ICTP-IITM-COLA TTA: "Towards Improved Monsoon Simulations", 13-17 June 2016

Diurnal Variations in Precipitation during East Asian Summer Monsoon

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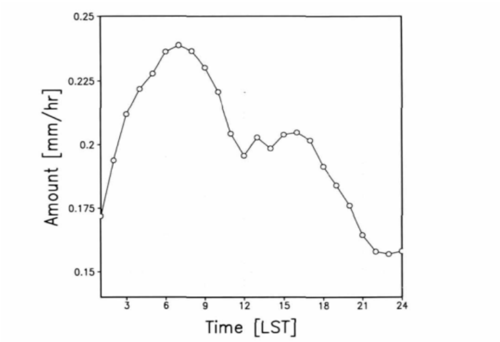
www.kiaps.org

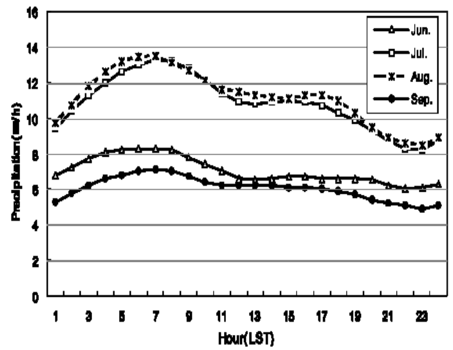
Contents

- **Characteristics of diurnal variations of precipitation over East Asia**
  - ✓ The diurnal variation of rainfall is a pronounced feature has a large contribution to the Earth's weather and climate.
  - ✓ Over the East Asia region including Korea, China, and Japan, the semi-diurnal cycle with two maximum peaks of precipitation are observed in the afternoon and early morning [Ramage, 1952; Jung and Suh, 2005]
    - Early morning maximum (06-08 LST): geographical location, land-sea breeze, radiative heating differences, diurnal cycle of surface convergence related to the radiative heating, slow warm rain process, etc.
    - Afternoon maximum (16-18 LST): convection related to the radiative heating (CAPE), cold rain process, etc.

SURFACE-BASED OBSERVATION



Diurnal variation of 17-year averaged hourly precipitation amount for Apr-Oct over South Korea [*Lim and Kwon*, 1998]



Diurnal variation of 30-year averaged hourly precipitation amount for JJAS over South Korea [*Jung and Suh*, 2005]

- **Characteristics of diurnal variations of precipitation over East Asia**
  - ✓ The diurnal variation of rainfall is a pronounced feature has a large contribution to the Earth's weather and climate.
  - ✓ Over the East Asia region including Korea, China, and Japan, the semi-diurnal cycle with two maximum peaks of precipitation are observed in the afternoon and early morning [Ramage, 1952; Jung and Suh, 2005]
    - Early morning maximum (06-08 LST): geographical location, land-sea breeze, radiative heating differences, diurnal cycle of surface convergence related to the radiative heating, slow warm rain process, etc.
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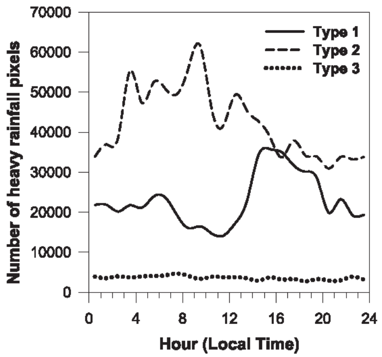
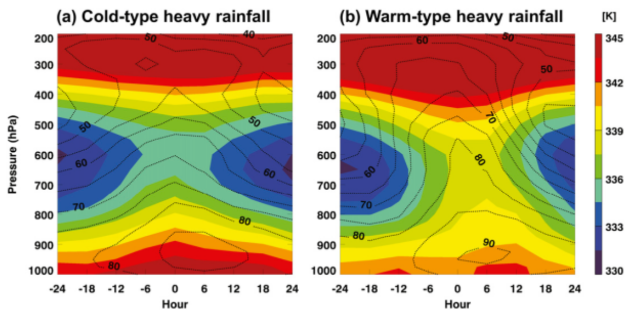
SATELLITE OBSERVATION (2002-2011 TRMM)



Diurnal variation of the occurrence of heavy rainfall over South Korea [*Song and Sohn*, 2015]

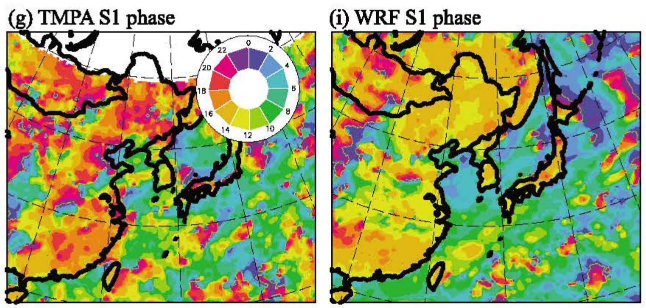


Vertical structure of composited equivalent potential temperature (color, K) and relative humidity (dotted line, %) for heavy rainfall over the Korean peninsula [*Song and Sohn*, 2015]

Modelling Issues in Simulating Diurnal Variation of Precipitation

- **Modeling issues**
  - ✓ The realistic simulation of diurnal cycle of precipitating convection, in particular, over the land is one of major shortcomings of physical parameterizations of numerical models.
  - ✓ Models tend to advance the time of the maximum precipitation over the land [e.g. Yang and Slingo, 20 01]

SATELLITE OBSERVATION & MODELING



Phase explained by precipitation diurnal cycle simulated f or JJA 2006 over East Asia [*Koo and Hong*, 2010]

Critical deficiency in m odeling studies :
phase shift problem (to o early in the afternoon peak)

Background and Objectives

✓ **To improve the diurnal cycle of precipitation**

- **Different cumulus parameterization scheme** - Simulated diurnal cycle of precipitation tends to be very sensitive to the CPS in land area due to the convection by surface radiative heating [Bechtold et al., 2008; Koo and Hong., 2010].

- **Increasing horizontal resolution** - The impacts of horizontal resolution in models with CPS are rather inconsistent among previous studies on diurnal cycle of precipitation [Lee et al., 2007; Dirmeyer et al., 2012],], while the life cycle and maximum intensity of convective systems could strongly depend on the model horizontal resolution in cloud resolving model [e.g. Petch et al., 2002].

- **Testing convection-permitting** – CRM can reproduce realistic diurnal variations of rainfall in phase, intensity, period and spatial structure [Sato et al., 2009; Dirmeyer et al., 2012].

- **Modifying the cumulus parameterization scheme** - A diagnostic convective closure linked to boundary layer forcing derived by Bechtold et al. [2014] significantly improved the diurnal cycle of convection.

Diurnal Variations of Precipitation with Different Cum
ulus Parameterization Schemes

Choi, I.-J., E. K. Jin, J.-Y. Han, S.-Y. Kim, and Y. Kwon (20
15), Sensitivity of diurnal variation in simulated precipitatio
n during East Asian summer monsoon to cumulus parame
terization schemes, J. Geophys. Res. Atmos., 120, 11,971
– 11,987, doi:10.1002/2015JD023810.

Model and Experimental Design

Model

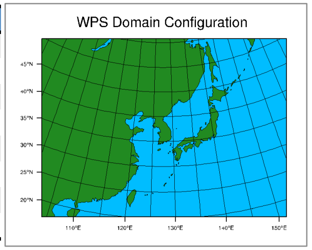
	Description
Model	WRF ARW v3.6
Radiation	Simple could-interactive shortwave (Dudhia, 1989) RRTM longwave (Mlawer et al. 1997)
PBL	YSU (Hong et al. 2006)
Land surface	Unified Noah land-surface model
Microphysics	WSM3 (Hong et al. 2004)

For CTL, **For sensitivity test,**

KF | SAS | BMJ | TDK | KFtr

Experimental design

Model	WRF ARW v3.6
Initial condition and lateral BC	NCEP RA2
Surface BC	OISST 6-hourly update
Vertical resolution	30 levels upto 50 mb
Horizontal resolution	**50 km**
Time step	240 sec
Domain (East Asia)	East Asia
Period	**JJA 2011**
Ensembles	5 member (ICs from 00UTC 21 to 25 May 2011)



- 90-minute mean rainfall of WRF output is summed as 3-hour mean rainfall identical to the TMPA data (observational counterpart).
- Ensemble mean data of 5 members is analyzed for the seasonal mean of JJA 2006.

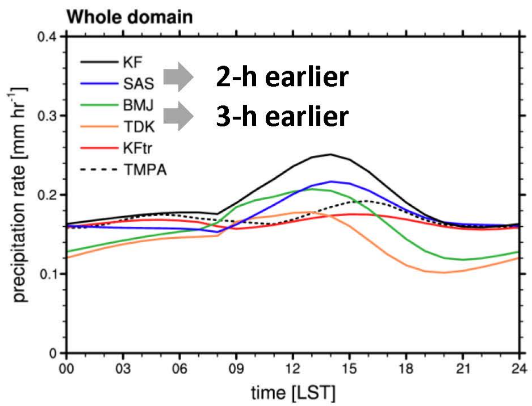
Model and Experimental Design

Scheme	Type	Trigger	Entrainment Formulation	Closure
KF	Mass-flux	Perturbation based on low-level vertical motion	Variability of cloud radius and cloud-depth threshold allowed	CAPE closure
SAS	Mass-flux	Parcel buoyancy	Height and RH dependent	Quasi-equilibrium Closure
BMJ	Adjustment	CAPE, cloud depth threshold value, and moist sounding needed	Convection profiles and relaxation time depends on cloud efficiency	
TDK	Mass-flux	Moisture convergence	RH dependent	CAPE closure
KFtr	Mass-flux	Perturbation based on local average moisture advection	Same as KF	Same as KF

Composited Diurnal Variations of Precipitation over East Asia

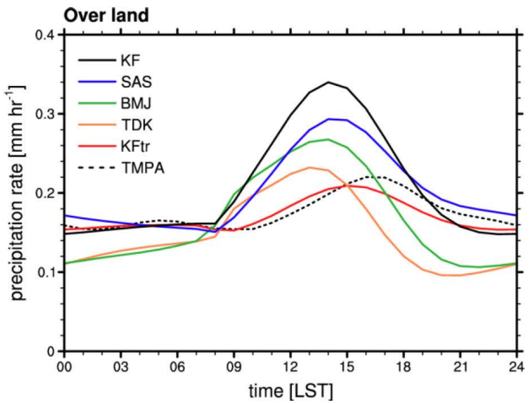
Observation :

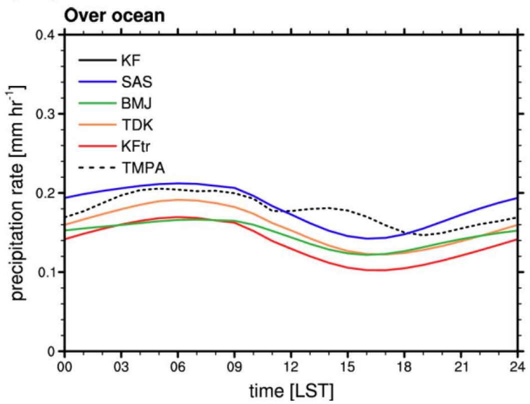
- Two peaks in the early morning at 05 LST and late afternoon at 16 LST.



