Dominating Controls for Wetter South Asia Summer Monsoon in the 21st Century

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Summary

We analyze a suite of GCMs from the 5th Phase of Coupled Models Intercomparison Project (CMIP5) archives to understand the mechanisms behind a net increase in the South Asian summer monsoon precipitation in response to enhanced radiative forcing during the 21st century despite a robust weakening of the monsoon circulation. Combining the future changes in the contributions from various moisture sources, which contribute to the moisture supply over South Asia, with those in monsoon circulation and atmospheric moisture content, we establish a pathway of understanding that partly explains these counteracting responses to increase in radiative forcing. Our analysis suggests that both regional (local recycling, Arabian Sea, Bay of Bengal) and remote (mainly Indian Ocean) sources contribute to the moisture supply for precipitation over South Asia during the summer season that is facilitated by the monsoon thermodynamics. Increase in radiative forcing fuels an increase in the atmospheric moisture content through warmer temperatures. For regional moisture sources, the effect of excessive atmospheric moisture is offset by weaker monsoon circulation and uncertainty in the response of the evapotranspiration over land, so anomalies in their contribution to the total moisture supply are either mixed or muted. In contrast, weakening of the monsoon thermodynamics has less influence on the moisture supply from remote source that not only is a dominant moisture contributor in the baseline period, but is also the net driver of the positive summer monsoon precipitation response in the 21st century. Our results also indicate that historic measures of the monsoon dynamics may not be well suited to predict the non-stationary moisture driven South Asian summer precipitation response in the 21st century.

Data and Methods

We analyze the GCMs outputs over the South Asian monsoon region from CMIP5 historical (1965-2005) and Representative Concentration Pathway 8.5 (RCP8.5; 2010-2099) experiments. We select 18 models for the historical period but 14 for RCP8.5 period based on the availability of ***6-hourly*** model output at the time of analysis, and use one ensemble run from each model. In addition, we analyze the NCEP/NCAR reanalysis I (NCEP R1) data in comparison with the model output over the historical period.

We analyze changes in ***three*** thermodynamic indicators used to quantify the strength of monsoon, together with three moisture terms (namely atmospheric precipitable water, moisture convergence and evaporation) used to quantify the apparent moisture supply for precipitation.

1) *Meridional tropospheric temperature gradient* (MTG), defined as the difference of climatological mean temperature between the upper tropospheric layers (200mb to 500mb) at 30°N and 5°N.

2) *Local Walker circulation index* (U-shear), defined as the vertical easterly shear of zonal winds between 200mb and 850mb averaged over 0°N-15°N and 50°N-85°E.

3) *Local Hadley circulation index* (V-shear), defined as the vertical meridional wind shear between 200mb and 850mb averaged over 5°N-30°N and 70°N-110°E.

Moisture Tracking Method

We use a Lagrangian moisture tracking method, developed by Dominguez et al. (2006), to determine the moisture sources that contribute to moisture supply over the South Asian sub-continent during JJAS, and the effects of increase in radiative forcing on their contributions to the changes in summer precipitation in the 21st century.

The variables used in the analysis of precipitation sources include daily precipitation and evaporation, and 6-hourly 3-dimensional horizontal wind and specific humidity. We define four exclusive but complementary moisture sources for the South Asian monsoon precipitation region:

1) ***Local*** - land grid points between 5°N to 40°N and 70°E to 90°E,

2) ***Arabian Sea*** - ocean grid points between 5°N to 30°N and 45°E to 80°E,

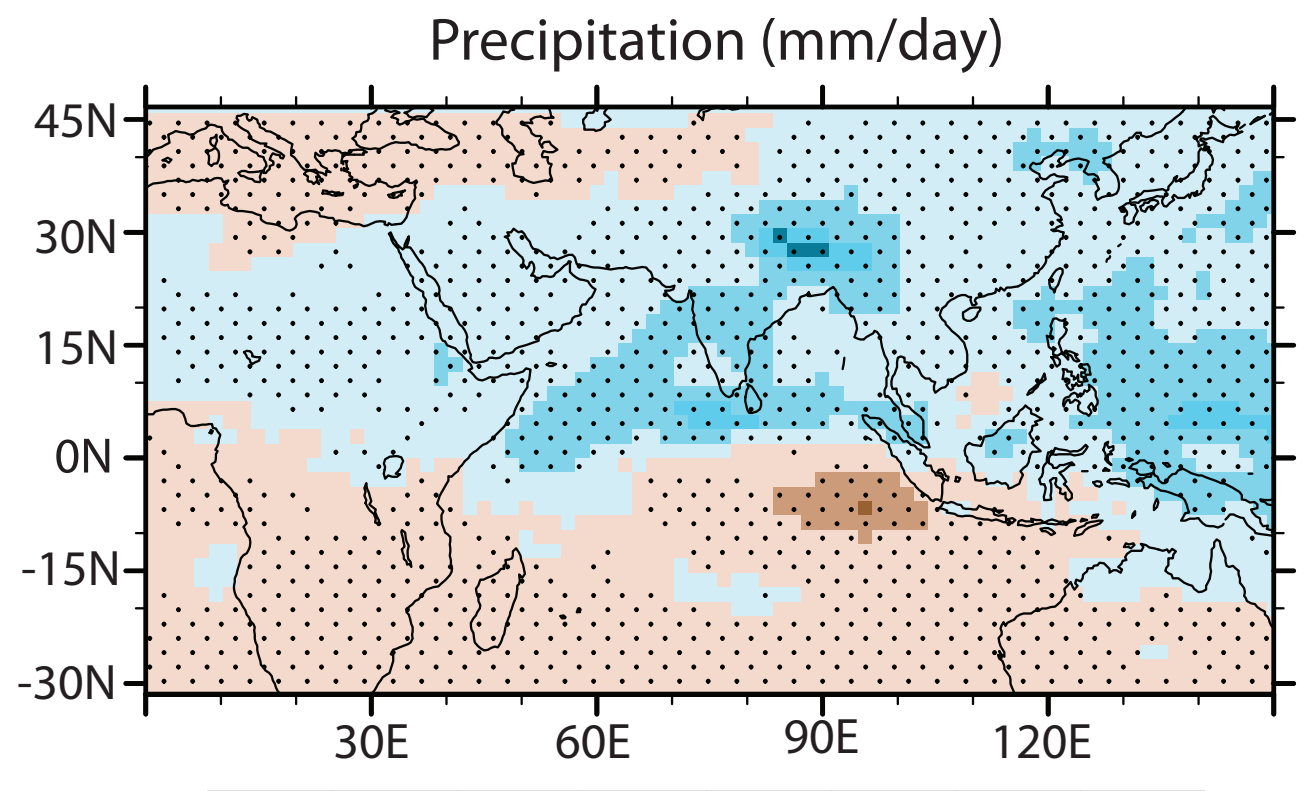
3) ***Bay of Bengal*** - ocean grids points between 5°N to 30°N and 80°E to 100°E, and

4) ***Remote*** - the rest of the globe (inferred based on the first three sources).

This precipitation sourcing analysis is restricted to the moisture over an evaporative moisture source domain spanning from 30°S to 45°N along the latitude and 0°E to 150°E along the longitude (Figure 1a), which can explain more than 90% of summer monsoon precipitation.

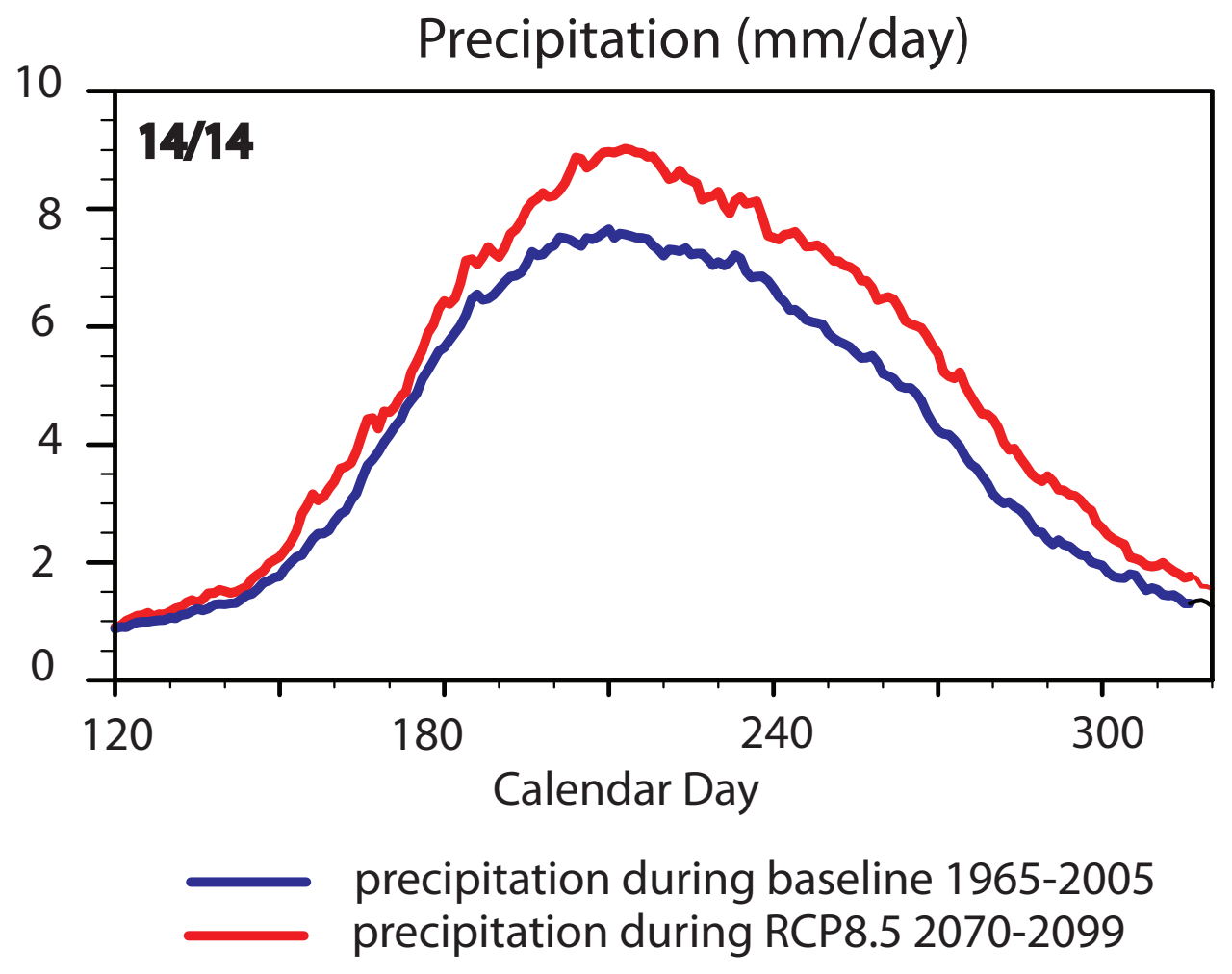
We present the results from our analysis with the multi-model mean. Only late 21st century period is shown here. We consider a projected signal as robust if two-thirds of the examined CMIP5 models simulate a response identical in sign to that of the multi-model mean.

