Response of Indian Summer Monsoon to Dust-induced Modification in Ice-Clouds

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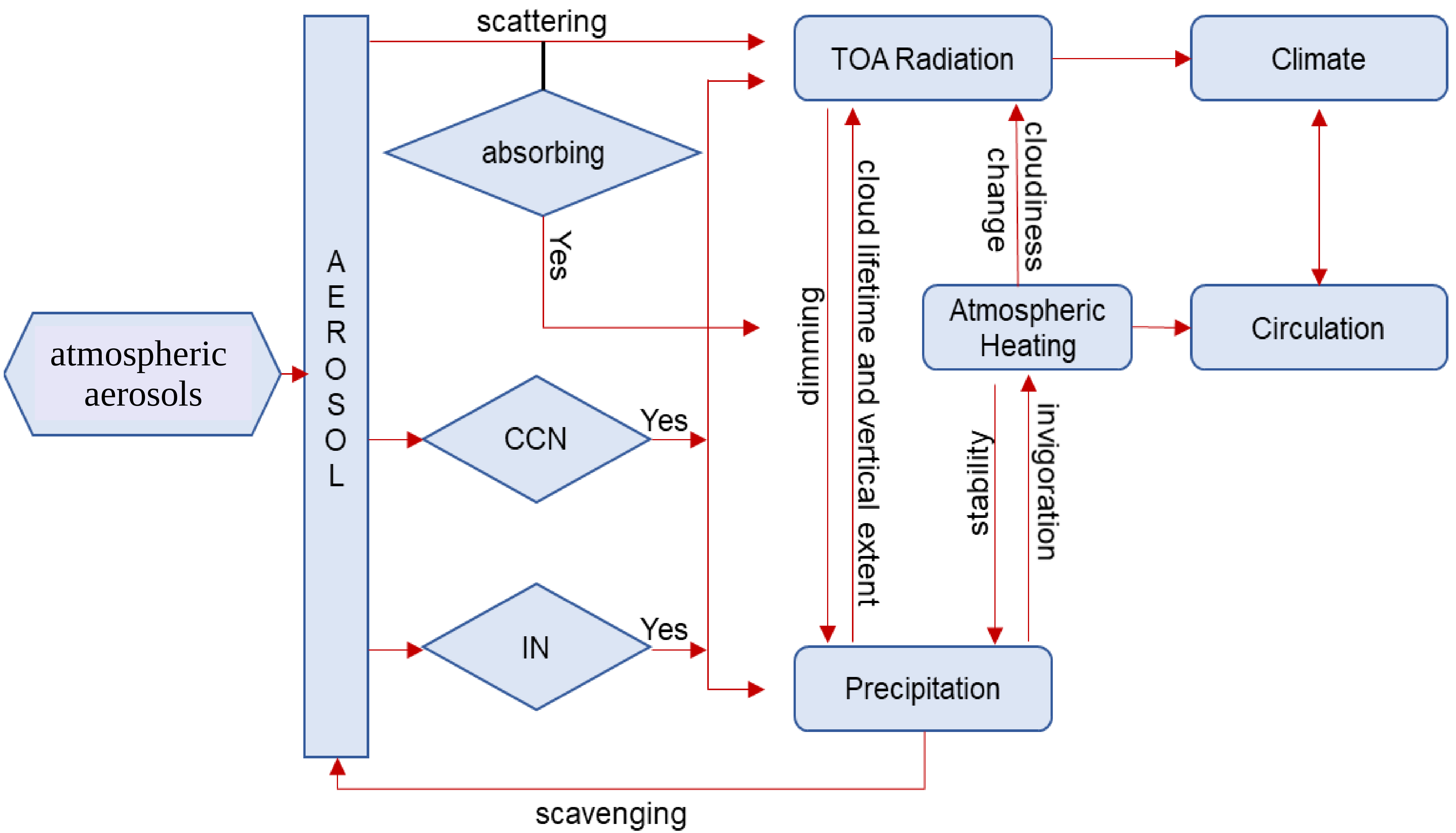
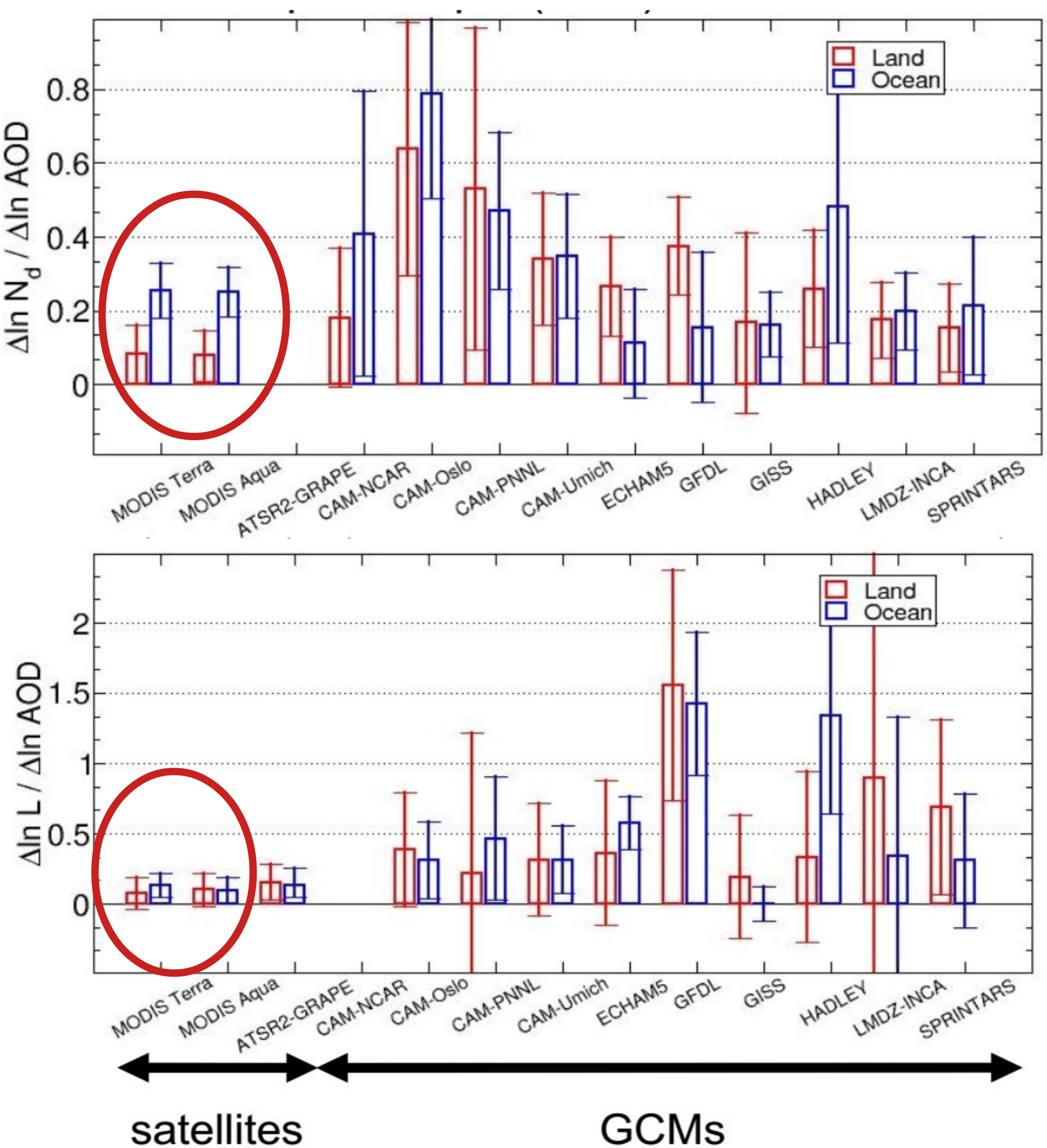
climatic implications of aerosols

