熱帯積雲対流に及ぼす大気大規模循環の効果

熱帯降雨観測衛星および気候モデルデータ
解析研究から

東京大学大気海洋研究所
高薮　縁

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渡部雅弘、木本昌秀

09/19/2012神戸大セミナー

Effects of the large-scale circulation on tropical cumulus convection

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- 自由対流圏の湿度依存性に関する観測研究からの示唆
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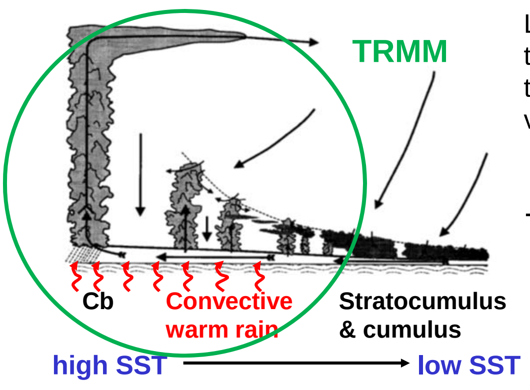
- CMIP3, CMIP5 気候モデルにおける対流パラメタリゼーションの湿度依存性

  --double ITCZ問題との関連
- CRM研究からの示唆

Tropical clouds are under the influences of SST and large-scale circulation

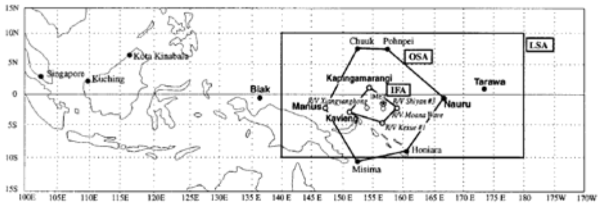


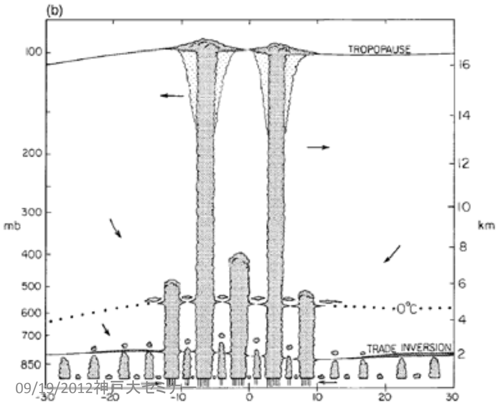
Warm SST destabilize the tropical atmosphere → cumulus convection starts to stabilize

Large-scale subsidence generates trade inversion and suppresses the deep convection (historical view)

→ Recent studies (*e.g.* Bretherton et al. 2004) indicate the importance of the free-tropospheric humidity for deep convection

TOGA-COARE revealed the tri-modality of the tropical convection

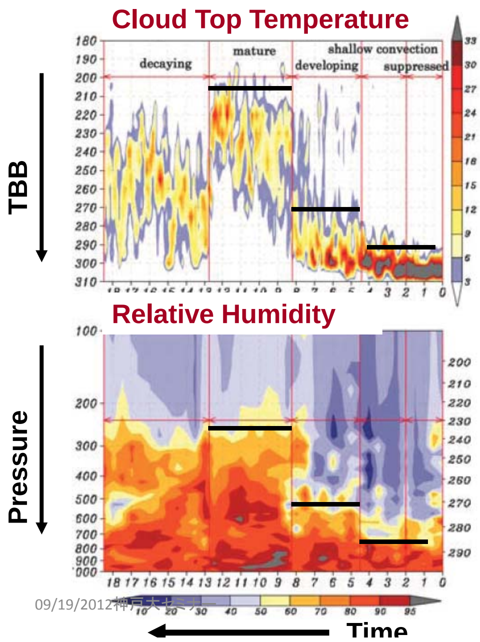




Abundance of cumulus congestus

Johnson et al. 1999

Effects of subsidence observed with the MJO in TOGA-COARE period

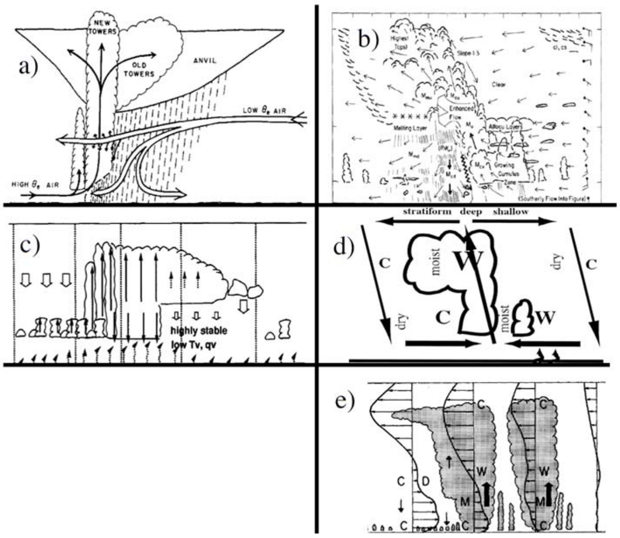


Three-steps-wise development of convections is observed in association with MJO.

In the shallow-convection stage, mid-troposphere is very dry, indicating strong subsidence as a part of the MJO structure.

Kikuchi and Takayabu (2004, GRL)

Similarity of lifecycles in various organized convection systems

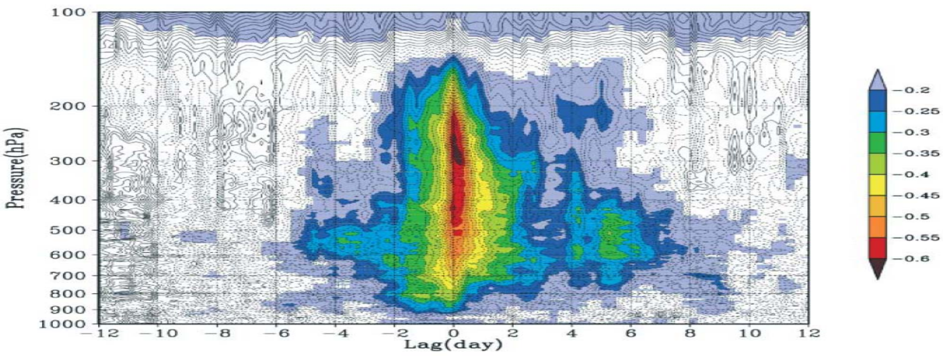


Mapes et al. (2006, DAO)

Fig. 1. Conceptual models of: a, b) mesoscale convective systems (Zipser 1969, Zipser et al. 1981); c) a two-day wave (Takayabu et al. 1996); d) a convectively coupled Kelvin wave (Straub and Kiladis 2003); and e) the Madden-Julian oscillation (Lin and Johnson 1996).

Lag-correlations btwn WV mixing ratio and GMS IR TBB

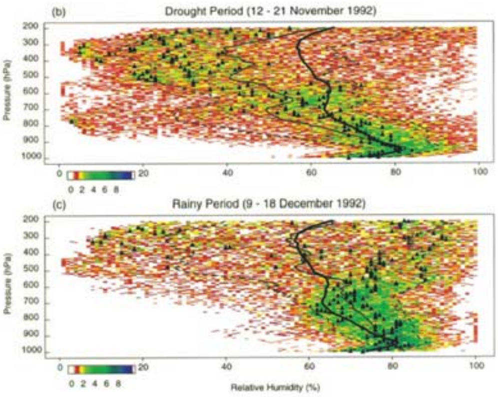
865 sondes launced over ocean from R/V Mirai, R/V Kaiyo, and R/V Natsushima

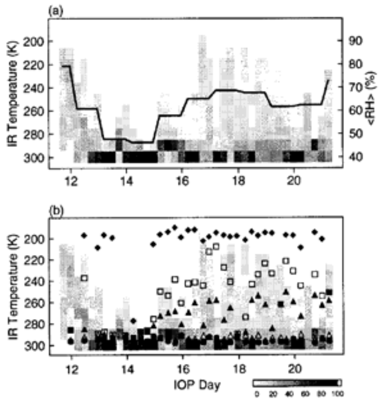


Takayabu, Yokomori et al. (2006, JMSJ)

Significance of mid-level humidity as a precursor of deep convection is suggested, consistent with Brown and Zhang (1997), Sherwood (1999), Bretherton et al. (2004), etc.

Brown and Zhang (1997)





Numaguti et al. (1995) and Yoneyama et al. (1995) suggested the mid-level dry intrusion associated with an MJO significantly suppressed the deep convection.

