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Intercomparison of methods of coupling between convection and large-scale circulation

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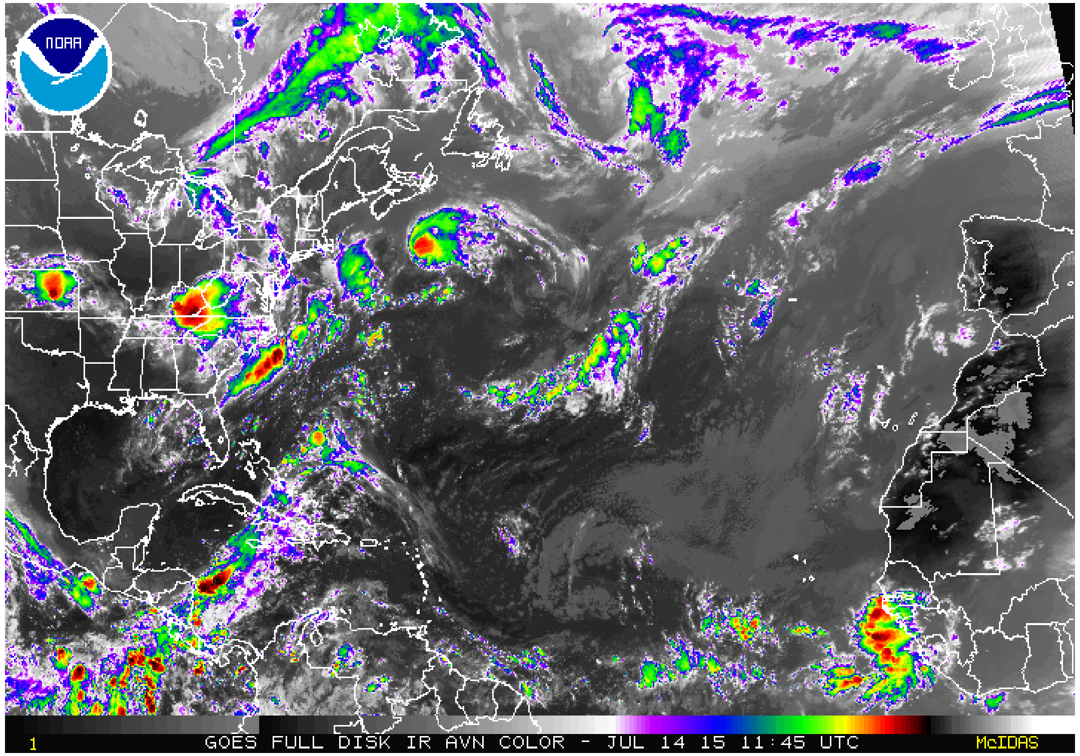
Outline

- Background
- Different methods of coupling between convection and large-scale circulation
- Motivation
- Models that participated in this project
- Experimental setup
- Results
- Conclusion

Background

Understand tropical climate and its variability



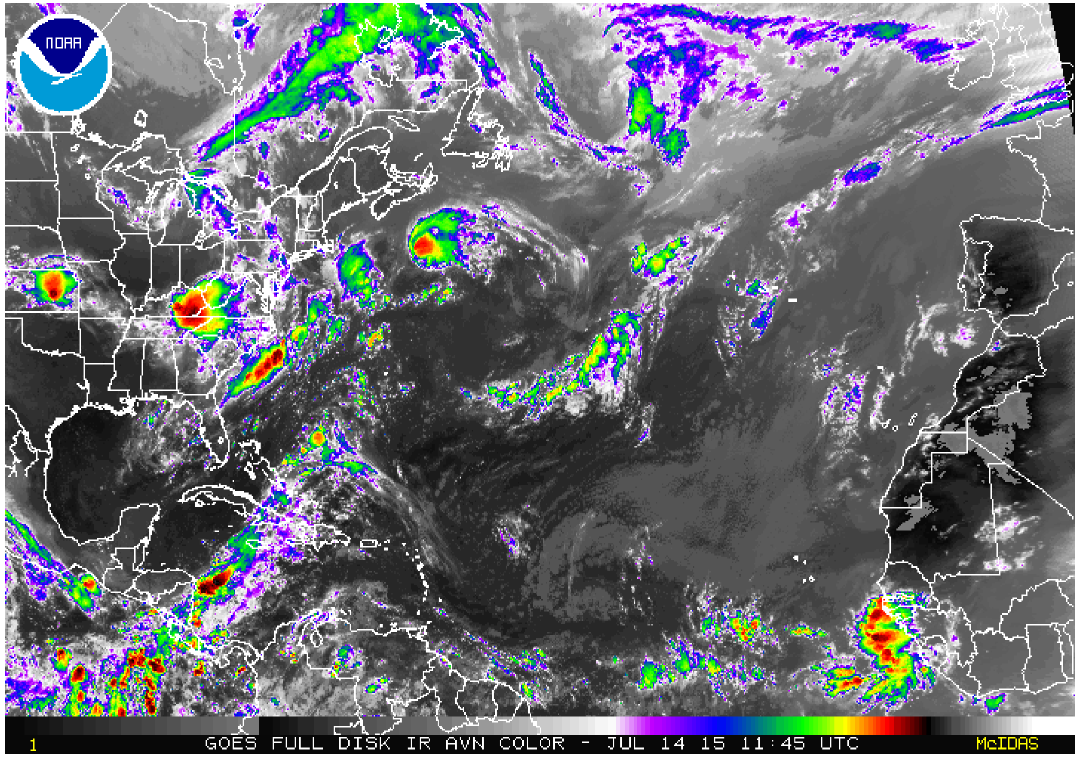
Snapshot of clouds taken on July 15th 2015 at 11:00 UTC.
http://www.ssd.noaa.gov/PS/TROP/Basin_Atlantic.html

Science questions:

- What initiates tropical convection?
- What conditions favour moist convection?
- How is moist convection interacts with the large-scale tropical environment?
- Why is tropical convection often organized in clusters?
- what conditions favour and what intensifies the aggregation of convection?

Background

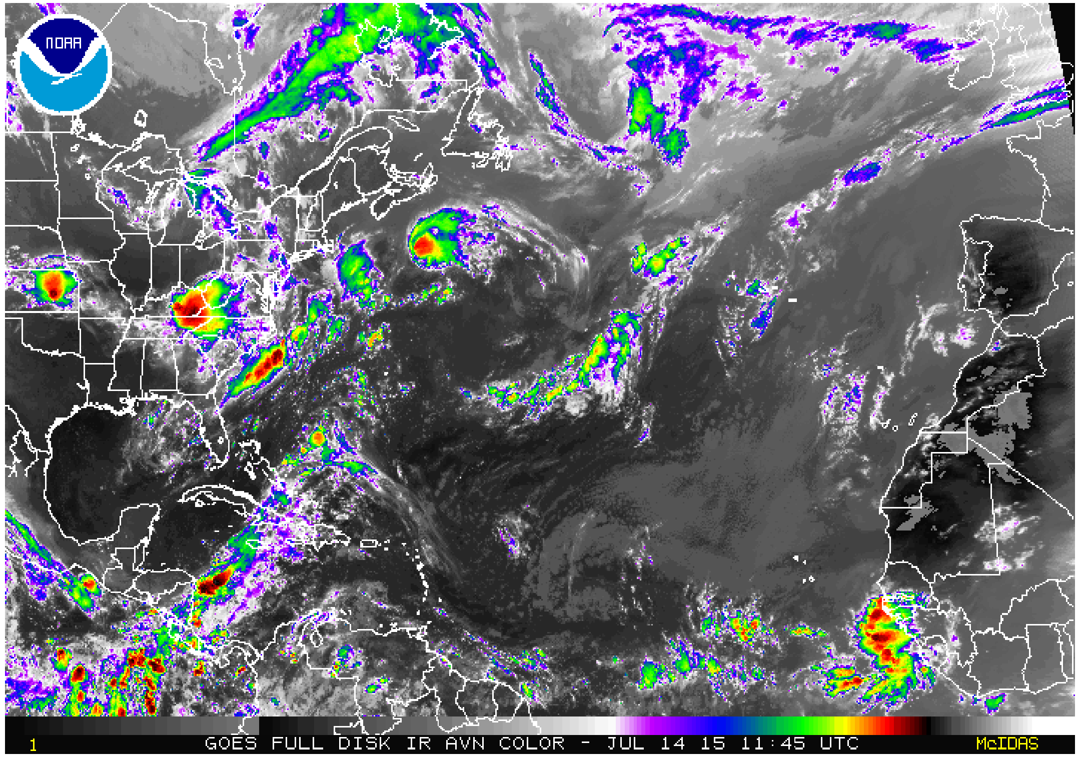
Understand tropical climate and its variability



- Option 1: observations
- Option 2: modelling

Background

Understand tropical climate and its variability



- Option 1: observations

  Field campaign with the appropriated meteorological instruments is very expensive

  The real atmosphere is complicated

- Option 2: modelling

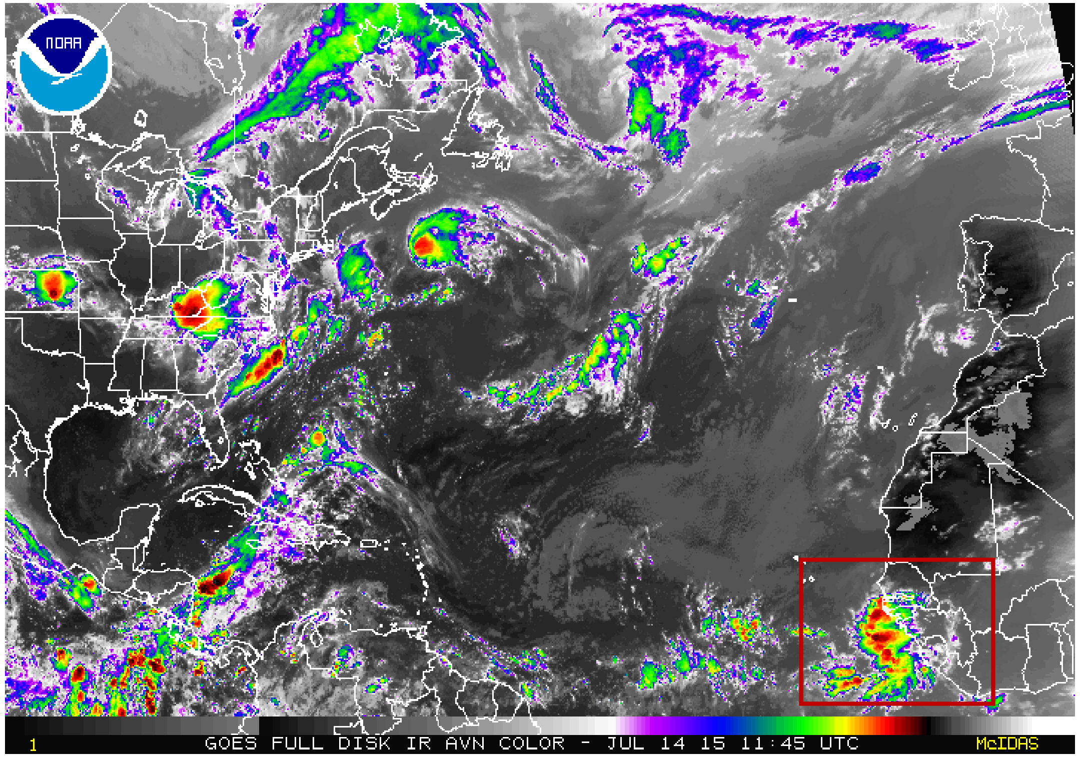
  Discrepancies between observations and numerical simulations

  Numerical models lack the representation of many real phenomena

Background

Understand tropical climate and its variability

- Option 2.1: modelling- Entire tropic
- Option 2.2: modelling- Limited area



Background

Understand tropical climate and its variability

- Option 2.1: modelling- Entire tropic

    individual convective cell ~ 100m-10 km

    large-scale circulation ~ 10 000 km

Large range of special scales between

convective cells and large-scale circulation:

Large domain CRMs (~ 10000km) or GCMs with very high horizontal resolution

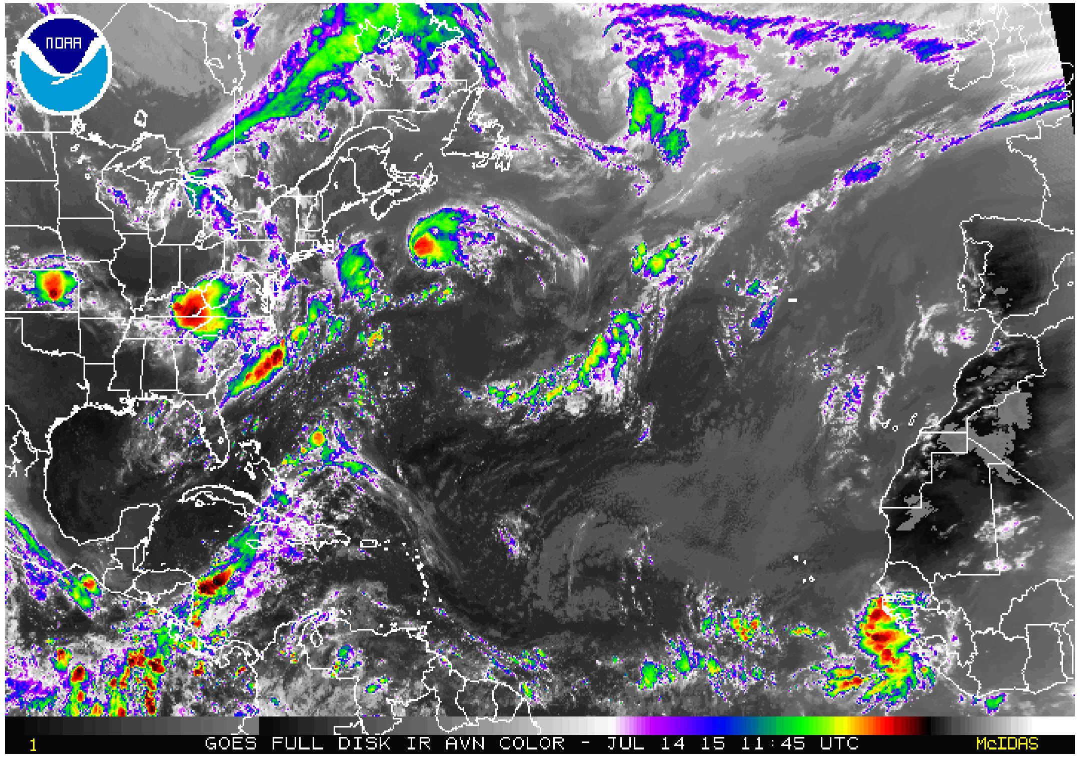
Large-domain, high-resolution experiments:

Cascade project *(Holloway et al., 2012)*

Computationally expensive

Alternative approach

GCMs, but convection is parameterized.



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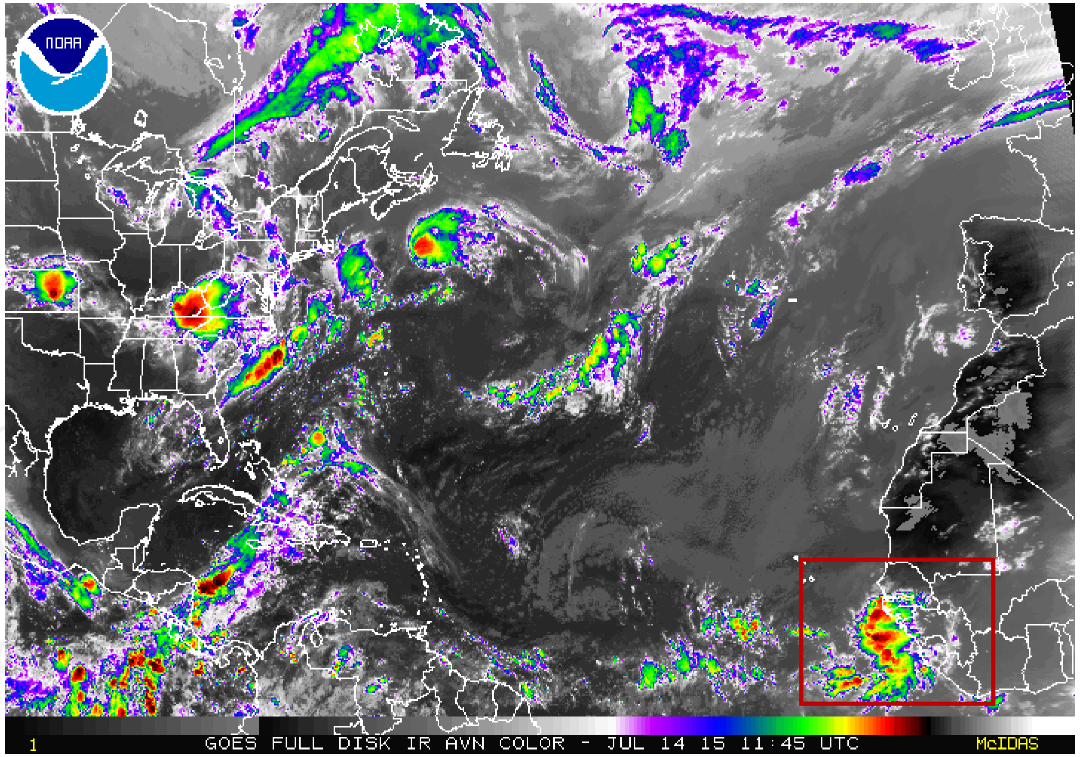
Understand tropical climate and its variability



- Option 2.1: modelling- Entire tropic

GCMs, but convection is parameterized.

Only few studies have simulated both convectio

Large domain CRMs (~ 10000km) or GCMs with

Large-domain, high-resolution experiments: Cas

- Option 2.2: modelling- Limited area

  Computationally cheap compared to option 2.1

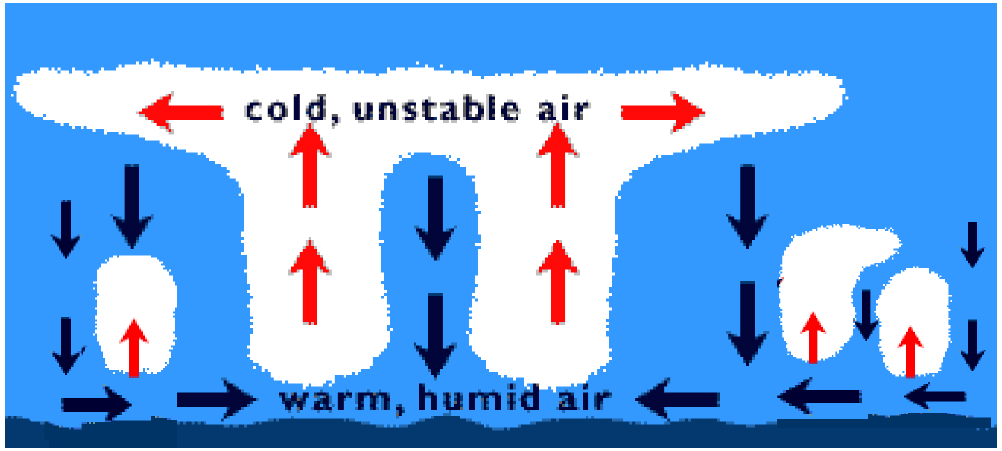
  CRMs are powerful tools to simulate tropical convection

Background

Understand tropical climate and its variability

- Option 2.2: modelling- Limited area
  - CRMs are often run in RCE mode

  - Convection generates T’
  - T’ drives a circulation
  - Cyclic BCs=winds turn inward
  - T’ cannot escape from the box



$$Evap - Precip = 0$$

and

$$LHF + SHF + Rad = 0$$

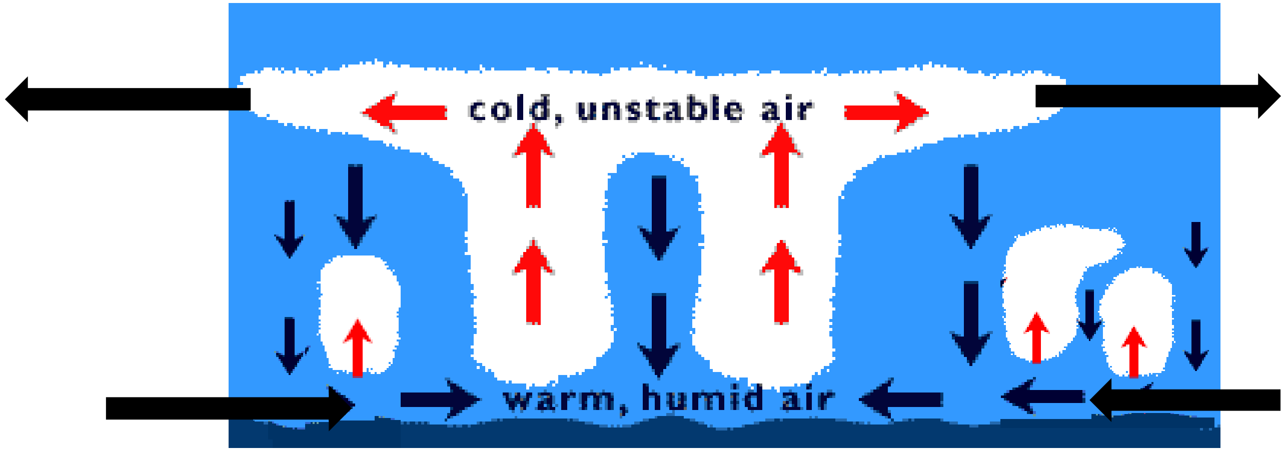
convection is disconnected from the influence of the large-scale flows

