Modeling Studies of Aerosol-Cloud-Climate Interactions

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Outline

- The effects of aerosols on the decadal variation of the late spring precipitation (AM) in south China

Hu and Liu (2013)

- Impacts of absorbing aerosol deposition on snowpack and hydrologic cycle in the Rocky Mountain region

Wu et al. (2016)

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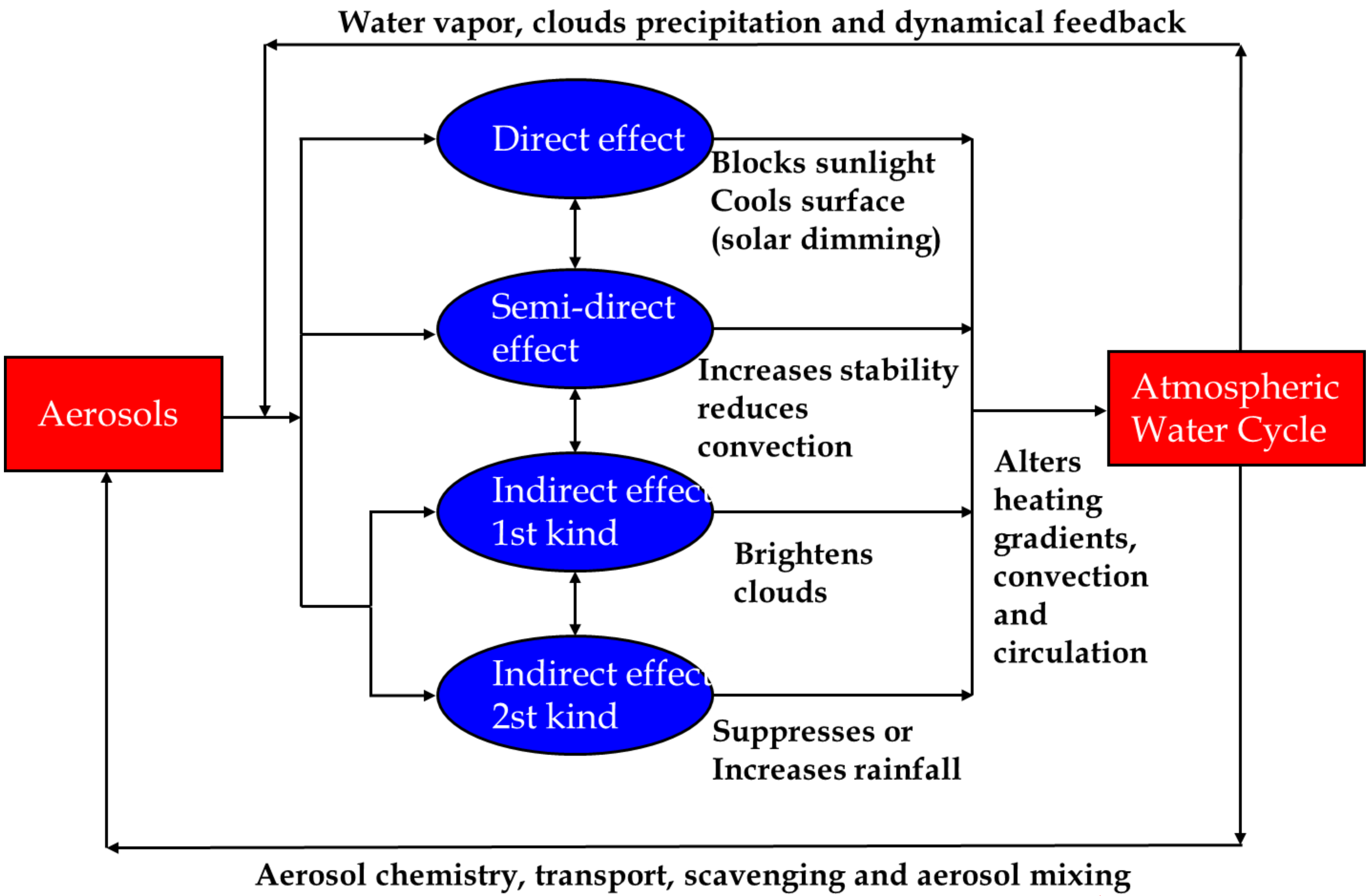
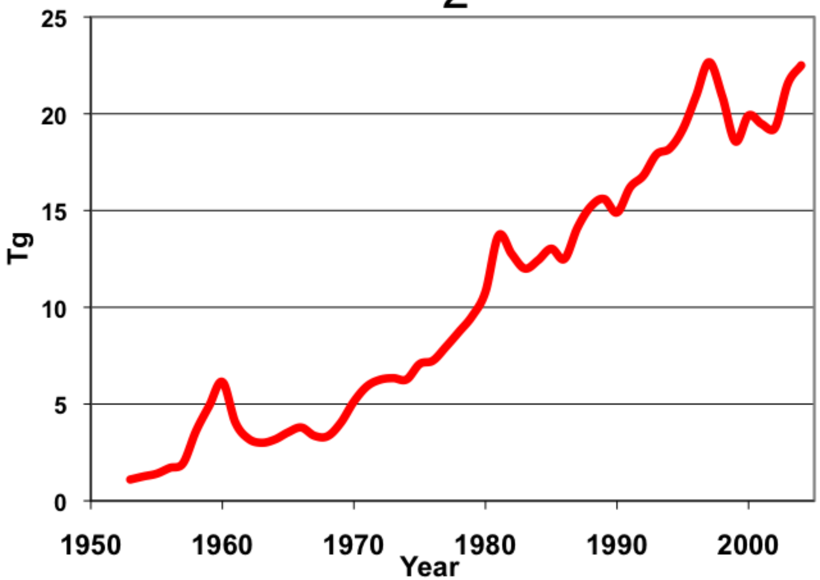
Background: Aerosol and Atmospheric Water Cycle Interactions



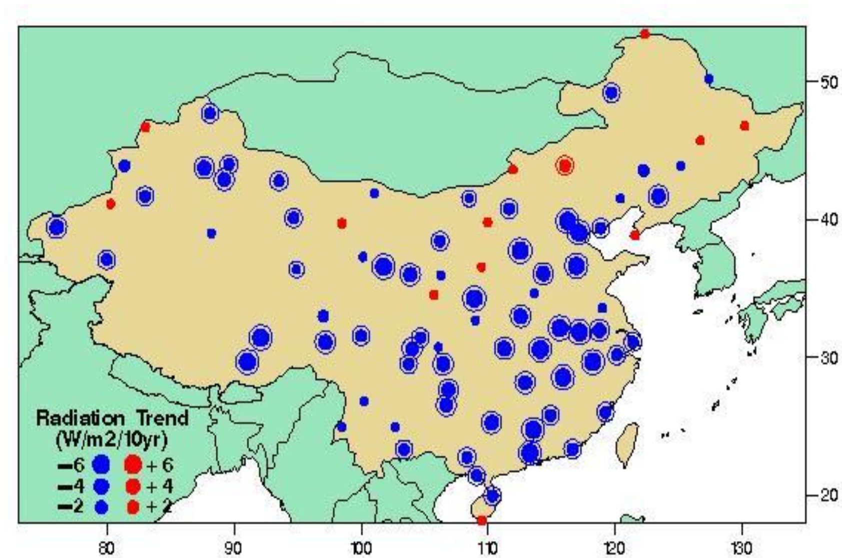
(Lau, BAMS, 2008)

Background: Aerosol Pollution in East Asia

China SO_2 Emission



Surface Flux Trend



Qian et al. (2006)

Observed climate trends accompanying with the increasing of pollutants

A decreasing trend of **horizontal visibility** (−2.1 km (10 yr)$^{-1}$) since the 1990s (Che et al. 2007), the maximal decreasing trend is during summer.

Drought in **south of the Yangtze River valley** during **late spring** since 1980s (Yu et al. 2004)

Summer drought in Yellow River valley since 1980s and weakening of summer monsoon circulation (Ding et al. 2008)

low-level cloud amount has an **increasing** trend in China from 1954 to 2005 especially after the mid-1990s, while the total cloud amount has a decreasing trend (Xia 2010).

Atmospheric stability has increased in recent 17 years over the central East China (Zhao 2006).

Data and Methodology

- **CESM1/CAM5 model**
  - Two-moment modal aerosol module (*Liu et al., 2012*)
  - Two-moment stratiform microphysics (*Morrison & Gettelman 2008; Gettelman et al. 2010*)
    - Prognostic '*cloud mass*' and '*cloud droplet number*' (Γ-function size distributions)
    - Diagnostic 'precipitation mass' and 'precipitation droplet number'
  - Cloud liquid droplet activation (*Abdul-Razzak & Ghan 2002*)
  - Cloud ice crystal nucleation (*Liu & Penner 2005*; *Liu et al. 2007*)
  - Aerosol direct, semi-direct and indirect effects are considered

- **ERA40 NCEP1 CRU long-term data**

AMIP-Type Experiments with CESM1/CAM5

Exp.	Aerosol	GHG	SST
ALL	Varying	Varying	Varying
AERO	Varying	PI	Varying
GHG	PI	Varying	Varying
SST	PI	PI	Varying