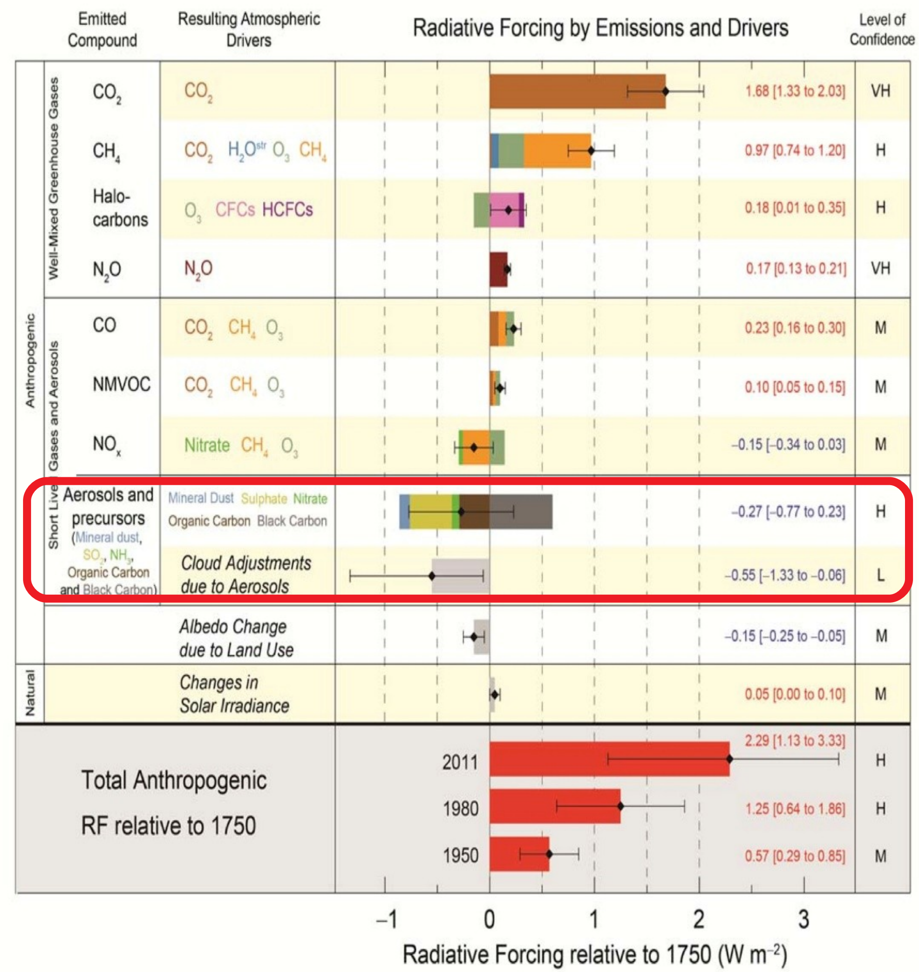


(Rosenfeld et al., 2014, *Rev. Geophys*)

caveats in aerosol-cloud interactions

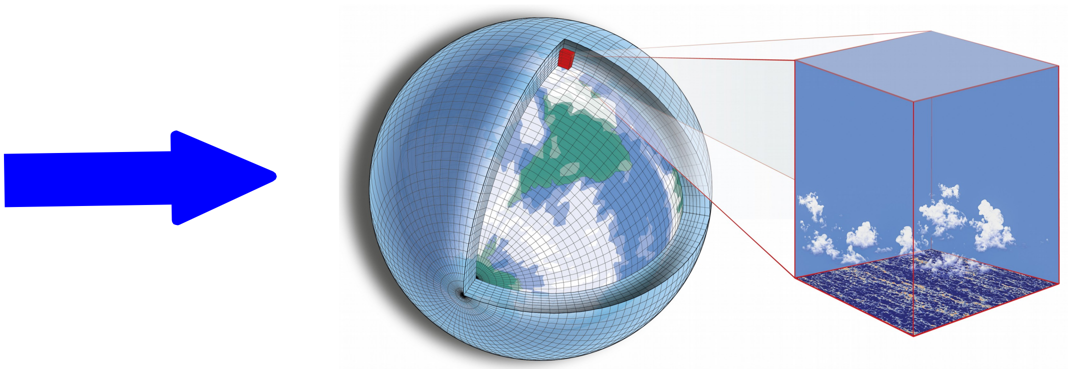


(Quaas et al., 2009, *ACP*)



(IPCC, AR5, 2013)

1. Large-scale parameterization -----> Sub-grid scale parameterization



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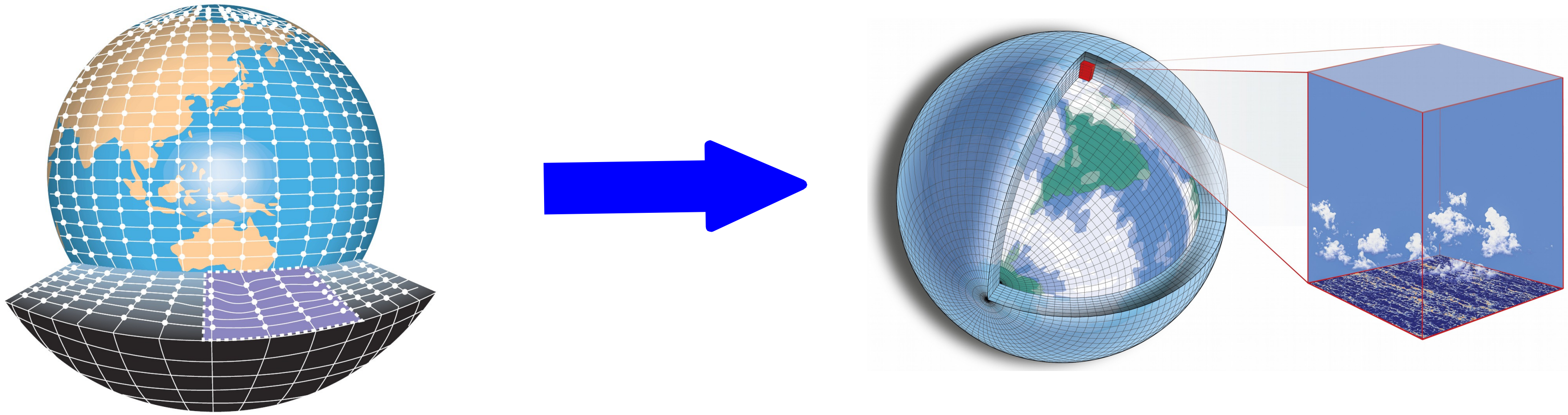
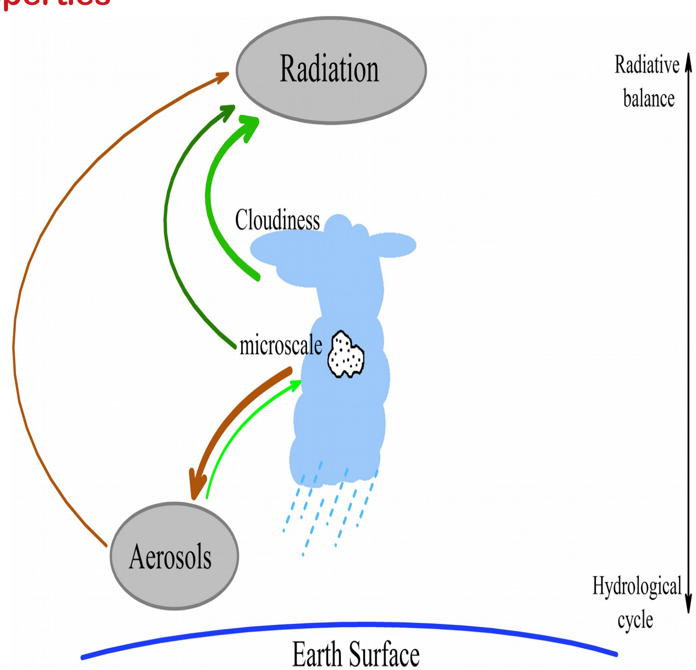


2. Microphysical-Dynamical Coupling

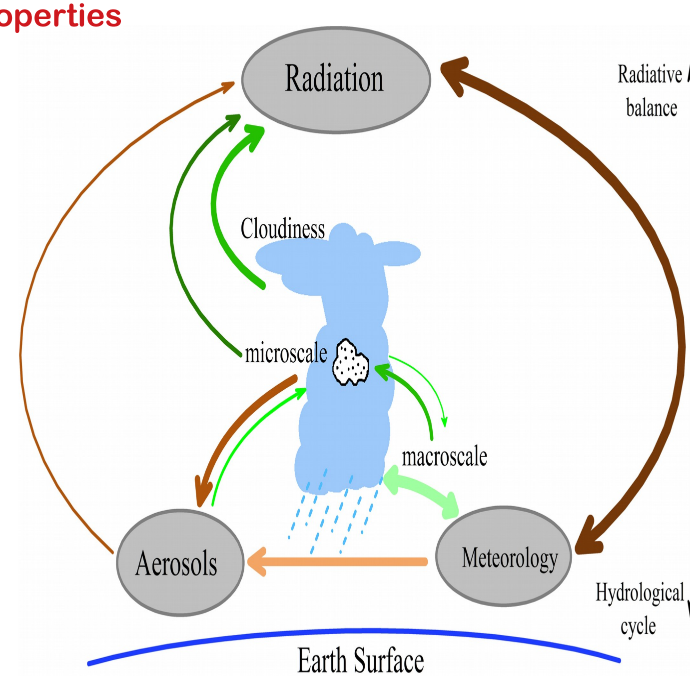
$$\delta C = \left(\frac{\partial C}{\partial A}\right)_M \delta A$$