Simulation :

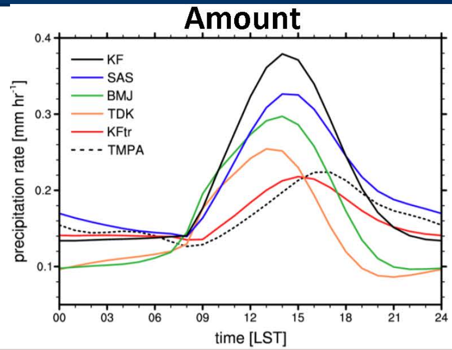
- Afternoon peaks with larger amplitude and earlier timing compared to the TMPA.
- KFtr scheme alleviates the excessive precipitation rate and delayed the afternoon peak by 1–2 h.





Diurnal Variations of Frequency and Intensity over Land

Over land

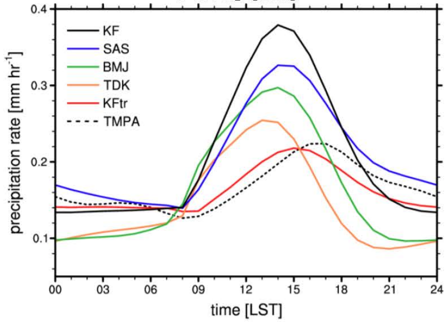


- Precipitation Amount: frequency X intensity
  - Frequency: percentage of time having measurable precipitation during analysis period
  - Intensity: precipitation rate during the precipitating time

Diurnal Variations of Frequency and Intensity over Land

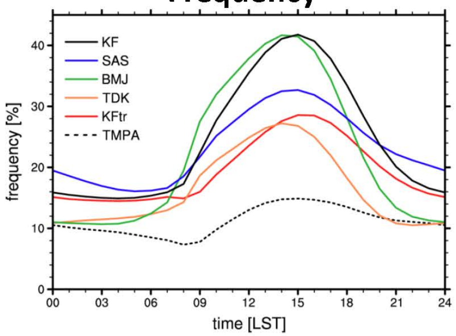
Over land

Amount



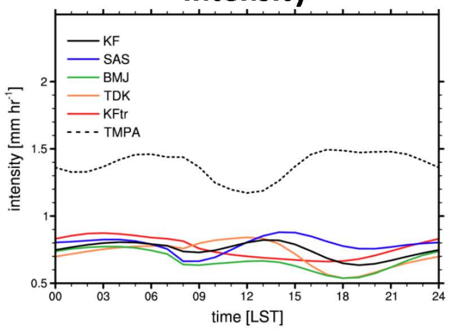
Similar

Frequency



Higher frequency and much lower intensity than TMPA.

Intensity



Overestimation of frequency
→ Amplitude and phase error

Out-of-phase intensity
→ Intensified phase error

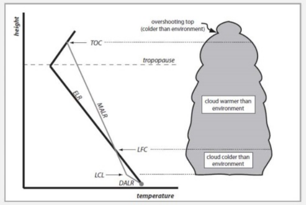
Impact of Trigger Function on Diurnal Variations

T at LCL　　　Environmental T

$$T_{LCL} + \delta T_{vv} > T_{ENV}$$

T perturbation

Very crucial in determining the prerequisite for a parcel to move upward and to trigger convection



Kain and Fritsch (1993, 2004)
: the role of **convergence** in destabilizing and moistening atmosphere

$$\delta T_{vv} = c_1 {w_g}^{1/3}$$

Grid-resolved vertical motion

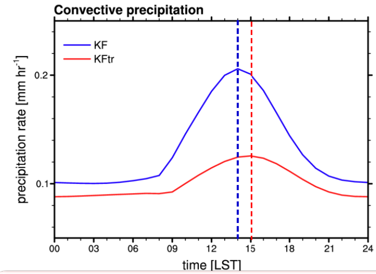
Modified Kain and Fritsch [Ma and Tan (2009)]
: the role of **moisture advection** in destabilizing and moistening atmosphere

$$\delta T_{vv} = R_h \delta T_{vvh} + R_v \delta T_{vvv}$$

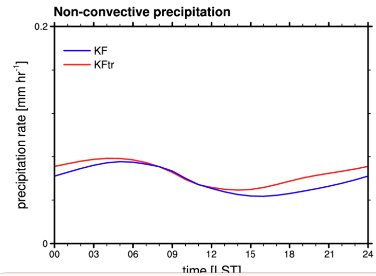
9 closest grid points　　3 sigma levels

$$R_{h/v} = \frac{(\vec{v}_M \cdot \nabla q_M)_{h/v} - Min(\vec{v}_M \cdot \nabla q_M)_{h/v}}{Max(\vec{v}_M \cdot \nabla q_M)_{h/v} - Min(\vec{v}_M \cdot \nabla q_M)_{h/v}}$$

$$0 < R_{h/v} < 1$$



Less sensitive initiation of convection activity due to the determination of temperature anomaly in trigger function and less frequent convective precipitation
→ Delayed peak in convective precipitation.



Through the interaction between convection and microphysics, non-convective precipitation increases in late afternoon. ◊
→ Delayed peak in convective precipitation is shifted to late afternoon .

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Impact of Trigger Function on Diurnal Variations

Impact of Trigger function

$T_{LCL} + \delta T_{vv} > T_{ENV}$

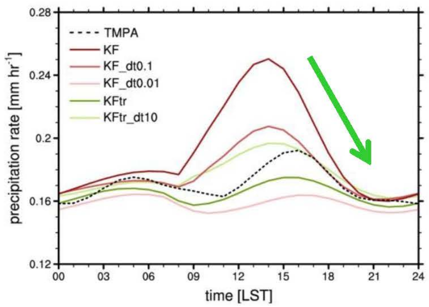
The KF scheme : the role of convergence

$\delta T_{vv} = c_1 {w_g}^{1/3}$

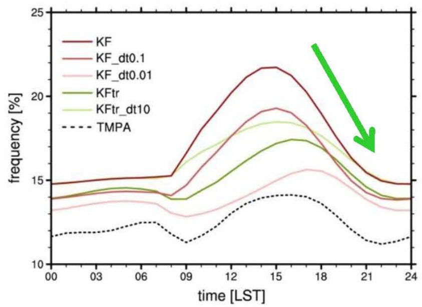
The KFtr scheme : the role of moisture advection

$\delta T_{vv} = R_h \delta T_{vvh} + R_v \delta T_{vvv}$

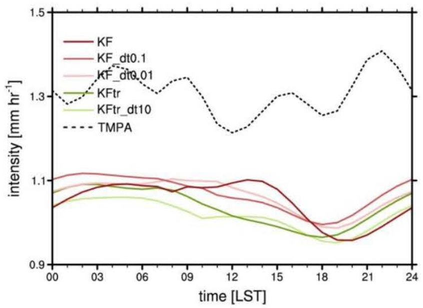
Amount



Frequency



Intensity

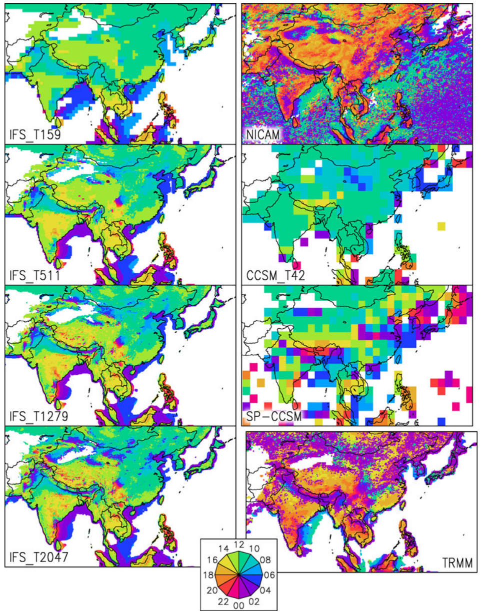


Modulation of trigger function can lead to improved diurnal cycle, but fails to improve statistical skill scores of precipitation.

Impact of Model Resolution on the Simulation of Diurnal Variations of Precipitation

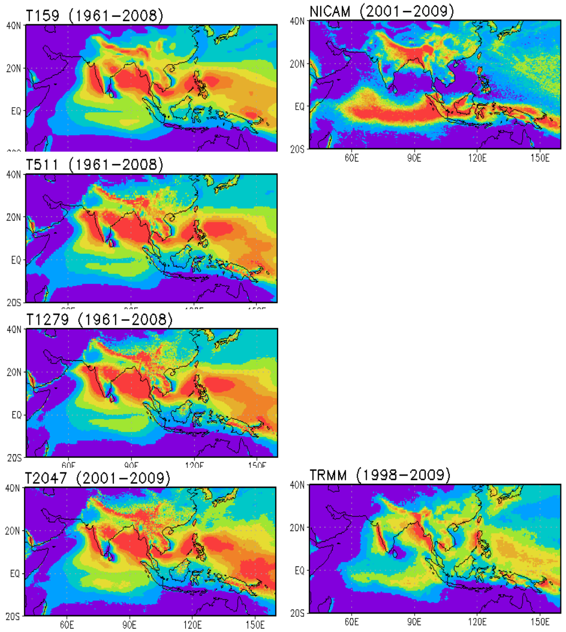
Jin, E. K., I.-J. Choi, S.-Y. Kim, and J.-Y. Han (2016), Impact of model resolution on the simulation of diurnal variations of precipitation over East Asia, J. Geophys. Res. Atmos., 121, 1652–1670, doi:10.1002/2015JD023948.

