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On the Contribution from Fast and Slow Responses to Local Precipitation Changes caused by Aerosol Perturbations

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1.Introduction of Energetic Approach

How to study aerosol effects on precipitation ?

A NEW PERSPECTIVE

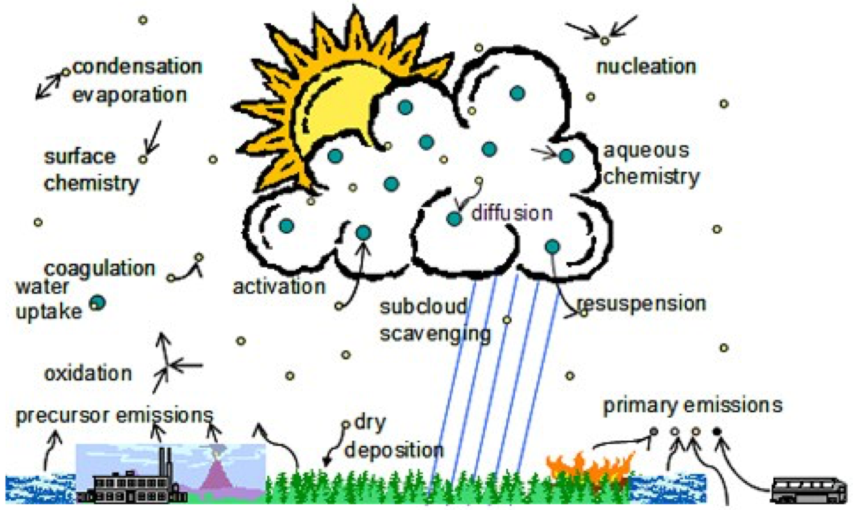
TOP-DOWN

Changes in latent heat need to be balanced by atmospheric radiative cooling and surface fluxes

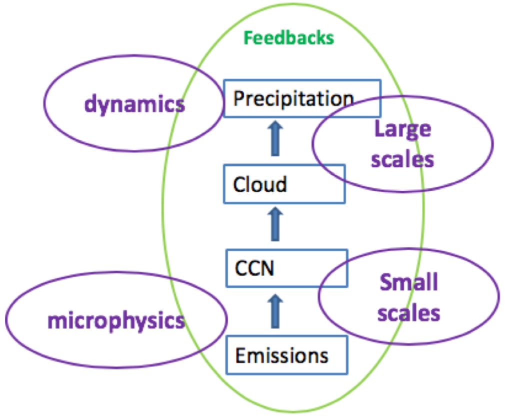
Global: $F_{RAD}^{TOA} - F_{RAD}^{SUR} - F_{SH} = L*P$

Regional: $F_{RAD}^{TOA} - F_{RAD}^{SUR} - F_{SH} + \nabla(\vec{U}S) = L*P$

S: dry static energy

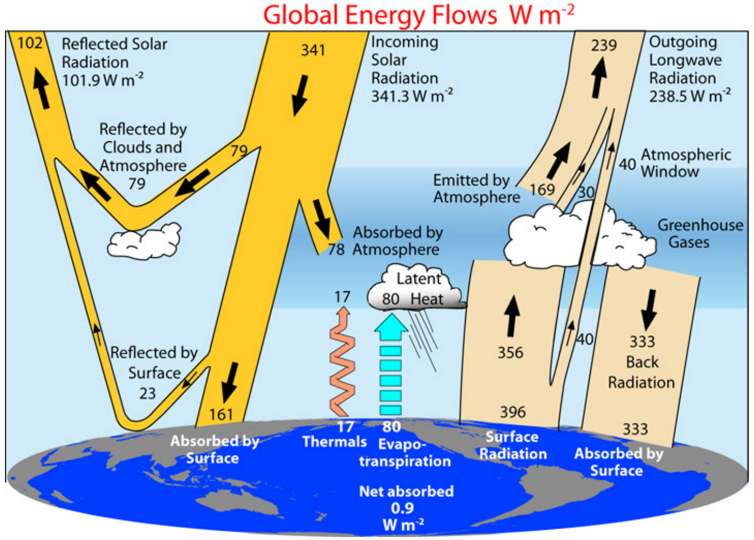


(Image: Anthony Watts)



- *Traditional*
- *Processes-based*

Bottom up



(Image: K. Trenberth, J. Fasullo, and J. Kiehl)

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2. Background: fast and slow responses of precipitation