PI: fixed at pre-industrial condition

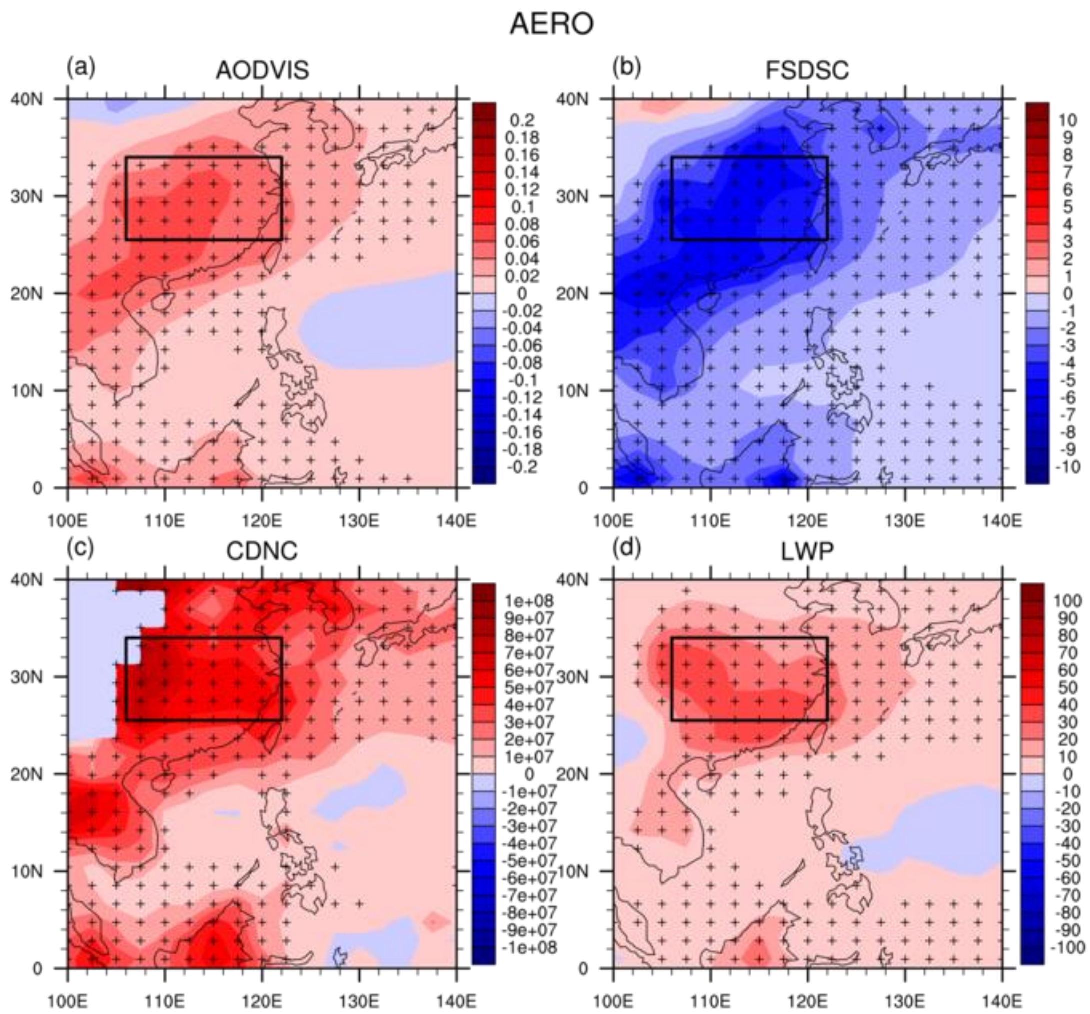
Late spring (AM)

All experiments: 3 ensembles,1850-2000 year, analyze 1950-2000 year

1.9 x 2.5 horizontal resolution, 30 vertical levels

Aerosol emissions: IPCC AR5 emissions (Lamarque et al., 2010)

AOD, FSDSC and Cloud Properties Change



The “change” is defined as the 1978-2000 late spring(AM) mean minus 1950-1977 late spring mean afterwards

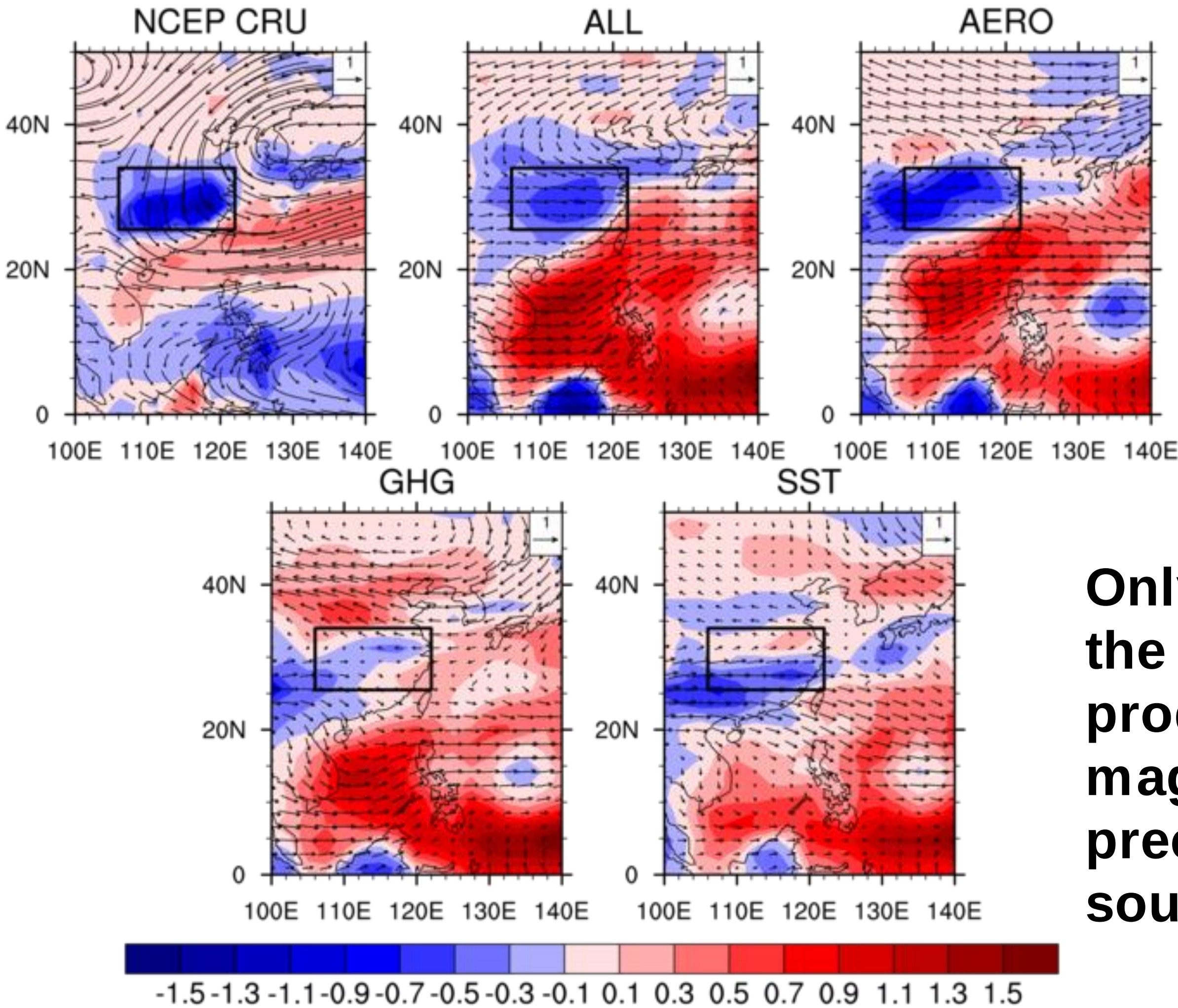
LWP by g/m^2

CDNC by $\#/m^2$

FDSDSC by W/m^2

Same hereinafter.