Diurnal Variation



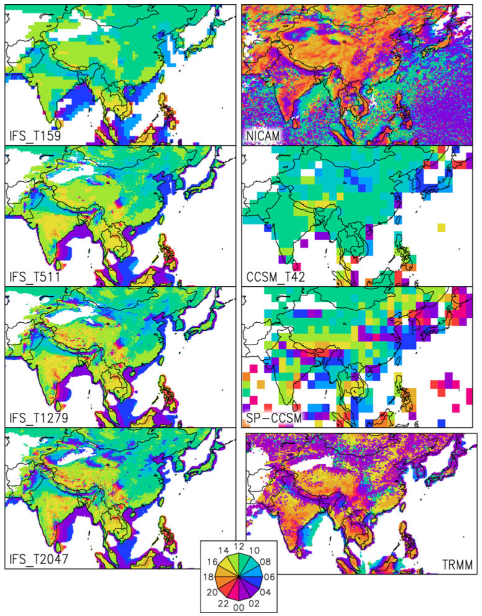
The local hour of maximum precipitation du ring JJA [*Dirmeyer et al. 2012*]

Mean Field



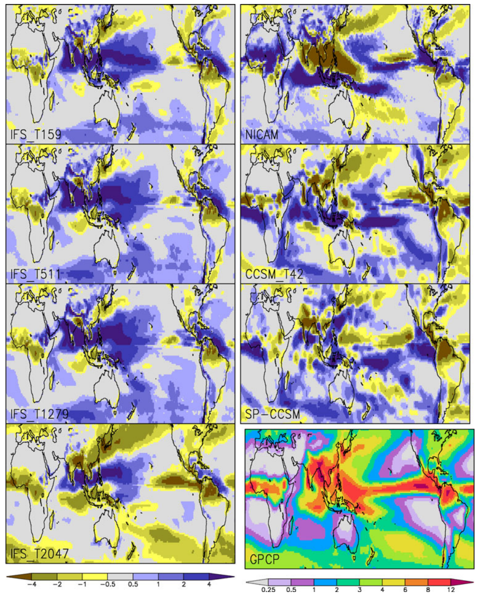
Project Athena: Resolution vs. Process-resolving

Diurnal Variation



The local hour of maximum precipitation du ring JJA [*Dirmeyer et al. 2012*]

Bias of Mean Field



Mean JJA precipitation from GPCP and the error s relative to GPCP for the various global model i ntegrations [*Dirmeyer et al. 2012*]

Model and Experimental Design

➤ Model

		Description
Model		WRF ARW v3.6
Radiation		Simple could-interactive shortwave (Dudhia, 1989) RRTM longwave (Mlawer et al. 1997)
PBL		YSU (Hong et al. 2006)
Land surface		Unified Noah land-surface model
Microphysics		**WSM3** (Hong et al. 2004)
Convection	**CPS**	• **SAS** • **Kain-Fritcsh (KF)** • **Kain-Fritcsh with modified trigger (KFtr)**
	No CPS	• **convection-permitting (CP)**

➤ Experimental design

Model	WRF ARW v3.6		
Initial condition and lateral BC	NCEP RA2		
Surface BC	OISST 6-hourly update		
Vertical resolution	30 levels upto 50 mb		
Horizontal resolution	**50**	**27**	**9**
Time step	180	72	30
Domain (East Asia)	108X79	200X146	588X434
Period	**JJA 2006** (from 00UTC 21~25 May to 00UTC 1 Sep 2006)		
Ensembles	5 member (ICs from 00UTC 21 to 25 May 2006)		

- 90-minute mean rainfall of WRF output is summed as 3-hour mean rainfall identical to the T MPA data (observational counterpart).
- Ensemble mean data of 5 members is analyzed for the seasonal mean of JJA 2006.

Seasonal mean circulation fields in JJA 2006

Reanalysis | 50 km | 27 km | 9 km

200 hPa GPH and wind

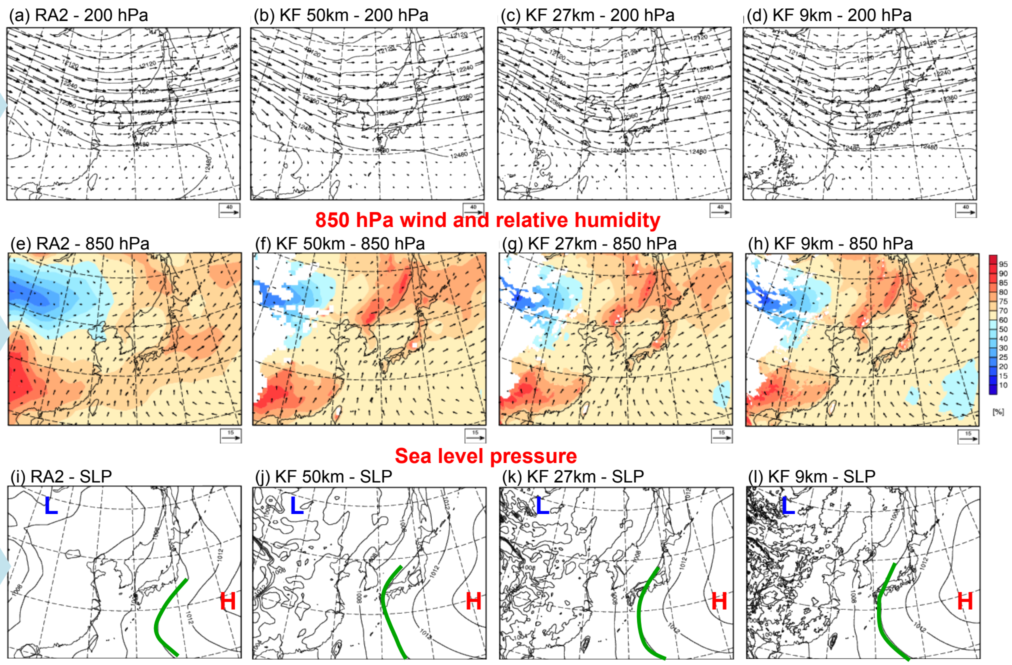
The upper-level jet along the 40°N associated with the summer monsoon rainfall in the south.

850 hPa wind and relative humidity

The southerly low-level jet (LLJ) brings the warm and moist air northeastward following to the western edge of the northwestern Pacific High.

Sea level pressure

The east-west pressure gradient pattern with a high pressure in the northwestern Pacific and a low pressure in the eastern China



The synoptic features of seasonal mean circulation in the KF runs of 50, 27 and 9 km are close to each other except the surface pressure patterns in the eastern China associated with the realistic representation of orography with increasing resolution.

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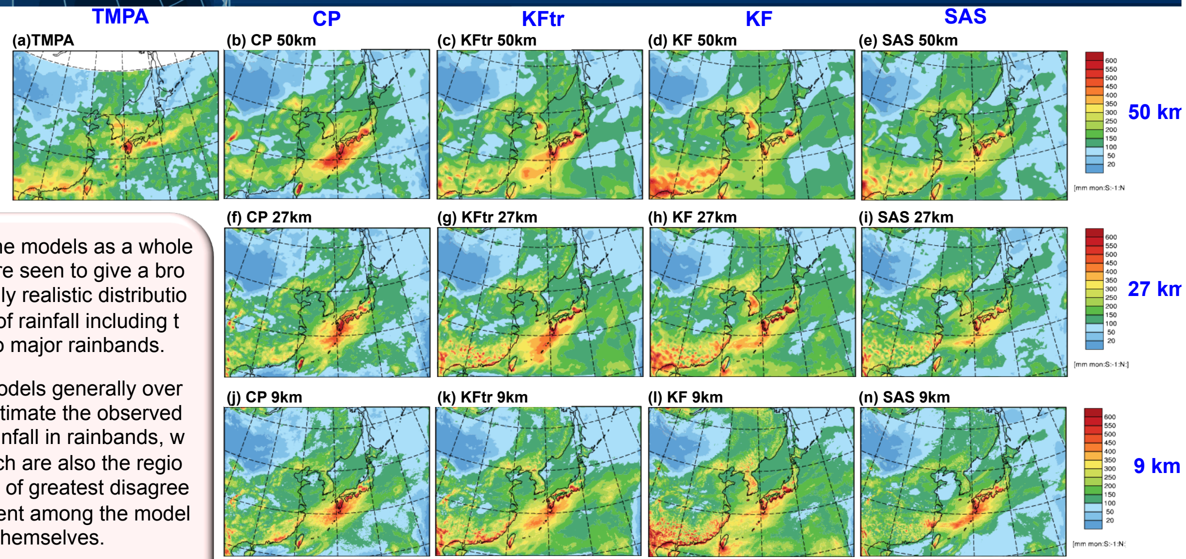
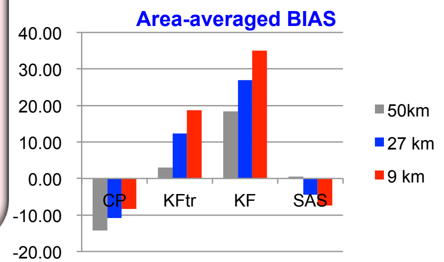
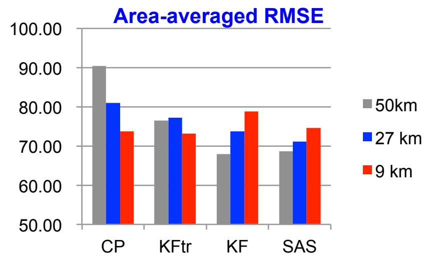
Seasonal mean precipitation in JJA 2006

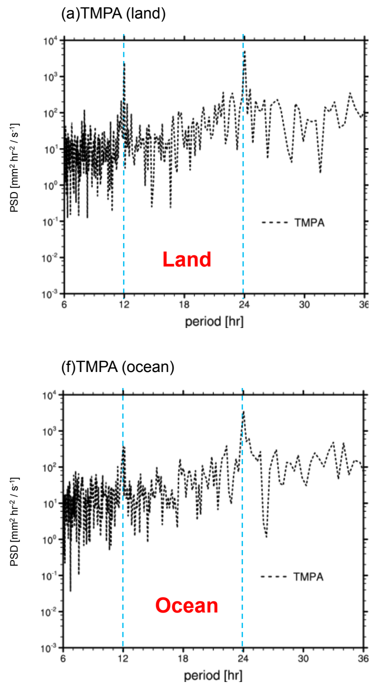


- The models as a whole are seen to give a broadly realistic distribution of rainfall including two major rainbands.
- Models generally overestimate the observed rainfall in rainbands, which are also the regions of greatest disagreement among the models themselves.
- The seasonal mean pattern of rainfall doesn't change substantially with increasing resolution.





