Effects of Explicit Convection on Global Land-atmosphere Coupling in the Superparameterized CAM

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Motivations

- Conventional global climate models may be prone to producing unrealistic land-atmosphere coupling signals due to convection parameterizations (Guilod et al. 2015).
- Explicitly resolved convection impacts the physics of land-atmosphere interactions (Hohenegger et al. 2009), but the effects on global land-atmosphere coupling dynamics is not explored systematically.
- To investigate the effects of could superparameterization (SP) in the segments of the soil moisture – precipitation feedback loop and understand the mechanisms of these effects at the process levels.

Models and simulations:

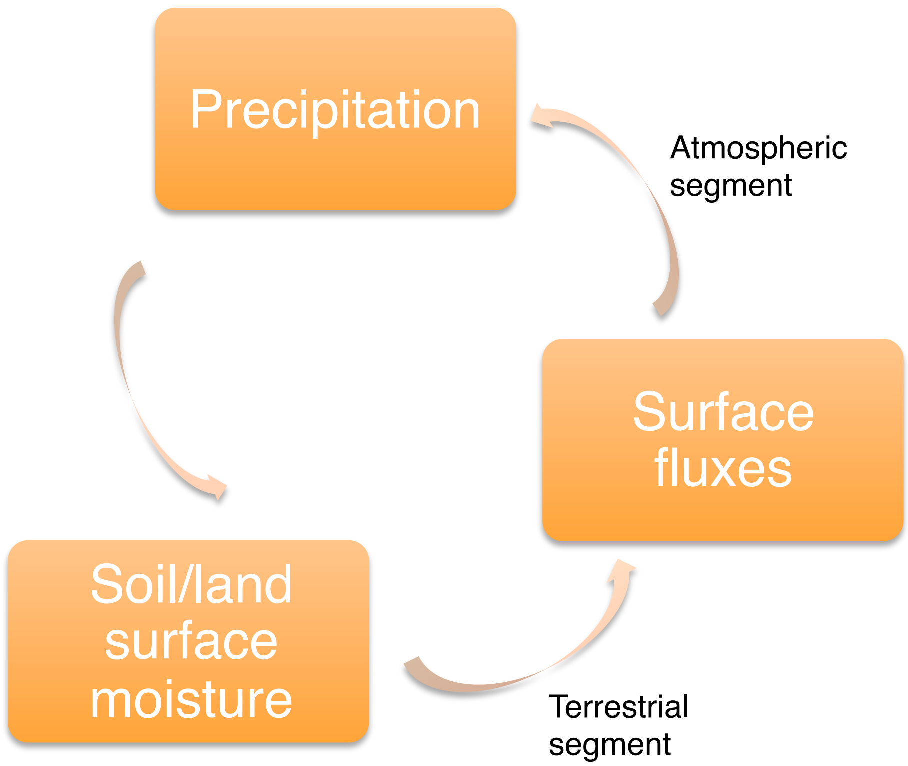
CAM3.5 and SPCAM3.5, same ocean climatology;

20 year sim, first 5 year spin-up; ~2.8° exterior spatial resolution and 8 CRM columns with 4km resolution; daily and hourly outputs in 15 JJAs for analysis.

Part 1

SP effects in different segments of soil moisture – precipitation feedback loop

Soil moisture – precipitation feedback loop

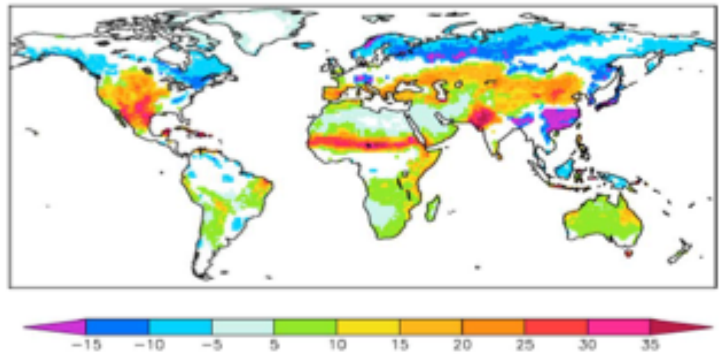


Processes involved in the soil moisture – precipitation coupling and feedback loop:

- Soil moisture plays a big role in surface flux partitioning.
- Both sensible and latent heat fluxes affect the planetary boundary layer (PBL) dynamics and further rainfall triggering; the mechanisms are complex and the effects are most uncertain in the feedback loop.
- Precipitation replenishes soil moisture.

SP changes geographical distribution but not overall magnitude of terrestrial coupling index

$$I_\phi = s_w \beta_\phi$$



I_{LH} of GSWP-2 data (10 JJAs), figure from Dirmeyer (2011).

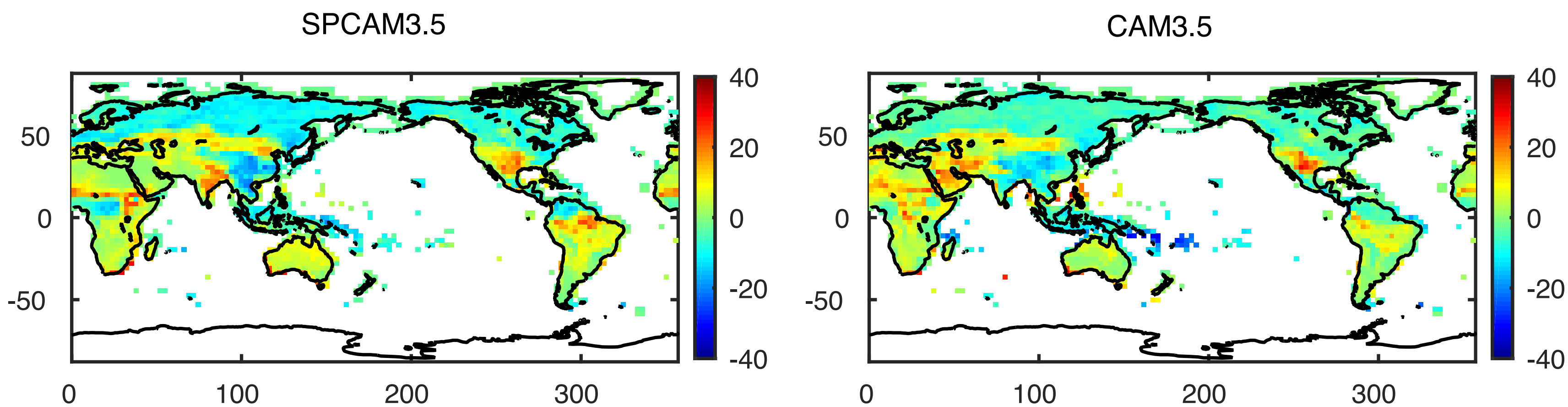
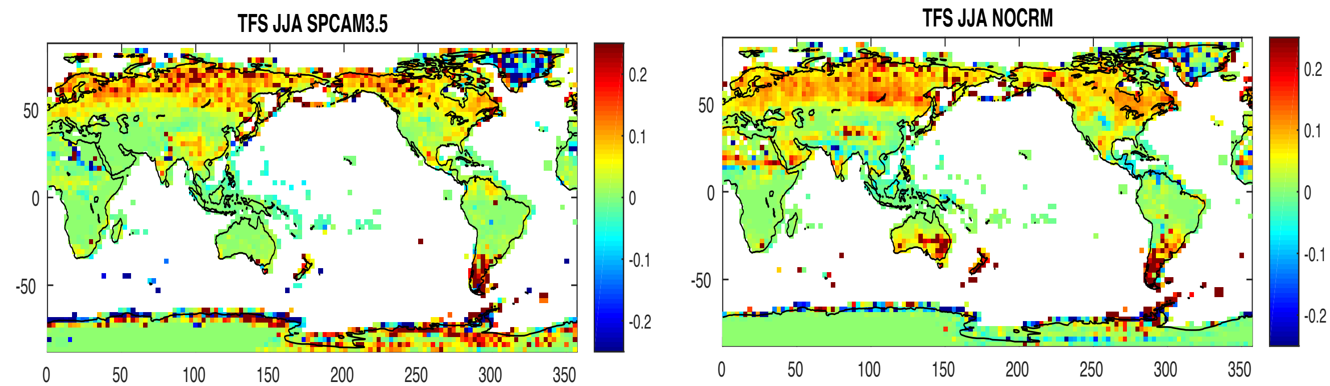


