6th WGNE workshop on systematic errors in weather and climate models:
2022/11/03 @ECMWF, Reading, UK

MEXT KAKENHI
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DNA Climate Project
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Integrated Research Program for Advancing Climate Models

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Large Ensemble Atmospheric and Environmental Prediction for Disaster Prevention and Mitigation

Recent Progress and Challenges on Global sub-5km mesh Model Experiments from the Sub-seasonal to Climate Scales

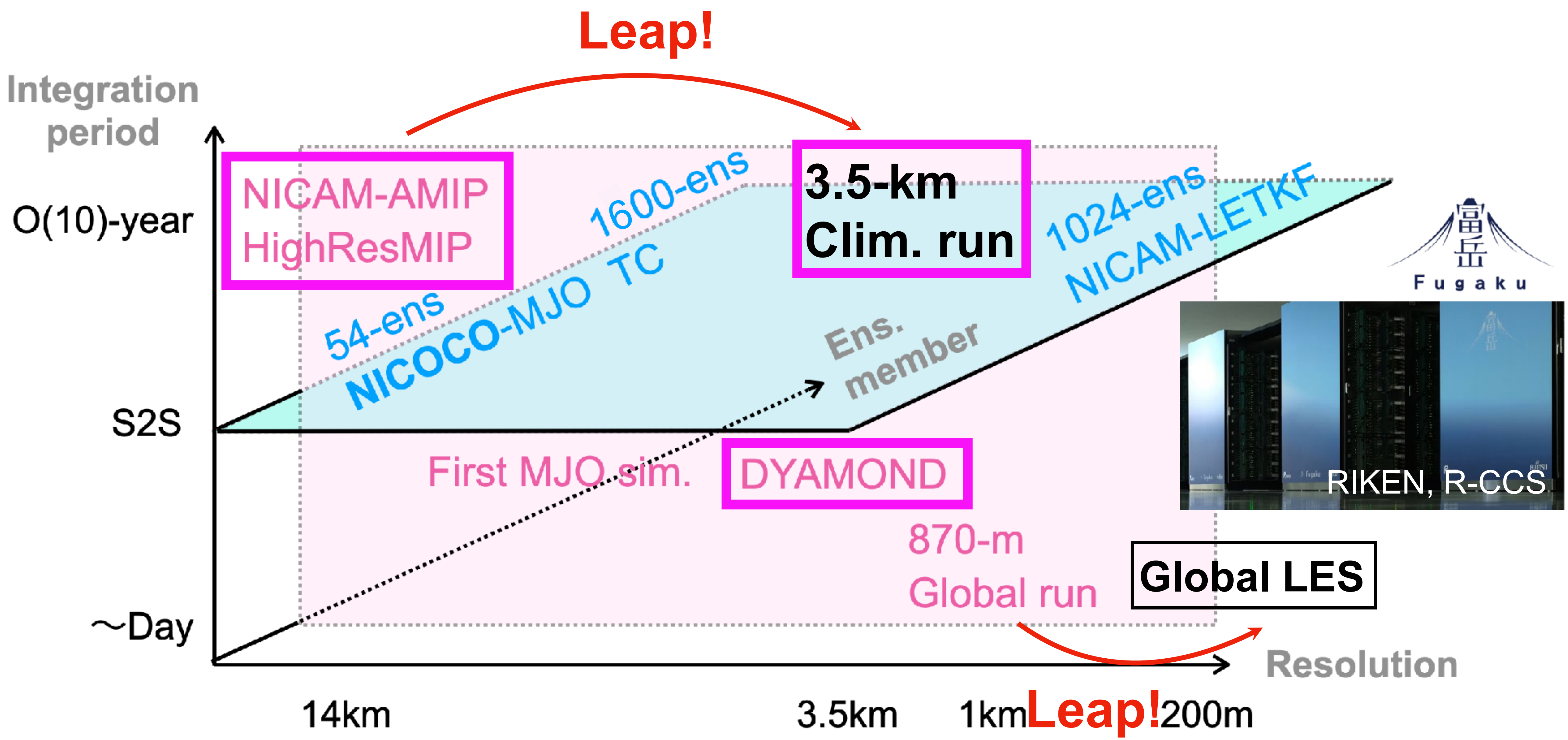
Daisuke Takasuka & **Tomoki Miyakawa** (Univ. of Tokyo)

Special thanks to **Chihiro Kodama** (JAMSTEC; a member of DE-LHA)

Mainly collaborate with Yuki Takano, Tamaki Suematsu, Tomoki Ohno, Yohei Yamada, Tatsuya Seiki, Hisashi Yashiro, Masuo Nakano, Hiroaki Miura, Akira T. Noda, Tomoe Nasuno, Ryusuke Masunaga, Masaki Satoh, and DYAMOND community.

Past & Present key NICAM activities

NICAM (w/ coupled ocean) with explicit convection has achieved some key simulations in terms of resolution, ensemble, & integ. period.



My talk's contents

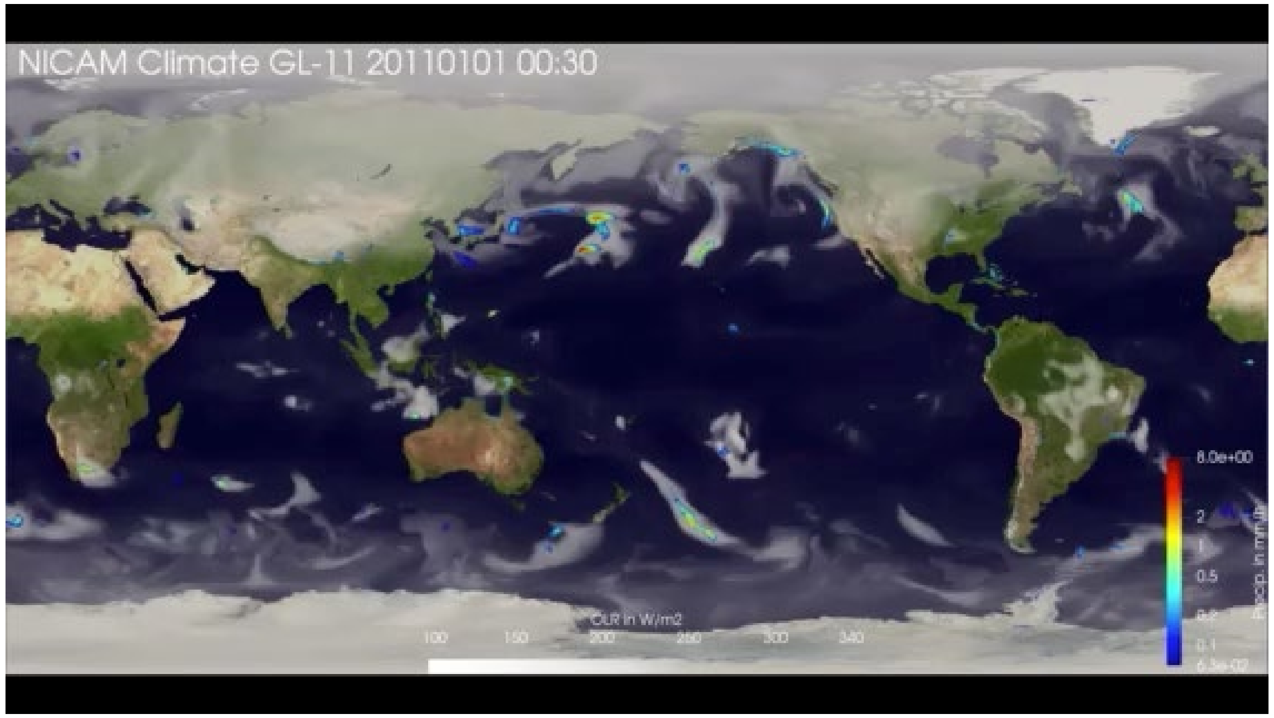
Can the resolution refinement solve model systematic errors?
→ Some aspects can be improved, but others cannot. (cf. Wedi et al., 2020)

1) Perspectives from NICAM climate simulations

- Improvements & long-standing biases in HighResMIP NICAM
- NICAM updates to reduce errors in k-scale modeling
- Good points and issues in a NICAM k-scale climate run

2) Perspectives from recent S2S-scale GCRM activities

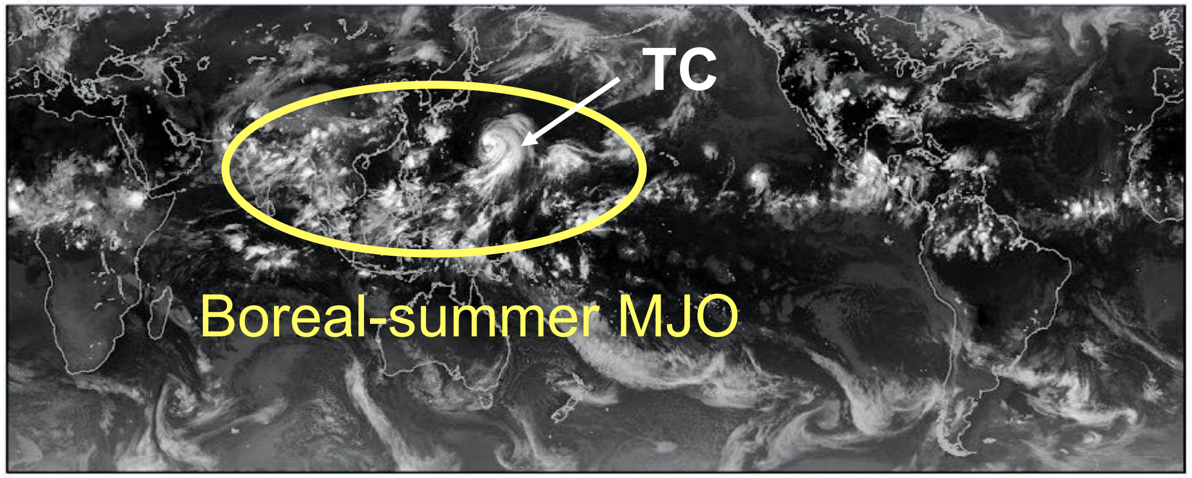
- Comparison of errors b/w k-scale models in DYAMOND2
- Recent science activities in S2S-scale NICAM experiments.



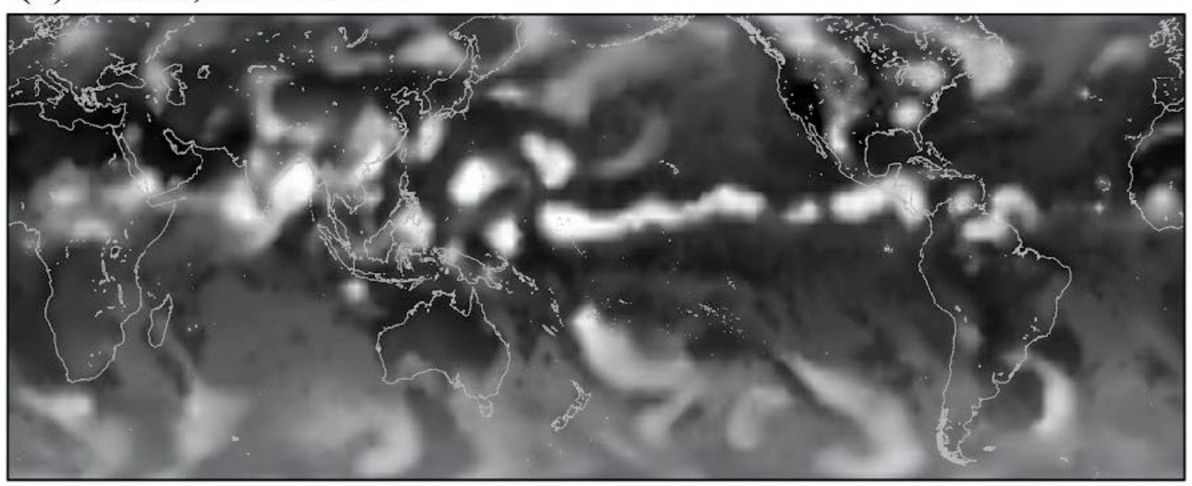
Data: Daisuke Takasuka
Visualization: Chihiro Kodama

“NICAM” as a global convection-resolving model

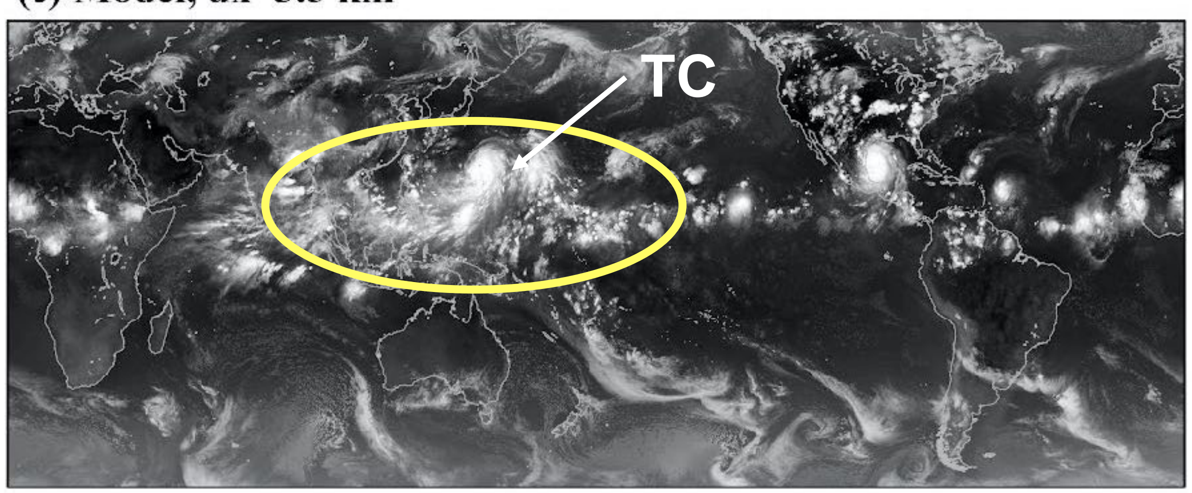
(a) Observation



(b) Model, dx=220 km



(c) Model, dx=3.5 km

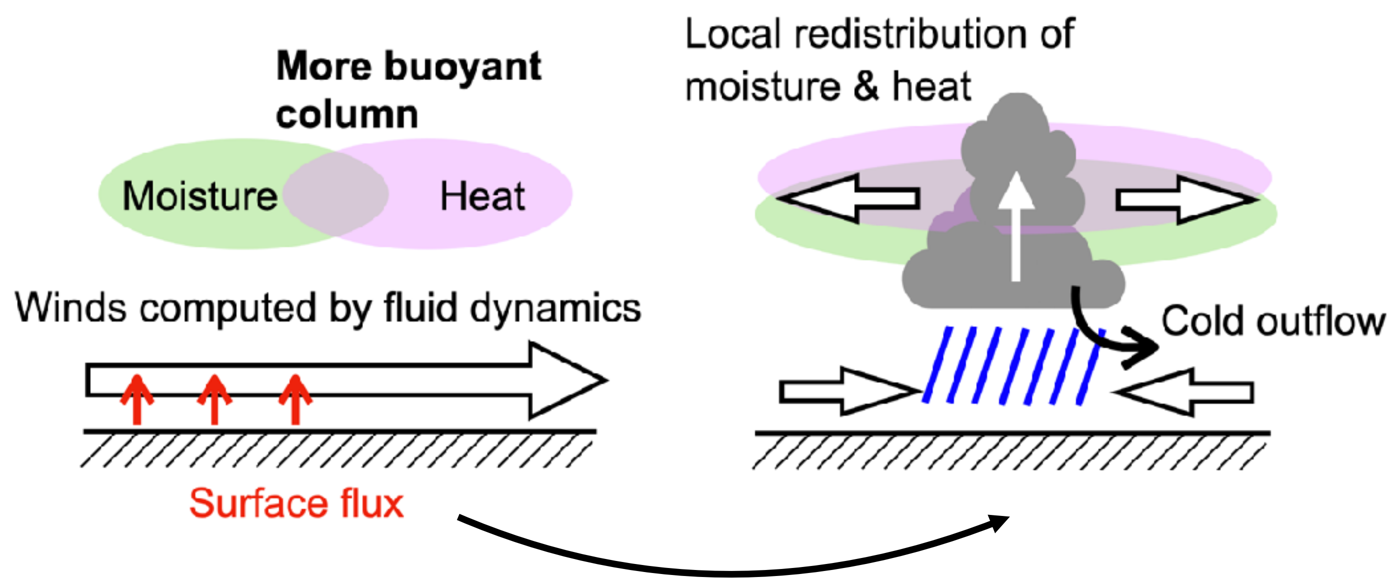


※ 3.5km NICAM data courtesy of **Ryosuke Shibuya**

<u>Convection-resolving:</u>

Deep convection and bulk cloud processes are explicitly treated.

→ Dynamics are directly coupled to cloud-related local thermodynamics.



Cloud is a **fast response**, which does not unnecessarily disturb slow-scale circulations.

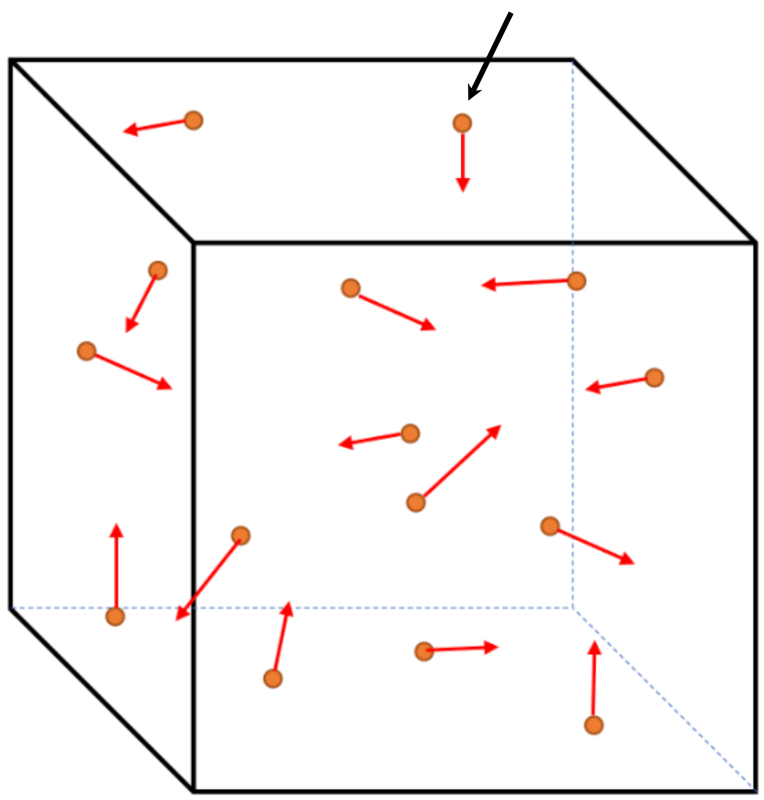
- More accurate heat/moisture transport
- Spontaneous realization of the hierarchical structure of cloud systems

(cf. Miura 2019; Satoh 2019)

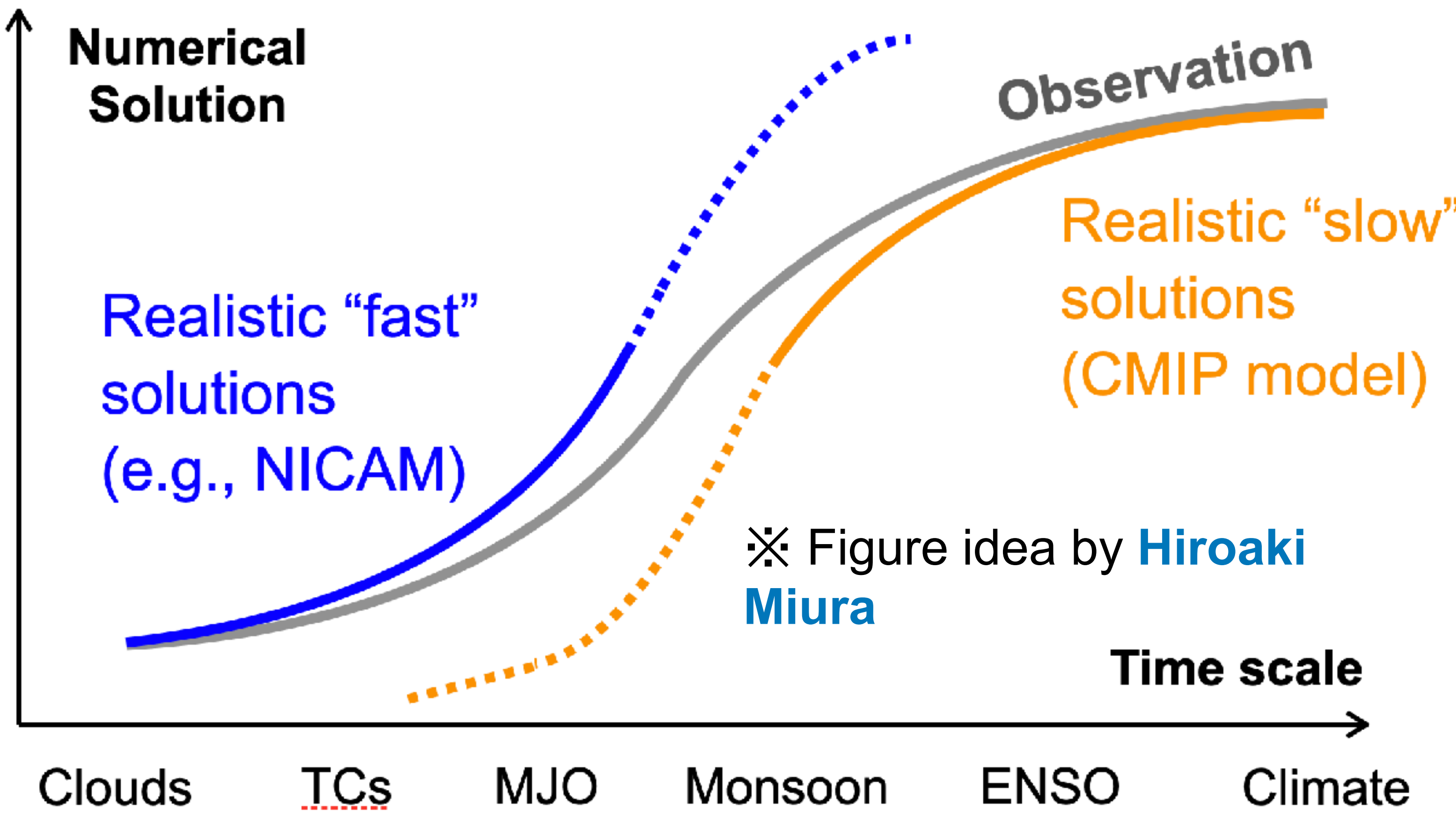
Can we “fast” solutions connect to “slow” ones?

It is non-trivial whether the accumulation of fast-response solutions in GCRMs leads to the accuracy of “slow” solutions (e.g., the climate).

Individual molecular motions
(= Fast process / micro)



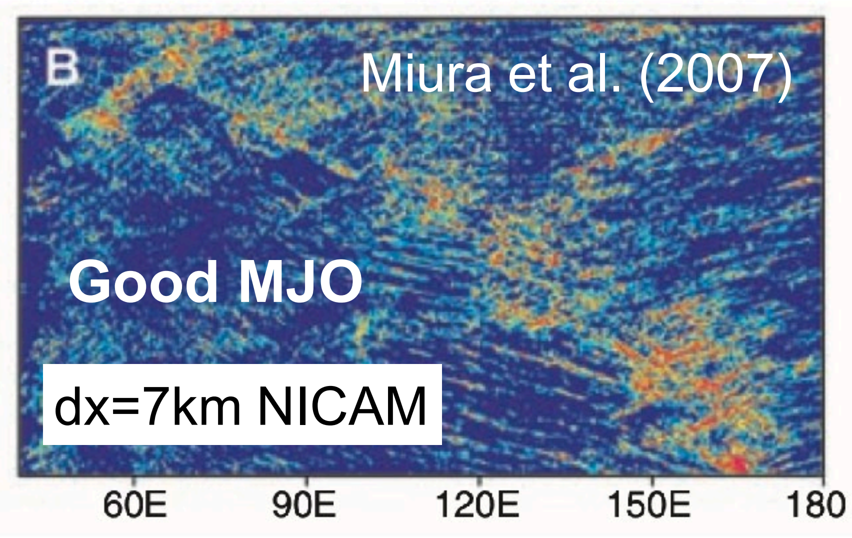
$(T, P, S...)$ Equilibrium states
(= Slow process / macro)

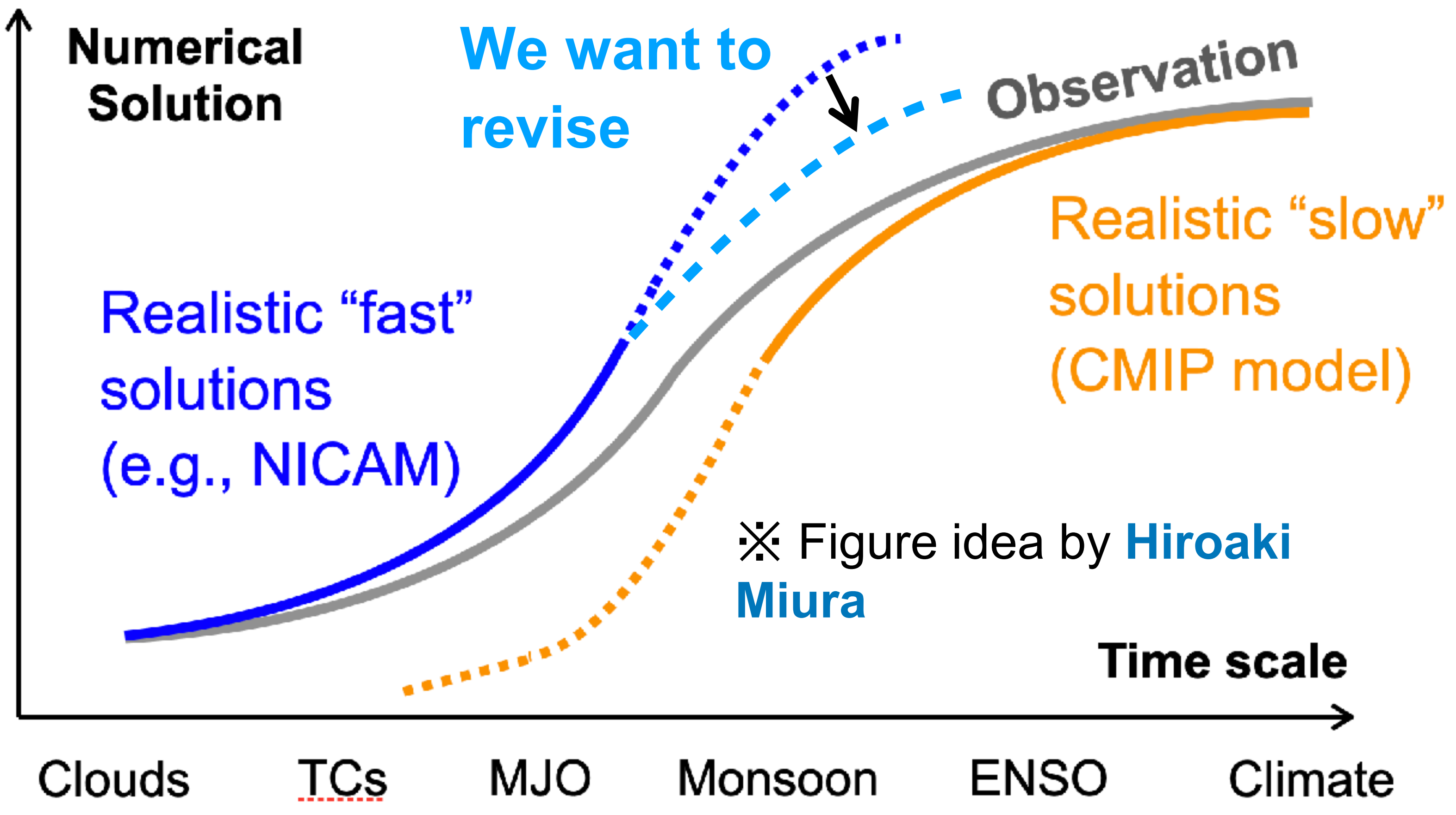


“Thermodynamics” does not require the computation of individual molecular motions to know macro states. “Statistical mechanics” analogy could be useful, but…

Can we "fast" solutions connect to "slow" ones?

