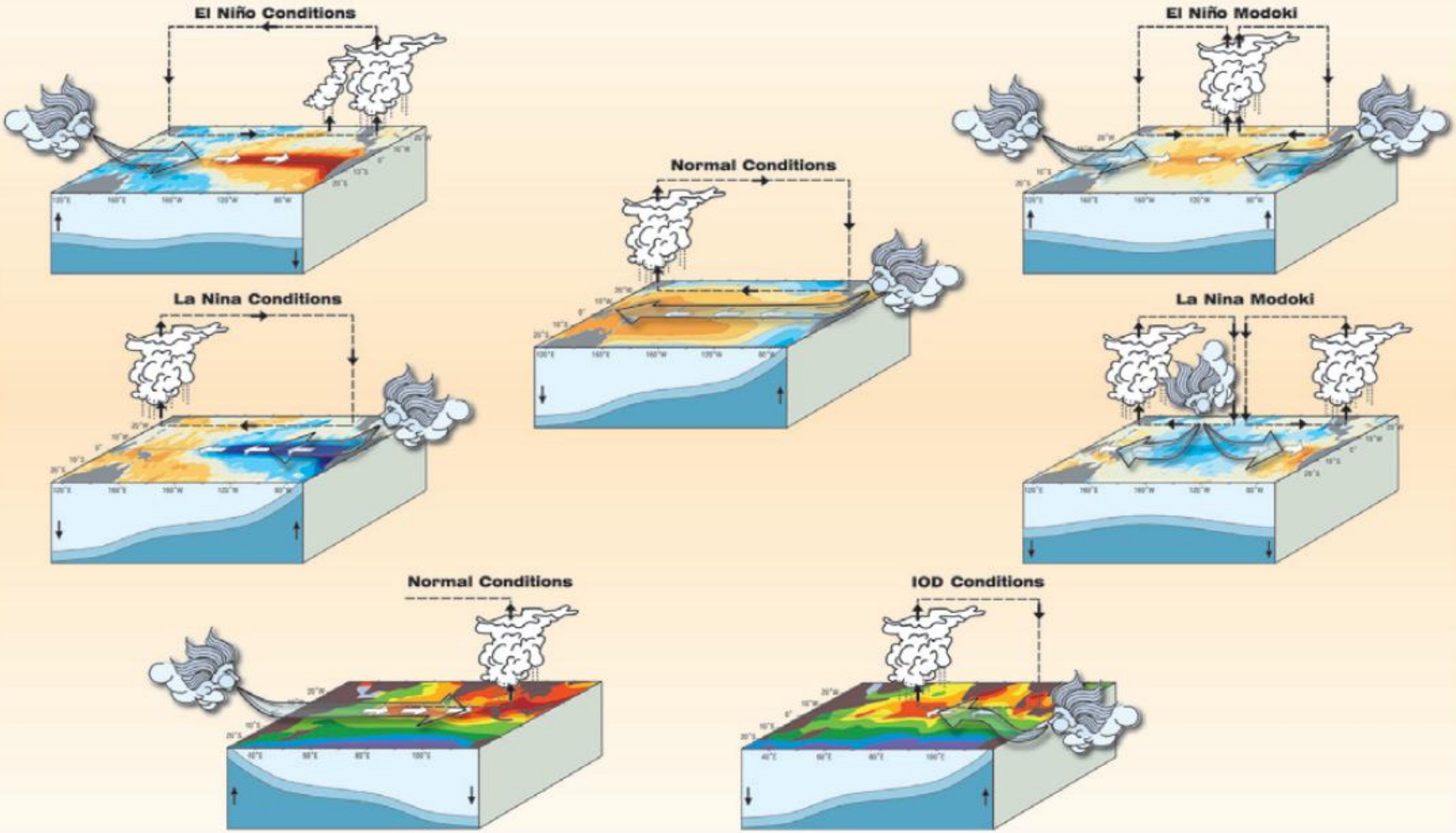
世界の年平均気温の変化（1891～2008 年）

観測機器によって得られた資料にもとづく、1891 年以後の世界全体の年平均気温の推移を示す。棒グラフは各年の平均気温の平年差（平年値との差）を示している。太線（青）は平年差の 5 年移動平均を示し、直線（赤）は平年差の長期的傾向を直線として表示したものである。平年値は 1971～2000 年の 30 年平均値。

出典：気象庁、2009

Prof. Toshio Yamagata (JAMSTEC)

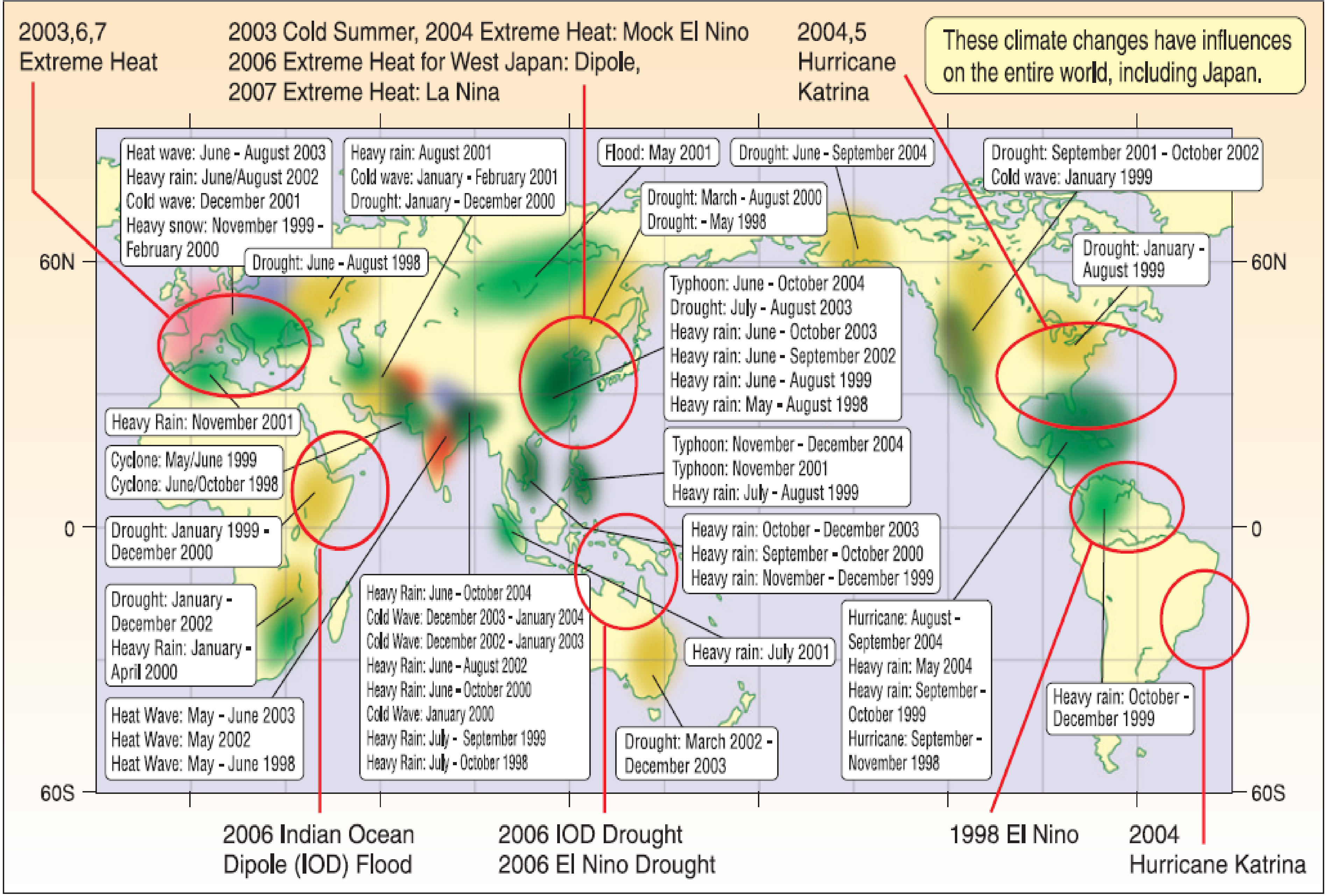
Indian Ocean Dipole Phenomenon and El Nino Modoki: Recent Discovered Factors Related to Global Warming