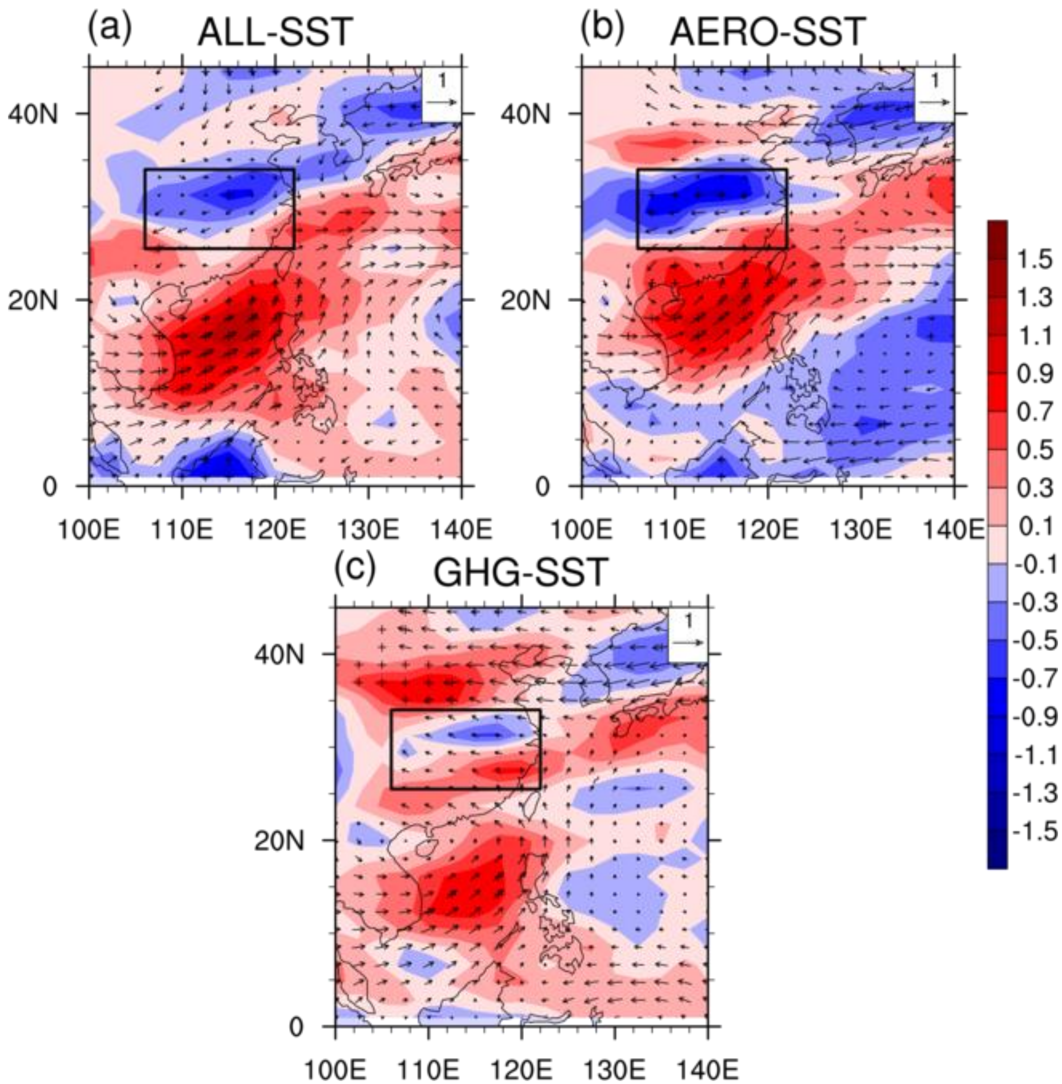
Precipitation and 850hPa Wind Change



Vector: 850 hPa wind
Shading: precipitation

Only simulations including the aerosol effect can produce comparable magnitude and position for precipitation decreasing in south China

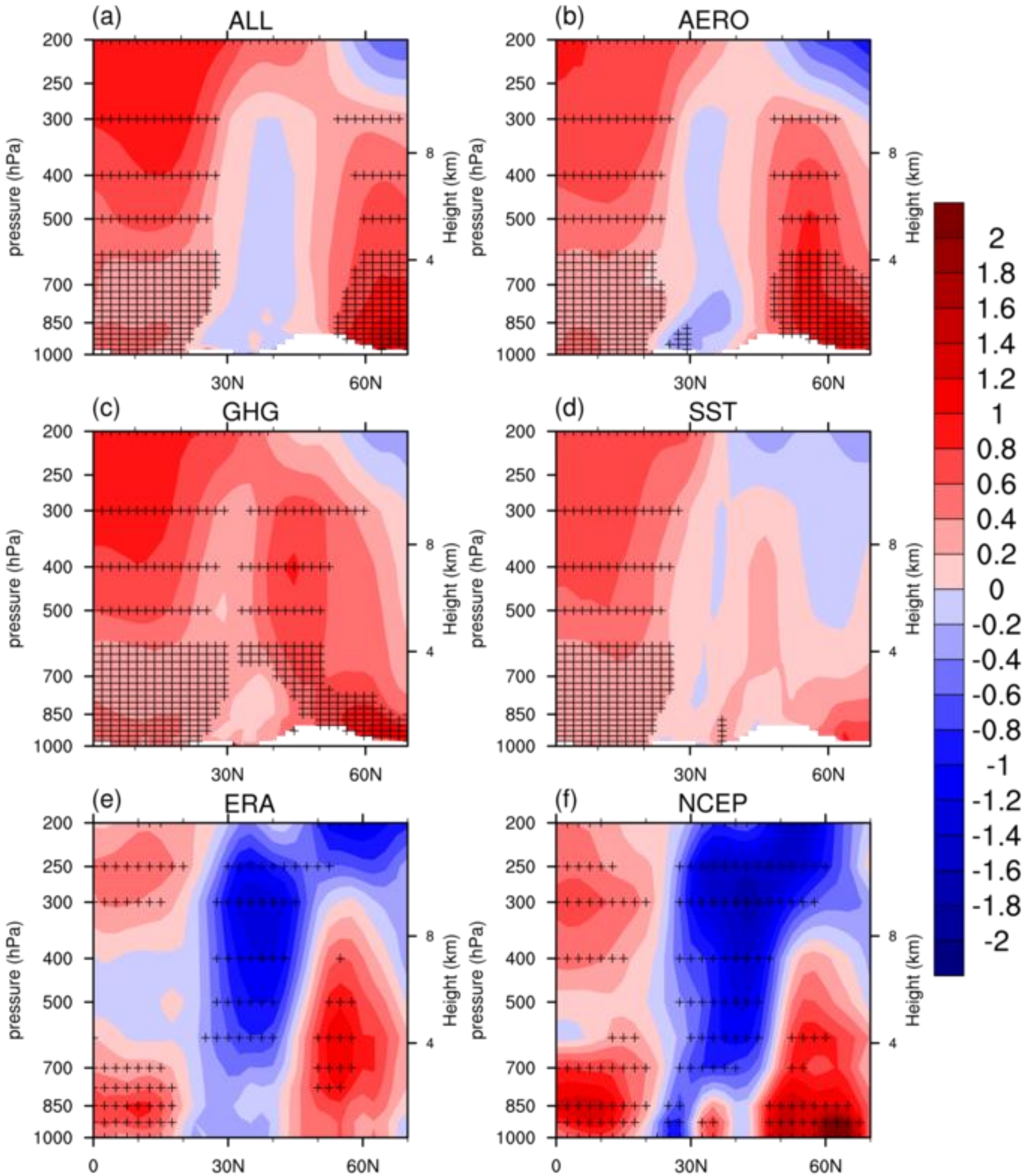
Net Effect of AERO and GHG on the Precipitation Change



It is the net effect of aerosols that induce the precipitation change, rather than GHGs.

Much smaller PRECL (can be affected by second aerosol effect in model) change compared to PRECC (affected mainly by circulaiton, stability)

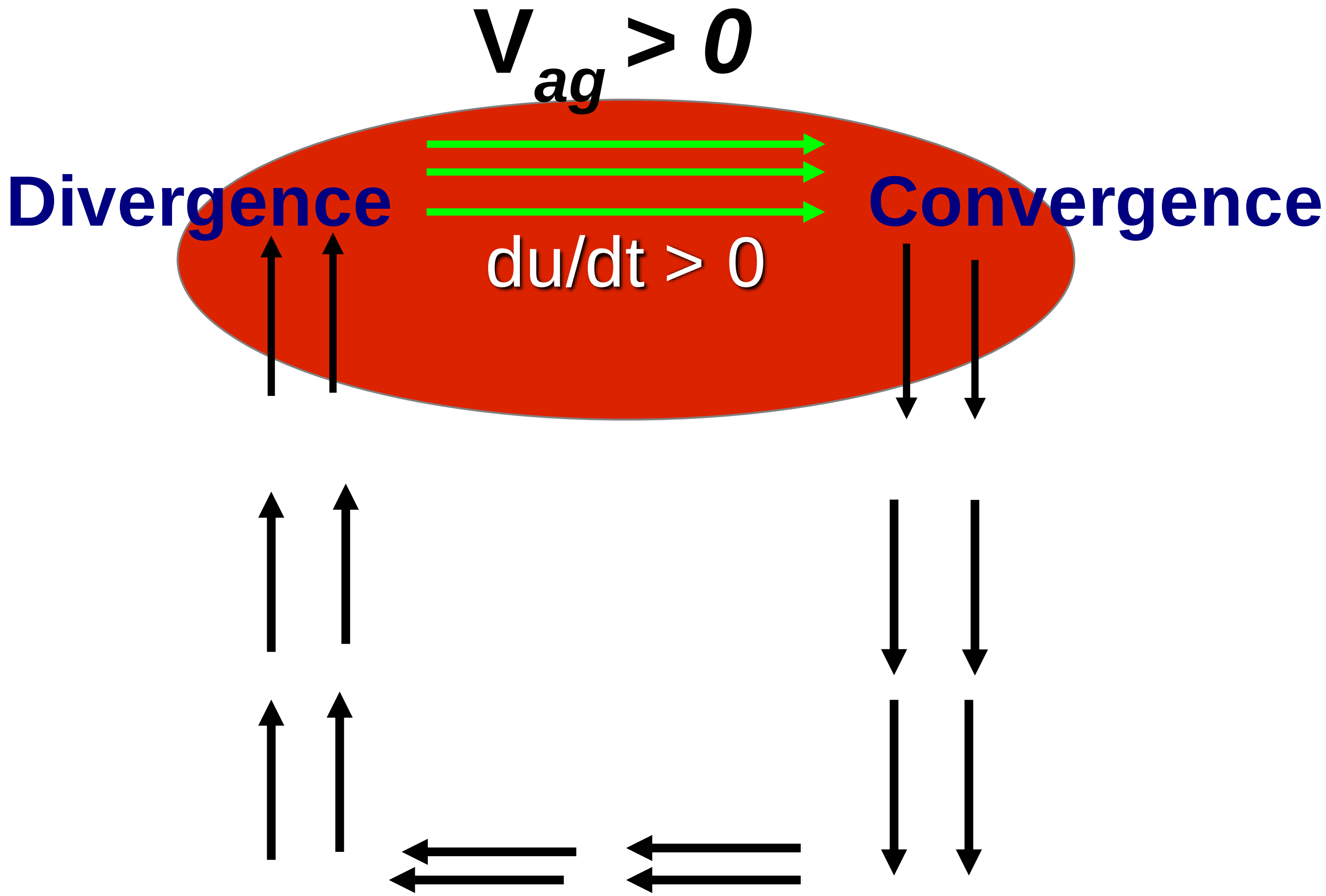
Temperature Change



The cross section is for Zonal Mean (105-120° E), hereinafter the same.