It is non-trivial whether the accumulation of fast-response solutions in GCRMs leads to the accuracy of "slow" solutions (e.g., the climate).





A kind of "**weather forecast**"

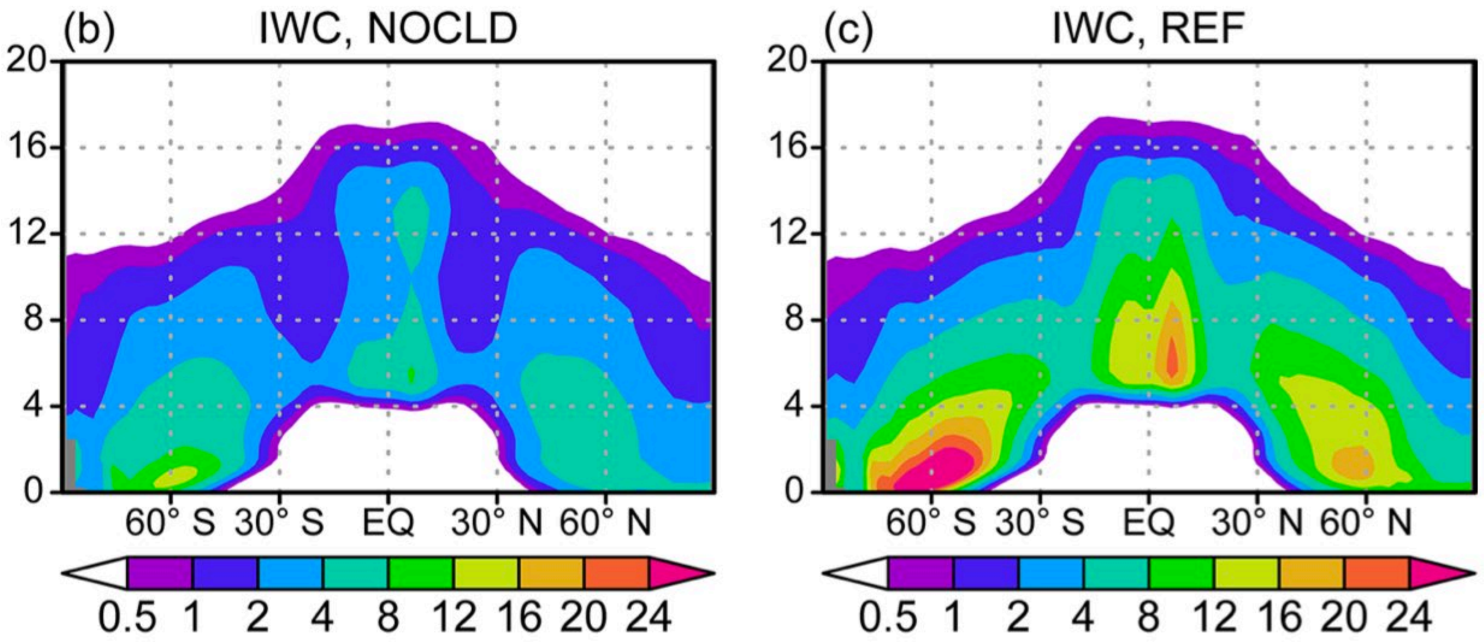
Need to solve a fast response (i.e., clouds, precipitation) to heat/moisture accurately.

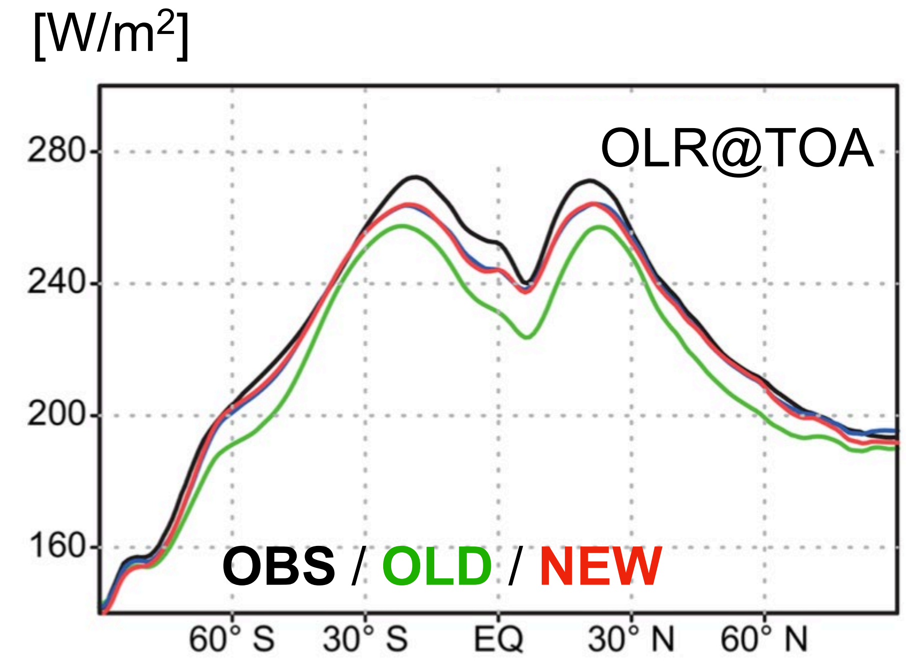
Requirement for "**climate simulations**"

Obtain a reasonable interaction between the radiation and moisture/clouds maintained as a result of populated convection.

Improvements in HighResMIP NICAM (dx=14km/L38)

Cloud microphysics and radiation schemes and surface albedo values are improved, which optimizes clim. mean radiation distributions.





Ice water content becomes closer to that in satellite observation

☞ Update of single-moment bulk microphysics based on TRMM (Roh & Satoh 2014; Roh et al. 2017)

- Explicitly generated cloud ice
- Modified mass and diameter relationship of snow

Kodama et al. (2021)

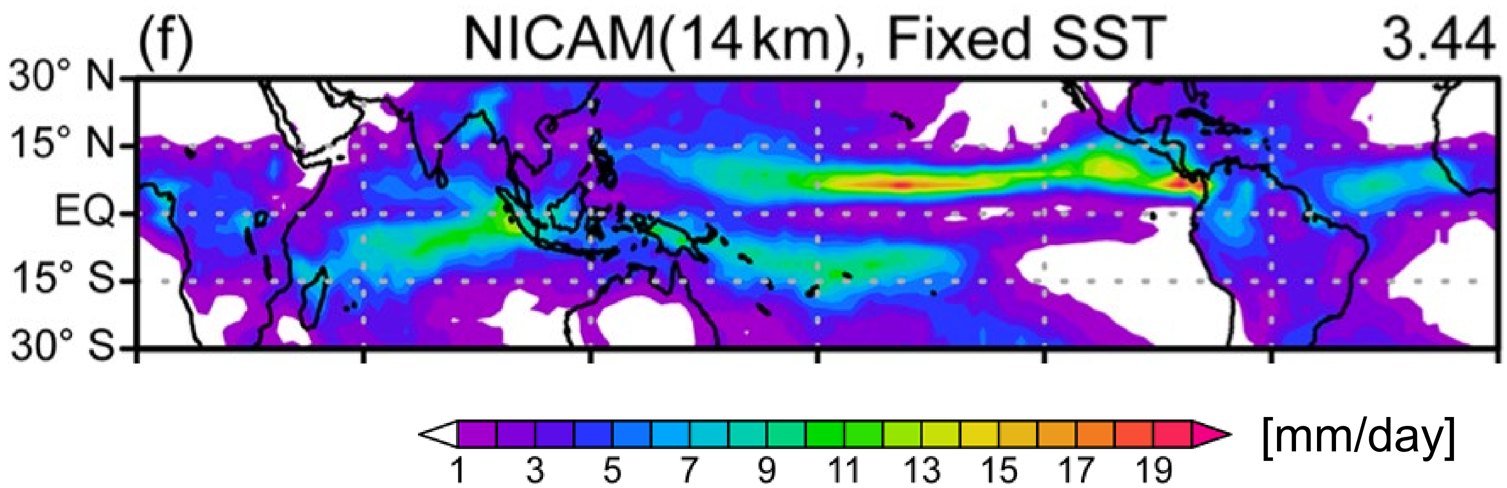
Lower OLR bias is reduced in almost all latitudes

☞ Consistent coupling b/w clouds and radiation

- Effective radii for liquid and ice hydrometeors

Long-standing systematic errors (dx=14km/L38)

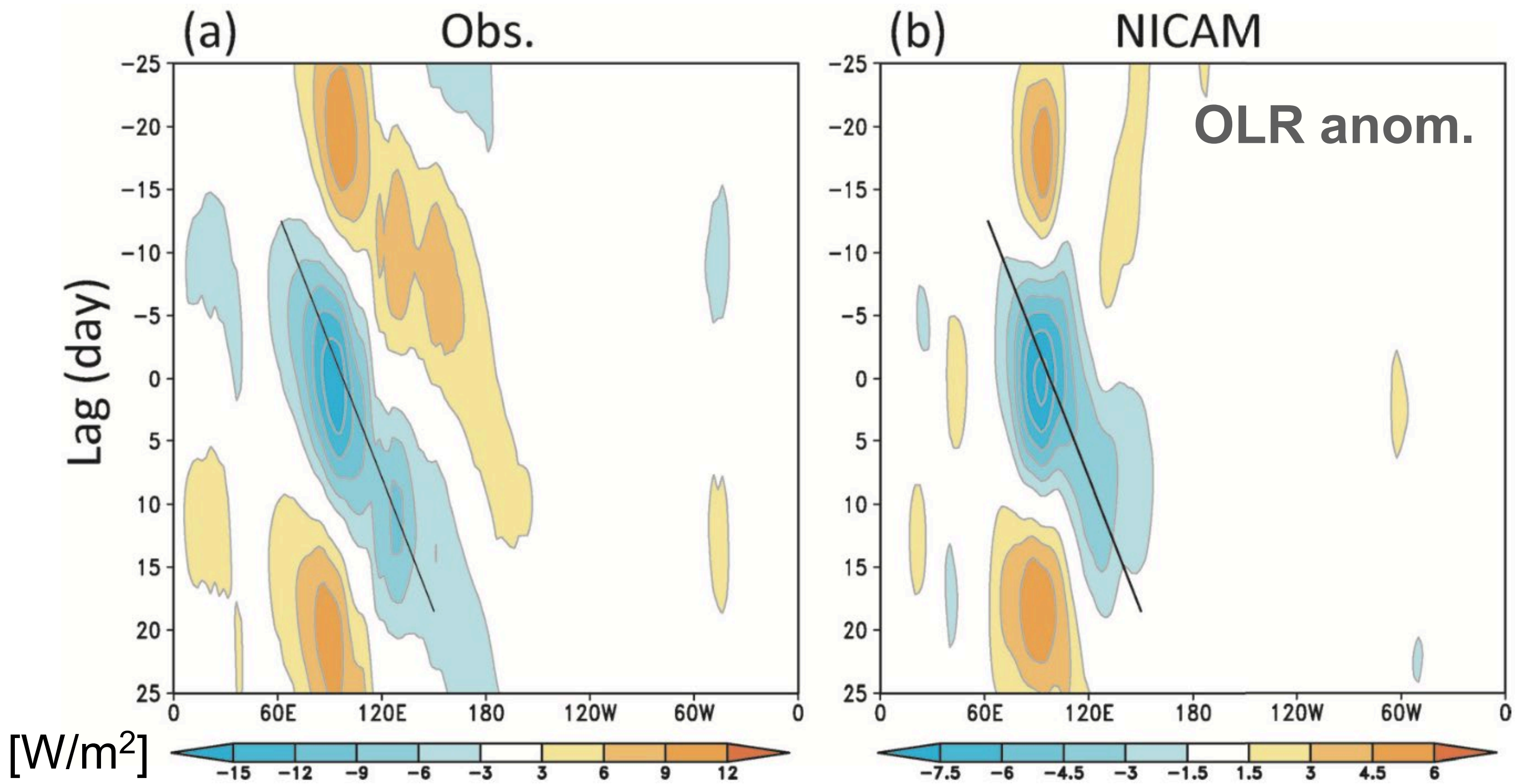
In exchange for the better radiation distributions, the representation of precipitation fields is not good in both mean states and S2S scale.



Double ITCZ bias is prominent.

(= too little precipitation at the EQ)

(Kodama et al., 2021)



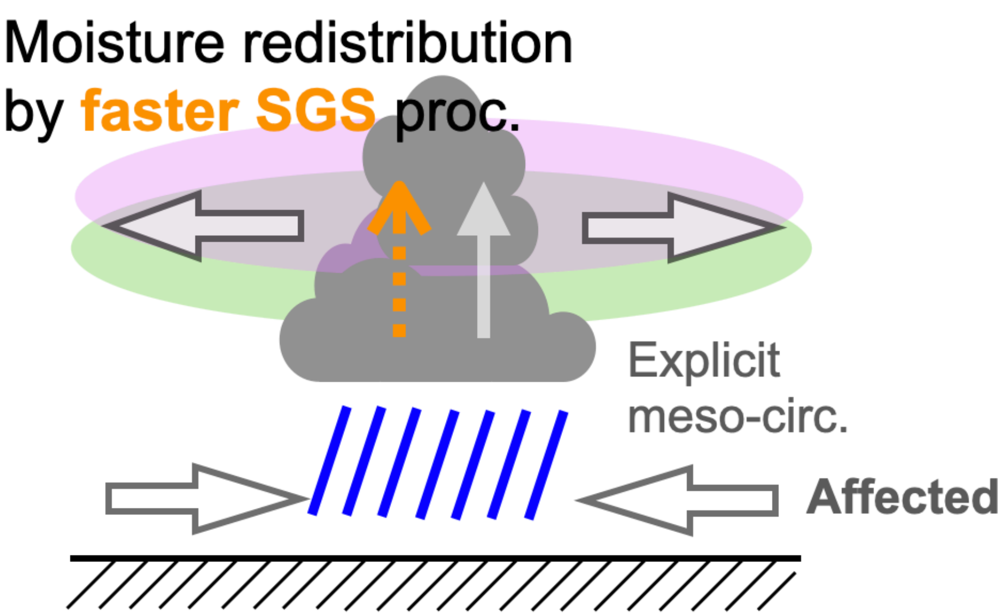
Exaggerated MC barrier effect on the MJO (e.g., Kodama et al., 2015)

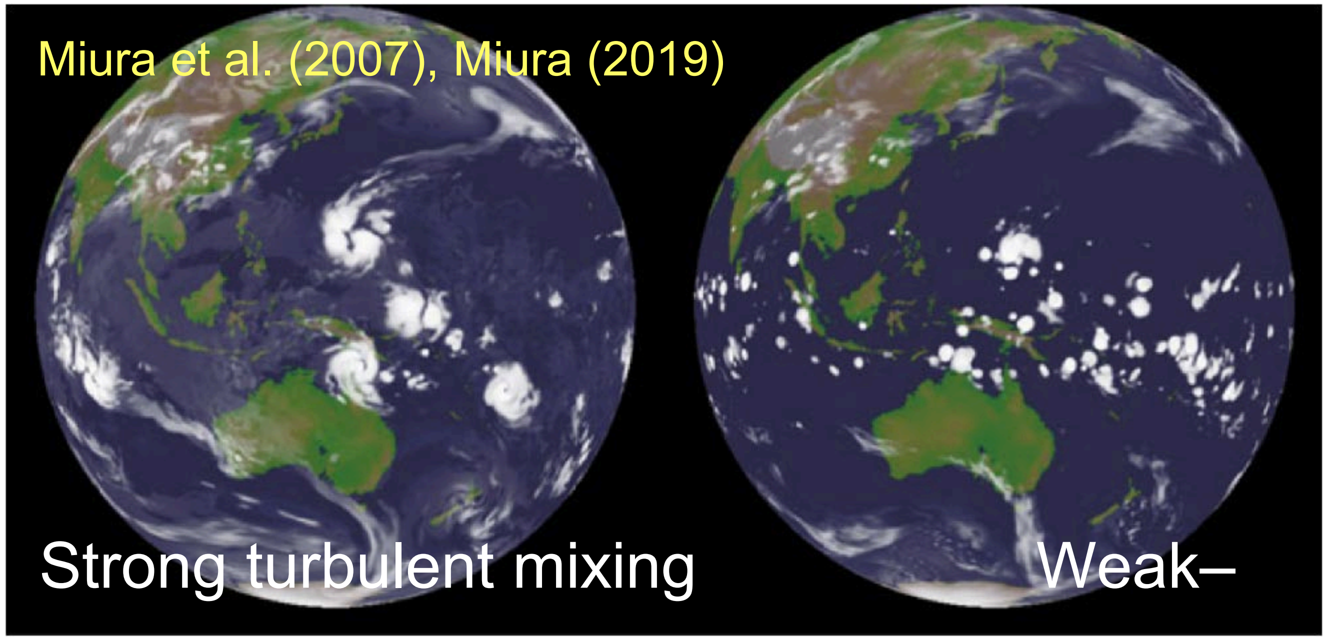
(= MJO conv. fails to propagate into the western Pacific)

➡ Totally different from NICAM solutions in S2S-scale runs

Issues because of “not truly convection-resolving”

Though GCRMs have a fewer “knobs” available to model tuning, SGS-physics–dyn. coupling can determine “**not truly GCRM**” performance.





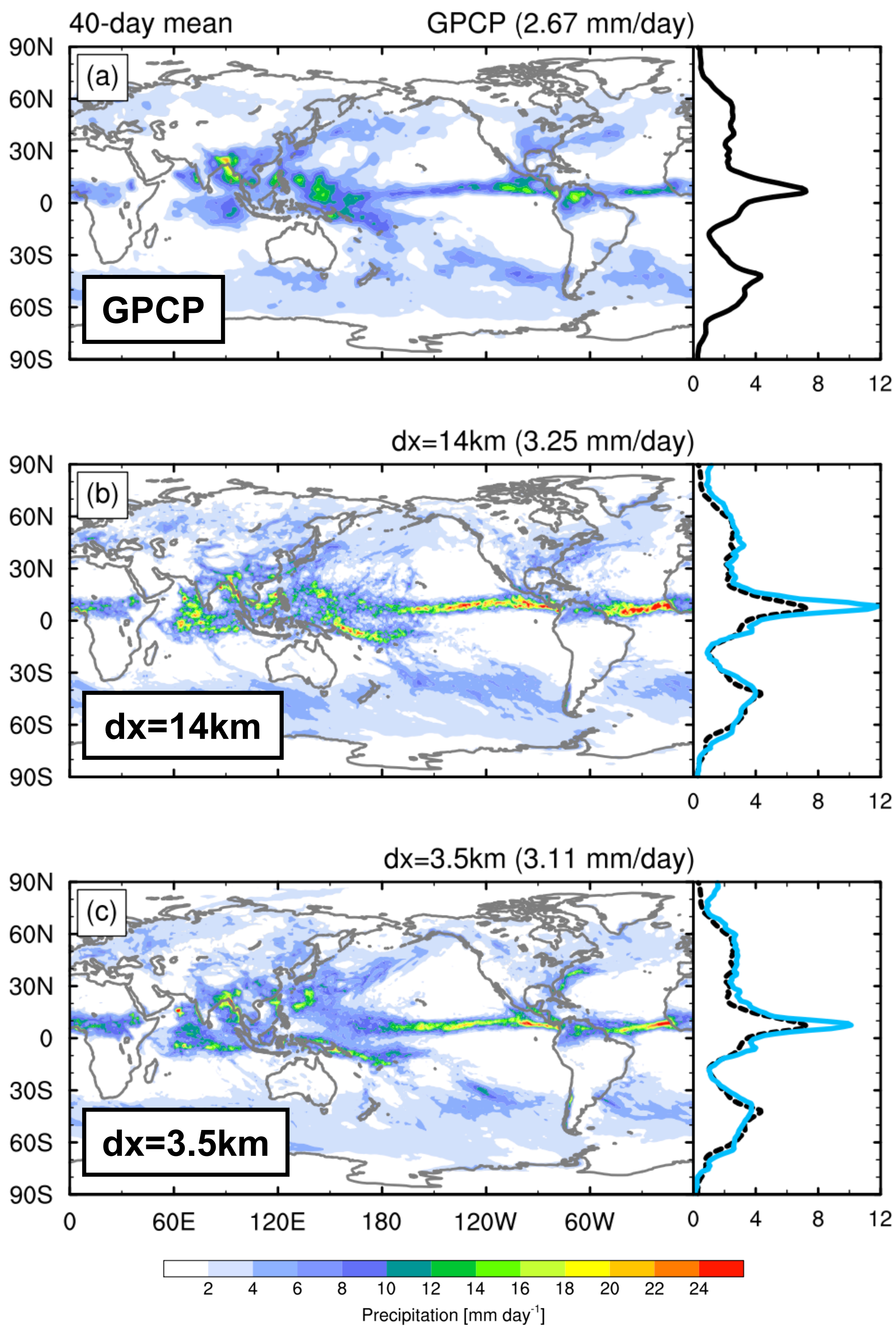
- **Cloud microphysics**
- **Unresolved turbulent mixing**

➡ Altering strength and time scale of (explicit) mesoscale circulations

Strong turbulent heat/moisture transport
→ Column is easily stabilized without explicit conv.
→ Individual convection tends to be inhibited,
leading to large-scale rad.–conv. feedback

Before going into k-scale, we may have to face a kind of “Microphysics/turbulence deadlock" (cf. Miura 2019)

Resolution independent errors



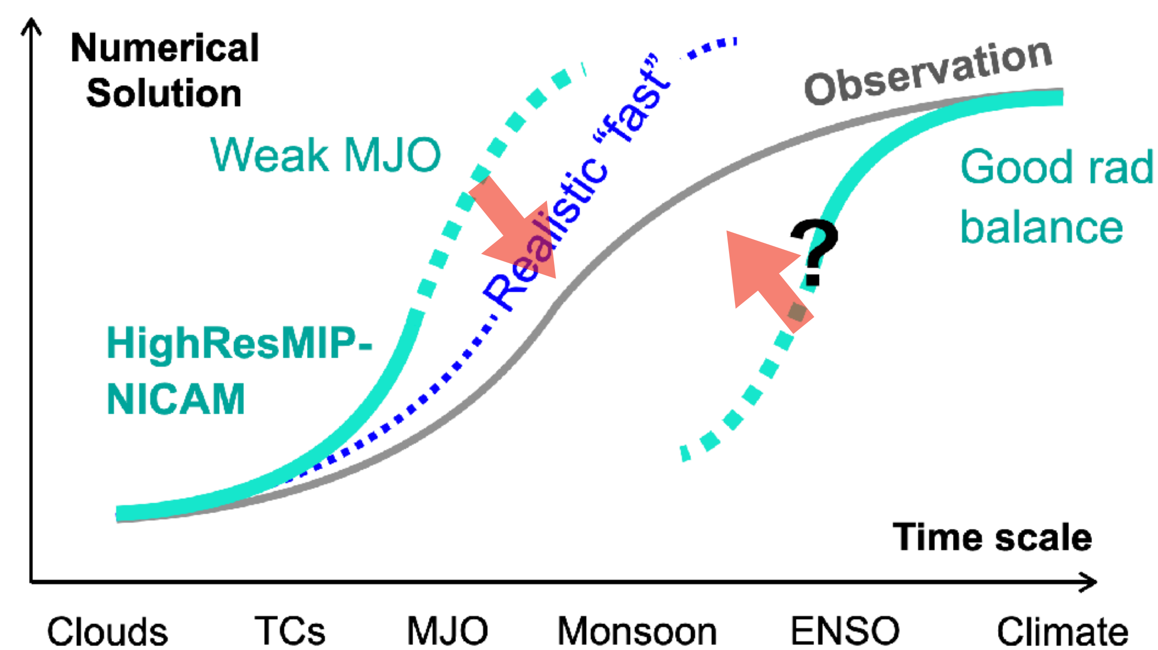
<u>40-day simulation</u> <u>(HighResMIP conf.)</u>

Common bias in dx=14km and 3.5km

- Double ITCZ-like split
- Deficient precipitation over the WP
- Too weak MJO (not shown)

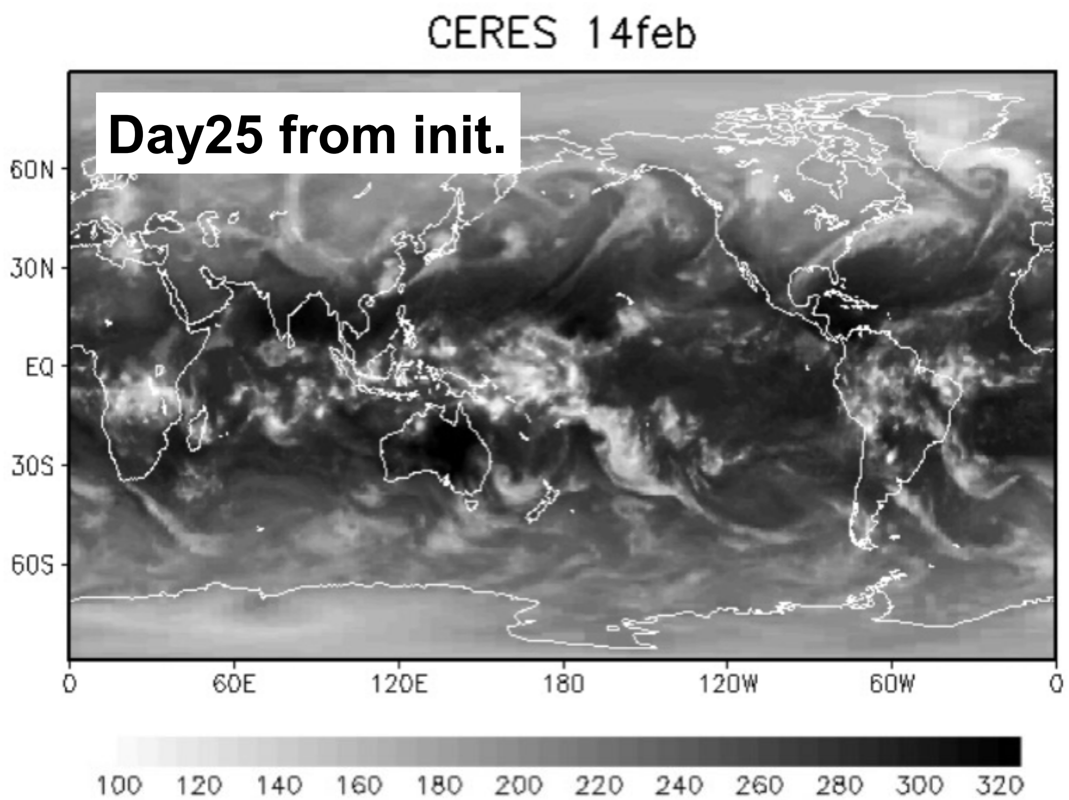
Phys–Dyn coupling uncertainties are expected to be resolution independent at *O*(1-10)-km scale.