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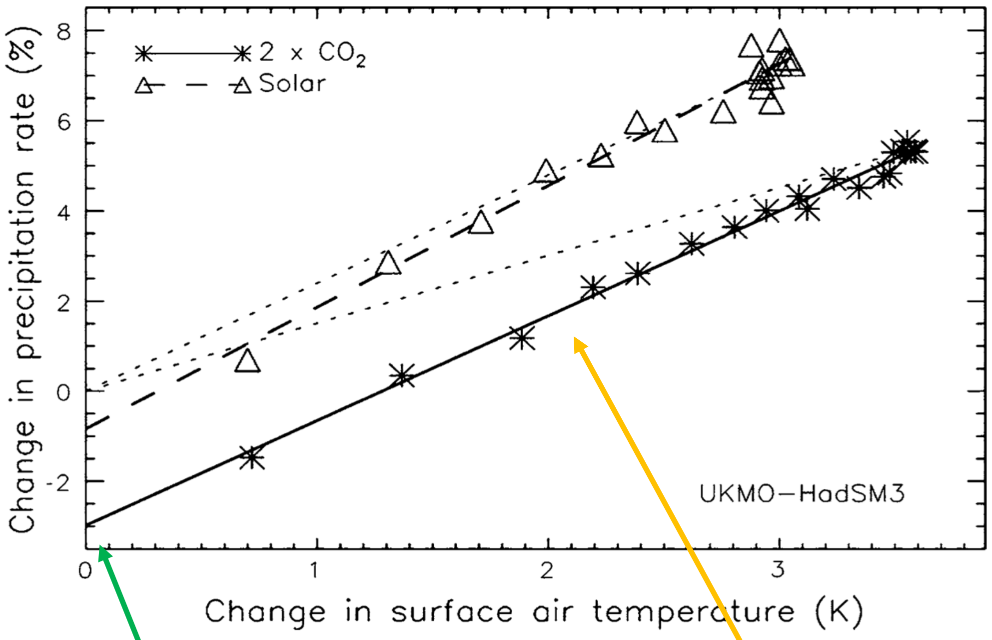
（Andrews, et al., 2009, JC)



Fast response:
independent of T change

Slow response:
Mediated by T change

Eg.

Global mean precipitation in response to increased GHGs emission:

- **decreases first (due to decreased radiative cooling)**
- **and then increases in the following years (due to increased SST)**

in response to increased GHGs emission

2. Background:Previous studies

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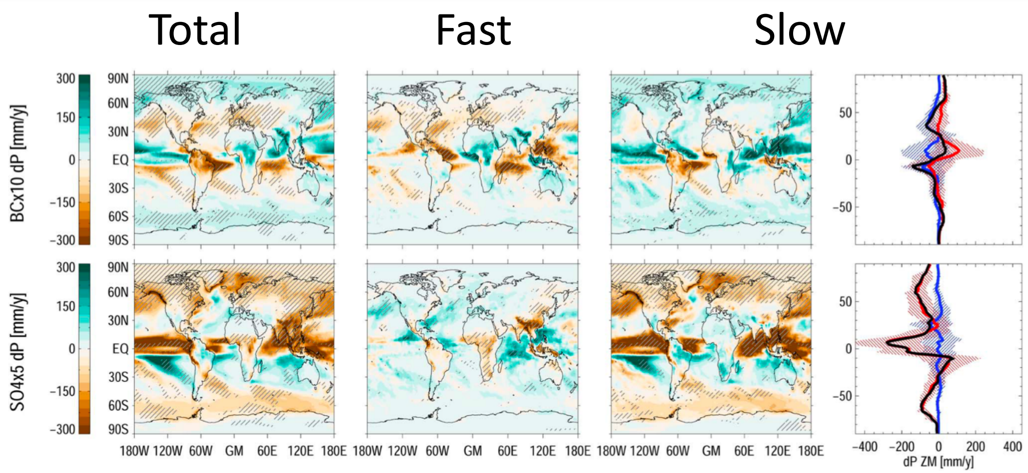
(To name a few)



(Samset, et al., 2016)

- Examined precipitation response to different climate forcers
- Focused on inter-comparison (PDRMIP)