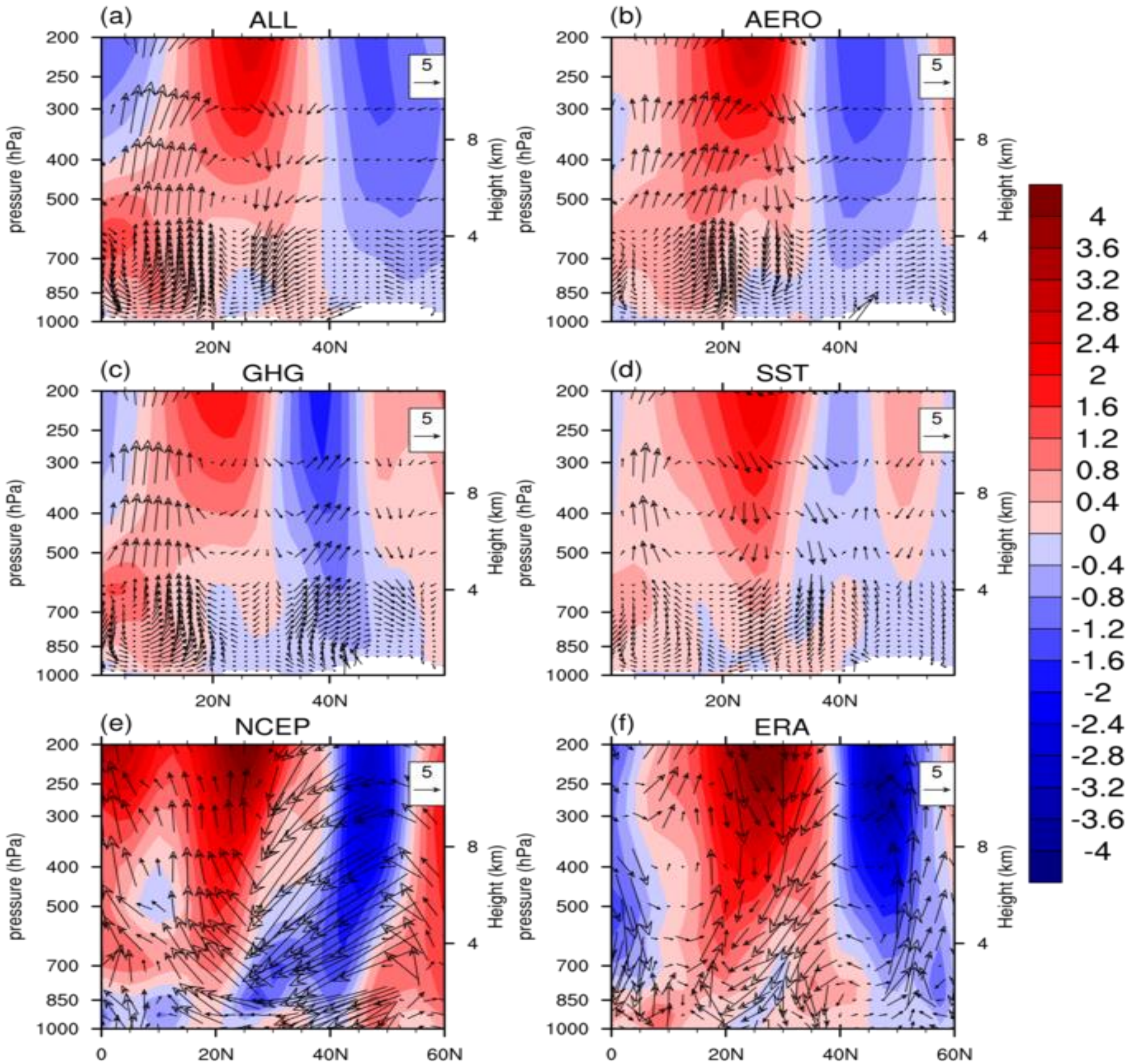
Aerosols cools the mid-latitude troposphere

- $du/dt = f(v - v_g) = fv_{ag}$ Holton, 2004



v_g is the geostrophic meridional wind, v_{ag} the ageostrophic meridional wind,

Circulation Change

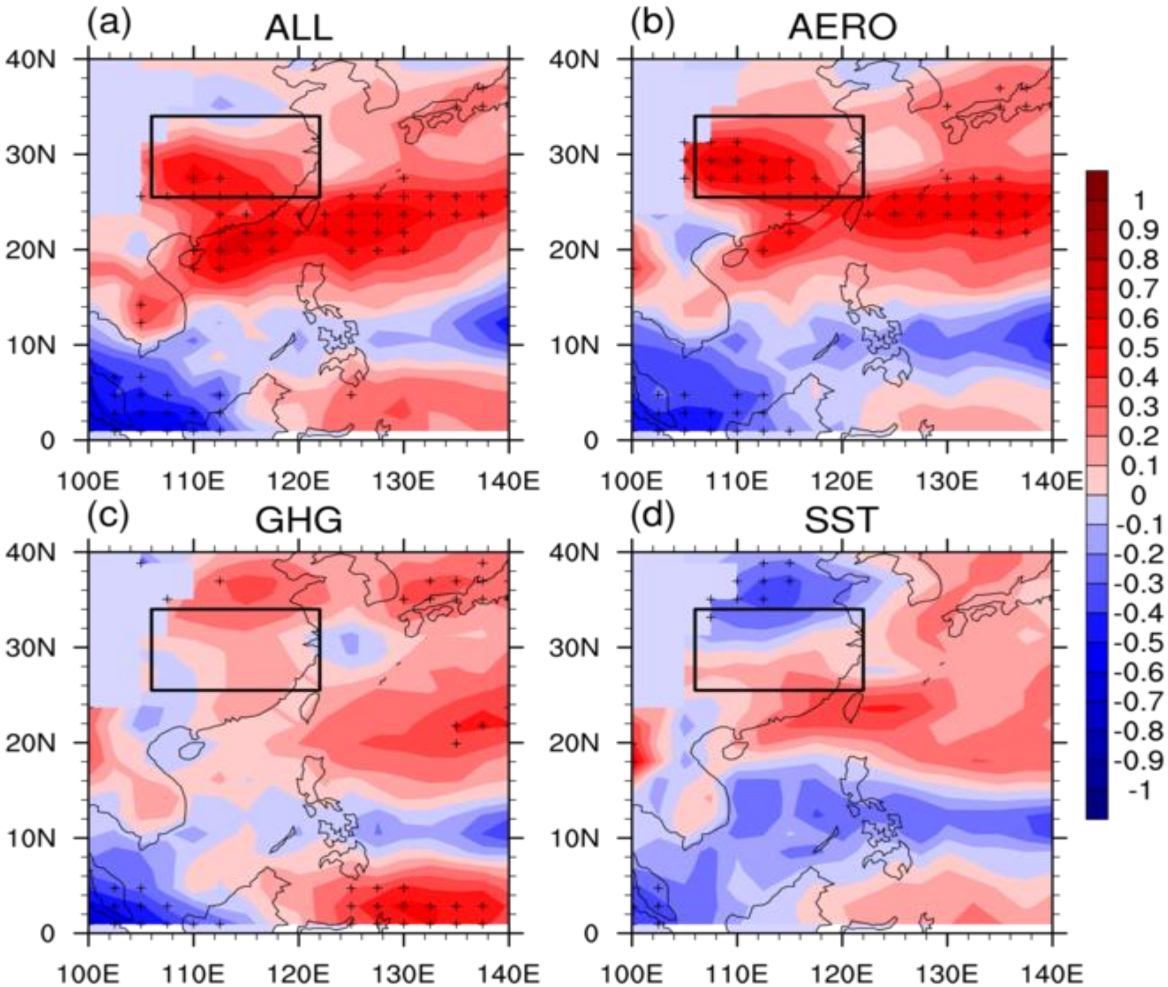


Shading:
zonal wind by m/s

Vector**:**
meridional component by m/s
Verical component by hPa/day

Obvious downward motion around 30N induced by aerosols

Atmospheric Stability Change



The stability index defined as the difference of equivalent potential temperature between two lower tropospheric layers averaged over 850-700 hPa and 1000-850 hPa respectively

Dimming effect → **More near surface cooling than upper levels** → **Stabilize lower troposphere**

Brief Summary

- Anthropogenic aerosols may play a dominant role in the weakening of late spring rainfall in south China.

- Anthropogenic aerosols may increase the atmospheric stability, reduce the atmospheric temperature, alter the atmospheric circulation, inhibit the deep convection and decrease the late spring rainfall in south China.

Caveat:

- Aerosol effect in Asia is very likely underestimated due to the underestimation of aerosol emissions.

- Aerosol indirect effect on convective clouds not included in CAM5.

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Rocky Mountain Region-Water emphasis

- Most of primary water resources in the inland western US comes from Rocky Mountains' snowpack.
- Climate change and absorbing aerosols in snow are two key factors to impact the snowpack and consequent hydrologic cycles.

Yellowstone River
Picture from wikipedia

Motivations

- Both the observations and model simulations have demonstrated the significant impacts of absorbing aerosol (e.g., BC, OC and dust) deposition on the snowpack and hydrologic cycles (e.g., Flanner et al., 2007; Qian et al., 2009; Hadley and Kirchstetter, 2012).