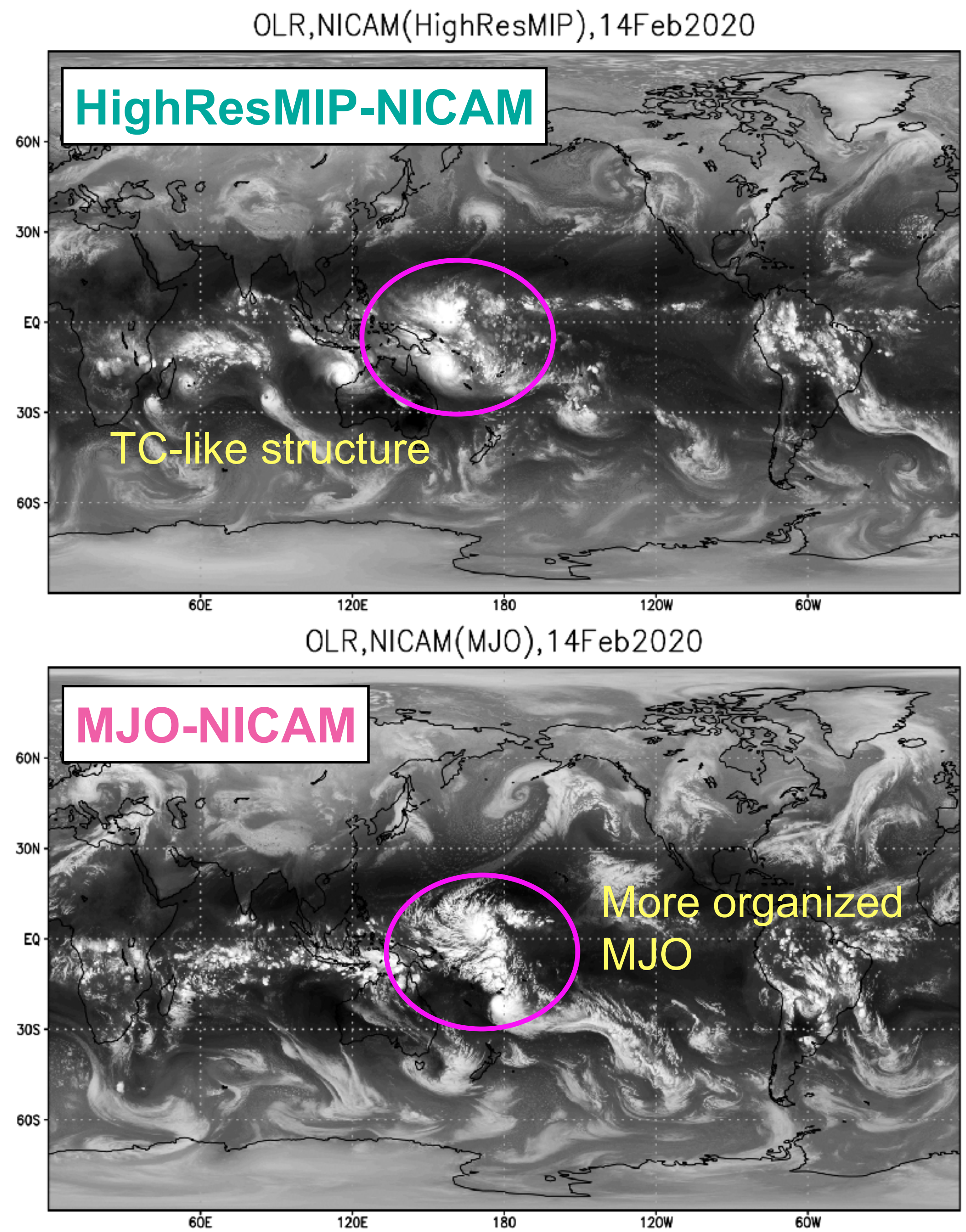
→ **Reconsider microphysics & turbulence**



Toward better “fast” solution (Tamaki Suematsu@RIKEN)

Tuning of cloud microphysics and surface flux schemes can improve the simulation skill of the MJO at the sub-seasonal scale.



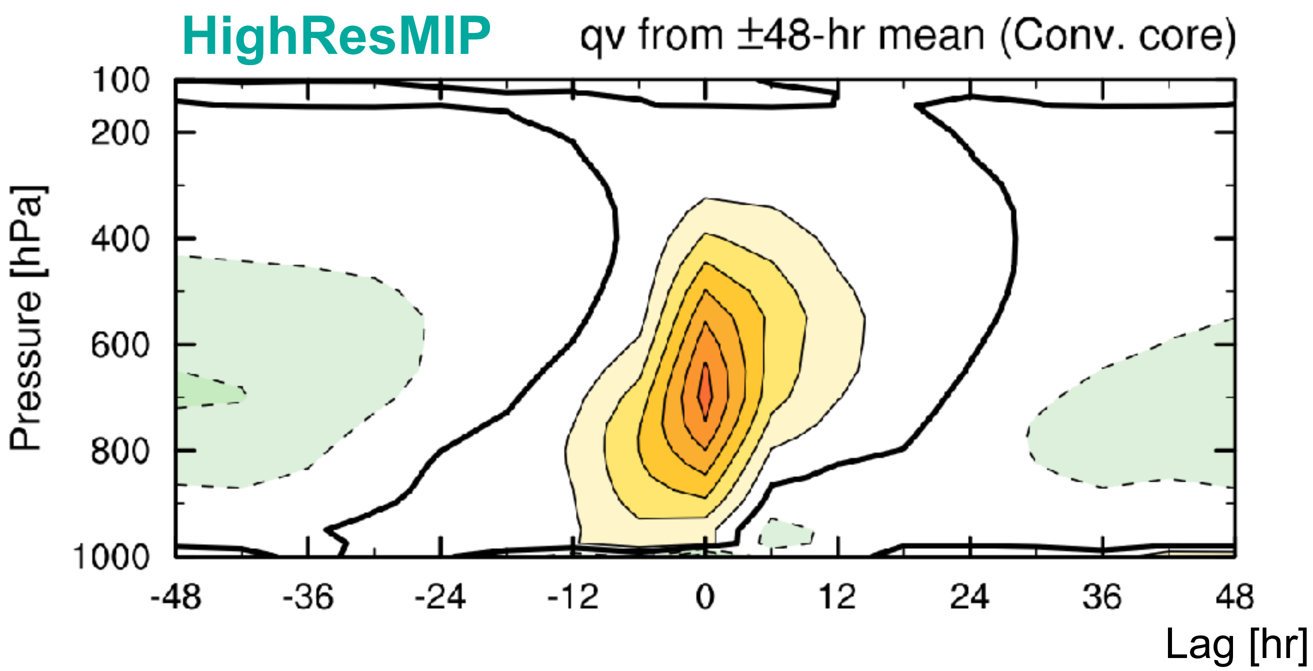


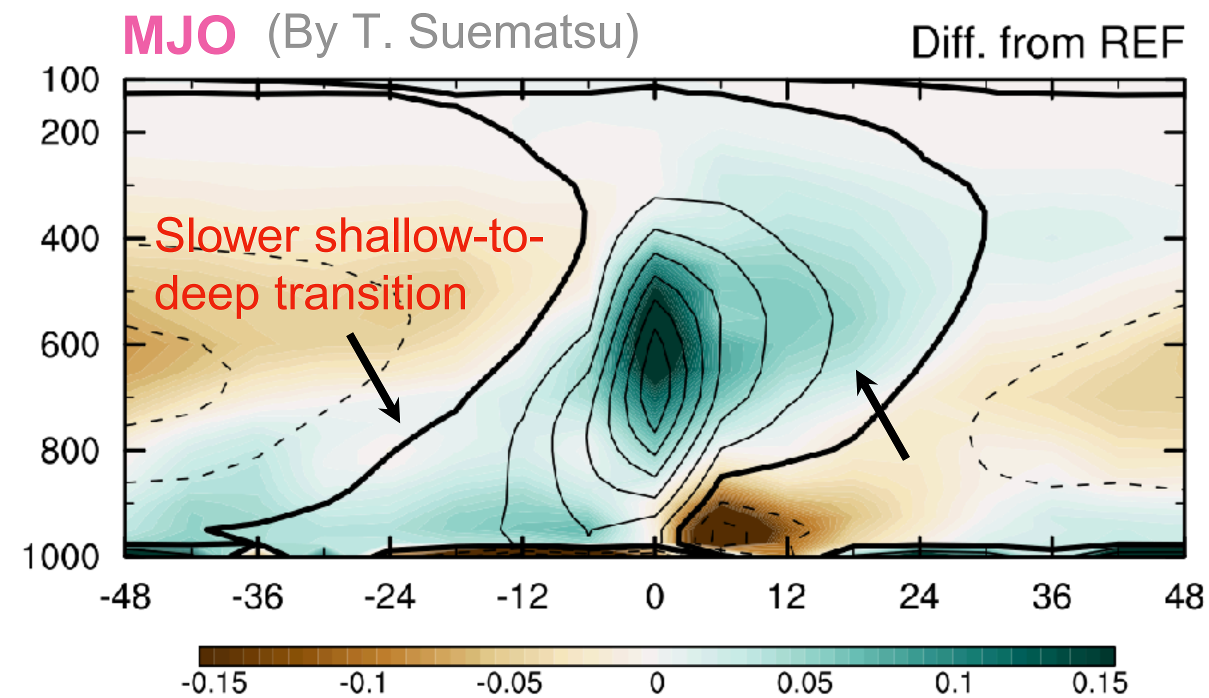
<u>3.5km NICAM for DYAMOND-Winter</u>

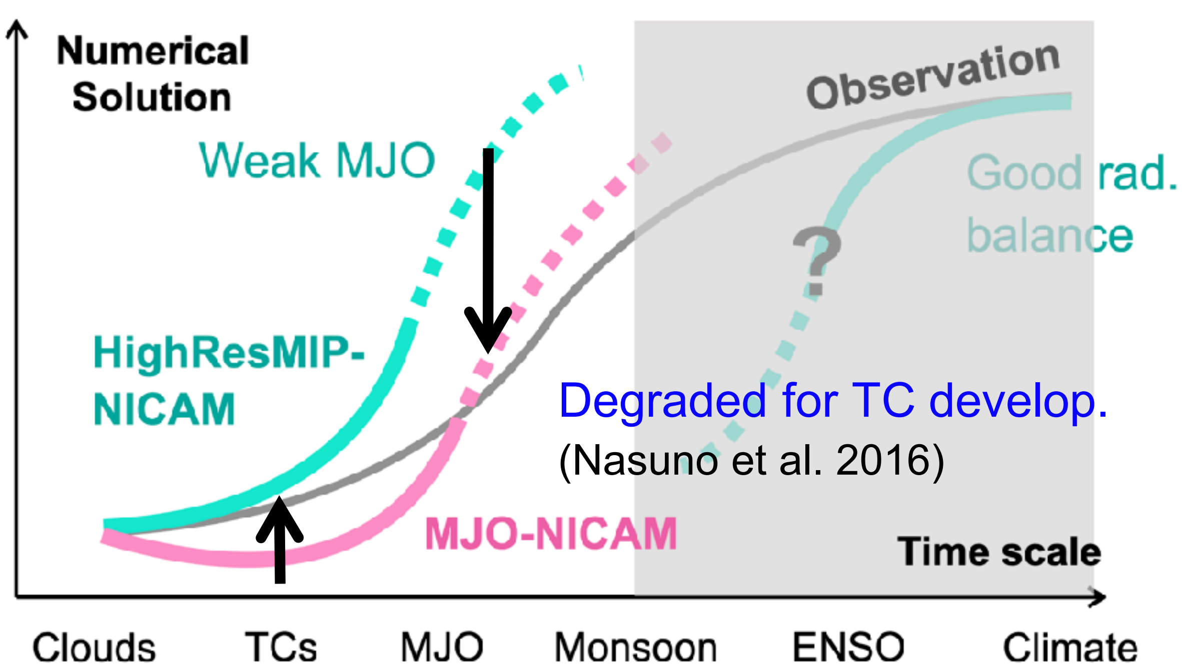
Model configuration greatly alters the characteristics of convective organization at the k-scale.

Diversity of moisture–convection relation

Characteristics of individual deep convection & associated moisture redistribution determine a favored time scale in "fast" solutions.







In MJO-NICAM (mainly tuned MP)

- Individual conv. is hard to be triggered.
- Mid-level moistening is promoted.

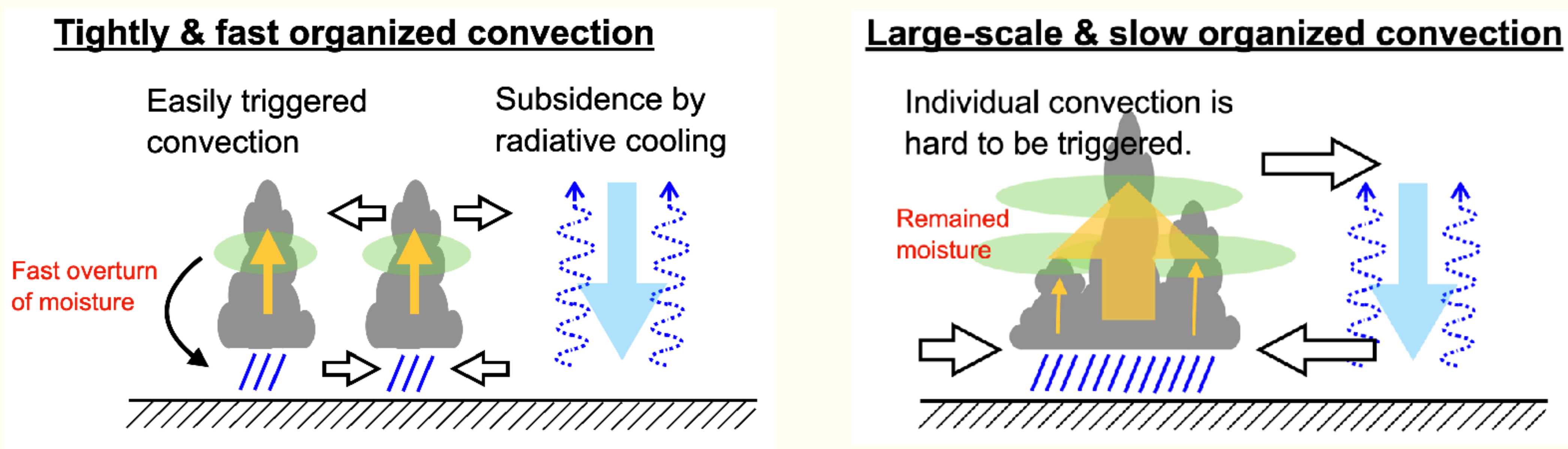
→ Moisture–conv–rad feedback at longer/ larger scale amplify rather than local circ.

(cf. Grabowski & Moncrieff 2004)

To control GCRM solutions…

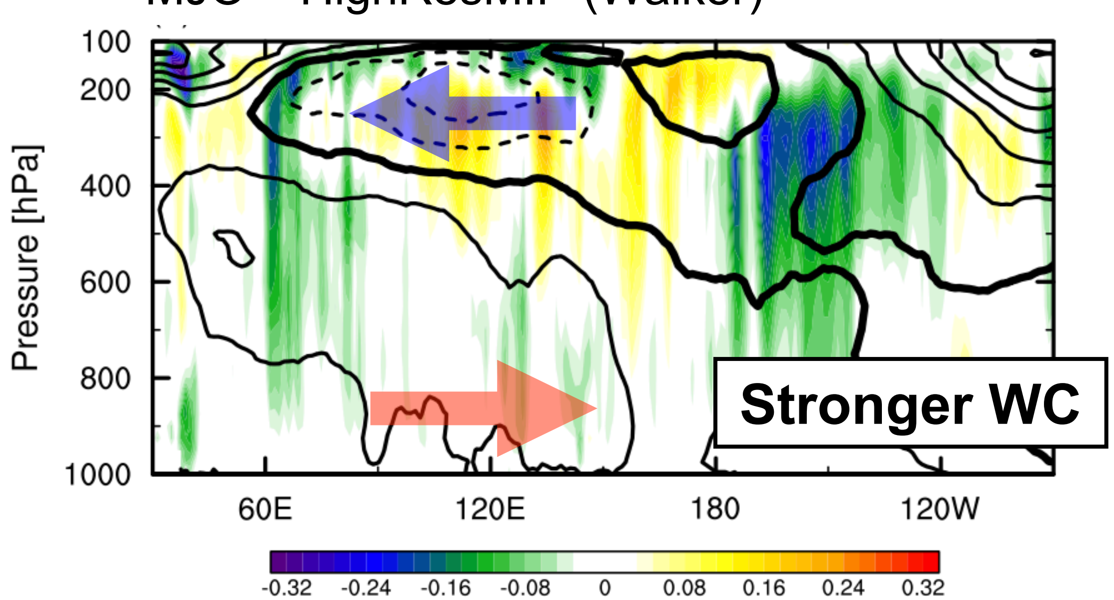
In GCRM framework, we have to find the appropriate partitioning b/w local (mesoscale) and large-scale circulations consciously.

Slow systems can't be captured.

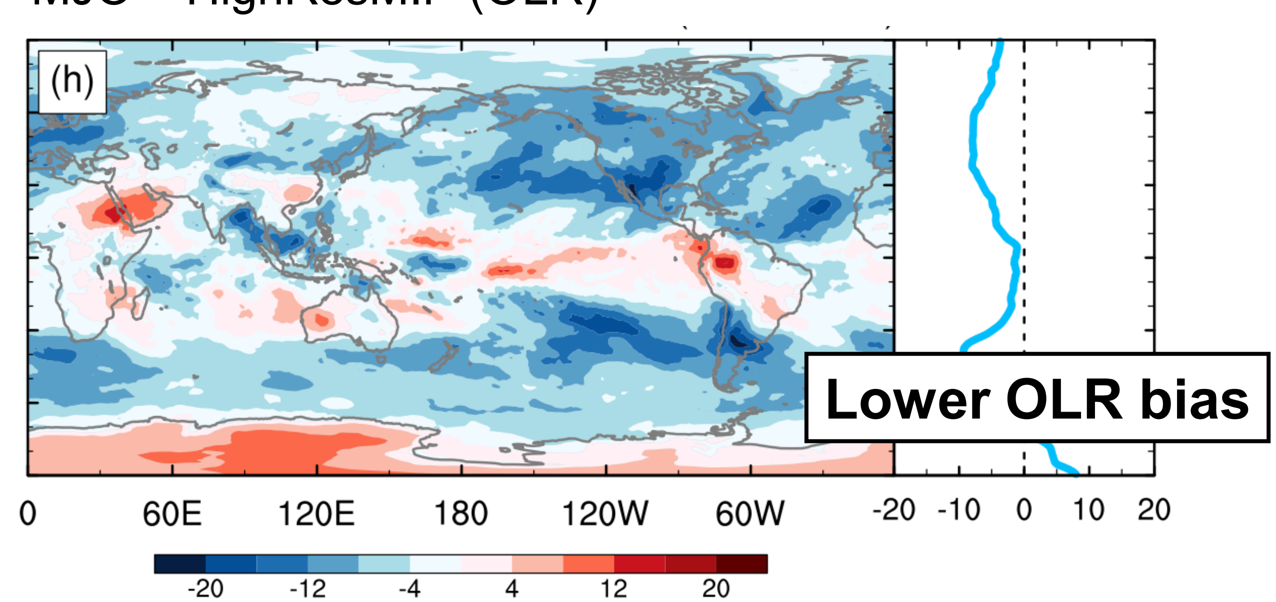


"Slow" solutions become biased…

MJO – HighResMIP (Walker)



MJO – HighResMIP (OLR)



Recent NICAM updates for reliable climate run

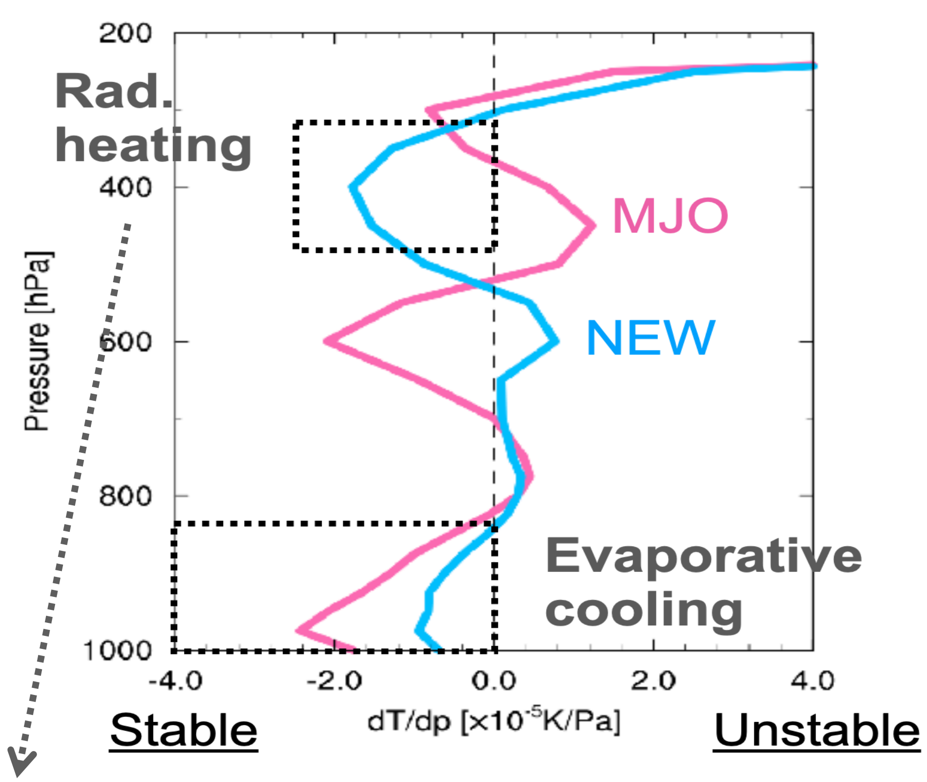
To control the favored time scale of convection appropriately, we have updated the model by focusing on moisture–convection relation.

(Takasuka et al., to be submitted to JAMES)

① Retune microphysics parameters

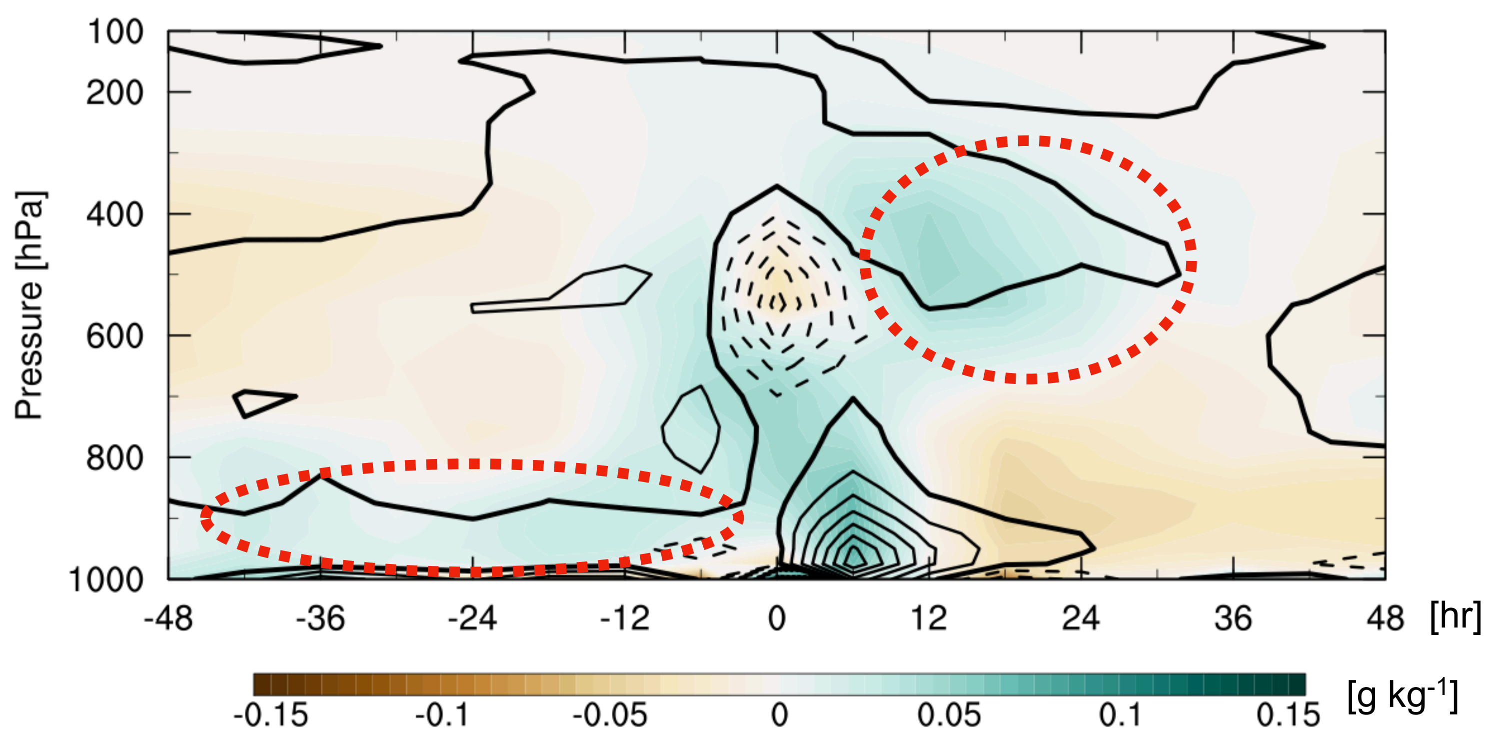
- ☞ Fall speeds of rain & snow → Change in static stability, conv. triggering, & *qv* redistribution
- ☞ Introduce cloud ice falling → Better representation of OLR at TOA

dT/dp diff. from HighResMIP



Due to more snow clouds

qv evolution with convection (diff. From HighResMIP / MJO)



Moisture evolution similar to “MJO” conf., but its amplitude is reasonably reduced.