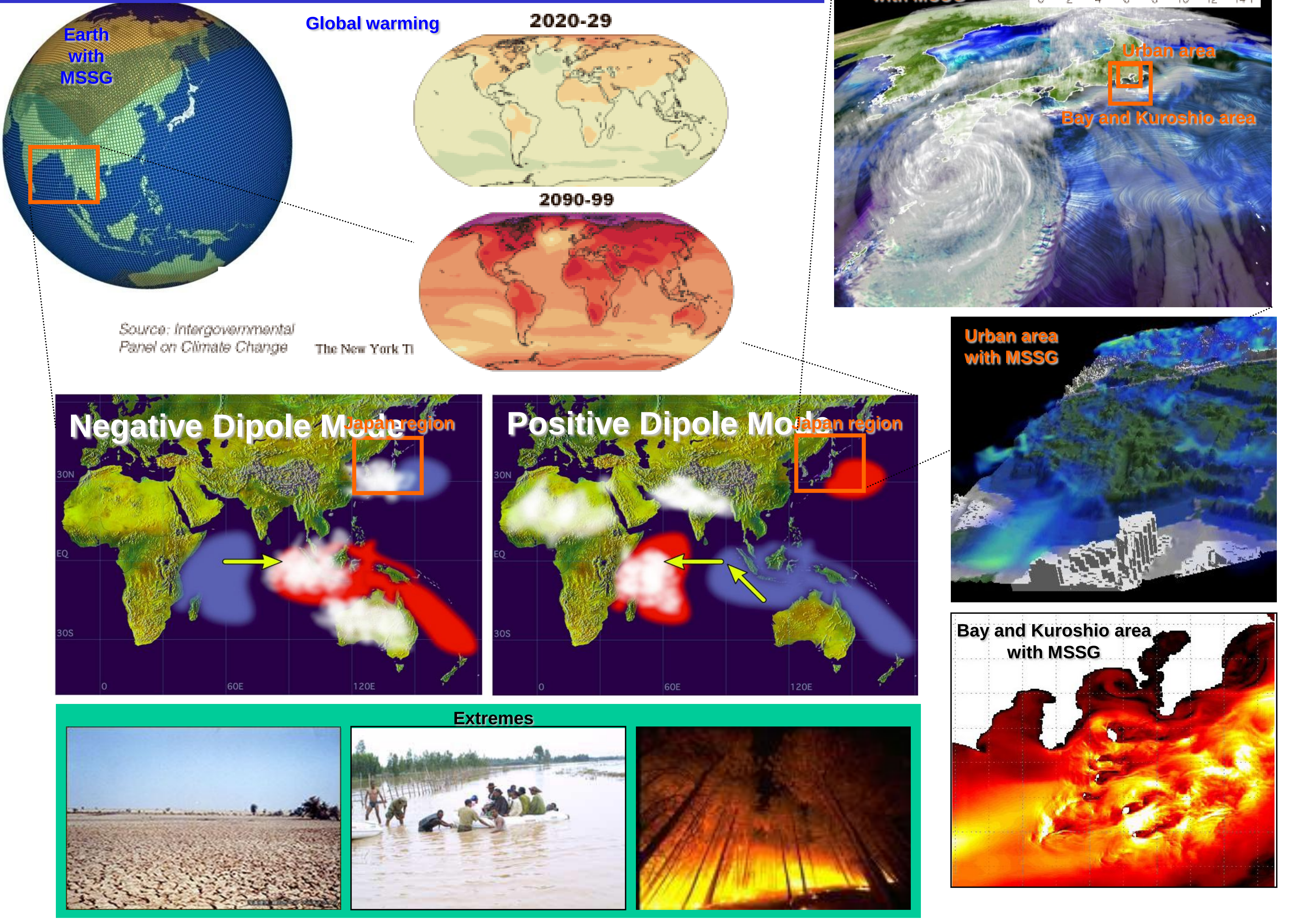
As global warming has progressed, the pattern of El Nino/La Nina (indicated in the left upper row, top and bottom, as the large gap in the east-west direction from climatic mean state indicated in the upper row, center) has been accompanied by an increasing number of El Nino Modoki/ La Nina Modoki patterns (the average indicated in the upper row center and the gap from the average indicated in the right upper row top/bottom) as

From the brochure of Application Lab of JAMSTEC

The Global Distribution of Major Weather Disasters (1998 - 2004) and Abnormal Weather due to Climate Change



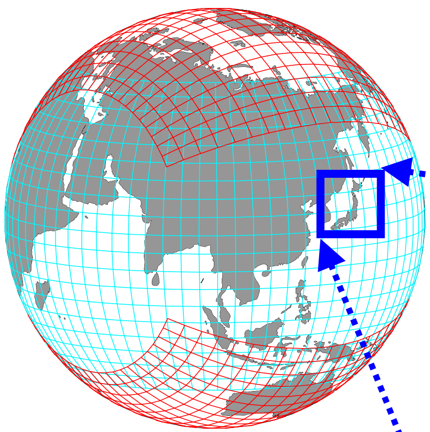
Outline of Seamless Simulations with MSSG



Multi-Scale Simulator for the Geoenvironment (MSSG)

Global :

Non-hydrostatic Coupled A-O model



Seasonal ~ Annual Prediction

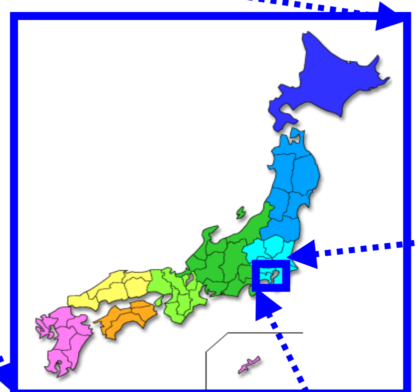
2- 40 km horizontal,
100 vertical layers

Regional, Meso-scale:

Non-hydrostaticCoupled A-O model

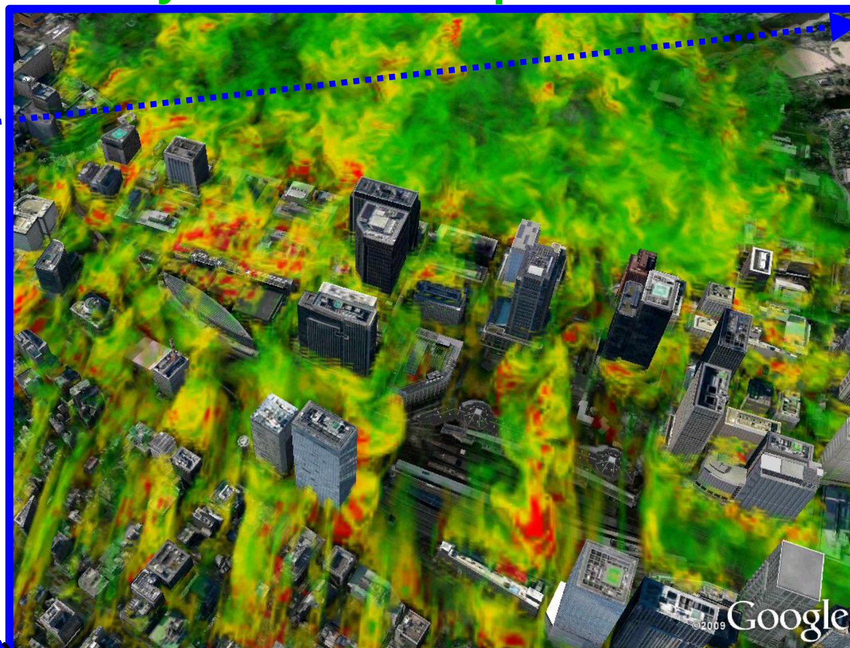
Daily ~ Weekly ~ Monthly forecasting
Typhoon, Baiu rain etc.

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



Urban Weather/Climate:

Non-hydrostatic Coupled A-O model

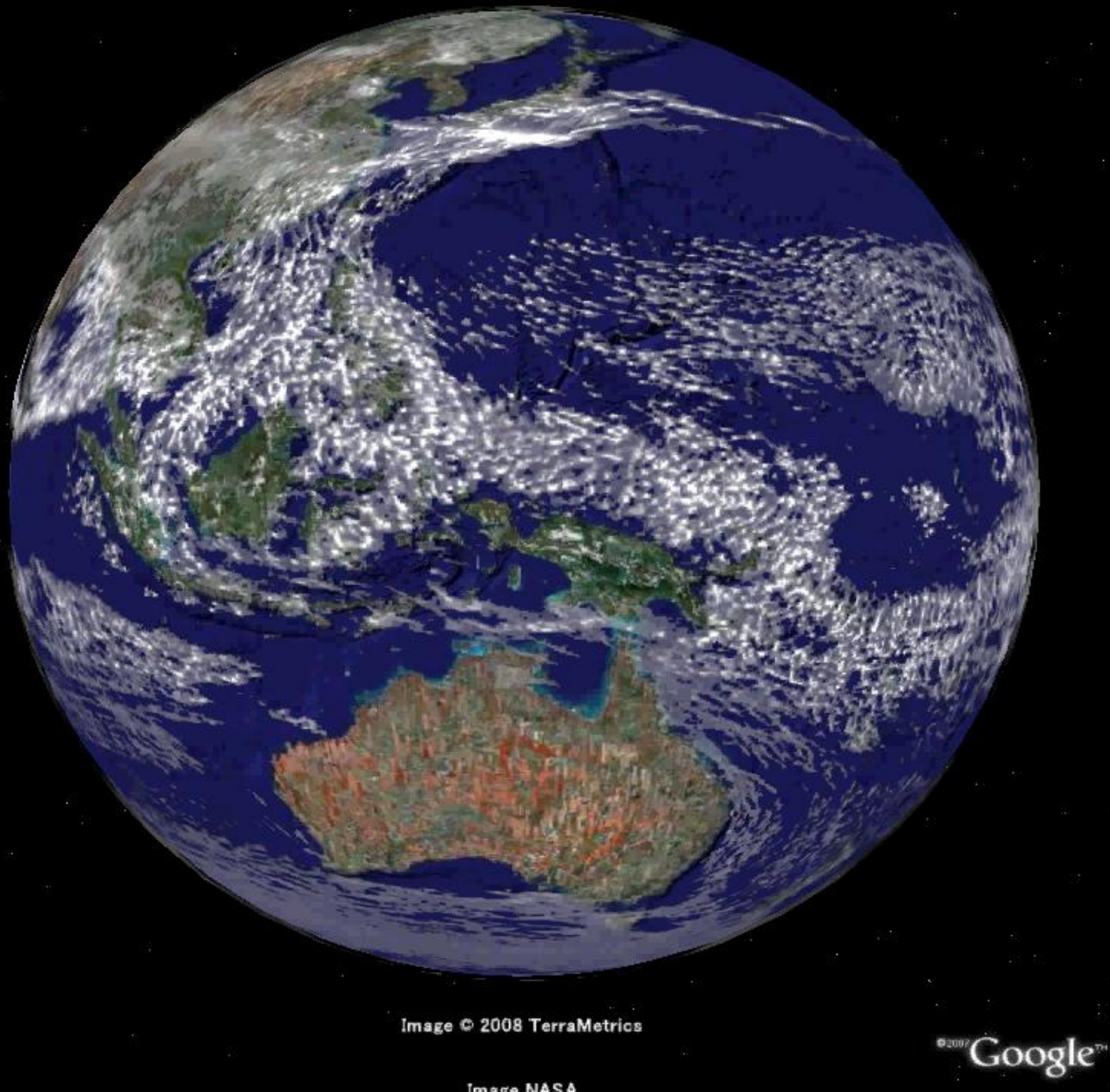


Hourly, Daily ~ Seasonal Prediction

O(1)m ~ O(100)m for horizontal,
200 vertical layers

（Data: Geographical Survey Institute）

Results from MSSG on Google Earth



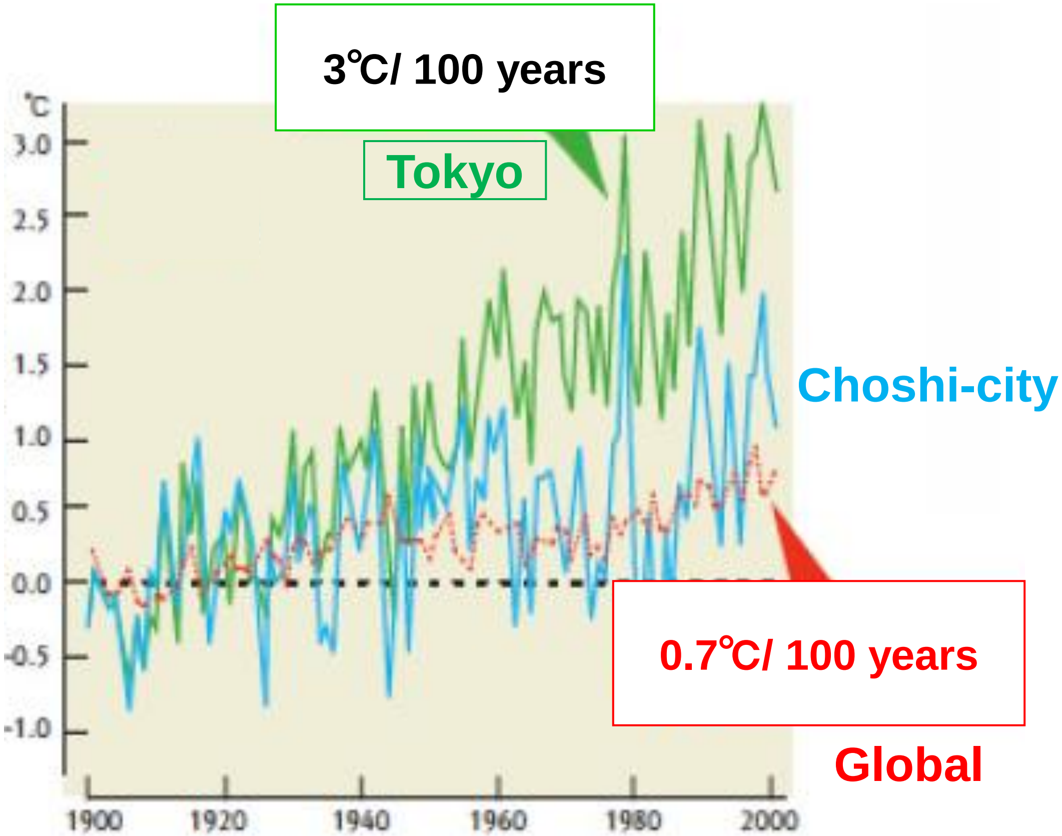
Outline of MSSG

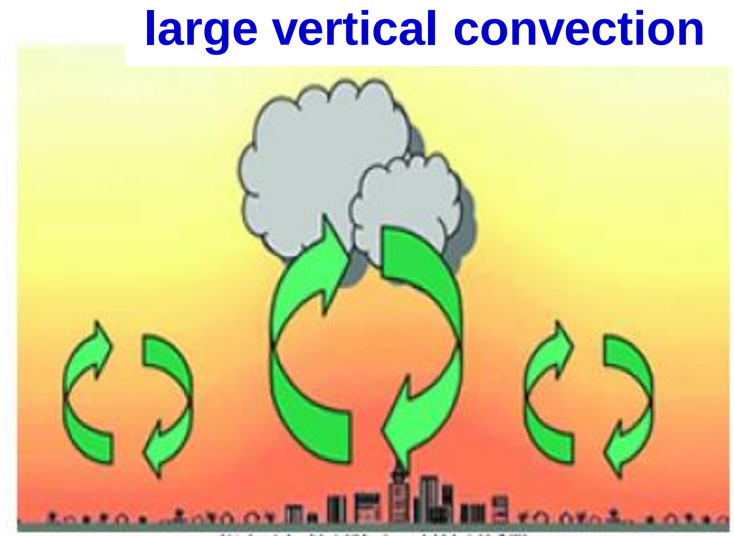
		MSSG-A	MSSG-O
		Non-hydrostatic AGCM	Non-hydrostatic /hydrostatic OGCM
governing eqs.		Fully compressive N-S eqs.	incompressive N-S eqs.
grid system		Yin-Yang grid (overlapped 2 lat-lon)	Yin-Yang grid (overlapped 2 lat-lon)
discritization	space	Arakawa-C grid (horizontal), Z* (vertical)	Arakawa-C grid (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

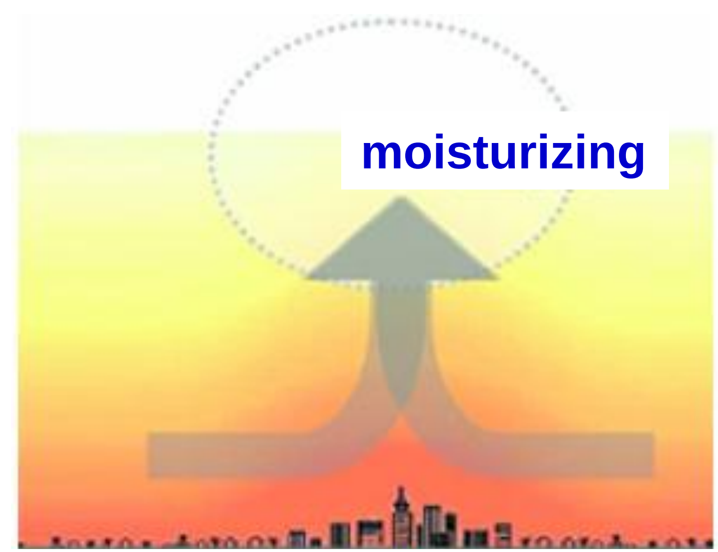
Multi-scale Multi-physics simulations


五反田駅
Gotanda Sta.

Increasing averaged temperature in Urban in Tokyo, during 100 yeas



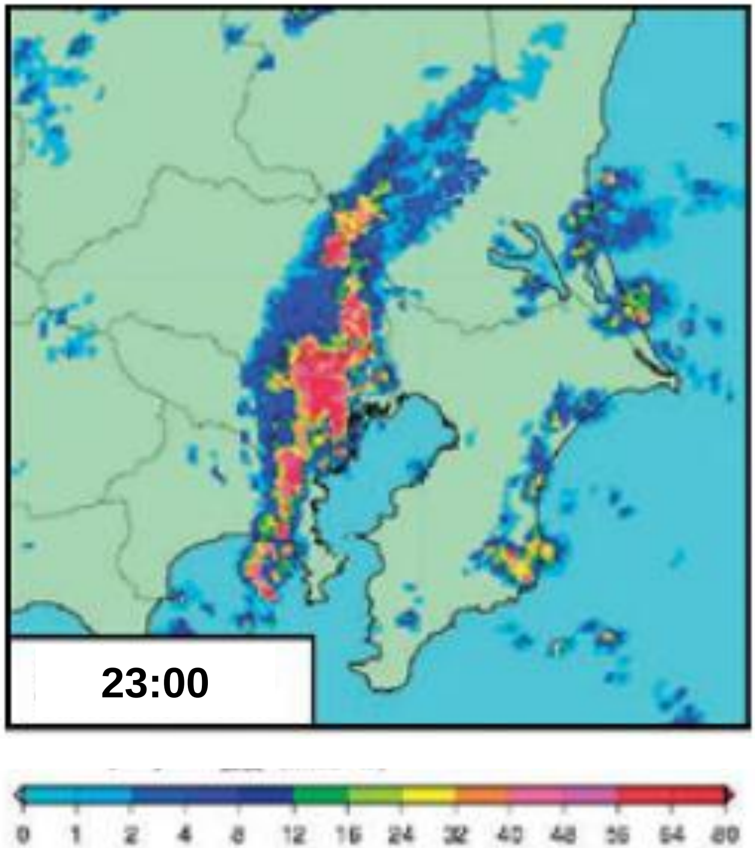




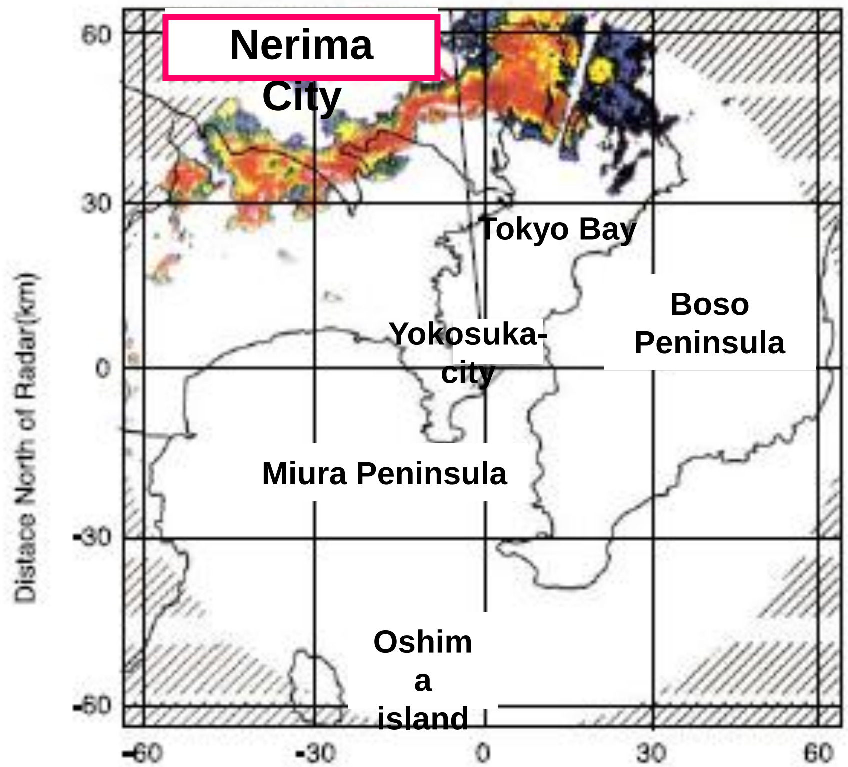
What does enhance the warming of about 2 ℃ more increasing?