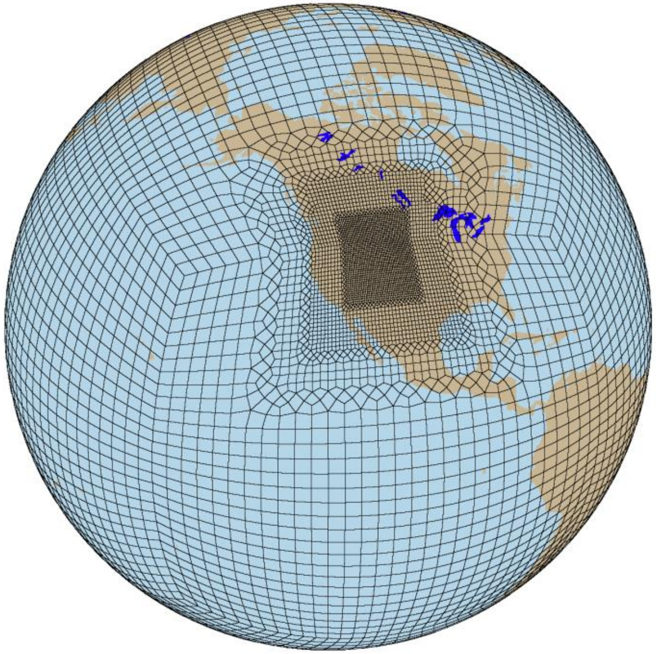
- Previous simulation studies use the coarse resolution GCMs, or high-resolution RCMs. However, there are weaknesses either for GCMs to resolve the snowpack over the regions of complex terrains due to the coarse resolution, or for RCMs to simulate the global transport of aerosols to deposit in the focused region.

- Instead, variable resolution GCMs (VR-GCMs) can overcome these weaknesses and serve a better tool to quantify the impacts.

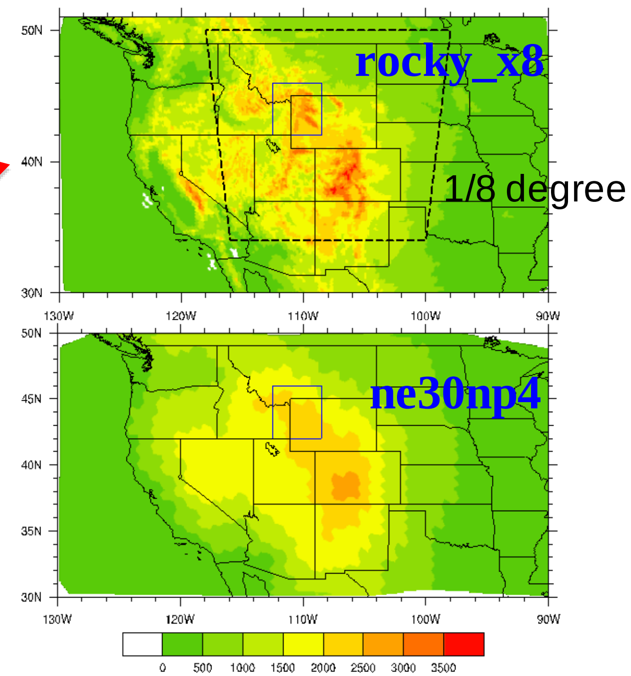
CESM variable-resolution simulations

Name	Configurations (CESM v1.2.0)	Period
Ne30np4 (~1º)	AMIP-mode, CAM-SE with a res of ne30np4	1981-1990
rocky_x8 (1º→0.125º)	AMIP-mode, CAM-SE with a res of rocky_x8	1981-1990
rocky_x8_NoDep	As rocky_x8, without aerosol (BC+dust) deposition-induced snow albedo changes	1981-1990

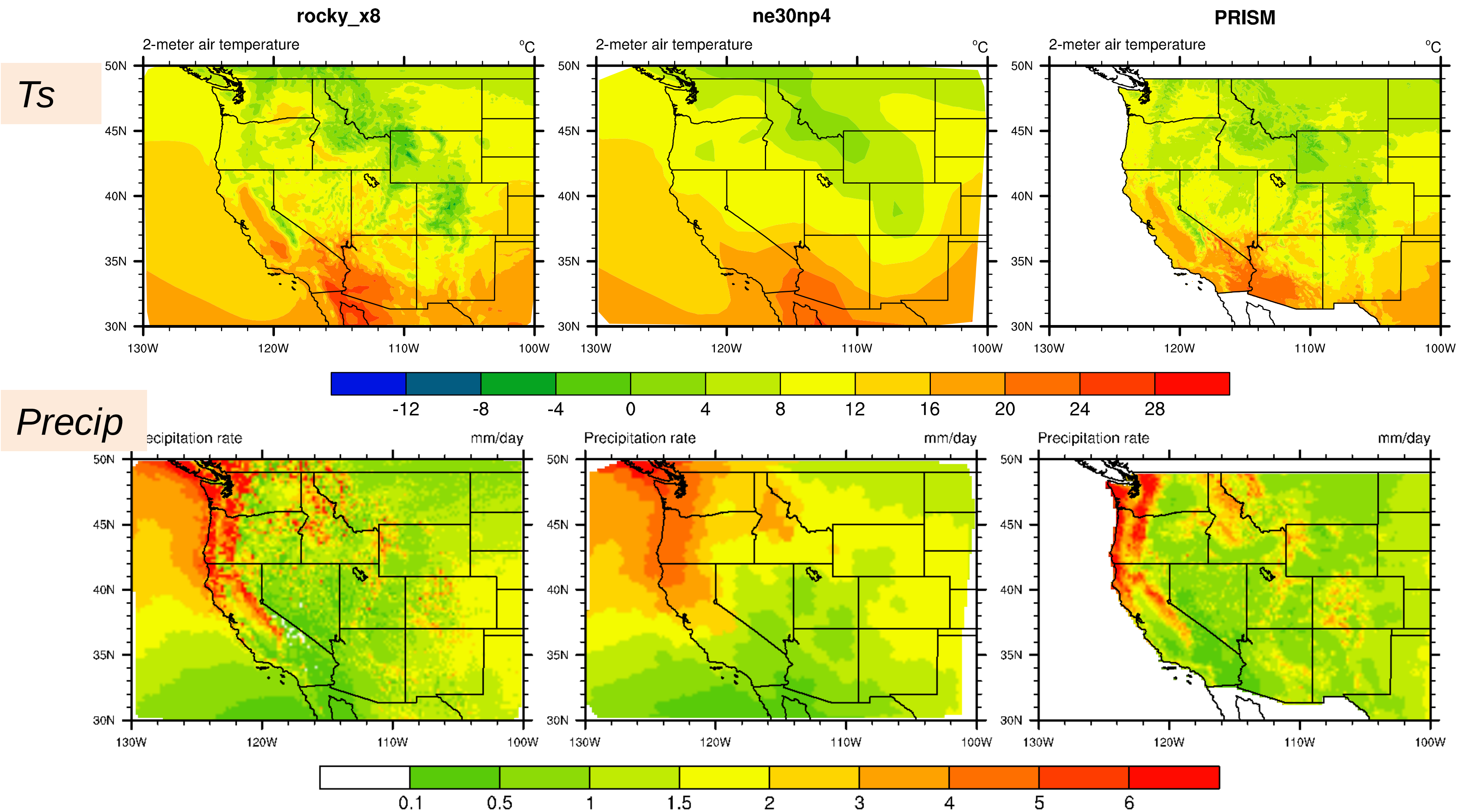
CAM-SE, rocky_x8



Terrain (m)