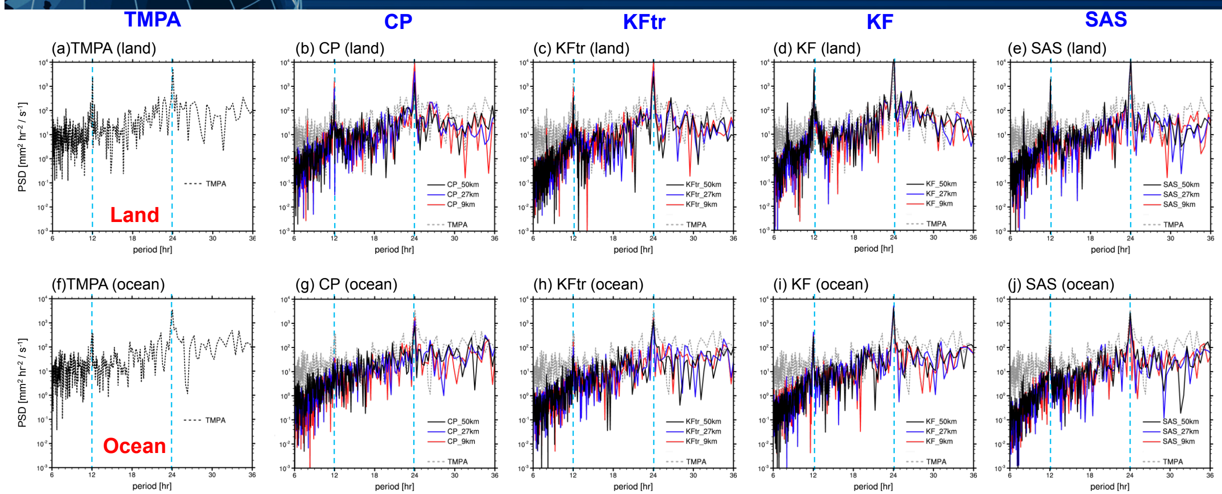
Power spectrum density of precipitation

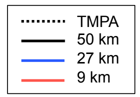


- Power spectrum density: a forward complex discrete Fourier transform of a real periodic sequence is cond ucted with the removal of t he least square linear tren d of time

- The observed diurnal varia tion of the summer rainfall in East Asia is characteriz ed by two maximum peaks at 24-hr (diurnal cycle) an d 12-hr (semi-diurnal cycle), especially over the land

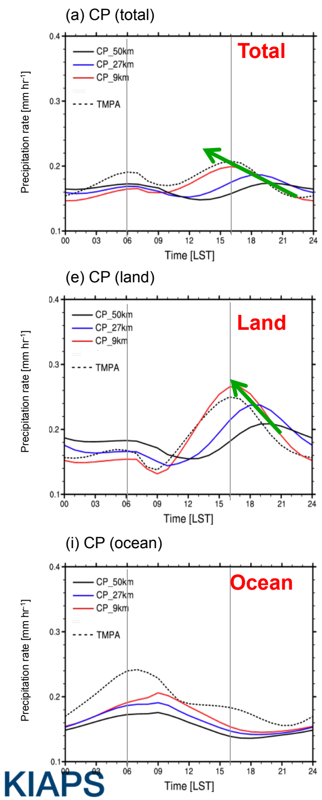
Power spectrum density of precipitation

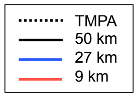




- Models reproduce two peaks of diurnal and semi-diurnal cycle very well from lowest to highest resoluti on, although they rather overestimate the amplitude of simulated PSD over the land.
- The power of the 24-hr and 12-hr peak gets stronger with respect to increasing resolution over the lan d in the KFtr and CP runs.

Diurnal variations of precipitation





- The diurnal variations of precipitation
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- The observed diurnal variation of tota
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- The afternoon peak is dominant over
  peak is dominant over the ocean.
- The CP runs reproduce two peaks ve
- The initiation of convective systems i
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- However, the afternoon peak of 9-km
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- There is a remarkable resolution dep
  amplitude of the diurnal cycle of rainf
  g. Sato et al. 2009], because the high resolution CRMs are only capable of the greatest realism in terms of explicitly resolving the vertical structure of cloud systems [e.g. Petch et al., 2002].
- The 9-km looks good enough to mimic the observed features in our case, nevertheless the optimal resolution to reproduce the observed diurnal variation varies depending on cases, target regions and seasons.

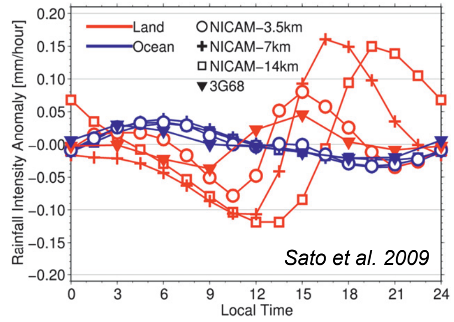

FIG. 5. Diurnal cycle of the precipitation intensity anomaly in the NICAM-3.5km (circles), NICAM-7km (crosses), NICAM-14km (squares), and 3G68 (filled triangles) runs averaged over 15°S–15°N. Red lines indicate land grids and blue lines indicate ocean grids.

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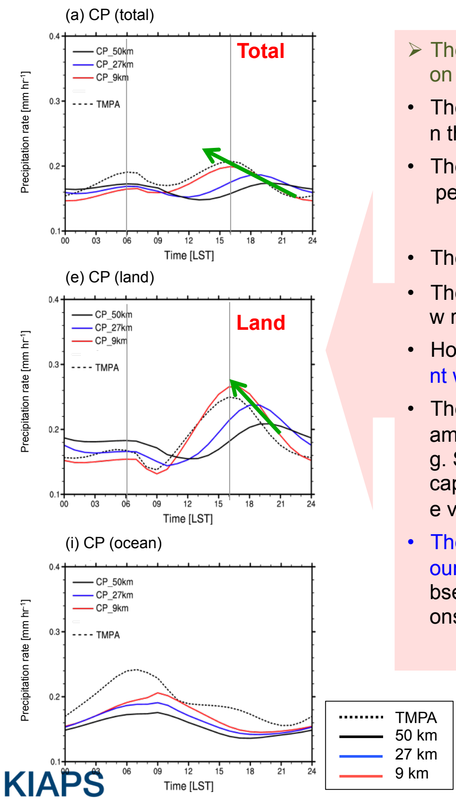
Diurnal variations of precipitation



- ➢ The diurnal variations of precipitation
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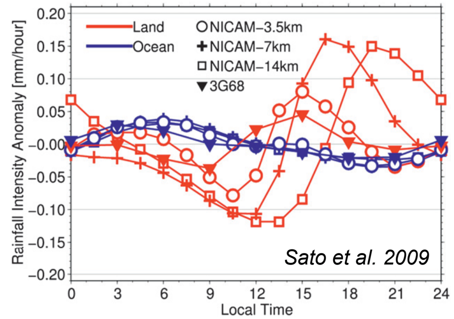
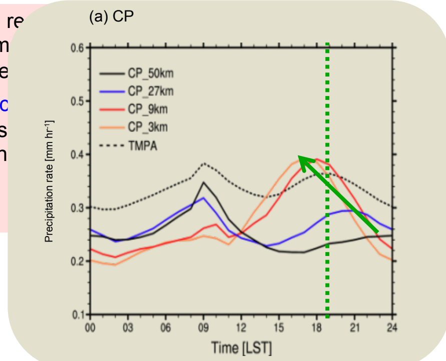


FIG. 5. Diurnal cycle of the precipitation intensity anomaly in the NICAM-3.5km (circles), NICAM-7km (crosses), NICAM-14km (squares), and 3G68 (filled triangles) runs averaged over 15°S–15°N. Red lines indicate land grids and blue lines indicate ocean grids.