Background

Understand tropical climate and its variability

- Option 2.2: modelling- Limited area

In the real world we need the influence of the surrounding environment $(\bar{u}_e, \bar{v}_e, \bar{w}_e)$



$$Evap - Precip + \boldsymbol{M_e} = 0$$

And

$$LHF + SHF + Rad + \boldsymbol{H_e} = 0$$

The environmental large-scale flow $(\bar{u}_e, \bar{v}_e, \bar{w}_e)$ has been shown to modulate convection *(Daleu et al 2015)*

Representation of the large-scale flow in limited area models

Understand tropical climate and its variability

- Option 2.2.1: modelling- Limited area-Imposed $(\bar{u}_e, \bar{v}_e, \bar{w}_e)$

$(\bar{u}_e, \bar{v}_e, \bar{w}_e)$ idealized profiles or defined from observations

-Large horizontal temperature gradients over the tropics (compared to observations over the tropics)
-convection does not feedback on the large-scale flow

convection $(\bar{u}_e, \bar{v}_e, \bar{w}_e)$ **One-way interaction**

-The rain rate is to much constrained

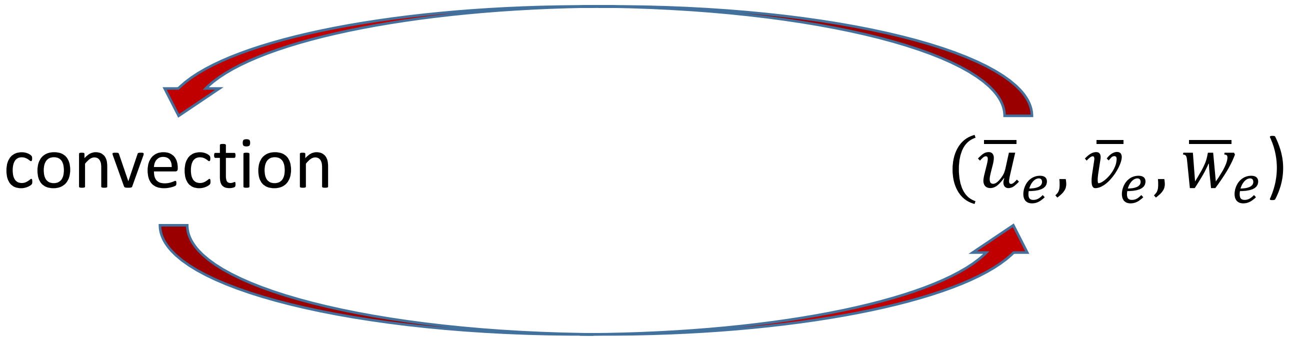
"what controls large-scale variations of tropical deep convection?"

Understand tropical climate and its variability

- Option 2.2.1: modelling- Limited area- Imposed $(\bar{u}_e, \bar{v}_e, \bar{w}_e)$

To understand "what controls large-scale variations of tropical deep convection?"

There is a need of frameworks which allow:



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Understand tropical climate and its variability

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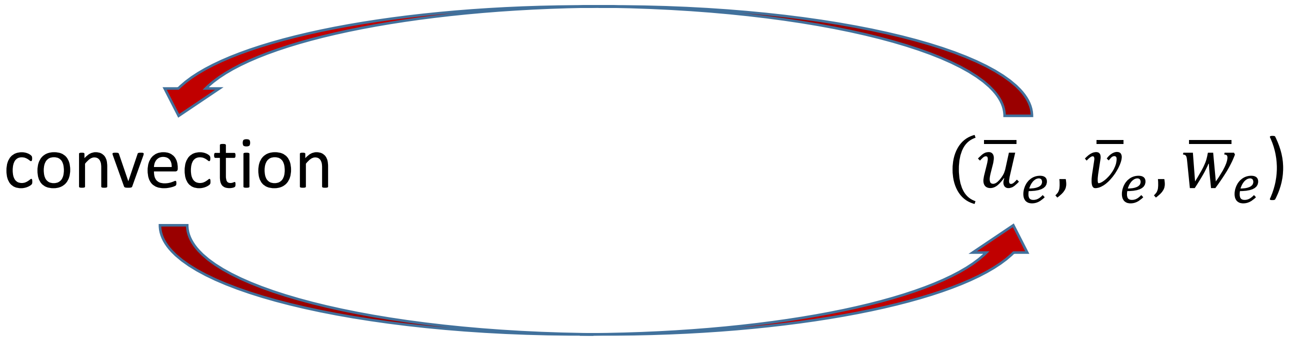

Two-way interaction

- Option 2.2.2: modelling- Limited area-parameterized $(\bar{u}_e, \bar{v}_e, \bar{w}_e)$

Let $(\bar{u}_e, \bar{v}_e, \bar{w}_e)$ be parameterized by the model itself

Background

Understand tropical climate and its variability

- Option 2.2.2: modelling- Limited area- parameterized $(\bar{u}_e, \bar{v}_e, \bar{w}_e)$

  Parameterization of the large-scale dynamics in SCMs and CRMs

  Simplified circulation models

  Parameterized environment using

- Weak-Temperature Gradient (WTG) / Spectral WTG (SWTG)
- Damped Gravity waves (DGW) / Weak Pressure gradient (WPG)

Motivation

Understand tropical climate and its variability

- Option 2.2.2: Modelling- Limited area- parameterized $(\bar{u}_e, \bar{v}_e, \bar{w}_e)$

  Parameterization of the large-scale dynamics in SCMs and CRMs

Different methods as well as different models of convection are used in different studies.

Previous results show **both similarities and discrepancies in model behaviour**

Can we attribute differences in the published results to either **large-scale parameterization method or model of convection?**

Time for an intercomparison !

GASS-WTG project

Proposed at the 1st Pan-GASS meeting in Sept 2012. Launched in February 2014.

- We performed a systematic comparison of the behaviour of a set of CRMs and SCMs under the same large-scale parameterization method; the WTG method and the DGW method
- We performed a systematic comparison of the WTG and DGW methods with a consistent implementation in a set of models with different physics and numerics.

Our points of interest are:

Q1: Can a large-scale circulation develop over uniform SST?

Q2: Can given SST and *T* profile support both a rainy and dry state, depending on initial moisture conditions?

Q3: How sensitive is a model (under the WTG/DGW method) to changes in the SST?

The weak temperature gradient

$$\frac{\partial\theta}{\partial t} + \vec{U}_h \,.\, \boldsymbol{\nabla}_h\theta + \mathrm{W}\frac{\partial\theta}{\partial z} = Q_d$$ (diabatic heating)

In the tropics, gravity waves redistribute $\boldsymbol{\theta}$'. Thus, $\boldsymbol{\nabla}_h\theta$ is very small

At equilibrium $\frac{\partial\theta}{\partial t} \sim 0$

The weak temperature gradient

$$\frac{\partial \theta}{\partial t} + \vec{U}_h . \boldsymbol{\nabla}_h \theta + W \frac{\partial \theta}{\partial z} = Q_d$$

Strict WTG method

Sobel and Bretherton (2000)

- $\frac{\partial \theta}{\partial t} = 0$
- $\boldsymbol{\nabla}_h \theta = \mathbf{0}$
- $W_{wtg} \frac{\partial \theta}{\partial z} = Q_d$

The weak temperature gradient

$$\frac{\partial \theta}{\partial t} + \vec{U}_h . \nabla_h \theta + W \frac{\partial \theta}{\partial z} = Q_d$$

Strict WTG method versus **Relaxed** WTG method

Sobel and Bretherton (2000)

- $\frac{\partial \theta}{\partial t}=0$
- $\nabla_h \theta = 0$
- $W_{wtg} = Q_d / \frac{\partial \theta}{\partial z}$

Raymond and zeng 2005

$\frac{\partial \theta}{\partial t}=0$

$\nabla_h \theta$ **is small**

$W_{wtg} = (\bar{\theta} - \theta_{Ref})/(\tau \frac{\partial \theta}{\partial z})$

τ is the adjustment time scale

Small but ≠ 0

The damped gravity wave

- Anelastic linearized perturbation equations of momentum:

$$\bar{\boldsymbol{\rho}}\frac{\partial u'}{\partial t} = -\frac{\partial p'}{\partial x} - \boldsymbol{\varepsilon}\bar{\boldsymbol{\rho}}u' \ , \ \bar{\boldsymbol{\rho}}\frac{\partial v'}{\partial t} = -\frac{\partial p'}{\partial y} - \boldsymbol{\varepsilon}\bar{\boldsymbol{\rho}}v'$$

- Continuity: $\frac{\partial \bar{\boldsymbol{\rho}} u'}{\partial x} + \frac{\partial \bar{\boldsymbol{\rho}} v'}{\partial y} + \frac{\partial \bar{\boldsymbol{\rho}} w'}{\partial z} = 0$

- Hydrostatic balance: $\frac{\partial p'}{\partial z} = \bar{\boldsymbol{\rho}}\, \mathrm{g}\frac{T'}{\bar{T}}$

The damped gravity wave

- Anelastic linearized perturbation equations of momentum:

$$\bar{\boldsymbol{\rho}}\frac{\partial u'}{\partial t} = -\frac{\partial p'}{\partial x} - \boldsymbol{\varepsilon}\bar{\boldsymbol{\rho}}u' \ , \ \bar{\boldsymbol{\rho}}\frac{\partial v'}{\partial t} = -\frac{\partial p'}{\partial y} - \boldsymbol{\varepsilon}\bar{\boldsymbol{\rho}}v'$$

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- Hydrostatic balance: $\frac{\partial p'}{\partial z} = \bar{\boldsymbol{\rho}}\,\mathrm{g}\frac{T'}{\bar{T}}$

- Solution, single horizontal wave number k: $\frac{\partial}{\partial z}\left\{\left(\frac{\partial}{\partial t} + \boldsymbol{\varepsilon}\right)\frac{\partial\bar{\boldsymbol{\rho}}w}{\partial z}\right\}=-k^2\,\frac{\bar{\boldsymbol{\rho}}g}{\bar{T}}T'$

- At equilibrium $\frac{\partial}{\partial t}\sim 0$ and $\frac{\partial}{\partial z}\left\{\boldsymbol{\varepsilon}\frac{\partial\bar{\boldsymbol{\rho}}w}{\partial z}\right\}=-k^2\,\frac{\bar{\boldsymbol{\rho}}g}{\bar{T}}T'$

WTG method

$$\overline{\omega}\frac{\partial\overline{\theta}_v^{Ref}}{\partial p}=\frac{\overline{\theta}_v-\overline{\theta}_v^{Ref}}{\tau}$$

DGW method

$$\frac{\partial}{\partial p}\left(\varepsilon\frac{\partial\overline{\omega}}{\partial p}\right)=\frac{k^2R_d}{\overline{p}^{Ref}}\left(\overline{T}_v-\overline{T}_v^{Ref}\right)$$

How do we implement the WTG and DGW methods

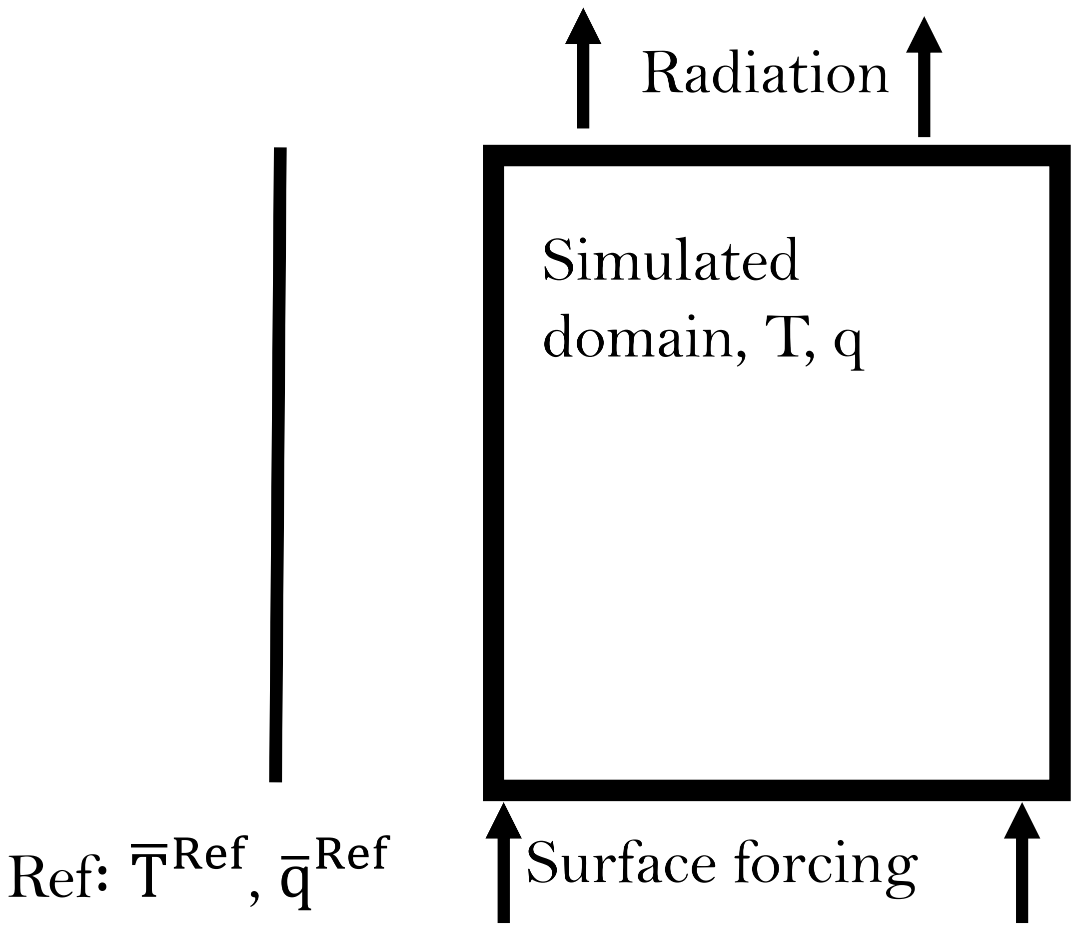
WTG method

$$\overline{\omega}\frac{\partial \overline{\theta}_v^{Ref}}{\partial p} = \frac{\overline{\theta}_v - \overline{\theta}_v^{Ref}}{\tau}$$

DGW method

$$\frac{\partial}{\partial p}\left(\varepsilon \frac{\partial \overline{\omega}}{\partial p}\right) = \frac{k^2 R_d}{\overline{p}^{Ref}}\left(\overline{T}_v - \overline{T}_v^{Ref}\right)$$

How do we implement the WTG and DGW methods



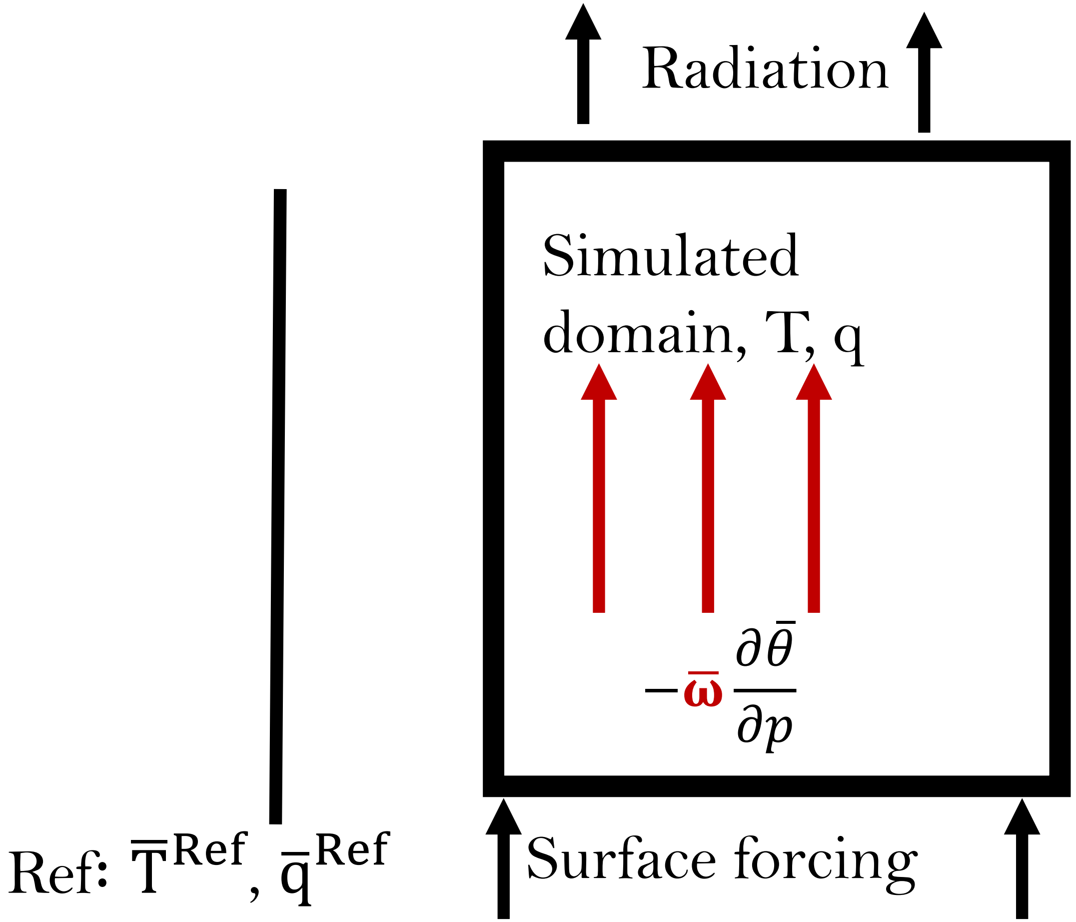
$\overline{\omega}$ is used to advect $\boldsymbol{\theta}$ and water vapour

WTG method

DGW method

$$\overline{\omega}\frac{\partial \overline{\theta}_v^{Ref}}{\partial p}=\frac{\overline{\theta}_v-\overline{\theta}_v^{Ref}}{\tau}$$

$$\frac{\partial}{\partial p}\left(\varepsilon\frac{\partial \overline{\omega}}{\partial p}\right)=\frac{k^2 R_d}{\overline{p}^{Ref}}\left(\overline{T}_v-\overline{T}_v^{Ref}\right)$$



Temperature tendencies due to $\overline{\omega}$

$$\frac{\partial \theta}{\partial t}=-\overline{\omega}\frac{\partial \bar{\theta}}{\partial p}$$