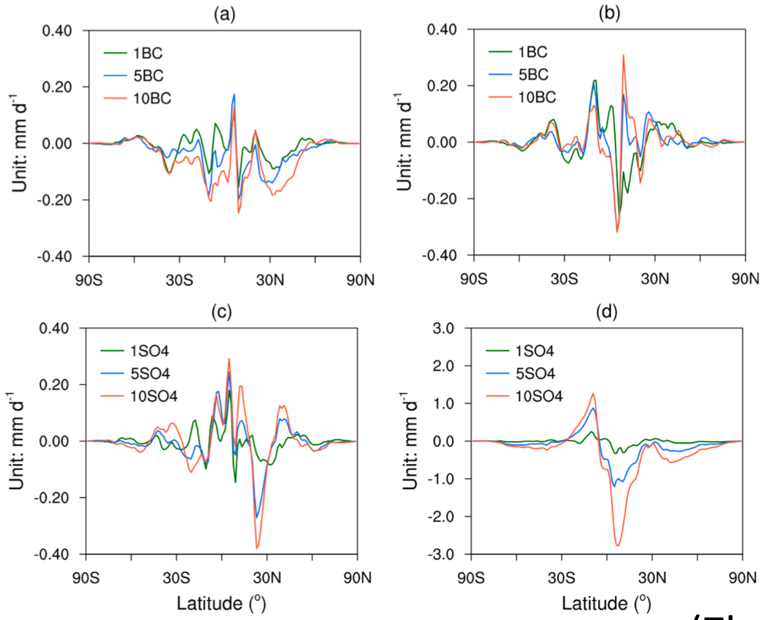
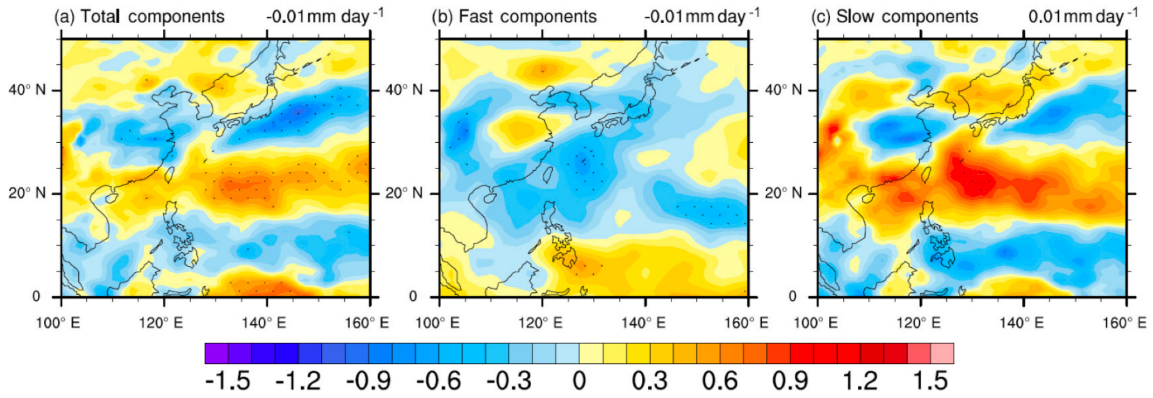


FIG. 5. (left) The zonal-mean fast precipitation responses (mm day^{-1}) caused by (a) BC and (c) SO_4. (right) The zonal-mean slow precipitation responses (mm day^{-1}) caused by (b) BC and (d) SO_4.

(Zhao & Suzuki, et al., 2019)

- Regional study: ITCZ shift
- Relationship with TOA forcing and responses



(Wang, et al., 2017)

- Regional study: Examined changes in monsoon
- Dynamics and thermodynamics

3. Methodology

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Model: ECHAM6-HAM2

Aerosols perturbation:
- Baseline,
- 10 times BC emission,
- 5 times SUL emission

(follow PDRMIP experiments)

Simulations:
- Fixed SST: 15 years (fast responses)
- MLO: 100 years(slow responses)

$$\Delta P_{slow} = \Delta P_{total} - \Delta P_{fast}$$

Equations

Energy budget: $L\delta P = \delta Q + \delta H$

Diabatic cooling: $Q = ARC - SH$

Atmospheric radiative cooling:

$$ARC = LW_{TOA} + SW_{TOA} - (LW_{SUR} + SW_{SUR})$$

Further decomposition:

$$ARC = ARC_{aerosol} + ARC_{cloud} + ARC_{clear,clean}$$

$$ARC_{aerosol} = ARC - ARC_{clean}$$

$$ARC_{cloud} = ARC_{clean} - ARC_{clear,clean}$$

4. Results: Global mean

(W m-2)	LΔP	ΔARC	$\Delta ARC_{aerosol}$	ΔARC_{cloud}	ΔARC_{cc}	-ΔSH
fast, 10BC	-3.64	-5.99	-8.42	0.93	1.50	2.41
slow, 10BC	0.38	0.70	-0.41	-0.06	1.18	-0.35
total, 10BC	-3.26	-5.29	-8.83	0.87	2.68	2.06
fast, 5SUL	-0.20	-0.26	0.21	0.03	-0.50	0.06
slow, 5SUL	-4.13	-3.82	-0.06	0.54	-4.30	-0.23
total, 5SUL	-4.33	-4.08	0.15	0.57	-4.80	-0.17

LP – latent heat released from precipitation,
ARC – atmospheric radiative cooling,
(further decomposed into contribution from aerosols, clouds and clear-clean sky.)
SH – sensible heat flux

- Precipitation is decreased from total responses in both cases.
- However:

  BC case dominated by fast responses (contributed by $ARC_{aerosol}$)

  SUL case dominated by slow responses (contributed by $ARC_{aerosol}$)