Consistently, in the drought period (Nov.12-21) of TOGA-COARE IOP, significant difference in RH is found in the mid-to-upper troposphere above 700hPa. (Brown and Zhang, 1997)

Bretherton et al. 2004

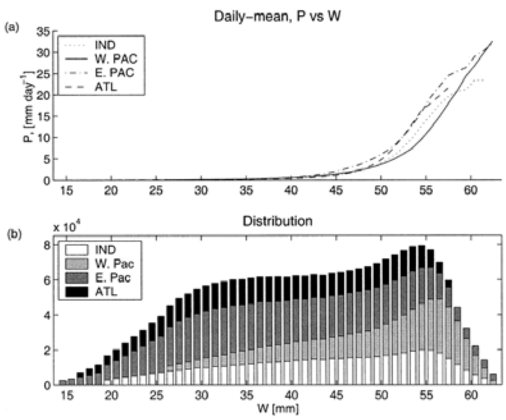


FIG. 2. (a) Mean daily averaged precipitation P in 1-mm-wide bins of water vapor path W, for the four tropical ocean regions in Fig. 1 for all months in 1998–2001. (b) Number of observations in each bin in the four regions.

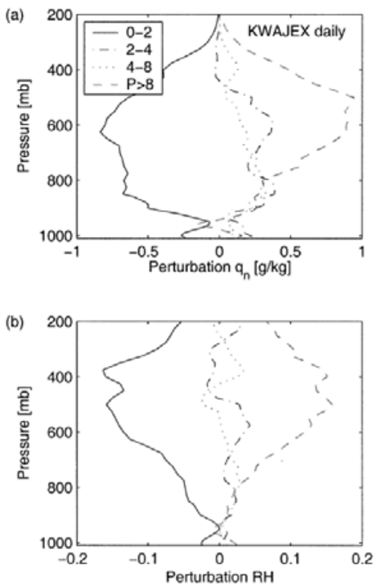
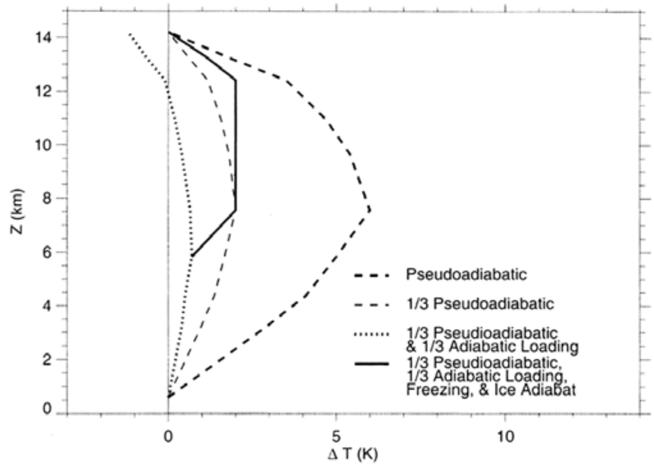


FIG. 10. Daily mean KWAJEX radiosonde-derived perturbation (a) normalized specific humidity and (b) relative humidity profiles bin averaged by daily mean radar-derived precipitation rate (mm day^{-1}).

Re-boost effect on the effective buoyancy with latent heating of freezing (Zipser, 2003)



- Discreteness of tropical convection
- Rareness of undiluted convection

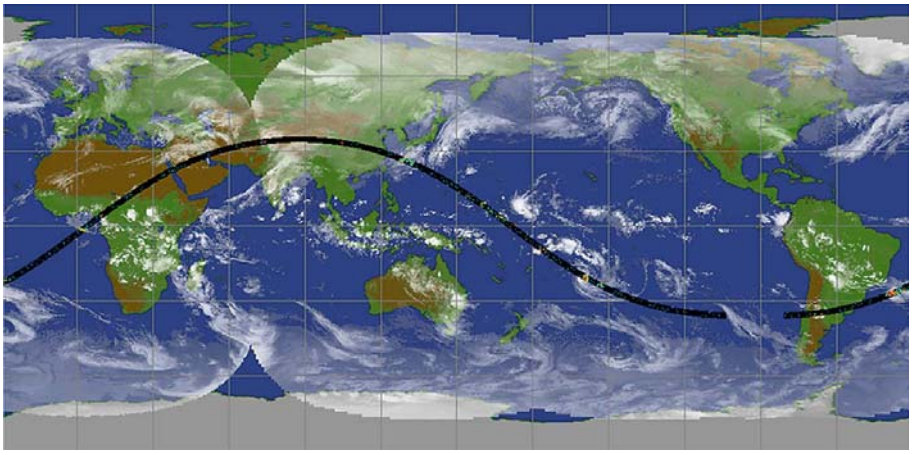
Takayabu, Y. N., S. Shige, W.-K. Tao, and N. Hirota, 2010, J. Clim.

SHALLOW AND DEEP LATENT HEATING MODES OVER TROPICAL OCEANS OBSERVED WITH TRMM PR SLH DATA

Tropical Rainfall Measuring Mission

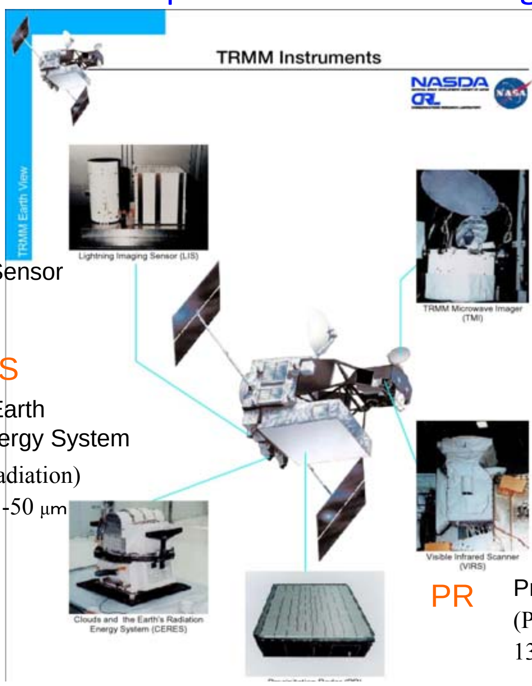
TRMM PR Single Orbit Rain Observation

8 Dec 1997 16:41-18:13 **presented by NASDA (JAXA)**



Swath width: ~220km Orbits: ~16 times/day

TRMM: Tropical Rainfall Measuring Mission



LIS

Lightening Imaging Sensor

CERES

Clouds and Earth Radiation Energy System

(Broadband Radiation)

0.3-5, 8-12,0.3-50 μm

TMI

TRMM Microwave Imager

(Precipitation, Sfcwnd, SST, Precipitable water)

10,19,21,37,85 GHz

VIRS

Visible Infrared Scanner

(Clouds)

0.63, 1.6, 3.75, 10.8, 12.0 μm

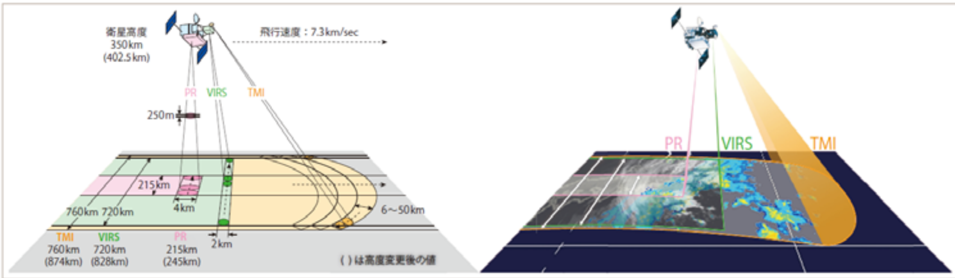
PR

Precipitation Radar

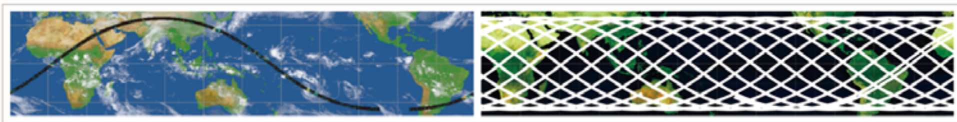
(Precipitation Profiles)

13.8GHz

TRMM降雨観測

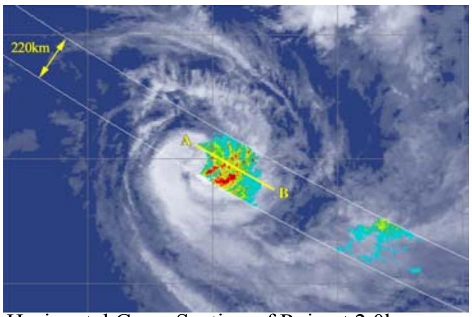


図❷ PR, TMI, VIRSによる降雨観測概念図



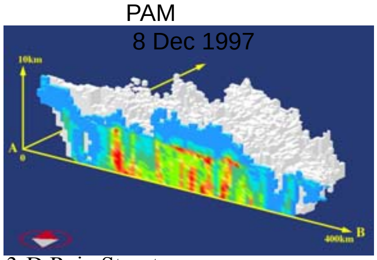
PR Swath width: 215km (245km)　Orbits: ~16 times/day