Changes in precipitation in the late 21st century



1)

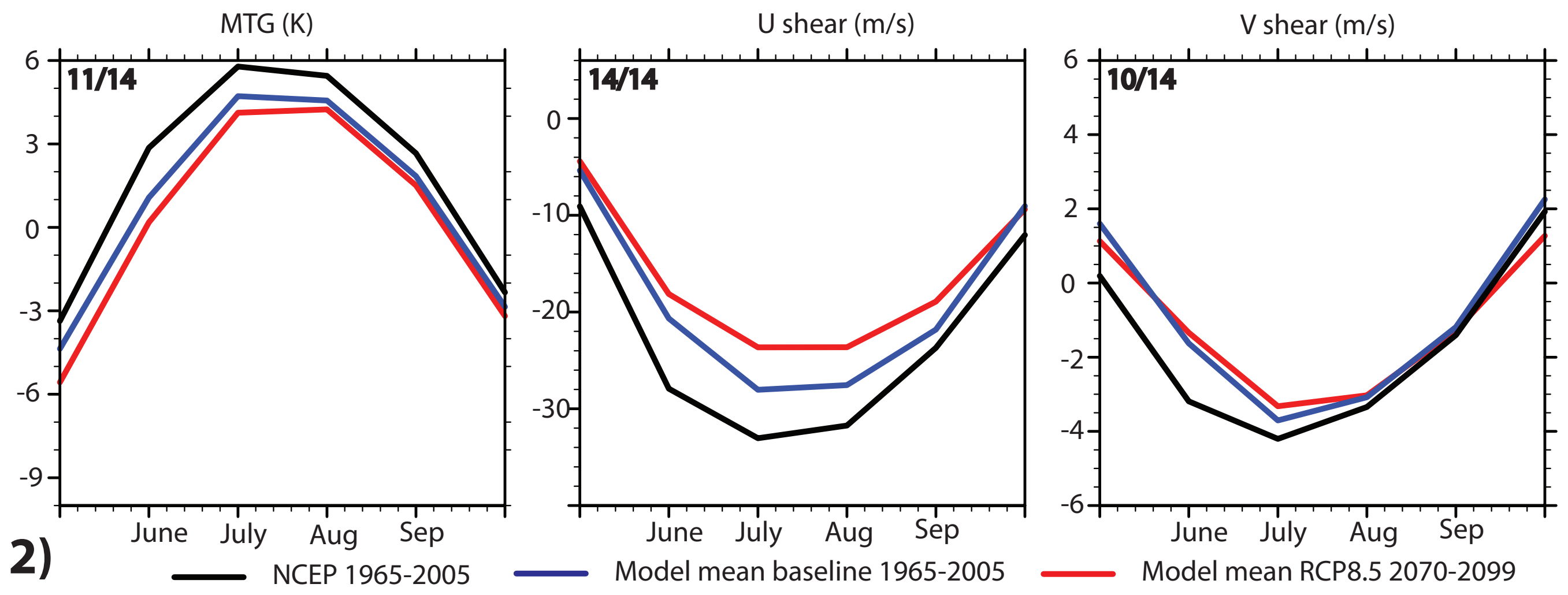
Change (2070-2099 minus 1965-2005) in summer precipitation spatial pattern (stippled area indicates more than 2/3 of the models show the same sign of change as multi-model mean)



Comparison of annual cycle of precipitation amount over continental South Asia ("N/14" in the panel indicates N out of 14 models show the same sign of change as multi-model mean)