Recent NICAM updates for reliable climate run

To control the favored time scale of convection appropriately, we have updated the model by focusing on moisture–convection relation.

(Takasuka et al., to be submitted to JAMES)

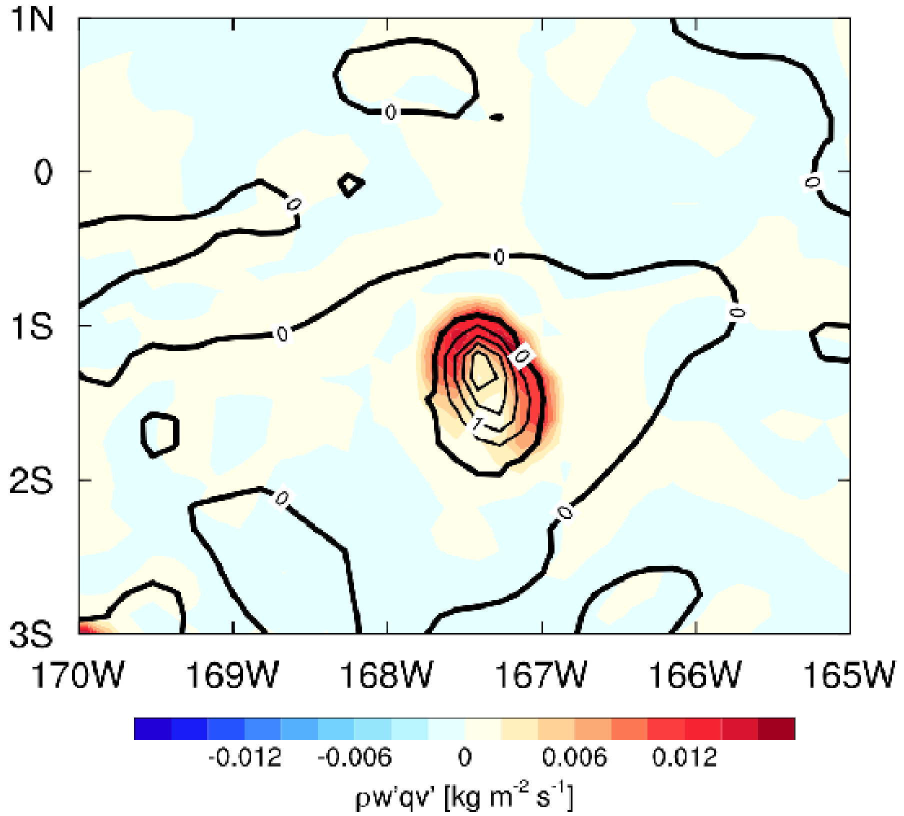
② Implement new turbulent diffusion effects

☞ Leonard term → Supplement turbulent mixing by CRM-grid scale eddies (cf. Moeng et al. 2010)

$$\tau^*_{wc} = K_f \left(\frac{\Delta^2}{12}\right) \nabla_h \tilde{w} \cdot \nabla_h \tilde{c}$$

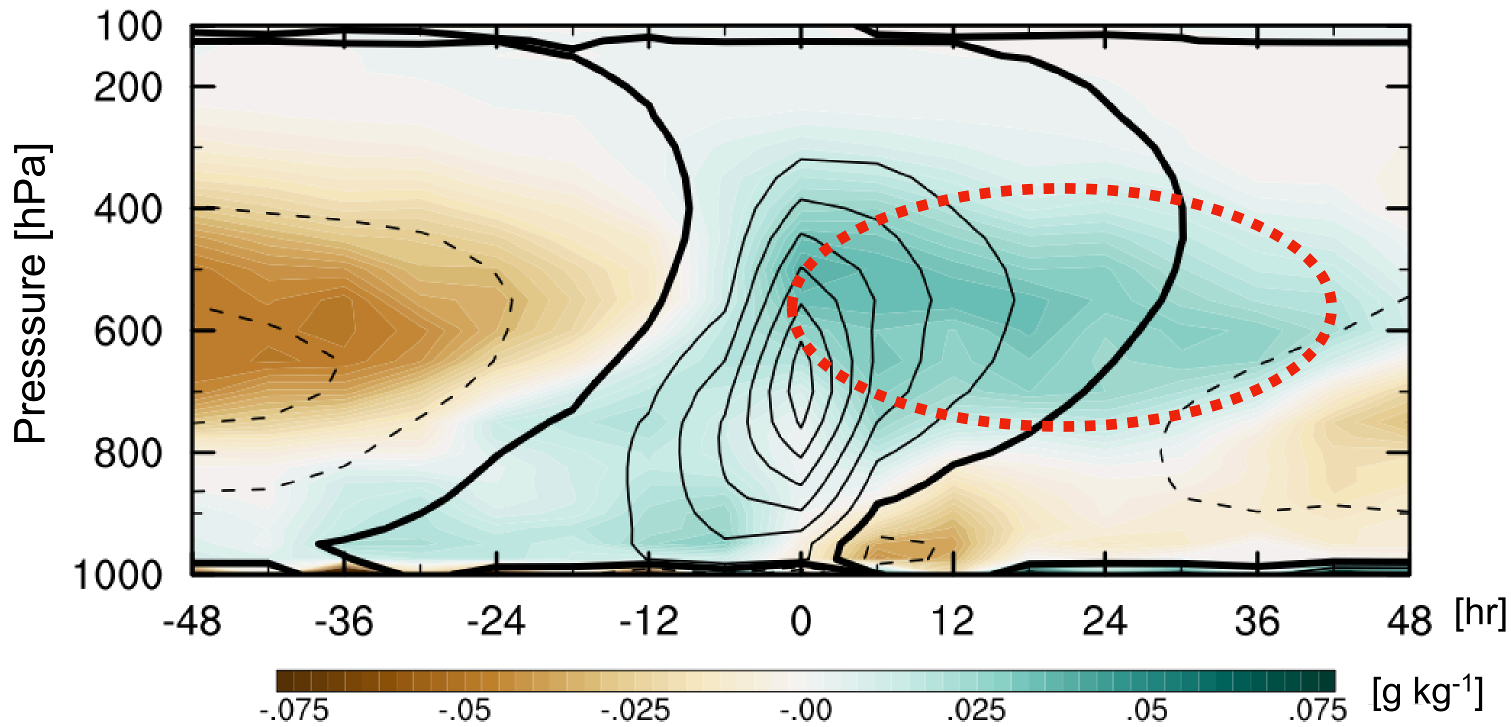
$$\tau^*_{v_h c} = K_f \left(\frac{\Delta^2}{12}\right) \nabla_h \widetilde{v_h} \cdot \nabla_h \tilde{c}$$

w'qv' by Leonard term (z = 6.2 km)



Moisture diffusion around deep convection

qv evolution with convection (diff. from NEW-MP)

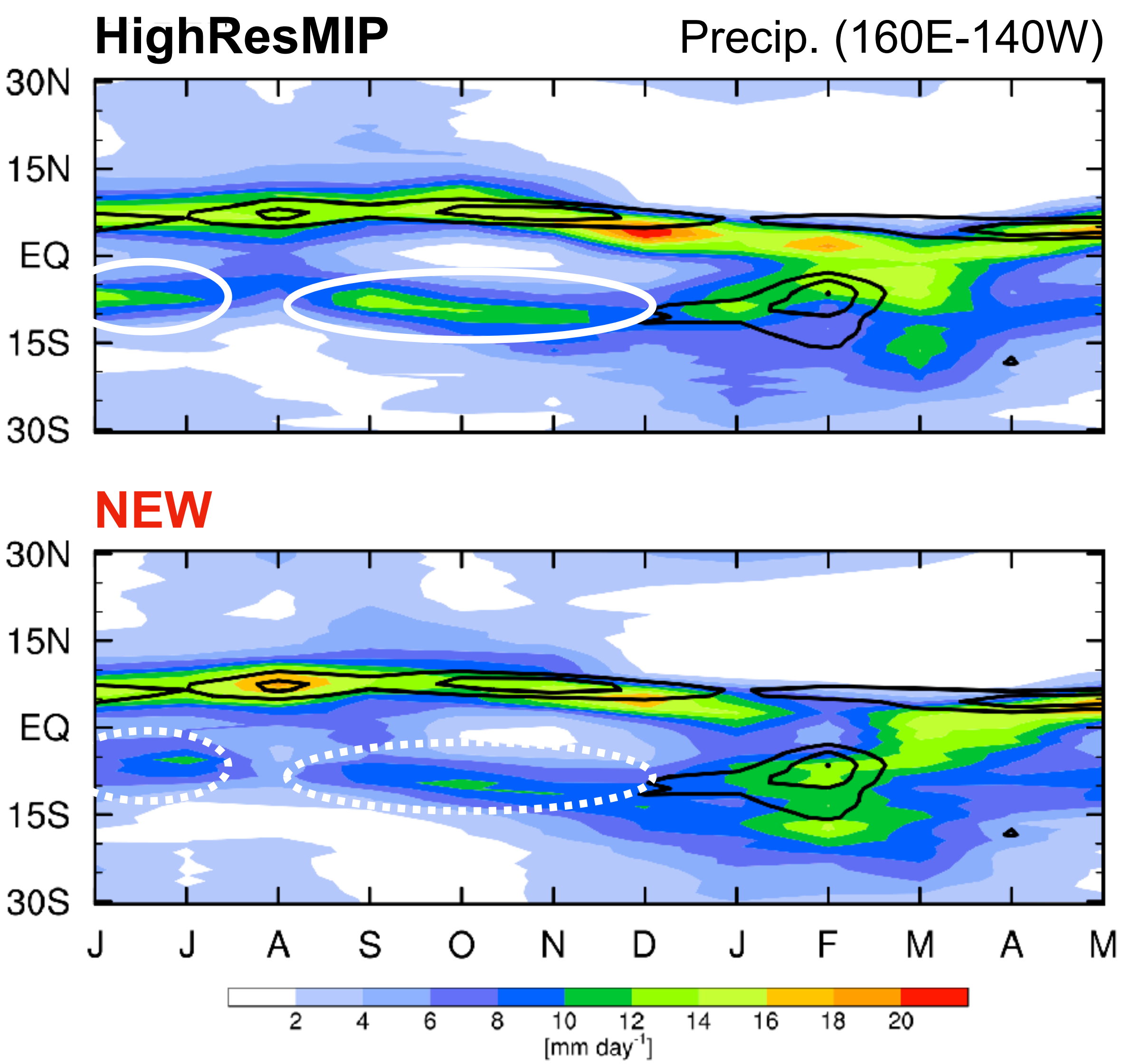


Mid-level moistening without disturbing convection triggering

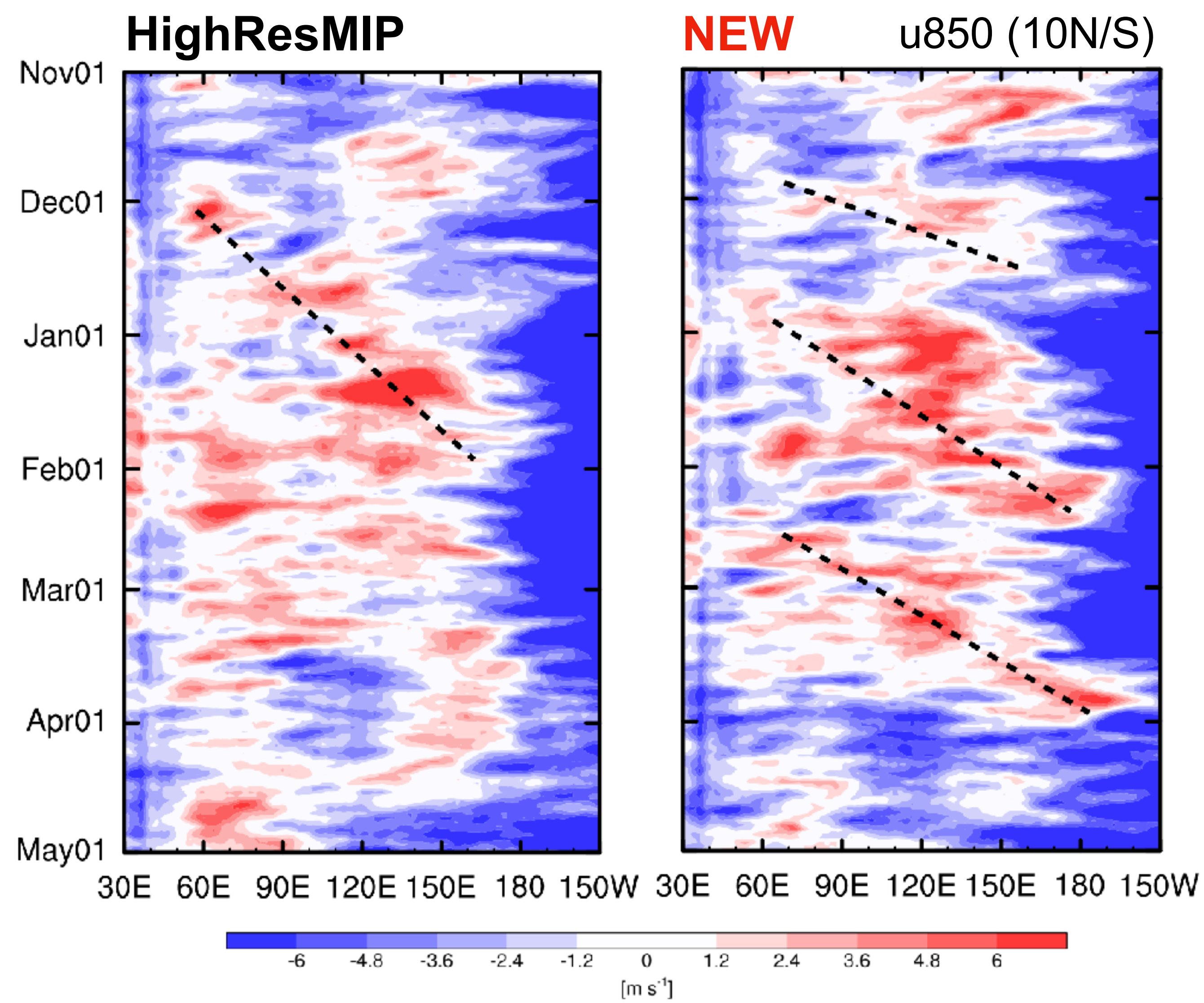
Impacts of model updates (1yr from June, 2004 / 14km)

The improved NICAM has succeeded in reducing long-standing biases in terms of both the mean characteristics and weather disturbances.

(Takasuka et al., to be submitted to JAMES)



Double ITCZ bias disappears, and seasonal march is also better.

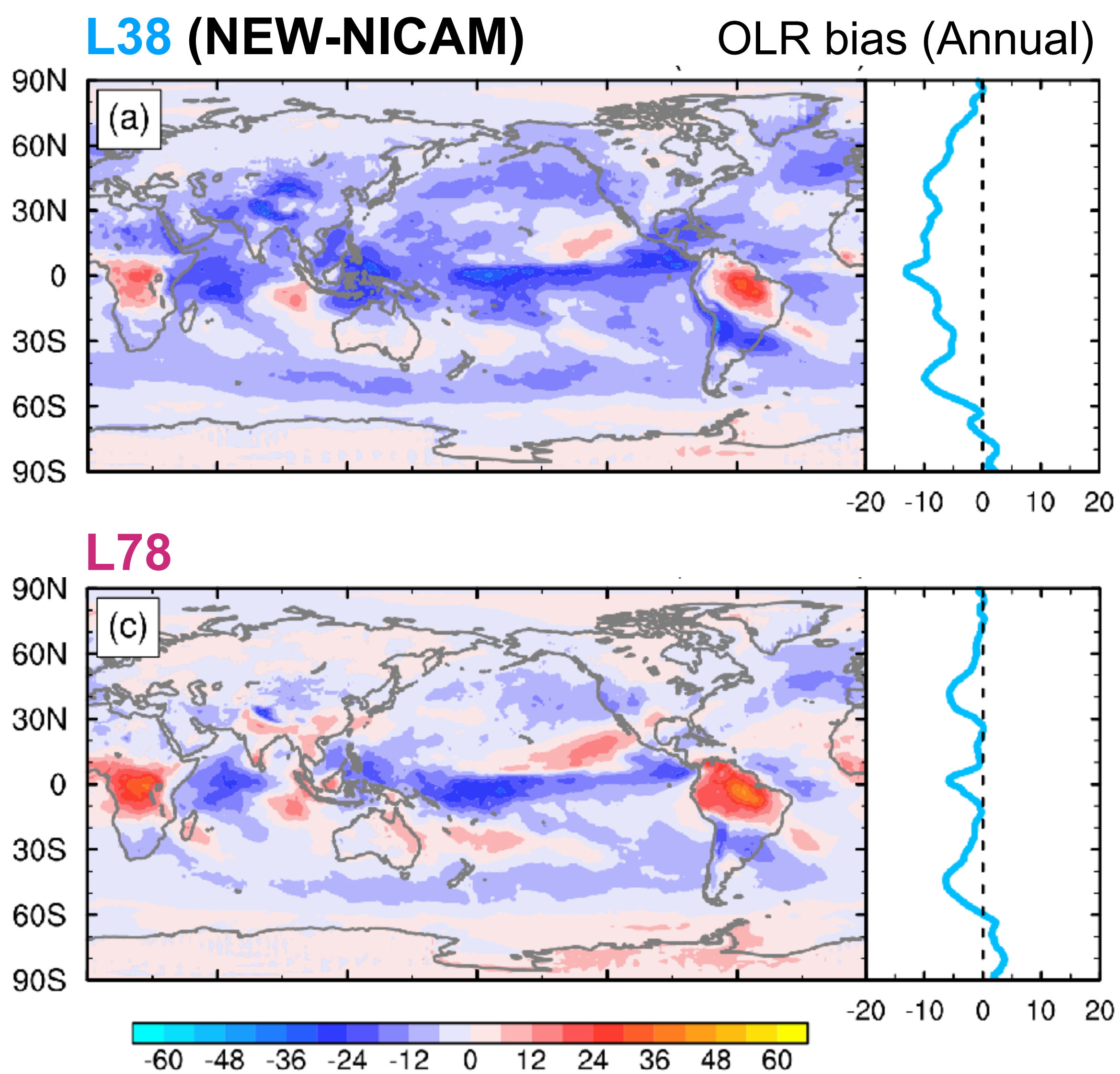


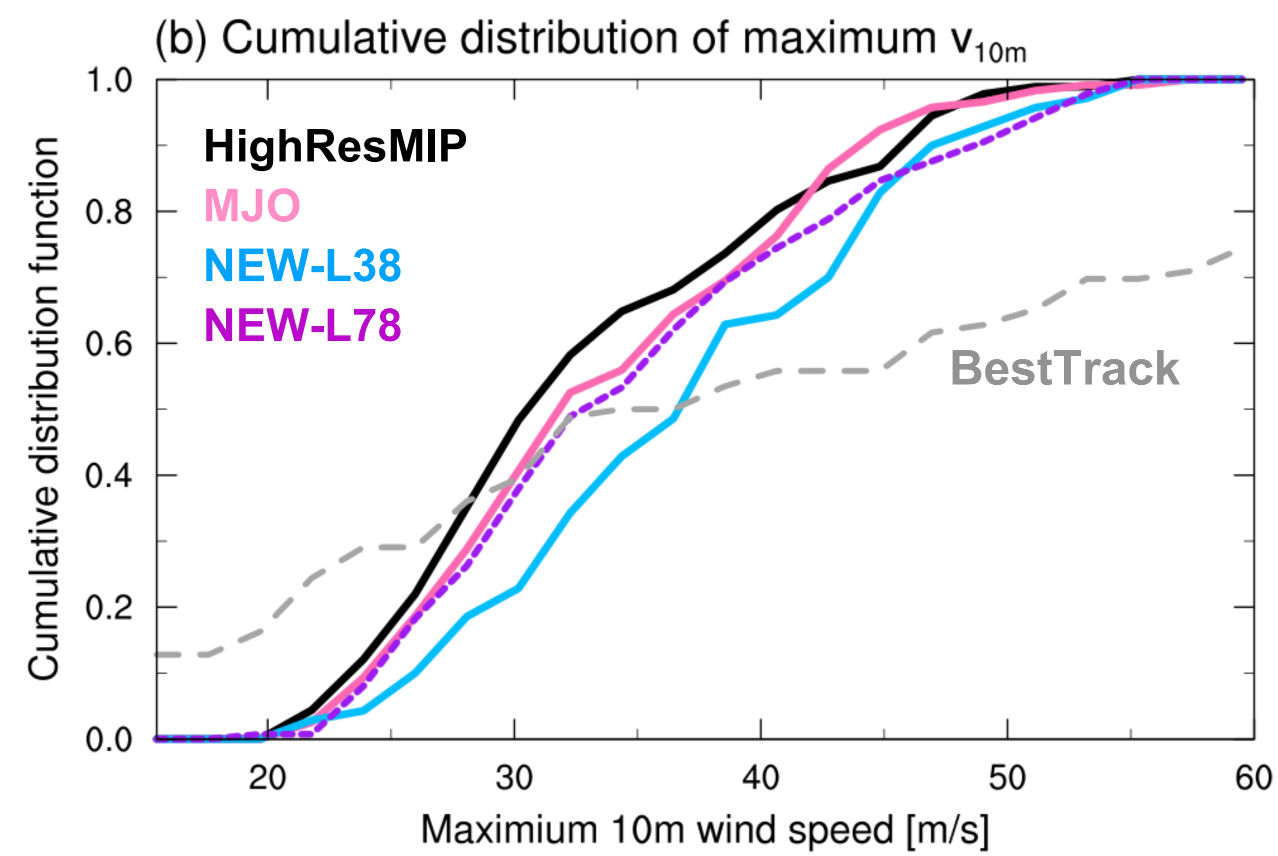
MJO is spontaneously reproduced with the intraseasonal quasi-periodicity.

Vertical resolution refinement (L38→L78; 14km)

Increase in vertical layers improve the representation of ice clouds & mid-latitude circ., while preserving “fast” solutions (or even better).

(Takasuka et al., to be submitted to JAMES)





More intense TCs (> 45m/s) can be generated, although it is still far from the observation.

Low OLR bias is largely mitigated.

(cf. Seiki et al., 2015)

Started 10-yr 3.5km/L78 simulation

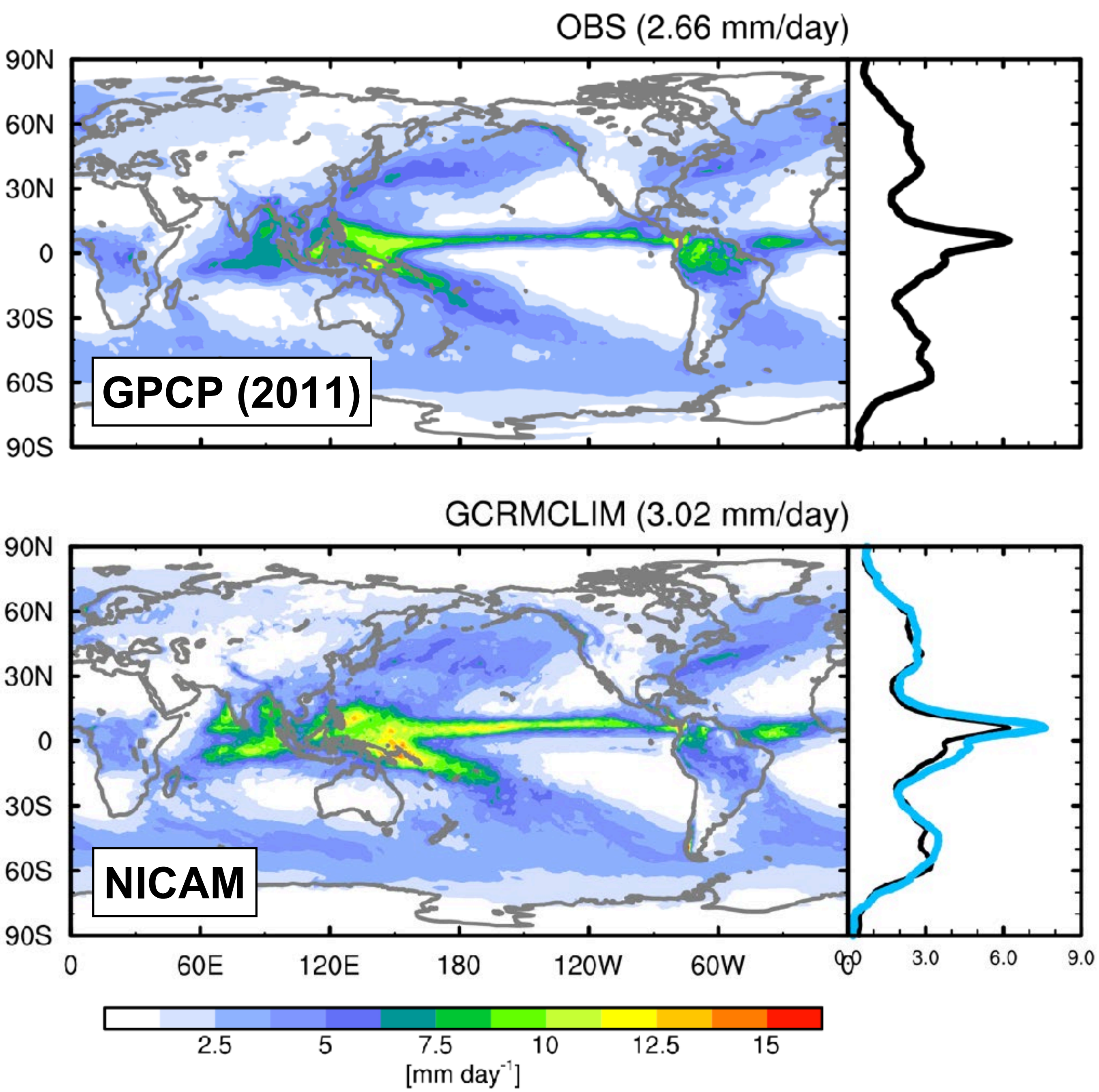
Simulation period: From Jan 1, 2011

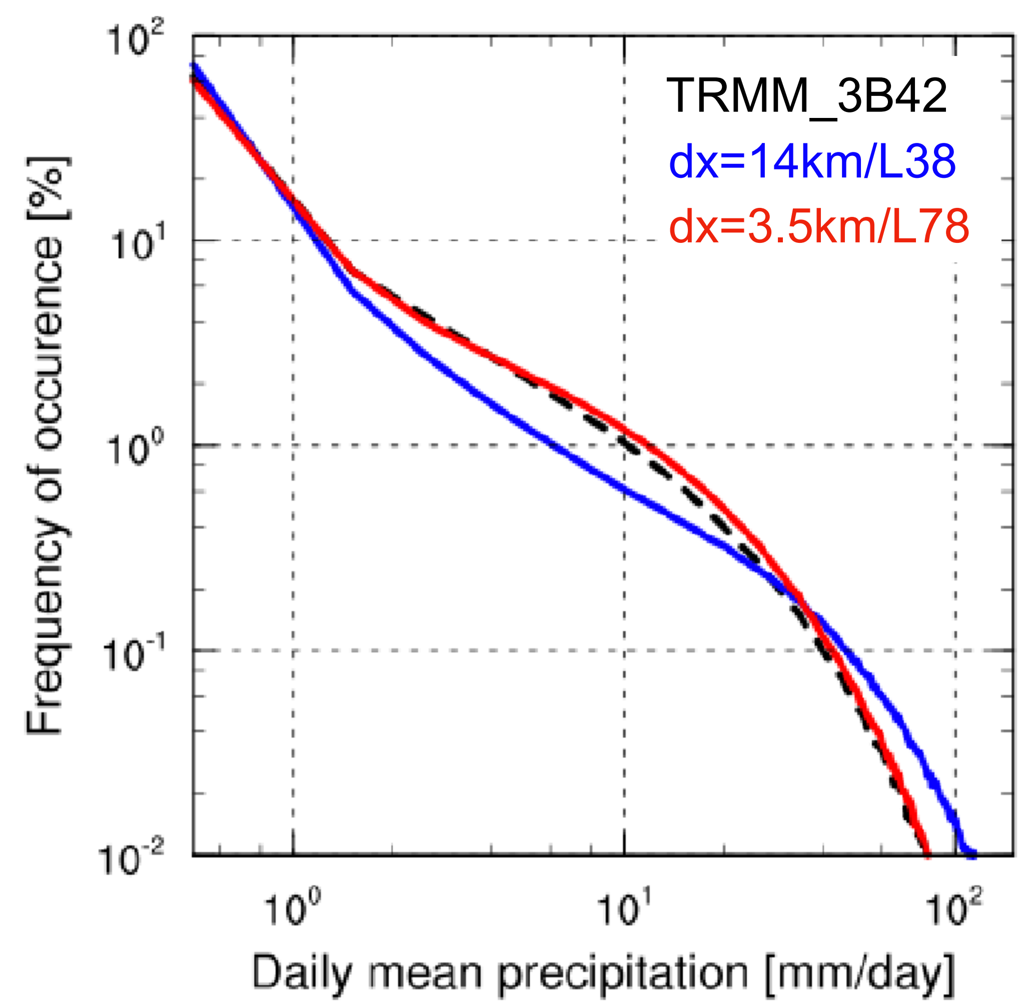
SST/ICE: OSTIA (daily; 1/20°; w/ slab)

