Anthropogenic aerosols and the weakening of the South Asian summer monsoon

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Aerosols: **much more** than "offset" GHGs → complex changes in regional water cycle and climate (still not fully understood or even known)

Monsoon: driven by differential heating. Aerosols interacts with monsoon heat sources and sinks, and alter the **land-sea thermal contrast**

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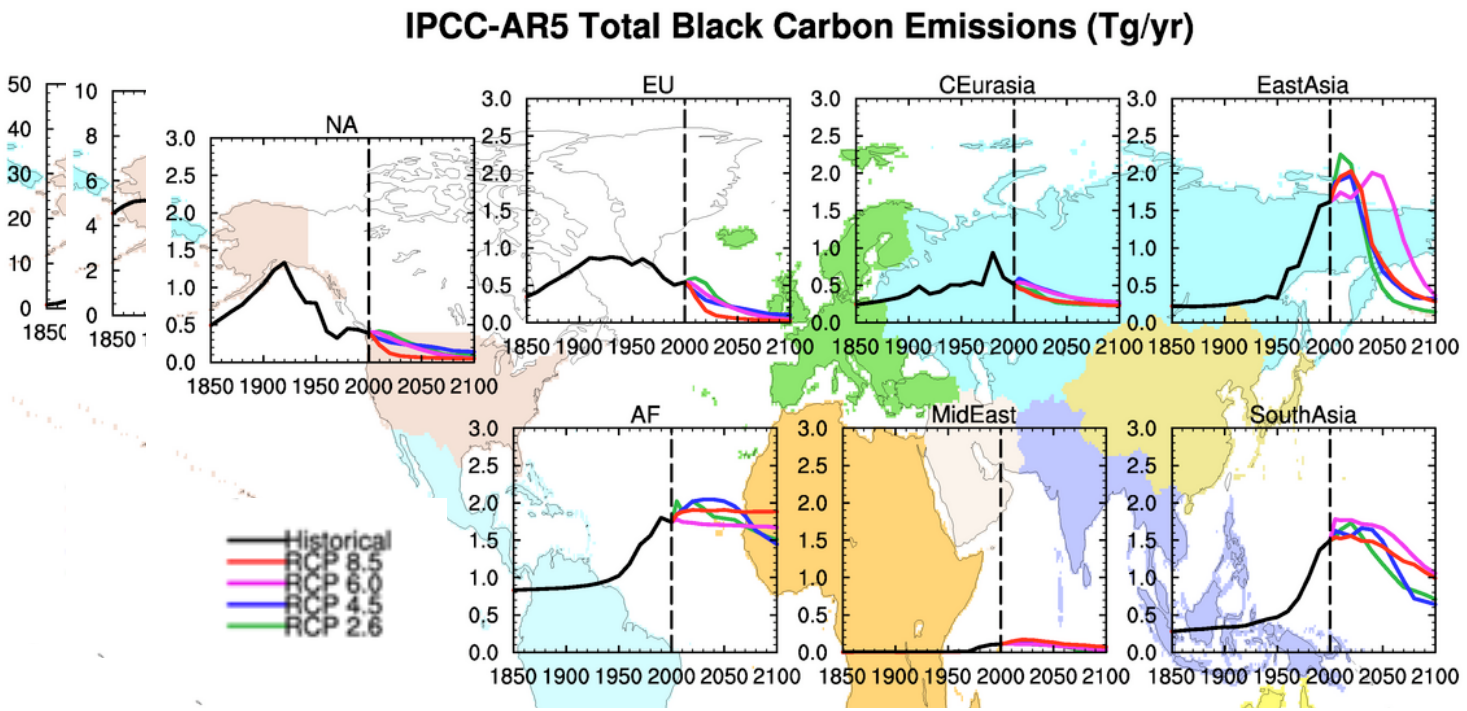
Global aerosol variations: past and future emissions



Courtesy of V. Naik (GFDL)

- The true magnitude of the GHG warming is not known, as well as climate forcing/sensitivity (e.g., Kiehl 2007)
- Aerosols will continue to play a role in regional climate change
- Realistic predictions of future climate change depend on climate models able to accurately represent not just present climate, but also the changes that have occurred over the past century
- Mitigation of warming by geo-engineering