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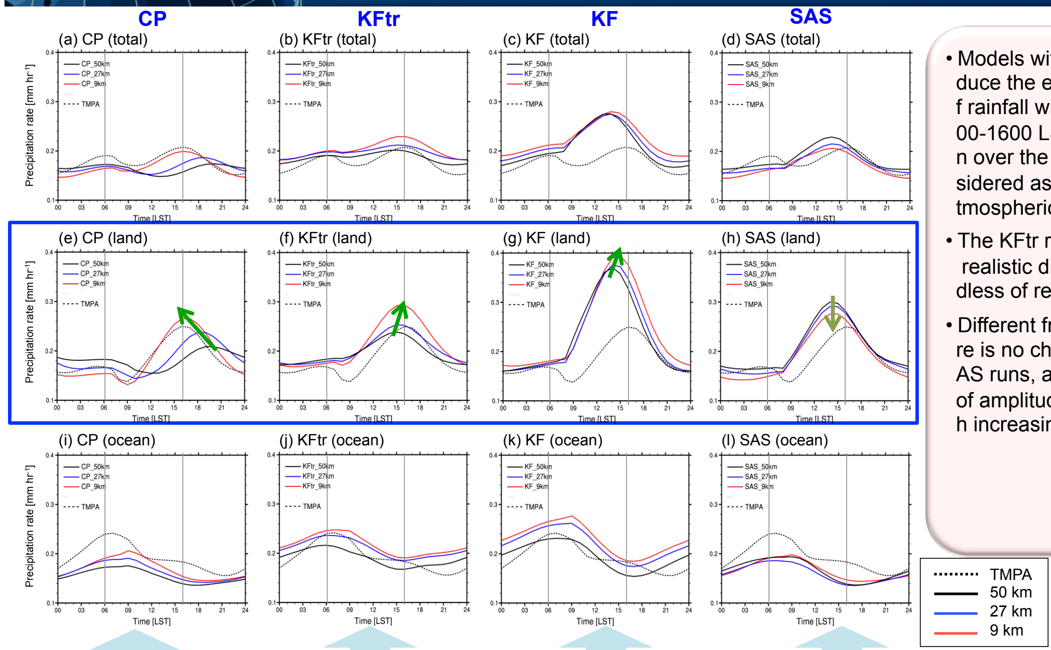
Diurnal variations of precipitation



- Models with CPS tend to produce the excessive amount of rainfall with earlier peak (1400-1600 LST) in the afternoon over the land, which is considered as a typical error in atmospheric models.
- The KFtr runs show the most realistic diurnal cycles regardless of resolution in general.
- Different from other runs, there is no change of phase in SAS runs, although the errors of amplitude are reduced with increasing resolution.

CP

- **Amplitude:** increase (improve)
- **Phase:** move forward over land (improve), no change over ocean

KFtr

- **Amplitude:** increase over land (worsen)
- **Phase:** delayed over land (improve), no change over ocean

KF

- **Amplitude:** increase (worsen)
- **Phase:** slightly delayed over land (improve), no change over ocean

SAS

- **Amplitude:** decrease (improve)
- **Phase:** no change over land, no change over ocean

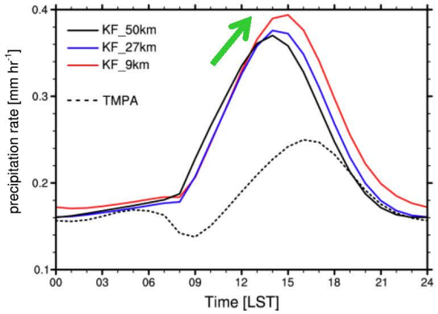
Impact of increasing resolution

Diurnal variations of precipitation over land

Over land

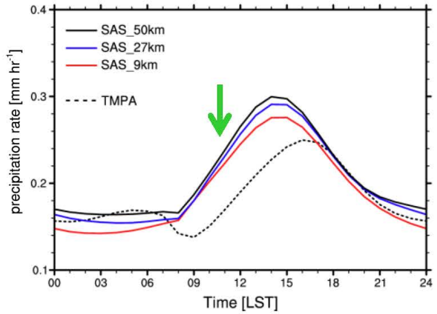
KF

- **Amplitude:** increase (worsen)
- **Phase:** slightly delayed (improve)



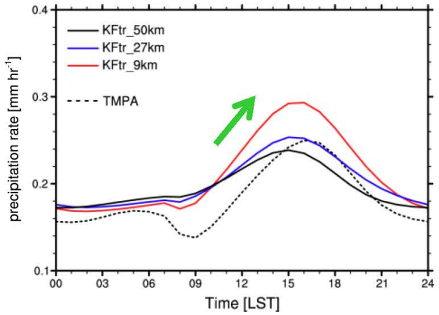
SAS

- **Amplitude:** decrease (improve)
- **Phase:** no change



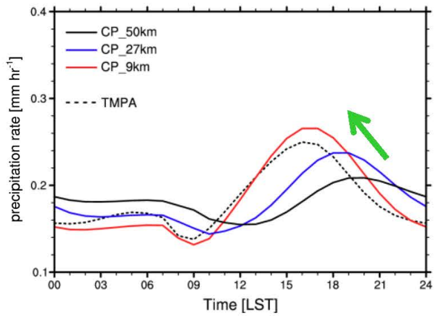
KFtr

- **Amplitude:** increase (worsen)
- **Phase:** slightly delayed (improve)

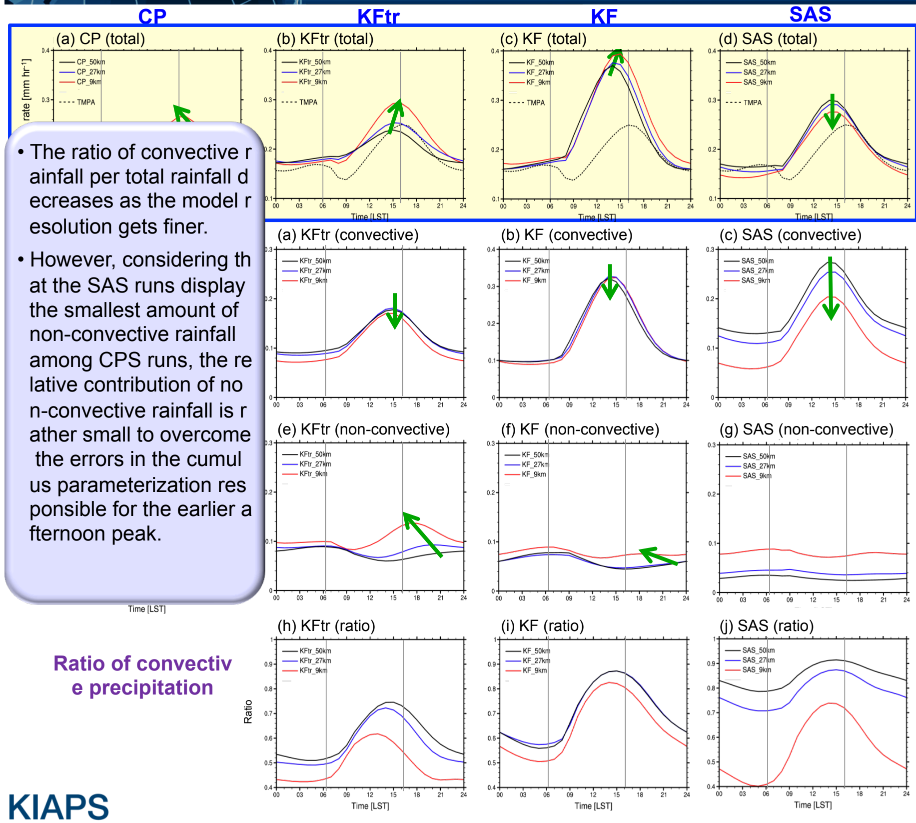


CP

- **Amplitude:** increase (improve)
- **Phase:** move forward (improve)



Diurnal variations of convective & non-convective precipitation over the land



- The ratio of convective rainfall per total rainfall decreases as the model resolution gets finer.
- However, considering that the SAS runs display the smallest amount of non-convective rainfall among CPS runs, the relative contribution of non-convective rainfall is rather small to overcome the errors in the cumulus parameterization responsible for the earlier afternoon peak.

Ratio of convective precipitation

- The diurnal variations of convective rainfall are mainly responsible for the afternoon peaks over the land.
- There is no change of phase with increasing resolution in the diurnal variations of convective rainfall.
- The modified trigger function based on moisture advection in the KFtr scheme delays the initiation of convection, and in turn change the timing of the afternoon peak close to the observation.

- The diurnal variations of non-convective rainfall show the semi-diurnal cycle.
- The KFtr and KF runs exhibit the earlier afternoon peaks with increasing resolution, which resembles the features in the CP runs.
- The improvement of diurnal variations with increasing resolution seems to be caused by the non-convective rainfall resulting from the cloud microphysics scheme.

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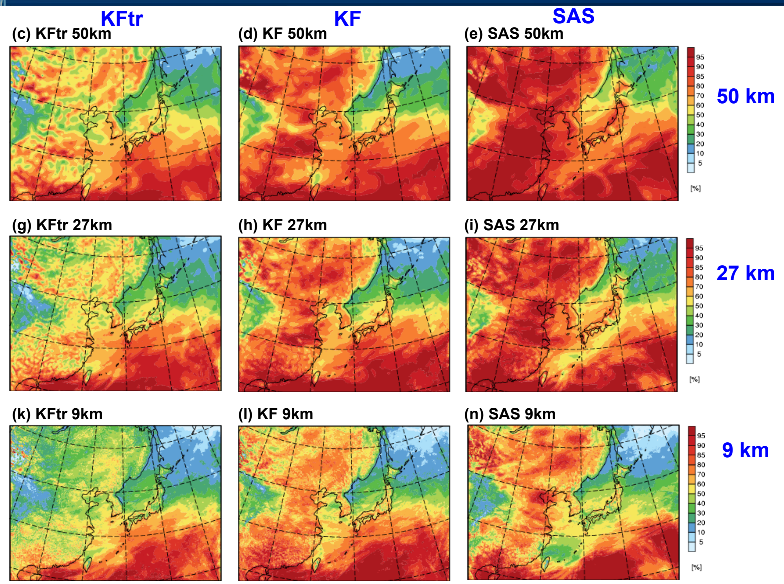
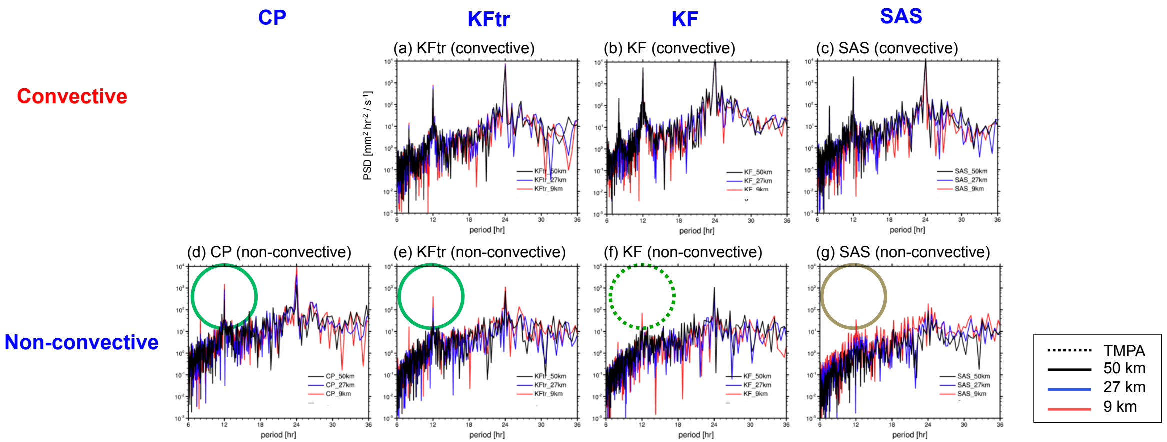
Ratio of seasonal mean convective precipitation in JJA 2006