Change in Cloud Properties — aerosol-driven



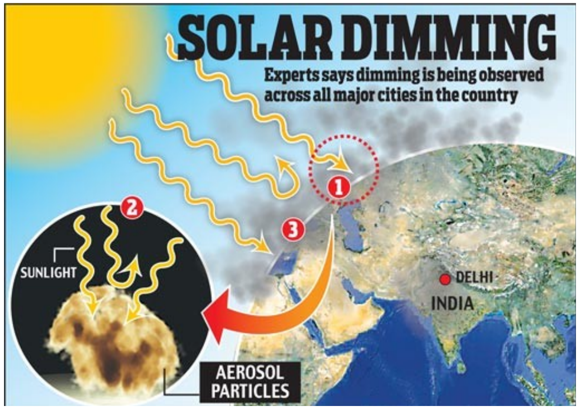
$$\delta C = \left(\frac{\partial C}{\partial A}\right)_M \delta A + \left(\frac{\partial C}{\partial M}\right)_A \delta M$$

Change in Cloud Properties — aerosol-driven — meteorology-driven

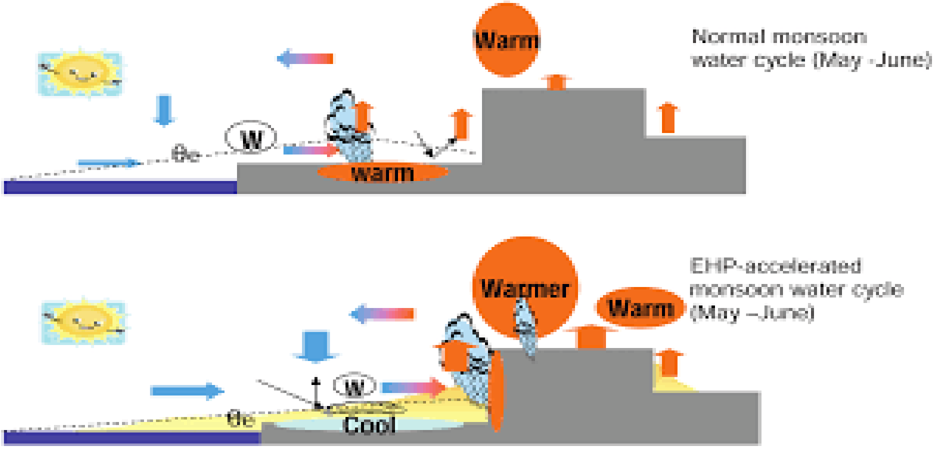


Previous Studies...

Decreasing trend of monsoon rainfall over Central India is due to increasing trend of anthropogenic aerosols [*Bollasina et al., 2011, Salzman et al., 2014*]

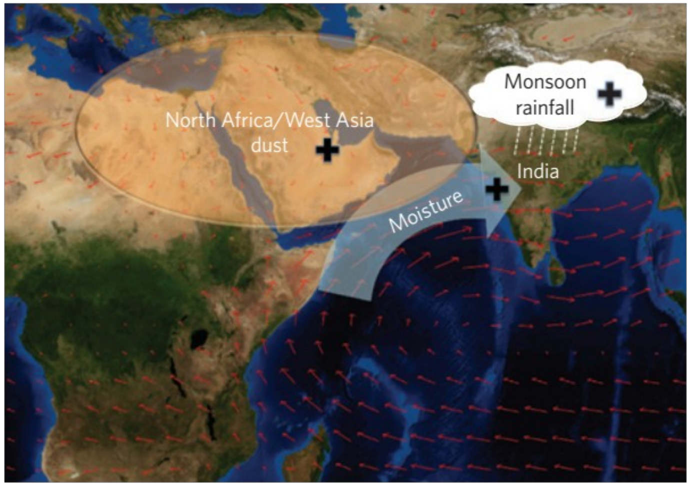


[*Ramanathan and Carmichael, 2008; Ramanathan et al., 2001*]



[*Lau and Kim, 2006; Gautam et al., 2009*]

Anthropogenic sources globally acccount for 25% of emissions, whereas natural dust sources acoounts for 75%. [*Ginoux et al., 2012*]



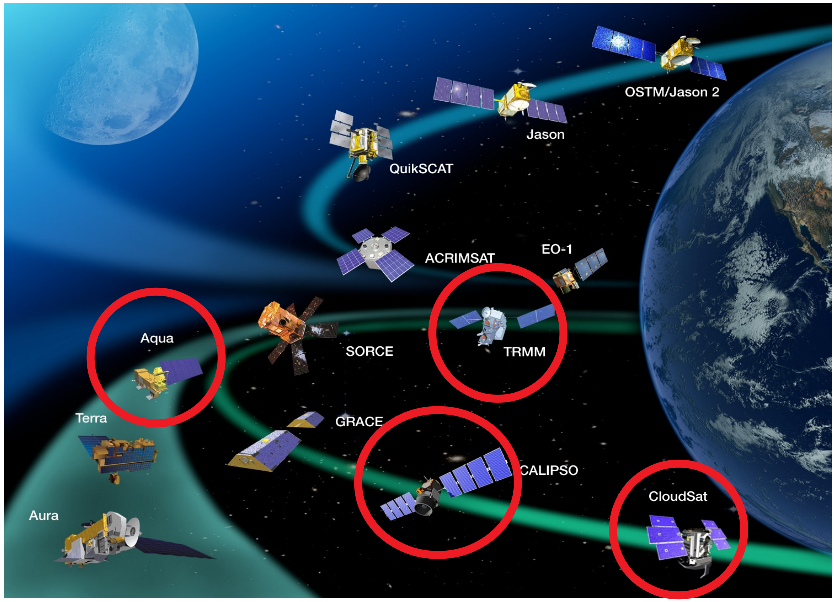
Radiative implications of dust modulate the monsoon rainfall over Central India [*Vinoj et al., 2014*]

Radiative forcing by aerosol-ice cloud interaction ---> -0.67 W m^{-2} to 0.70 W m^{-2} [*IPCC, 2013; Fan et al., 2016*]

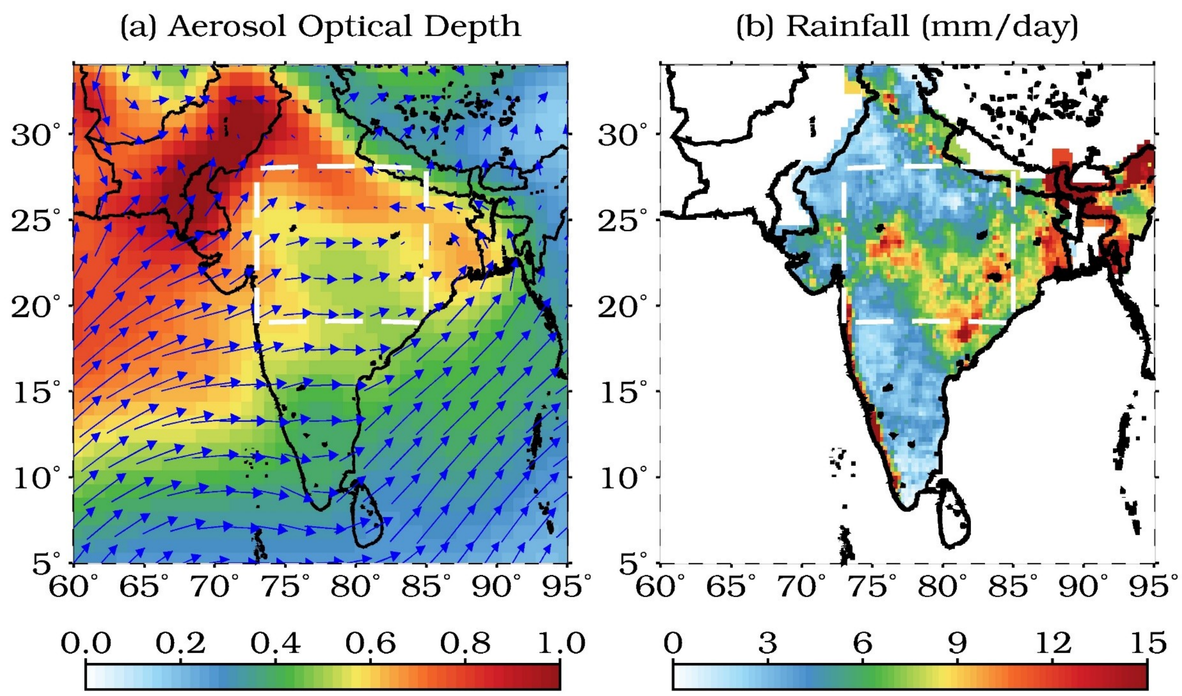
Datasets

Table List of datasets used in our analysis.