Figure: Terrestrial coupling indices of soil moisture (top 3cm) and latent heat flux(LH) of 15 JJAs.

- SPCAM3.5 reduces the coupling strength of soil moisture and LH in central America, mitigates the signal in Middle East, shrinks strong coupling areas in North Africa, and reverses the coupling sign (from negative to positive) in India.

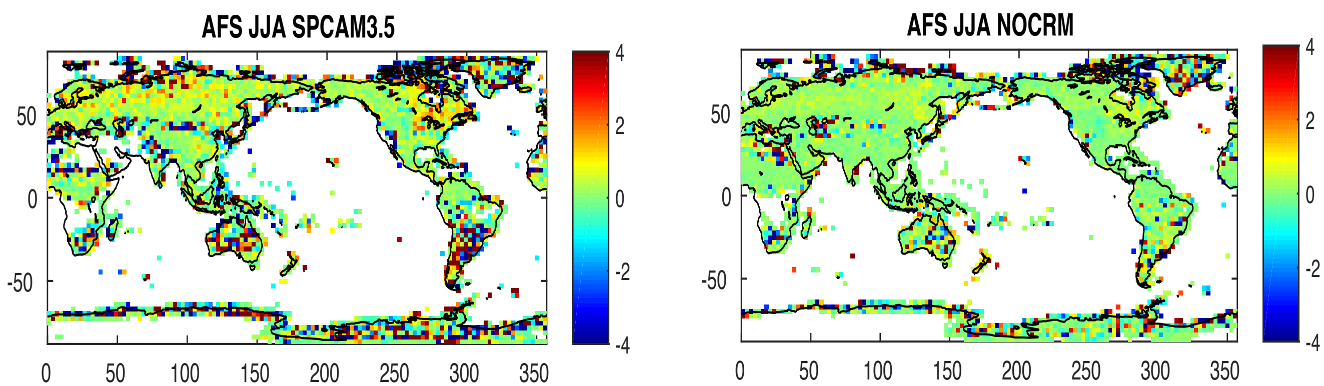
SP reduces TFS but strengthens AFS signal in atmospheric segment

Triggering feedback strength: $$\mathrm{TFS} = \sigma_{\mathrm{EF}} \frac{\partial \Gamma(r)}{\partial \mathrm{EF}}$$



- TFS: afternoon (noon-6pm) rainfall frequency changes with morning (9am-noon) EF;

Amplification feedback strength: $$\mathrm{AFS} = \sigma_{\mathrm{EF}} \frac{\partial \mathrm{E}[r]}{\partial \mathrm{EF}}$$



- AFS: accumulated afternoon rainfall amount changes with morning EF if afternoon rainfall occurs

Figure: Global distribution of TFS and AFS (indices from Findell et al. 2011) in 15 JJAs, screening out days with early morning rainfall.

TFS agrees with NARR and matches PBL properties sensitivity to EF in SP

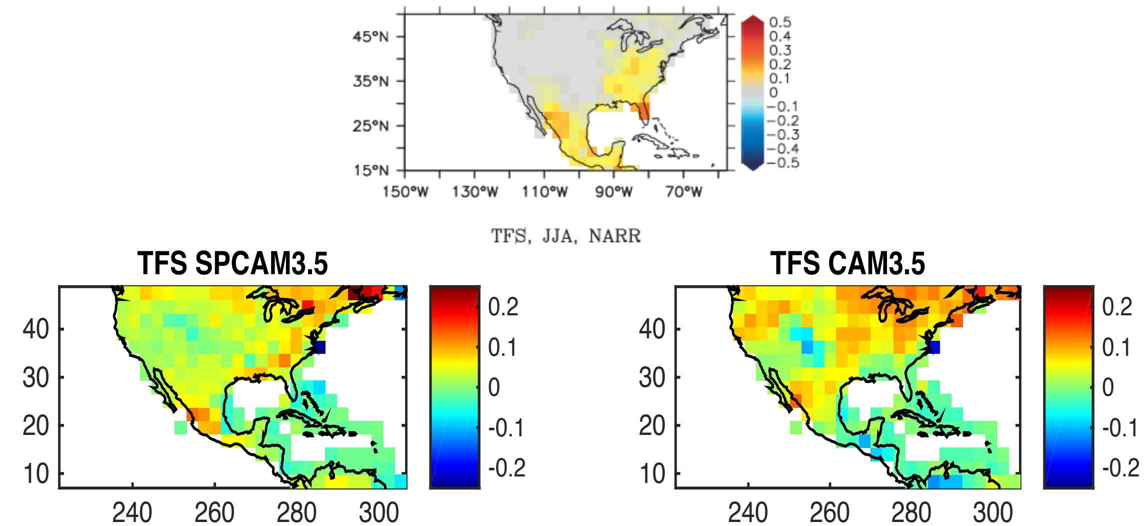


Figure: TFS and AFS of models and NARR (from Berg et al. 2013) in North America.