$\overline{\omega}$ cancels $\boldsymbol{\theta}'$ via adiabatic lifting

WTG method

DGW method

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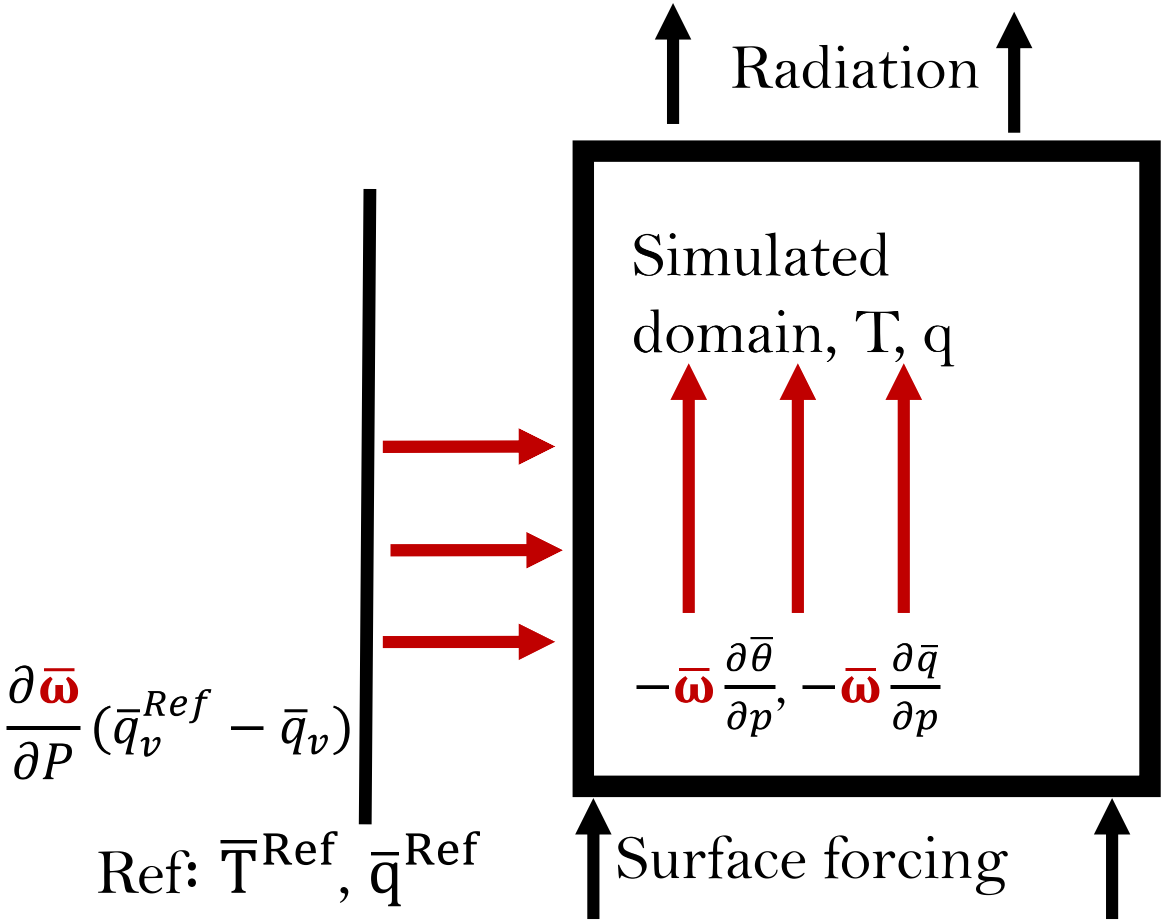
$$\bar{\omega}\frac{\partial\bar{\theta}_v^{Ref}}{\partial p}=\frac{\bar{\theta}_v-\bar{\theta}_v^{Ref}}{\tau}$$

$$\frac{\partial}{\partial p}\left(\varepsilon\frac{\partial\bar{\omega}}{\partial p}\right)=\frac{k^2R_d}{\bar{p}^{Ref}}\left(\bar{T}_v-\bar{T}_v^{Ref}\right)$$

Temperature tendencies due to $\bar{\omega}$

$$\frac{\partial\theta}{\partial t}=-\bar{\omega}\frac{\partial\bar{\theta}}{\partial p}$$

$\bar{\omega}$ cancels T’ via adiabatic lifting



Moisture tendencies due to $\bar{\omega}$

$$\frac{\partial q_v}{\partial t}=-\bar{\omega}\frac{\partial\bar{q}_v}{\partial p}+\max\left(\frac{\partial\bar{\omega}}{\partial P},0\right)\times(\bar{q}_v^{Ref}-\bar{q}_v)$$

Inflow only

WTG method

DGW method

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$$\bar{\omega}\frac{\partial\bar{\theta}_v^{Ref}}{\partial p}=\frac{\bar{\theta}_v-\bar{\theta}_v^{Ref}}{\tau}$$

- $\tau = 3\text{hr}$
- Prescribed BL top=850 hPa
- Apply WTG from BL top to 100hPa
- $\overline{\omega}(p > 850\ hP)$= linear interpolation in pressure from $\overline{\omega}(p = 850\ hPa)$ to 0 at the surface

$$\frac{\partial}{\partial p}\left(\varepsilon\frac{\partial\bar{\omega}}{\partial p}\right)=\frac{k^2 R_d}{\bar{p}^{Ref}}\left(\bar{T}_v-\bar{T}_v^{Ref}\right)$$

$\varepsilon(constant) = 1/day$ and

$k = 10^{-6}/km$

apply DGW from the surface to 100hPa

$\overline{\omega}(100\ hPa)$ = $\overline{\omega}(surface) = 0$

no BL treatment

Models that participate in this project

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	Models	Contributor	Dimension	Horizontal size(km)	Horizontal res (km)
Cloud-Resolving Models	WRF	S. Wang	3D	190×190	2×2
	MesoNH	P. Peyrille	3D	150×150	3×3
	LaRC_CRM	A. Cheng	2D	256	4
	MNTCMv3	M. J. Herman	2D	200	1
	LEMv2.4	C. Daleu	2D	128	0.5
Single-Column Models	**LMDzA**	**G. Bellon**	-	-	-
	LMDzB	**G. Bellon**	-	-	-
	GISS_SCM	D. Kim	-	-	-
	APRv6	G. Bellon	-	-	-
	UMv7.8	**C. Daleu**	-	-	-
	EC-Earthv1	**P. Siebesma**	-	-	-
	EC-Earthv3	**P. Siebesma**	-	-	-

-Time independent SST

-Fixed radiative cooling through most of the free troposphere

Q1: Can a large-scale circulation develop over uniform SST?

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WTG and DGW simulations over uniform SST

- The Ref state of each model is defined with profiles from the RCE simulation of that model.
- For each model, we performed WTG and DGW simulations with the SST of the Ref state.
- The WTG and DGW simulations are initialized with profiles from the corresponding Ref state.
- Note that RC is fixed throughout most of the troposphere

The reference state and the simulated column have same characteristics at time=0

Q1: Can a large-scale circulation develop over uniform SST?

To evaluate the WTG and DGW simulations

We used $\Omega = \frac{\int \bar{\omega} dp}{\int dp}$ and the ratio $\mathbf{P/P_{Ref}}$

$\mathbf{P}$: mean precipitation in the simulated column

$\mathbf{P_{Ref}}$: mean precipitation of the Ref state.

A simulation reproduces the RCE conditions to a good approximation if:

$\mathbf{0.9 < P/P_{Ref} < 1.1}$ and $-0.4 \times 10^{-2} < \Omega\left(\frac{\text{Pa}}{\text{s}}\right) < 0.4 \times 10^{-2}$

The large-scale circulation is significant if:

large-scale ascent: $\Omega\left(\frac{\mathbf{Pa}}{\mathbf{s}}\right) > \mathbf{0.4 \times 10^{-2}}$ and $\mathbf{P/P_{Ref} > 1.1}$

large-scale descent: $\Omega\left(\frac{\mathbf{Pa}}{\mathbf{s}}\right) < \mathbf{-0.4 \times 10^{-2}}$ and $\mathbf{P/P_{Ref} < 0.9}$

Uniform SST (K)= 298, 300, 302

WTG and DGW simulations which produce $\mathbf{0.9 < P/P_{Ref}}$<1.1 and $|\Omega| < \mathbf{0.4 \times 10^{-2}}$ **Pa/s**

Under both WTG and DGW, regardless of the SST:

●WRF and ◁ LMDzA

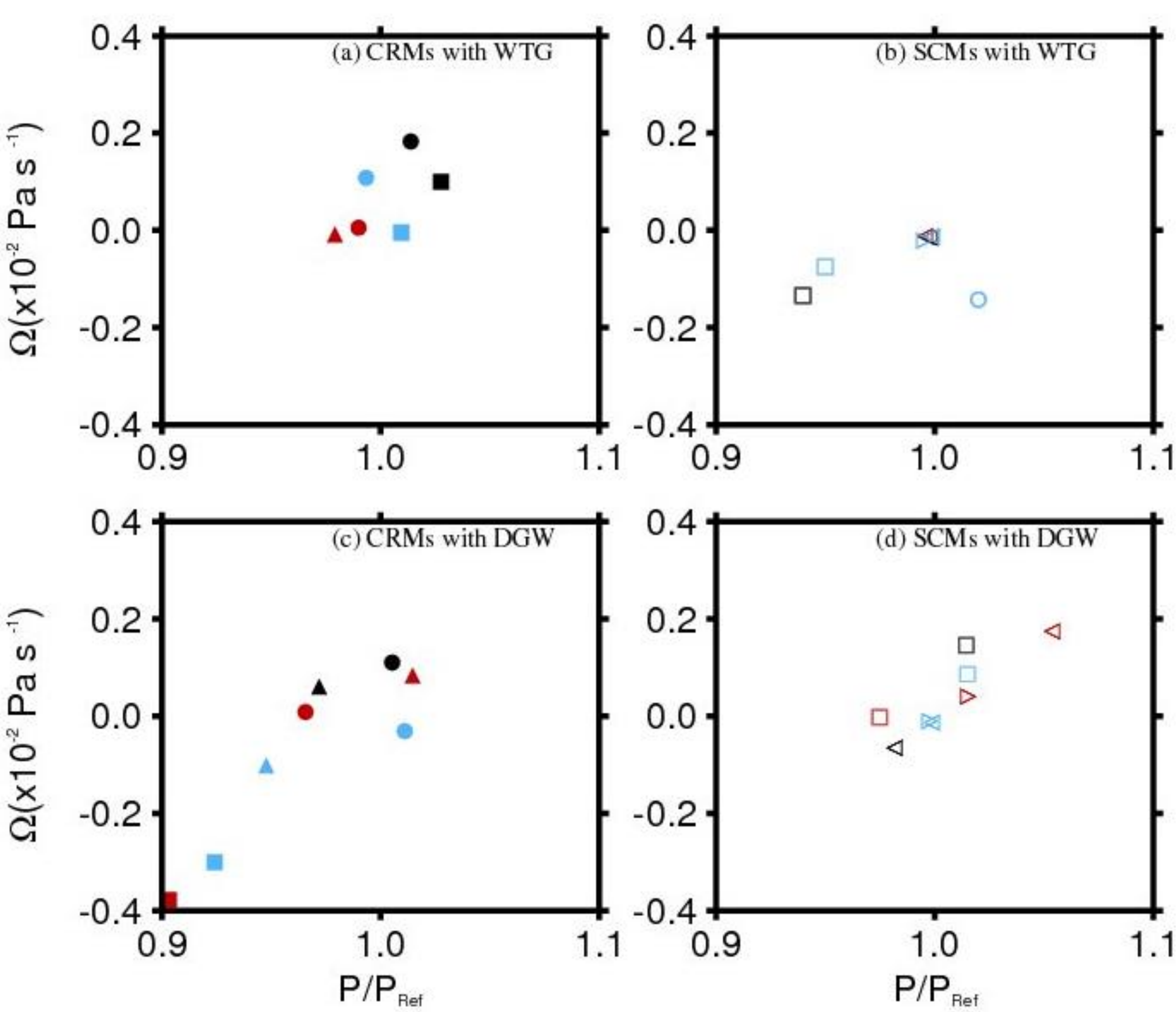
Under WTG/DGW, for some SSTs only:

▲MesoNH, ■NMTCMv3

▷LMDzB, ○GISS-SCM and

□ EC-Earthv3

Not for model like ☆ UMv7.8

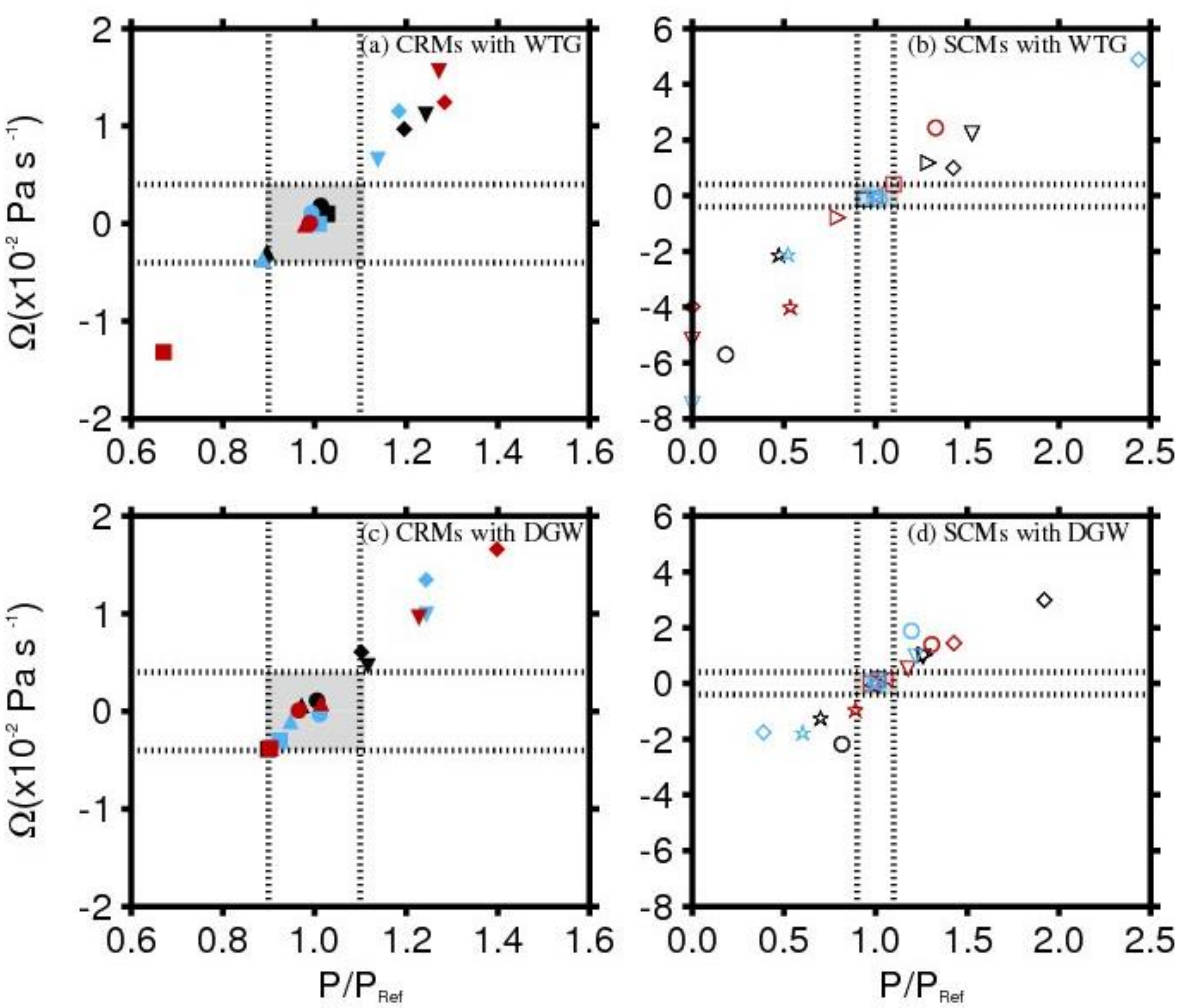


Q1: Can a large-scale circ develop over uniform SST? **YES**

SSTs of 298, 300, 302 K

Symbol definitions

- ● WRF
- ▲ MesoNH
- ◆ LaRC_CRM
- ■ NMTCMv3
- ▼ LEMv2.4
- ◁ LMDzA
- ▷ LMDzB
- ○ GISS_SCM
- ▽ ARPv6
- ☆ UMv7.8
- ◇ EC-Earthv1
- □ EC-Earthv3



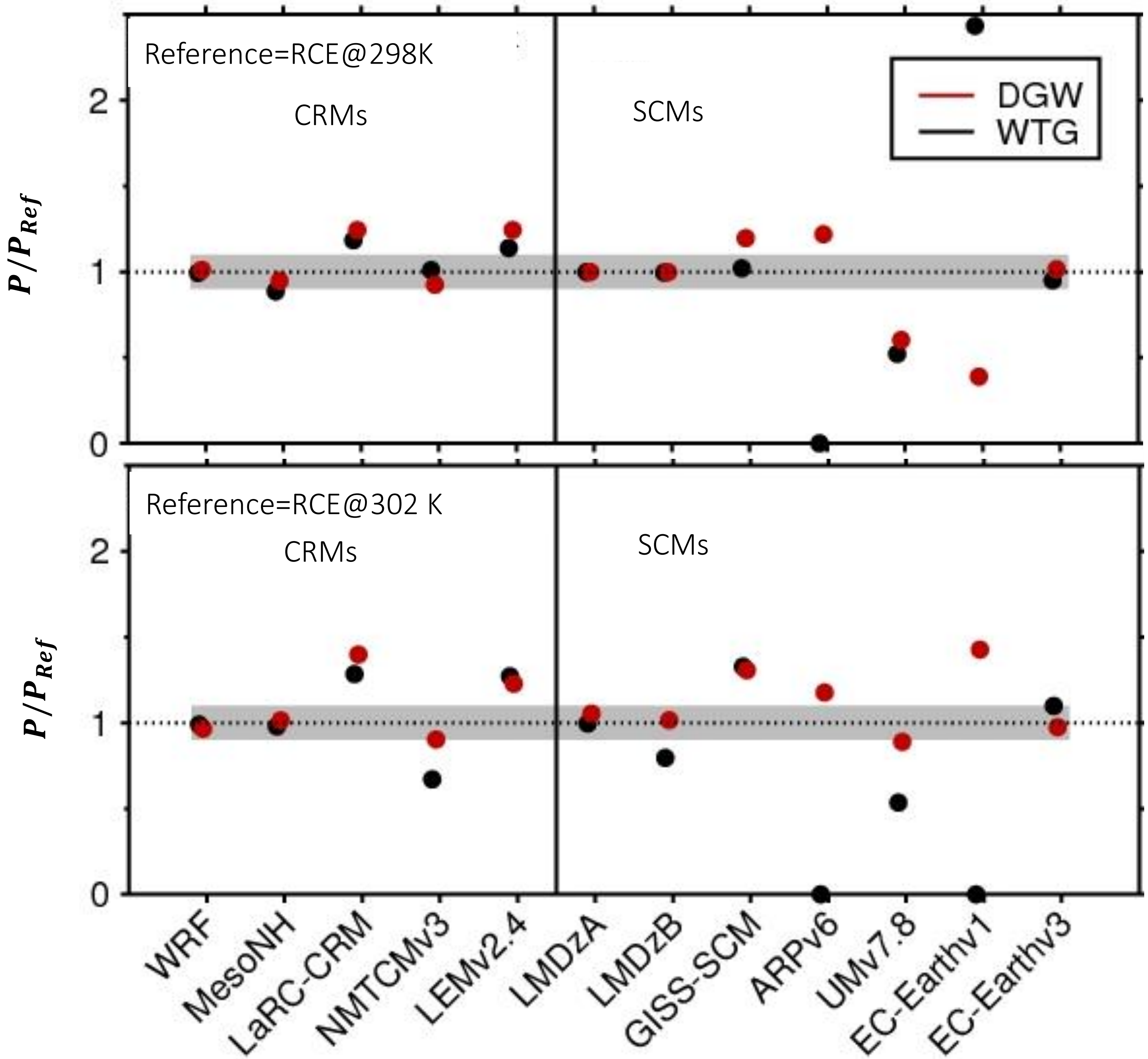
CRMs show a fairly linear relationship between P and Ω. SCMs show deviations from this relationship

Q1: Can a large-scale circ develop over uniform SST? YES

Grey areas indicates $0.9 < P/P_{Ref}$ <1.1

SCMs display a much wider ranges of behaviour

- Some SCMs under the WTG can produce **P=0** mm/day (e.g. ARPv6) within an individual SCM, a
- WTG sim and a corresponding DGW sim can produce different signs of the circulation (e.g., EC-Earthv1)



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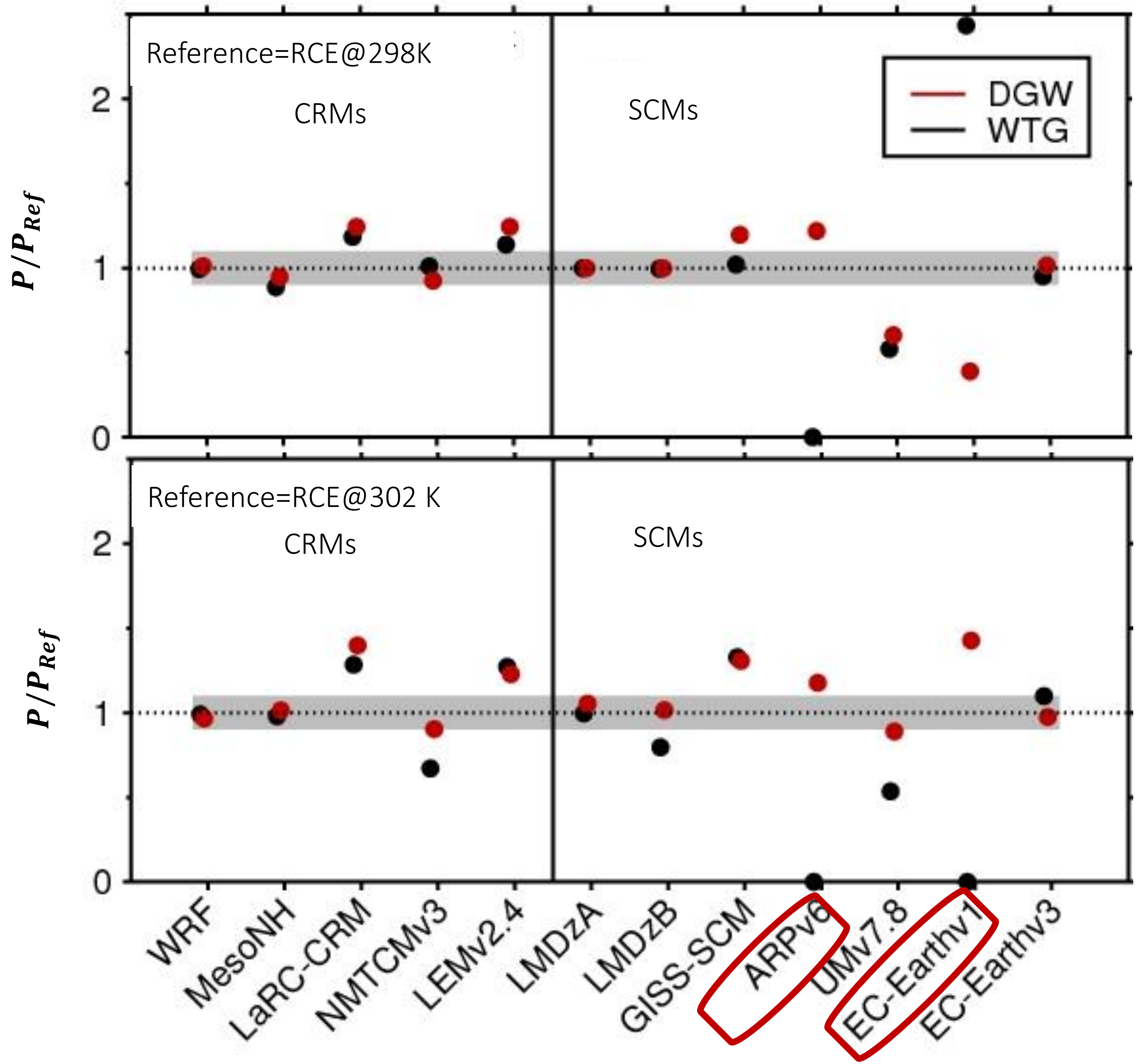