Satellite/Sensor	Data product	Parameters	Horizontal resolution
CALIPSO/CALIOP	CAL_LID_L2_05kmALay CAL_LID_L2_05kmCLay CAL_LID_L2_05kmAPro	Aerosol/cloud layer top/base altitude, CAD score, extinction QC, feature classification flags, Backscattering coefficient at 532 nm, Extinction coefficient at 532 nm	5 km along track
Aqua/CERES	CERES-SSF-L2	Ice cloud effective temperature, Ice cloud effective radius, Ice cloud water path	20 km x 20 km
Aqua/MODIS	MYD04	Aerosol optical depth	10 km x 10 km
CloudSat/CPR	2B-CWC-RO	Ice number concentration, Ice water content, Ice effective radius,	1.7 km along track
TRMM	3B42RT	Precipitation rate	0.25° x 0.25°
ECMWF	ERA-Interim	Vertical velocity at 500 hPa, Relative humidity at 500 hPa, Convective available potential energy	0.7° x 0.7°



Methodology

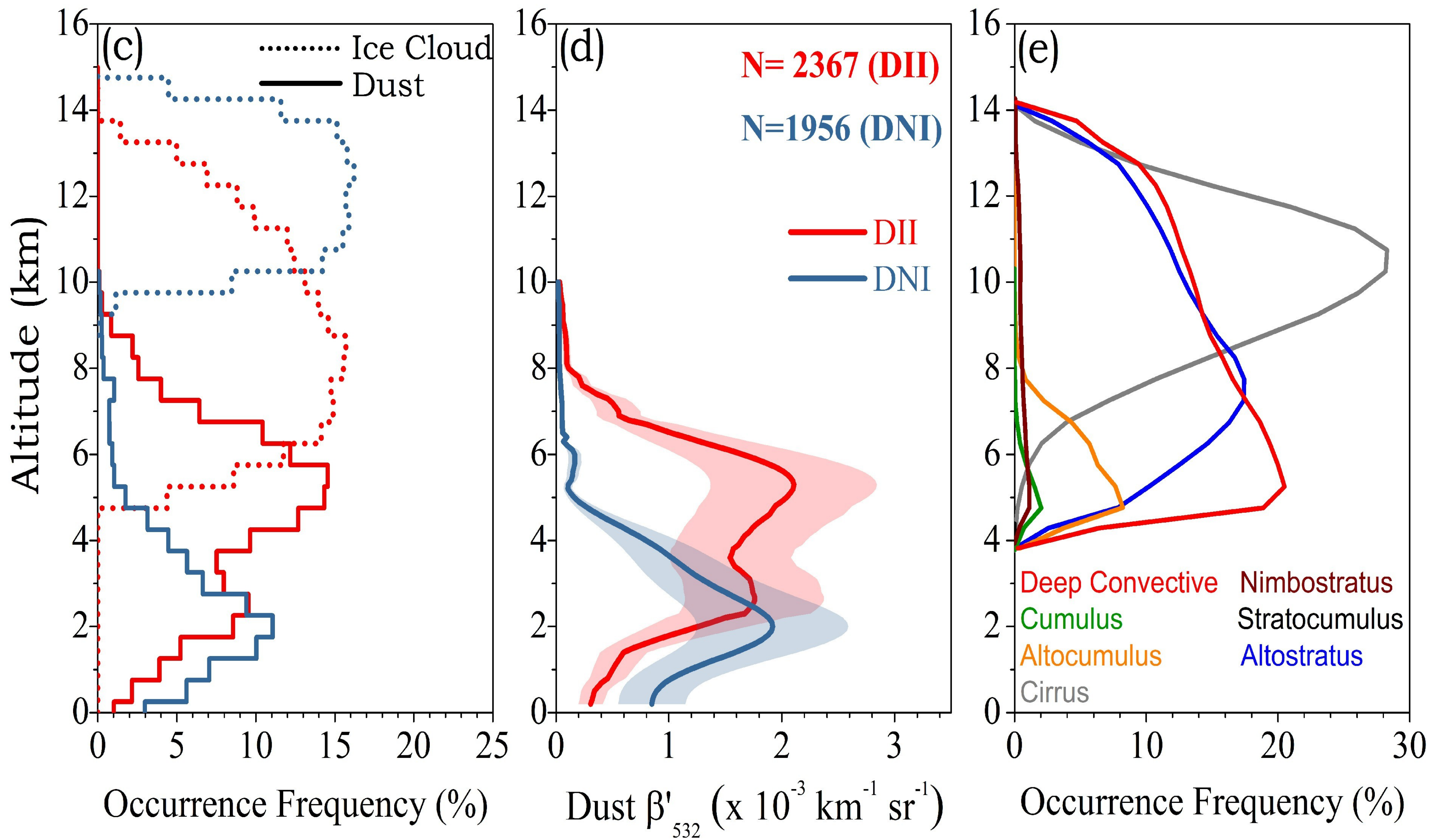


- **11-years (2006-2016) of multi-satellite observations and reanalysis data from June to September over Indian Summer Monsoon Region**
- **Identification of dust and ice cloud layers (using quality flags : CAD score and Feature Classification Flag)**
- **Two cases:**

  (i) DII : Dust and ice-cloud layers are within 200 m

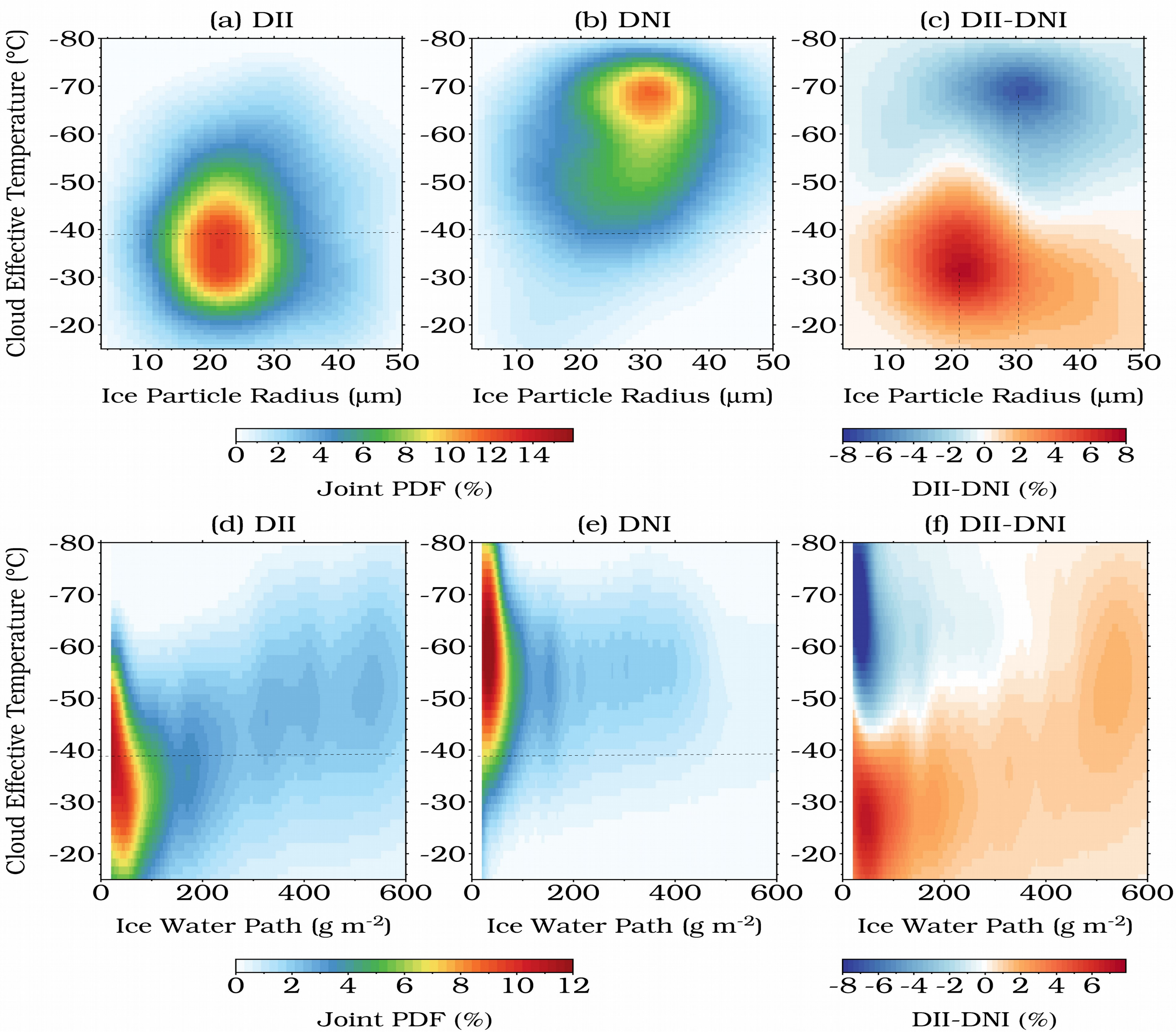
  (ii) DNI : Dust and ice-cloud layers are not within 200 m
- **CloudSat and CERES : 1 km and 10 km radius**
- **TRMM & ECMWF: closest pixel (for rain rate and dynamics)**