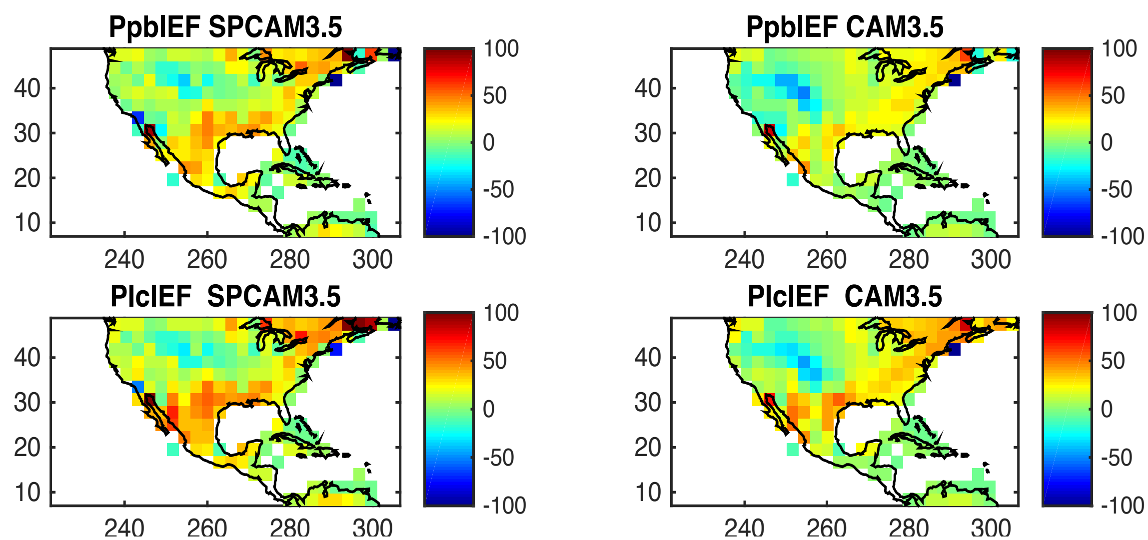


Figure: PBL height and LCL coupling strength with EF in North America.

- SPCAM3.5 displays strong TFS signal along the east coast and Mexico that agrees with the results of NARR.
- CAM3.5 shows TFS signal in central and northwestern US instead of the east coast.
- The spatial patterns of afternoon PBL height and LCL (lifting condensation level) variations with morning EF generally match the TFS signal in SPCAM3.5, but not in CAM3.5.

Functional relationship of normalized TFS and AFS vs. EF in North America

$$\mathrm{normTFS} = \frac{\overline{\mathrm{EF}}}{\overline{\Gamma(r)}} \frac{\partial \Gamma(r)}{\partial \mathrm{EF}} = \frac{\overline{\mathrm{EF}}/\overline{\Gamma(r)}}{\sigma_{\mathrm{EF}}} \mathrm{TFS}$$

$$\mathrm{normAFS} = \frac{\overline{\mathrm{EF}}}{\overline{\mathrm{E}[r]}} \frac{\partial \mathrm{E}[r]}{\partial \mathrm{EF}} = \frac{\overline{\mathrm{EF}}/\overline{\mathrm{E}[r]}}{\sigma_{\mathrm{EF}}} \mathrm{AFS}$$

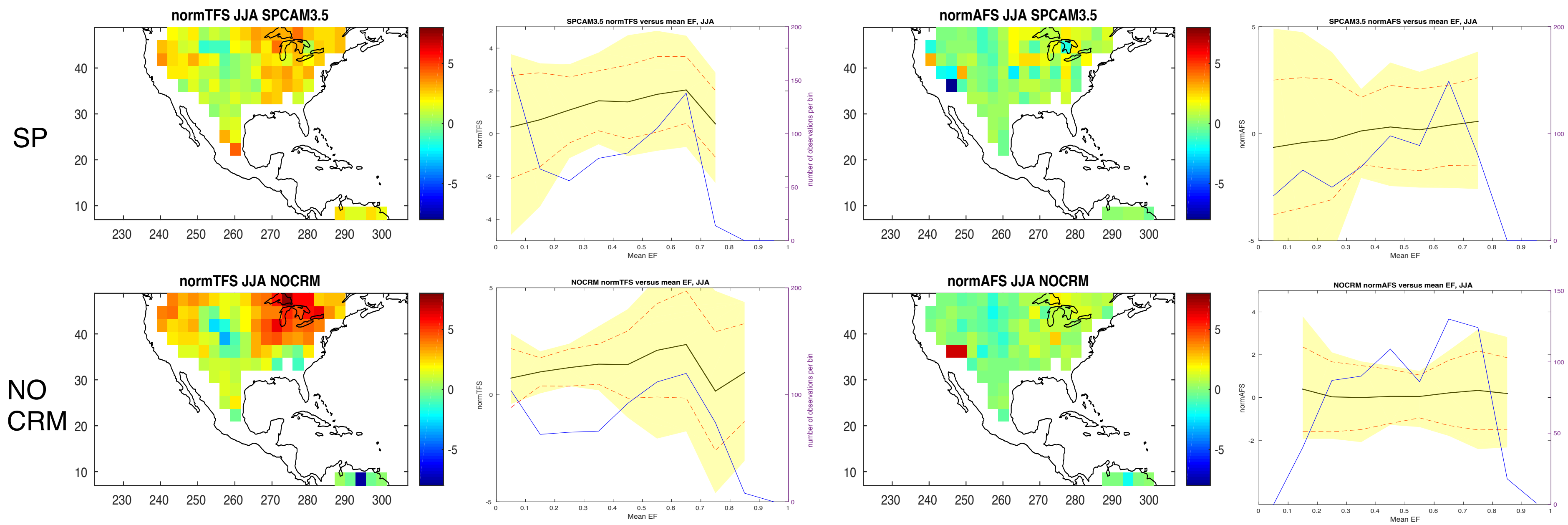


Figure: Spatial distribution and function relationship of normalized TFS and AFS vs. EF in North America.

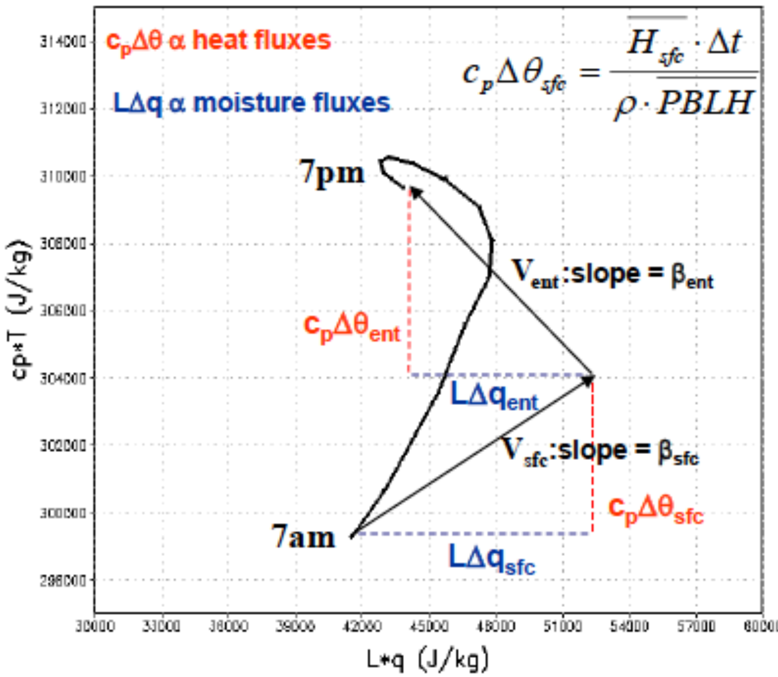
- By normalization, TFS and AFS can be compared against each other.
- Normalized TFS slightly increases with EF in both models.
- The insensitivity of normalized AFS to EF is more obvious in CAM3.5.