TRMM　PR による3次元降雨観測

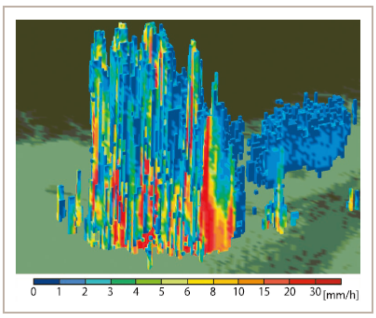


Horizontal Cross Section of Rain at 2.0km

Tropical Cyclone
PAM
8 Dec 1997



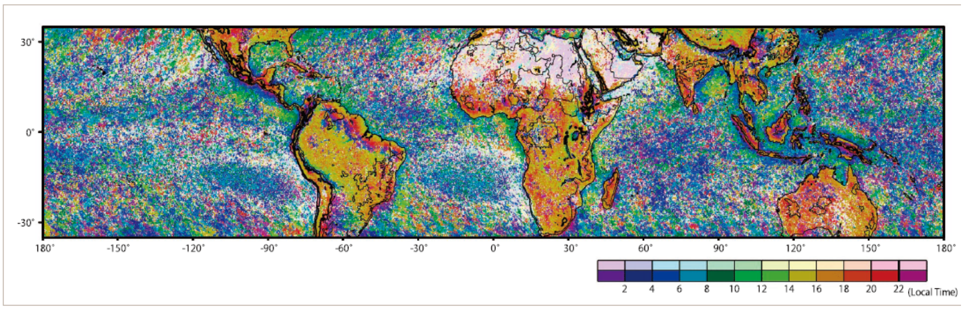
3-D Rain Structure



図❸ 1998年5月28日20時59分(世界時)にTRMMで観測した降雨
バングラデシュ付近で観測された南側からのPRの立体画像と鉛直断面図

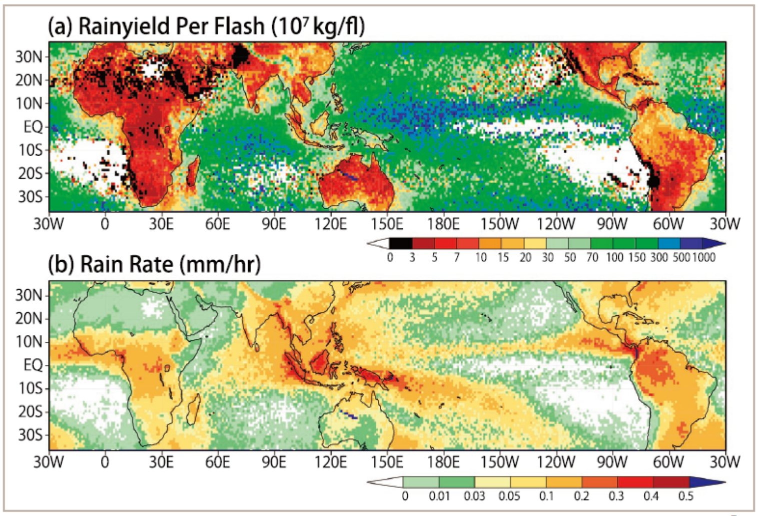
JAXA EORC 提供

降雨の日変化



図❷ TRMMマイクロ波放射計(TMI)による降水の日周変化
色は降雨量のもっとも多い地方時を示す。陸上で午後の雨(暖色系)、海上で午前の雨(寒色系)が多いことがわかる。

降雨特性：降雨量/発雷比



図❶ TRMMのPRおよびLIS観測から求められた(a)3年平均の降雨／発雷比(RPF, 単位10^7 kg/fl)、および(b)8年平均降雨率全球分布(北緯36°-南緯36°)
赤系の色は雷の多い性質の雨、青系は少ない雨を示す。海陸の降雨特性の違いが顕著である。

Takayabu, 2006

Apparent Heat Source (Yanai et al. 1973)

$$Q1 \equiv \frac{D\overline{s}}{Dt} = \frac{\partial \overline{s}}{\partial t} + \overline{v} \bullet \nabla \overline{s} + \overline{\omega}\frac{\partial \overline{s}}{\partial p}$$

$$= QR + L(\overline{c} - \overline{e}) - \nabla \cdot \overline{s'v'} - \partial/_{\partial p}\, \overline{s'\omega'}$$

$$\text{where } s = CpT + gz \text{ dry static energy}$$

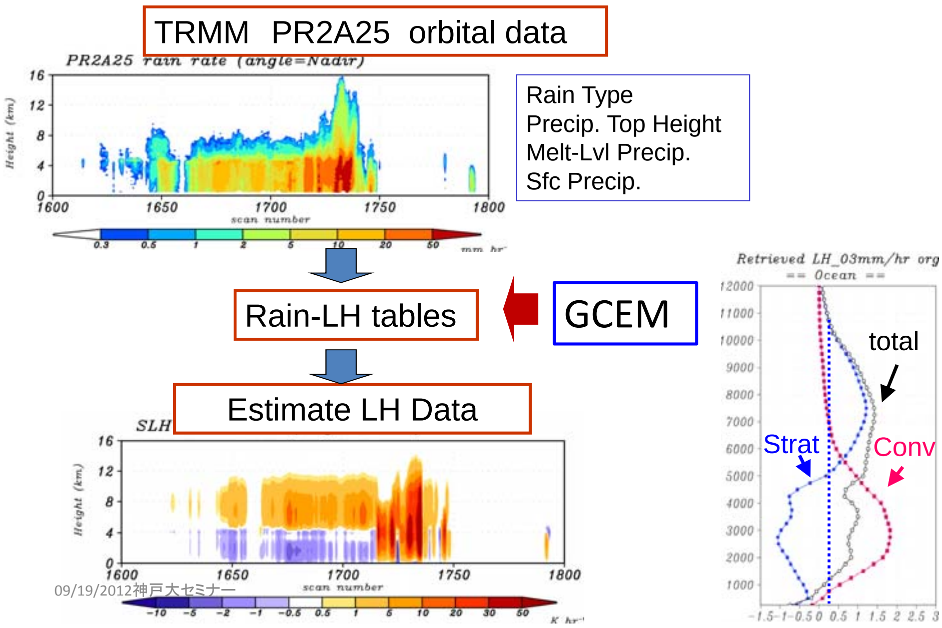
$$\bar{\ }: \text{grid mean}, ': \text{deviation from the grid mean}$$

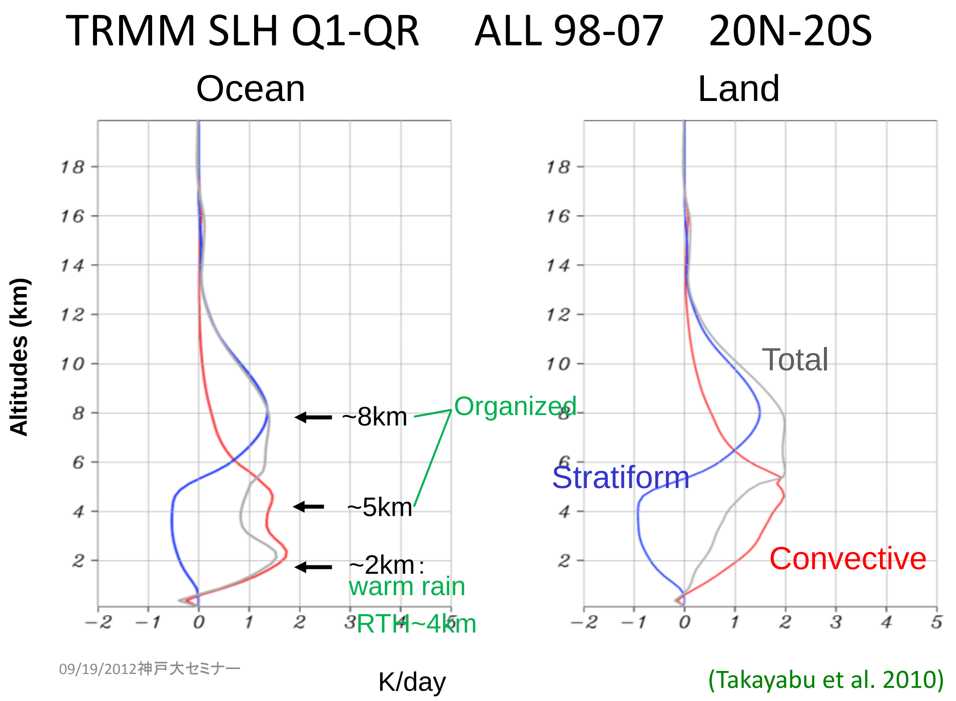
- 3D Q1-QR data from the SLH database are used: generated in TRMM2A25 original resolution and gridded into monthly, 0.5degx0.5deg: L3LH, Dec.1997-Nov.2007