Anthropogenic aerosols and the SA monsoon

Observational studies (e.g., Ramanathan et al. 2005; Goswami et al. 2006; Kumar et al. 2006; Rajeevan et al. 2008; Dash et al. 2009; Gosh et al. 2009; Lau and Kim 2010): **drying trend** from the 50s, contradictory results, incomplete physical insight into the large-scale dynamics and mechanisms

Both aerosol forcing and global warming influence the South Asian monsoon

- **Sulfate aerosols**: reduction of monsoon precipitation (e.g., Mitchell and Johns 1997; Ra

- **BC**: Co

Was the widespread drying caused by natural variability or human influence?

If the latter, what were the contributions of anthropogenic greenhouse gases and aerosols?

- **GHGs**: Despite a weakening of the tropical circulation, most studies project an intensified monsoon rainfall (e.g., Hu et al. 2000; Meehl et al. 2000; Meehl and Arblaster 2003; May 2004; Ueda et al. 2006; Annamalai et al. 2007; Kripalani et al. 2007; Dairaku et al. 2008)

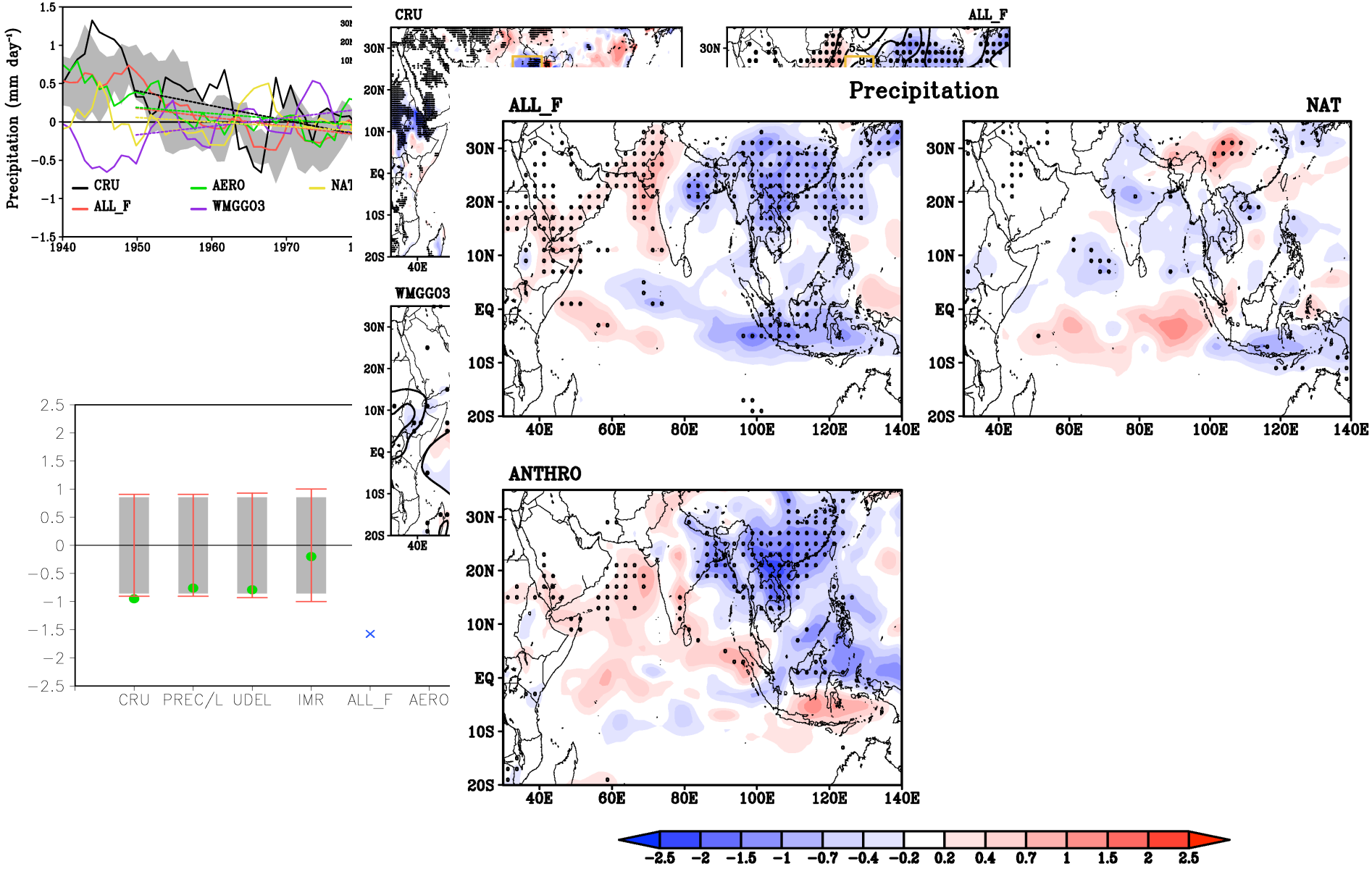
Incomplete treatment of aerosol effects, offline aerosols
Large uncertainties due to a relatively poor model skill for monsoon simulation at regional scale