Vertical distribution



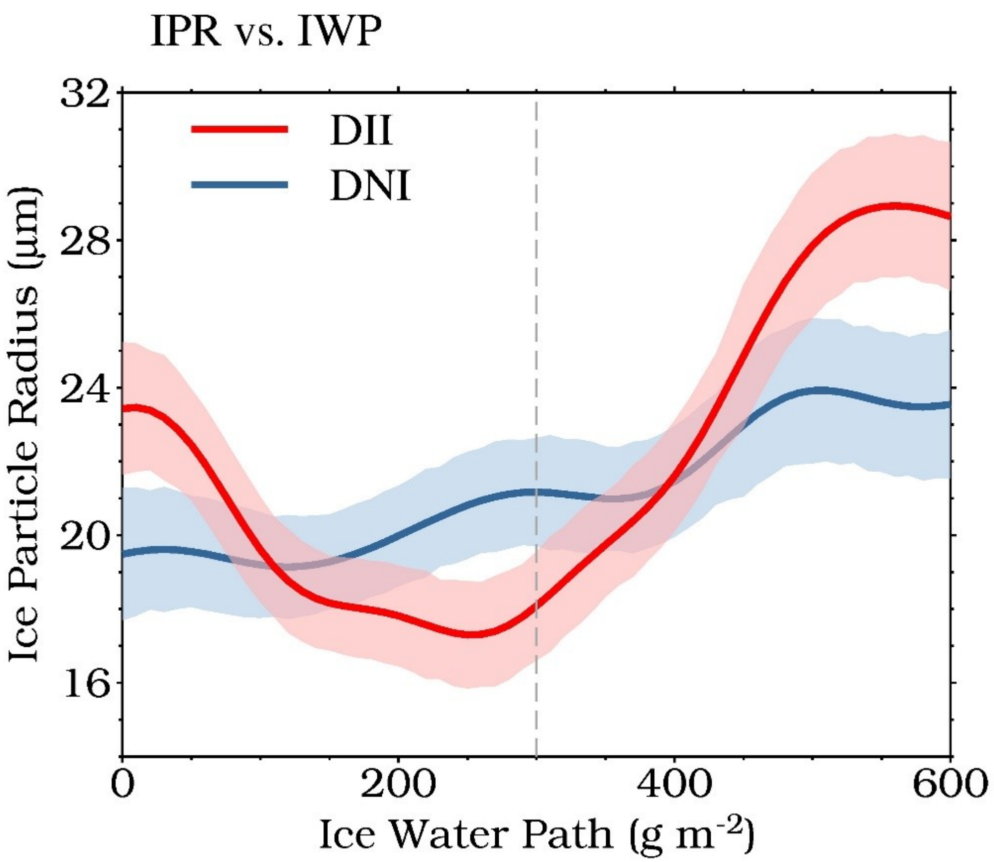
(Patel et al., 2019, GRL, in-press)

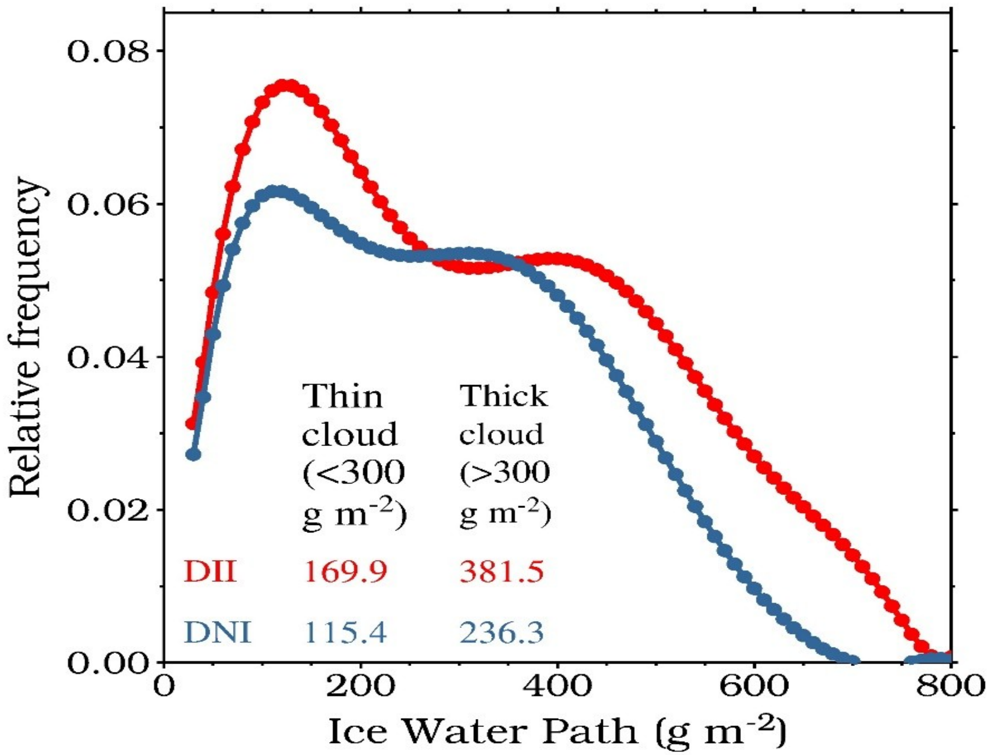
Dust-induced ice-cloud properties



Homogeneous threshold temperature conditions : > -38°C (*Min et al., 2009, 2010*)

(Patel et al., 2019, GRL, in-press)





For DII,

IPR ↓ (~25%) for thin cloud (IWP<300 g m^{-2})

IPR ↑ (~40%) for thick cloud (IWP>300 g m^{-2})

For DNI,

IPR consistent for thin cloud (IWP<300 g m^{-2})

IPR ↑ (~13%) for thick cloud (IWP>300 g m^{-2})

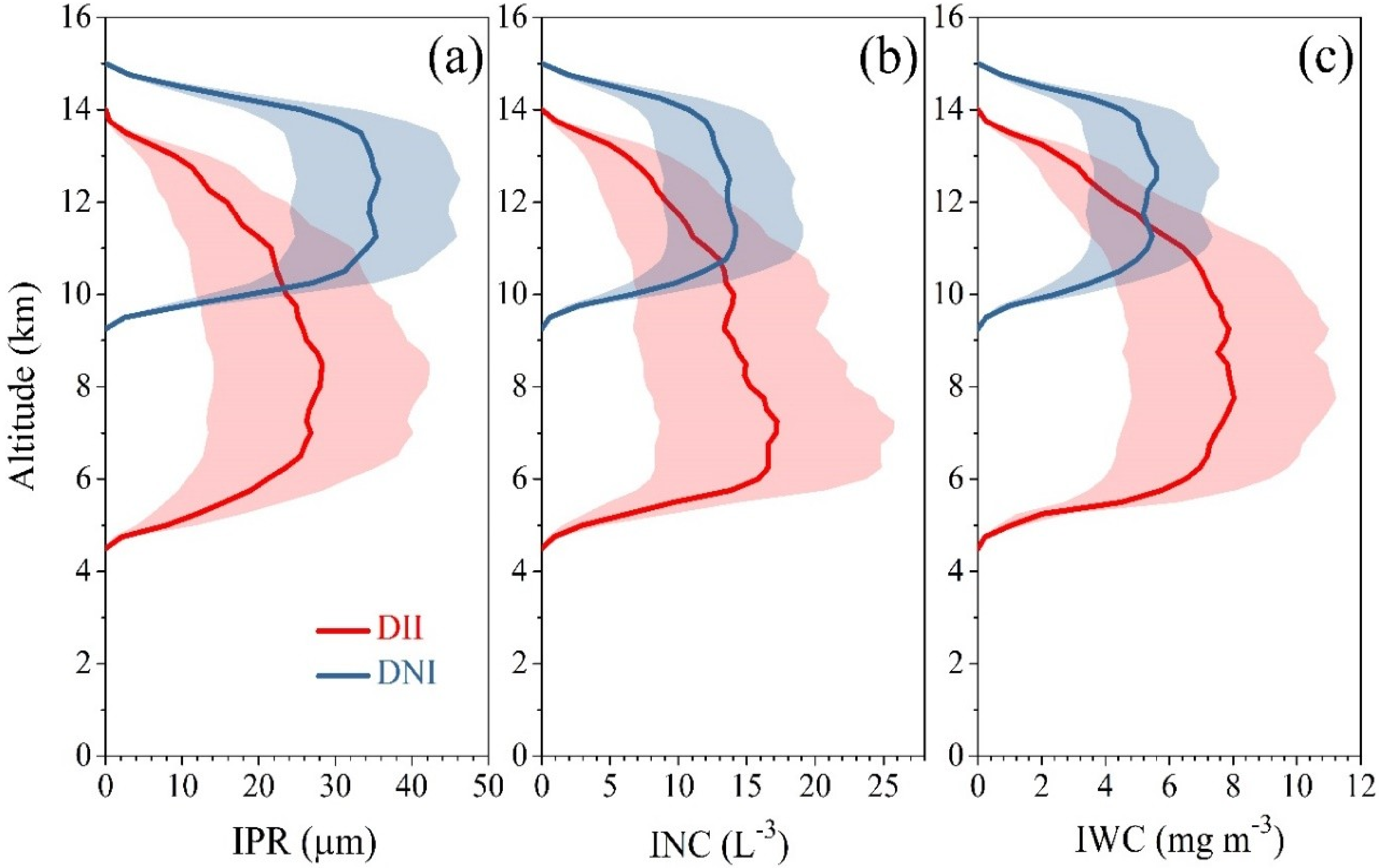
Mean IWP ↑ (~30%) for thin ice cloud regime in DII :