 Shige et al. (2004) http://www.eorc.jaxa.jp/TRMM/lh/index.html

Data: TRMM Spectral Latent Heating (SLH)

Shige et al. 2004, JAMC




TRMM SLH Q1-QR ALL 98-07 20N-20S
Ocean
Land
Altitudes (km)
~8km
~5km
~2km：
warm rain
Organized
RTH~4km
Total
Stratiform
Convective
K/day
(Takayabu et al. 2010)
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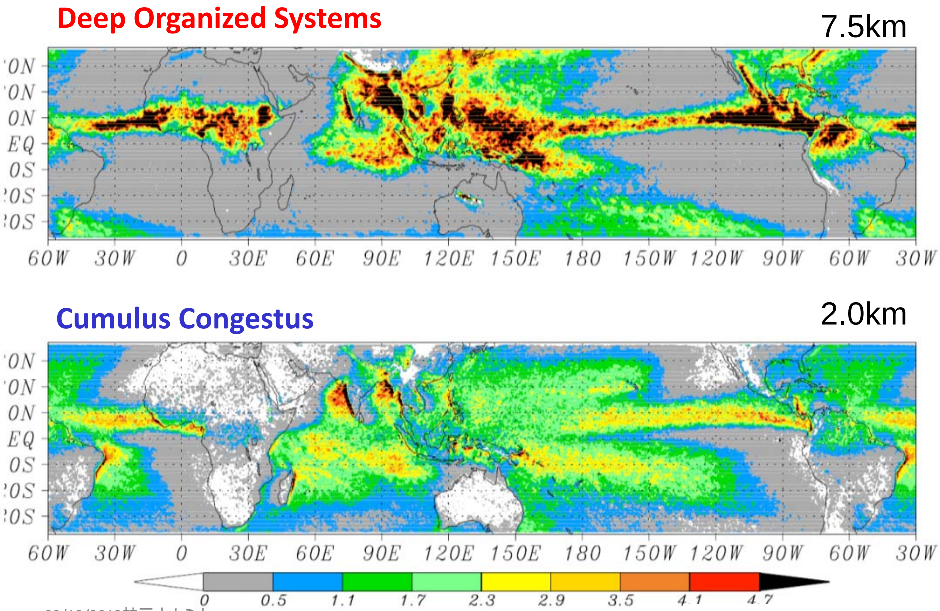
Warm convective rain
or cumulus congestus
09/19/2012神戸大セミナー

10-year mean Q1-QR JJA 98-07



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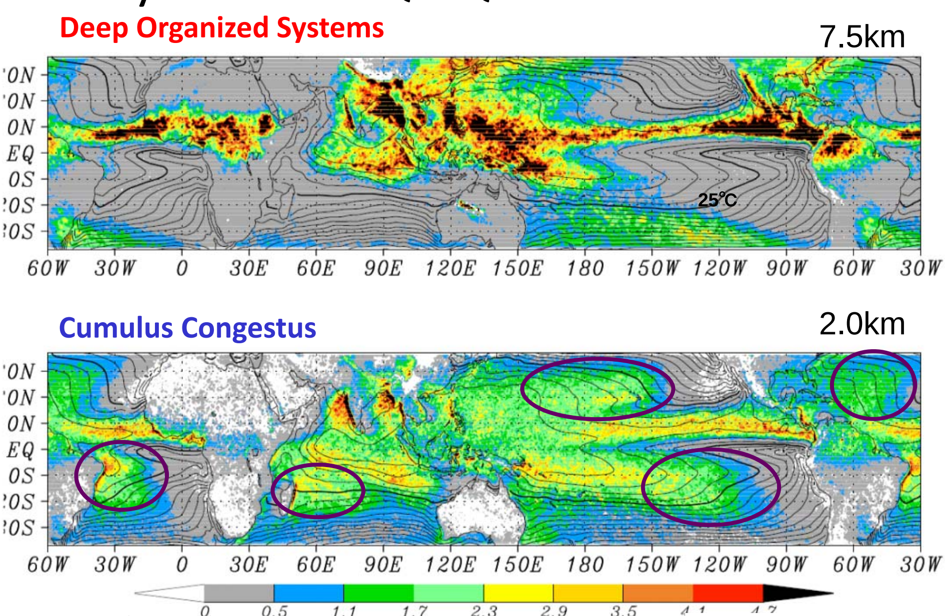
(Takayabu et al. 2010)

10-year mean Q1-QR & SST JJA 98-07



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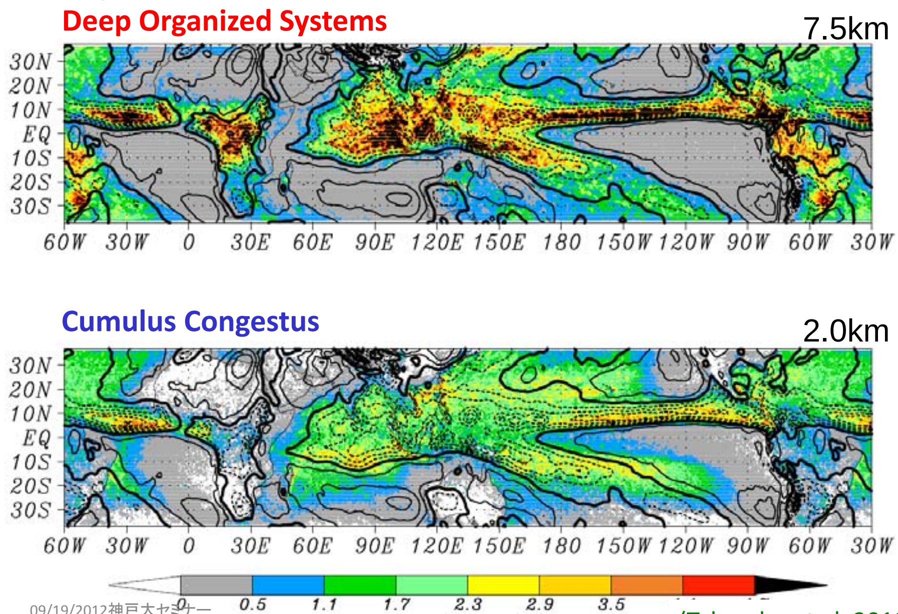
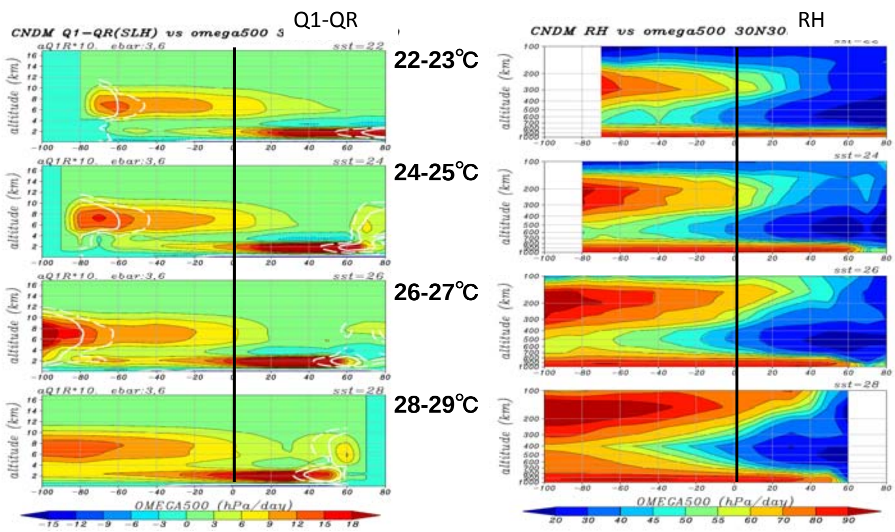
(Takayabu et al. 2010)

10-year mean Q1-QR & ω500 JJA 98-07



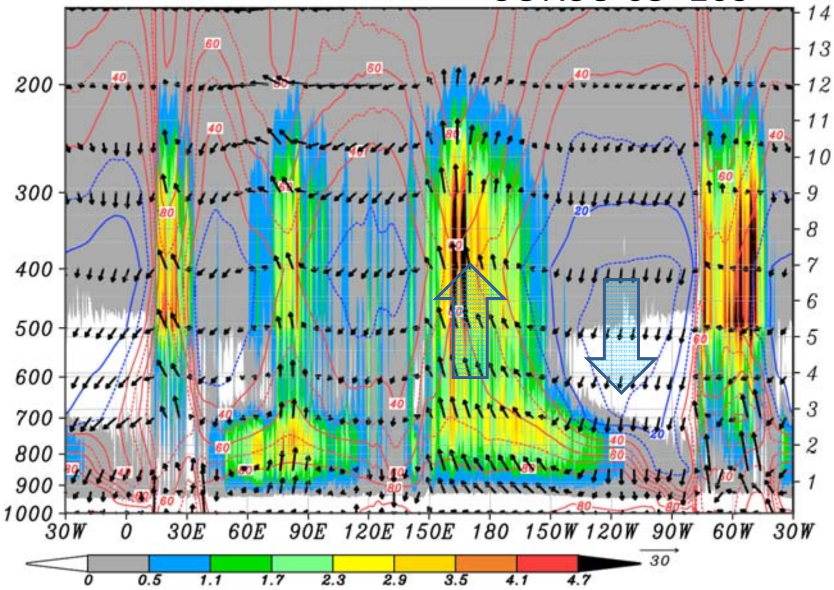
(Takayabu et al. 2010)

Cond-Mean Q1-QR & RH vs ω500hPa 30N30S 9804



In order to separate the effects of large-scale circulation from those of SST, plots are separated in terms of SST. It was shown that similar significant dryness in the mid-to-lower troposphere is found in the subsidence region irrespective of the SST.