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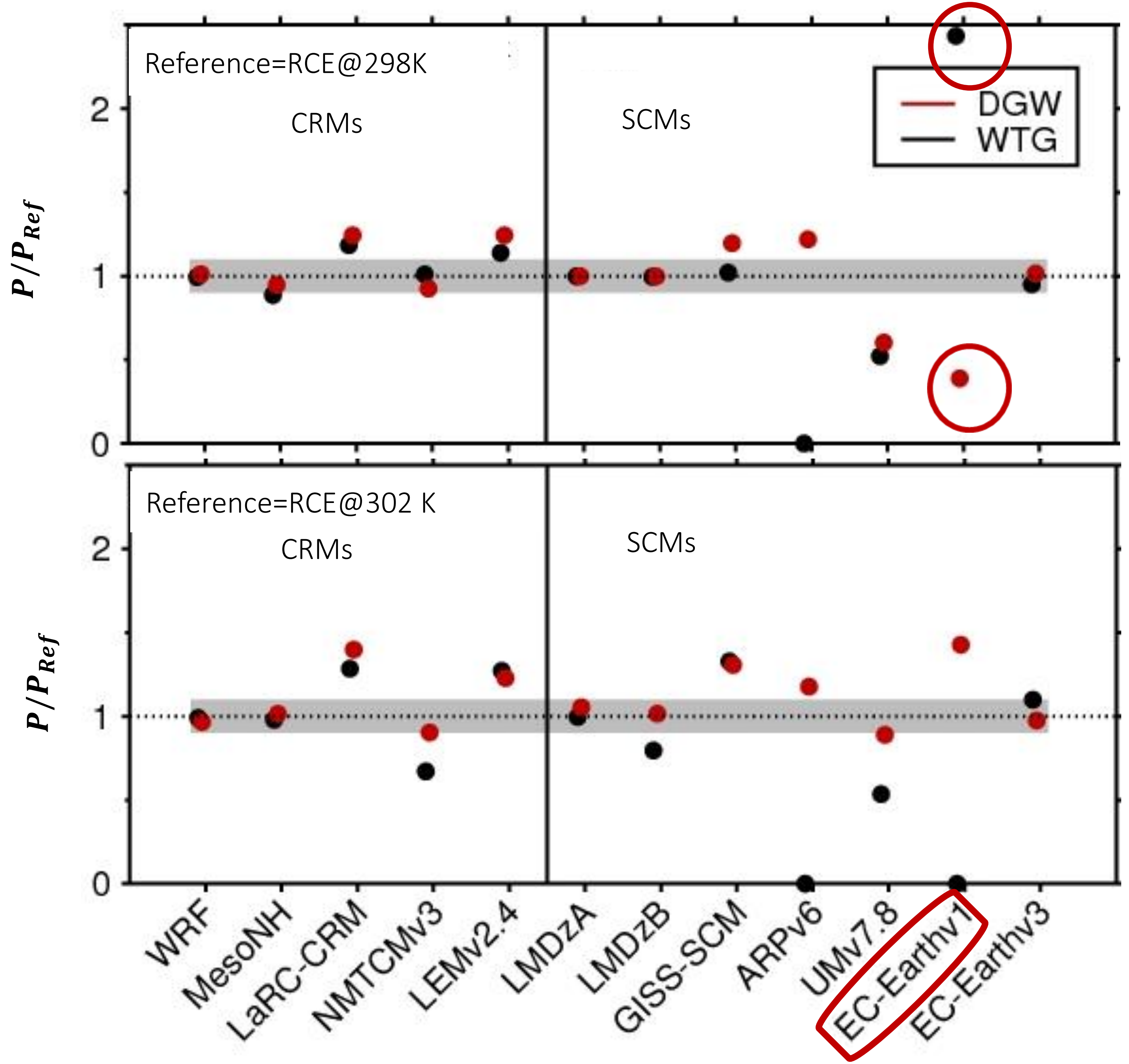
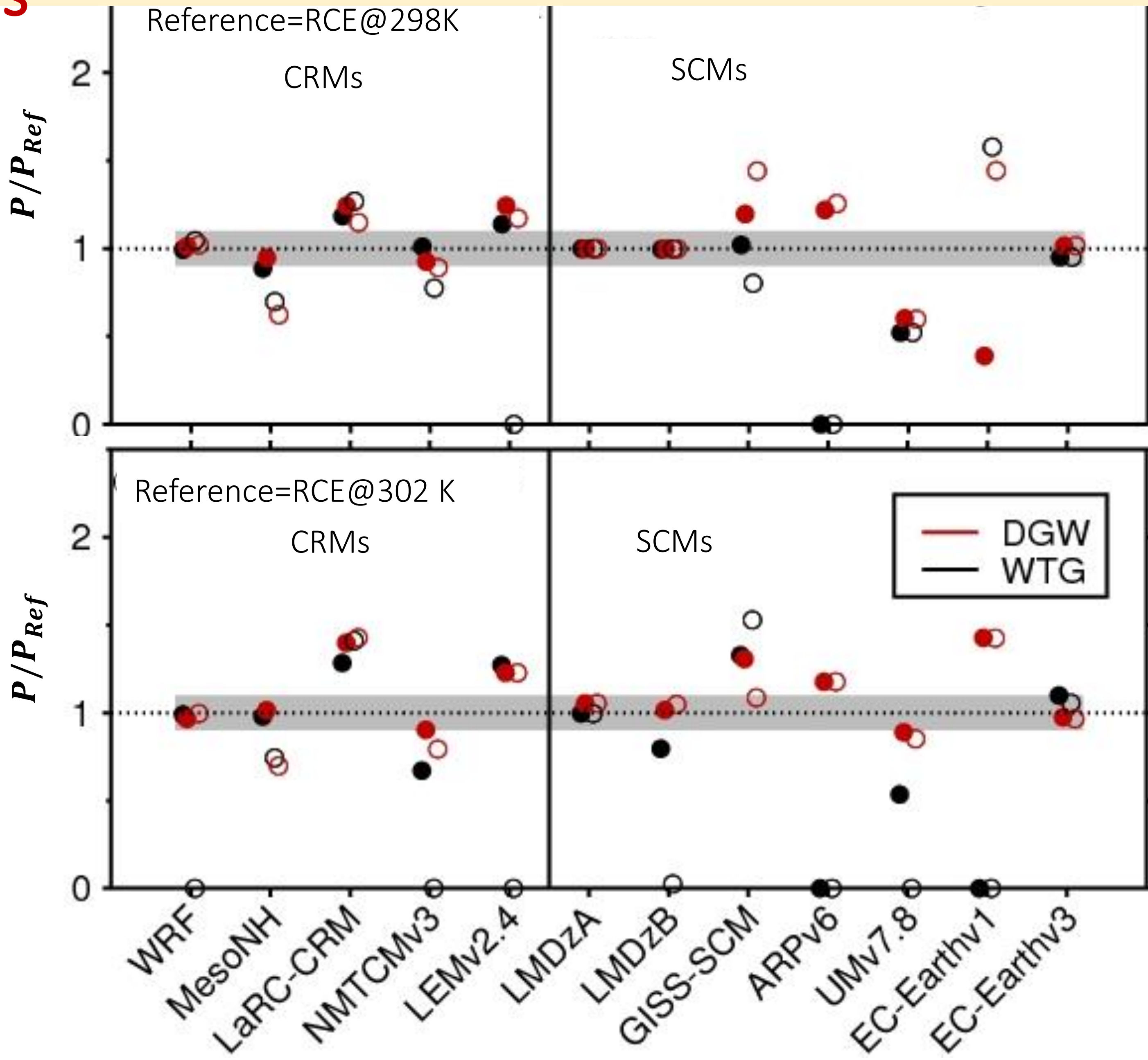


Q2: Can given SST and *T* profile support both a rainy and dry state, depending on initial moisture? Yes

Sensitivity to the initial moisture conditions

- Initialized with RH of the RCE state (full circles)
- Initialized with 0% RH (open circles)



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1-Some models are **not sensitive** to the initial RH

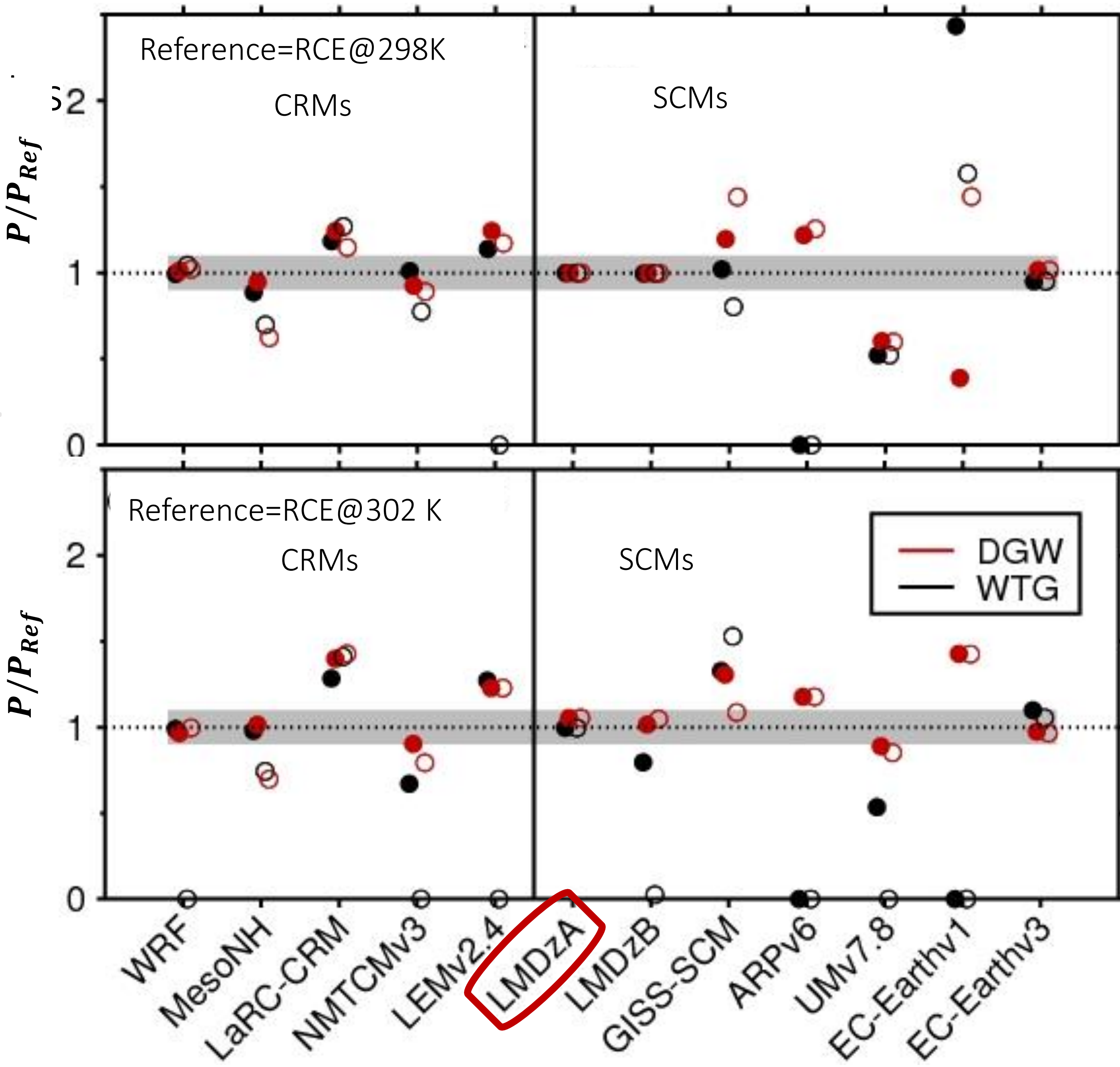
2-Some models can sustain two distinct precipitating equilibrium states (MesoNH).

3-Some models produce enhanced precip from the initially dry moisture

4-DWG simulations always produce precipitating equilibrium states.

5-In contrast to the DGW, some models under the WTG can sustain a state with zero precip or a state with persistent, precipitating convection depending of the initial RH. Here after called multiple equilibria (ME).

6-ME is more likely at higher SST.



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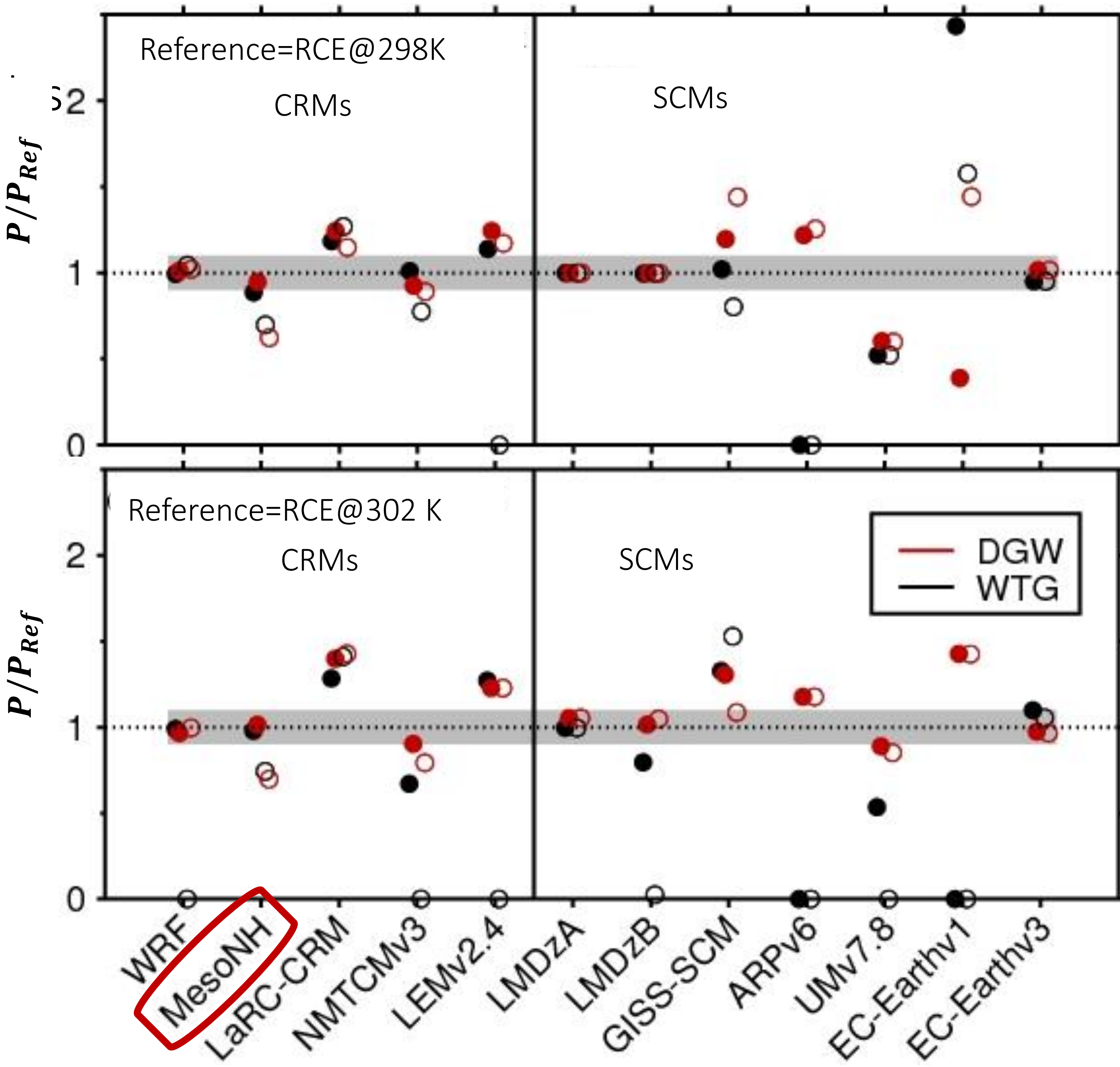

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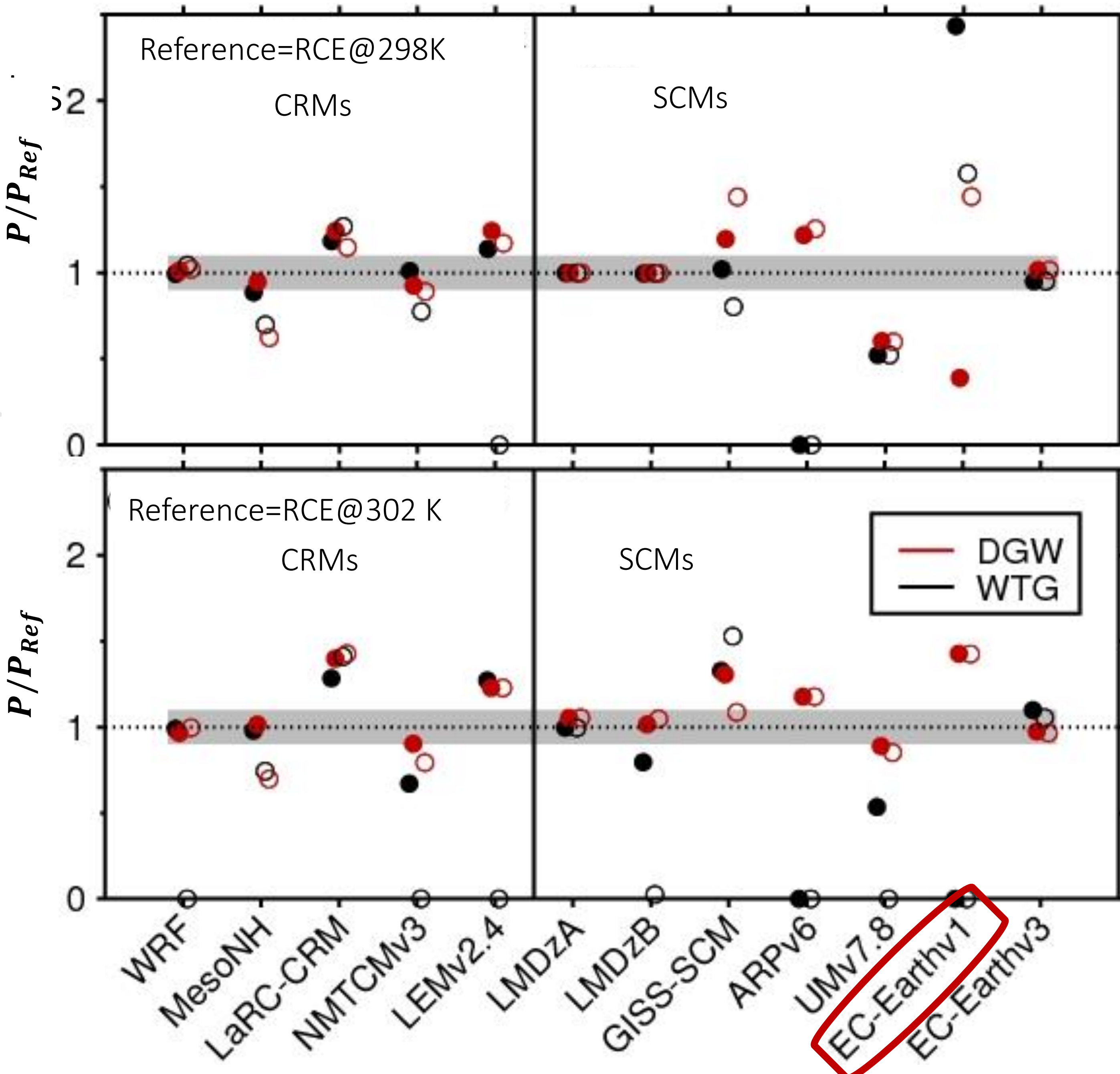