Monsoon Dynamics in the 1965-2005 and RCP8.5 2070-2099 periods

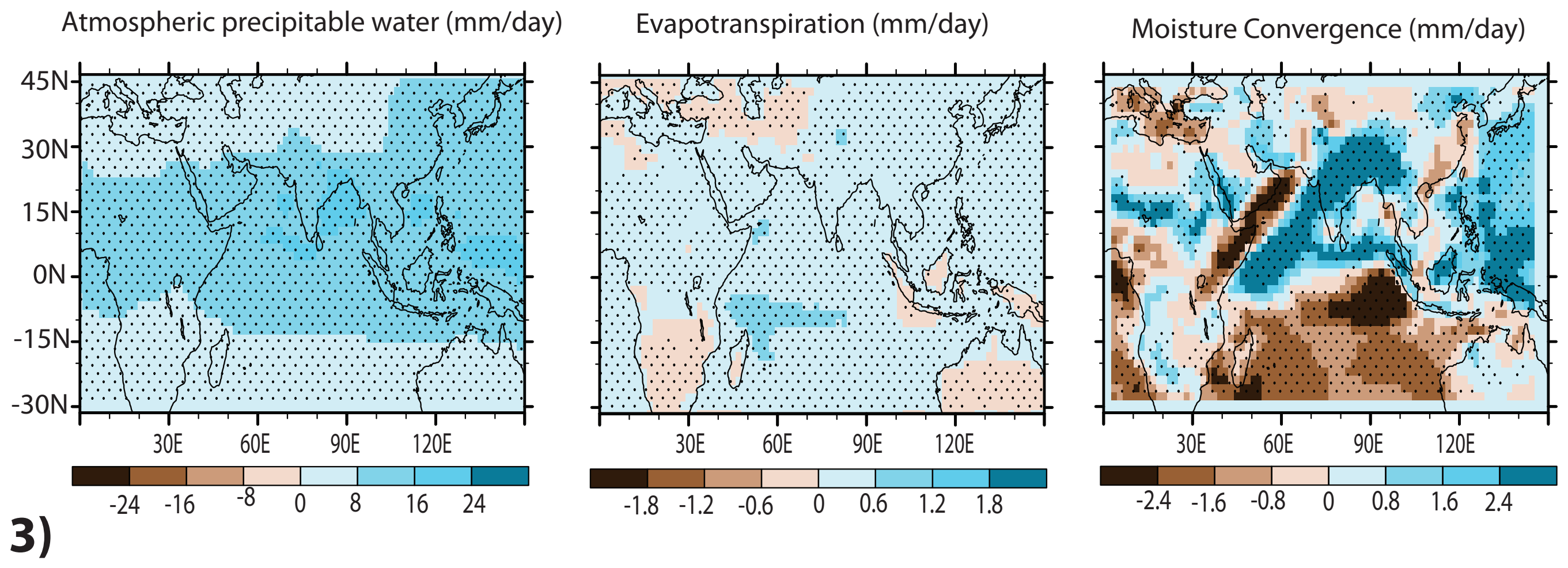
Comparison of Meridional Tropospheric temperature gradient (MTG), Easterly vertical shear of zonal wind (U-shear) and Vertical meridional wind shear (V-shear)



2)

Changes (2070-2099 minus 1965-2005) in three moisture terms

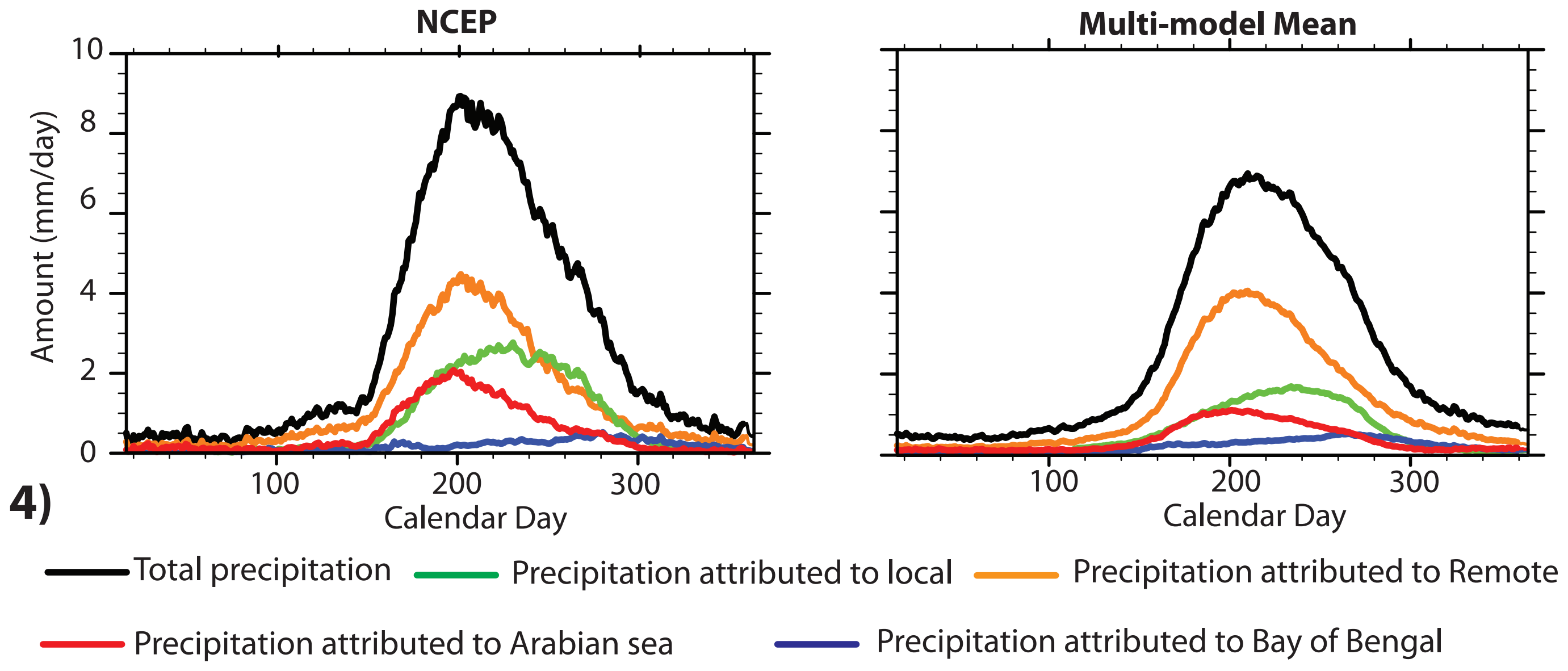
Change (2070-2099 minus 1965-2005) in summer atmospheric precipitable water, evapotranspiration and moiture convergence (stippled area indicates more than 2/3 of the models show the same sign of change as multi-model mean).