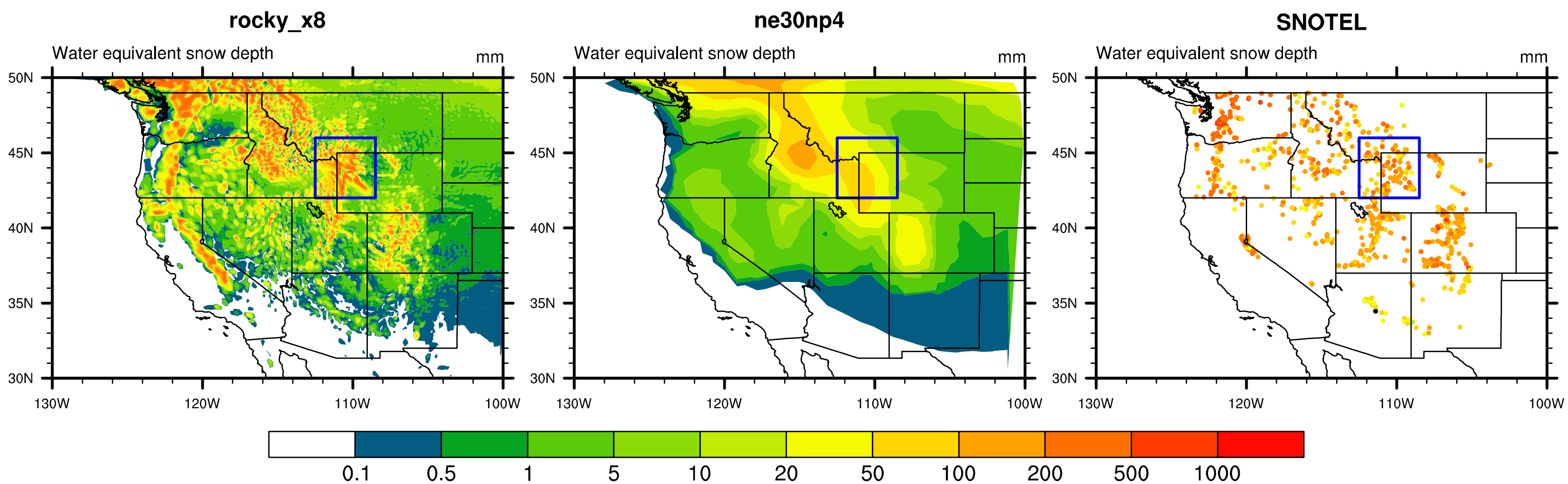


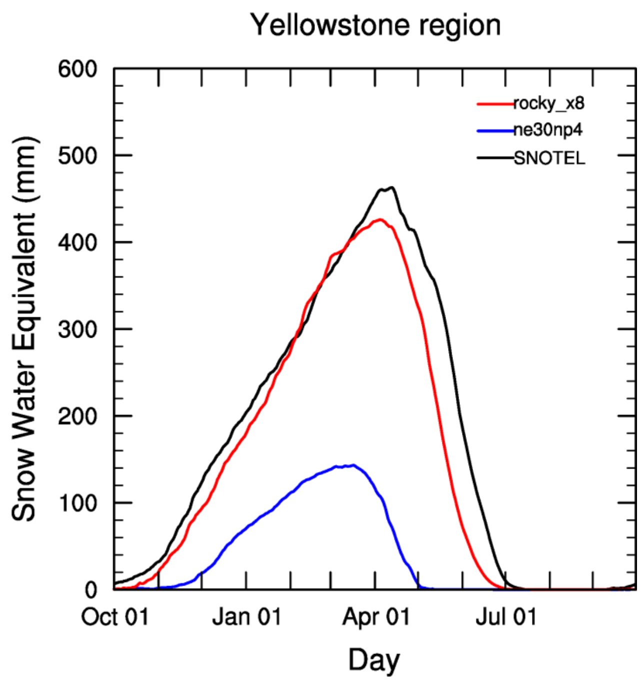
Annual mean temperature & precipitation



Rocky_x8 can much better capture the spatial distributions of temperature and precipitation, while coarse resolution (ne30np4) has low ability to reproduce the distributions.

Simulation of snowpack



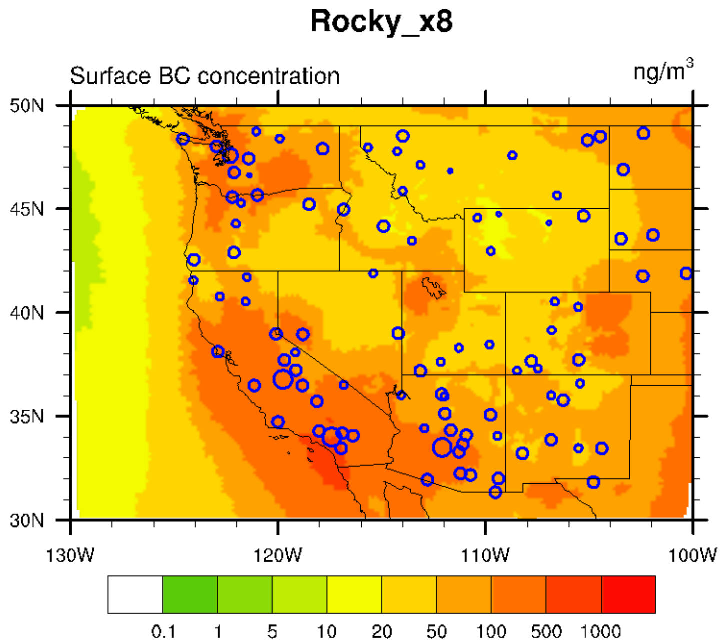


Average of 51 stations in Yellowstone region

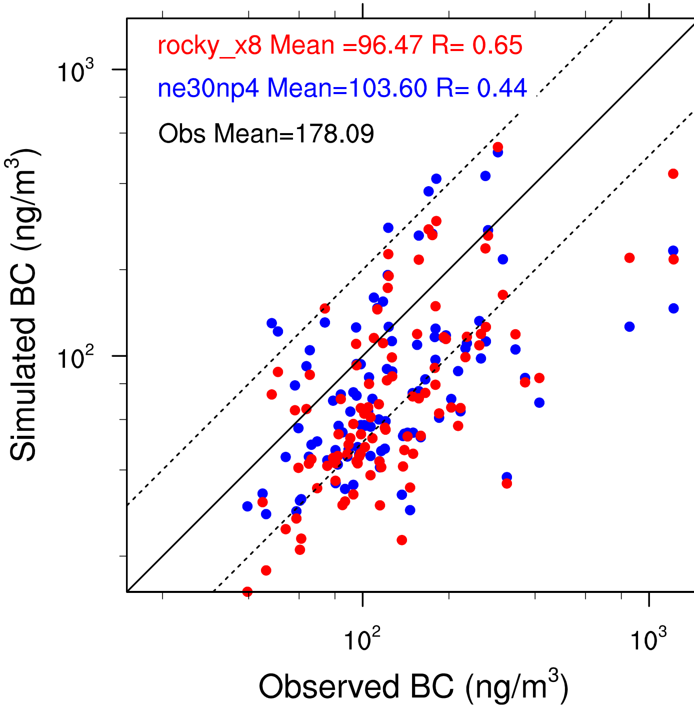
The peak and evolution of snowpack in rocky mountains are better resolved by rocky_x8.

Surface BC concentrations

Cold season average: DJF & MAM



Compared with IMPROVE observation

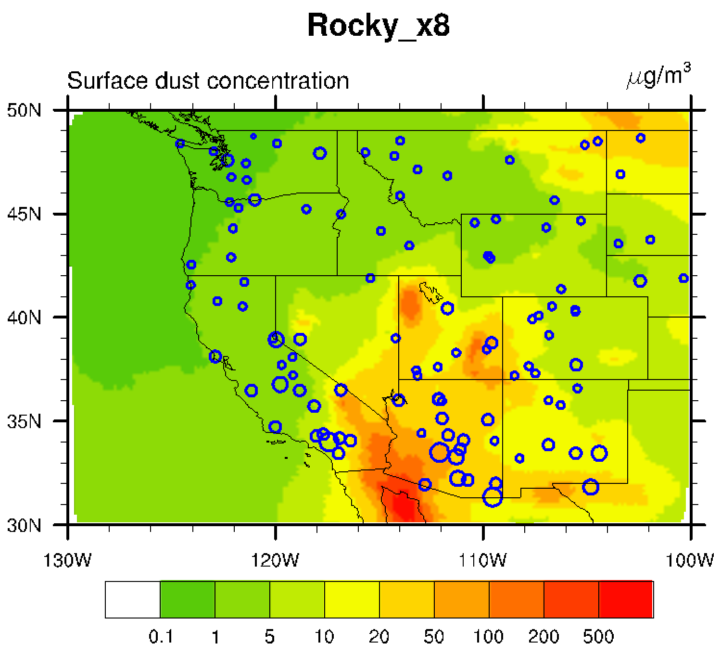


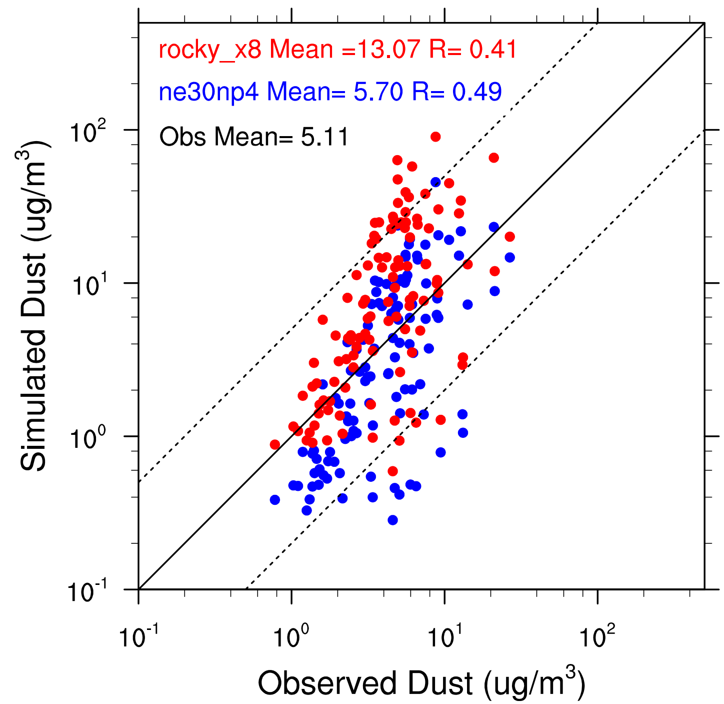
The spatial distribution of Surface BC is significantly improved, probably due to better representation of the transportation of BC.