Part 2

SP effects on land – atmosphere coupling at process levels

mixing diagram approach

LoCo – Mixing diagram approach



Mixing diagram approach in local land-atmosphere coupling (LoCo) framework of Santanello et al. (2009):

- For a given time step, plot 2m T&Q in energy space;
- Surface vector can be calculated with PBL height, H_{sfc} and LE_{sfc};
- Residual vector then can be derived from the T-Q trajectory and surface vector, which represent the atmospheric response including entrainment, advection, etc.

SP adds bigger curvature in mixing diagrams with 2m T&Q

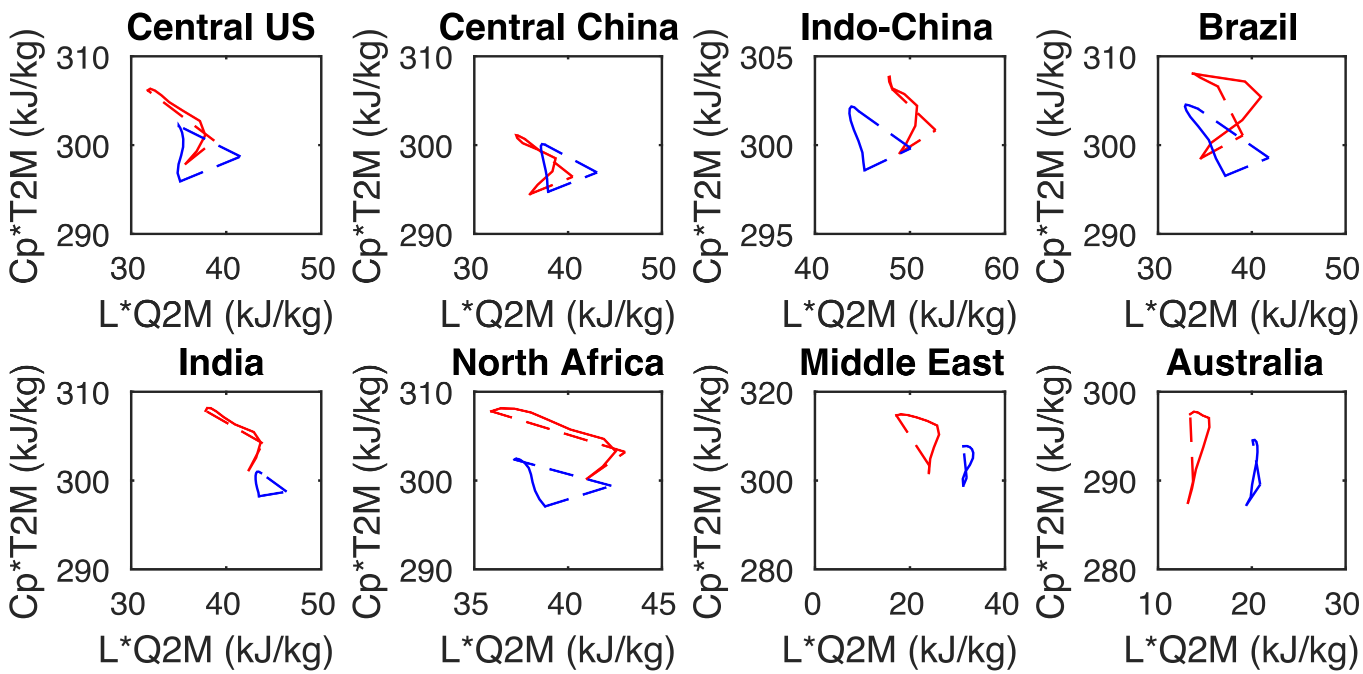


Figure: Mixing diagrams of SPCAM3.5 (red) and CAM3.5 (blue) with 2m temperature and humidity during daytime (LST 8am-5pm) in eight grids globally.

- SPCAM3.5 shows bigger curvature, associated with surface moistening in the early morning then drying during the rest of day.
- CAM3.5 has weaker diurnal surface moisture cycle; the early morning moistening process is not seen or neglected at most locations.

SP alters atmospheric response vector at ARM SGP

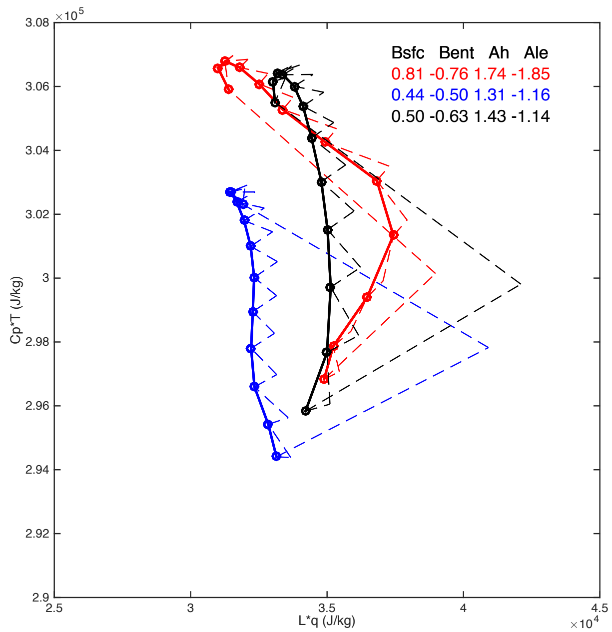


Figure: Hourly decomposition of mixing diagram from 2m T and Q at ARM SGP site in SPCAM (red), CAM (blue) and ARMBE (black).