O3, Aerosol, GHG: HighResMIP protocol

Orographic GWD: None

CPU: Use 10240 proc.
(**2% node on Fugaku** [2560 node])



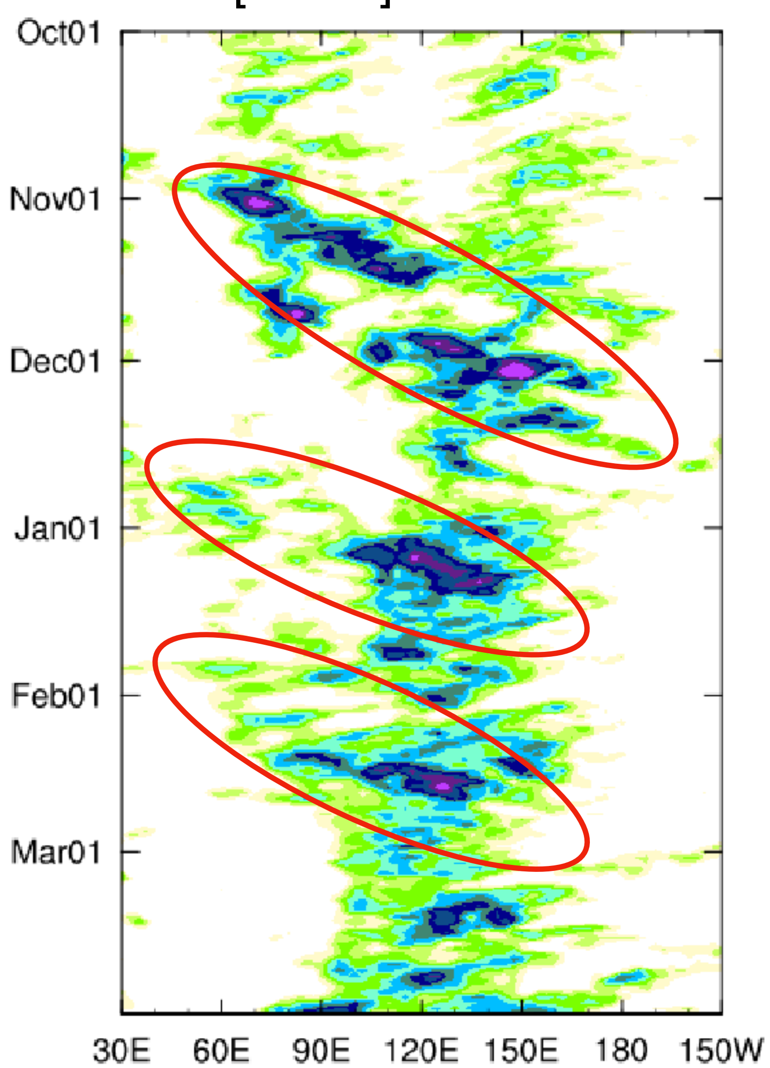


- Zonal contrast over Indo-Pacific region
- No double ITCZ / Good storm tracks
- Realistic frequency of precip. intensity.

Started 10-yr 3.5km/L78 simulation

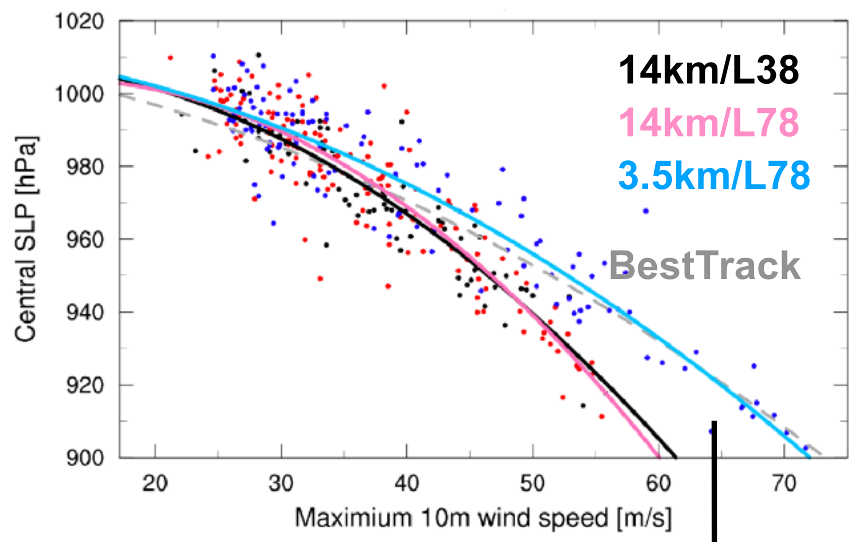
Representation of weather disturbances (MJO, TCs, precipitation diurnal cycle) becomes much more realistic across wide time scales.

OLR [10N/S]



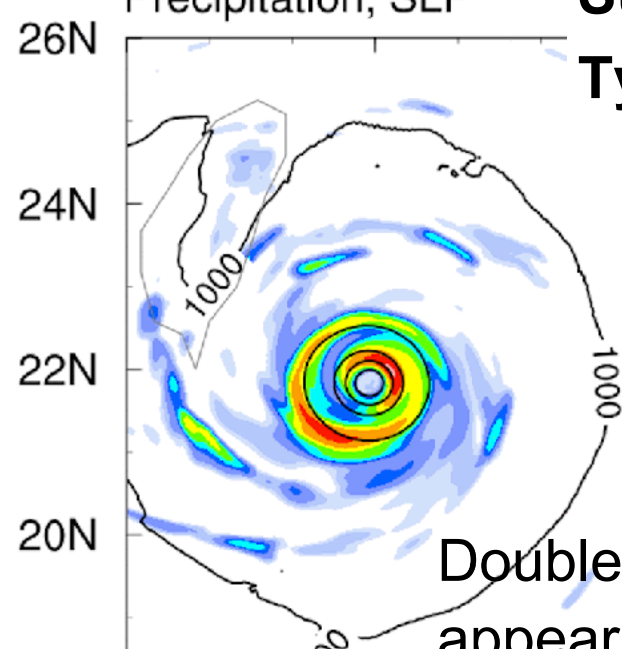
MJO conv. spontaneously propagates eastward.

Relation b/w v10m-max & SLP



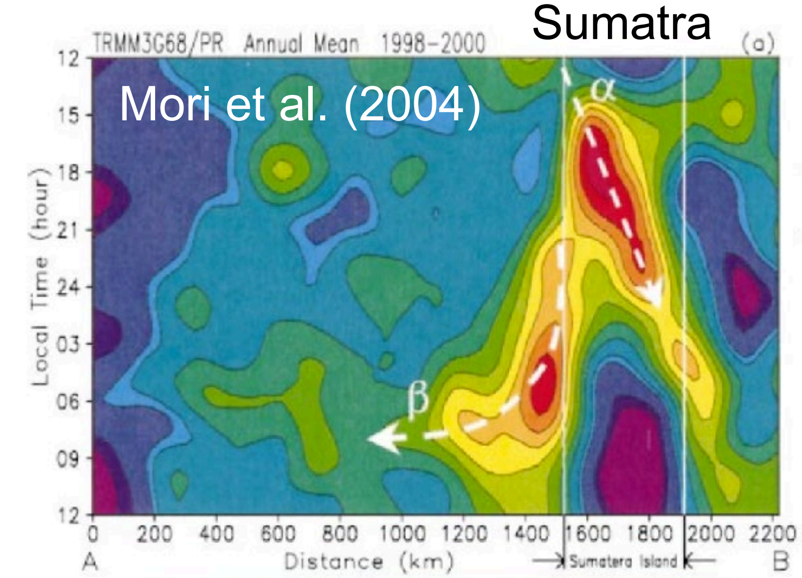
Super Typhoon

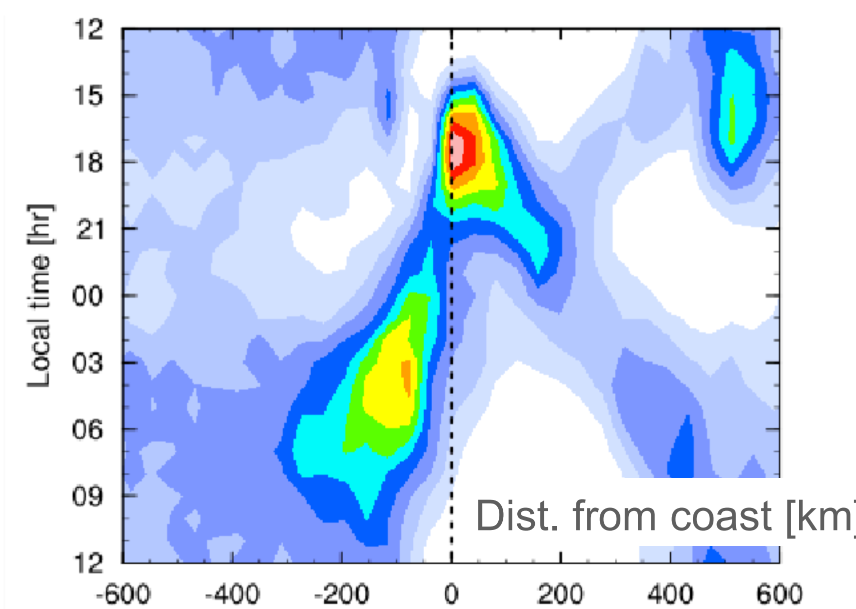
Precipitation, SLP



Double eyewalls appear.

Sumatra

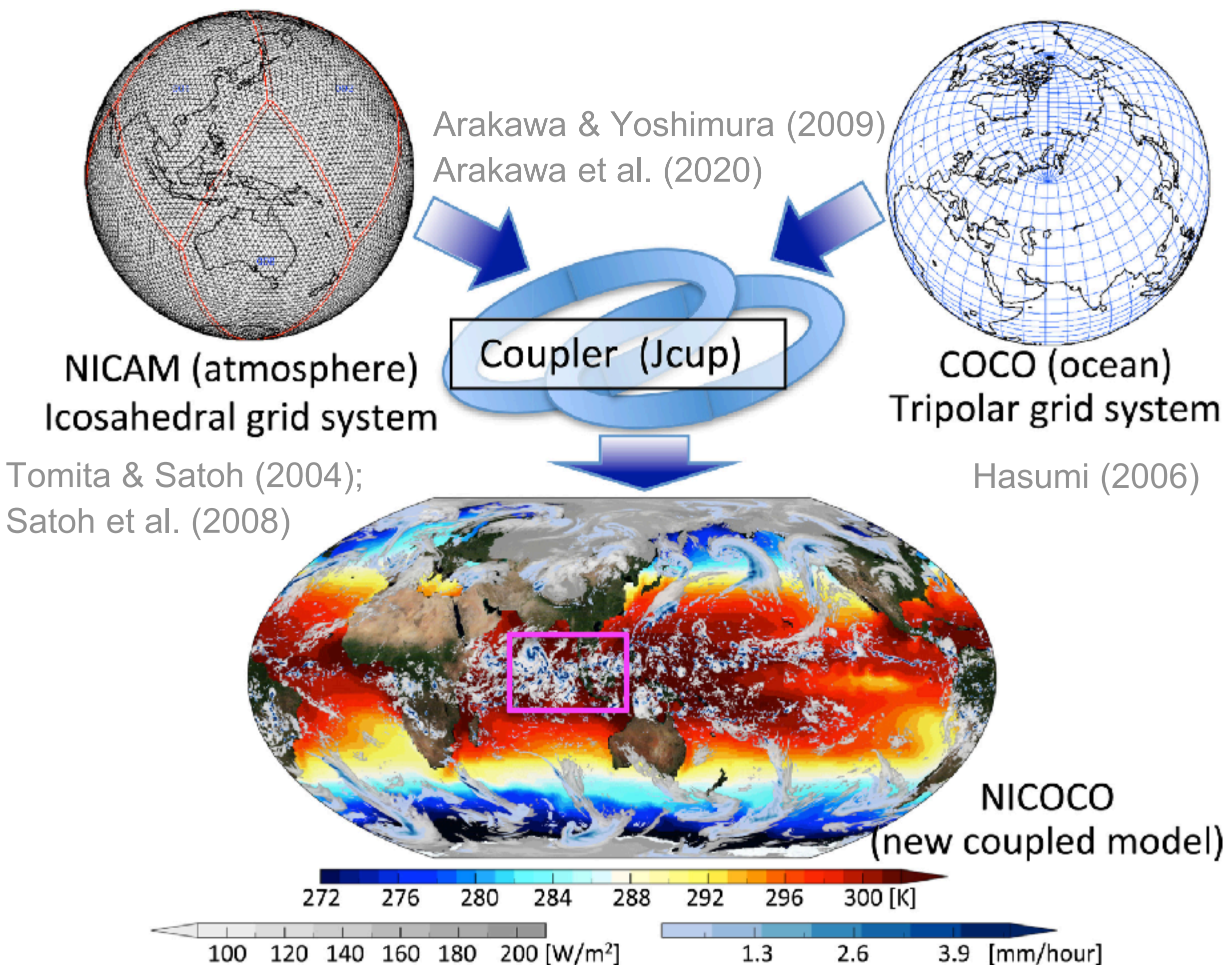




Offshore/Inland propagation is realistically simulated.

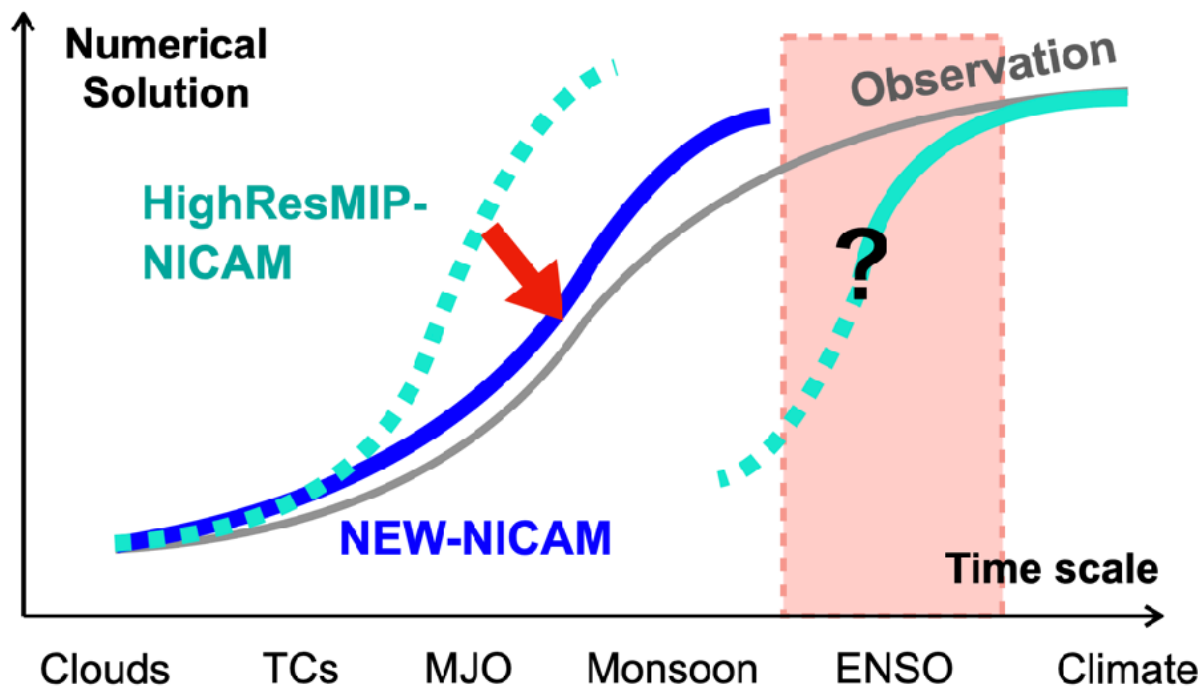
Coupled climate simulation by NICOCO

Decadal run by NICOCO (NICAM coupled w/ ocean model “COCO”) is now also ongoing, and the simulated coupled-mode is evaluated.



Miyakawa et al. (2017)

- Good performance for the S2S-scale phenomena (e.g., MJO) has been confirmed.
- ENSO transition as init. value prob. is represented.



<u>How is ENSO reproduced in GCRMs?</u>

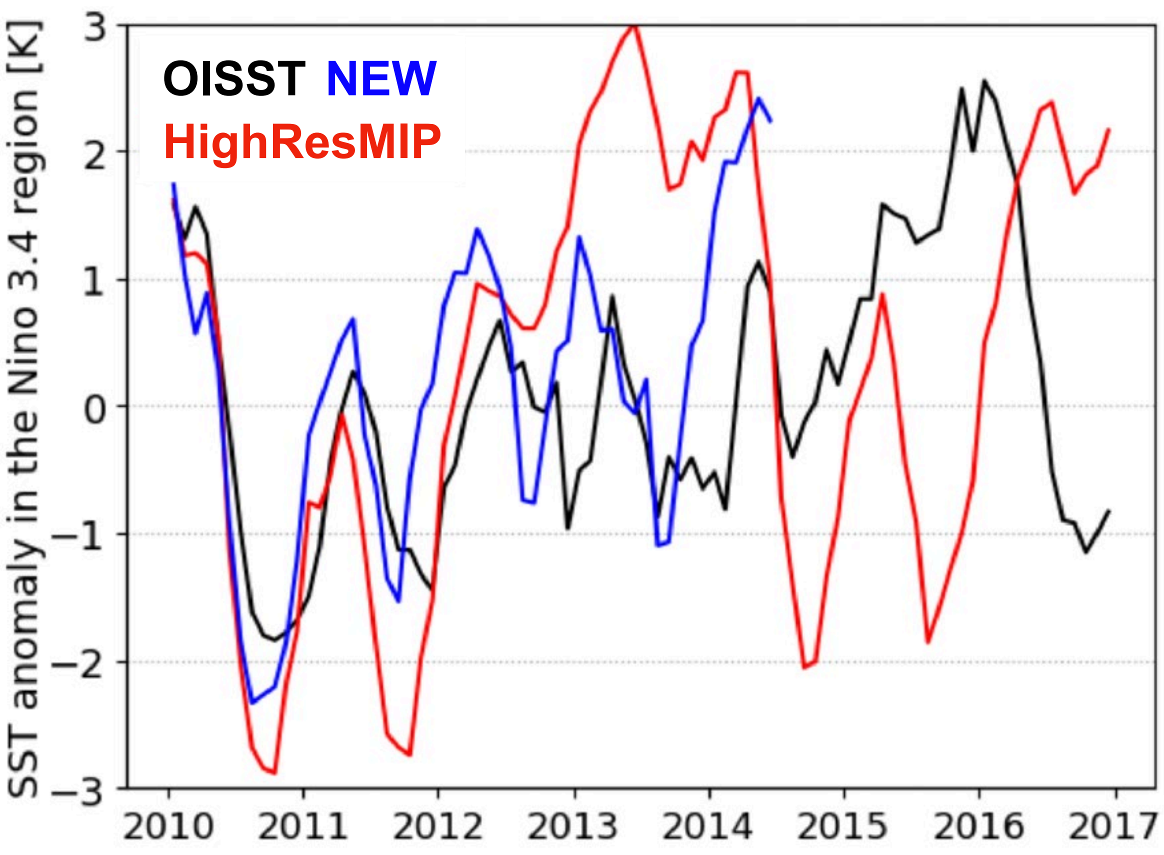
- 10–30yr simulation on Fugaku
- Atmos: dx=14km, Ocean: dx=0.25deg
- Compare HighResMIP- and NEW conf.

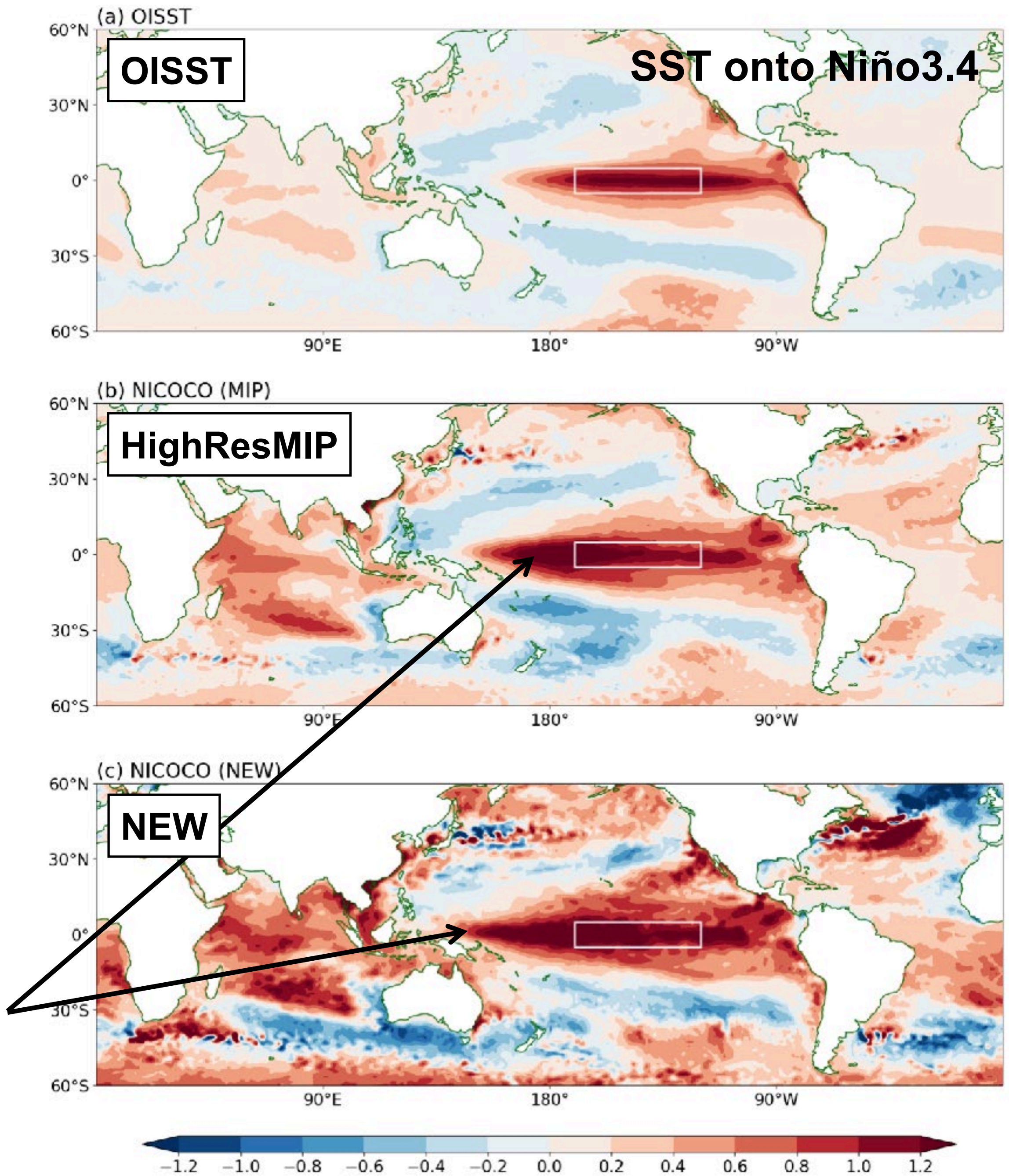
※ Simulated by Yuki Takano (JAMSTEC)

ENSO reproduced in NICOCO (Yuki Takano@JAMSTEC/UTokyo)

Spatial pattern of SSTs associated with the Niño3.4 variability captures the observed characteristics, although amplitude is a bit larger.