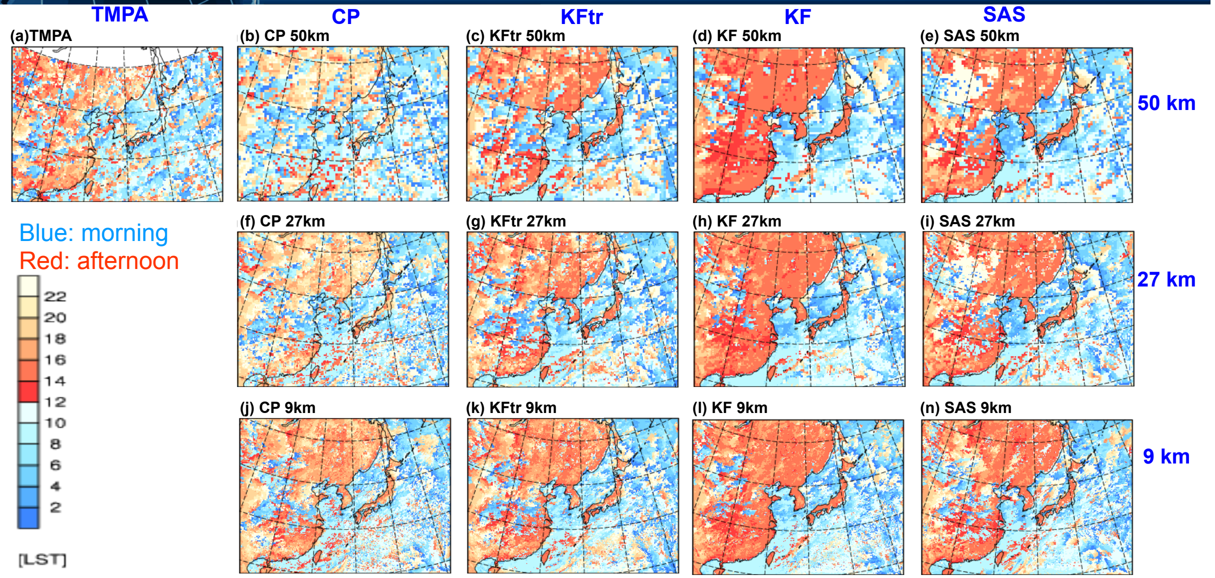
- The relative amount of convective rainfall is one of unique features of each cumulus param eterization scheme.
- The convective rainfall ratio decreases with increasing resolution over the land.
- The SAS scheme generates the highest convective rainfall ratio, while the lowest value in KFtr scheme, in particular over the land.
- The relatively withholding convective rainfall is likely to imply the dominant contribution of t he cloud microphysical process in the KFtr runs, close to the CRM.

PSD of convective & non-convective precipitation over the land



- There are no clear signs of the resolution dependency in the convective rainfall.
- In case of non-convective rainfall, results indicate that the 12-hr peak becomes enhanced with increas ing resolution in models supporting the improvement of semi-diurnal cycles of rainfall attributable to th e more realistic representation of the afternoon peak.
- However, in the KF and SAS runs, the 12-hr peak of the non-convective rainfall is rather weak even in the 9-km runs suggesting that the increasing resolution isn't enough to intensify the role of microphysi cal process due to the prevailing role of cumulus parameterization scheme.

Maximum peak time of hourly precipitation



- TMPA shows dominant morning peak over ocean and afternoon peak over land, even though morning peaks also occurs ov er some of inland area.
- Models fairly mimic the pronounced land-sea contrast.
  - The increase of resolution moves forward (becomes realistic) the late afternoon peak in the CP runs.
  - The increase of resolution delays (become realistic) the early afternoon peak in the CPS runs, .
  - KFtr reproduces the most realistic diurnal cycle, particularly over the land.
  - There are only little changes of peak of maximum rainfall over the ocean depending on the resolution.

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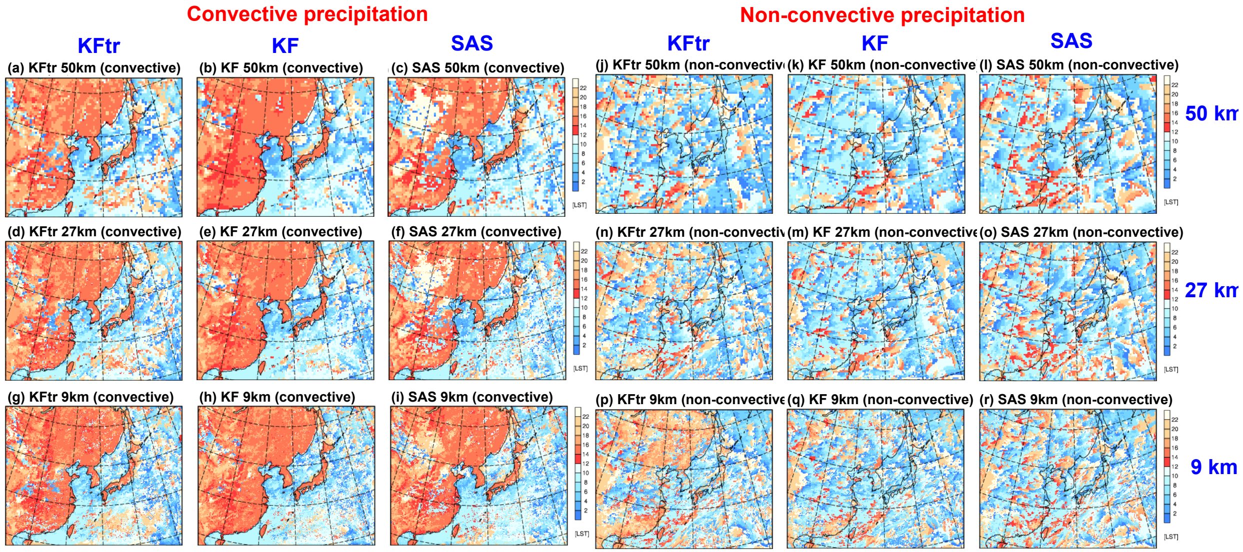
Maximum peak time of hourly convective & non-convective precipitation



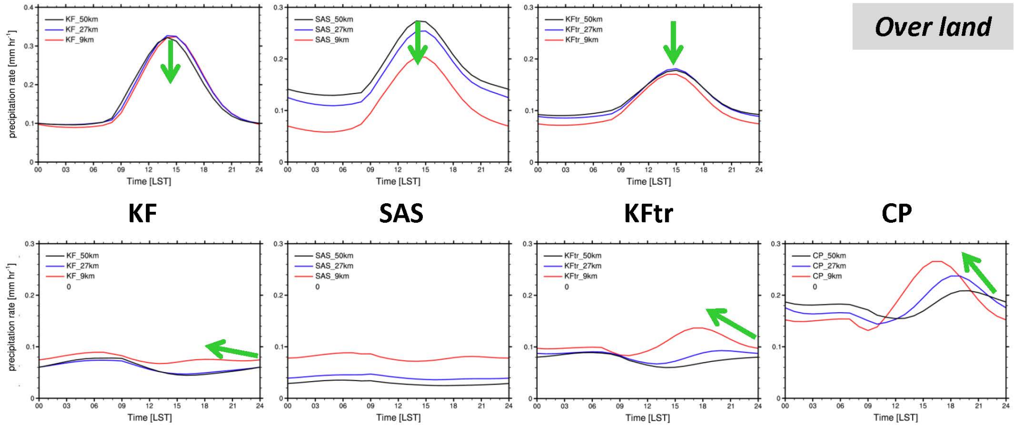
- Models with CPS display the distinctive land-sea con trast with the early afternoon peak over the land rega rdless of increasing resolution.
- The changes with increasing resolution are consider ably small.

- The maximum peak time of non-convective rainfall, particularly in the low resolution runs with CPS, occurs at the midnight or t he daybreak over the land.
- Only the KFtr runs exhibit the afternoon peak in the higher reso lution runs as noted earlier. The pattern of changes with increa sing resolution resembles that of the CP runs.
- There are minor changes of peak time from the midnight to the late afternoon in the KF runs, whereas the peak time of the SA S runs are rather insensitive to the change of resolution.