TRMM SLH Q1-QR, JRA25 winds, RH
SON98-05 10S

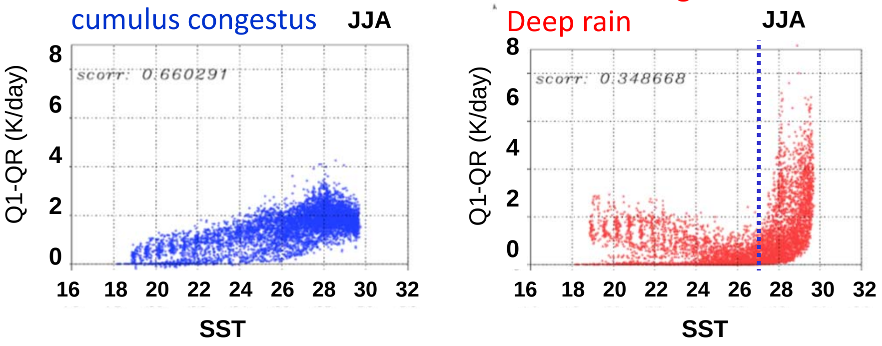


(Takayabu et al. 2010, modified)

Unconditional mean Q1-QR vs. SST 97-05 30N-30S

2.0km heating
cumulus congestus

7.5km heating
Deep rain



While congestus responds linearly to SST, which means obedient to the low-level instability, deep rain is controlled by another factor.

(Takayabu et al. 2010)

From the TRMM SLH Analysis

- Distinct two regimes of convective heating with TRMM-PR based Q1-QR; a cumulus congestus rain with a peak at ~2km, and with a peak for deep organized rain at ~8km.
- Under large-scale subsidence, cumulus congestus rain dominates over ocean, but not over land.
- Congestus rain responds linearly to SST, while deep organized convection is effectively suppressed by large-scale subsidence, probably through the entrainment of free tropospheric dry air.

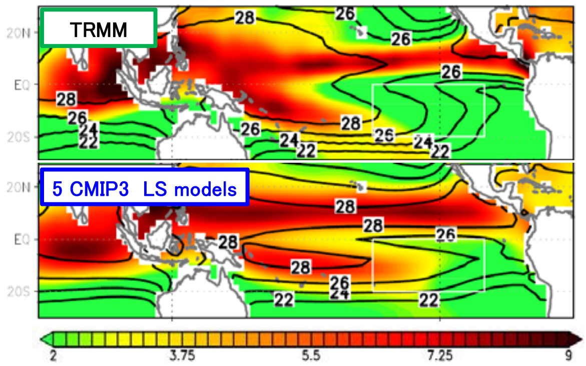
Hirota, N., Y. N. Takayabu, M. Watanabe, and M. Kimoto, 2011 *J. Climate*

PRECIPITATION REPRODUCIBILITY OVER TROPICAL OCEANS AND ITS RELATIONSHIP TO THE DOUBLE ITCZ PROBLEM IN CMIP3 AND MIROC5* CLIMATE MODELS

***MIROC5: U.TOKYO/JAMSTEC/NIES NEW MODEL FOR CMIP5**

Double ITCZ in climate models

Precipitation (color), SST (contour) [SON]

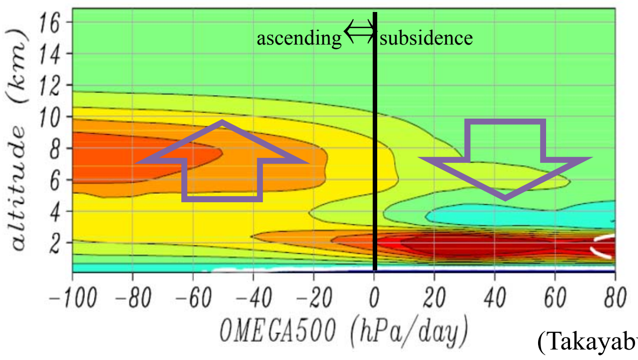


- Systematic precipitation bias over the southeastern Pacifc (Mechoso et al. 1995; Szoeke and Xie 2008)
- Double ITCZ appears even in AGCMs (Zhang et al. 2007; Chikira, 2010)
- Mitigated by modification of convective parameterization (Song and Zhang 2009, Chikira 2010)

(Hirota et al., 2011)

Effects of SST and subsidence

Heating (color; TRMM SLH) stratified against ω500 (abscissa; JRA)



(Takayabu et al. 2010)

We have seen subsidence regions had very dry layer in the middle trop. (~600 hPa)
→ Entrainment of dry air reduces buoyancy of convection
→ suppression of deep convection

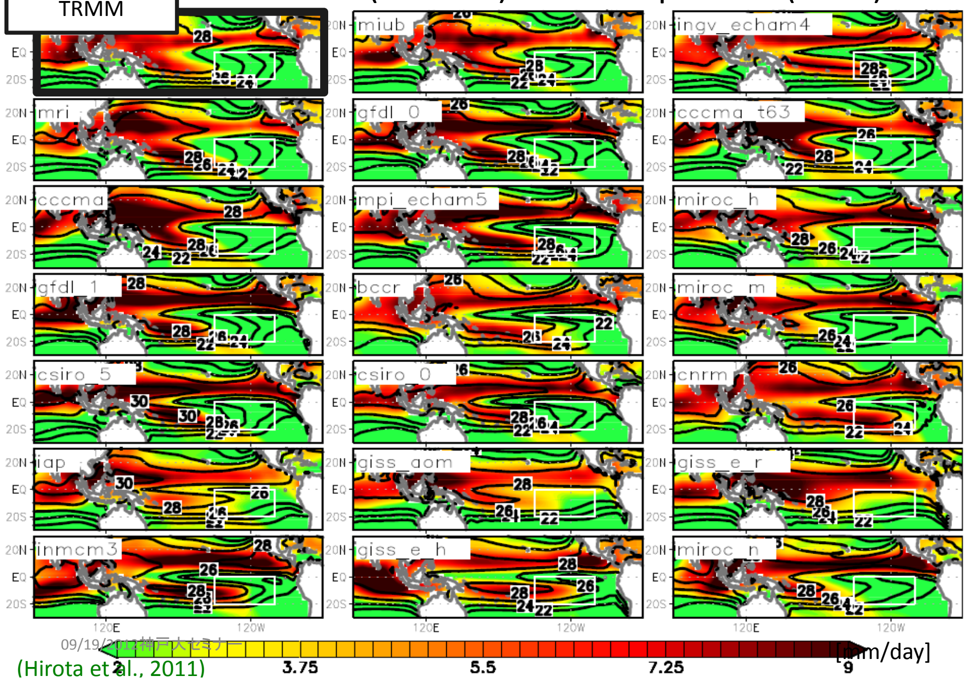
DOUBLE ITCZ IN CMIP3 MODELS

熱帯海洋上の降雨分布とCMIP3, CMIP5モデルのダブルITCZ問題

✓ 深い対流のSSTと環境場の湿度への感度

Precipitation distributions over the tropical oceans and the double ITCZ problem in CMIP3 and MIROC5 models are investigated, in terms of sensitivity of deep convection to SST and environmental humidity.