4. Results: Geographical pattern of precipitation responses

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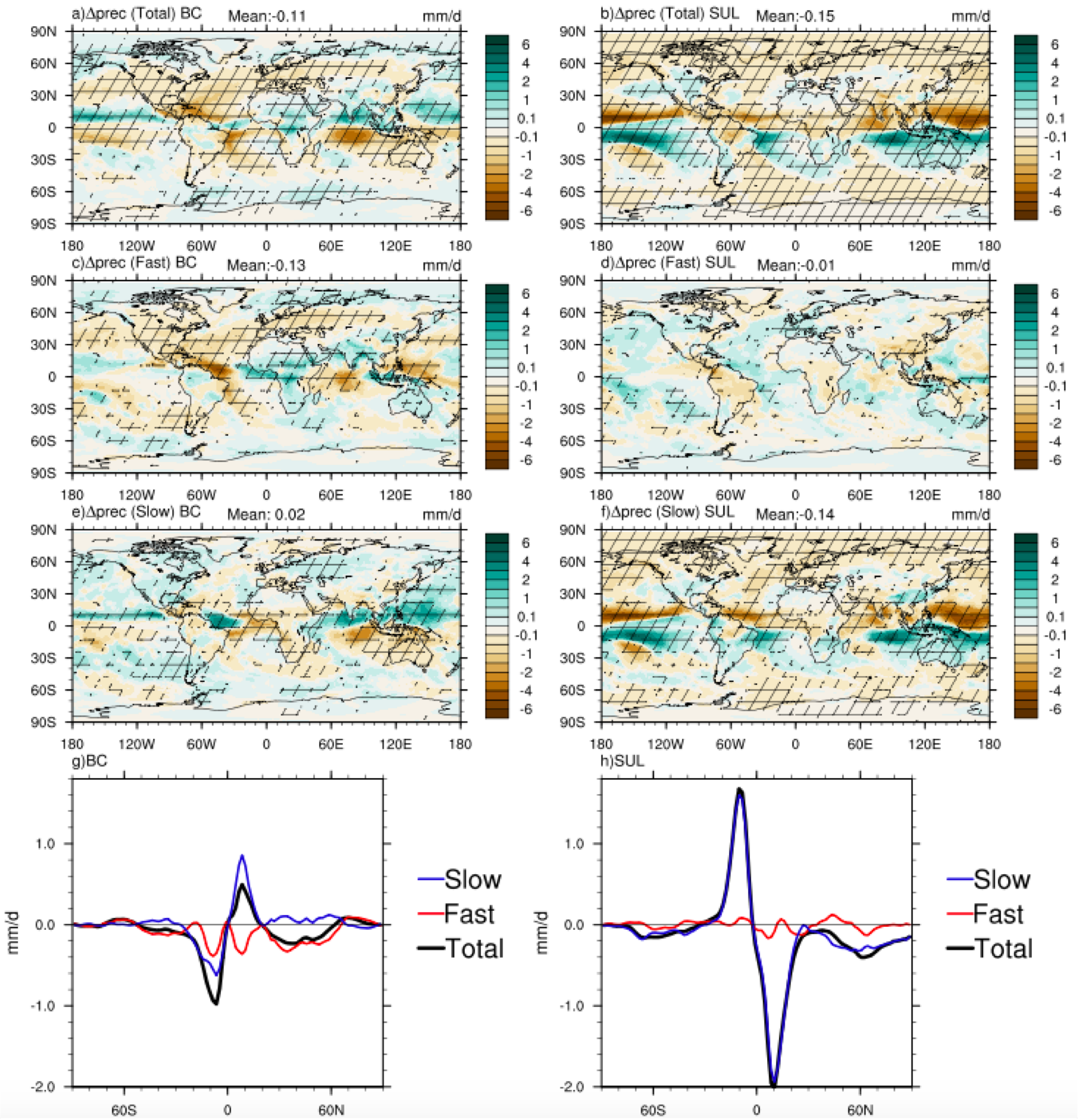

- ITCZ shifts **northward**, contributed by slow responses
- Precipitation at mid-lats decreases, contributed by fast responses

- ITCZ shifts **southward**, contributed by slow responses
- Precipitation at mid-lats decreases, contributed by slow responses

4. Results: Quantify the contribution

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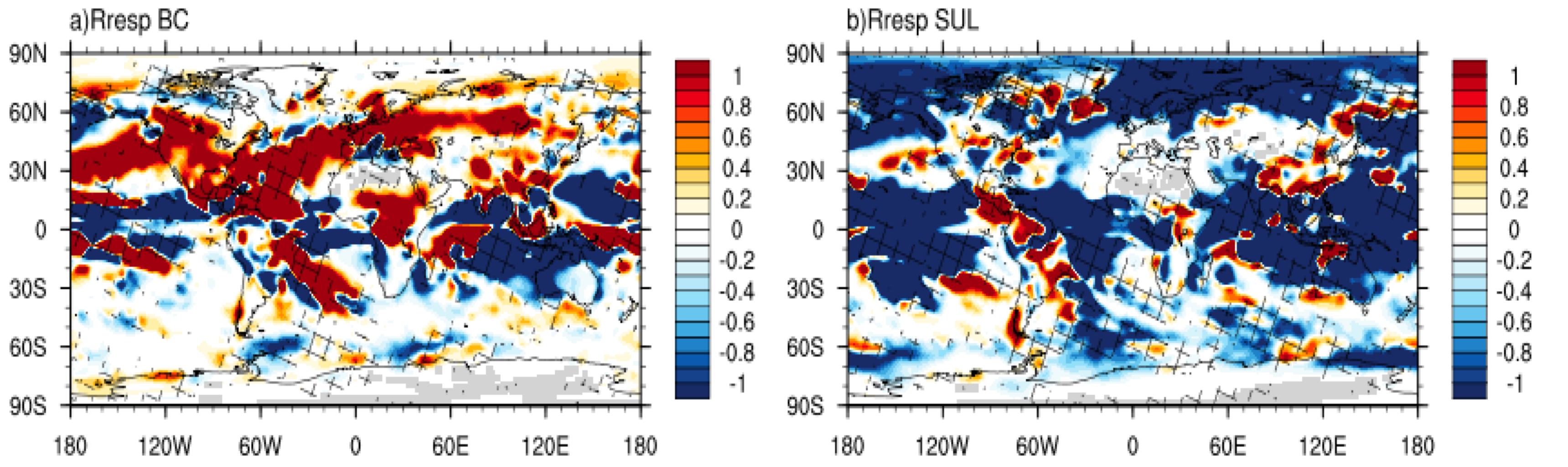
$$R_{resp} = (|\Delta P_{fast}| - |\Delta P_{slow}|)/(|\Delta P_{fast}| + |\Delta P_{slow}|)$$