Dust microphysical effect

Mean IWP ↑ (~40%) for thick ice cloud regime in DII :

Microphysical - dynamical coupling

(Patel et al., 2019, GRL, in-press)



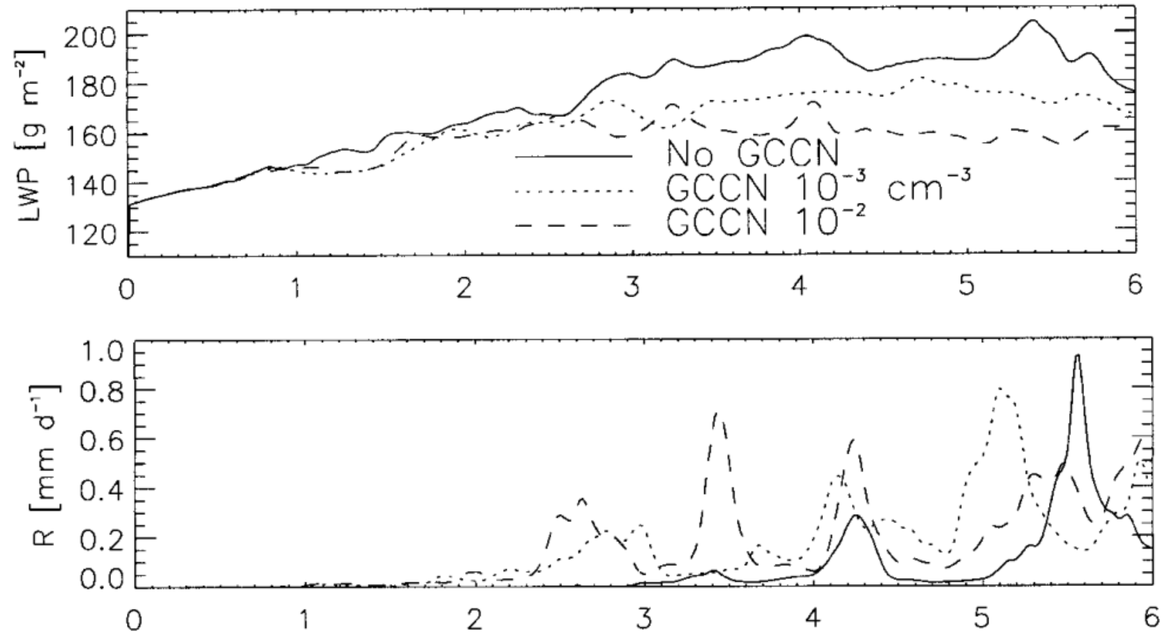
IPR ↓ (~20%), INC ↑ (~30%), IWC ↑ (~30%) (Dust Microphysical Effect)

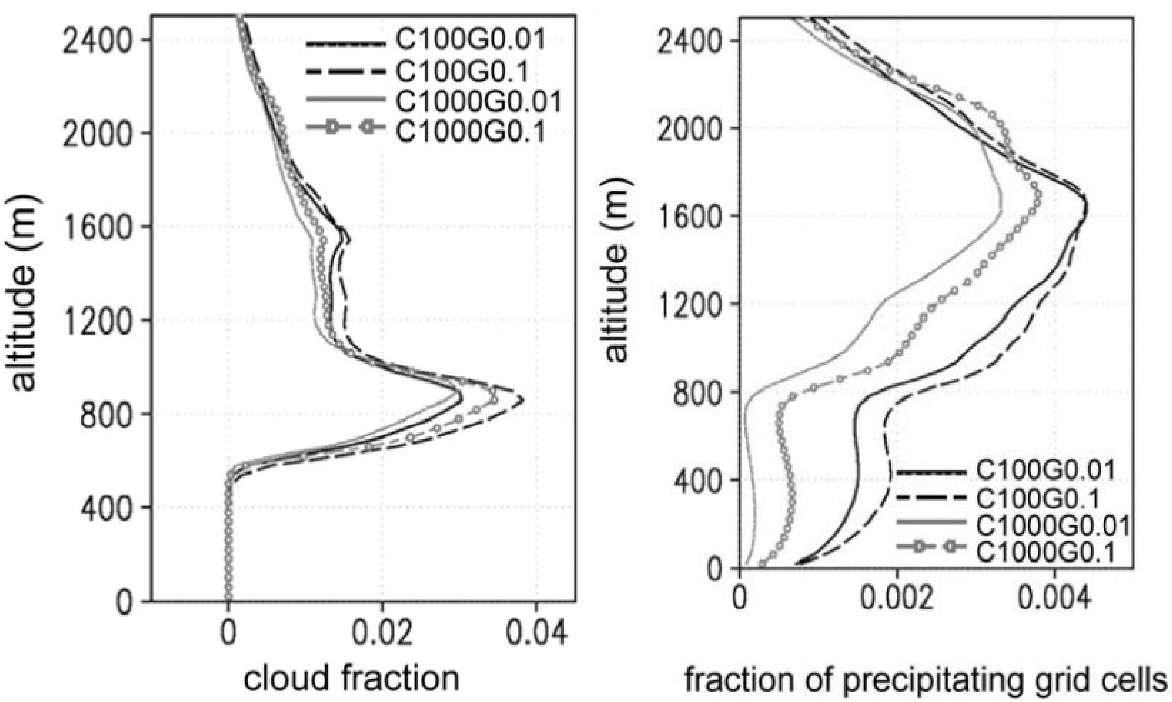
Vertical Growth ↑ (~40%) (Cloud Invigoration Effect)

(Patel et al., 2019, GRL, in-press)

role of aerosol/CCN size

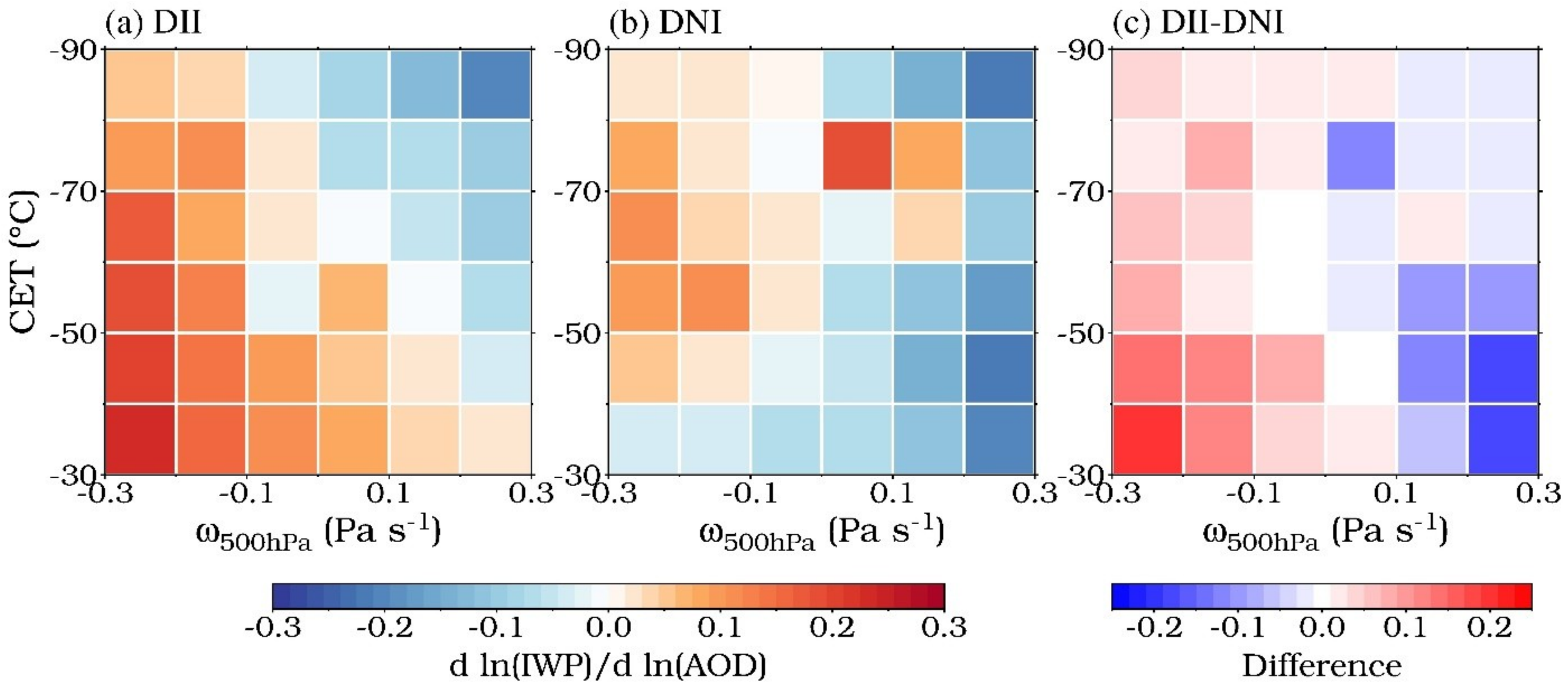
(Feingold et al., 1999, JAS)