The GFDL coupled model and Experiments

- GFDL coupled atmosphere-ocean GCM CM3 (~200 km, 48 levels; Donner et al. 2011):
  - **Improved** and more comprehensive representation of **aerosol physics** and effects, including the **indirect** ones in liquid clouds; improved parameterization of **aerosol-cloud** interactions; internal mixing
  - Starting from emissions, aerosols are transported and removed (forward approach)
  - **Realistic simulation** of the climatological monsoon features at regional scale
  - **Simulated aerosol properties** compare well with observations

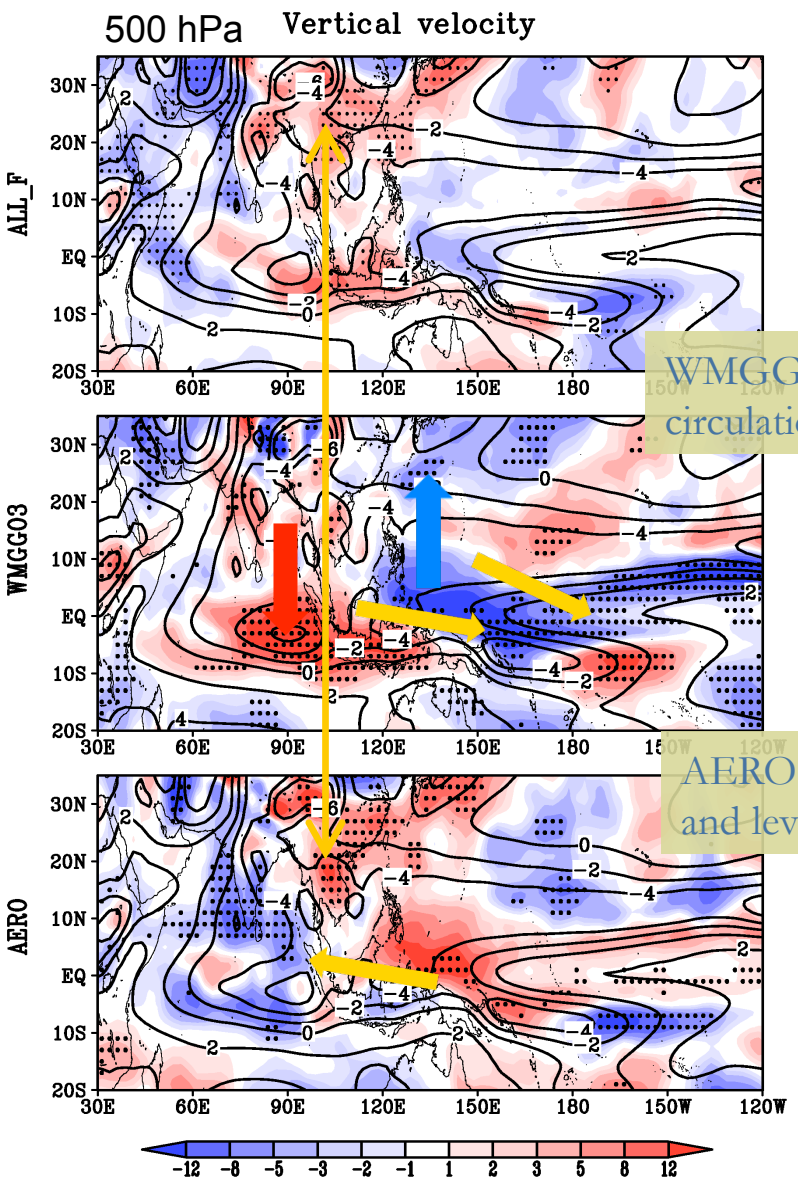
- *Historical perturbation experiments* (1860-2005):
  - **All-forcing** (ALL_F): 5 members, natural and anthropogenic forcings
  - **Greenhouse and ozone-only** forcing (WMGGO3): 3 members, GHGs and ozone
  - **Aerosol-only** forcing (AERO): 3 members, aerosols
  - **Natural-only** forcing (NAT): 3 members, solar variations and volcanoes
  - **Anthropogenic-only** forcing (ANTHRO): 3 members, GHGs, ozone, aerosols, and land use
- *Control run* (800 years): time-invariant radiative forcing agents fixed at 1860 values