Diurnal variations of convective & non-convective precipitation over the land

Convective precipitation — No phase change with increasing resolution

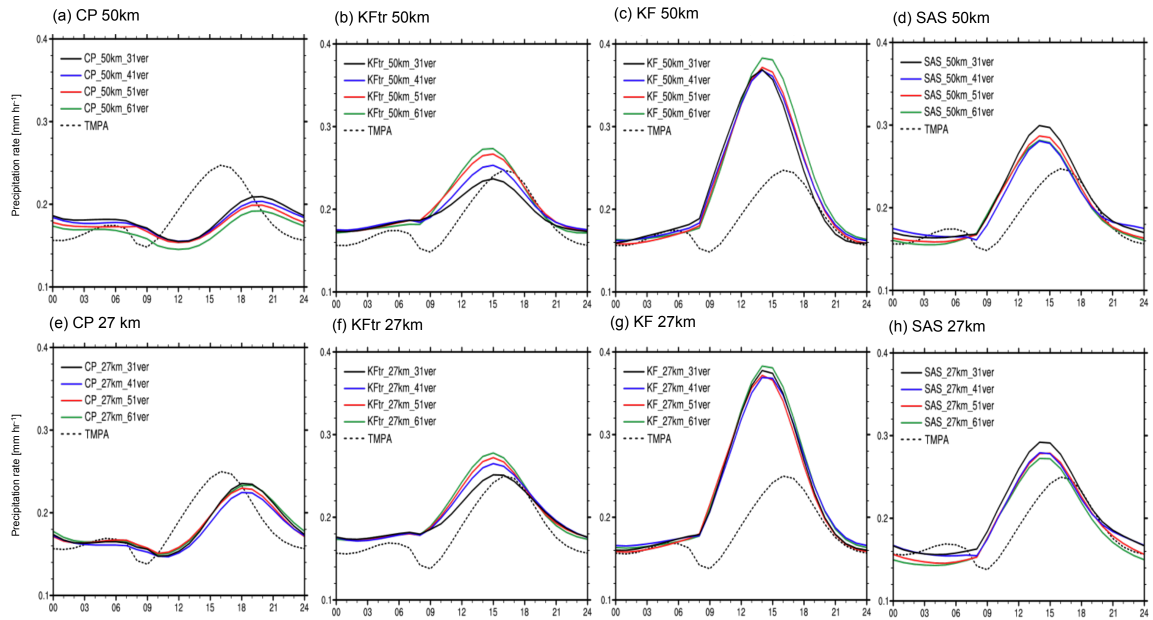
Over land



Non-convective precipitation — Earlier afternoon peaks in KF and KFtr CPSs

→ The improvement of diurnal cycle with increasing resolution is primarily governed by the non-convective precipitation!

Sensitivity to the vertical resolution



Testing 31, 41, 51, and 60 vertical levels

→ The phase of diurnal variation of precipitation is insensitive t o the vertical resolution of model.

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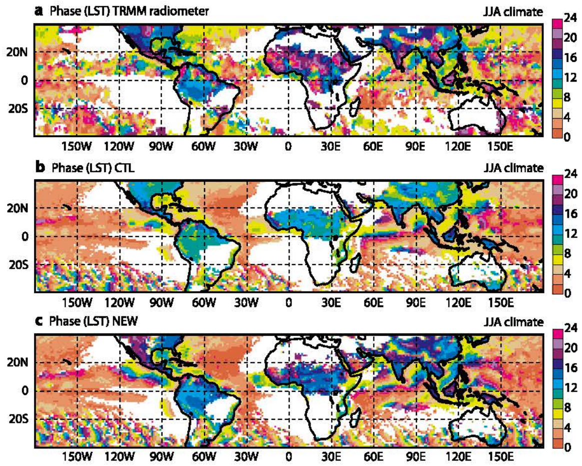
Improvement of Diurnal Variations of Precipitation with the SAS CPS in GCM

Courtesy of S.-Y. Hong and I.-J. Choi

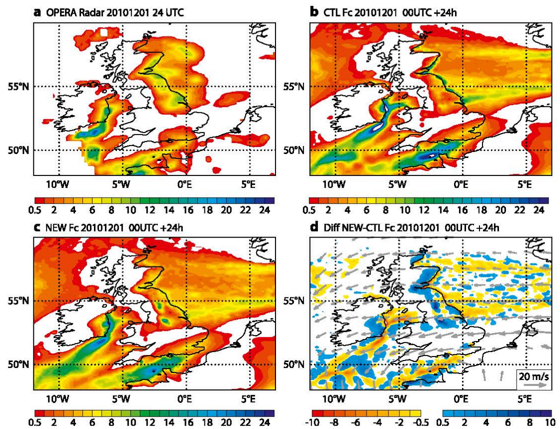
Modification of Convective Closure in SAS CPS

Bechtold et al. (2014) shows that a new diagnostic CAPE closure based on a planetary b oundary layer (PBL)-CPS equilibrium theory does improve the diurnal cycle of precipitat ion in IFS AGCM.

Improved Diurnal Cycle



Improved Forecast of Convective Shower



→ This extended diagnostic CAPE closure involving appropriate boundary layer time scales ov er land and water, is possible to represent not only large-scale synoptically driven convection, but also nonequilibrium boundary layer–driven convection with its characteristic diurnal cycle, and the inland advection of wintry convective showers.

Modification of Convective Closure in SAS CPS

Following the study of Bechtold et al. (2014), a planetary boundary layer (PBL)-CPS equilibrium theory to hold rapidly varying boundary layer forcing is applied in the convective closure of SAS CPS.

Original

$$f = \frac{cloud\ work\ function}{\tau}$$

τ : convective adjustment time scale

Advanced

$$f = \frac{cloud\ work\ function - A_{pbl}}{\tau}$$

$$A_{pbl} = g\ \Delta h_{pbl} \frac{\tau_{pbl}}{\Delta t}$$

$\tau_{pbl} = \tau$ over land

$\tau_{pbl} = \frac{H_{base}}{\bar{u}_{pbl}}$ over water

Δh_{pbl}: Change of PBL height between t and $t - \Delta t$

τ_{pbl} : boundary layer time scale

Model and Experimental Design

- **Case : 01 July 2013 – 31 July 2013**
  - Medium-range forecasts for 10 days from every 00 UTC

Model : GRIMs v3.3	
Horizontal resolution	T254 (approximately 50 km)
Vertical level	28
Time interval	300 sec
Initial/boundary condition	GFS analysis

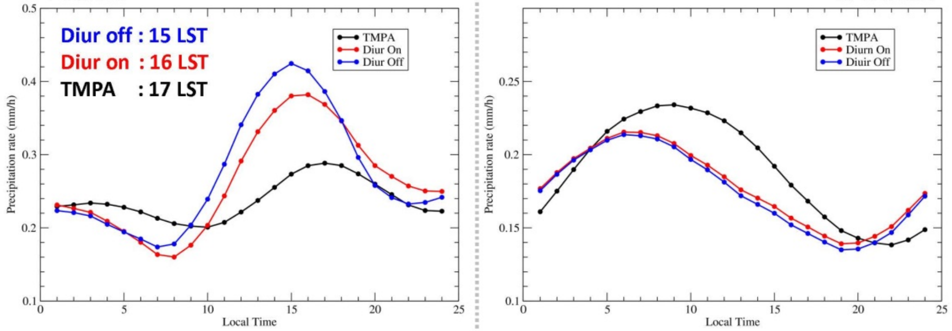
Physics options for control simulation			
Deep Convection	**SAS**	Radiation	**RRTMG**
Shallow convection	**GRIMs**	Vertical diffusion	**YSU**
Microphysics	**WSM5**	Land surface	**NOAH**
Cloudiness	**Prognostic scheme**	Gravity wave drag	**Kim and Arakawa [1995]**

Experiment	
Diur off	Original closure
Diur on	Modified closure with PBL-CPS equilibrium

Diurnal Variation of Precipitation

Over East Asia

Land | **Ocean**



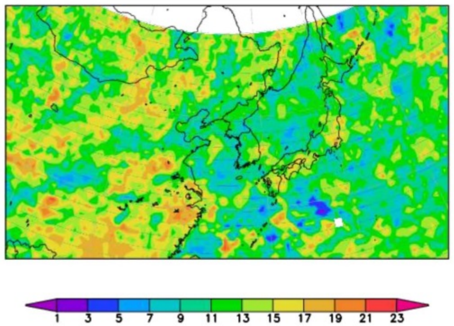
Delayed afternoon peak (1 hour)
Reduced precipitation rate

More impact over land than over ocean

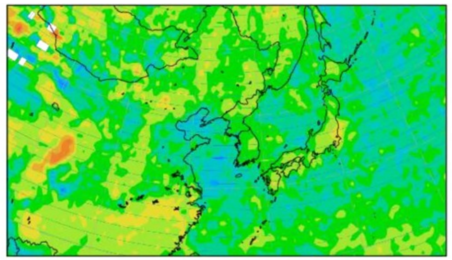
→ Diurnal cycle of precipitation is improved.

Maximum Peak Time of Hourly Precipitation

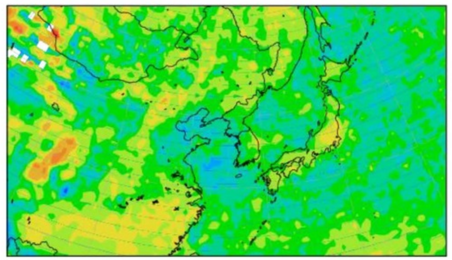
TMPA



Diur off



Diur on

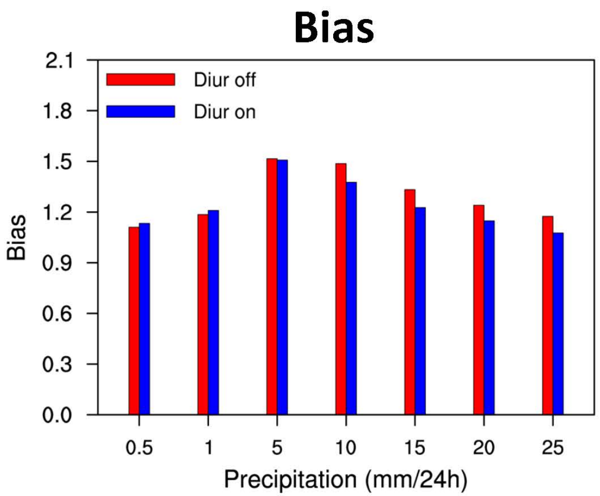


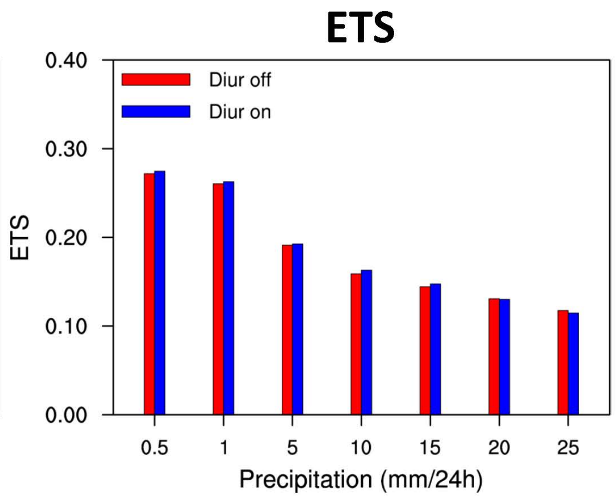
Slightly delayed peak time over land, closer to TMPA

Clear land-sea contrast

Forecast Skill of Global Precipitation

Data : Climate Prediction Center (CPC) unified gauge-based analysis





→ Skill improvement in the bias and slightly in the ETS again st the CPC unified gauge-based analysis of global precipitati on.