- Fast responses dominate in BC case, both for regional and global precipitation
- Except for ITCZ shift
- Slow responses dominate in SUL case, regionally and globally

4. Results: Diabatic cooling and energy transport

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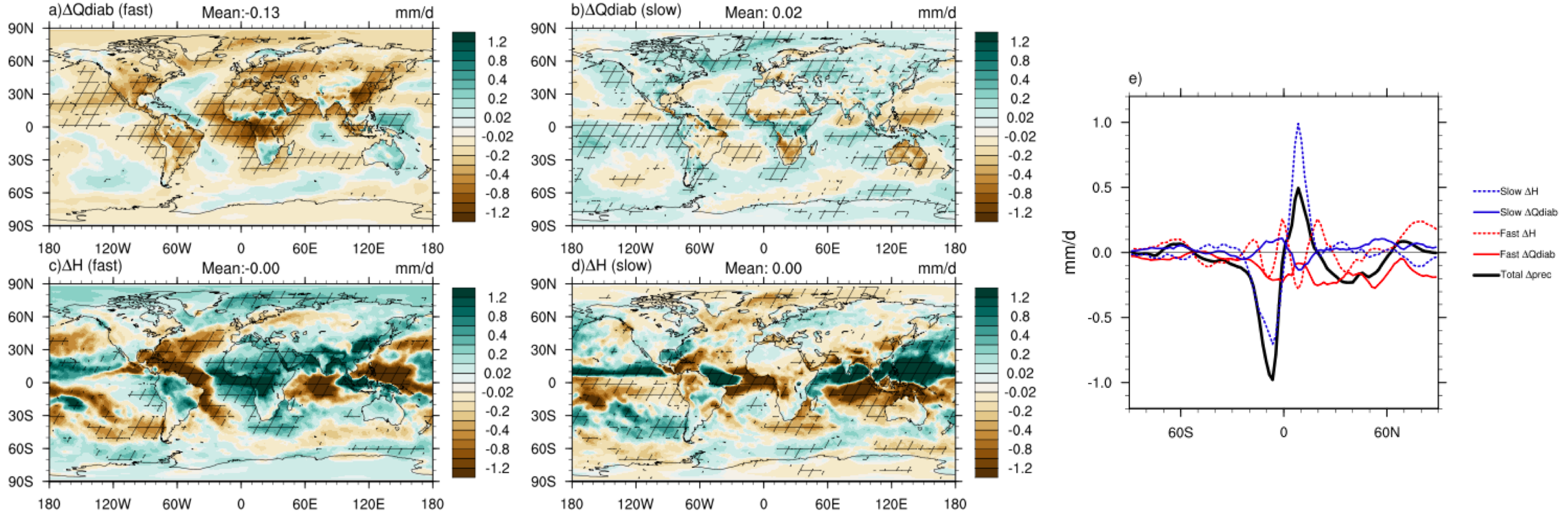
BC case

$$L\Delta P_{total} = \Delta Q(fast) + \Delta H(fast) + \Delta Q(slow) + \Delta H(slow)$$



Total responses of precipitation

- Tropic: largely contributed by energy transport term from **slow responses**
- Mid-lats: largely contributed by energy transport term from **fast responses**