3)

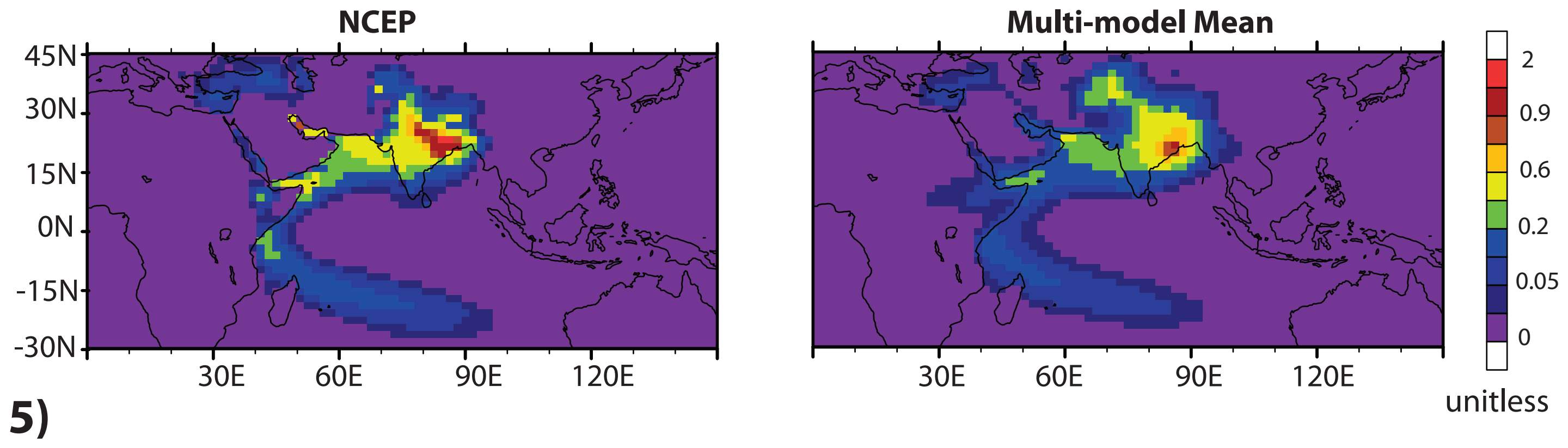
Precipitation sources over South Asia

Annual cycle of precipitation amount and its four contributing moisture sources in 1965-2005 period in NCEP R1 and multi-model CMIP5 GCMs mean