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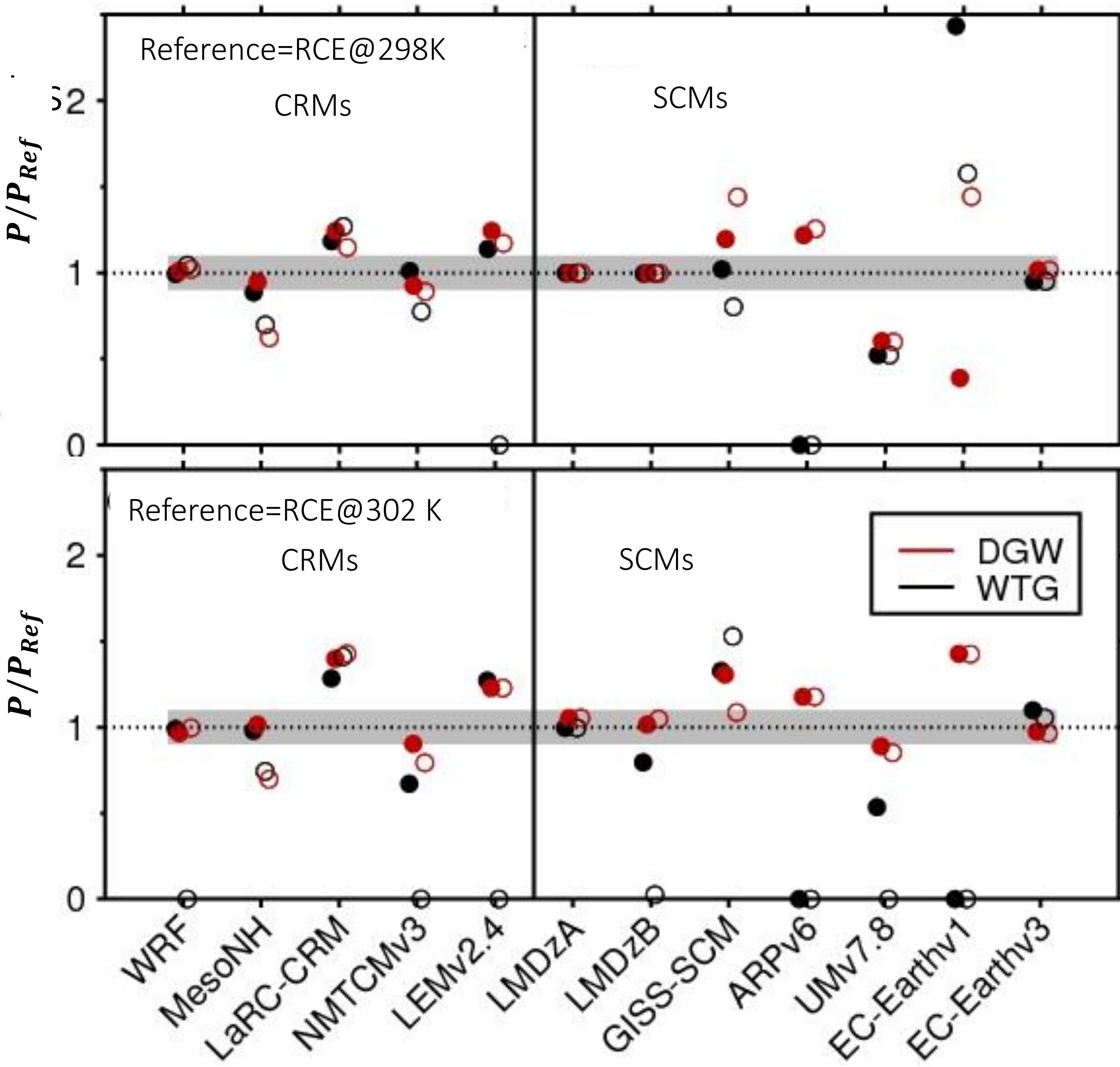
2-Some models can sustain two distinct precipitating equilibrium states (MesoNH).

3-Some models produce **enhanced precip from the initially dry moisture**

4-DWG simulations always produce precipitating equilibrium states.

5-In contrast to the DGW, some models under the WTG can sustain a state with zero precip or a state with persistent, precipitating convection depending of the initial RH. Here after called multiple equilibria (ME).

6-ME is more likely at higher SST.



Can given SST and *T* profile support both a rainy and dry state, depending on initial moisture? **Yes**

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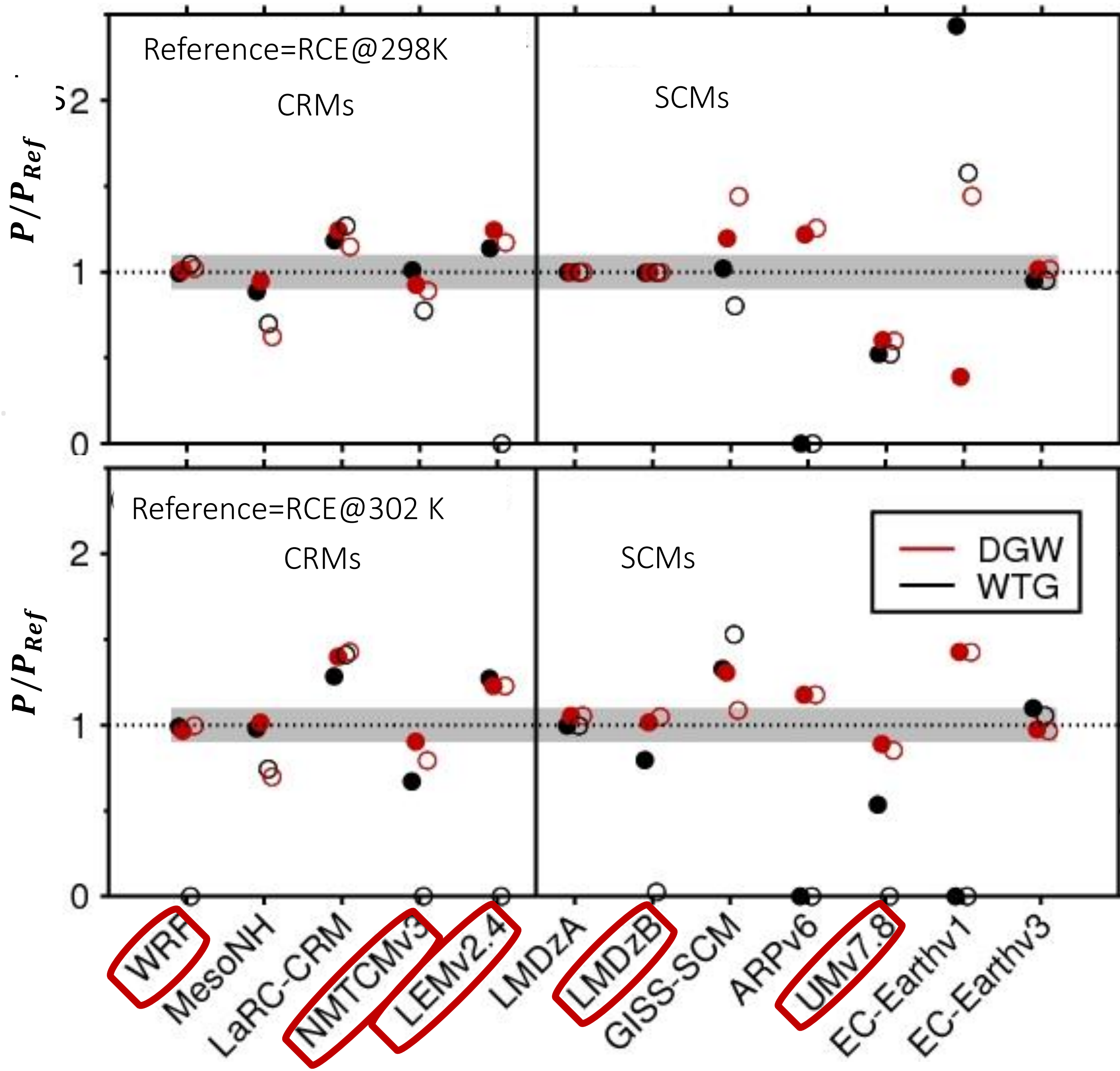

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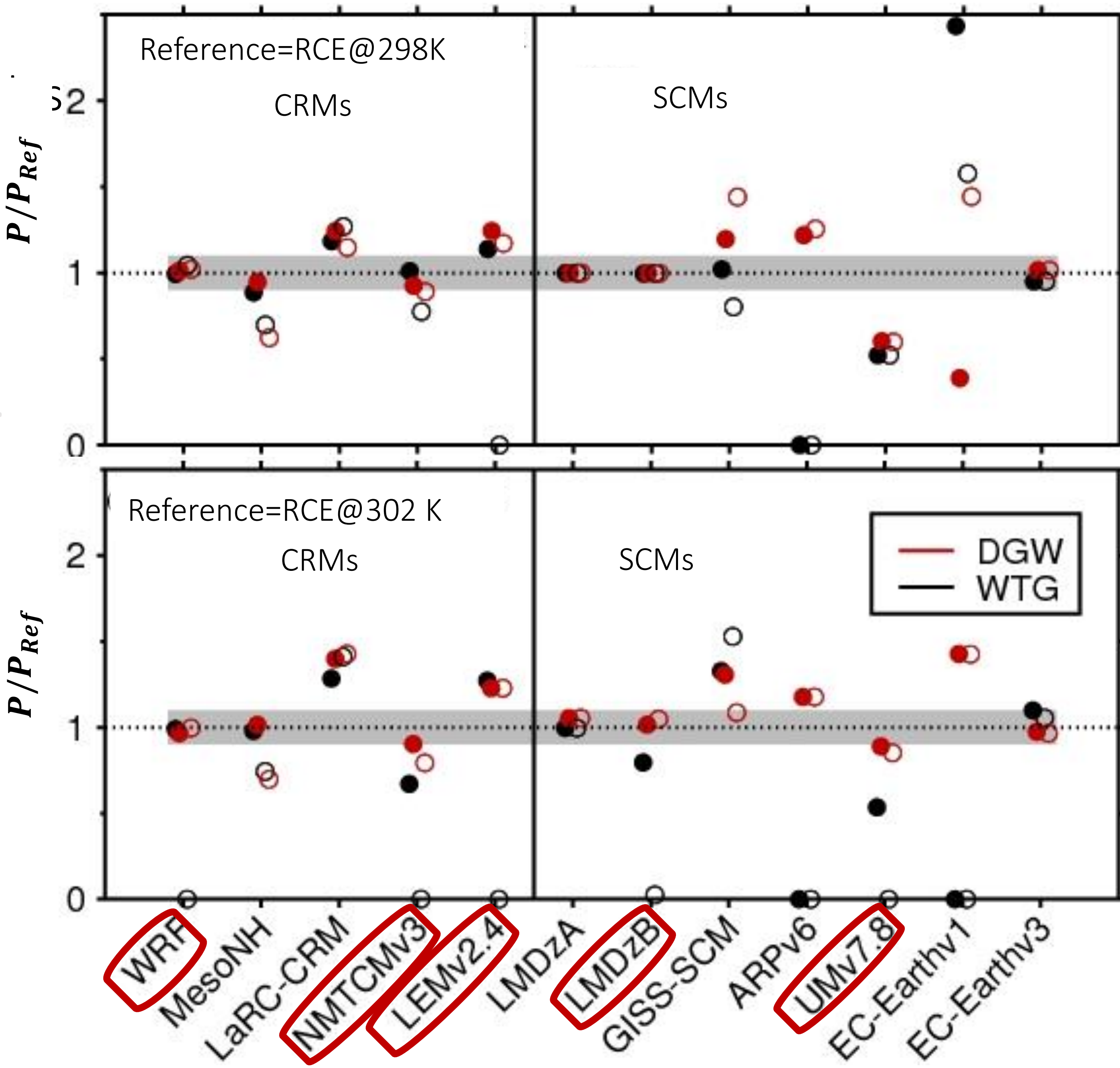

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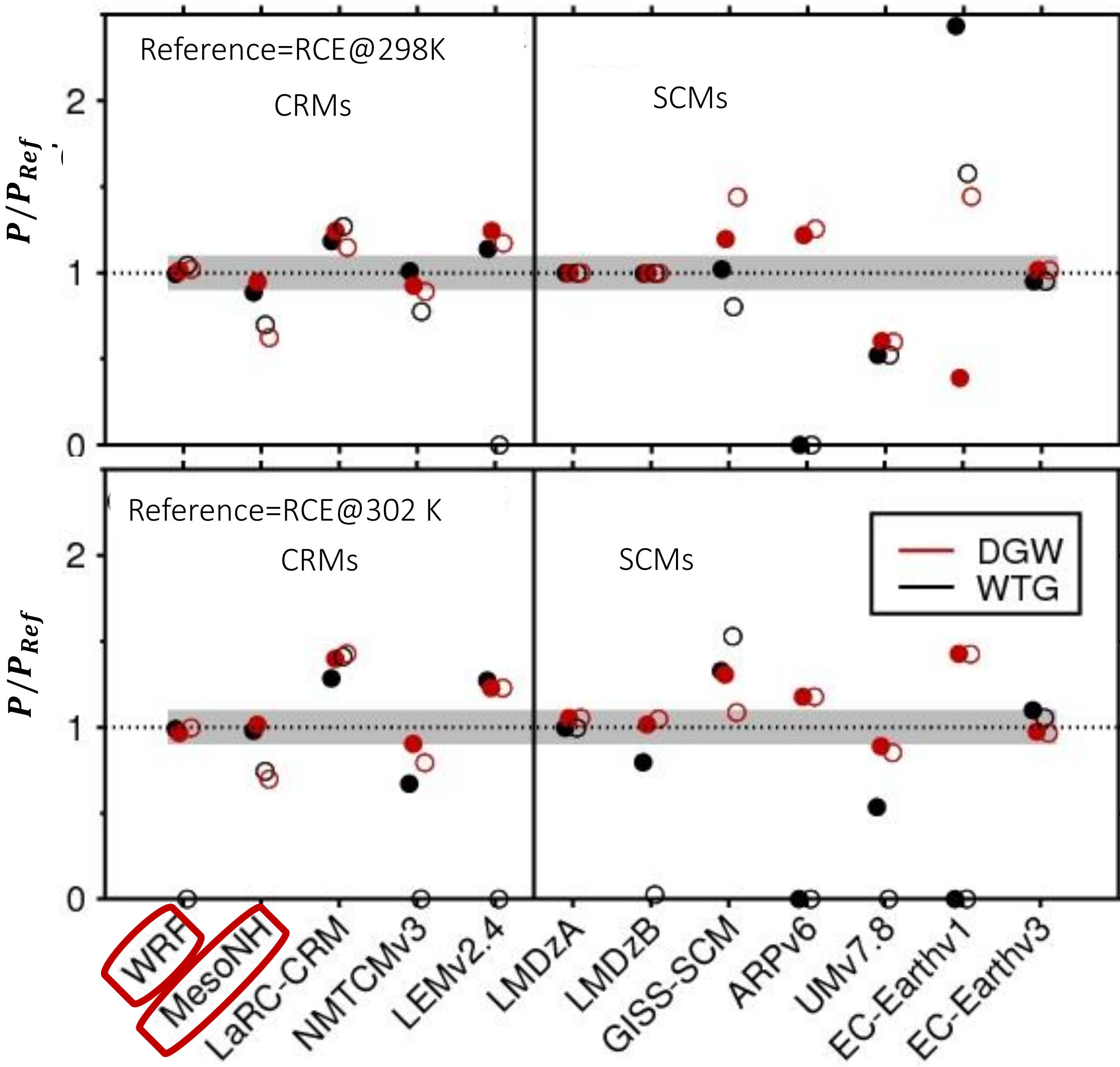
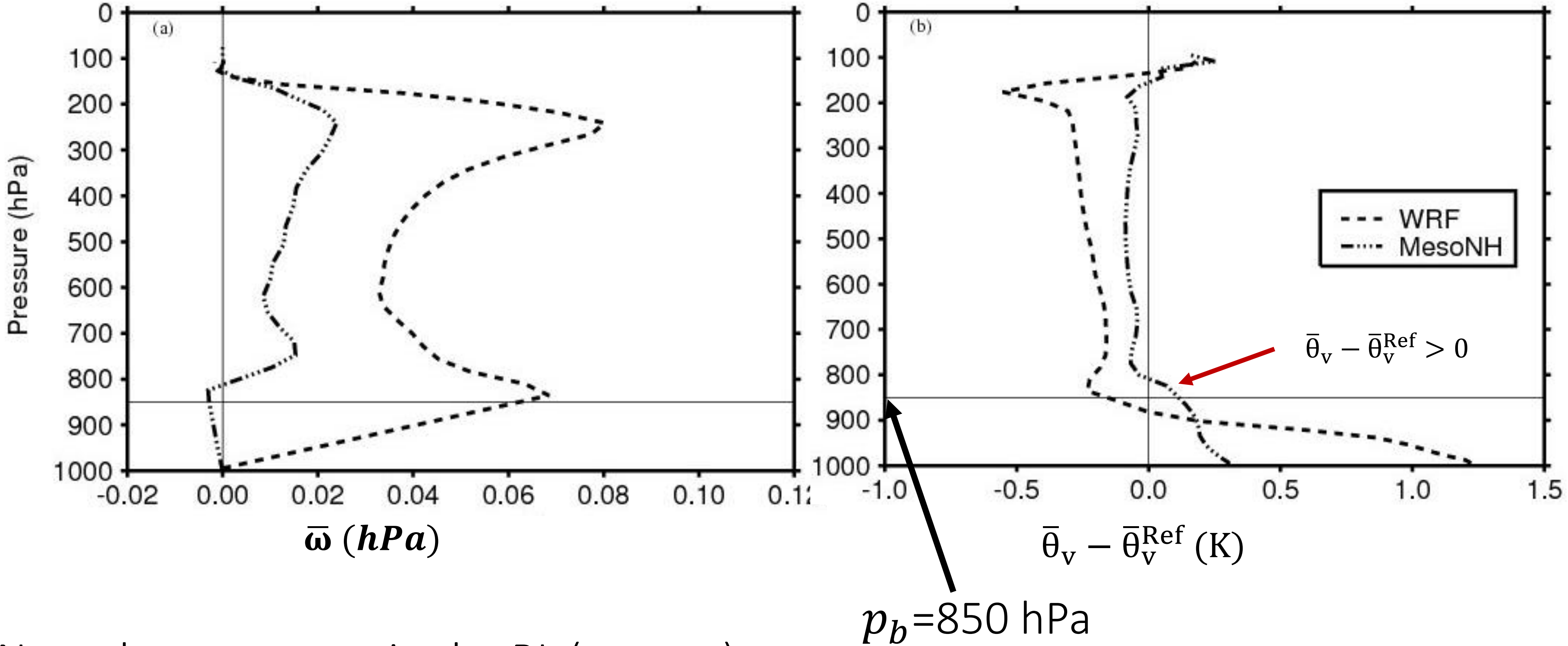
Under the WTG, some models sustain ME, while other models do not

why ?



Sensitivity to initial moisture conditions

Over a uniform SST=302 K, we compared the initially dry WTG simulations of WRF and MesoNH



Note the treatment in the BL ($p > p_b$):
The sign of $\overline{\theta}_v - \overline{\theta}_v^{Ref}$ at the 1st model level above p_b determines the sign of $\overline{\omega}$ in the BL.