Surface dust concentrations

Cold season average: DJF & MAM

Compared with IMPROVE observation





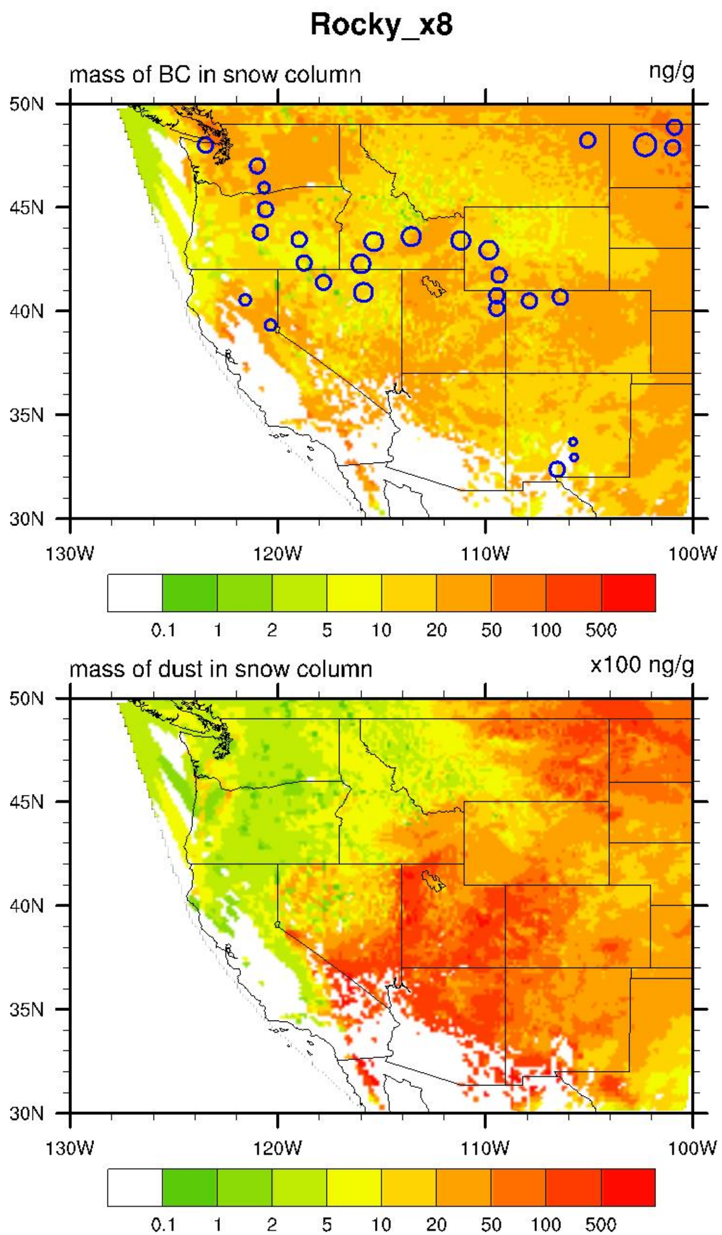
Total dust emission in North America:
22 Tg/year (ne30np4)
62 Tg/year (rocky_x8)

Dust concentration by rocky_x8 is about 2.3 times as large as that by ne30np4.

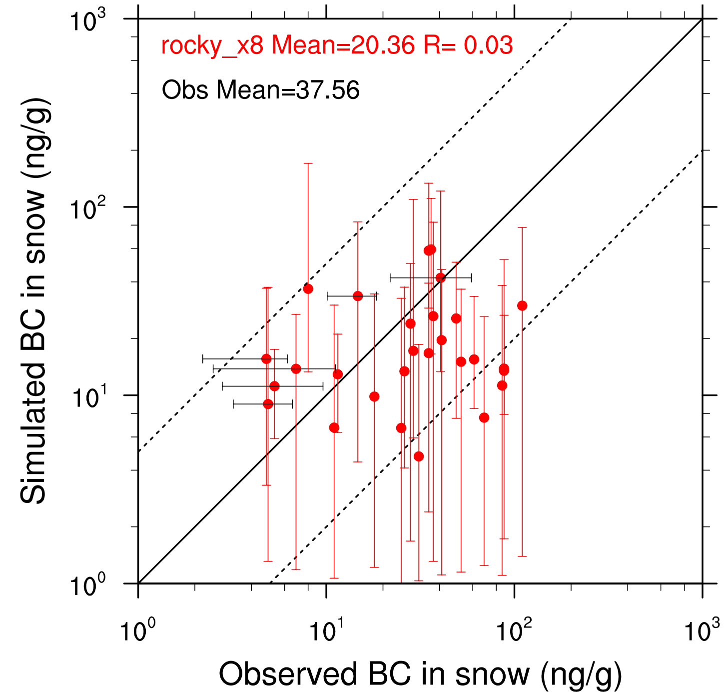
BC/Dust in snow

BC

Dust



Compared with field observations

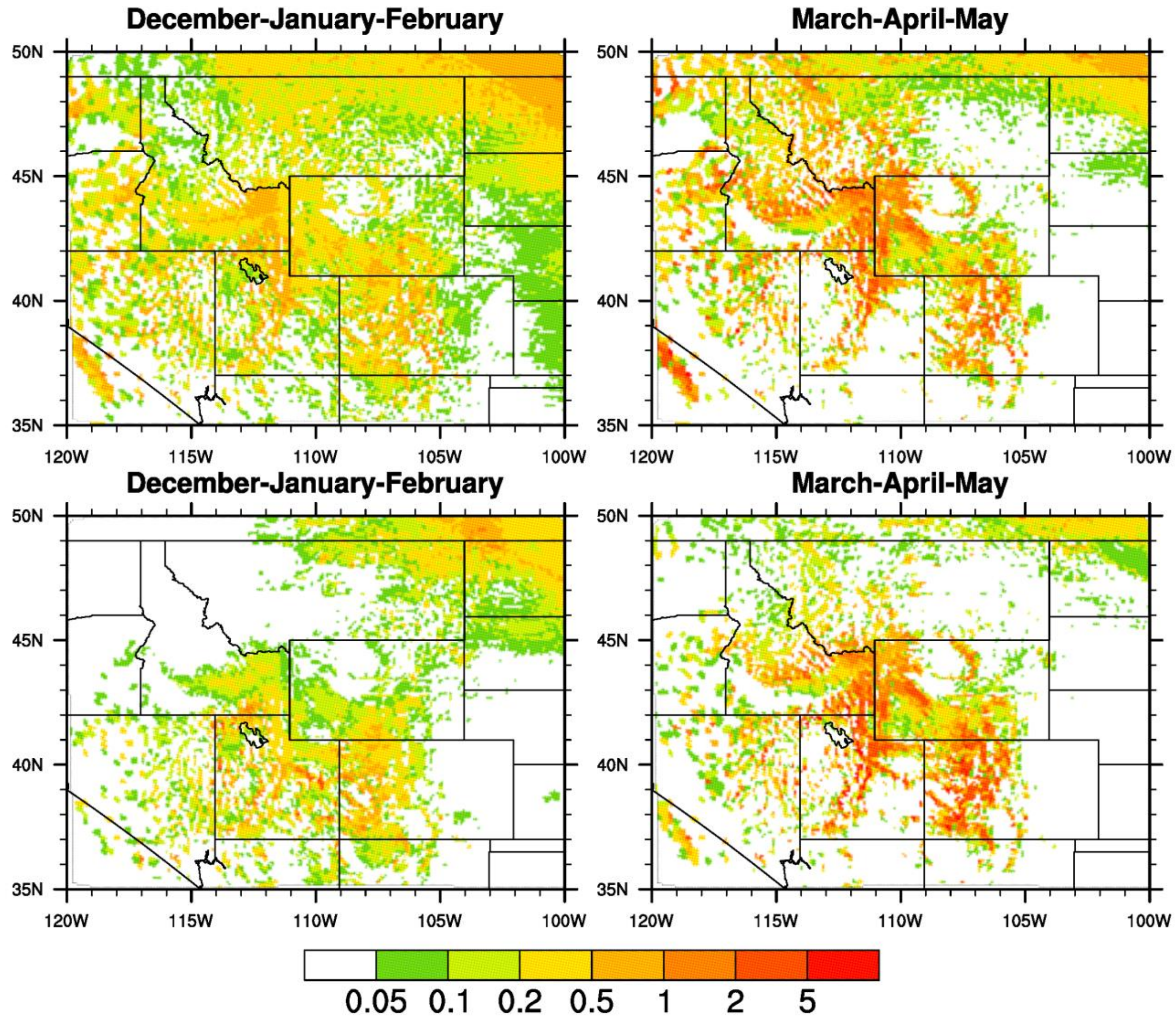


The magnitude of simulated BC mass in snow is comparable to field observations.

Surface radiative forcing (W/m²)

BC-induced

Dust-induced

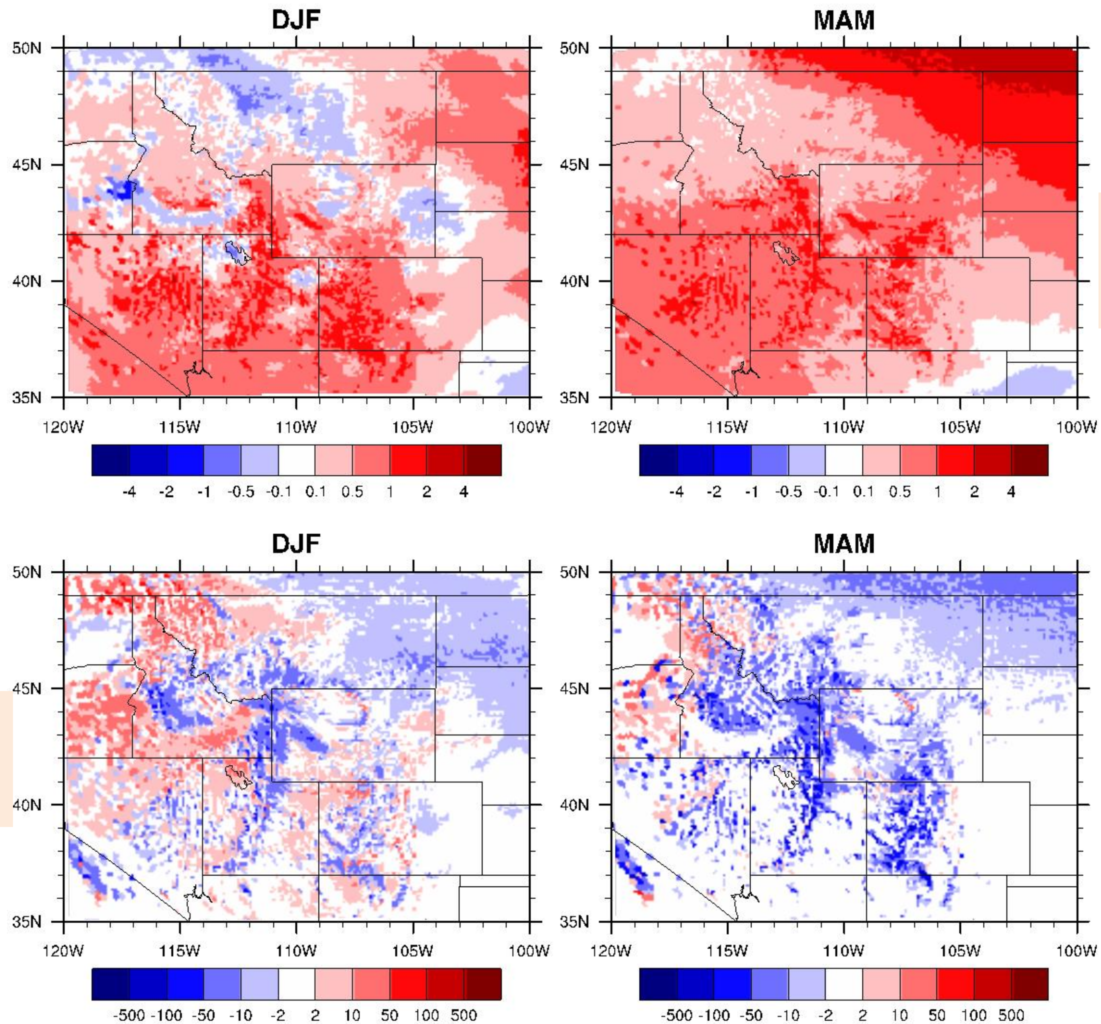


Larger in spring, larger in mountain region
Similar magnitude for BC and dust-induced RF.