4. Results: Diabatic cooling and energy transport

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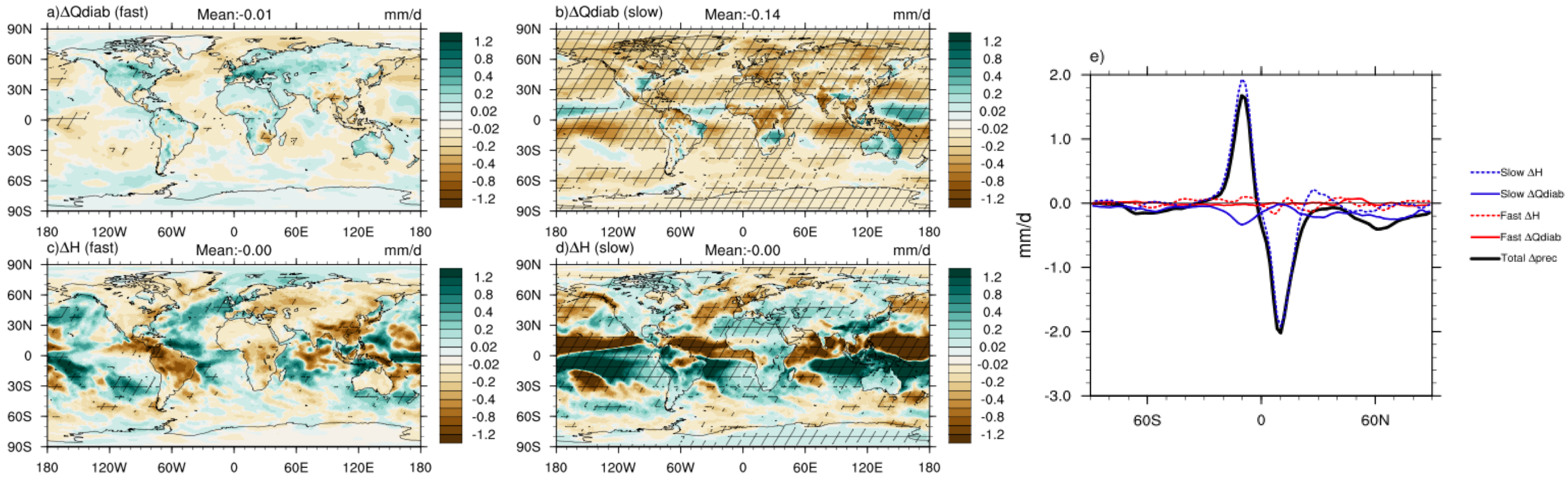
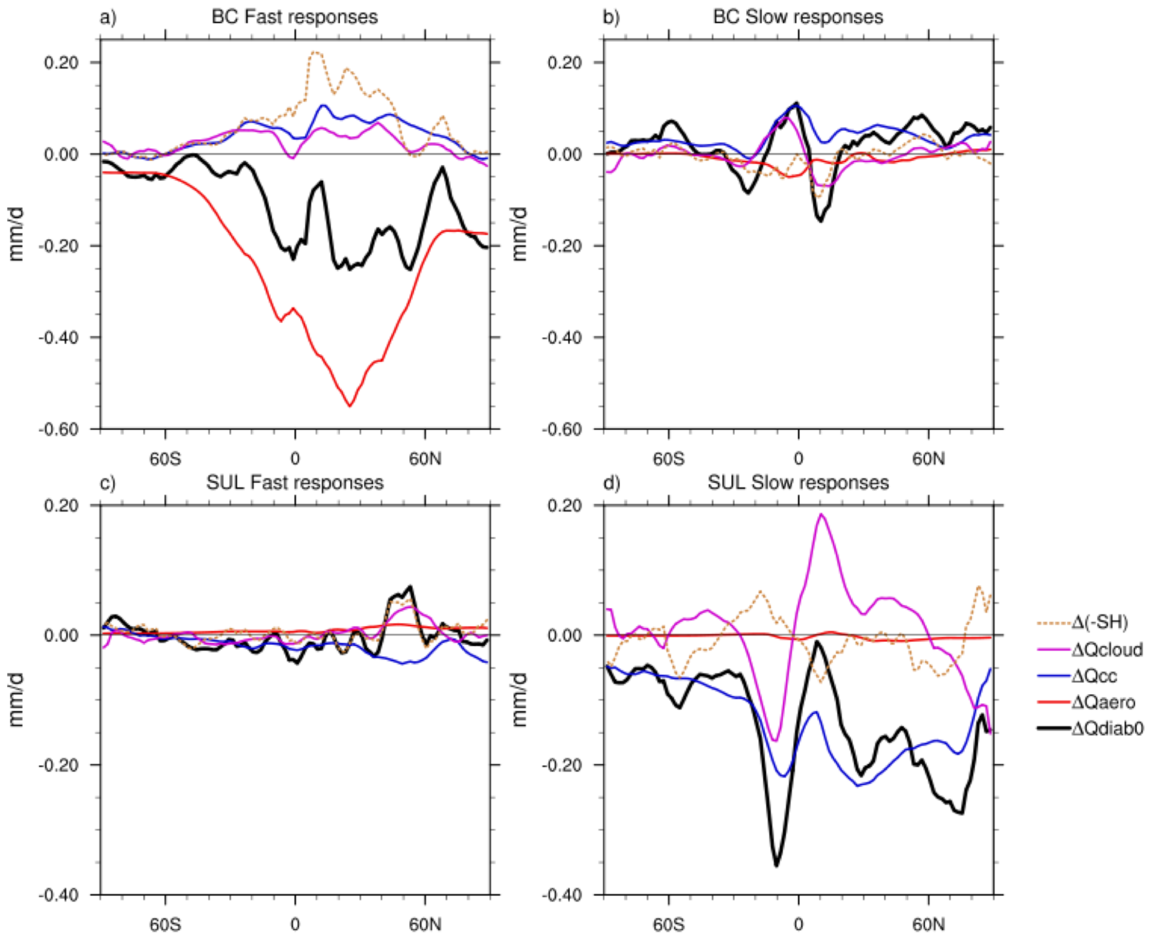
SUL case