CMIP3 SST (contour) and Precipitation (color)

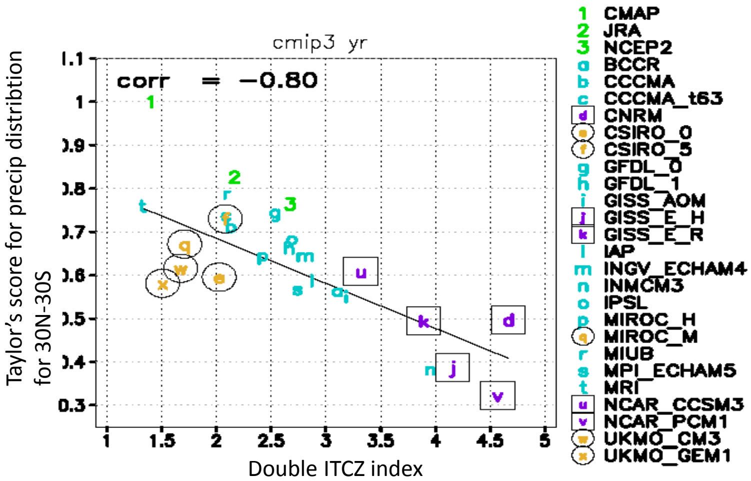


(Hirota et al., 2011)

Observation	TRMM PR 2A25
CMIP3	
BCCR	GISS_E_R
CCCMA*	IAP
CCCMA_t63*	INGV_ECHAM4
CNRM	INMCM3*
CSIRO_0	MIROC_H
CSIRO_5	MIROC_M
GFDL_0	MIUB*
GFDL_1	MPI_ECHAM5
GISS_AOM	MRI*
GISS_E_H	(*flux adjustment)
For CMIP5	MIROC5

Precipitation distributions in CMIP3 models and new MIROC5 are evaluated against the TRMM Precipitation Radar data

Double ITCZ ~ Taylor(2001)'s score for tropical precip.

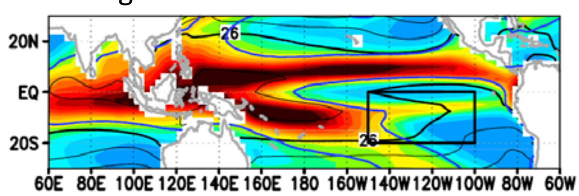


Among CMIP3 models, Taylor(2001)'s score for tropical (30N-30S) annual precipitation and the double ITCZ index have a significant negative correlation.

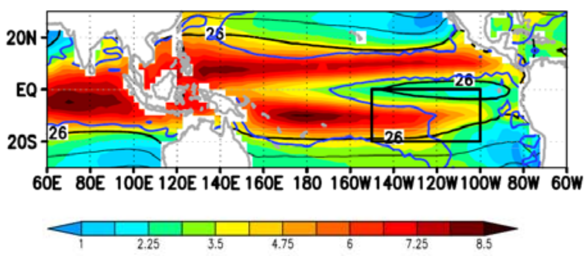
Modified from Hirota et al. 2011 JC

CMIP3 High and Low Performance Models in tropical precip. distribution(30N-30S 0-360E)

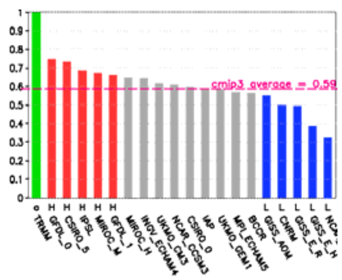
5 High Performance Models



5 Low Performance Models

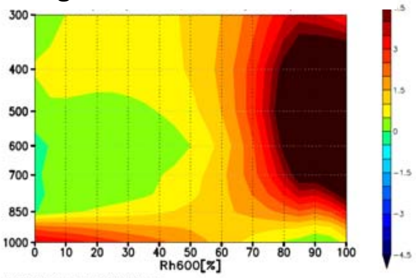


High performance models in terms of precipitation distribution also behave well with ITCZ structure, for CMIP3 models.



Diabatic Heating (Q1)sorted with RH600hPa

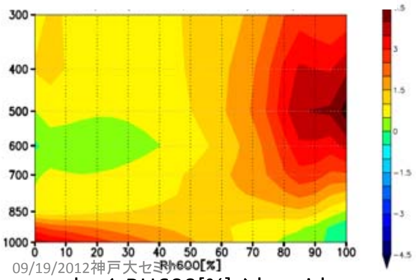
5 High Performance Models



CMIP3

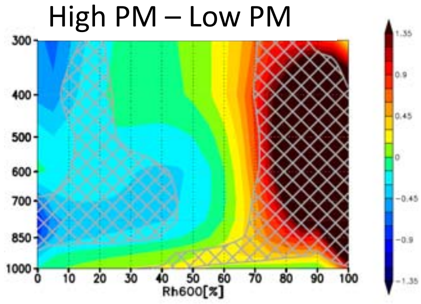
Convection in high performance models is more sensitive to the mid-to-lower tropospheric relative humidity. So that deep convection is effectively suppressed when the RH600 is low. (Hirota et al., 2011)

5 Low Performance Models



dry←RH600[%]→humid

High PM – Low PM



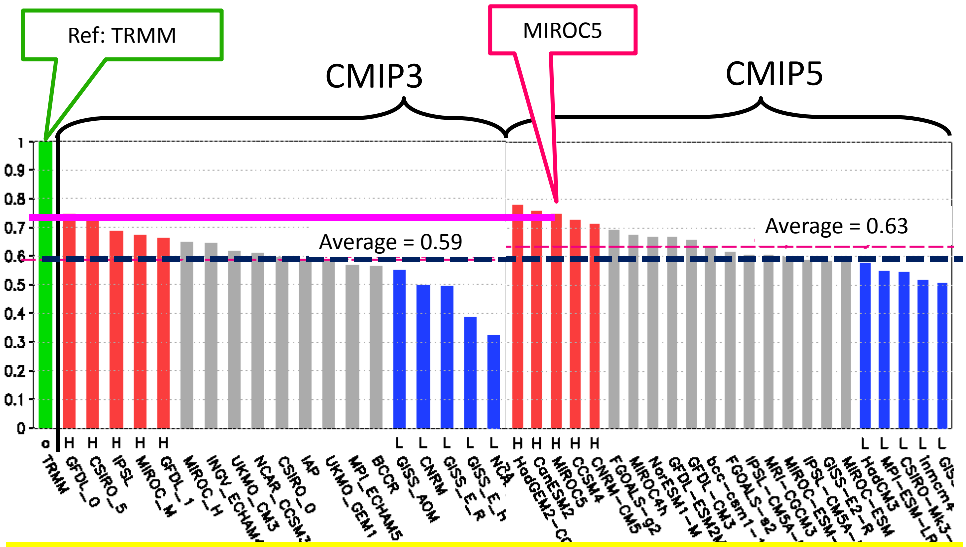
dry←RH600[%]→humid

CMIP5 CASE

Taylor's score for tropical precip.: CMIP3 vs CMIP5

$$S \equiv \frac{(1+R)^4}{4(SDR+1/SDR)^2}$$ (Taylor, 2001)

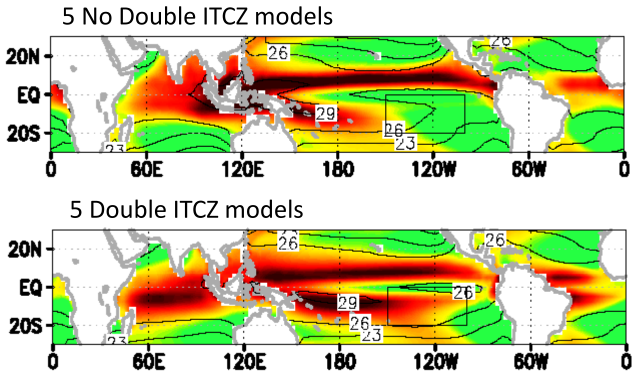
(Hirota et al., 2012)

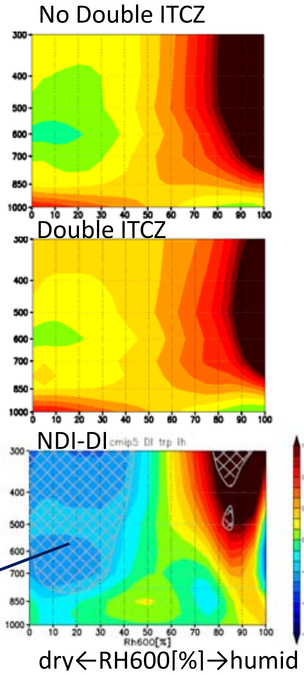


DI ←Corr -0.8→ Taylor Score DI ←Corr -0.2→ Taylor Score

CMIP5 for ITCZ distribution

(Hirota et al., 2012)

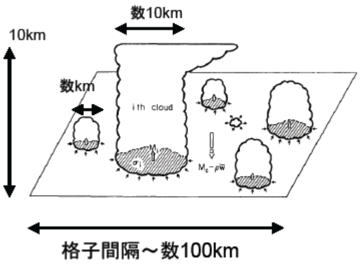




CMIP5 models without double ITCZ problem also tend to be sensitive to the mid-to-lower tropospheric relative humidity, suggesting the importance of free tropospheric entrainment of the convection.