A large-scale ascent is produced by MesoNH, consistent with $\overline{\theta}_v - \overline{\theta}_v^{Ref} > 0$
A large-scale descent is produced by WRF whilst $\overline{\theta}_v - \overline{\theta}_v^{Ref} > 0$

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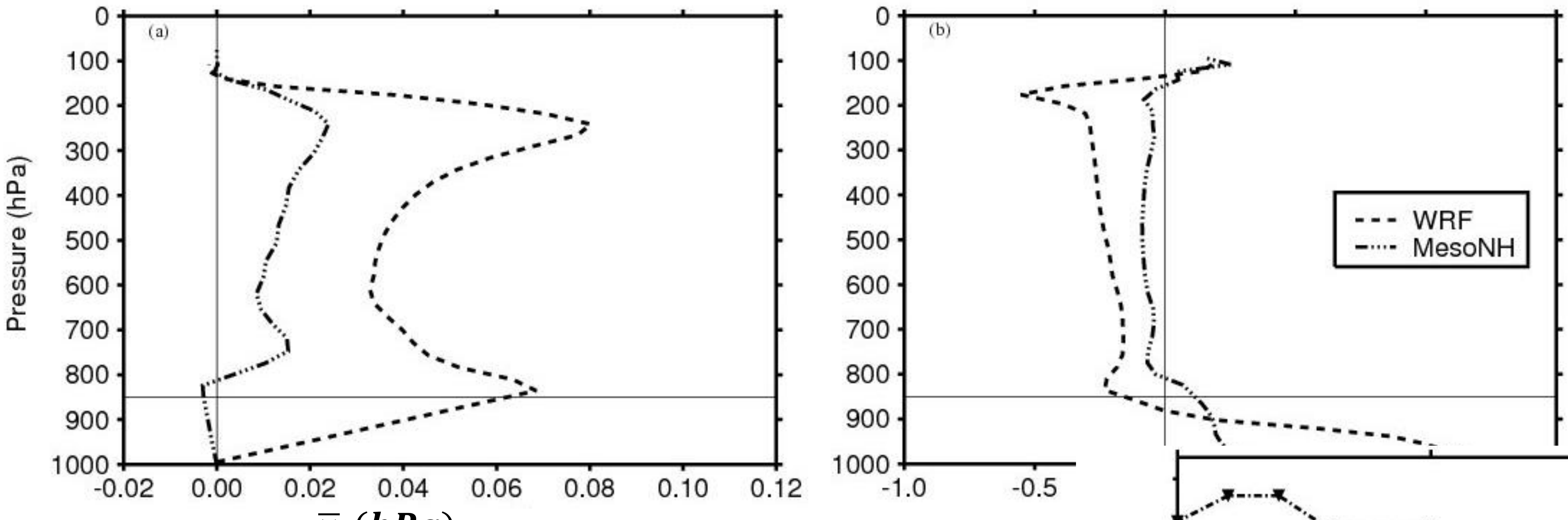
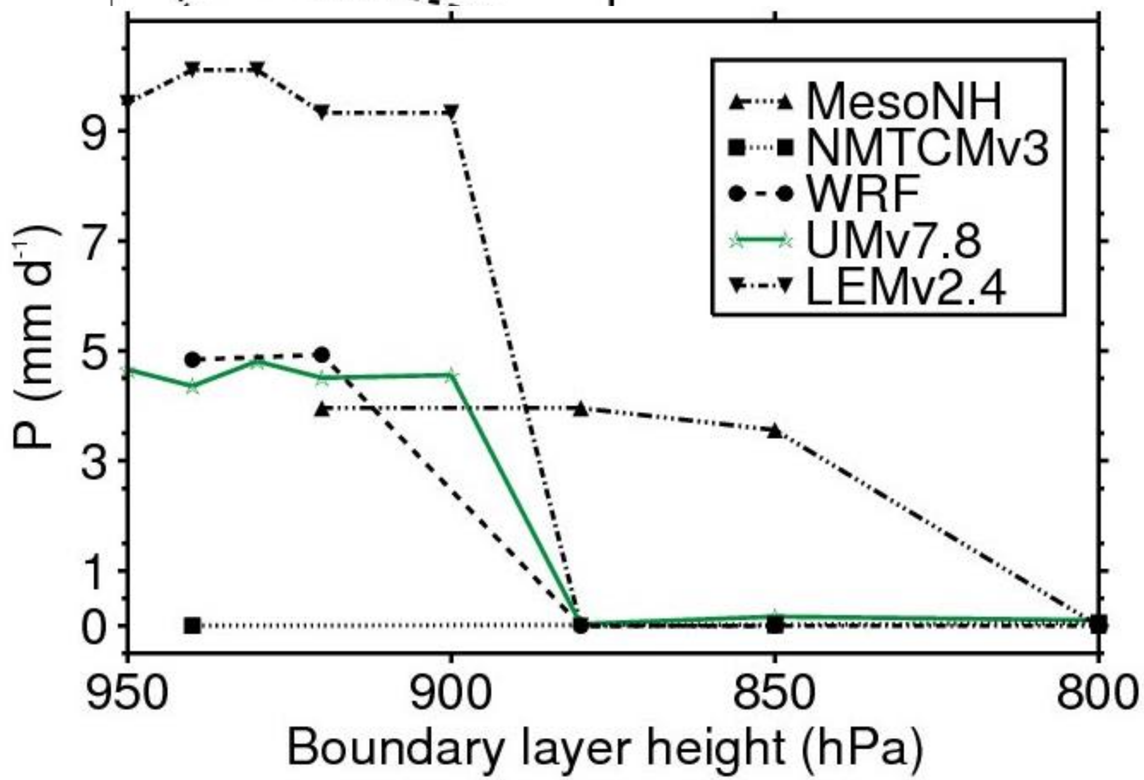
ME and sensitivity to the PBL depth



$\overline{\omega}$ (hPa)



Uniform SST=302K and initial RH=0%

p_0=800, 850, 900, 920, 930, 940 and 950 hPa

MesoNH with p_0=800hPa produces P=0 mm/d

A shallower BL can result in P$\neq 0$ (except NMTCMv3)

ME are also sensitive to other WTG parameters

ME and sensitivity to the PBL depth

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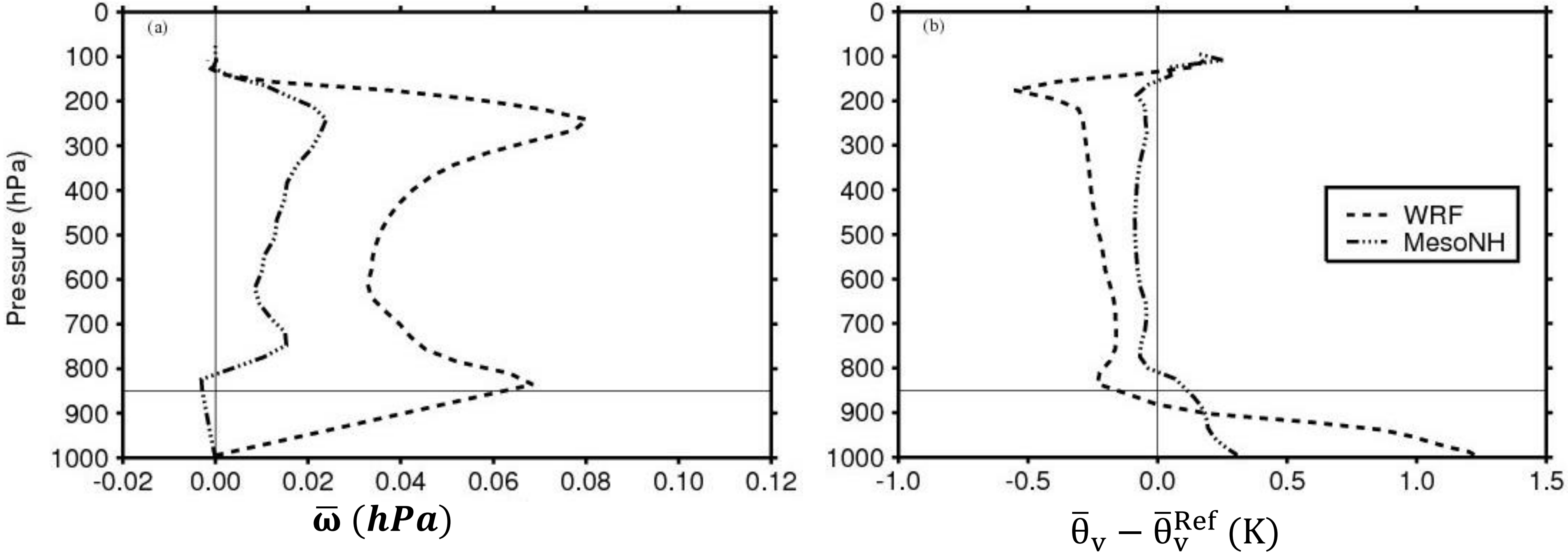


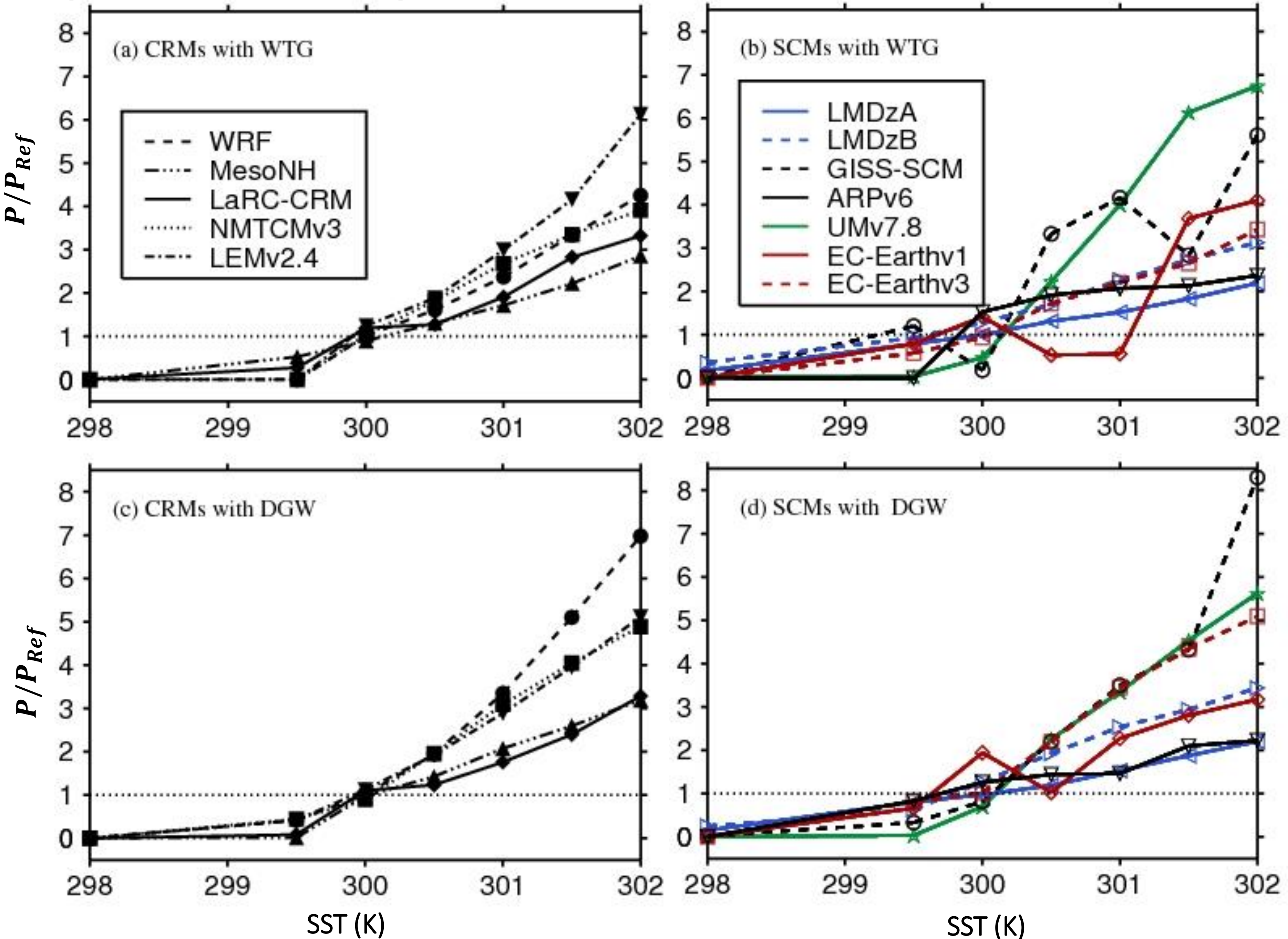
Uniform SST=302K and initial RH=0% and BL top=850 hPa

- A shallower BL can result in P$\neq 0$ (except NMTCMv3)
- $\overline{\mathbf{w}}\frac{\partial\overline{\theta}_v^{Ref}}{\partial z}=\frac{\overline{\theta}_v-\overline{\theta}_v^{Ref}}{\tau}f(z)$, $f(z)=\sin(\boldsymbol{\pi} z/H)$ can result in P$\neq 0$ (LEMv2.4, UMv7.8)
- A longer WTG adjustment time scale ($\boldsymbol{\tau}$) can result in P$\neq 0$ (LEMv2.4, UMv7.8 and LMDzB)

ME is very sensitive to the details of the implementation of the WTG method

How sensitive is a model (under the WTG/DGW method) to changes in the SST?

Ref state= RCE at 300K.
SSTs=298, 299.5, 300, 300.5,301, 301.5, and 302 K



How sensitive is a model (under the WTG/DGW method) to changes in the SST?

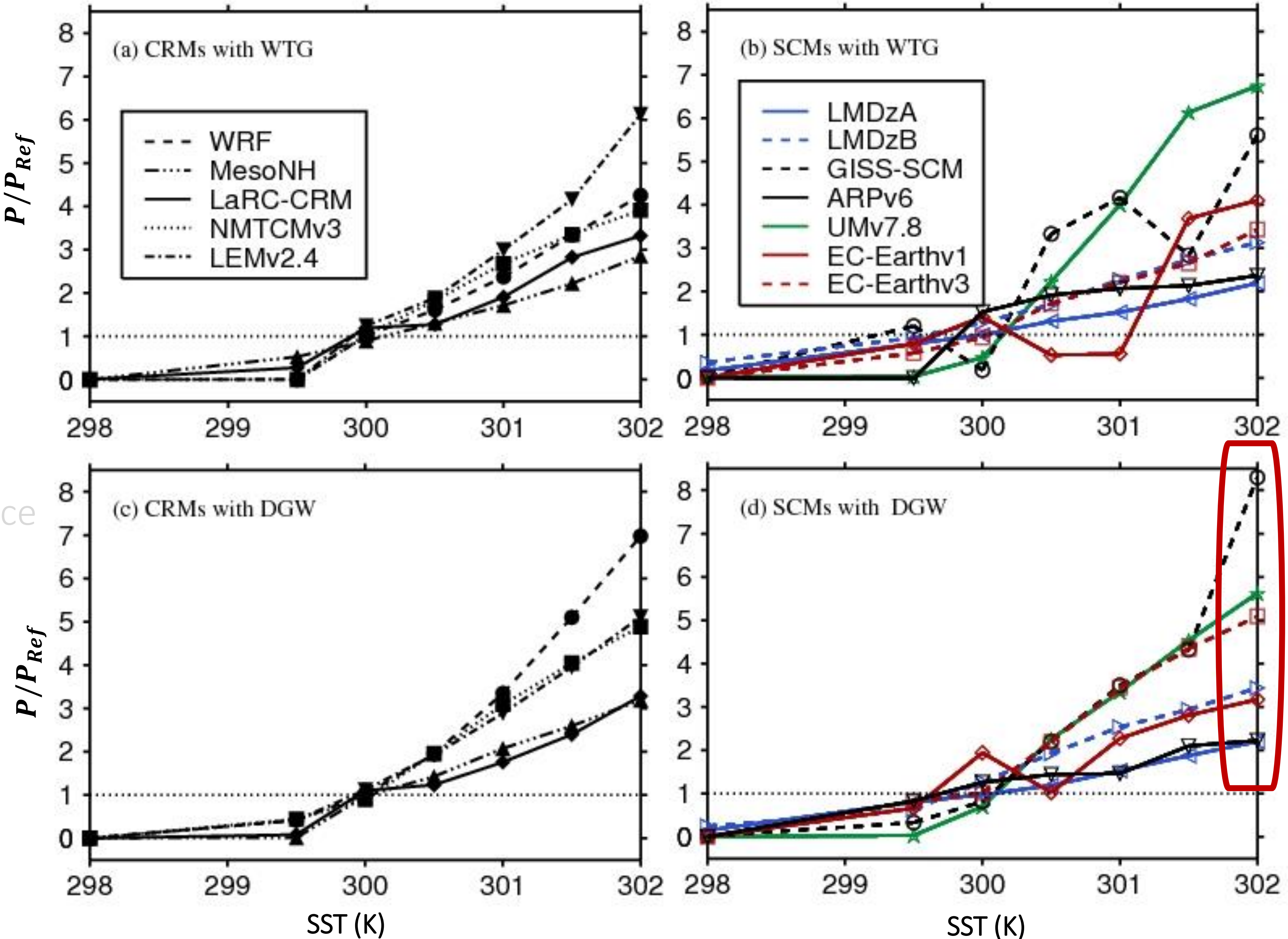
Ref state= RCE at 300K.
Various SSTs

1-Under the same large-scale parameterization method models produce different solutions

2-within an individual model a WTG and corresponding DGW simulations can produce different solutions (e.g., EC-Earthv1)

3-for all CRMs, P increase Non-linearly with SST

4-SCMs shows sensitivity Of P to the SST which is not is not always monotonic (e.g.,., GISS-SCM).



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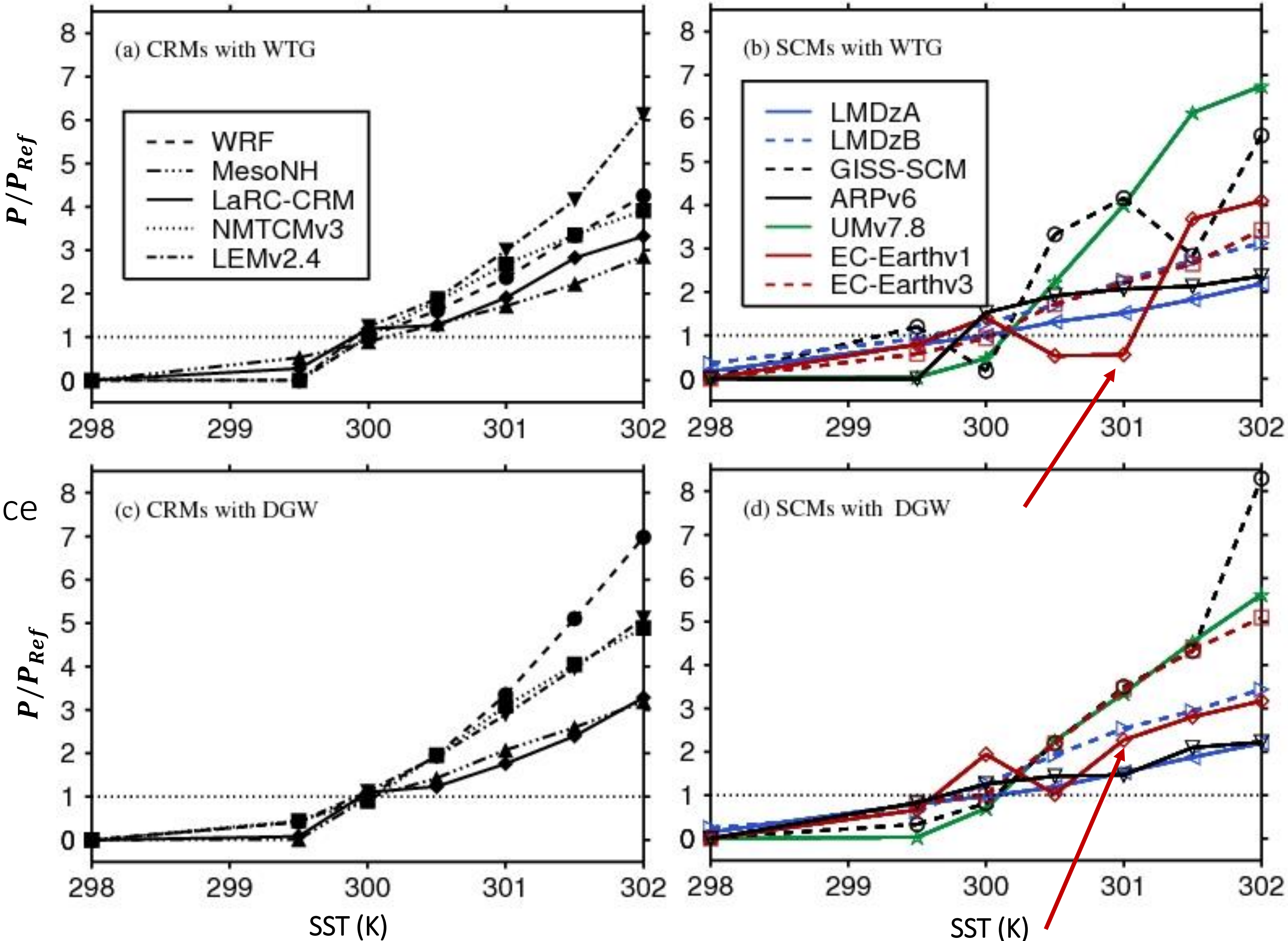