Heat island due to anthlopogenic activities ?

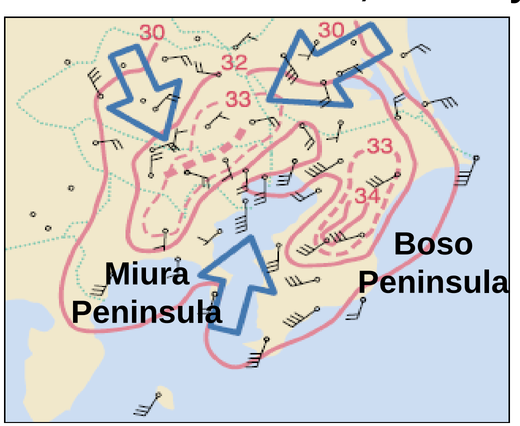
Heavy Rain in Tokyo Urban Area



Observational Data with Radar System (mm/h) at 23:00 on 4th September 2005



Observational Data at 16:07, 21th July, 1999

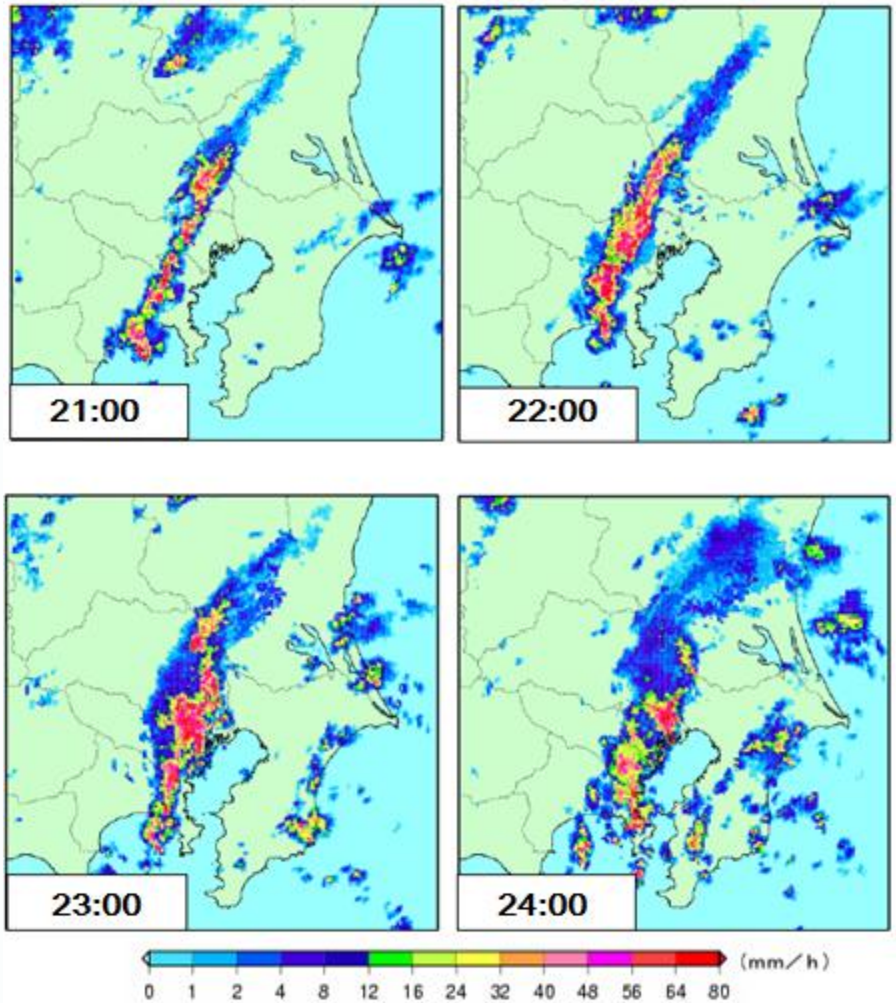


Coupling urban-scale to meso-scale phenomena

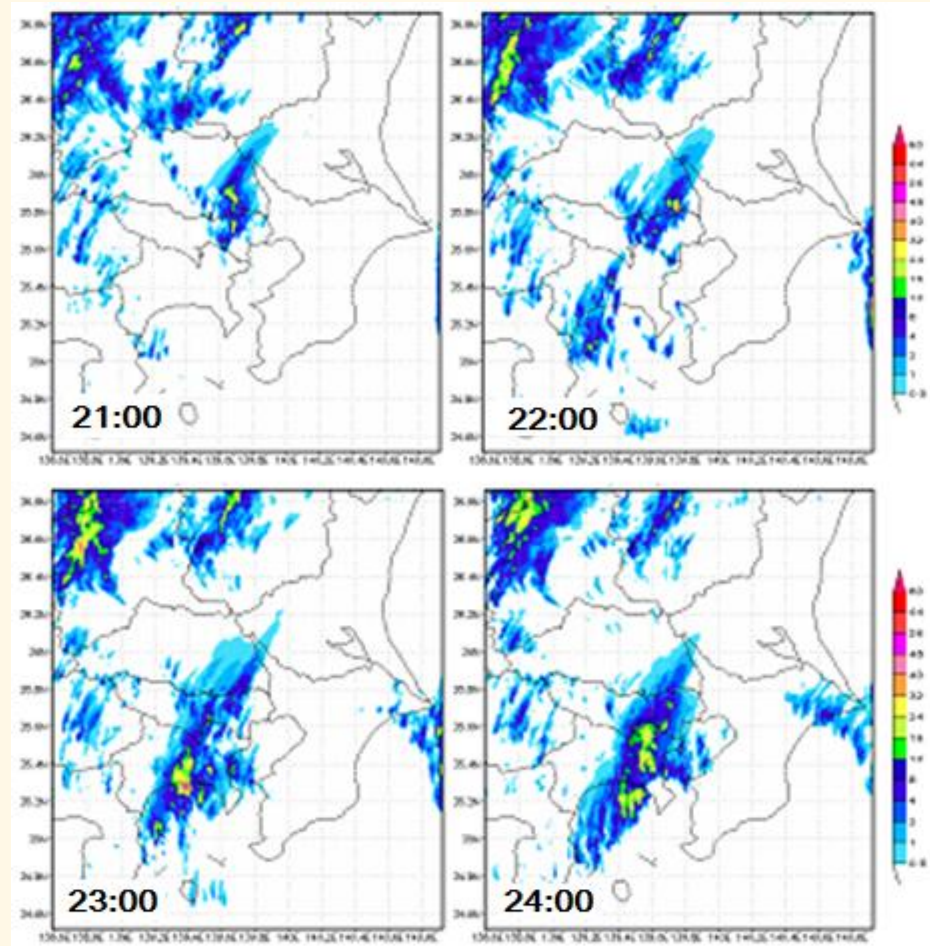
Hindcast Simulation with Urban Canopy Layer Model in MSSG

Tokyo Heavy Rain in 2005

Obaservational Data



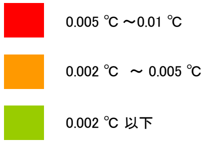
Simulation Results



Organized/rapid cloud development can not be seen in simulations

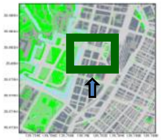
Impacts of Three Dimensional Radiation Processes to Heat Content in Urban Canyon

Differences of temperature distribution between with 3D radiation process model and without the model.



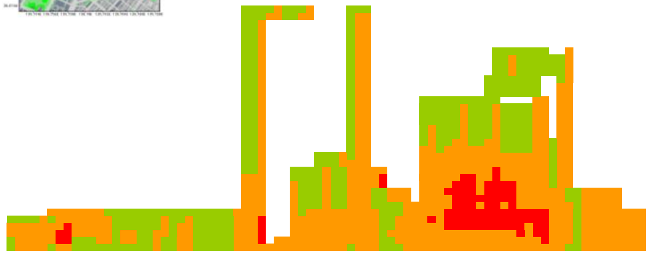
temperature distribution on walls for East.

temperature distribution on walls for West.



temperature distribution on walls for South

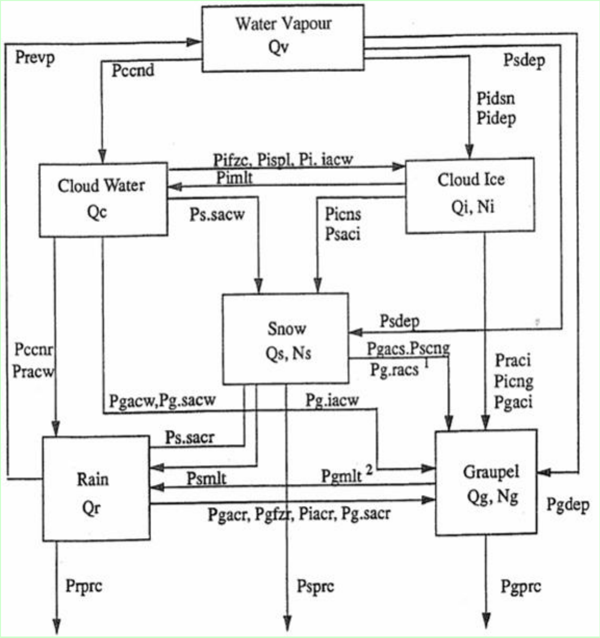
temperature distribution on walls for North



Heat content tends to be stored in lower level in urban canopy layer and its tendency was appeared on walls toward the all direction.