EFFECT OF ENTRAINMENTS

A-S Cumulus parameterization



Spectral representation of cumulus convection

Arakawa and Schubert (1974)

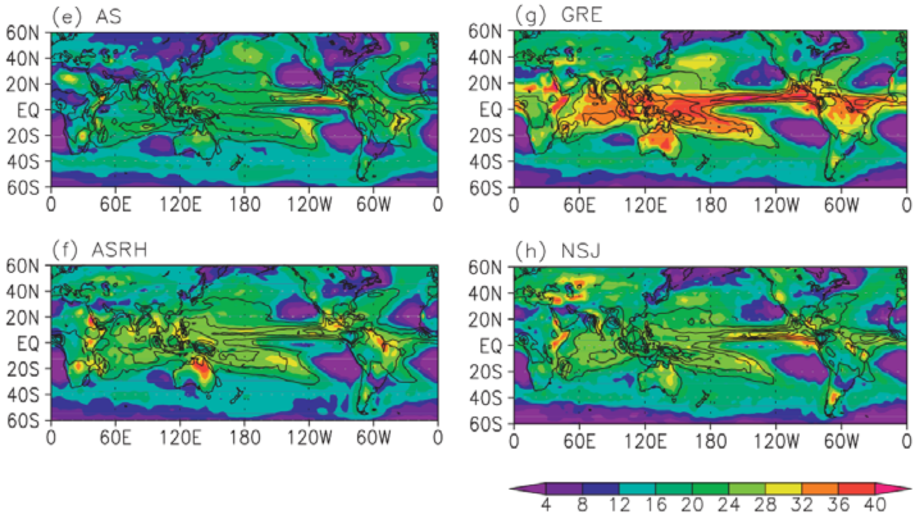
Treatment of entrainments

$$\frac{1}{M_c(z)}\frac{dM_c(z)}{dz} = \epsilon(z)$$

- Arakawa and Schubert (1974): $\epsilon(z) = \frac{2\alpha}{R}$
- Chikira and Sugiyama (2010): $\epsilon(z) = C_\epsilon \frac{aB(z)}{\hat{w}_c(z)^2}$

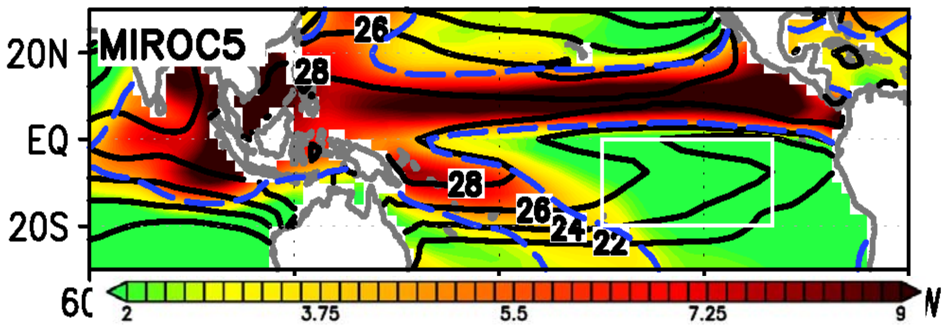
Chikira 2010b

Fraction of detrainments at yeta=0.55 to total



Cumulus congestus related detrainments increases with the modified GRE entrainment scheme

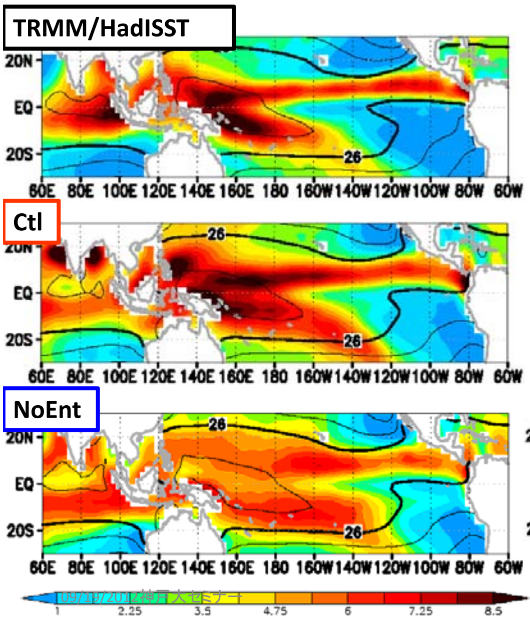
Precipitation, SST, and dp/dt500



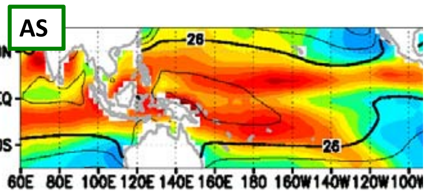
MIROC5 with Chikira's implementation of modified GR01 state-dependent entrainment to AS parameterization, shows a good performance. Deep convection is largely suppressed with subsidence over moderately warm SST regions.

(Hirota et al., 2011)

Precipitation Distributions in TRMM and MIROC-AGCM



Atmospheric GCM experiments with only entrainment parameter is modified show that entrainment is essential to avoid the double ITCZ problem.



(Hirota et al., 2012)

Message

To avoid the double ITCZ problem in climate models, a proper treatment of entrainment of the tropospheric air in the cumulus parameterization is essential.

ただし、SSTバイアスの要因には、積雲のパラメタリゼーションに加えてもうひとつの要素があることが、CMIP5の解析から示唆されている。（解析中）

Derbyshire, S. H. et al. 2004: Sensitivity of moist convection to environmental humidity. Q. J. R. Meteorol. Soc., 130, 3055-3079.

Kuang, Z., and C. S. Bretherton, 2006: A mass-flux scheme view of a high-resolution simulation of a transition from shallow to deep cumulus convection. J. Atmos. Sci., 63, 1895-1909.

Khairoutdinov, M. and D. Randall, 2006: High-resolution simulation of shallow-to-deep convection transition over land. J. Atmos. Sci. 63, 3421-3436.

Del Genio, A. D., and J. Wu, 2010: The role of entrainment in the diurnal cycle of continental convection. J. Clim. 23, 2722-2738.

WHAT HAVE BEEN SHOWN FROM CRM STUDIES

Khairoutdinov and Randall 2006

FIG. 2. Visualization of the simulated cloud field at 0130 in the afternoon as would be seen from the surface. Note that the clouds on the left are as high as 12 km.

Kuang and Bretherton 2006

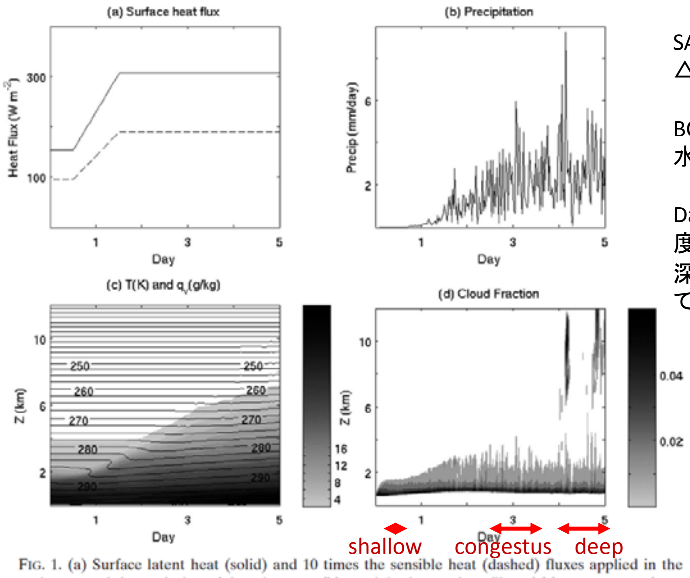
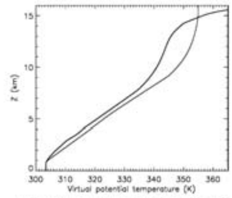


FIG. 1. (a) Surface latent heat (solid) and 10 times the sensible heat (dashed) fluxes applied in the experiment, and the evolution of domain-mean (b) precipitation, and profiles of (c) temperature (contours) and water vapor specific humidity (shading), and (d) cloud fraction.