(Takano et al., to be submitted)

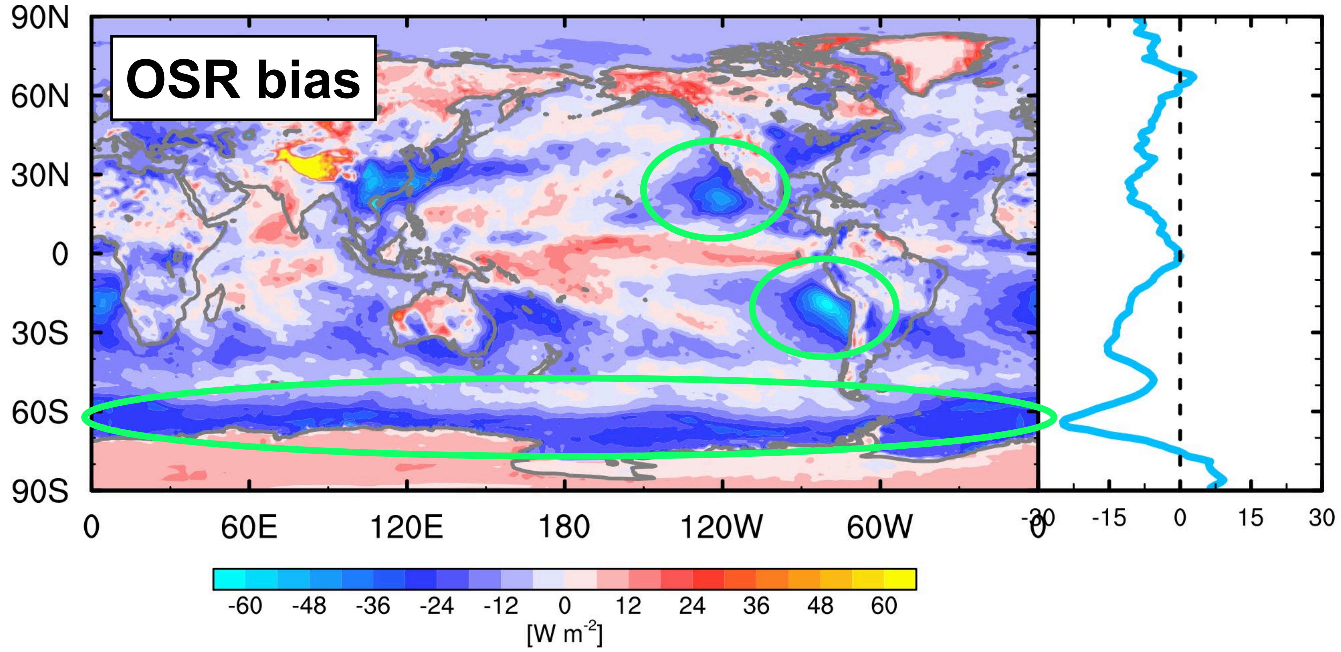


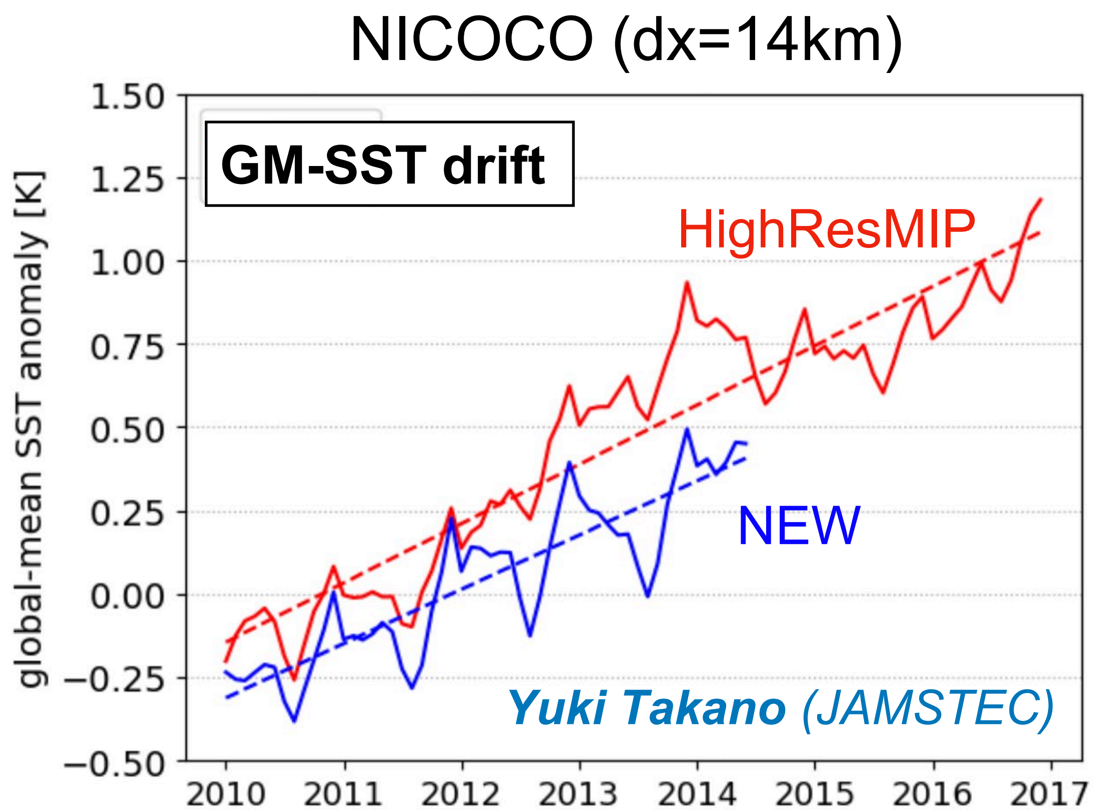


- Surprisingly, Niño3.4 for the NEW setting is realistically simulated until around 2013.
- Amp. maximum shifts westward compared to the observation.

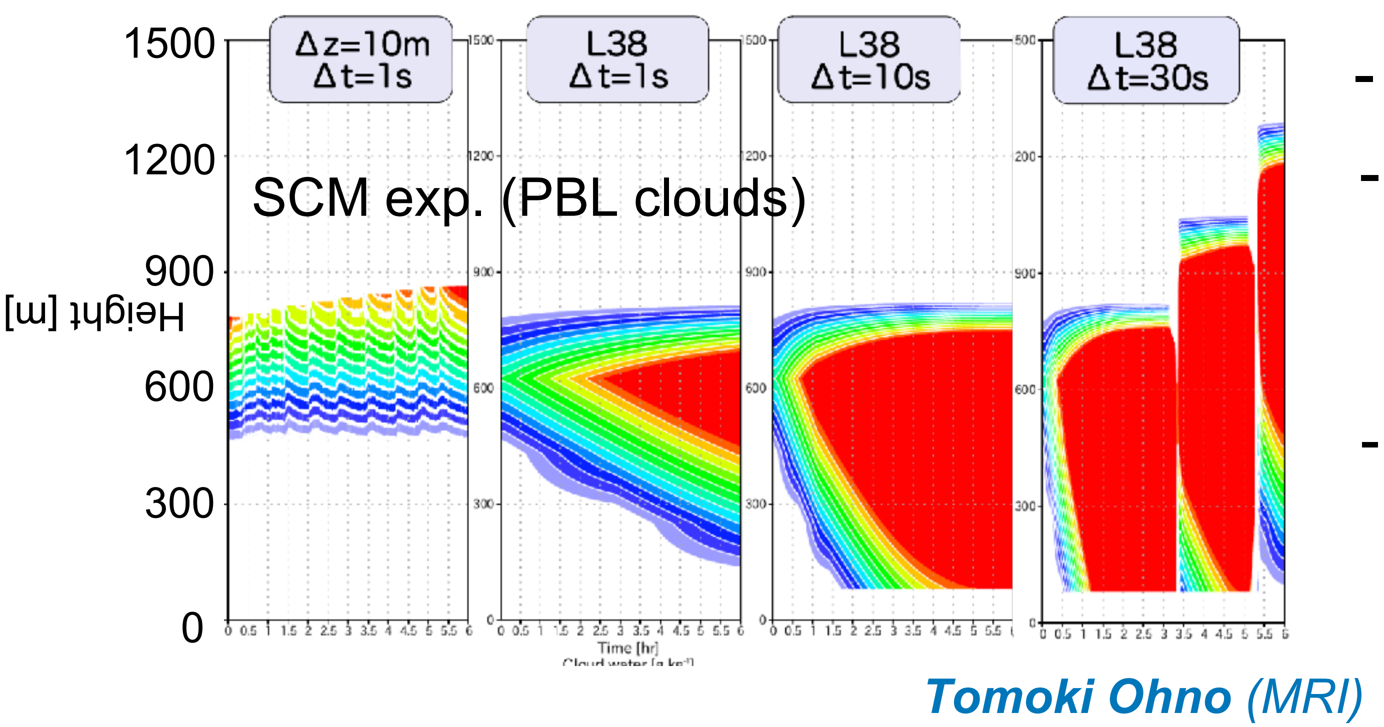
Biggest issue in k-scale NICAM/NICOCO

★ "Few low clouds" problem





Prominent lower OSR bias → **SST warming drift**



- Vert. resl. refinement for selected physics (Yamaguchi et al. 2017)
- Improved microphysics
  [Mixed-phase clouds, 2-moment scheme]
  (Seiki & Roh 2020; Seiki & Ohno 2022)
- PBL cloud development largely depends on both vert. resolutions & time step.

Shouldn't dismiss phys.-dyn. coupling

My talk's contents

Can the resolution refinement solve model systematic errors?

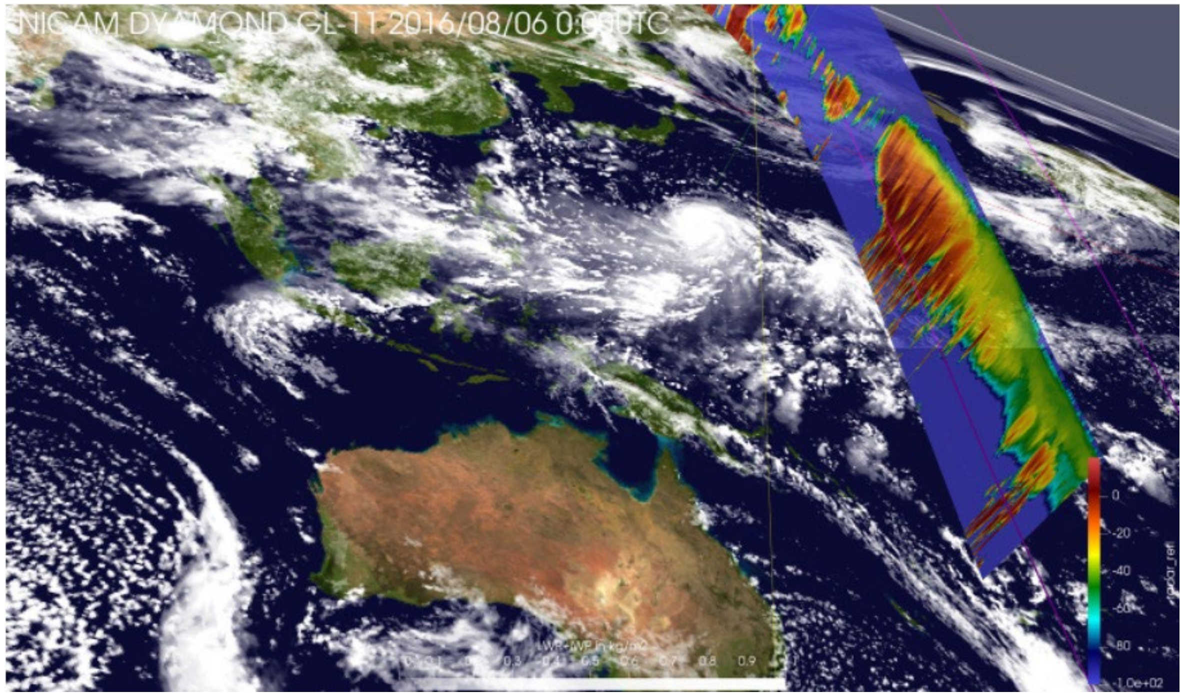
→ Some aspects can be improved, but others cannot… (cf. Wedi et al., 2020)

1) Perspectives from NICAM climate simulations

- Improvements & long-standing biases in HighResMIP NICAM
- NICAM updates to reduce errors in k-scale modeling
- Good points and issues in a NICAM k-scale climate run

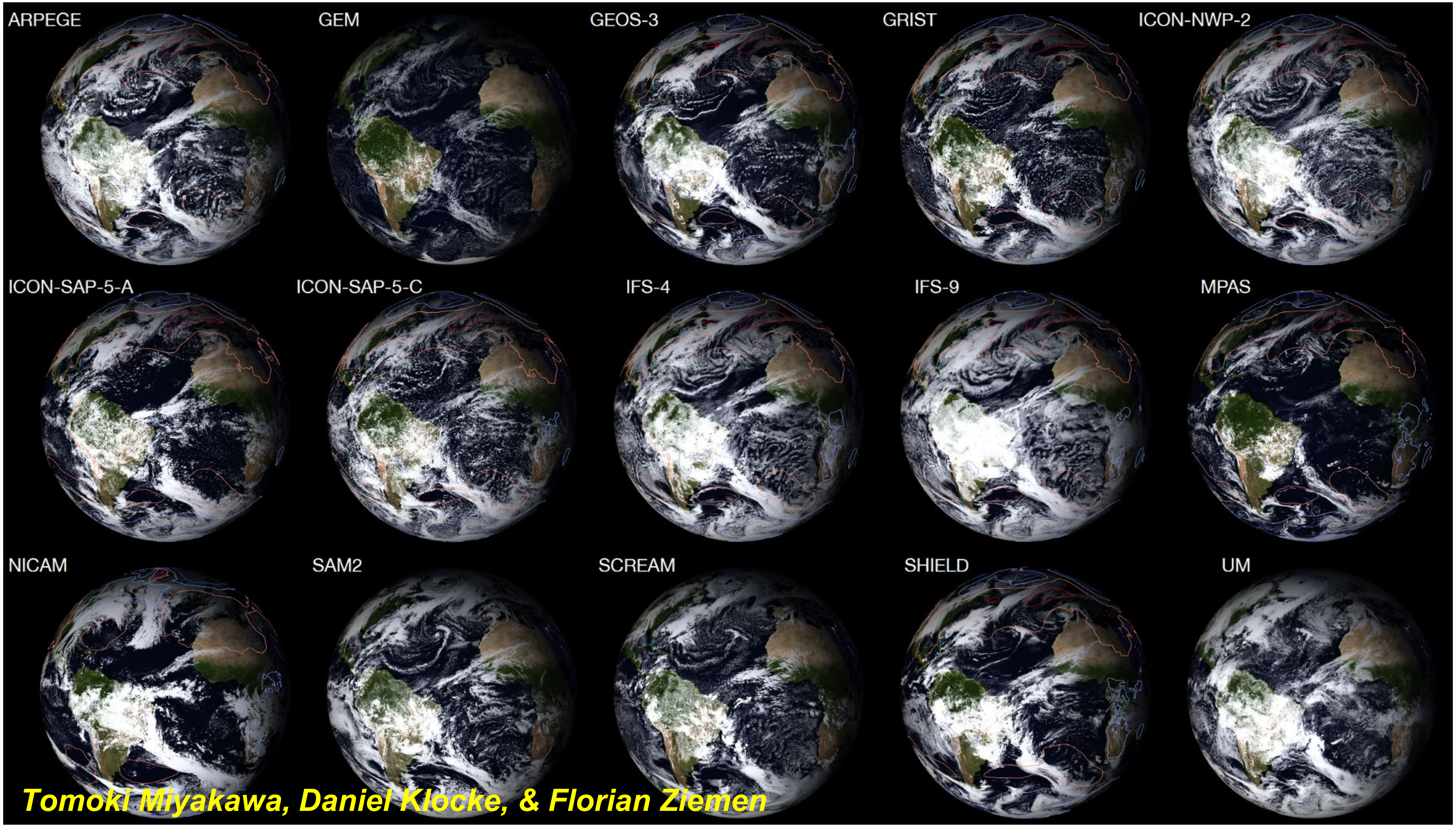
2) Perspectives from recent S2S-scale GCRM activities

- Comparison of errors b/w k-scale models in DYAMOND-Winter
- Recent science activities in S2S-scale NICAM experiments.



DYAMOND-Winter (DYAMOND2) activities

Gallery of **sub-5km mesh global models** (40-day run from 2020/01/20: EUREC^{4}A)



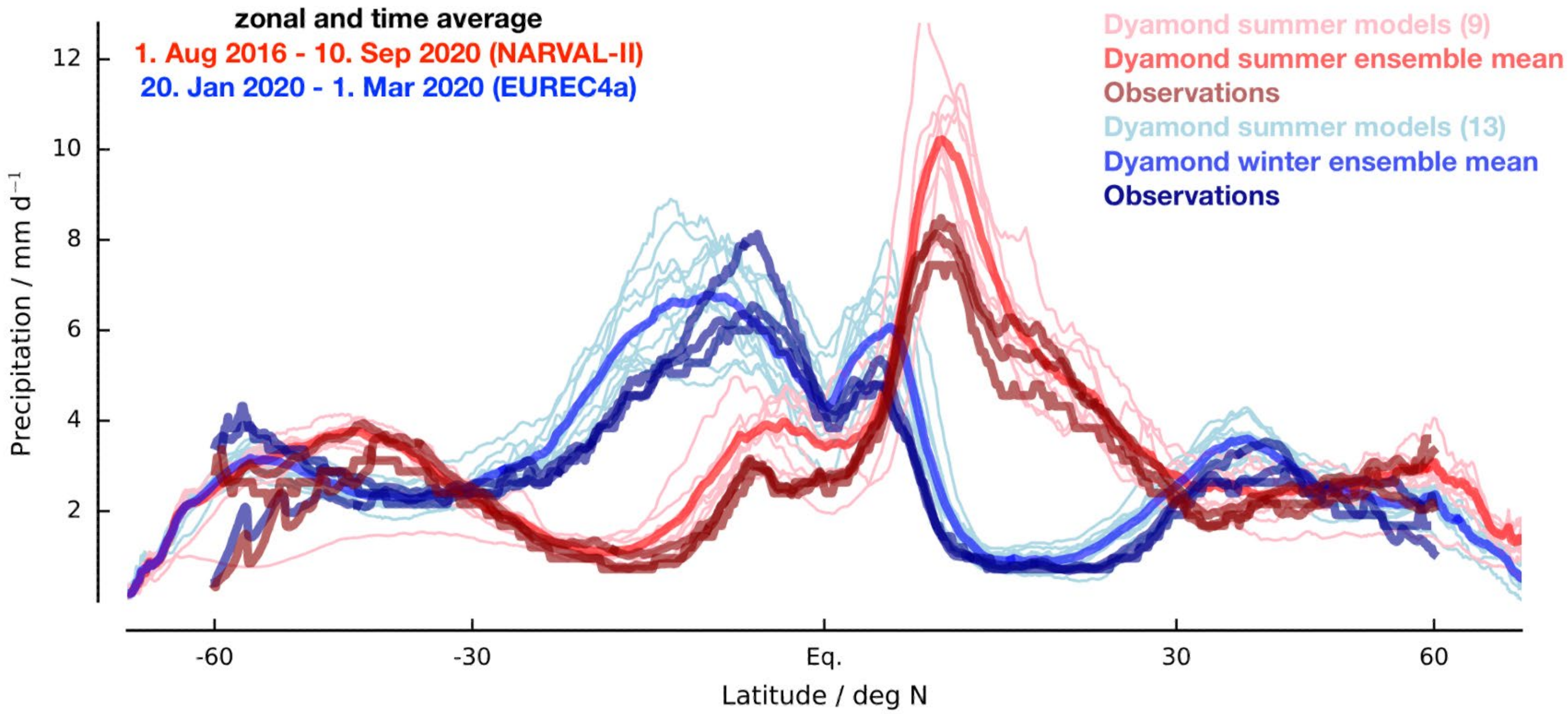
Spirit: **"Don't try to be precise, do what you can"**

Clouds are not in good agreement among the models…

Precipitation fields (Tomoki Miyakawa@UTokyo)

Summer 2016/Winter 2020

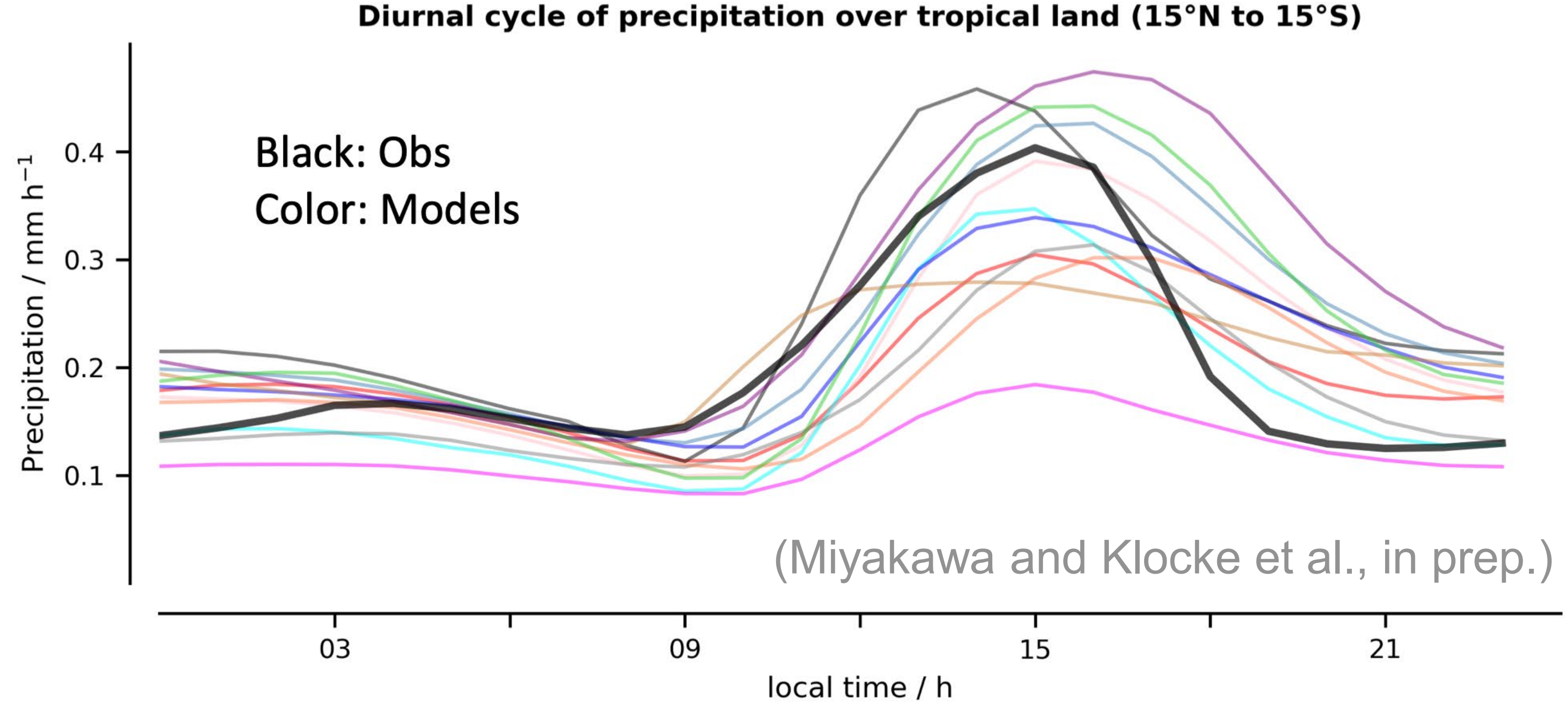
Courtesy of ***Daniel Klocke (MPI)***



Winter also including 4 coupled atmosphere-ocean models

Peaks to the south of EQ shifted southwards.
Peaks near 5N overestimated.
(Double ITCZ)

Not heavily tuned in most of the models

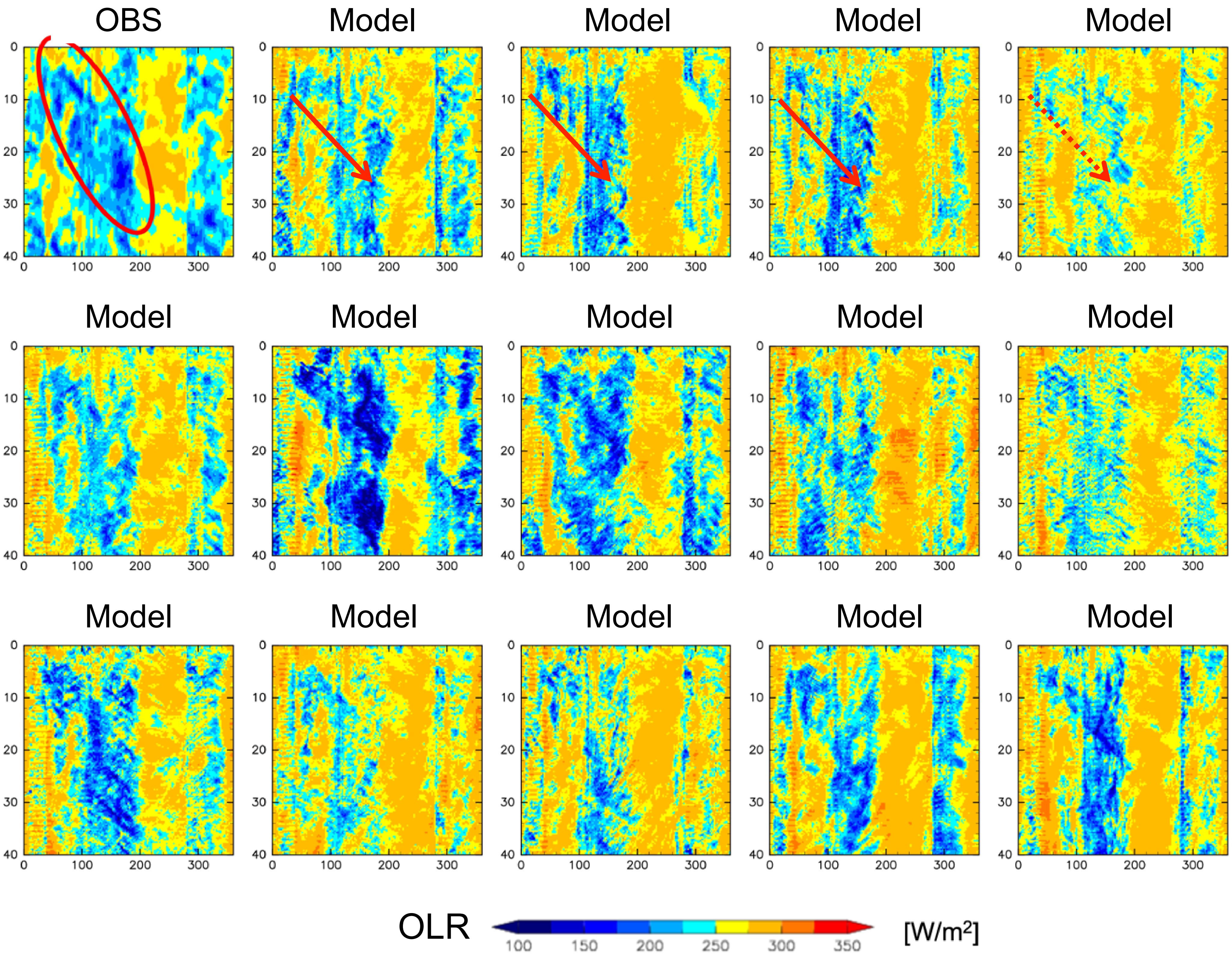


Precipitation diurnal cycle (Land)

- Peak timing is mostly within 1 hour within 3pm.
- Amplitudes are quite different!
  → seeking for reasons

MJO in DYAMOND2 (Tomoki Miyakawa@UTokyo)

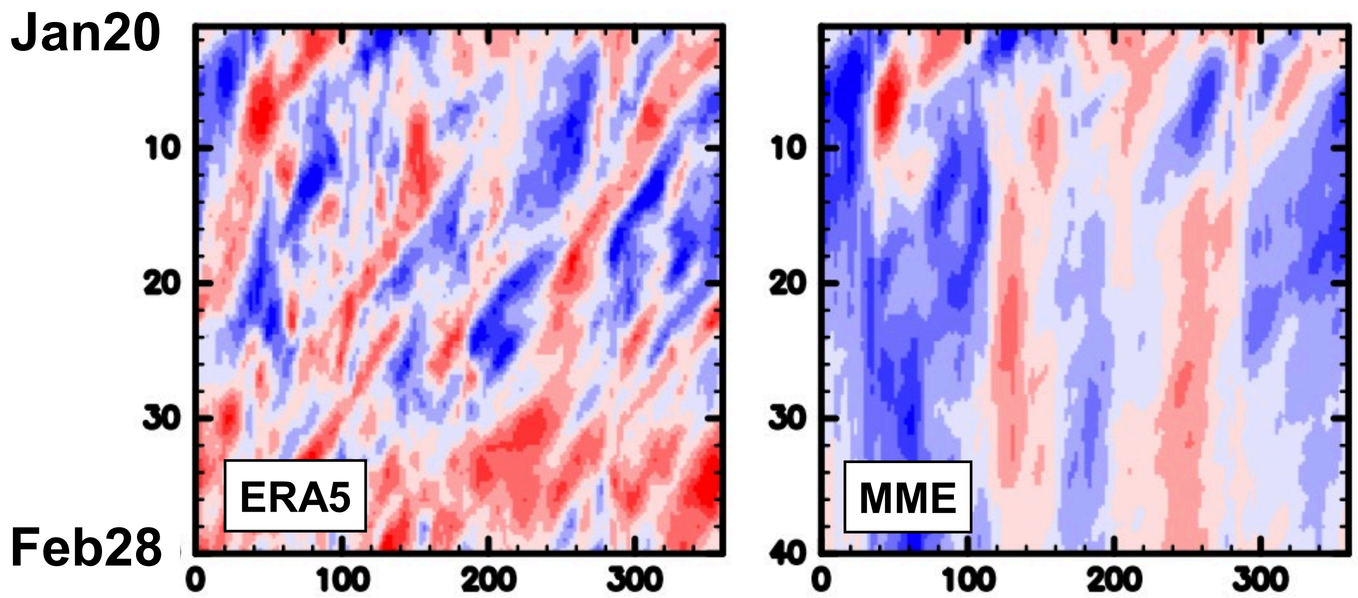
Some kind of eastward propagation is found in most of the models.