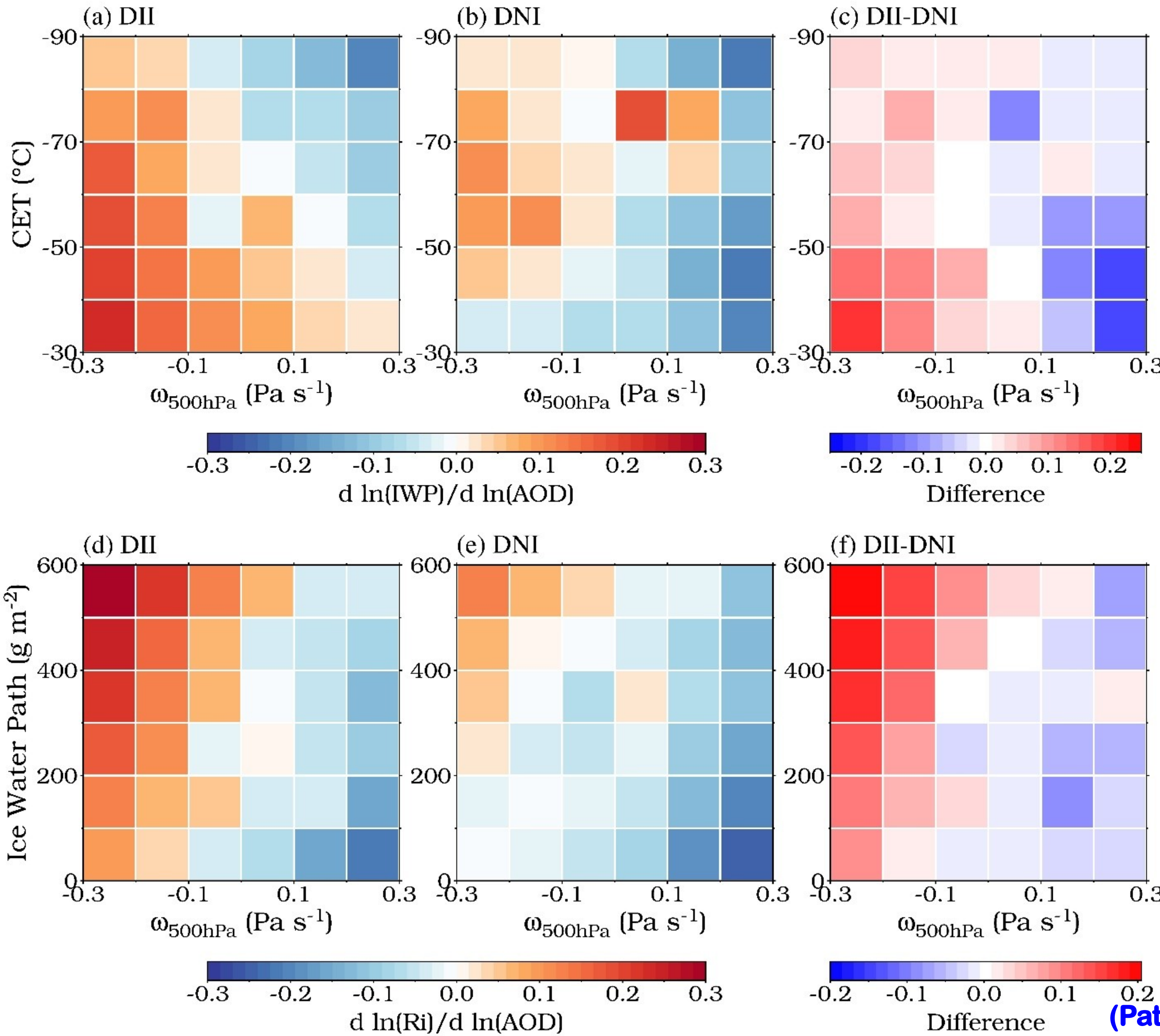
(Cheng et al., 2009, JGR)

Meteorological feedback



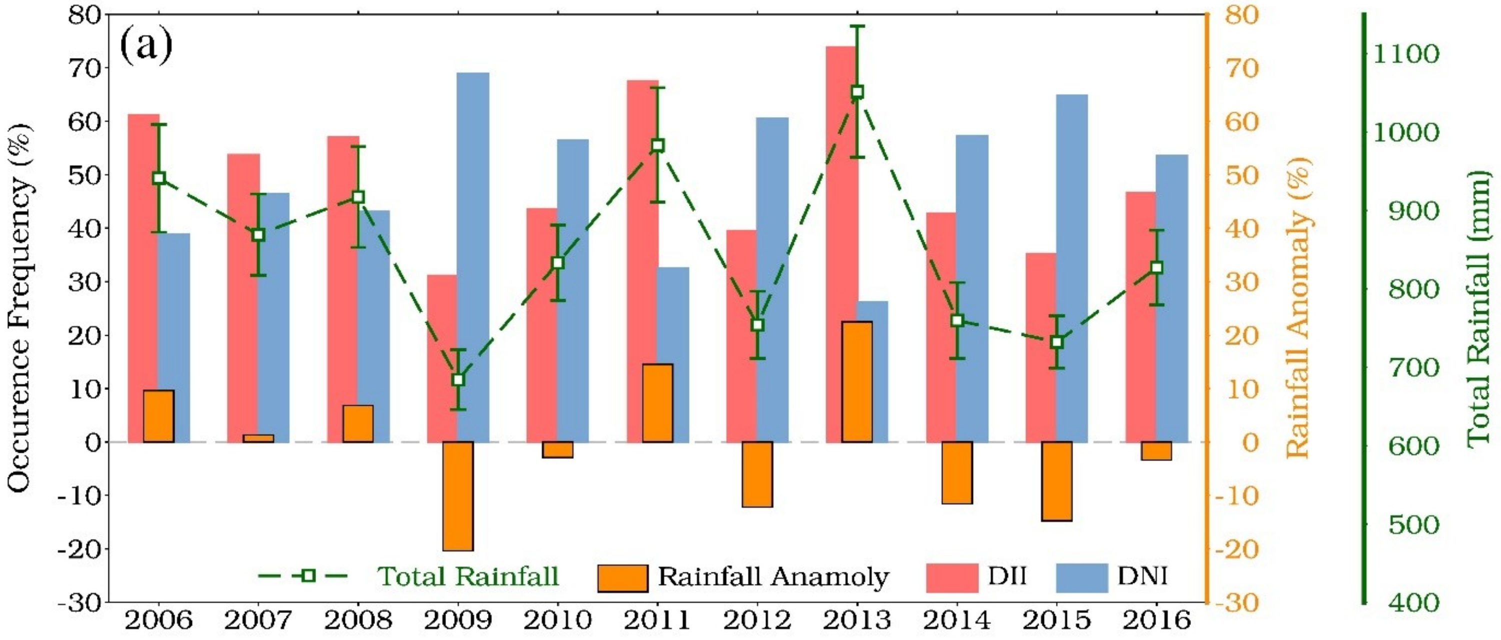
(Patel et al., 2019, GRL, in-press)