SAM （CSU)
△x: 100m, L256

BOMEXの環境場
水平風のnudging なし

Day2ですでに15km高度まで浮力がある↓が、深い対流は抑制されている



Kuang and Bretherton 2006

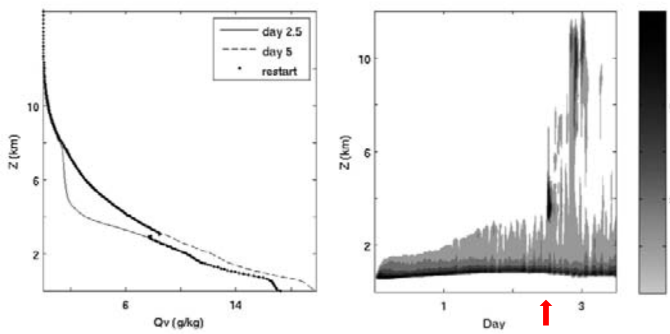


FIG. 3. (a) Domain-averaged q_v profile at the end of day 2.5 (solid) and day 5 (dashed) of the control run. The difference between the dotted line and the solid line was added to the new run, which restarted at the end of day 2.5 of the nominal run. (b) The evolution of cloud fraction profile in the restarted run. The first 2.5 days are the same as the nominal run shown in Fig. 1d.

Day2.5以降、z>3kmの比湿に下駄：day5の比湿を与える
→即座にdeep convectionが発生

Kuang and Bretherton 2006

Cloudy mass flux

Shallow regime

deep regime

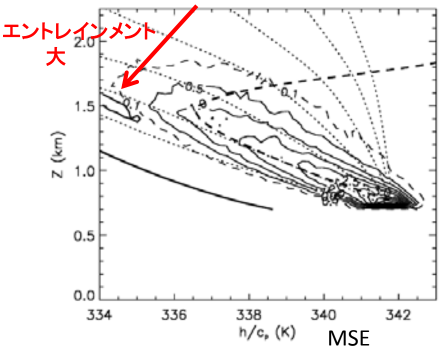


FIG. 9. The cloudy updraft/downdraft mass flux at each height binned by their MSE h (expressed as h/c_p in temperature units). The bin size is 0.18 K. The interval of the solid contours is 0.5 g m^{-2} s^{-1} bin^{-1}, the dashed contour is for 0.1 g m^{-2} s^{-1} bin^{-1}, and the thick solid contour is for −0.1 g m^{-2} s^{-1} bin^{-1}, representing the downdrafts. The dotted lines are the MSEs predicted by entraining plume models with fractional entraining rates of (from right to left) 0.0625 km^{-1}, 0.125 km^{-1}, 0.25 km^{-1}, . . . , 4 km^{-1}. The thick solid line to the far left is the domain mean MSE profile, and the thick dashed line is the domain mean saturation MSE profile.

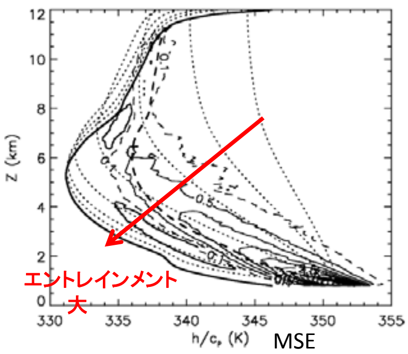


FIG. 11. Same as Fig. 9, except for the deep cumulus regime and for a bin size of 0.5 K in h/c_p.

Shallow clouds の方がエントレインメント率が高い。ただ、Deep cloudsも0.125km^{-1}線を下回らない。Size dependencyの示唆。

Khairoutdinov and Randall 2006

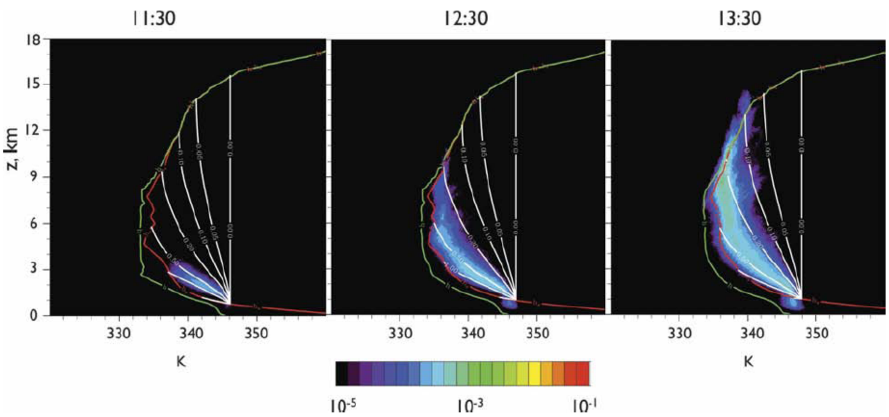


FIG. 12. As in Fig. 11 except for the updraft cores defined by the vertical velocity being in excess of 5 m s^{-1}.

Khairoutdinov and Randall 2006

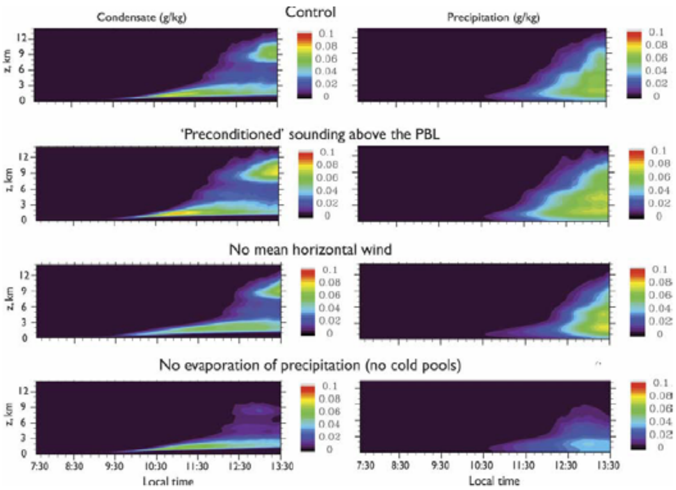


FIG. 15. Evolution of mean vertical profiles of (left) nonprecipitating cloud condensate and (right) precipitating water for the (top) control run and (bottom) three sensitivity runs (see text for details).

CTL

自由大気の加湿

一般風なし

Cold Pool なし

感度実験： この実験では、中層はすでに十分湿っていたので、湿度の上乗せにはさほど感度がないが、効果は見える。Cold Poolは大きなBoundary Layer thermalを作ることを通じて、entrainmentの小さい対流を可能にすると解釈。

Del Genio and J. Wu 2010

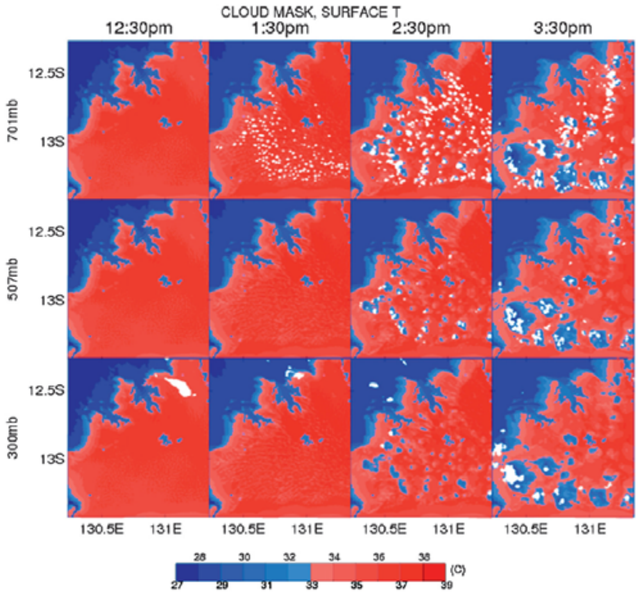


FIG. 4. Near-surface temperature, with cloud mask overlain in white, at (top) 701, (middle) 507, and (bottom) 300 mb at different times of day in the CONTROL simulation.

LBA diurnal cycle
WRF dx: 125m, 600m

Congestus also creats cold pools

KB06, KR06:
Cold pool convergence creats larger eddies at the gust front.

Suggestion:
Implementation of the Gregory(2001) parameterization requires a specification of the initial convective parcel updrafts speed enhancement due to downdraft cold pool convergence.

CRM studiesから

- 中層(>3km)の湿度が深い対流にもたらす効果を確認
- エントレインメントのサイズ依存性：浅い雲の方が深い雲より大きい。雲のサイズが大きい方がentrainment小さい。
- ただし、深い（大きい）雲でもentrainmentが0.1を下回らない。
- Congestus（雄大積雲：水雲）でも、cold poolが形成される。
- Cold poolがより大きいplumeの生成を通じて深い対流をトリガーする効果の重要性が指摘された

まとめ

- From long-term TRMM data, the effect of the large-scale subsidence was observationally indicated. It suppresses the deep convection through drying the mid-level troposphere, thus generating cumulus congestus regime of precipitation.
- The “double ITCZ problem” in climate models is closely linked to the sensitivity of the cumulus parameterization to the tropospheric humidity.
- Above results are in concert with MIROC5 with the state-dependent entrainment rate (Chikira and Sugiyama 2010)
- Significant role of cold pools for triggering the deep convection has been suggested from CRM studies.