OLR could be dominated by high thin clouds.

What does the moisture field look like?

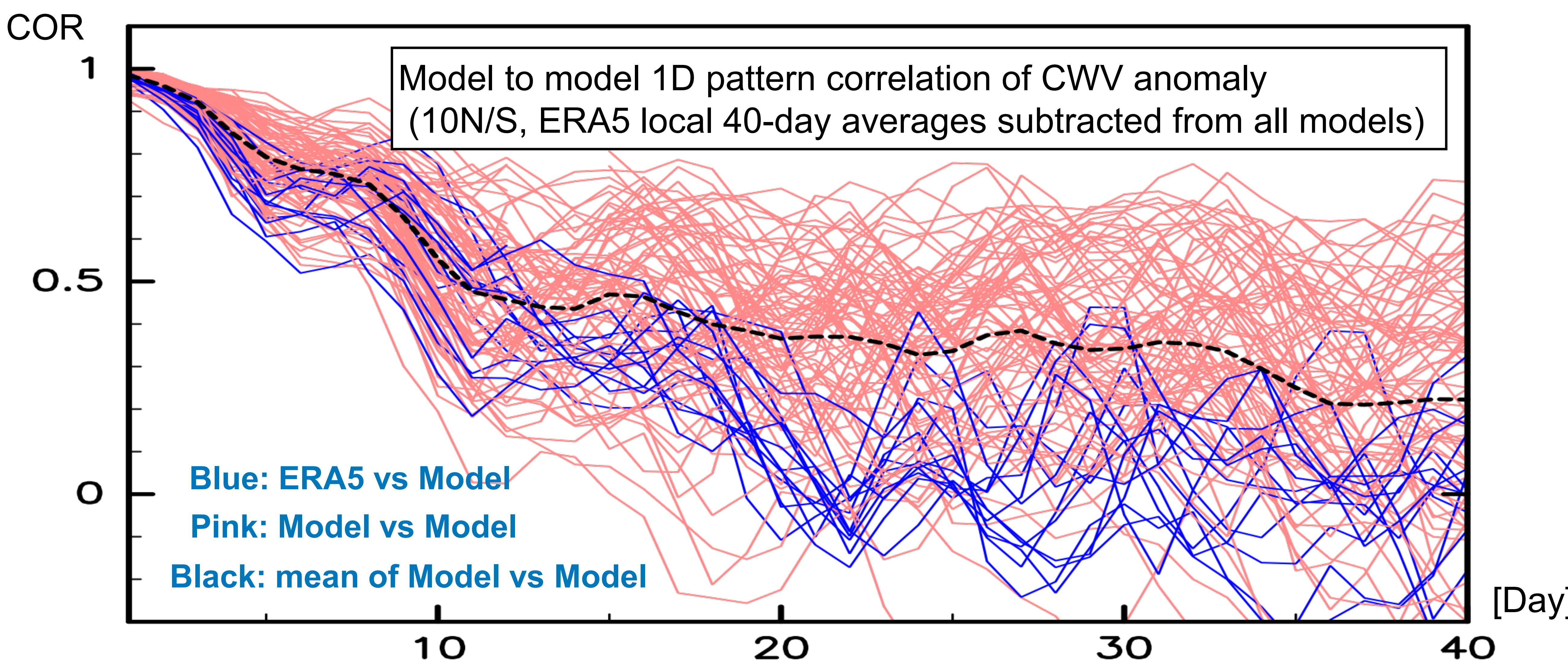
Moisture evolution bias (Tomoki Miyakawa@UTokyo)



CWV anom. from 40-day ERA5 mean

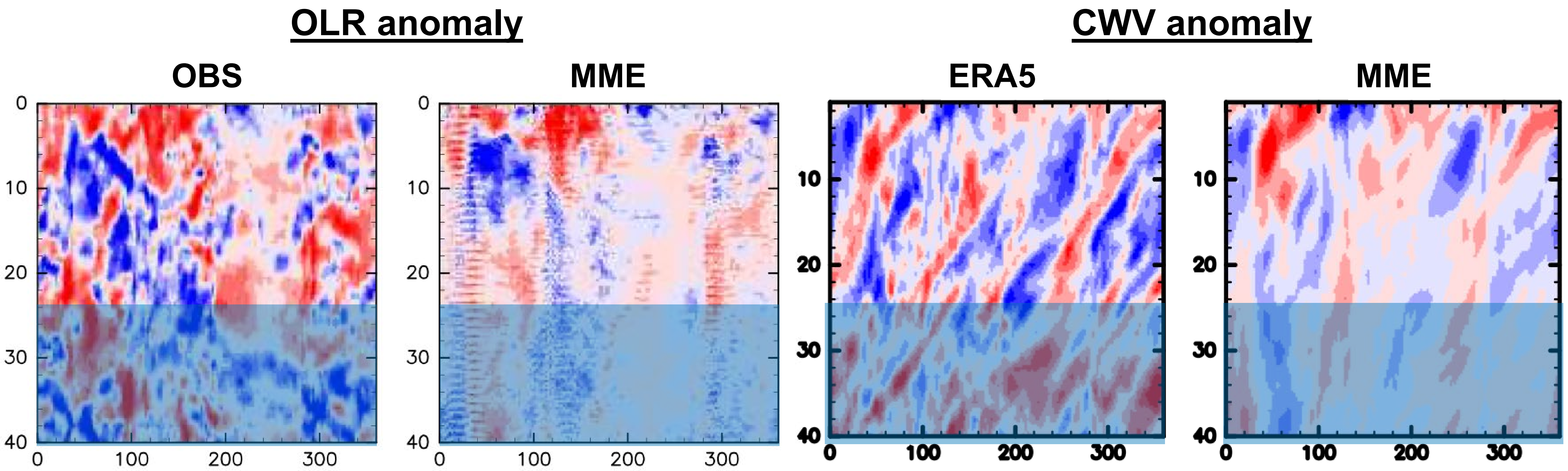
Bias against ERA5 kicking in quickly…

DYAMOND2 models tend to be more similar with each other than with ERA5, especially after 20 days



Limitation of S2S-MJO simulation (Tomoki Miyakawa@UTokyo)

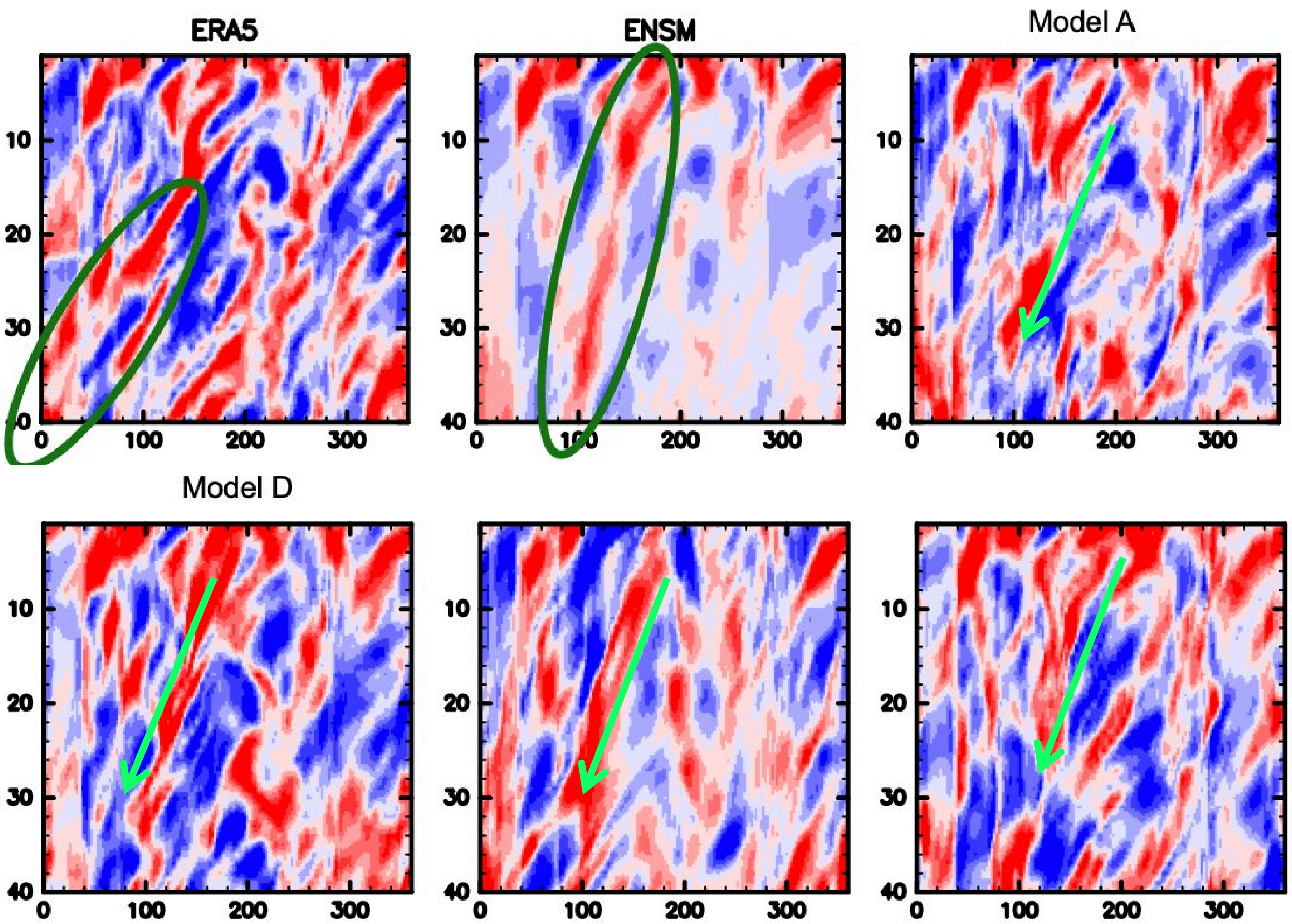
Simulated OLR / CWV anomaly are quite similar with observation **until 20–25 days**, in terms of multi-model ensemble mean.



- Eastward MJO propagation after day 25 (= decoupled from main convection) is unclear in many models.
- Periodic positive / negative CWV anomaly in MJO convective envelopes is captured to some extent (→ CCEWs?)

Behavior of wave-like signals (Tomoki Miyakawa@UTokyo)

Westward signal commonly too slow in many models near 100-150E of the northern hemisphere (over Indochina peninsula, not shown).



Why?

- Difference in heating profile?
- Difference in convective adjustment time scale?

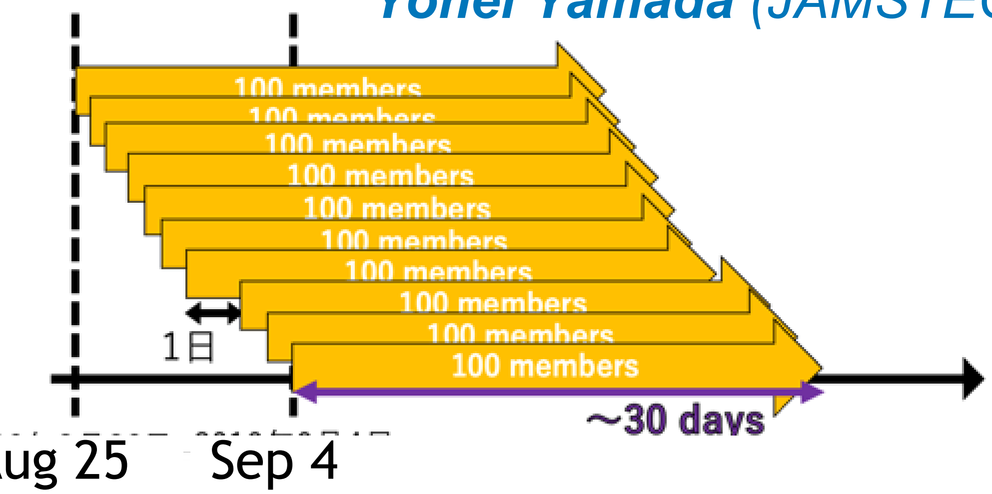
NICAM activities: Large-ensemble sim. for TCs

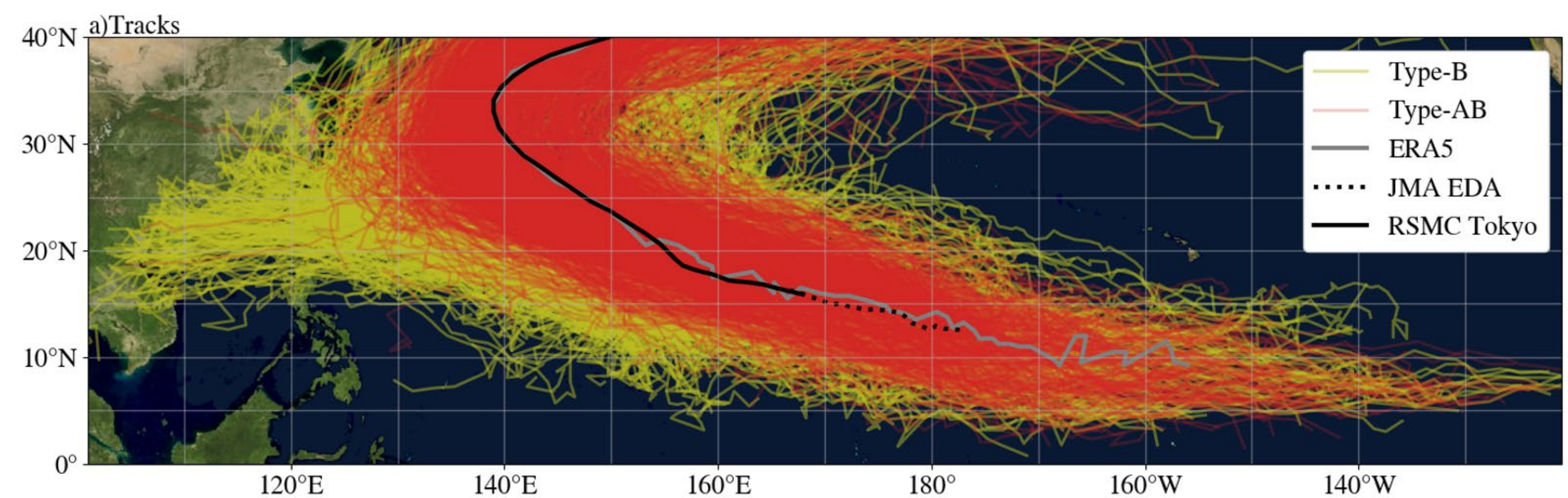
Typhoon Faxai (2019) initiated on Sep. 5, hit Eastern Japan on Sep. 9, and caused severe damage.

→ How many days in advance can we predict this?

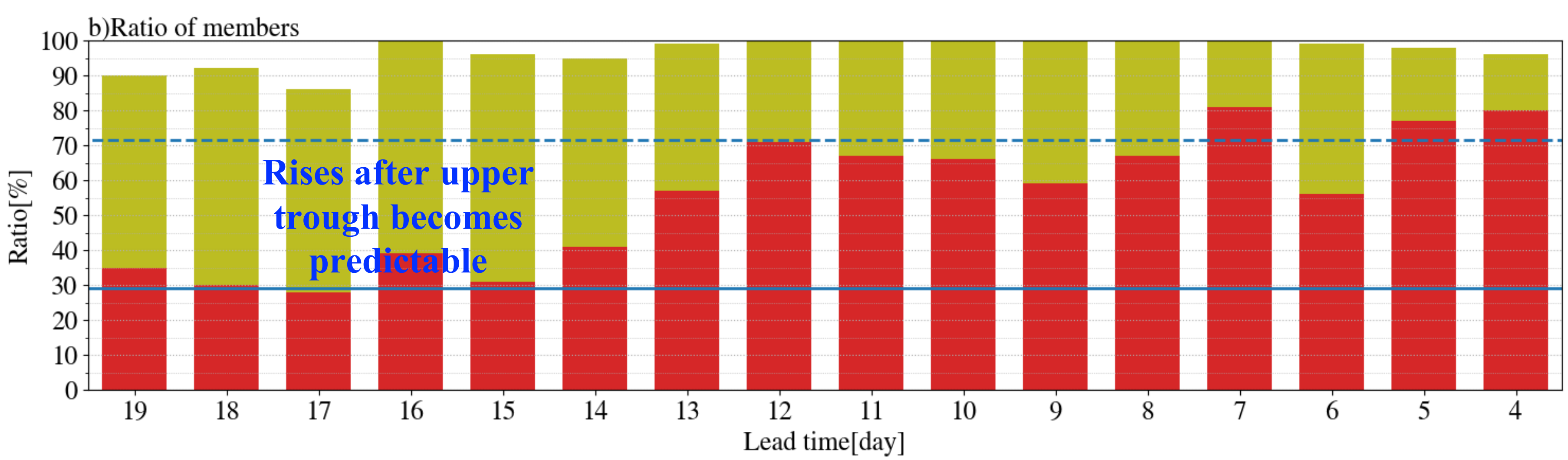
1600-member ensemble exp.

Yohei Yamada *(JAMSTEC)*





TCs approaching Japan like Faxai were generated in 55% of total members (885/1600).

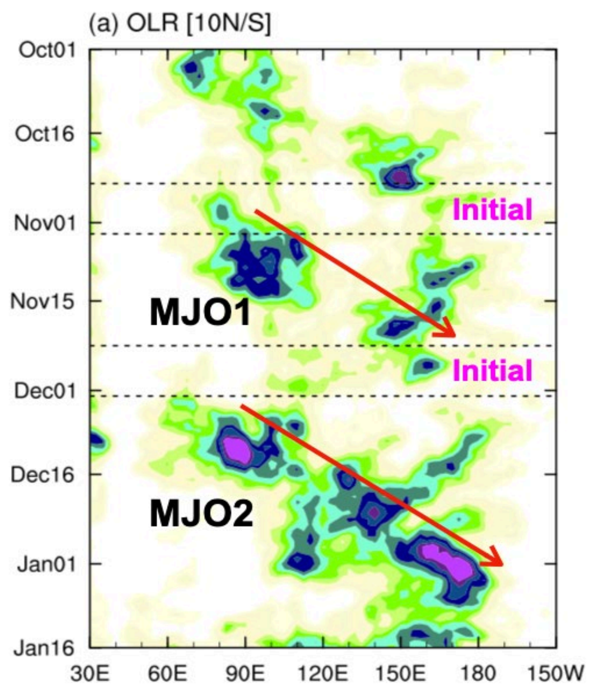


NICAM could predict with high accuracy **two weeks** before landfall that the vortex was likely to head toward Japan.

NICAM activities: Large-ensemble sim. for MJO

Is MJO propagation deterministic? (as inferred from a linear theory)
→ **NO.** Timing of MJO prop. sometimes has bifurcated solutions.

(Takasuka et al., in prep.)



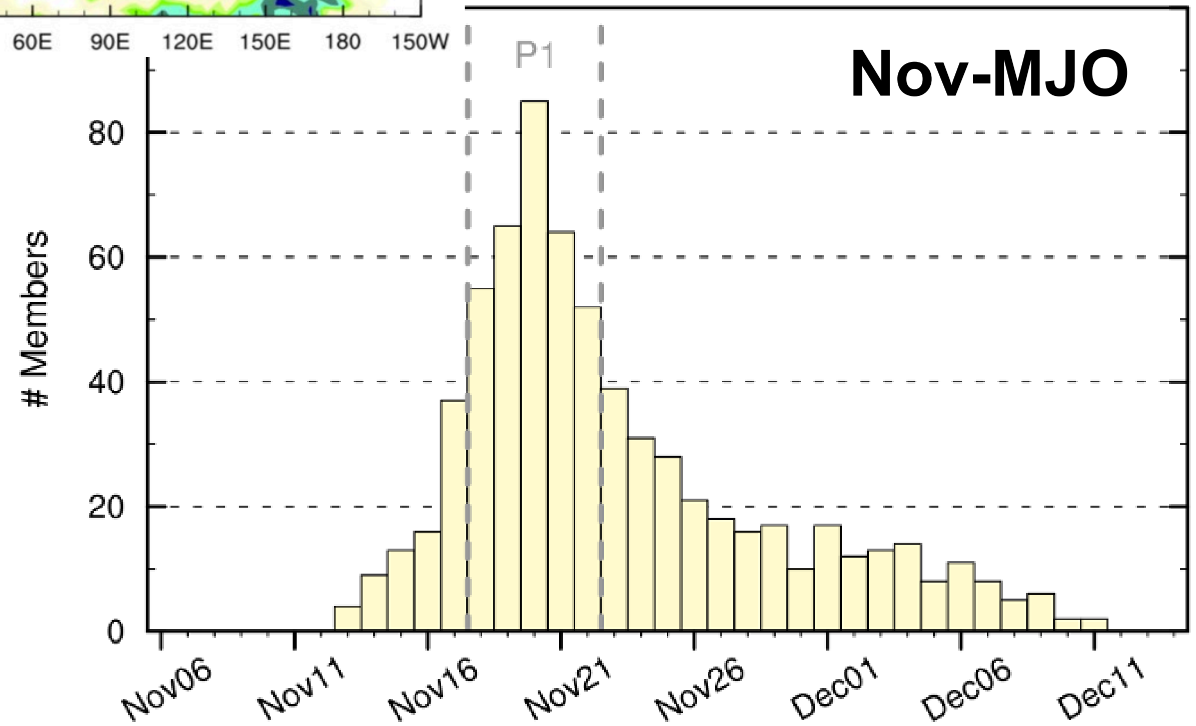
Two MJOs in 2018 are targeted (Nov- & Dec-MJO)
→ For each MJO, 1,000-member simulations are conducted.

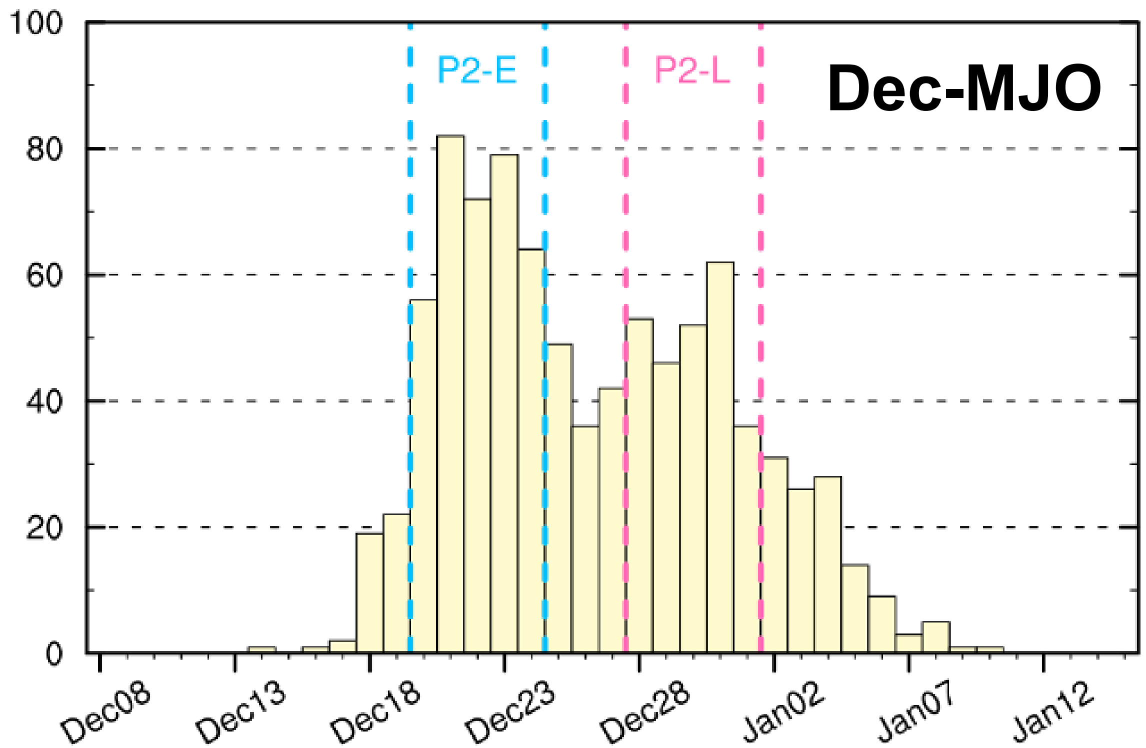
(Total: 2,000 mem)

Nov-MJO: Tends to be **uniquely determined**

Dec-MJO: **Multiple regimes are allowed** for MJO prop.