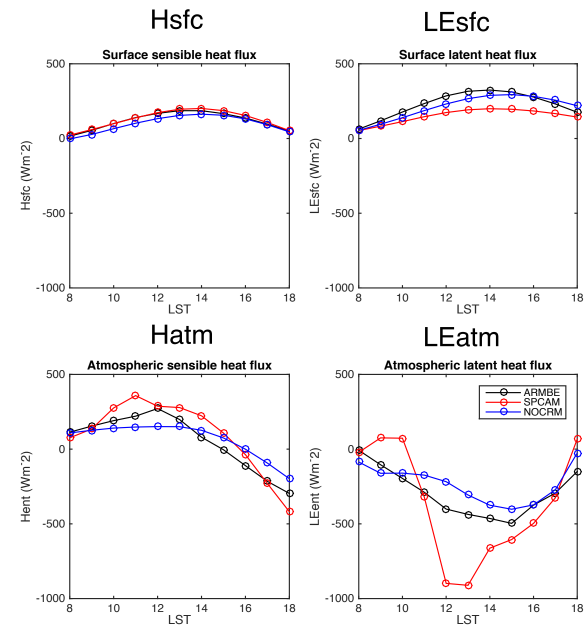


Figure: Diurnal cycle of each component in the surface and atmospheric response vectors shown at left.

- SP introduces a desirous but exaggerated counterclockwise rotation of the 2-m atmospheric response vector in the T-Q plane, from a morning heating- to afternoon drying-dominated regime.
- Relative to ARM data, the diurnal moisture cycle is too extreme in SP, and an unrealistic "atmospheric response" of early morning moistening occurs.

Bulk PBL energetics are insensitive to SP

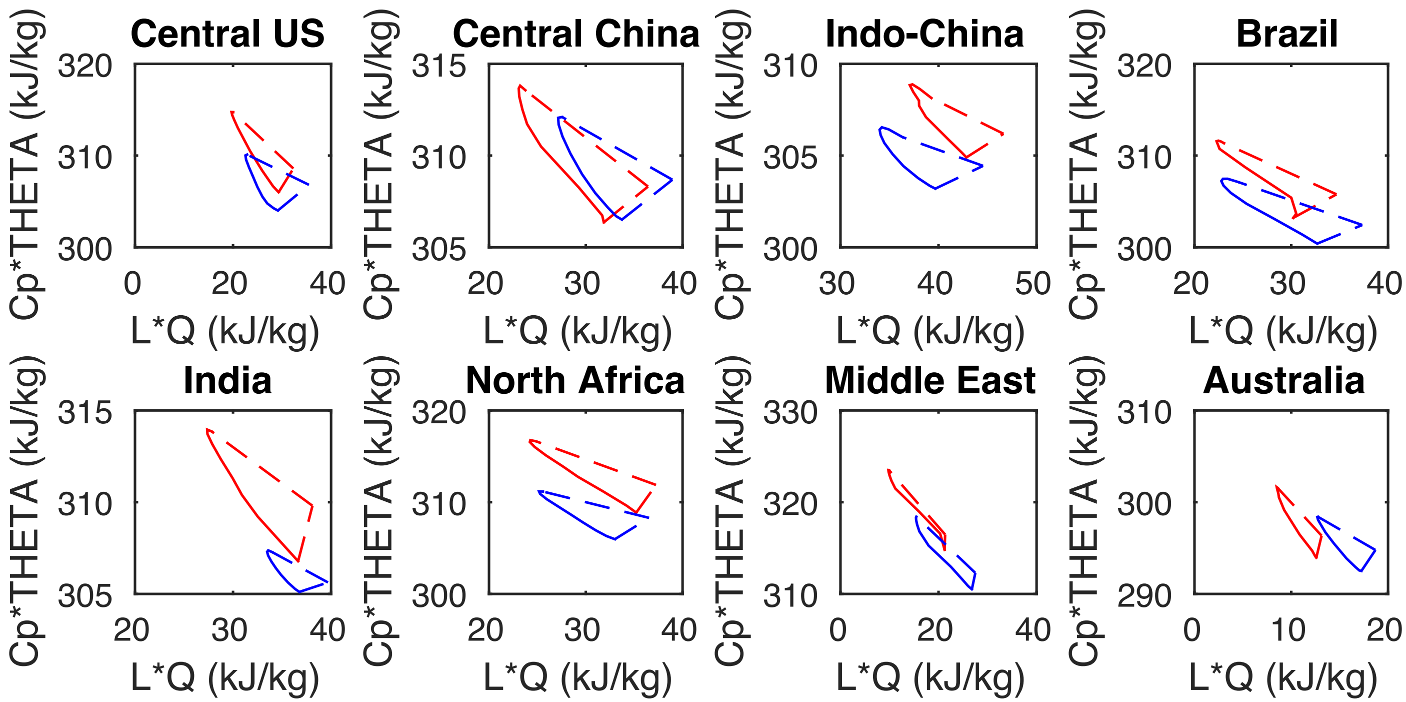


Figure: Mixing diagrams of SPCAM3.5 (red) and CAM3.5 (blue) with integrated PBL mean temperature and humidity during daytime (LST 8am-5pm) in eight grids globally.

- In mixing diagrams with explicitly integrated PBL mean heat and moisture, the early morning moistening process (as seen in 2m T-Q diagrams) nearly disappears at all locations, implying it is mostly a near surface effect.