Total responses of precipitation

- Tropic: largely contributed by energy transport term from **slow responses**
- Mid-lats: largely contributed by diabatic cooling from **slow responses**



Decomposition of Q reveals:

- Fast responses in BC case largely contributed by $ARC_{aerosol}$ (BC SW absorption)
- Slow responses in SUL case largely contributed by $ARC_{clean,clear}$

4. Results: Changes in large-scale circulation and thermodyamics

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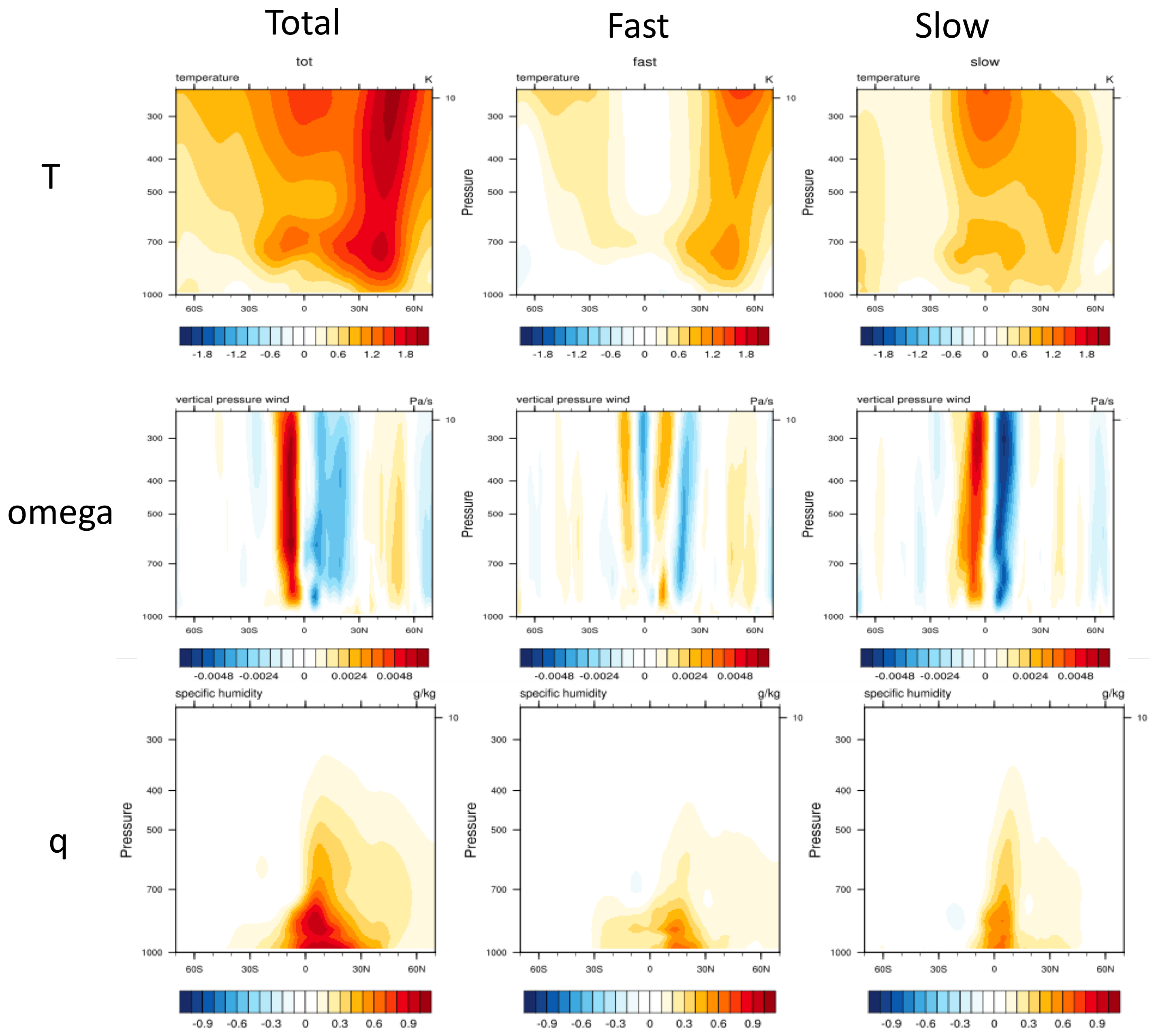

ITCZ:

- changes in omega (vertical pressure velocity) indicates the shift of Hadley cell, therefore the associated precipitation changes.
- This is a slow process

Mid-lats:

- increased temperature at higher troposphere stabilize the atmosphere, therefore leads to a decrease precipitation.
- The stabilization of atmosphere is a fast process.