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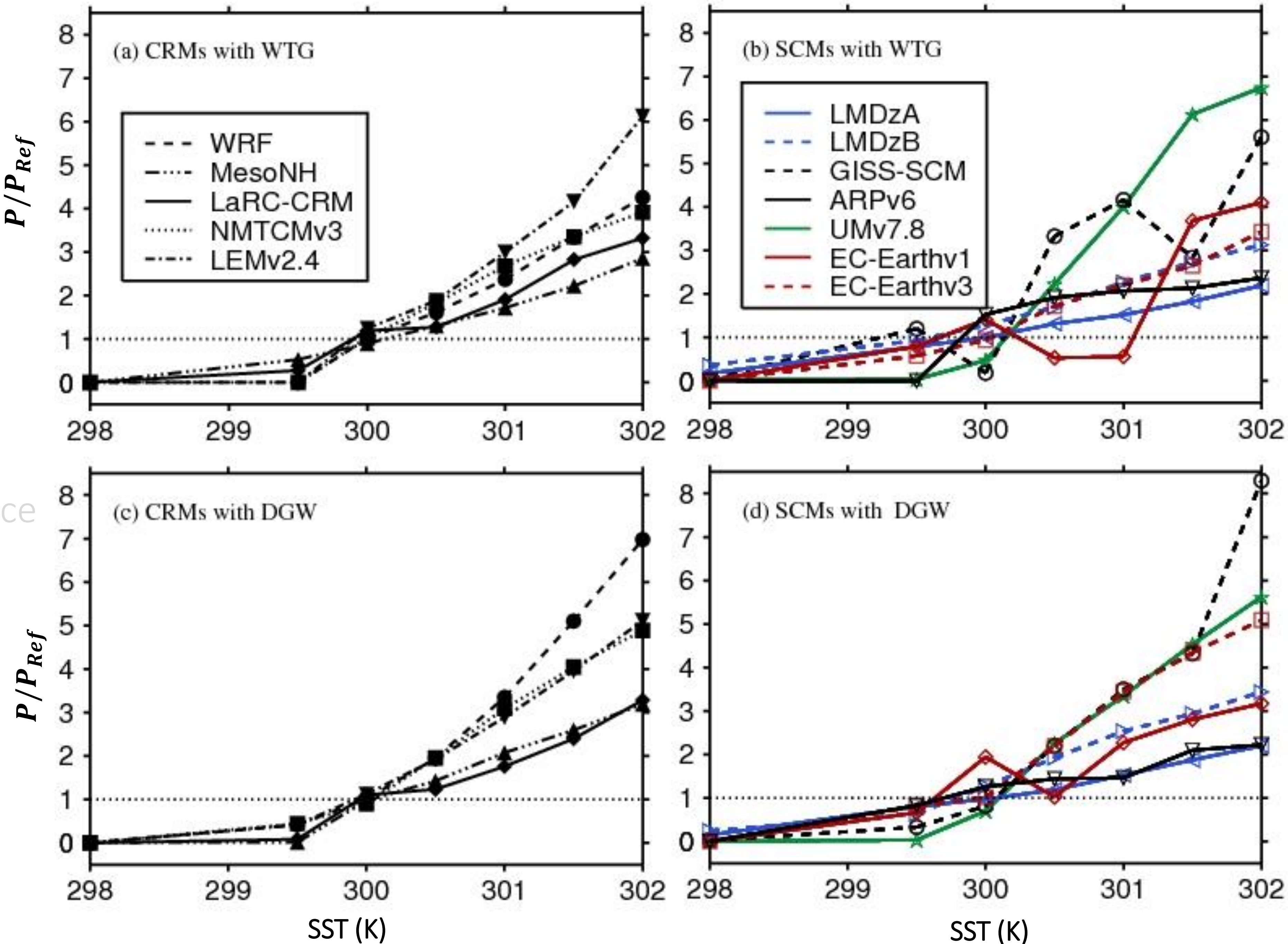

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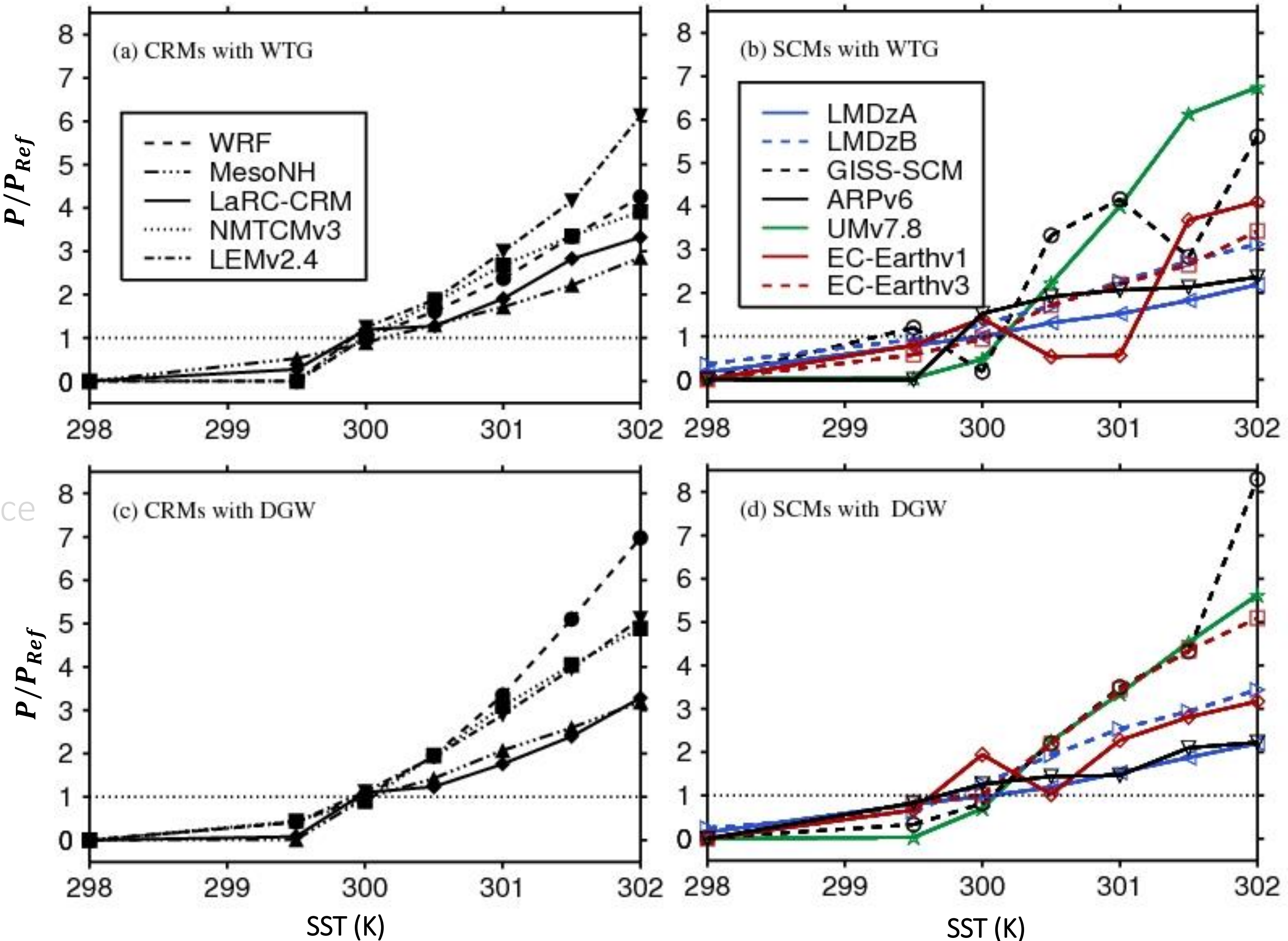
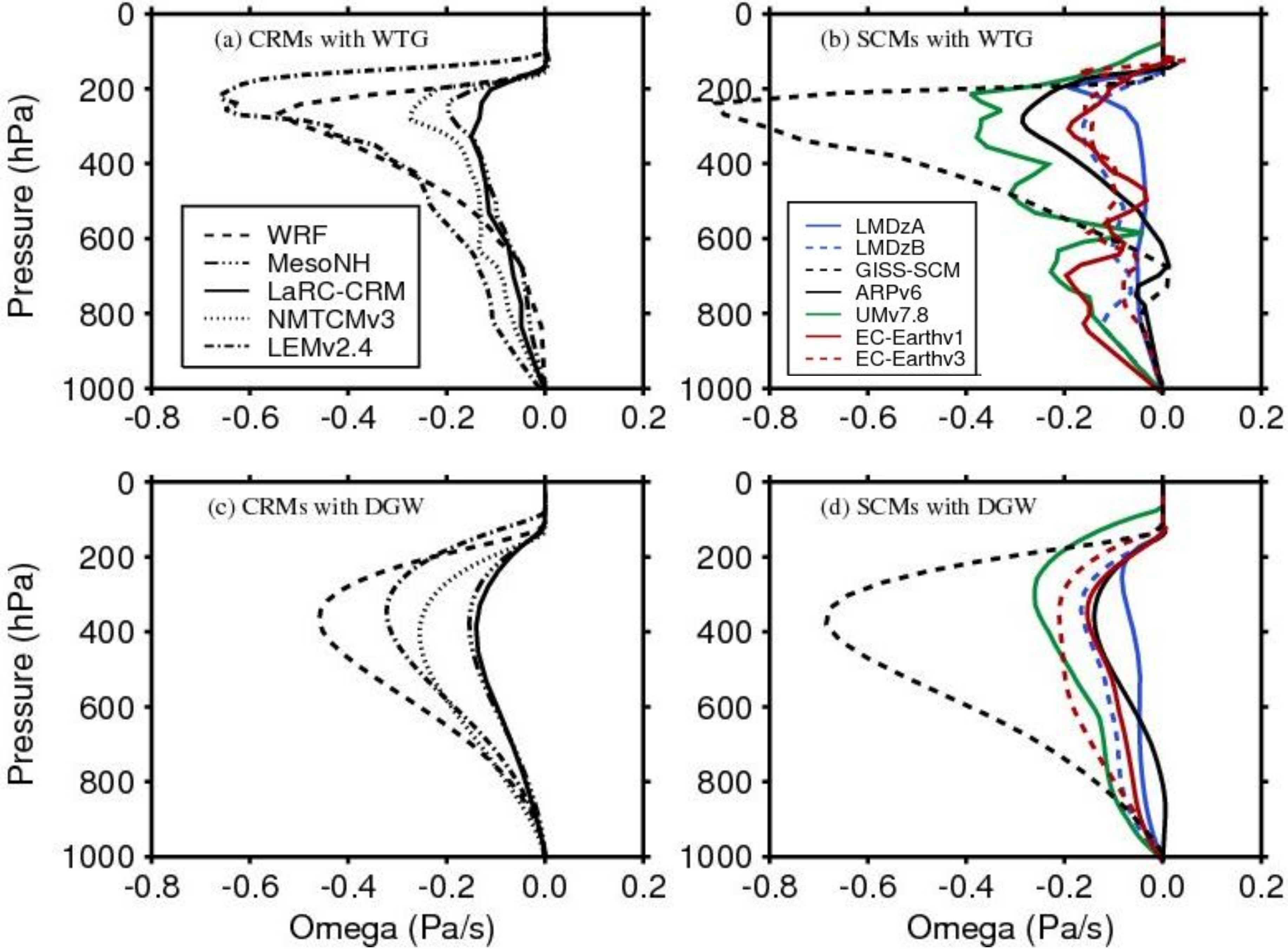


WTG and DGW simulation over non-uniform SST

Ref state= RCE at 300K.

SST = 302 K

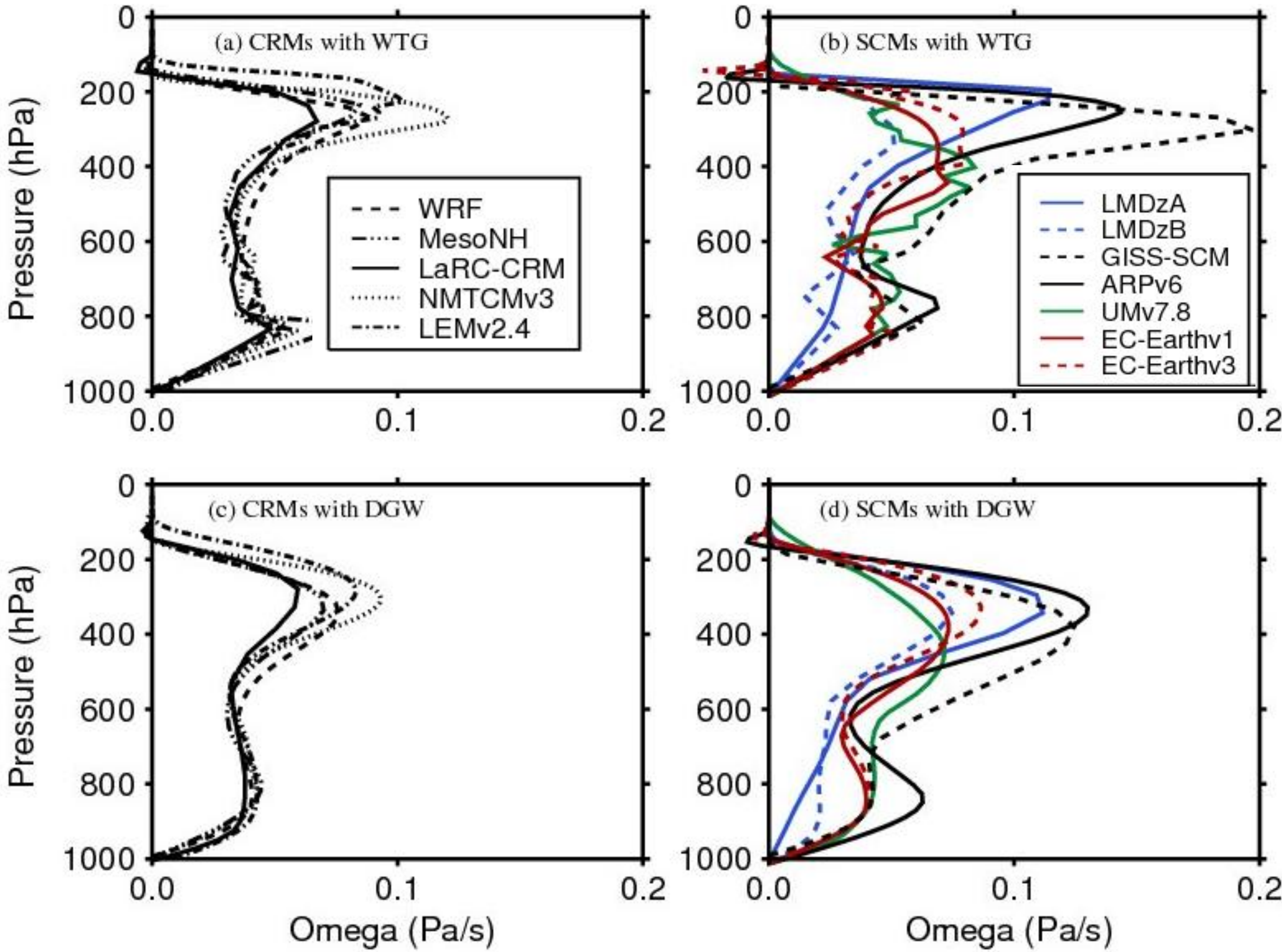


Profiles produced by DWG are smoother and less top-heavy compared to those produced by WTG

WTG and DGW simulation over non-uniform SST

Ref state= RCE at 300K.

SST = 298 K



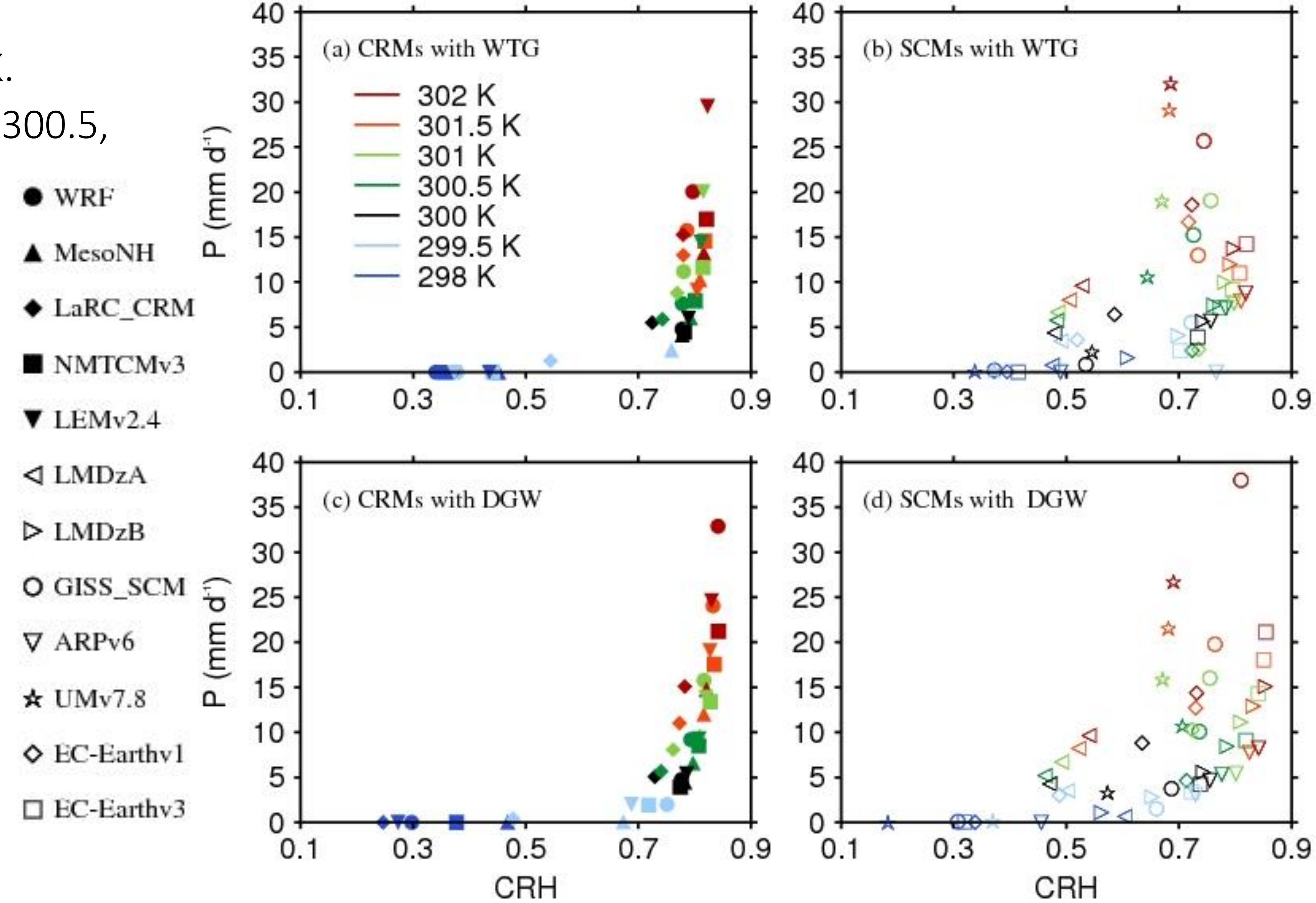
- CRMs produce very similar profiles
- SCMs under both WTG and DGW methods result in a much wider range of behaviours

WTG and DGW simulation over non-uniform SST

Ref state= RCE at 300K.

SST = 298, 299.5, 300, 300.5, 301, 301.5 and 302 K

- CRMs under both WTG and DGW methods produce very similar relationship between P and CRH.
- SCMs results in a much wider range of behaviours



Summaries

- Over uniform SST, large-scale circ develops under the WTG/DGW in some models but not all. More likely under the WTG than under the DGW.
- Some models sustain multiple equilibria (ME) under the WTG, while others do not.
- ME are more likely at higher SST, but sensitive to PBL depth
- No model sustain ME under the DGW.

Overall

- The WTGs produce a wider range of behaviours than DGWs
- CRMs under the WTG/DGW method behave broadly in a similar way, while SCMs exhibit a much wider range of behaviours.

Comparison between CRMs and SCMs under the WTG/DGW may be a useful tool for trying to reduce biases or improve the SCMs or a useful tool when developing and testing parameterization schemes.

Questions?