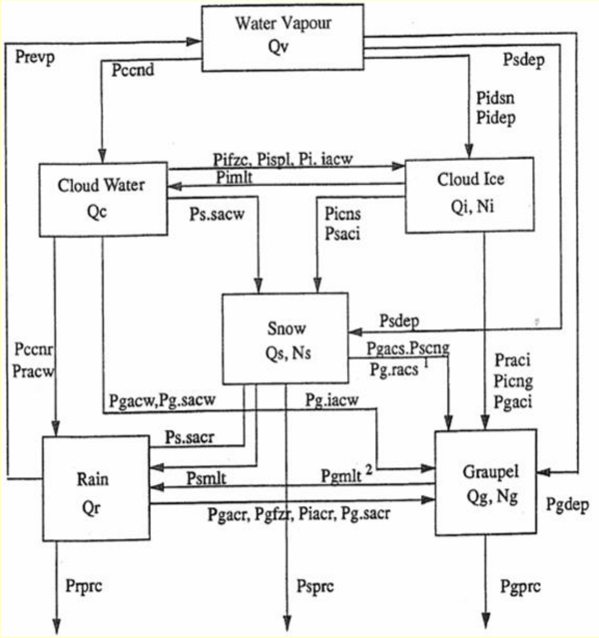
MSSG-Bin Method
(Hybrid-Bin Method)

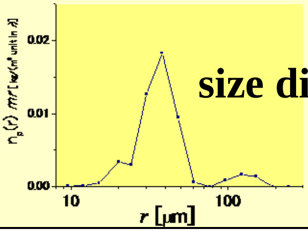
Bulk



Reisner et al. (1998)

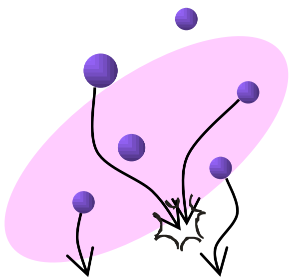
MSSG-Bin





size distributions

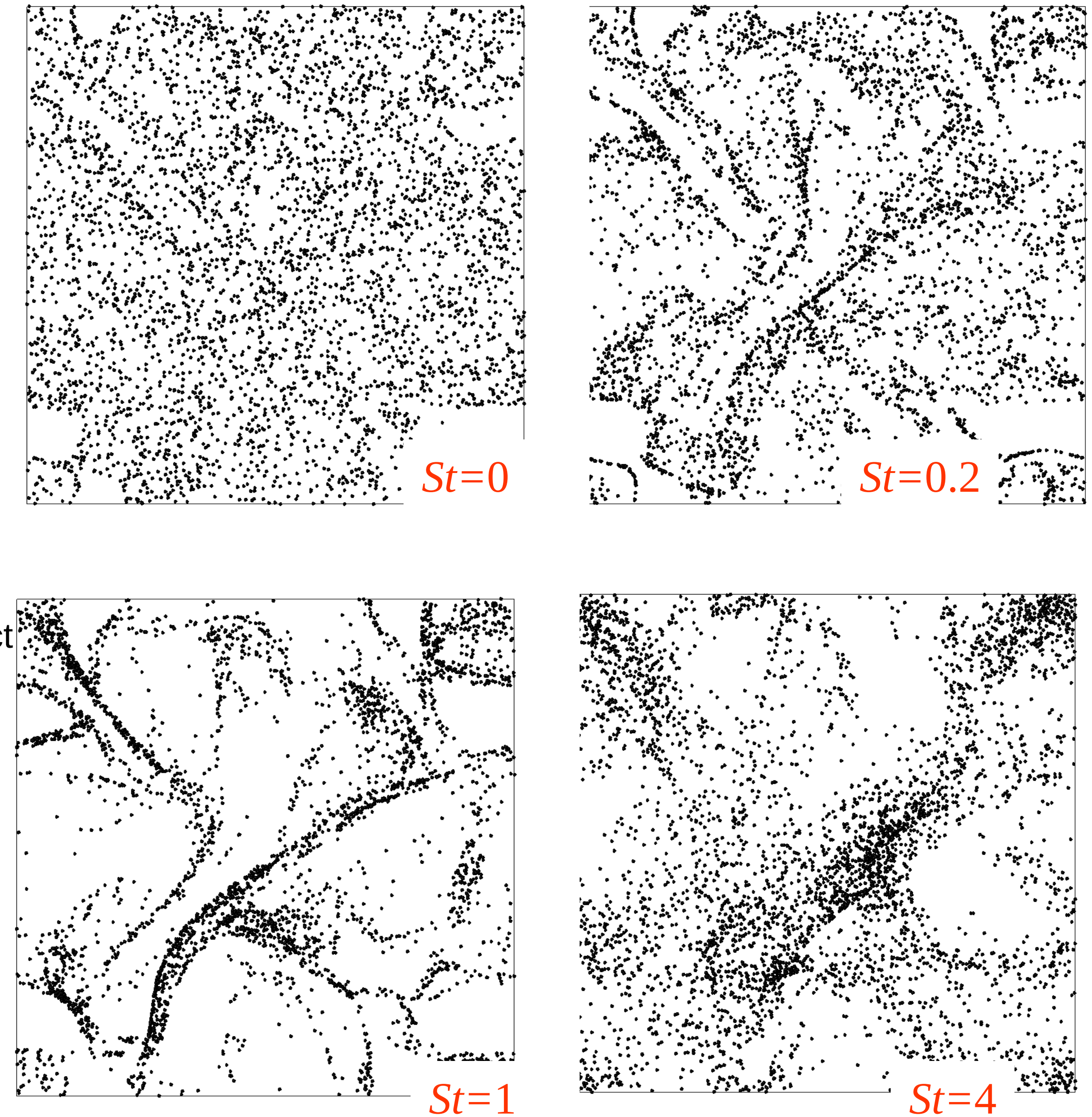
Turbulent Collision Kernel Model



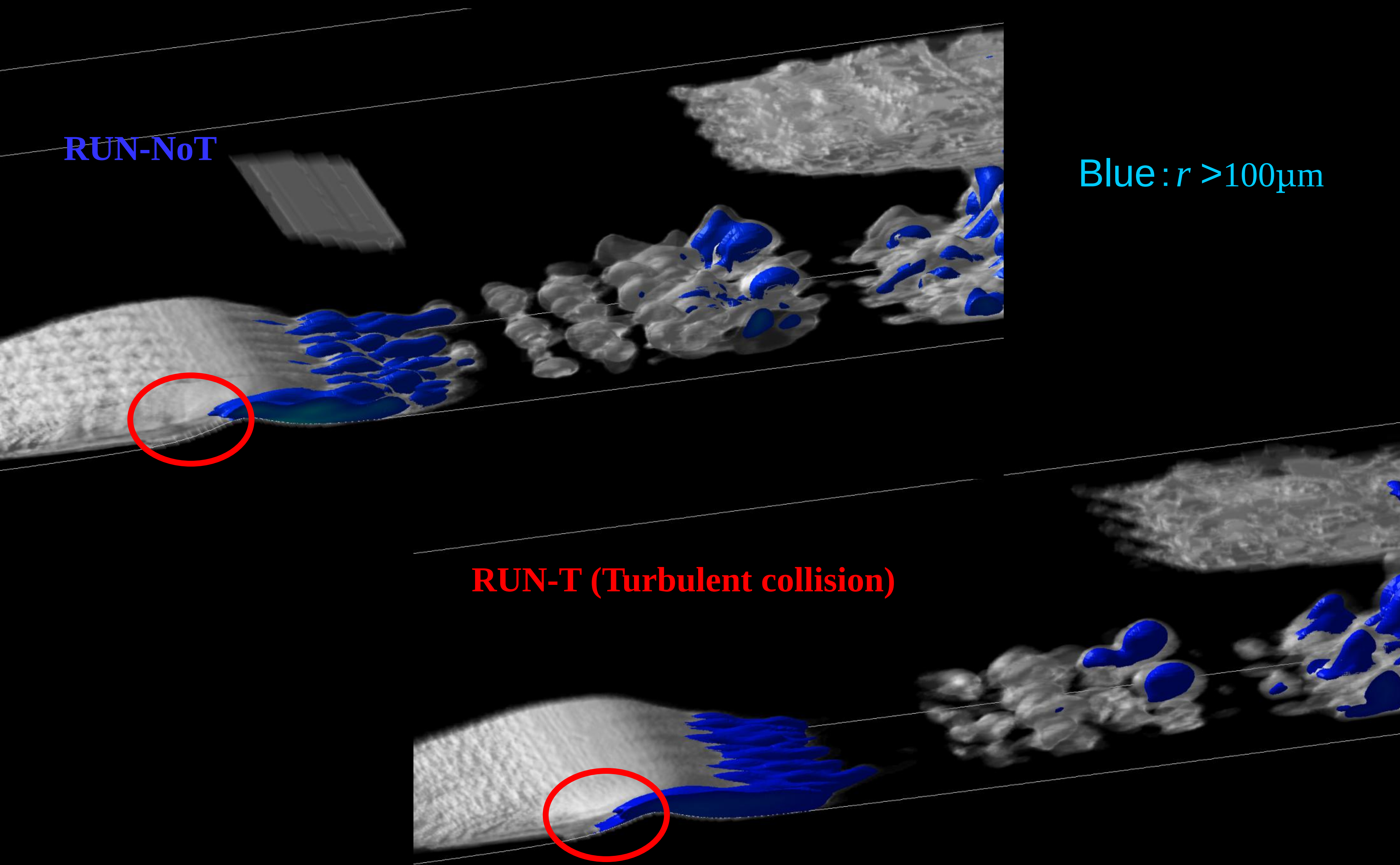
$$\langle K_c(r_1, r_2) \rangle = 2\pi R^2 \langle |w_r| \rangle g(R)$$

- R : collision radius (=r_1+r_2)
- $|w_r|$: radial relative velocity at contact
- $g(R)$: radial distribution function at contact