SP effects on near-surface PBL diurnal dynamics at ARM SGP

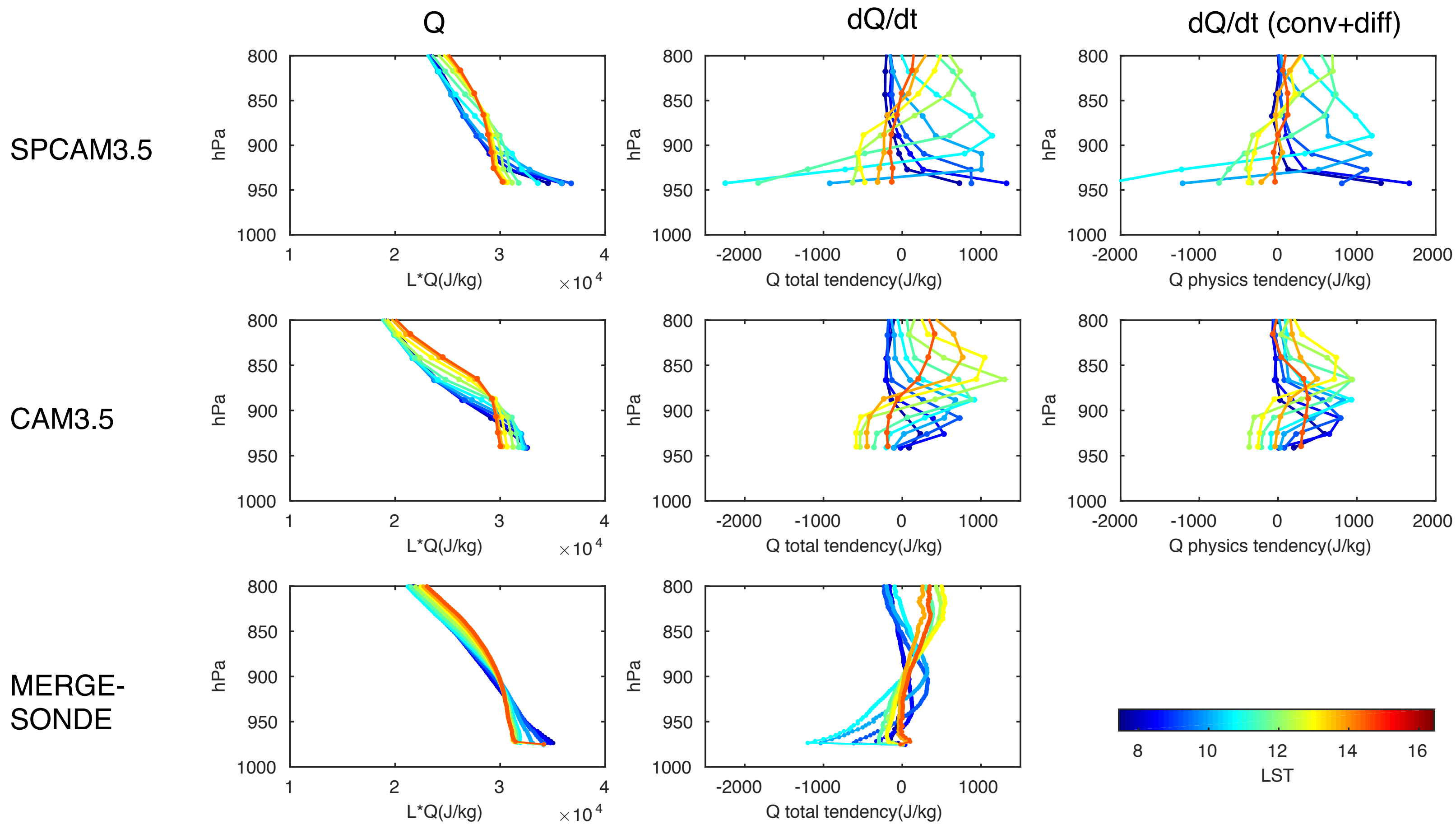


Figure: Mean diurnal cycle at ARM SGP of PBL heat content (left column), its tendency (center column) and the tendency due to moist convection plus vertical diffusion (right column).

- SP introduces enhanced moisture contrast between lowest and overlying model levels.
- SP introduces observed late morning surface-amplified drying, but the magnitude is too strong
- SP introduces unobserved early morning near-surface moistening

SP effects on near-surface PBL diurnal dynamics at ARM SGP

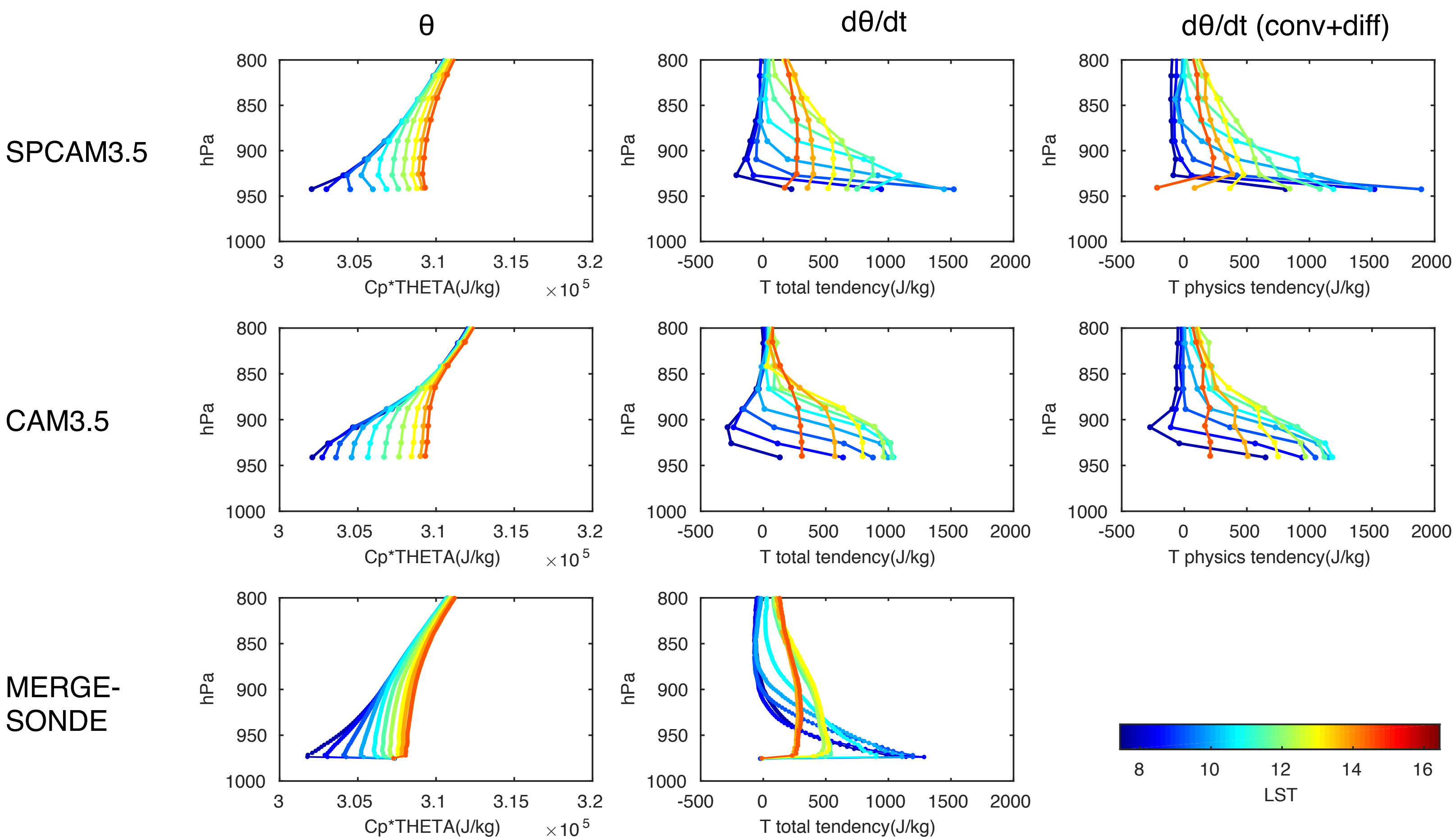


Figure: Mean diurnal cycle at SGP of PBL heat (left column), its tendency (center column) and the tendency due to moist convection plus vertical diffusion (right column).

- SP introduces enhanced heat contrast between lowest and overlying model levels.
- In SP, early morning sensible heating is trapped in the lowest model level leading to exaggerated near-surface heating rate.