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4. Results: Changes in large-scale circulation and thermodyamics

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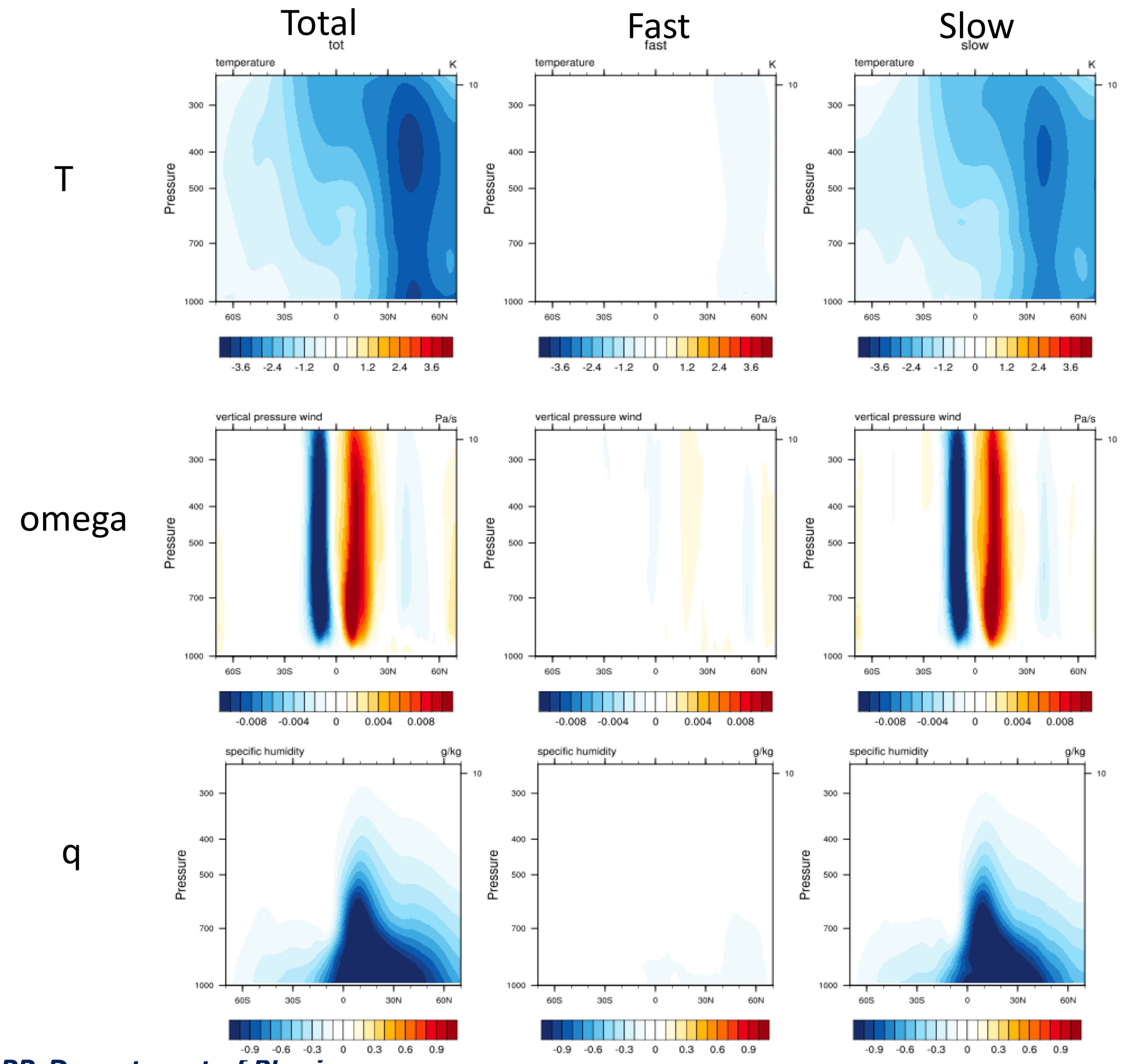

ITCZ:

- Mechanisms similar to BC case, except for a southward shift of preciptiation
- This is a slow process

Mid-lats:

- Decrease SST leads to decreases of temperature of the whole column of troposphere, and decreased specific humidity. Thus decreased temperature
- This is a slow process.

4. Take-home messages

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- ❑ Both cases show a decrease in global-mean precipitation

- ❑ Intertropical convergent zone (ITCZ), shifts northward in the BC case, while southward in the SUL case. Precipitation is decreased in other regions in both cases.

- ❑ For the BC case, whereas slow responses dominant changes in ITCZ, fast responses dominant changes in other regions.
  - Changes in tropical rainfall is dominated by slow responses of energy transport term, associated with changes in Hadley cells in response to cross-hemispheric energy imbalance due to aerosol perturbations. Outside the tropics, decreased precipitation is caused by increased aerosols shortwave absorption through fast responses. Precipitation responds strongly to local changes in thermodynamic conditions, in which absorbing aerosols directly heat the mid-troposphere, stabilize the column, and suppress precipitation.

- ❑ slow response is found to be the dominant mechanism in nearly all regions for the SUL case.
  - In the extra-tropics, unlike black carbon, non-absorbing aerosols decreases surface temperatures through slow processes and stabilize atmospheric columns from the lower boundary, which can be seen from the decreased radiative cooling from clean-clear sky (without clouds and aerosols).

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Thank you!