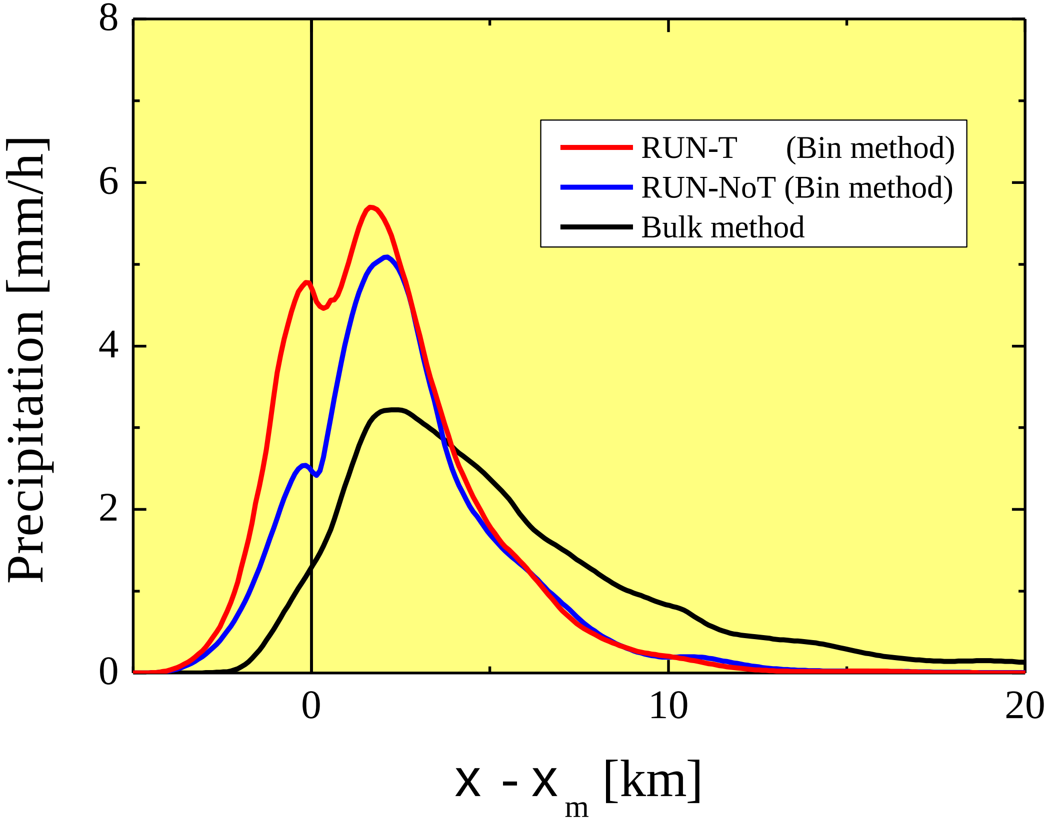
$$St = \tau_p / \tau_\eta$$



Visualized clouds (t = 3T)



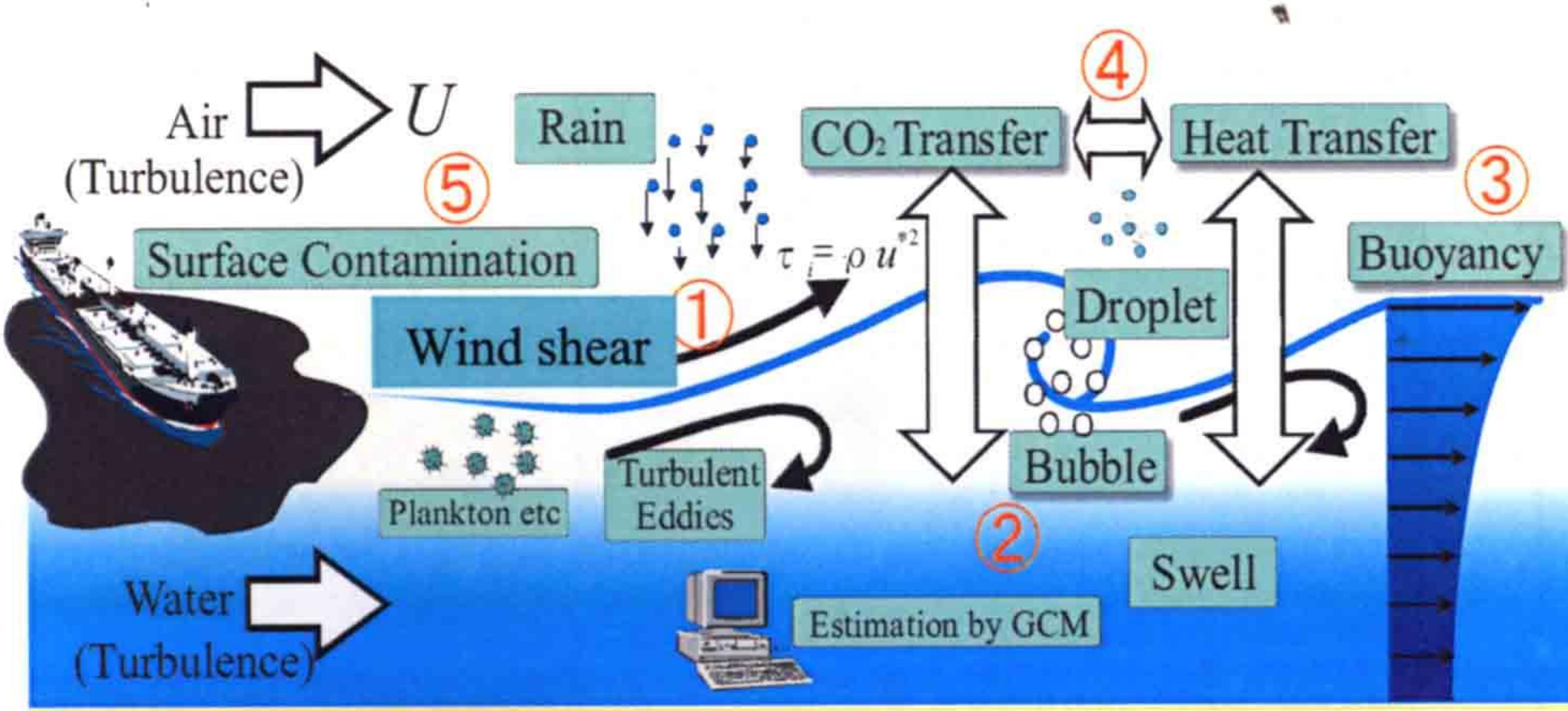
Averaged precipitation over the mountain



	Ave. Precip.[mm/h]
RUN-NoT	2.8
RUN-T	3.4
Bulk method	2.1

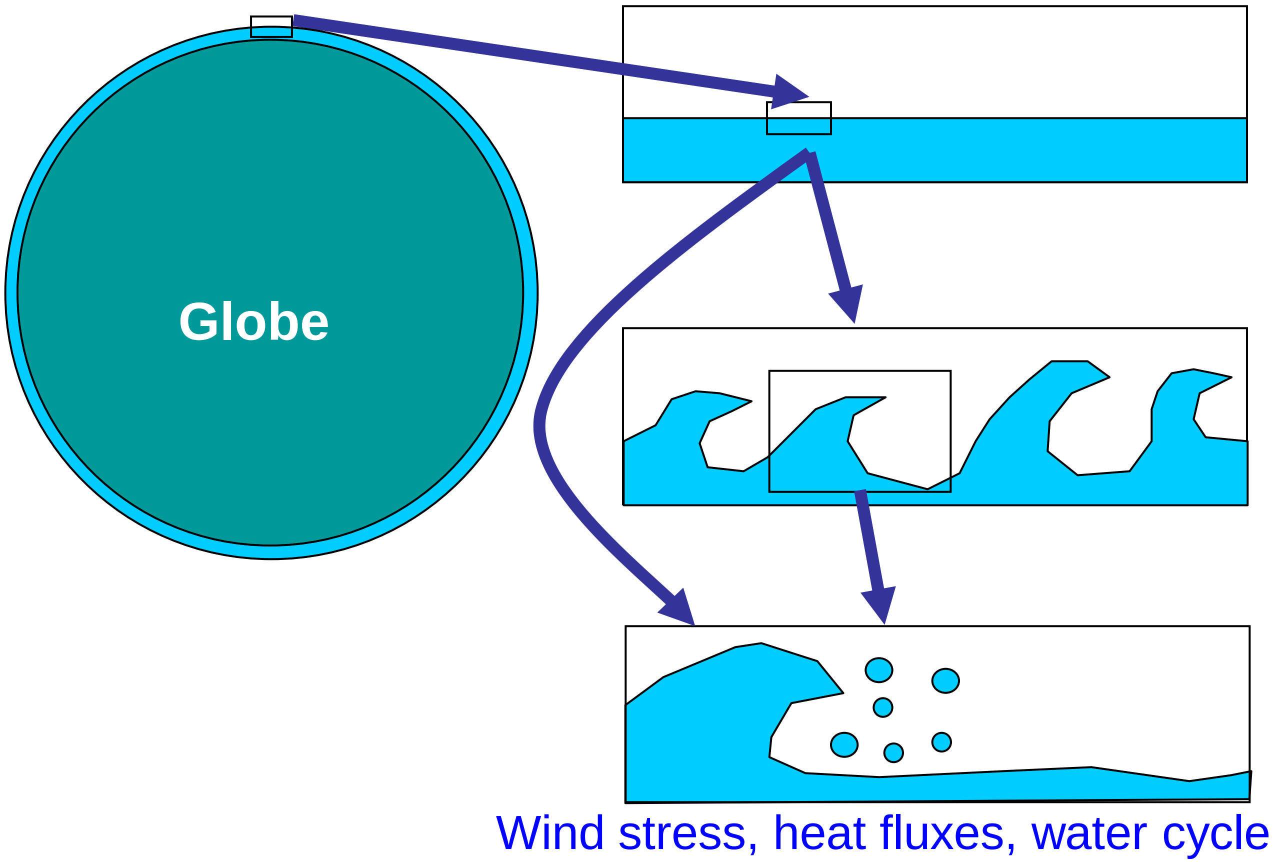
21% enlarged

Some factors affecting the mass transfer velocity across the air-sea interface



CO_2 flux per unit area : $F = k_L\ s\ \Delta pCO_2$

Concept of multiple interaction on boundary



Wave code

[WAM, WaveWatch]