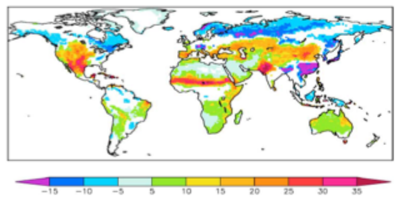
Summary and conclusions

- SP alters the geographical distribution of strong terrestrial segment coupling regions although the overall magnitude does not change much globally.
- Overall, SP reduces TFS signal (rainfall triggering), while strengthens AFS signal (rainfall amount).
- North America: regional distributions of PBL height and LCL sensitivities to EF match that of TFS signal in SP, but not in CAM.
- SP strongly amplifies diurnal heating and especially moistening in the model layer immediately adjacent to the land surface. The lowest model level's state properties are less tightly coupled to overlying model levels than in CAM.
- Trapping of early morning surface fluxes in the lowest model layer of CRM.
- Compared to ARM data, the early morning moistening in SPCAM is unrealistic but the emergence of late morning surface-amplified drying is an improvement over CAM.

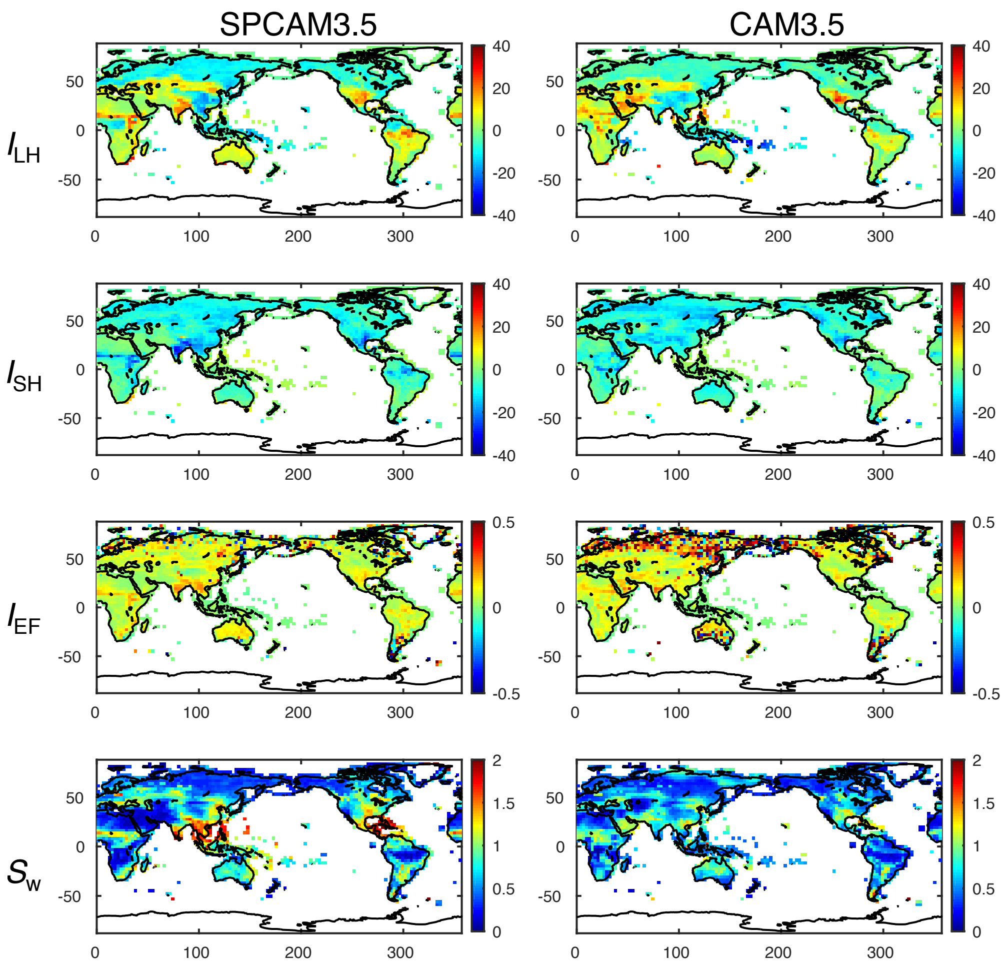
Thank you!