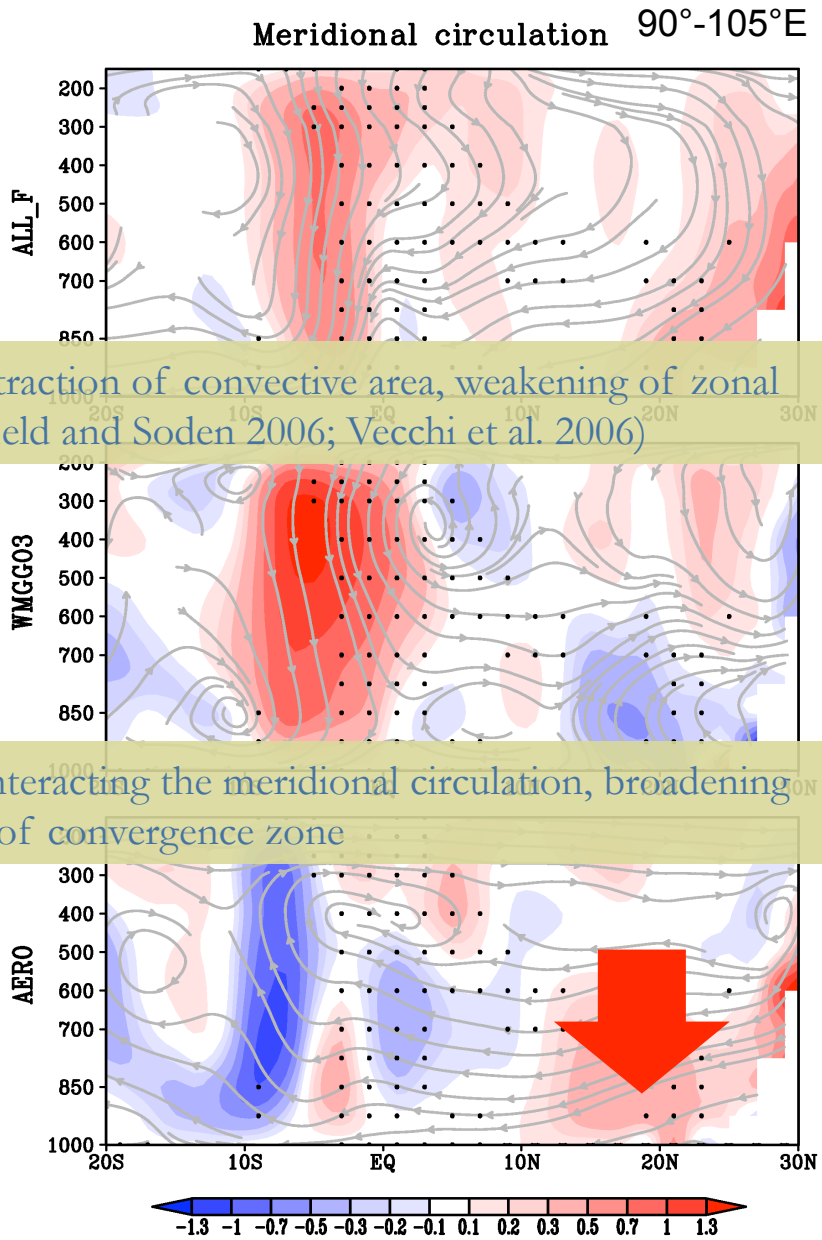
Precipitation trend in observations and CM3 model experiments