Radiative-Convective Equilibrium (RCE) simulations

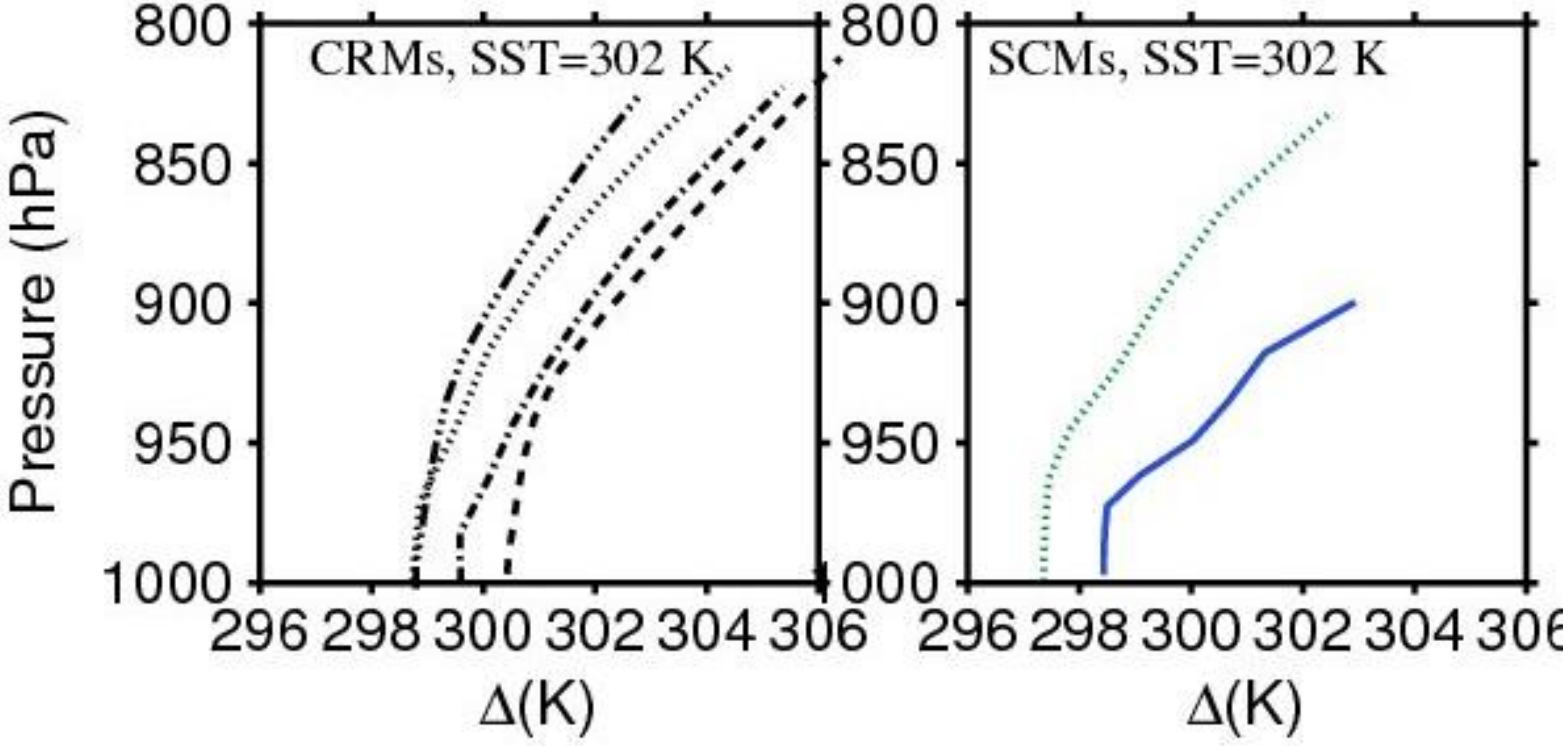
Fixed sea surface temperature (SST) and no Coriolis force is applied

Idealized radiative forcing profile:

$$\frac{\partial T}{\partial t} = \begin{cases} -1.5 & if\ \overline{p} \geq 100 \\ -1.5 \times \frac{\bar{p} - 100}{100} - \alpha_T \times \frac{200 - \bar{p}}{100} \times (\bar{T} - 200) & if\, 100 < \bar{p} < 200 \\ \alpha_T \times (\bar{T} - 200) & if\ \bar{p} \leq 100 \end{cases}$$

$\bar{p}(hPa)$

RCE simulations with SST =298, 300 and 302 K

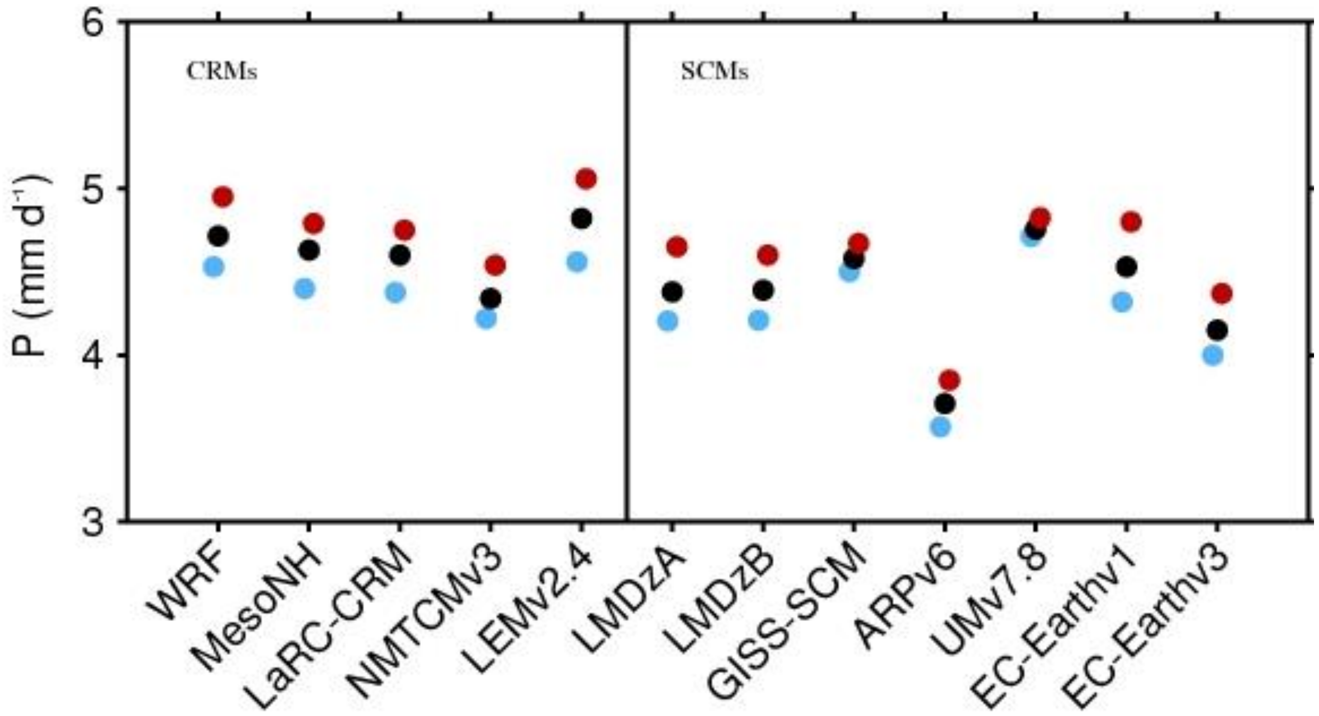


Potential; temperature in the lowest 200 hPa.

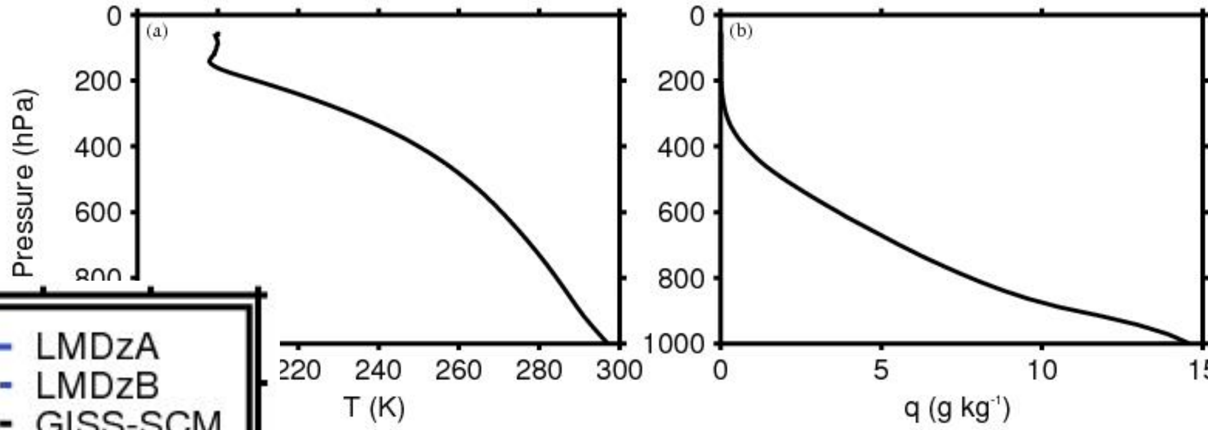
RCE simulations with SST=302K

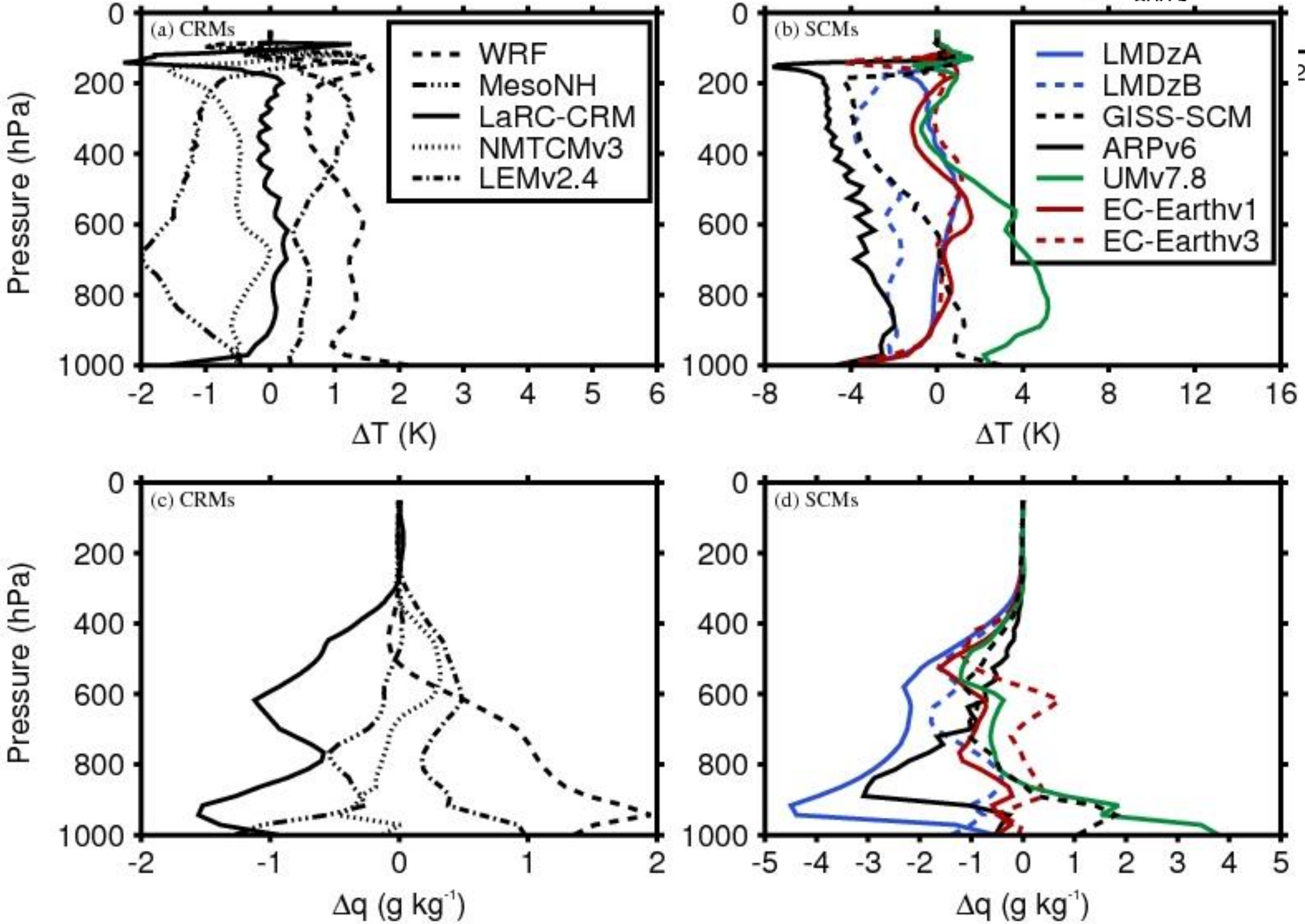
RCE simulations with SST =298, 300 and 302 K

Colour code: **298**, **300**, **302** **K**



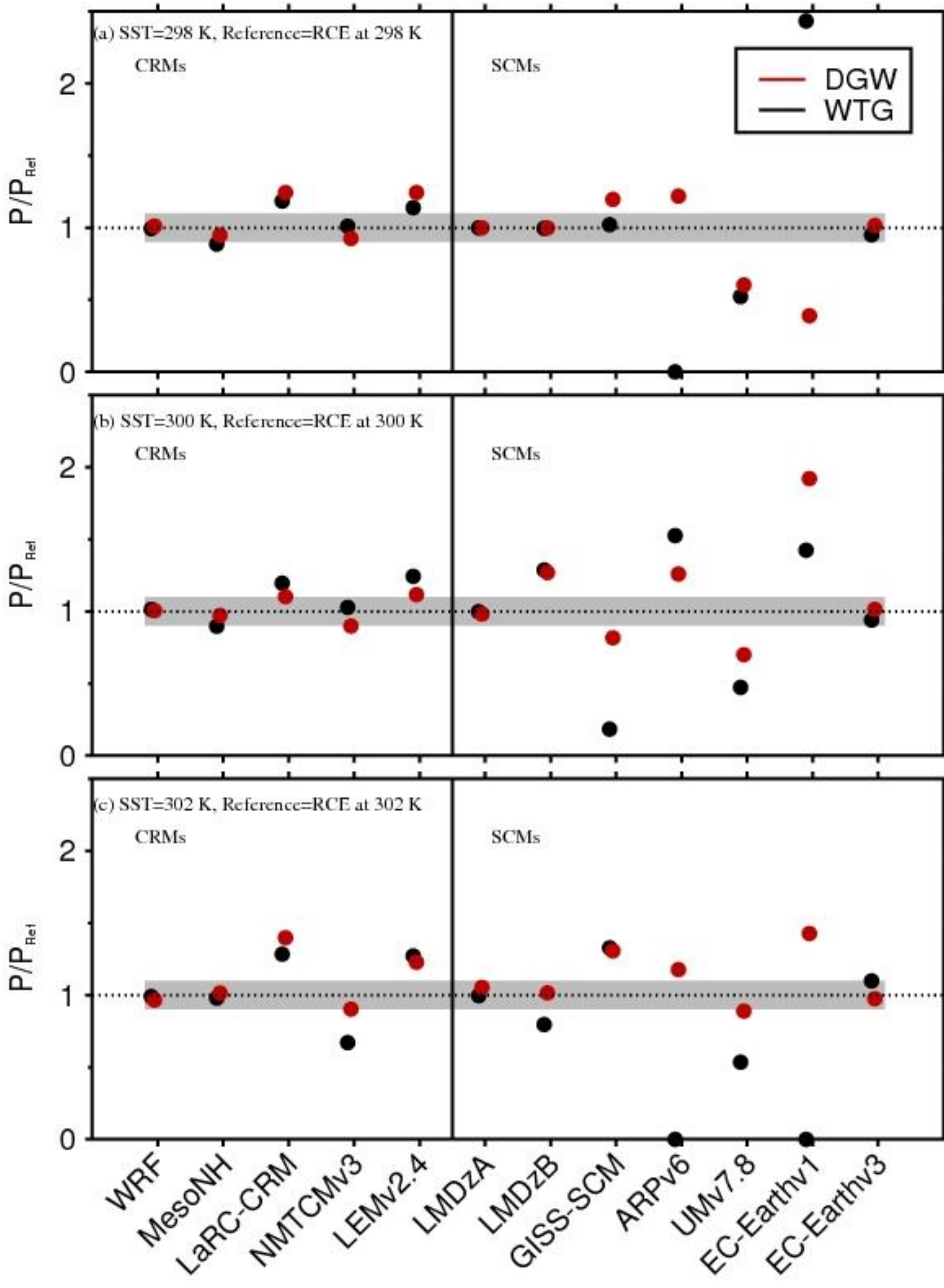
RCE simulations with SST = 300 K





WTG and DGW simulation over uniform SST

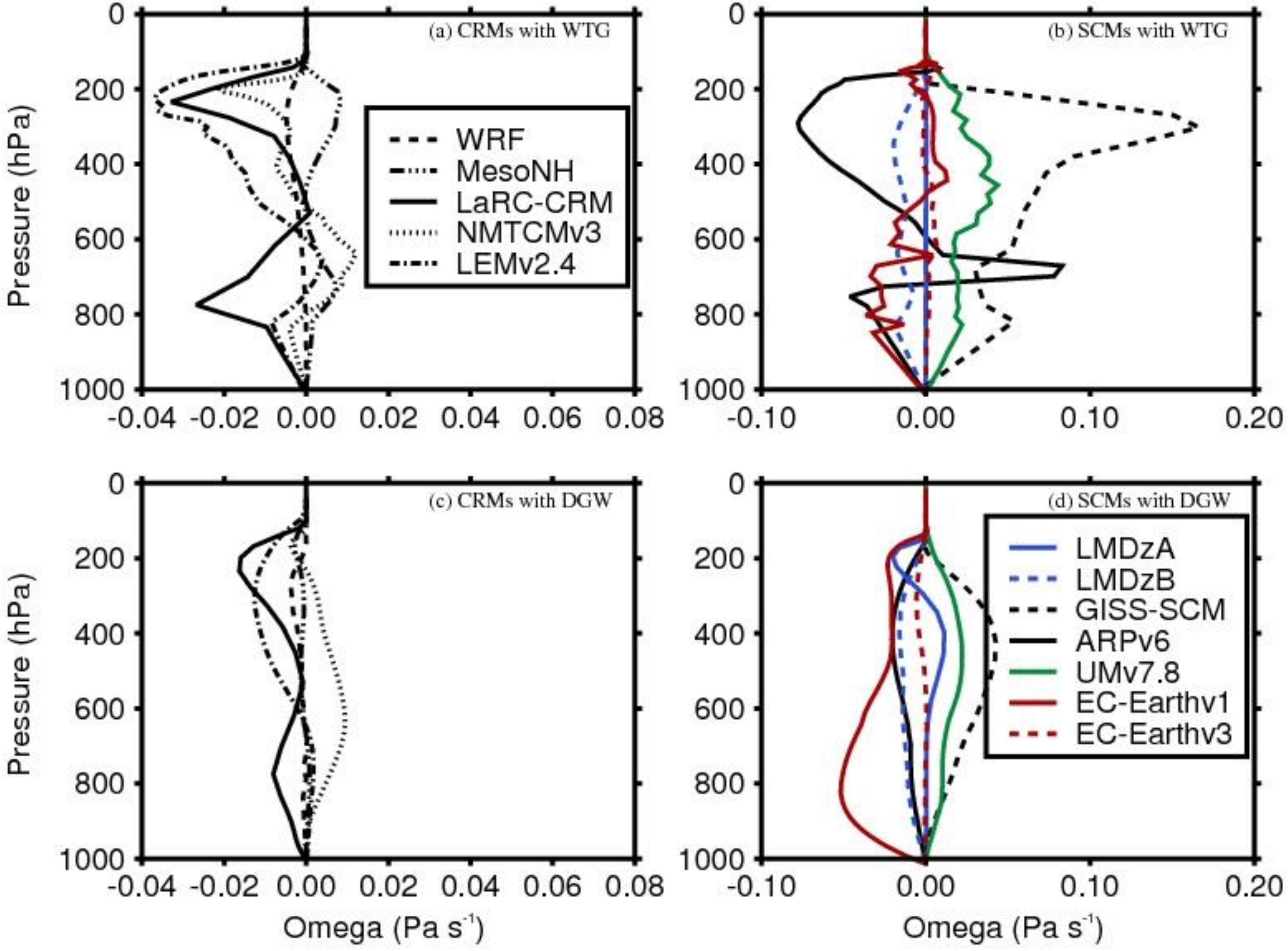
- The reference state of each model comes from the radiative-convective equilibrium (RCE) simulations of the same model.
- The WTG and DGW simulations are performed over uniform SST of 298, 300 and 302 K with the reference state from the same SST.
- The WTG and DGW simulations are initialized with profiles from the reference state.



Wider range of behaviours across SCMs compared to CRMs

WTG and DGW simulation over uniform SST

- Wider range of behaviour across SCMs compared to CRMs
- The profiles produced by DGW simulations are smoother compared to those produced by WTG simulations



We defined $\Omega = \frac{1}{\Delta p}\int \bar{\omega} dp$

A simulation replicate the RCE State to a good approximation

If

$0.9 < \mathrm{MRR}/\mathrm{MRR}_{\mathrm{RCE}} < 1.1$

and

$-4 \times 10^{-3} < \Omega < 4 \times 10^{-3}$

Sensitivity to initial moisture conditions

- Initialized with RH from the RCE state (full circles)
- Initialized with 0% RH (open circles)

Some simulations are insensitive to the initial RH.

No dry equilibrium under the DGW method

Over a uniform SST of 302 K,
we compared the profiles at equilibrium in the WTG simulations of WRF, NMTCMv3, LEMv2.4, UMv7.4, LMDzB to those obtained in the WTG simulation of MesoNH