sea surface height, wave cycle

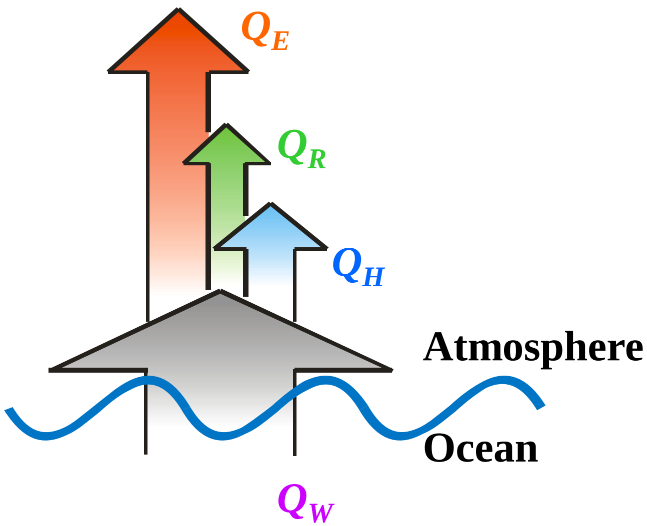
Detail analysis near boundary

[VOF, CIP, TW_MPS]

Outstanding features of Moving Particle Semi-Implicit (: MPS) method

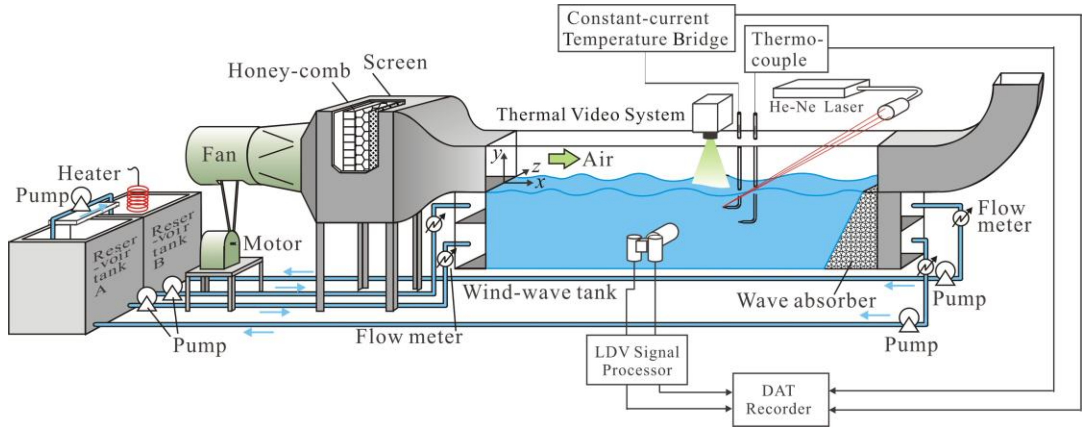
- **Mesh-free (Lagrange form)**
- **Applicability to liquid breakup**
- **Applicability to complicated boundaries**

(Prof. Satoru Komori, Univ. of Kyoto)

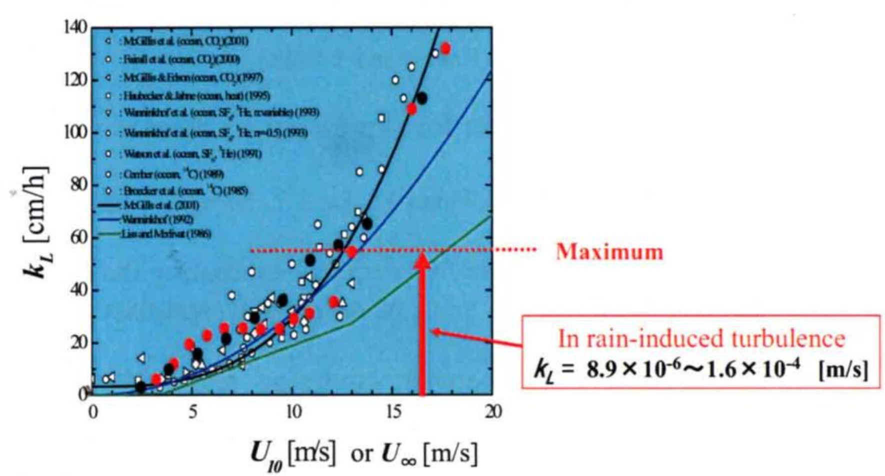


$$Q_E + Q_R + Q_H = Q_W$$

latent heat flux — radiative heat flux — sensible heat flux — total heat flux

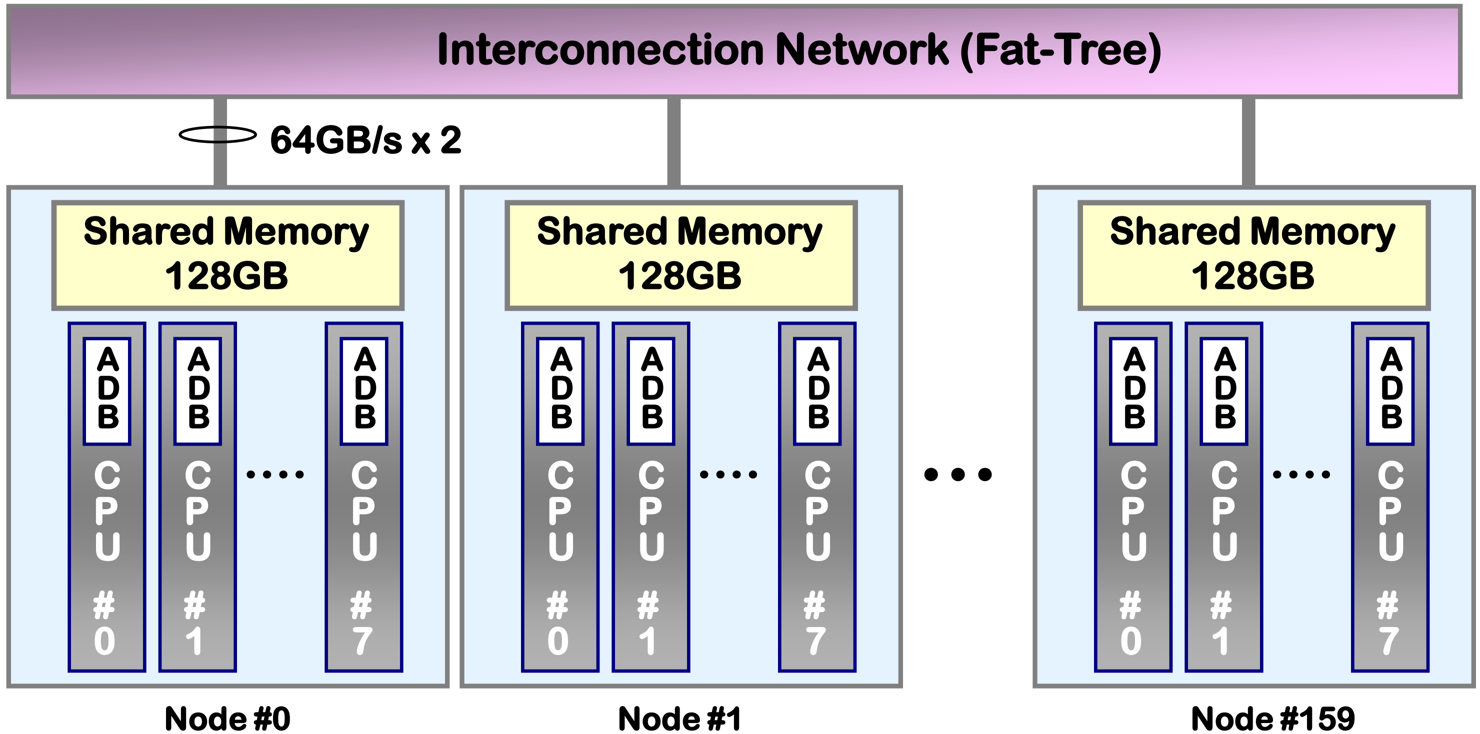


Comparison of mass transfer coefficient in rain-induced turbulence with that in wind-driven turbulence



The mass transfer coefficient in rain-induced turbulence corresponds to that in wind-driven turbulence with wind speeds of 3~13m/s.