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Summary and Conclusions

✓ **Different cumulus parameterization schemes**

- With overestimated precipitation rate, the simulated afternoon peaks occur earlier than the observed peaks.
- The scheme with alternative trigger function (KFtr) based on moisture advection provides slightly better results in terms of alleviating the overestimated precipitation rate and frequency and delaying the afternoon peaks.

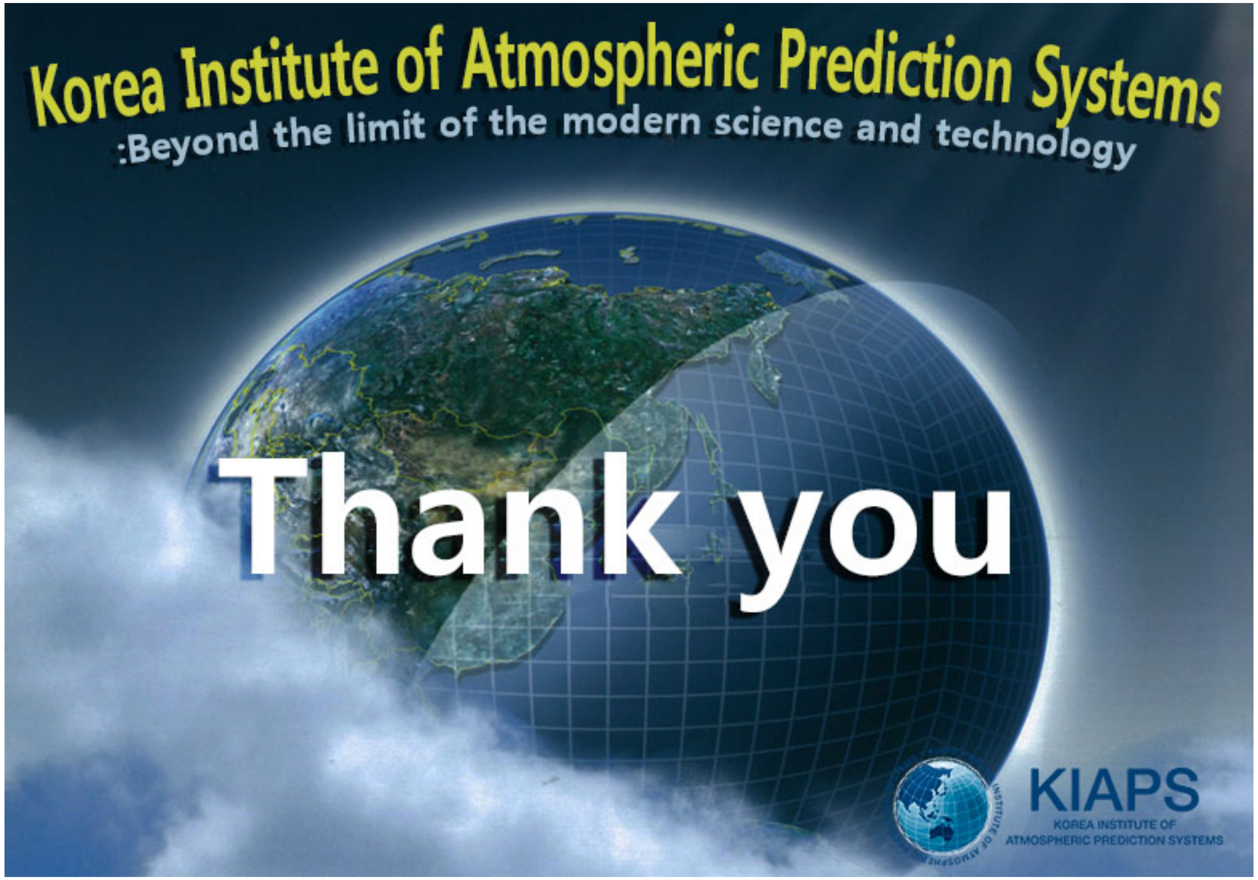
✓ **Increasing horizontal resolution**

- The increase of resolution improves the phase and amplitude of diurnal cycle in the CP runs due to the explicit representation of the realistic cloud system.
- The contribution of non-convective precipitation from the microphysical process significantly improves the phase of diurnal cycle in the CPS runs.

✓ **Modification of convective closure**

- A comparison of medium-range forecasts shows that the new closure can improve the diurnal cycle of simulated precipitation by delaying afternoon peak.
- The impact of the new closure on diurnal cycle of precipitation looks more apparent over land than over ocean.

Remarks: Improvement of diurnal cycle does not guarantee the improvement in skill of precipitation forecasts.


Korea Institute of Atmospheric Prediction Systems
:Beyond the limit of the modern science and technology
Thank you
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KOREA INSTITUTE OF
ATMOSPHERIC PREDICTION SYSTEMS

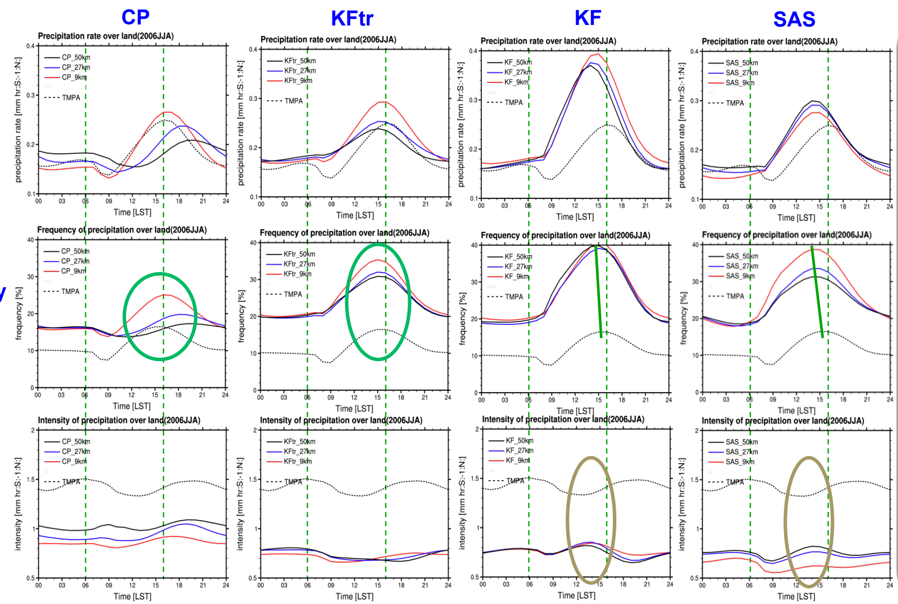
Diurnal variations of frequency & intensity over land

Land

Total

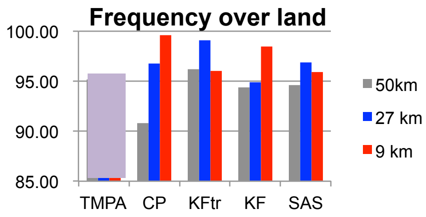
Frequency

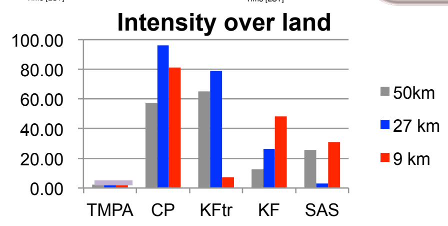
Intensity



- ➢Frequency: percentage of time having measurable precipitation during analysis period
- ➢Intensity: precipitation rate during the precipitating time
- ➢Amount: frequency X intensity
- • TMPA shows that the contribution of frequency to the diurnal cycle in precipitation is dominant over land area.

Percentage variance of diurnal cycle in precipitation amount explained by frequency and intensity





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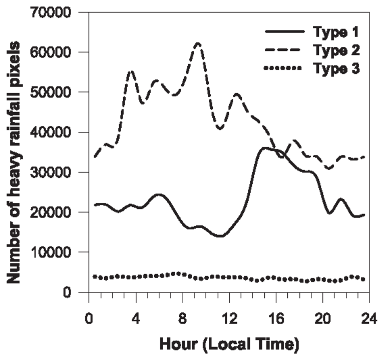
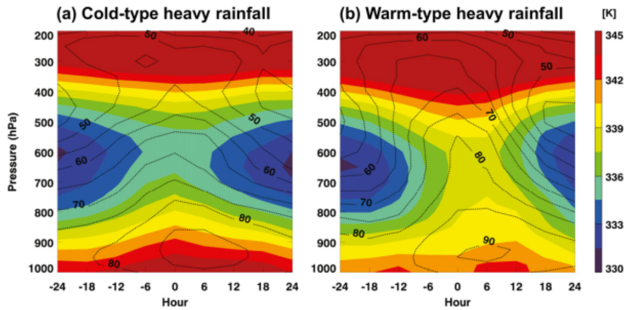
Observed Diurnal Variations

Cold-type rain	Warm-type rain
• High storm height and abundant ice water under c onvectively unstable condition • Inland China • Eastward moving cloud system with an oval shap e	• Lower storm height and lower ice water content • Ocean • Wide spatial distribution over an area extending from the southwest to northea st • Low-level moisture convergence area to the vertically aligned divergence area formed over the jet stream level → push air upward under moist-adiabatically near-neutral condition → heavy rainfall

SATELLITE OBSERVATION (2002-2011 TRMM)



Diurnal variation of the occurrence of heav y rainfall over South Korea [*Song and Sohn* , 2015]



Vertical structure of composited equivalent potential te mperature (color, K) and relative humidity (dotted line, %) for heavy rainfall over the Korean peninsula [*Song and Sohn*, 2015]

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