AERO = meridional direction; WMGG = along Equator

Circulation changes



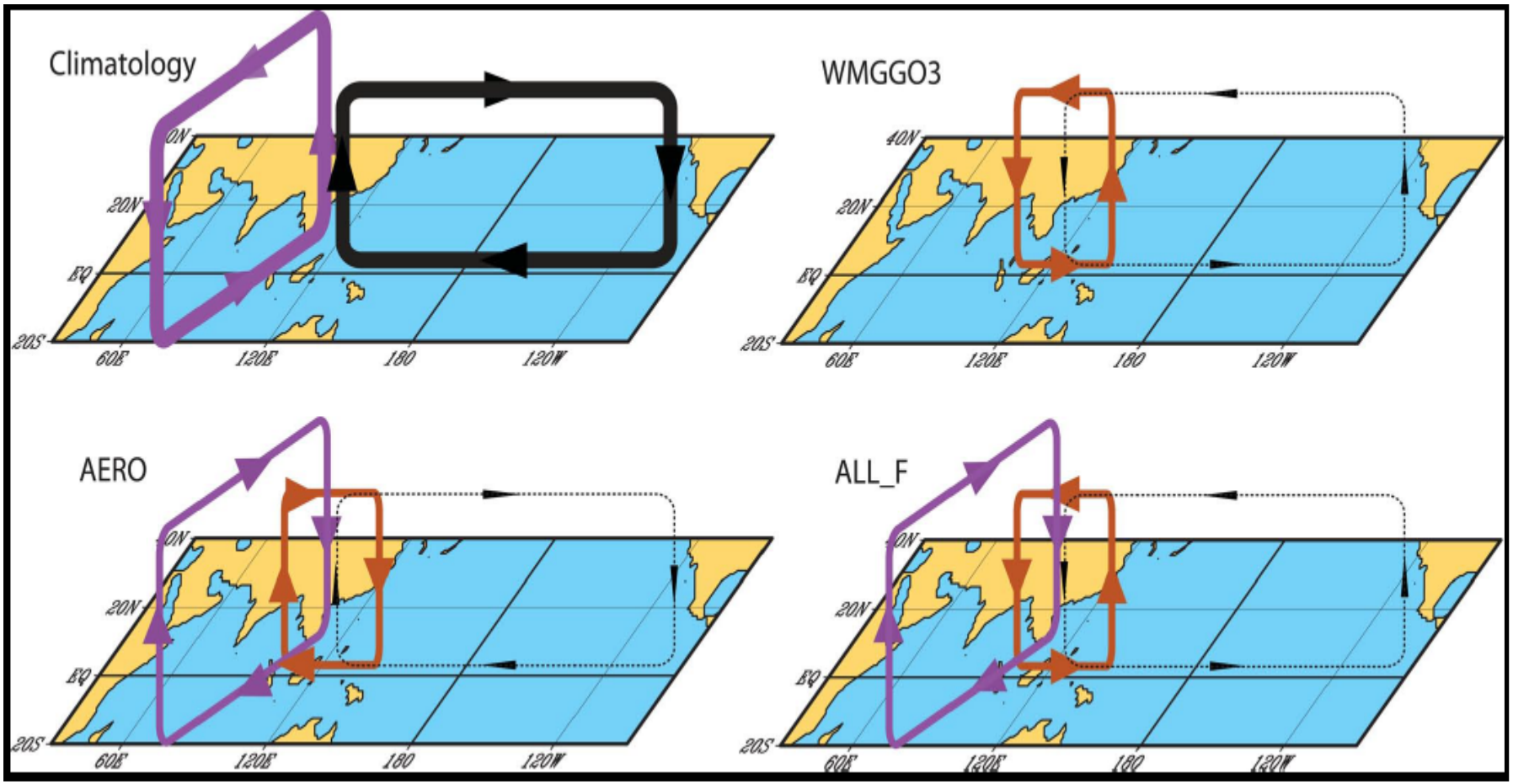


WMGG: contraction of convective area, weakening of zonal circulation (Held and Soden 2006; Vecchi et al. 2006)