Histogram of the date when MJO convection has reached "Phase 7"





Summary

- Become aware of uncertainties rooted in microphysics & unresolved turbulent mixing even at k-scale.

  → Correspond to controlling the preferred time scale in moisture–conv. relation

- Long-standing bias (e.g., dITCZ, weak MJO...) can be largely reduced.
  - Microphysics tuning (especially for falling speeds of droplets)
  - Implementation of Leonard-term turbulent diffusion
  - Vertical resolution refinement
- K-scale NICAM can improve the representation of precip. statistics & weather disturbances (MJO, TCs, precip. diurnal cycle), whereas "too few low clouds" problem is serious.
- There seem to be aspects common to many GCRM/GSRMs.
  - Diurnal cycles, Error evolution of moisture fields, MJO predictability, CCEWs representation (e.g., slower westward-propagating signals)…
- GCRM ensemble sim. can open up new science for S2S-scale phenomena.

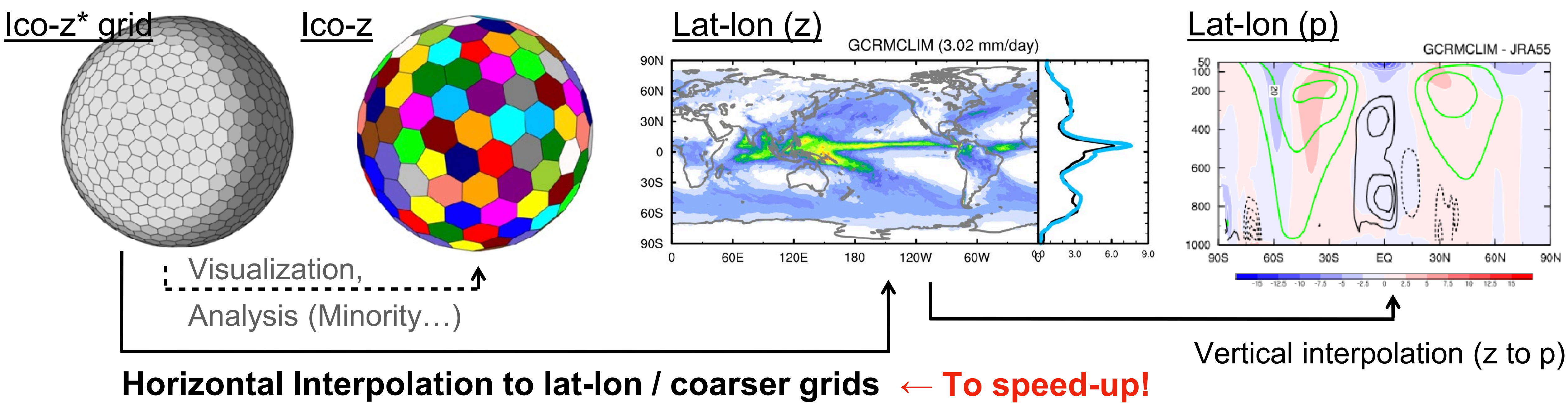
Thank you for listening!

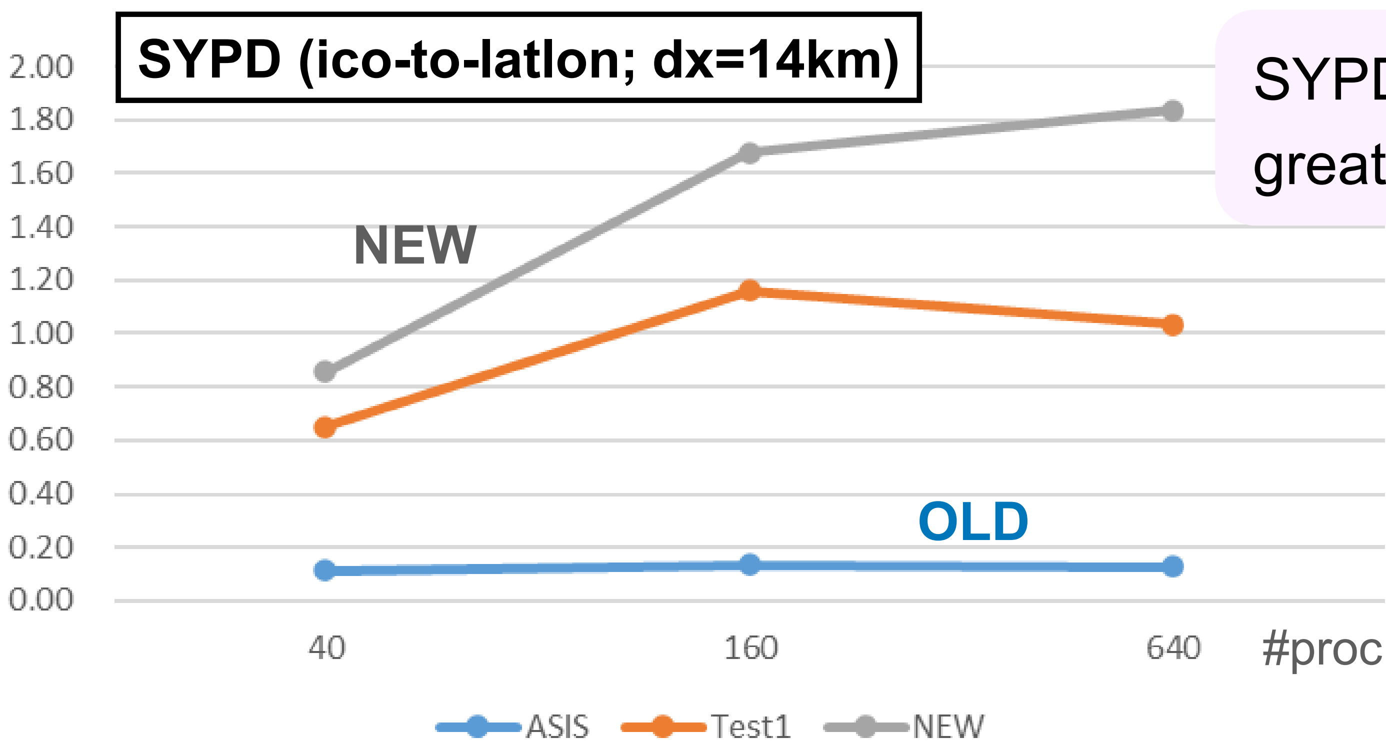
Any questions?

Radar reflectivity diagnosed by COSP CloudSat simulator.
Background image by NASA.

Technical improvement: Post-process (By Chihiro Kodama)

While the NICAM output data are on icosahedral grids, lat-lon grids are practically convenient for data analyses, which requires post-process.





SYPD for the remapping (0.85 / 40proc) is greater than that for the simulation (0.3 / 640proc).

- Parallelize file output at the cost of many lat-lon files for each layer.
- Reduce amount of MPI communication.
- Use local SSD disk on Fugaku.

Where will we go?: Our plans & remained challenges

FY2022: Complete a 10-yr NICAM run at dx=3.5 km & NICOCO run at dx=14km.

→ **Realistic seamless representation over wide timescales is expected.**

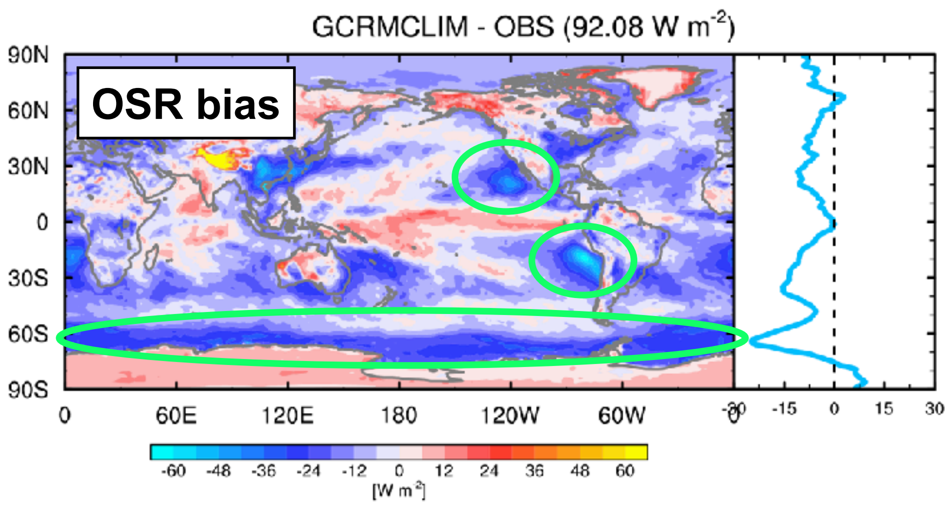
➡ **Centenarian 3.5-km/0.1deg NICOCO run is planned in 5 years.**

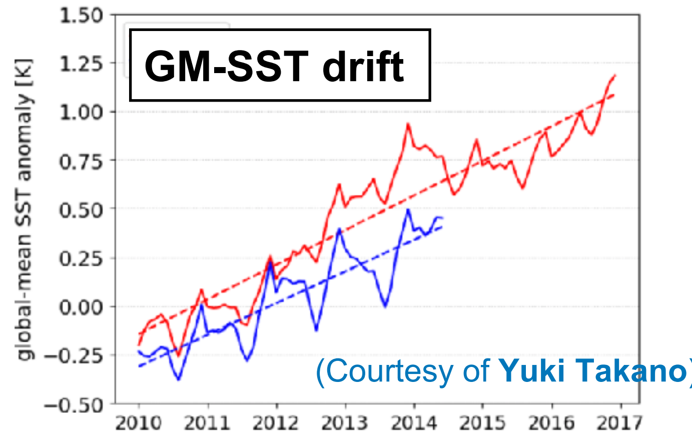
- Historical & Future climate run
- Many targets (Extremes, TCs, ENSO, Decadal variability…) will be argued.

(Other options: Large-ensemble climate simulations at ~10-km mesh)

● There still remain several challenges to be tackled…

- How can we improve the representation of low clouds in GCRMs?





In k-scale NICAM/NICOCO,

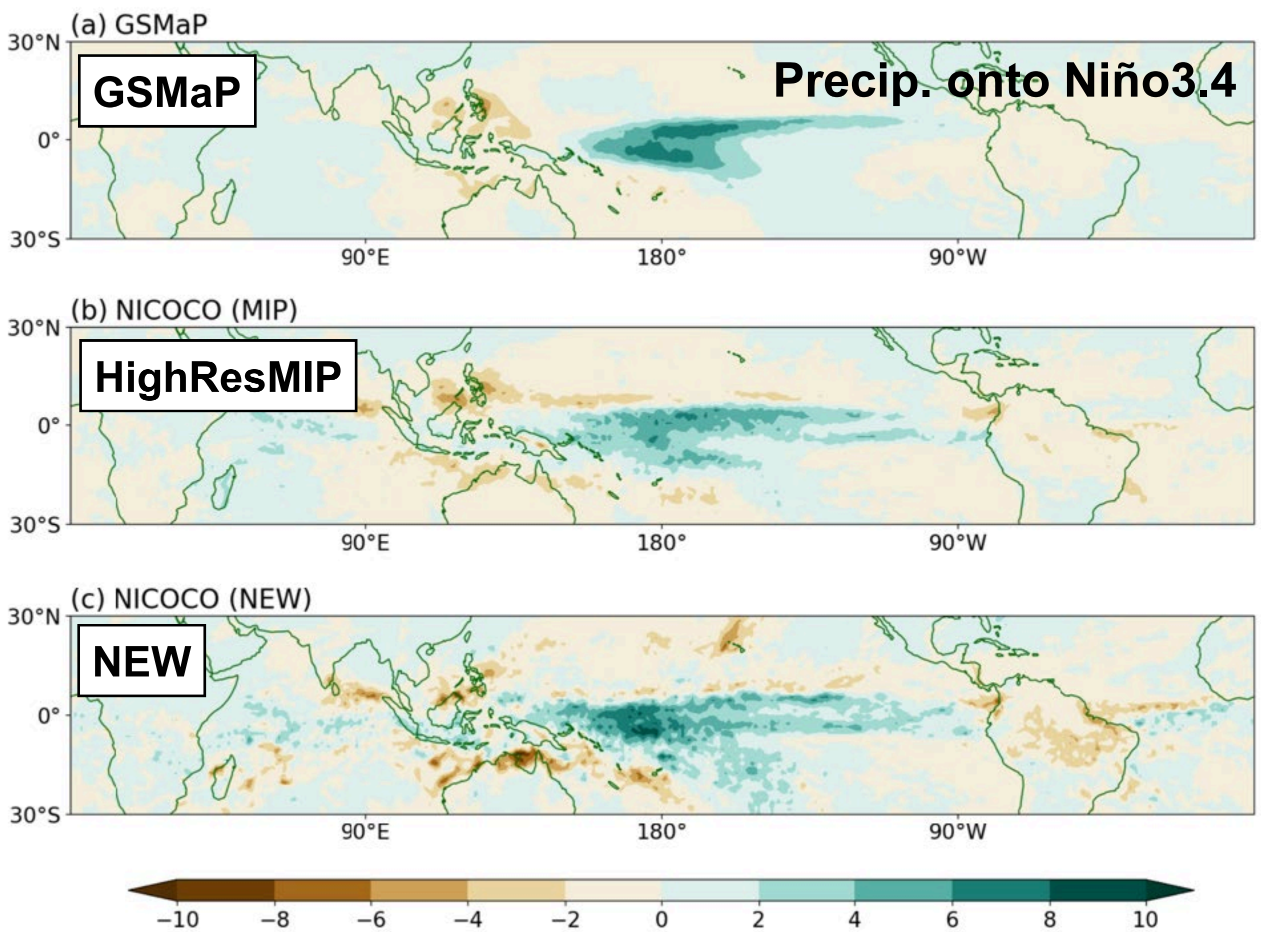
- Prominent low-OSR bias
- Associated SST drift

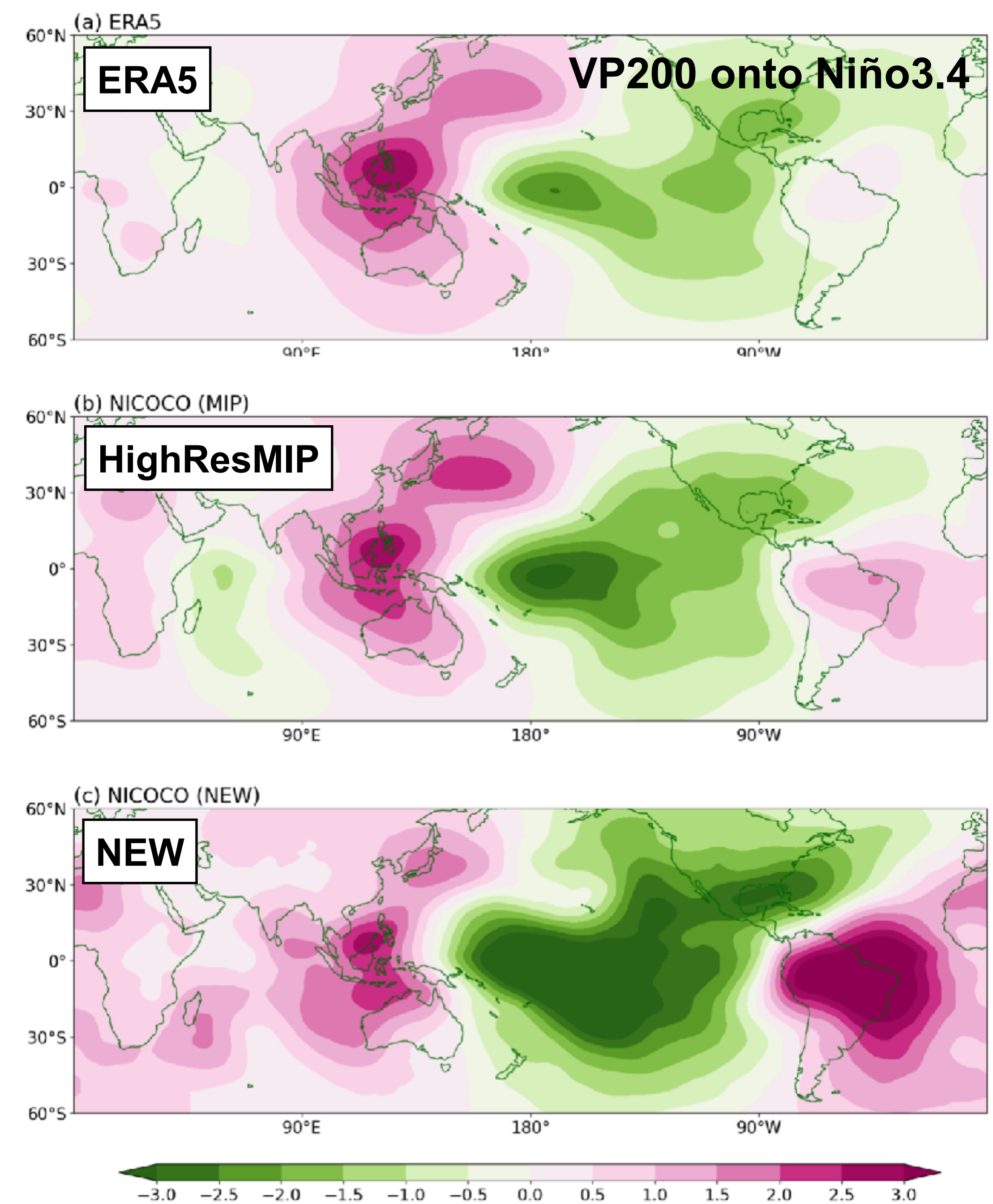
- How do we deal with physics-dynamics coupling in GCRMs?
- Model acceleration by GPU (It is well performed for dyn; by **Hisashi Yashiro** (NIES))

How is the atmos. response to the ENSO? (By Yuki Takano)

Modulation of tropical precip. & circulation and its remote response is also consistent with the ENSO mode (despite biases in amp).

(Takano et al., to be submitted)



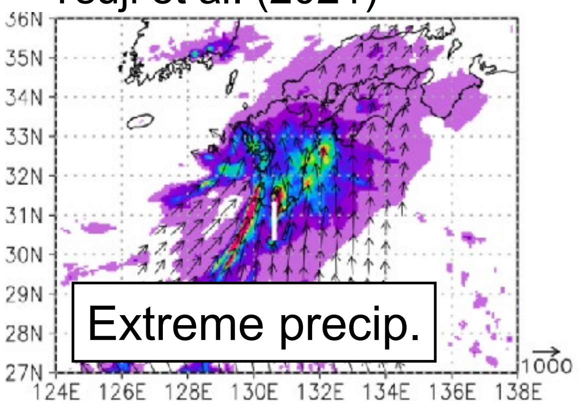


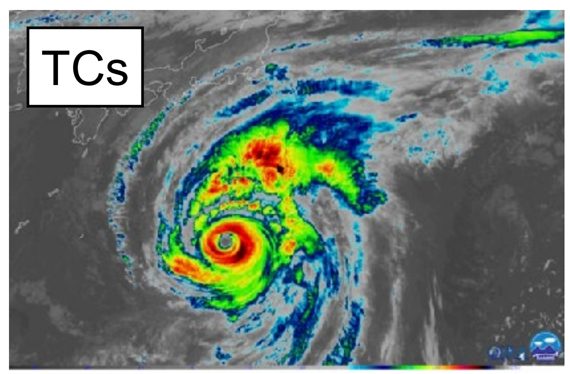
- Pattern of ENSO-related precip. variability and teleconnection to the mid-lat. is reasonable.
- Response amplitude tends to be larger for the NEW-NICAM conf.

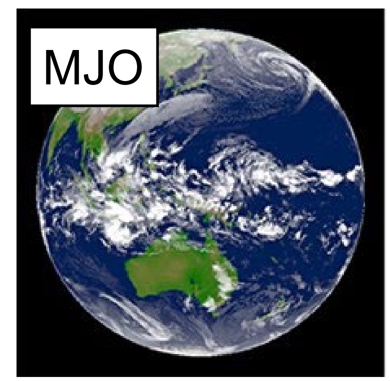
Where will we go?: Science targets

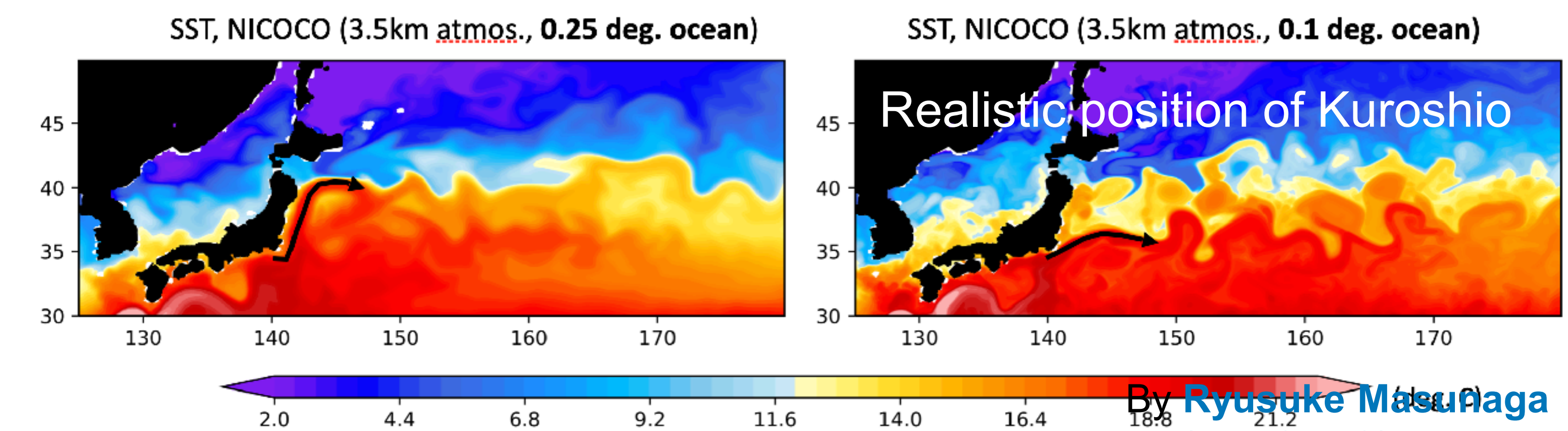
In addition to the analysis of tropics-origin convective systems, we will expand the field into **the mid-latitude and longer variability**.

Tsuji et al. (2021)

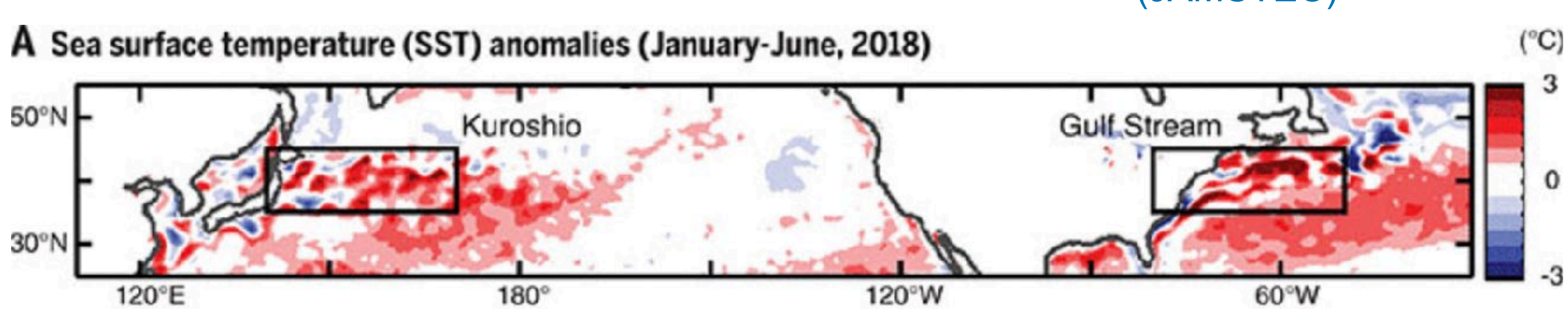








By Ryusuke Masunaga (JAMSTEC)



(Kohyama et al. 2021, Science)

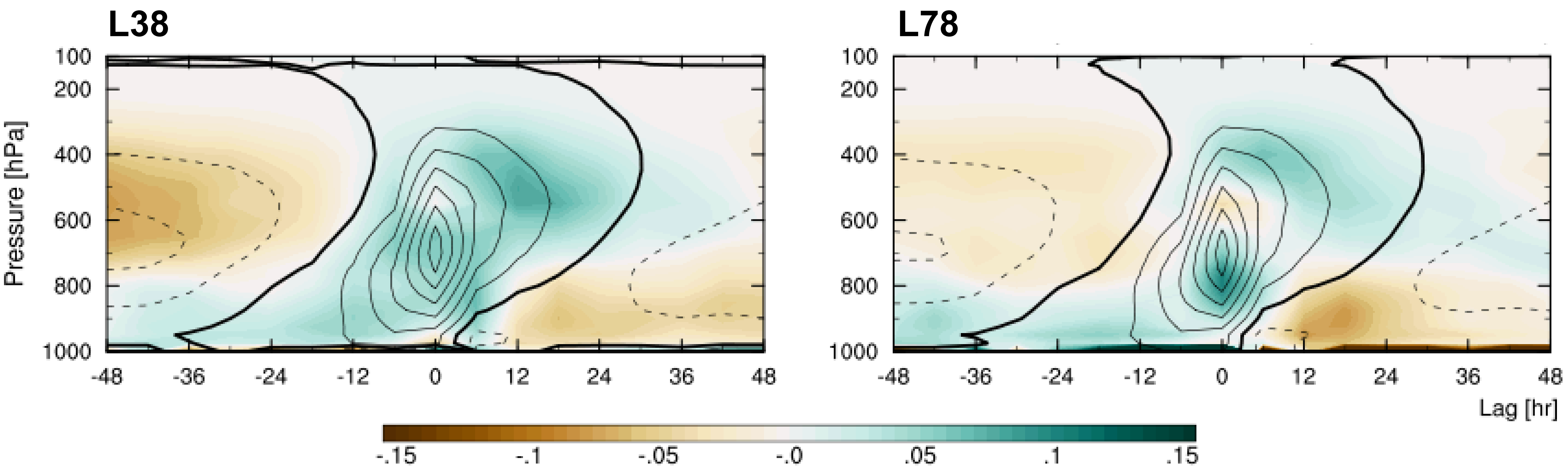
Statistical process understanding and **future projection** of convective organized systems

Ultra-high resolution atoms/ocean enables us to discuss a coupled mode contributed by fine-scale phenomena.

- ENSO phase transition
- Local & inter-basin WBC–atoms interaction

Figure gallery

L38 versus L78 for NEW-NICAM



L78 for NEW-NICAM