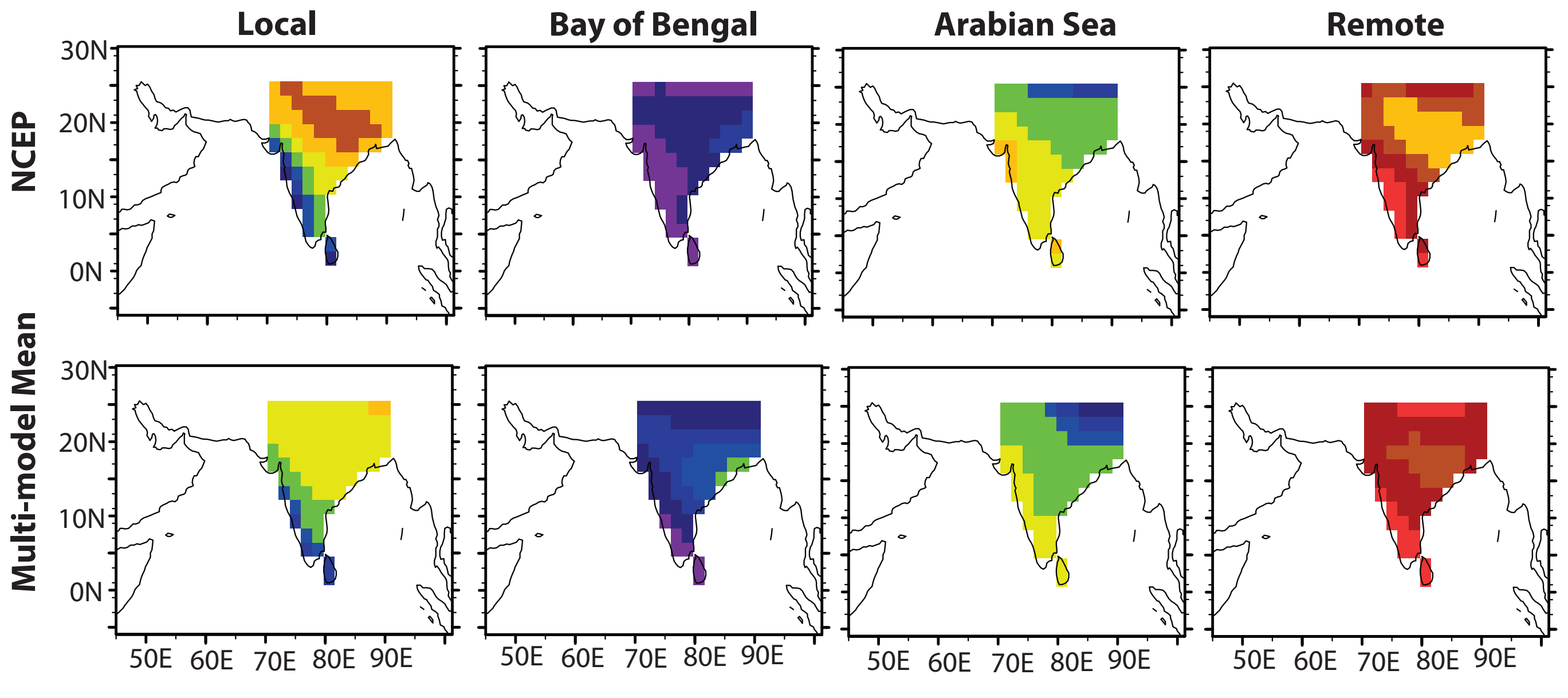
4)

Percentage contribution to continental South Asian summer precipitation from the evaporative source domain (normalized) in 1965-2005 period in NCEP R1 and multi-model CMIP5 GCMs mean



5)

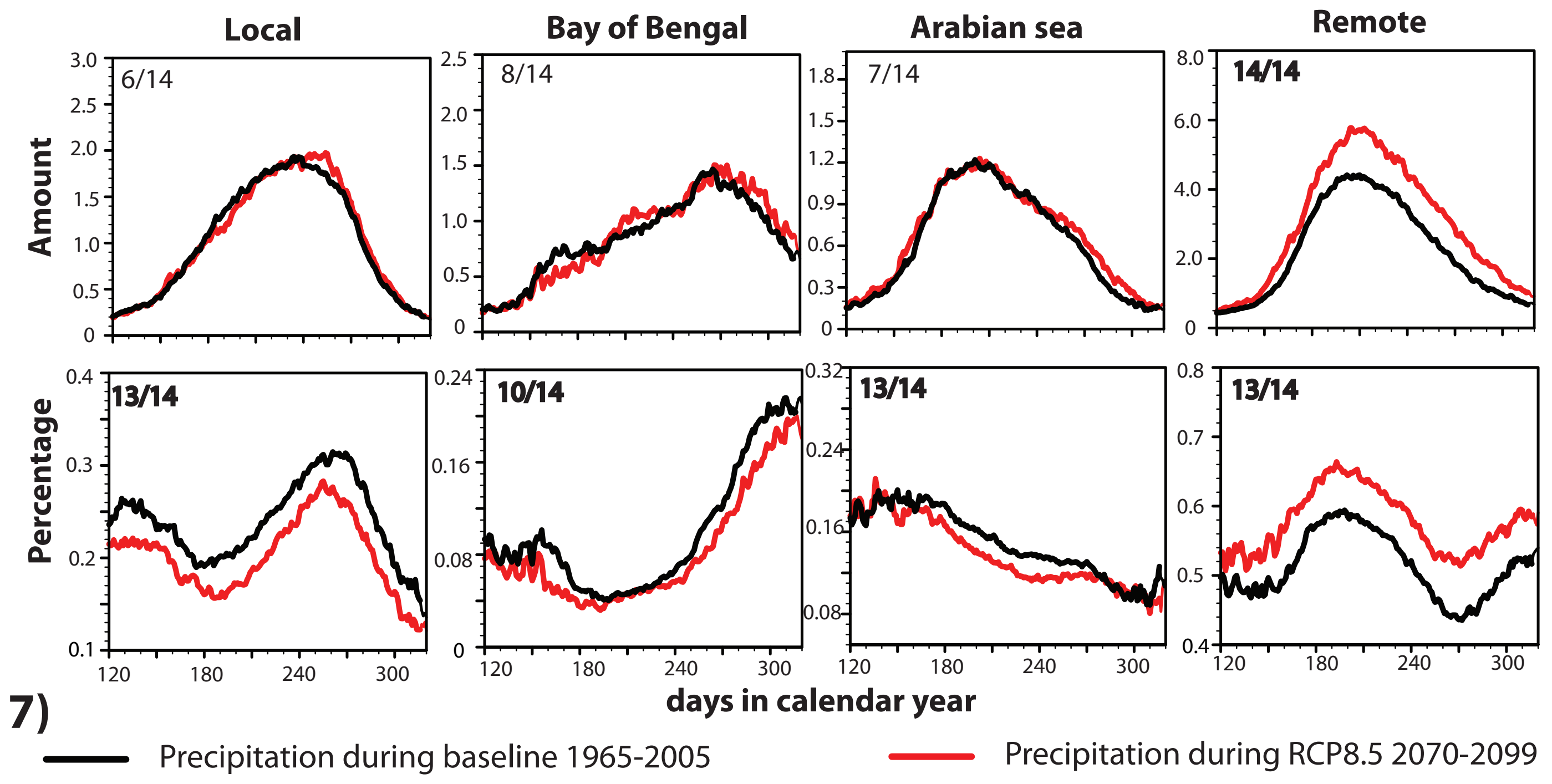
Summer precipitation percentage contribution to each gridcell of South Asian continent from different sources in 1965-2005 period in NCEP R1 and multi-model CMIP5 GCMs mean