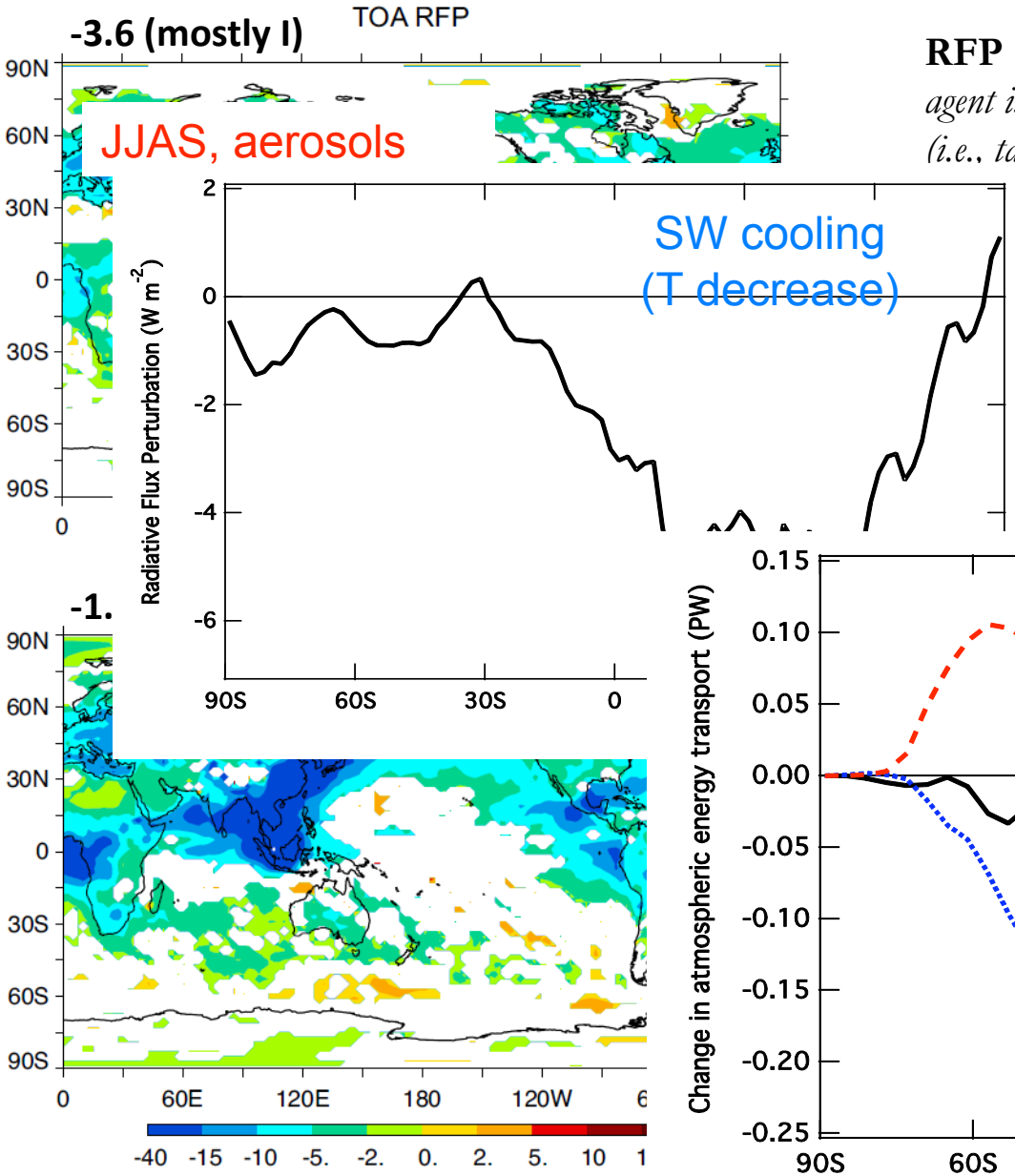
AERO: counteracting the meridional circulation, broadening and leveling of convergence zone