System configuration of the Earth Simulator



- Peak performance per CPU (single core): 102.4GFLOPS
- Number of nodes: 160
- Number of CPUs: 1280
- Total system peak performance: 131TFLOPS
- ADB: Assignable Data Buffer (Software-controllable)

Computational Cost Breakdown of MSSG-A (3km Run)

- 1280-core ES full system (after performance tuning)

Dominated by dynamics (51%), physics (21%), and water substances (18%)

Processes	Wall-Clock Time (sec)	Cost Ratio (%)	GFLOPS /core
Total	108.2	100.0	33.0
Transport of water substances	19.5	18.0	59.2
Subtotal for Navier-Stokes equations	55.1	50.9	34.4
fast mode terms	32.7	30.2	34.9
slow mode terms	22.4	20.7	33.6
Subtotal for Physical processes	22.7	21.0	18.0
cloud microphysics	14.9	13.8	20.2
surface flux	3.9	3.6	8.2
radiation	1.6	1.5	17.0
land	0.8	0.7	3.0
others	1.5	1.4	29.2
Diagnosis of temperature, velocity, etc	4.5	4.2	16.4
MPI communication of prognostic variables	5.0	4.6	0.2
Shapiro filter	1.1	1.1	39.5
Others	0.2	0.2	0.0

Revised Byte/Flop (RBF)

RBF = AMEM x F /AFLOP

AMEM: Actual number of memory accesses

F: Factor determined by numerical precision

F= 8 for double precision

F= 4 for single precision

AFLOP: Adjusted total number of floating-point operations

For arithmetic units having dedicated adders and multipliers

AFLOP=Max(ADD, MULTIPLY)x2

For arithmetic units having fused multipliers and adders

AFLOP=(FMA+(ADD-FMA)+(MULTIPLY-FMA))x2

Here

FMA: Total count of multiply-add operations

ADD: Total count of additions

MULTIPLY: Total count of multiplications

Characteristics of RBF

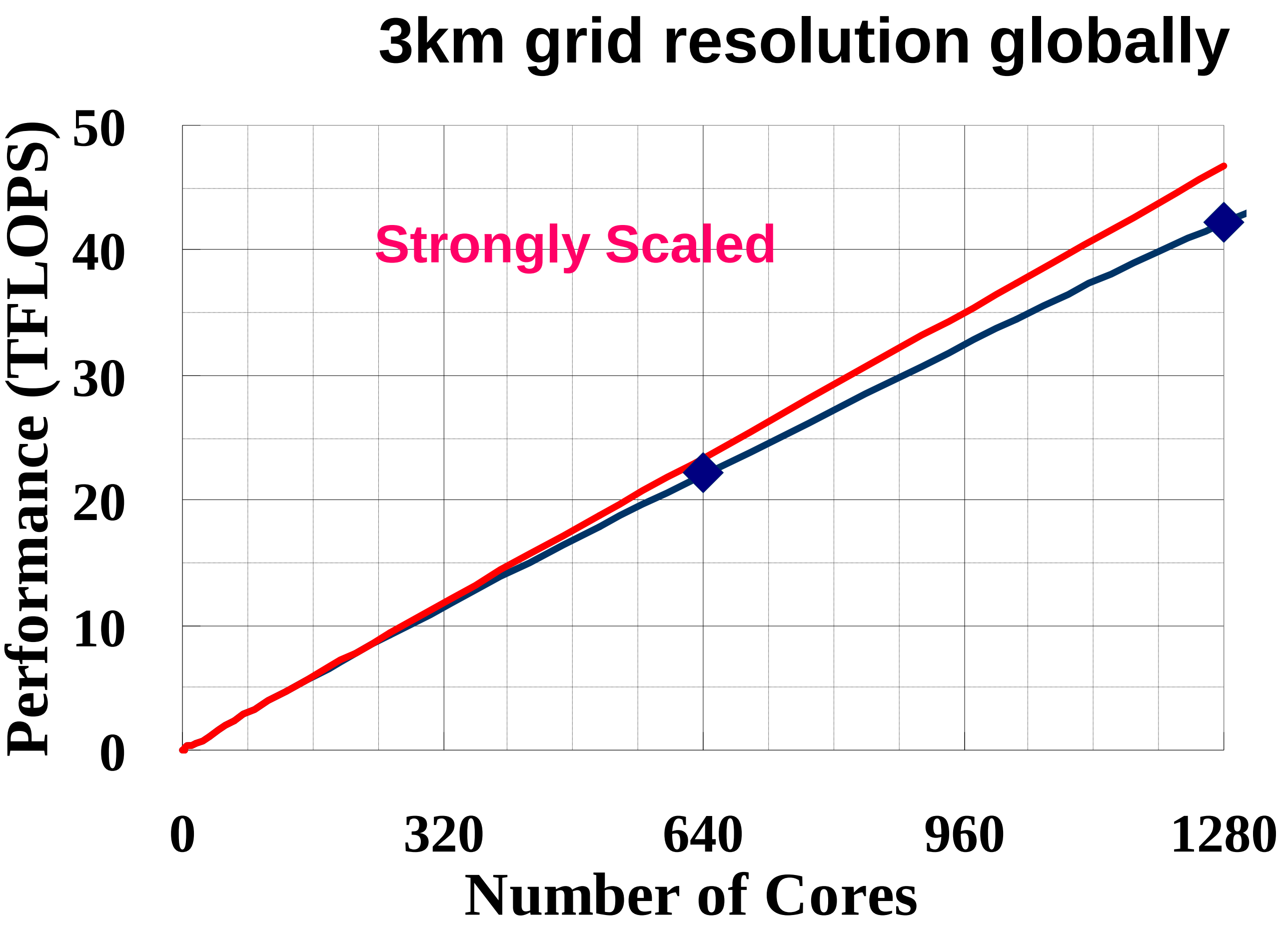
The followings factors are taken into account to give more realistic B/F ratio.

1) Data reusability
   – The accesses to reusable data allocated to the cache and/or register are excluded from the counting, giving a realistic estimation

2) Degree of exploitation of arithmetic units
   – The difference in the composition ratio of each arithmetic unit and that of each arithmetic operation count in the source code can be incorporated.

Takahashi, Keiko et al., World-highest Resolution Global Atmospheric Model and Its Performance on the Earth Simulator, Proceeding of SC '11 State of the Practice Reports, Doi: 10.1145/2063348.2063376, 2011.

MSSG-A Global Atmospheric Model on the ES2



Blue: sustained
Red: ideal line

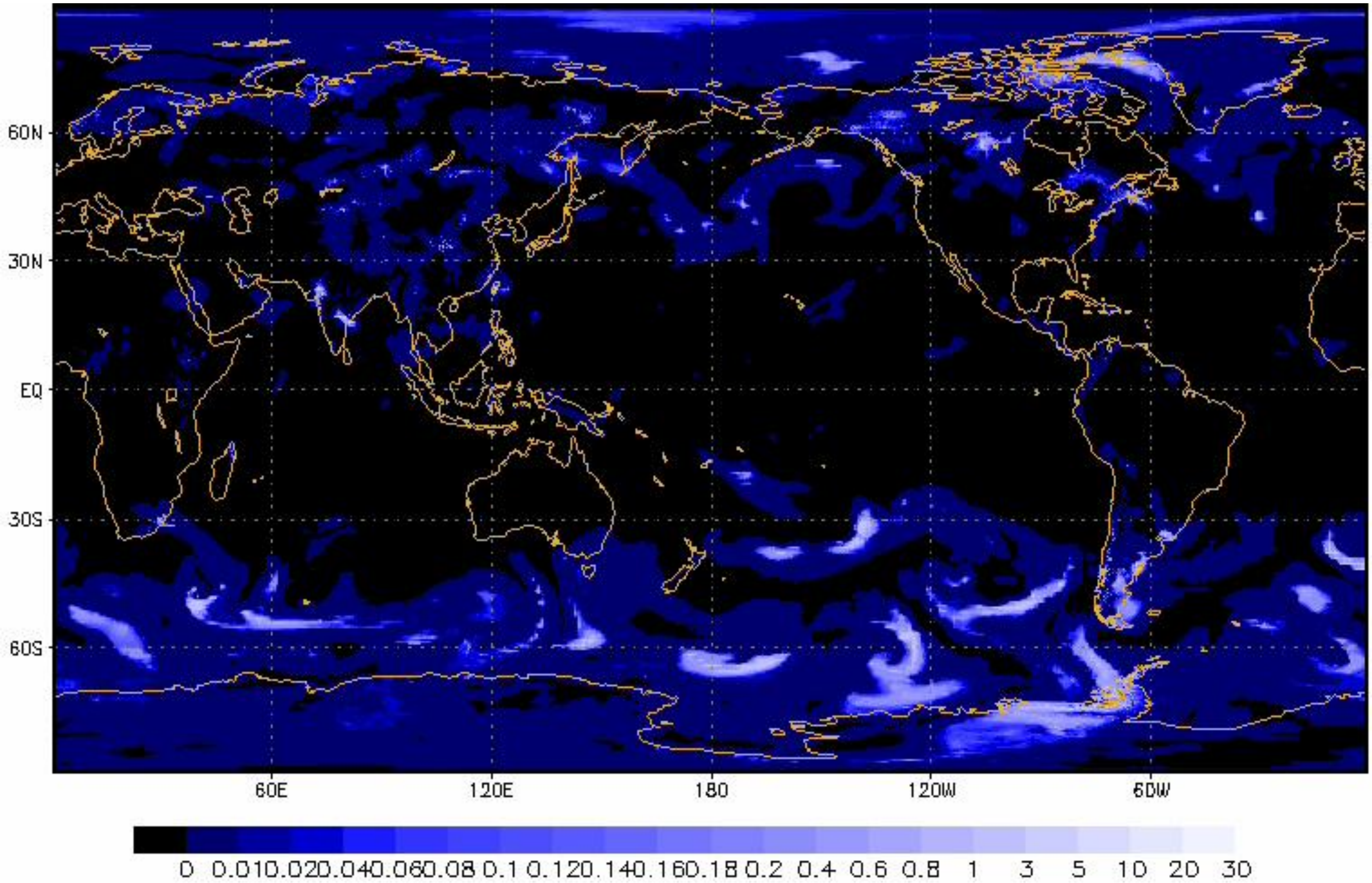
Parallelizationratio : 99.9915%

32.2% efficiency achieved on the ES2 full system

Global forecasting with 11km horizontal, 40 vertical layers
- **5 days (120 hours) forecasting → 5 hours on 48 nodes of ES2**
- **3 month forecasting → 2.5 days on 80 nodes (1/2) of ES2**

Global Atmosphere Simulation with MSSG-A

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



Future Plan and Requirements

– Multi-scale Multi-physics simulation is ESSENTIAL.

– Coupling Urban-scale to Meso-scale ~ Baisin Phenomena

– Time Evolution of Thermal Turbulence Flow
– 3D Cloud Development
– 3D Radiation Effects to Boundary Layer
– 3D interaction between Atmosphere and Ocean

Different HPC elements are included
in Algorithm (DNS), Schemes (3D-Rad.) and
Parallelization

“ON DEMAND” Characterized High Performance Computation

Thank you.