6)

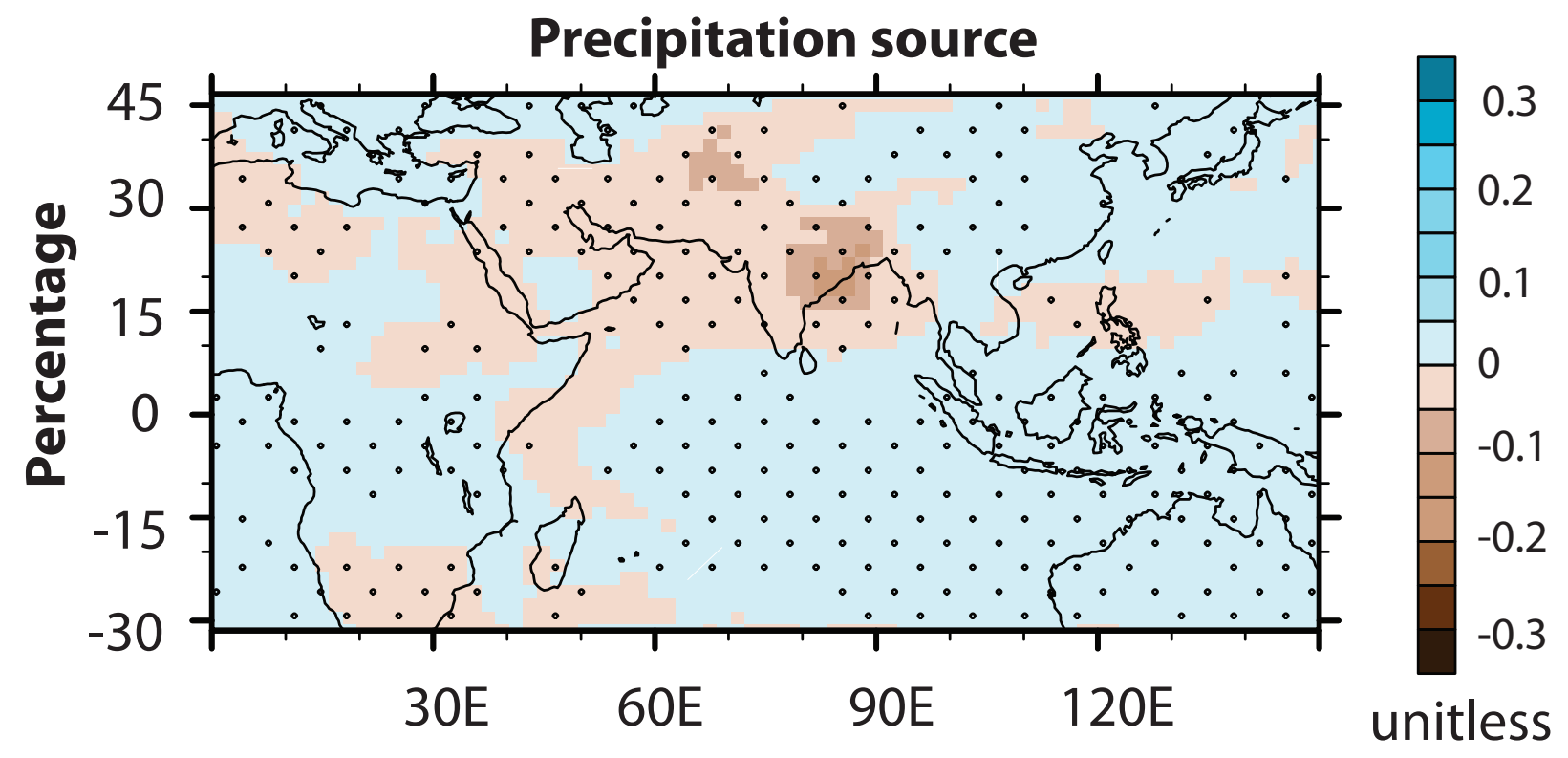
Changes in precipitation sources over South Asia in the 21st century