Schematic of the changes

Thermodynamical (WMGG, zonal) vs. *dynamical* (AERO, meridional) components of the tropical circulation adjustment to radiative forcing



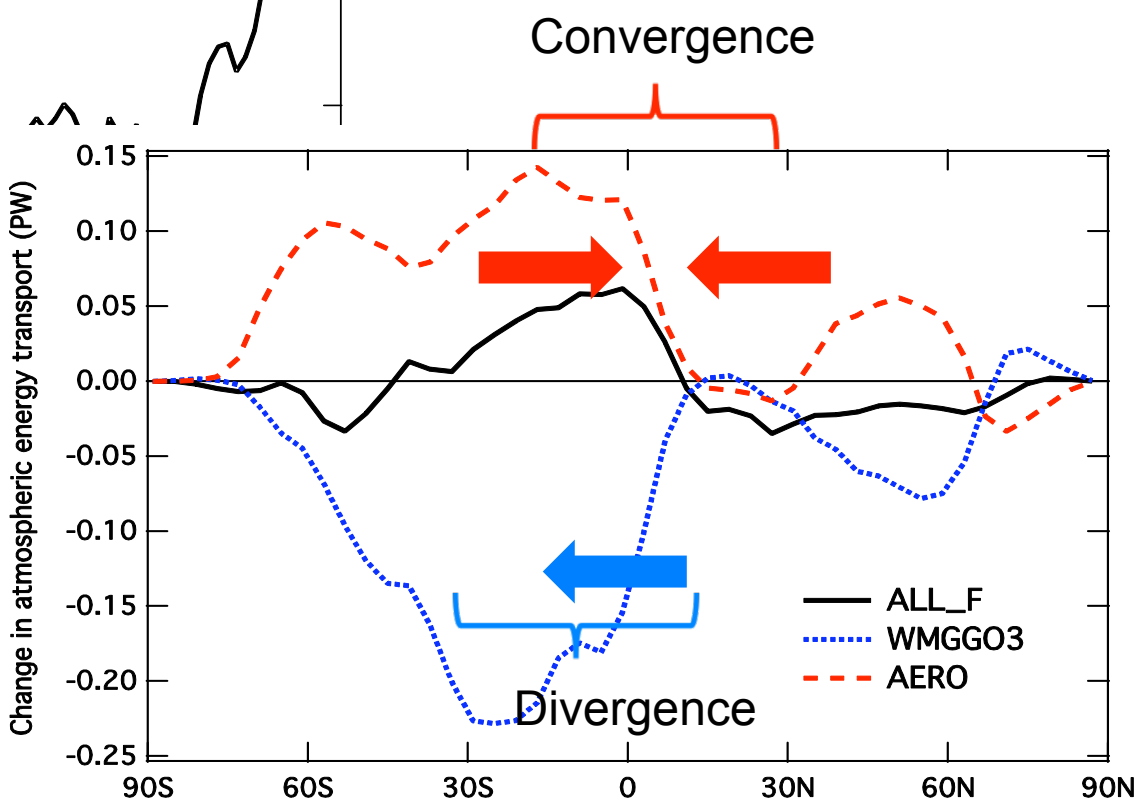
Changes in Atmospheric Energy Transport



1981-2000 annual-mean RFP (W m^{-2}) due to anthropoge

RFP = *change in TOA radiative flux after the forcing agent is introduced and atmosphere adjusts, with fixed SST (i.e., takes fast feedbacks and interactions into account; e.g., al. 2010)*

Interhemispheric imbalance



Key issues and summary

- The observed change in monsoon rainfall is likely of **anthropogenic** origin and is mainly attributable to **increased aerosols**
- This perspective focus on the **slowdown** of the tropical atmospheric circulation brought about by the **aerosol-induced energy imbalance** between the northern and southern hemispheres
- Aerosols interact with the monsoon circulation mainly through altering clouds (the **indirect effects**)
- Low tropospheric **stability** shows no appreciable change in late spring; the large-scale land-ocean thermal contrast appears to mediate the aerosol impact
- An important step toward the understanding the impact of climate change at fine scales
- Useful framework for understanding the combined climate response to aerosols and greenhouse gases