SP effects in terrestrial segment

$$I_\phi = s_w \beta_\phi$$

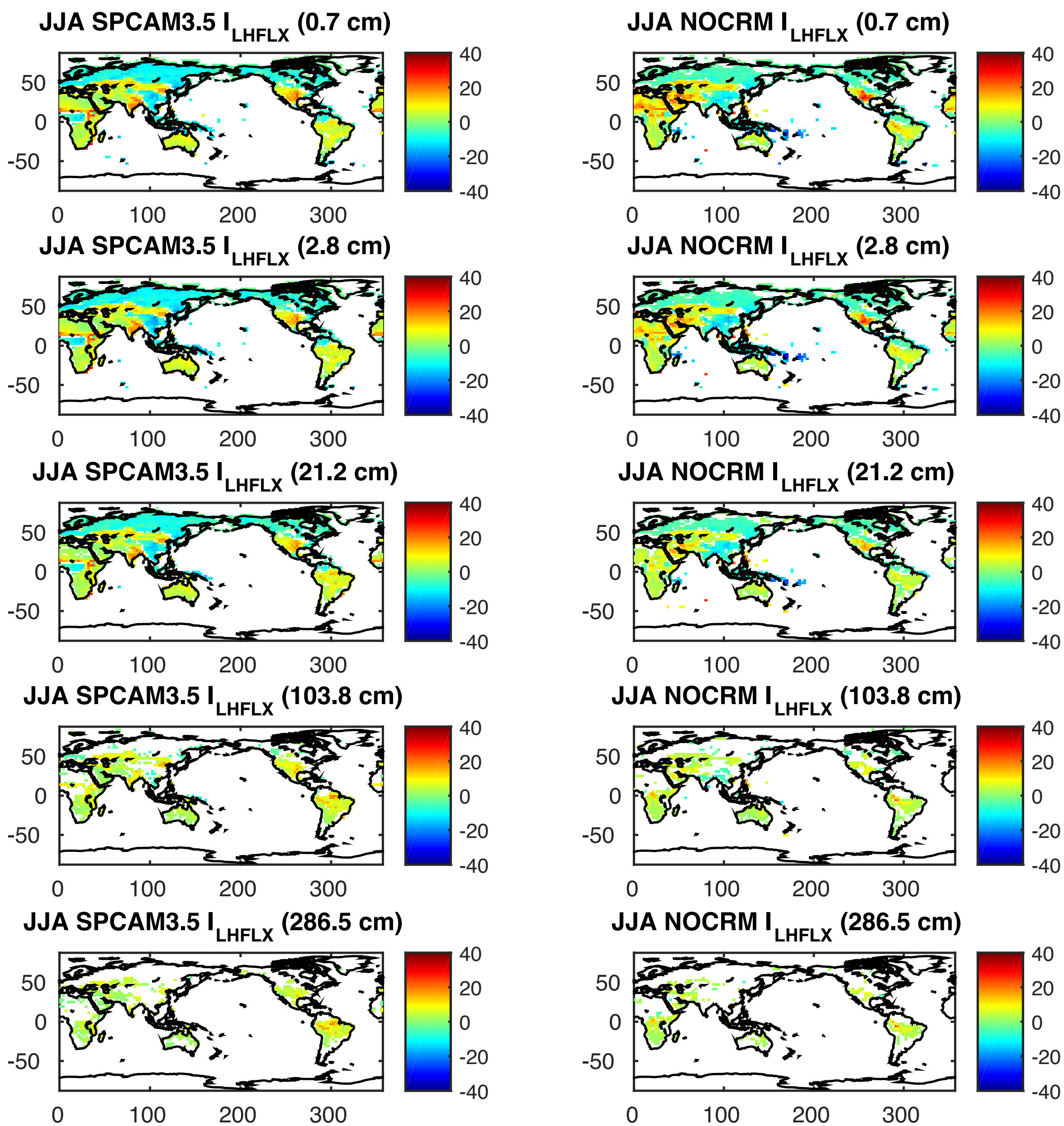


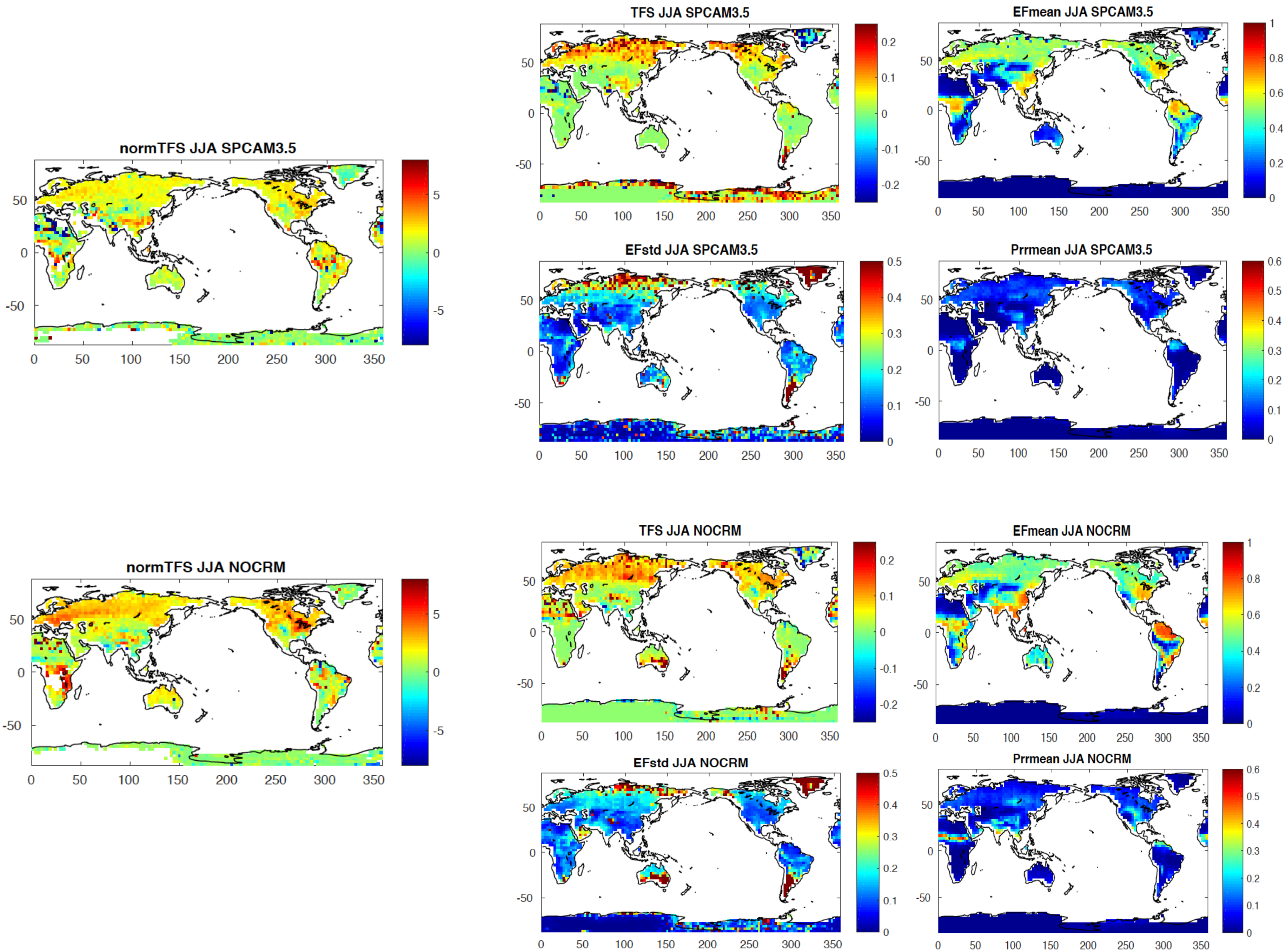
I_{LH} of GSWP-2 data (10 JJAs), figure from Dirmeyer (2011).



- Regional patterns of the terrestrial coupling index are different, although the overall magnitudes are similar.
- The model discrepancies are distributed differently when considering different fluxes in the coupling index.
- The regions displaying different strength of the terrestrial coupling signals generally show different variations of soil moisture (due to precipitation).

Figure: Terrestrial coupling indices of soil moisture (top 3cm) and latent heat flux(LH), sensible heat flux(SH), and evaporation fraction(EF), standard deviation of soil moisture (SM) anomalies of 15 JJAs.


JJA SPCAM3.5 I_{LHFLX} (0.7 cm)
JJA NOCRM I_{LHFLX} (0.7 cm)
JJA SPCAM3.5 I_{LHFLX} (2.8 cm)
JJA NOCRM I_{LHFLX} (2.8 cm)
JJA SPCAM3.5 I_{LHFLX} (21.2 cm)
JJA NOCRM I_{LHFLX} (21.2 cm)
JJA SPCAM3.5 I_{LHFLX} (103.8 cm)
JJA NOCRM I_{LHFLX} (103.8 cm)
JJA SPCAM3.5 I_{LHFLX} (286.5 cm)
JJA NOCRM I_{LHFLX} (286.5 cm)
50
0
-50
0
100
200
300
40
20
0
-20
-40


TFS JJA SPCAM3.5
EFmean JJA SPCAM3.5
normTFS JJA SPCAM3.5
EFstd JJA SPCAM3.5
Prrmean JJA SPCAM3.5
TFS JJA NOCRM
EFmean JJA NOCRM
normTFS JJA NOCRM
EFstd JJA NOCRM
Prrmean JJA NOCRM