Comparison of Annual cycle of precipitation amount/percentage from different contributing sources

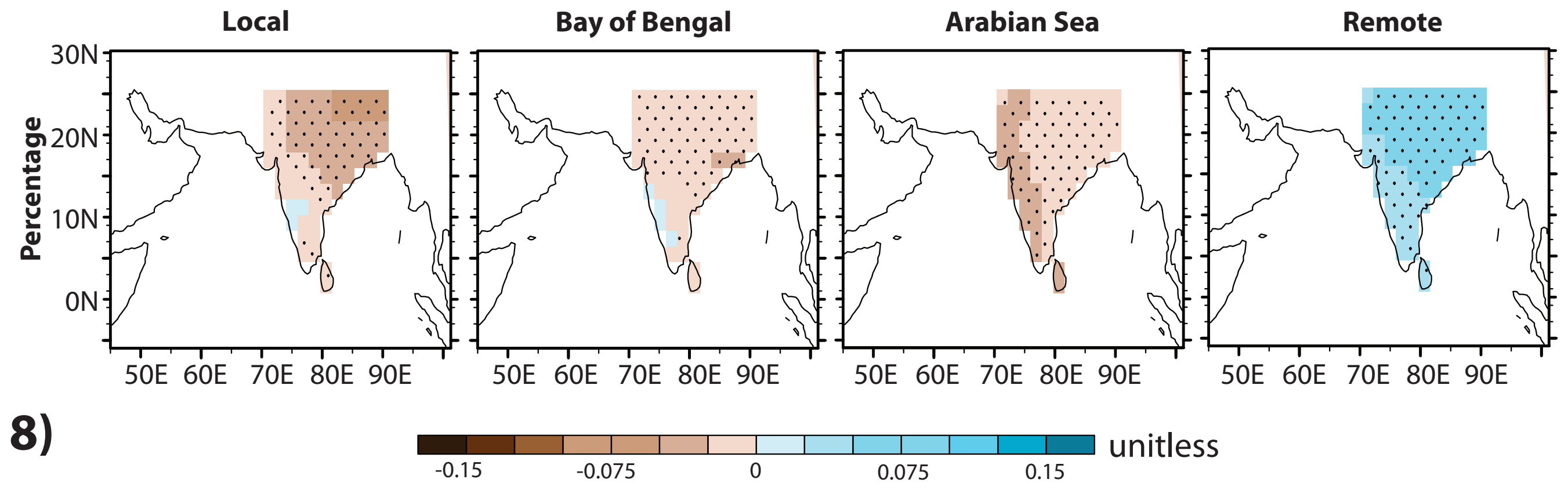


7)

Change (2070-2099 minus 1965-2005) in percentage contribution to continental South Asian summer precipitation from the evaporative source domain (normalized)



Change (2070-2099 minus 1965-2005) in summer precipitation percentage contribution to each grid cell of South Asian continent from different sources (stippled area indicates more than 2/3 of the models show the same sign of change as multi-model mean)



8)

Main Points

We, for the first time, show various moisture sources that contribute to the summer precipitation over the South Asia (4-6). Our analysis suggests that both regional (local recycling, Arabian Sea, Bay of Bengal) and remote (mainly Indian Ocean) sources contribute to the moisture supply for precipitation over South Asia during the summer season that is facilitated by the monsoon thermodynamics.

Among the four defined moisture sources, remote contributes the most representing 46% (55%), followed by the local recycling representing 30.4% (23%), Arabian Sea contributing 19.6% (15%) and Bay of Bengal contributing 4% (7%) in the analyzed GCMs (NCEP R1) (4).

More than two-thirds of the 14 models simulate an increase in the absolute and percentage contributions from remote sources and a decrease in percentage contributions from all regional sources. However, there is no consensus among the models in the simulation of future changes in the absolute contribution from regional sources (7).

Increase in radiative forcing fuels an increase in the atmospheric moisture content through warmer temperatures (3). For regional moisture sources, the effect of excessive atmospheric moisture is offset by weaker monsoon circulation and uncertainty in the response of the evapotranspiration over land, so anomalies in their contribution to the total moisture supply are either mixed or muted (3 and 7).

In contrast, weakening of the monsoon thermodynamics has less influence on the moisture supply from remote source that not only is a dominant moisture contributor in the baseline period, but is also the net driver of the positive summer monsoon precipitation response in the 21st century (6 and 7). More than two-thirds of the 14 models simulate an increase in the absolute and percentage contributions from remote sources.

Our analysis also indicates that traditional measures of South Asian monsoon strength may be less applicable to evaluating precipitation changes in the warmer and moister climate of the 21st century.

Acknowledgment
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