Temperature and SWE change

Surface temperature change (° C)

Snow water equivalent change (mm)



Up to 1–2 ° C

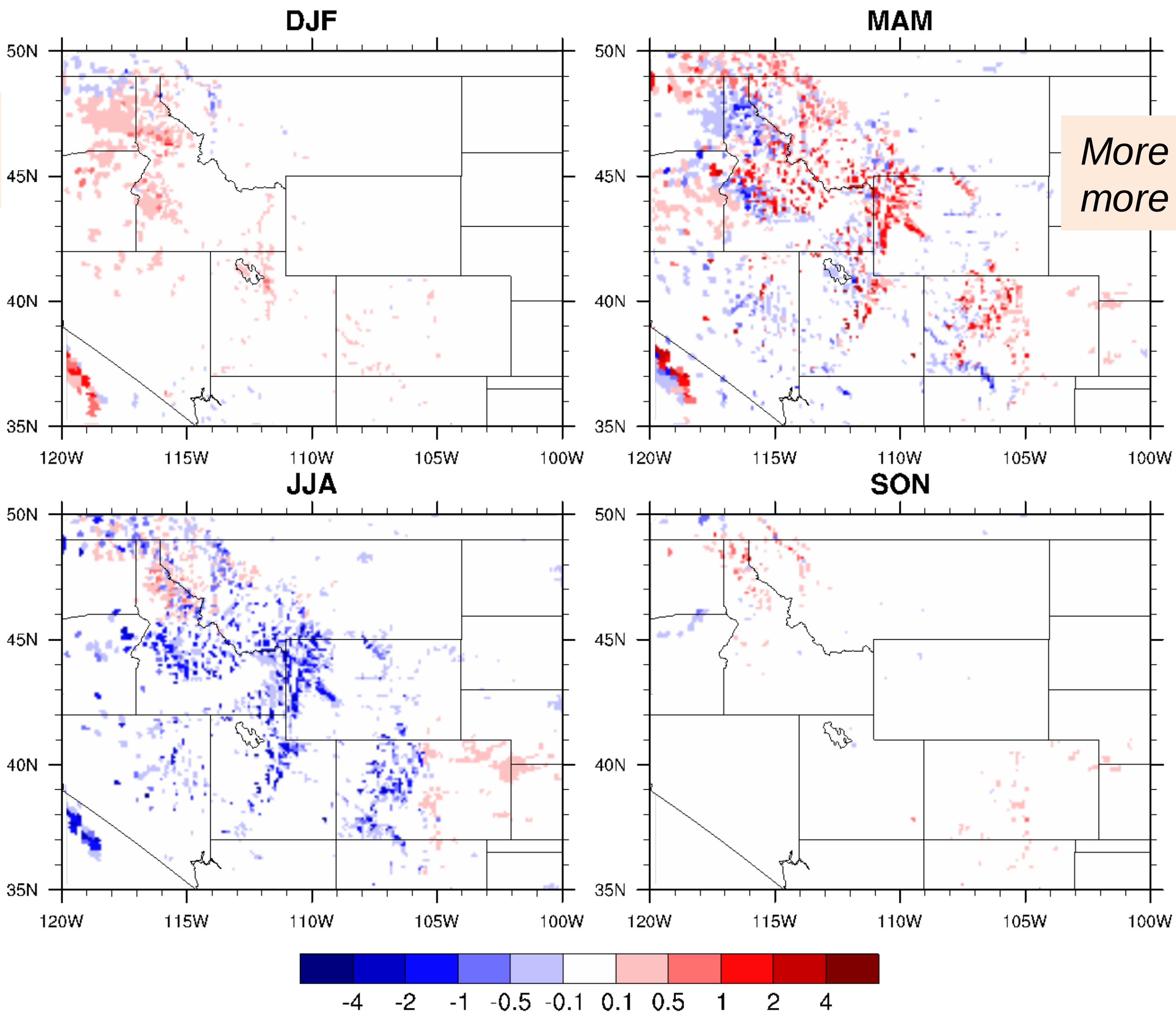
Up to 100 mm

Runoff change (mm/day)

More liquid rainfall for runoff

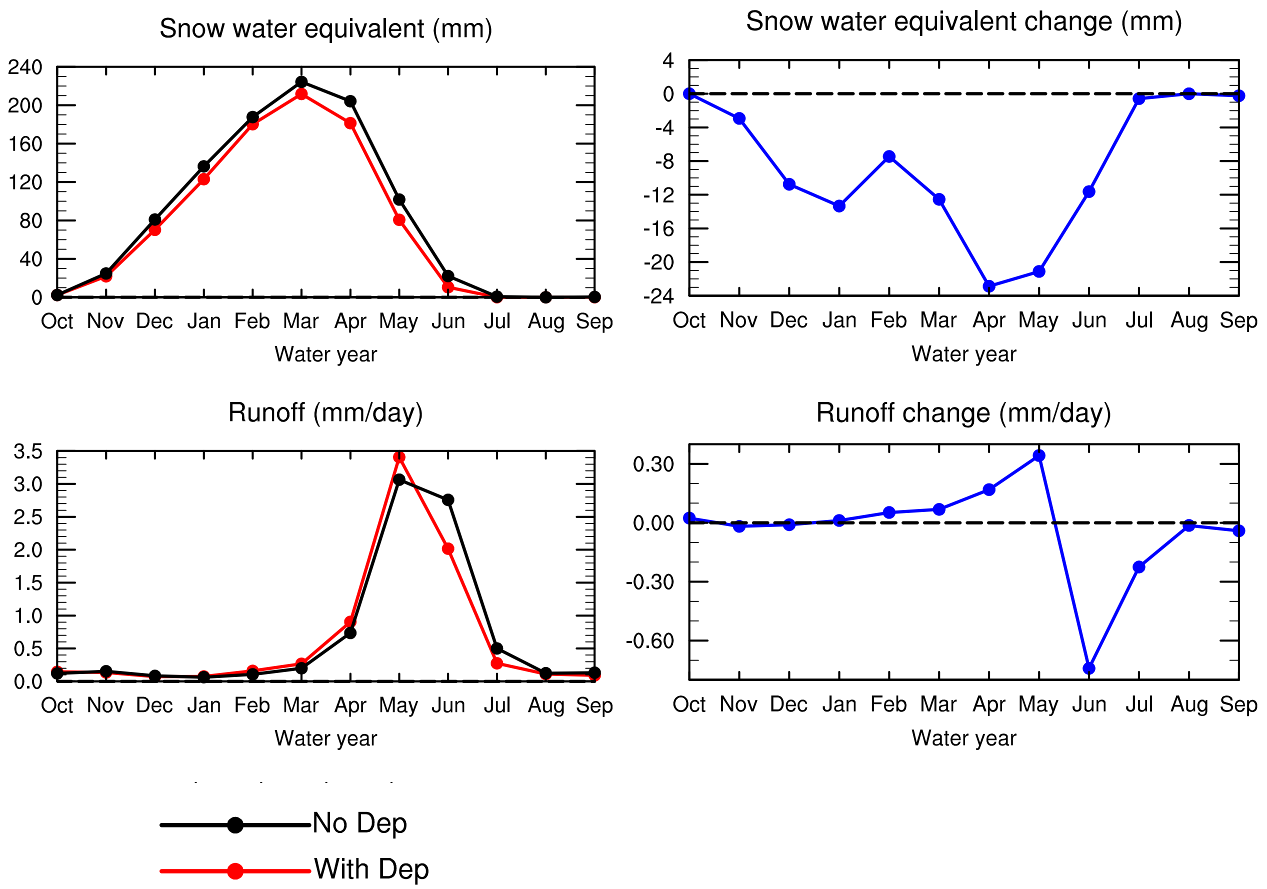
More liquid rainfall, more snowmelt

Less snow for melt



Change in seasonal variations

Yellowstone Region



Mean: −10%
Apr: −11%
May: −20%

Mean: −5%
May: +11%
Jun: −26%

Conclusions

- Variable resolution CESM can greatly improve the simulation of regional climate patterns in the rocky mountain regions. It can also much better reproduce the temporal evolution of snowpack.

- Due to BC & dust deposition onto snow, seasonal mean net SW radiation can change by 1-5 W/m^2, leading to a 0.5-2 ^oC warming of surface temperature in the mountain region. During the meting period, SWE can be reduced by 20% and runoff by 26% regionally.