Meteorological feedback



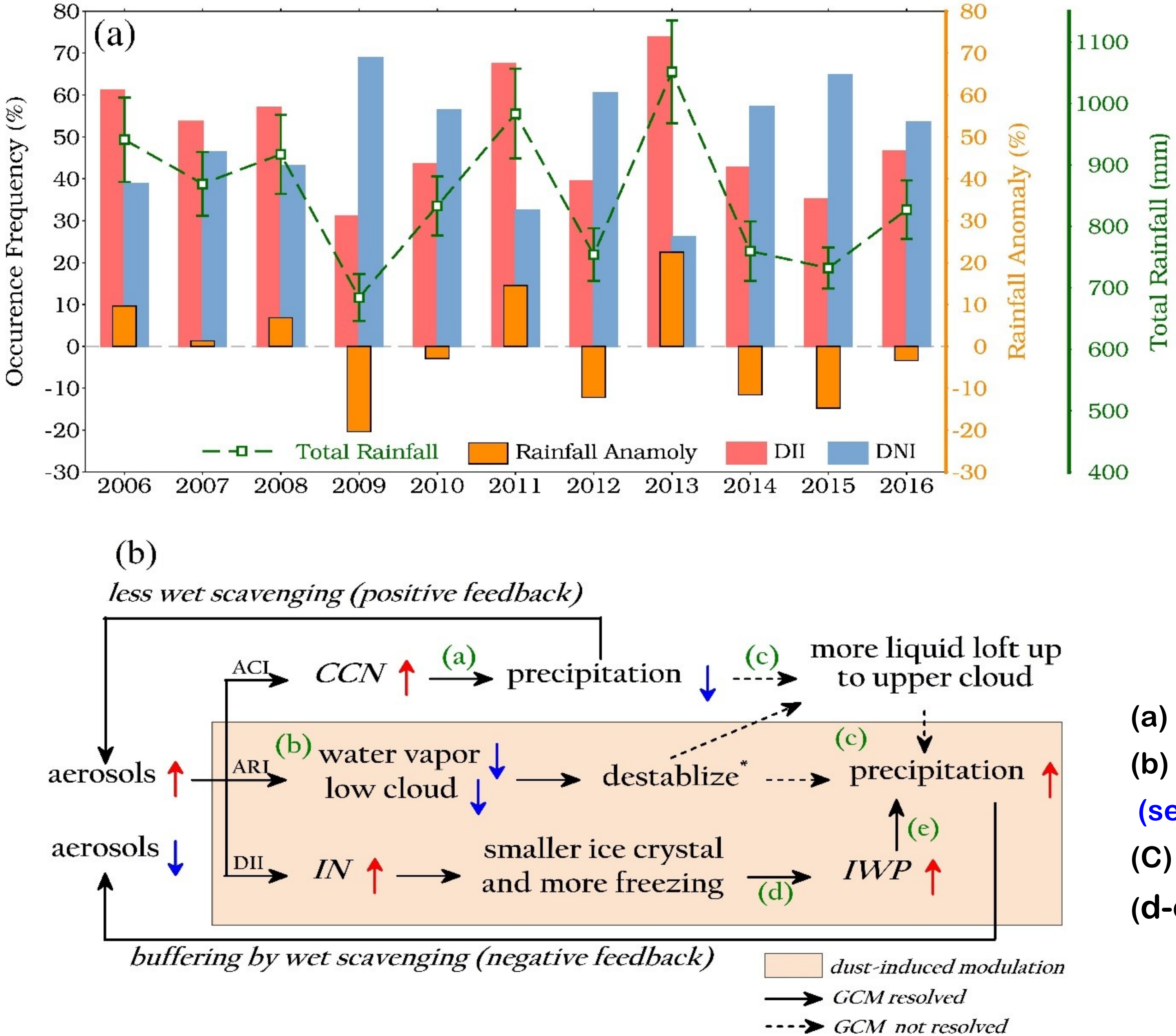
(Patel et al., 2019, GRL, in-press)

Discussion & Feedback



(Patel et al., 2019, GRL, in-press)

Discussion & Feedback



(a) aerosol-cloud interactions

(b) aerosol-radiation interactions (semi-direct effect)

(C) cloud invigoration

(d-e) This study

(Patel et al., 2019, GRL, in-press)

Conclusion

- ✔ **Dust Microphsyical Effect** : elevated dust act as efficient IN toward producing small ice particles at warmer temperature through heterogeneous nucleation mechanism in thin ice-clouds.

- ✔ **Microphysical-Dynamical Coupling (Cloud Invigoration)**: responsible for deepening of cloud in thick ice-clouds.

- ✔ **~63% large dust-induced positive IWP susceptibility** under unstable and greater humid conditions strongly suggests the **importance of dynamics in dust-ice cloud interactions**.

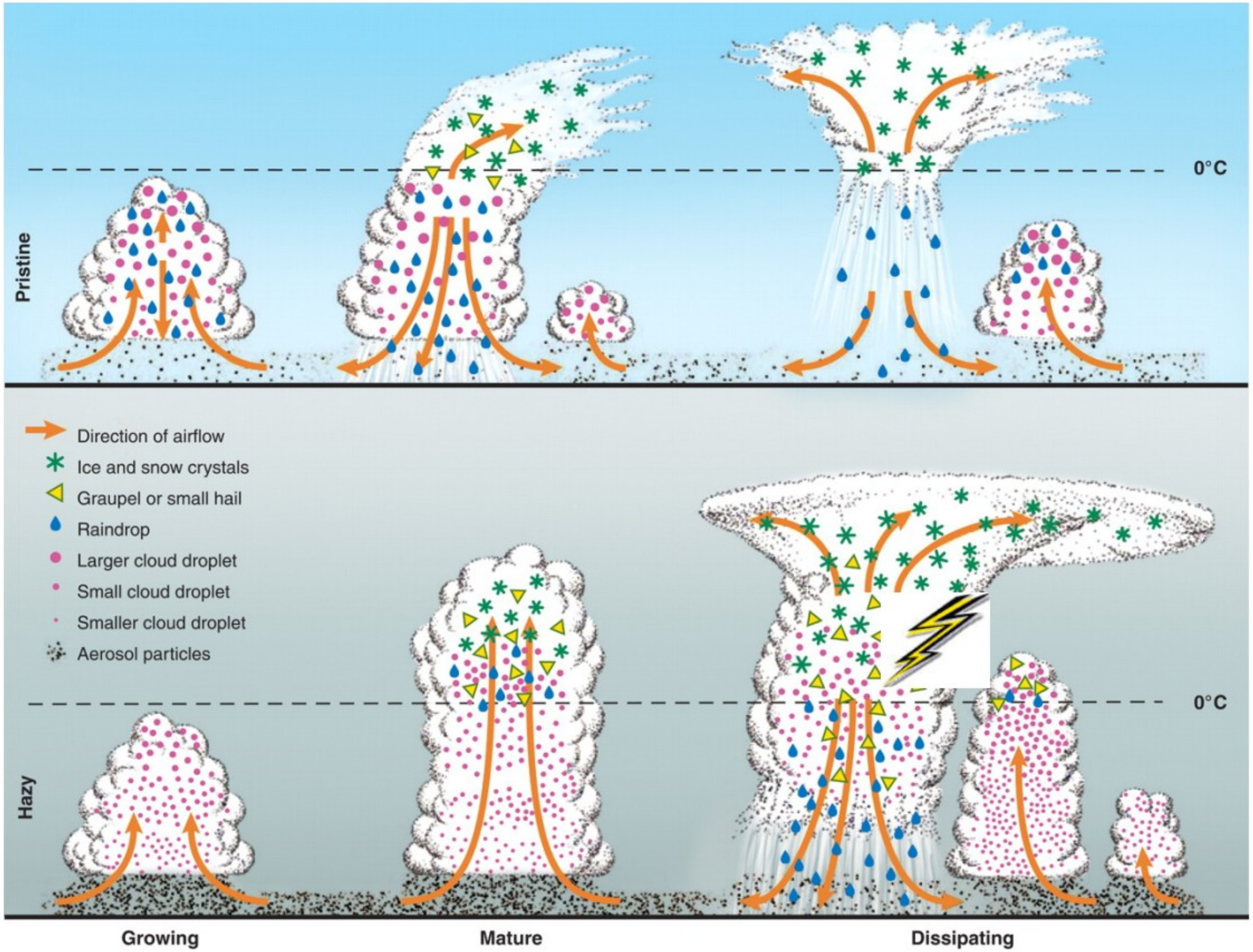
- ✔ **~60% large positive precipitation susceptibility** under strong updraft regime in thick ice-cloud regime suggests the **strengtheing of Indian summer monsoon precipaition susceptibility** via microphysical-dynamical interaction (cloud invigoration).

- ✔ This microphysical-dynamical coupling provides a **negative feedback** on aerosol-cloud interaction, which **buffers (mitigates) the aerosol effects due to enhanced wet scavenging**. Thus underscore the importance of incorporating **regime-dependent dust-ice cloud-precipitation interactions** for improved climate simulations.

- ✔ These observational-based process-level findings of dust-ice cloud-precipitation interactions would help improve **resolving the discrepancy in aerosol-cloud-precipitation interactions between models and observations.**

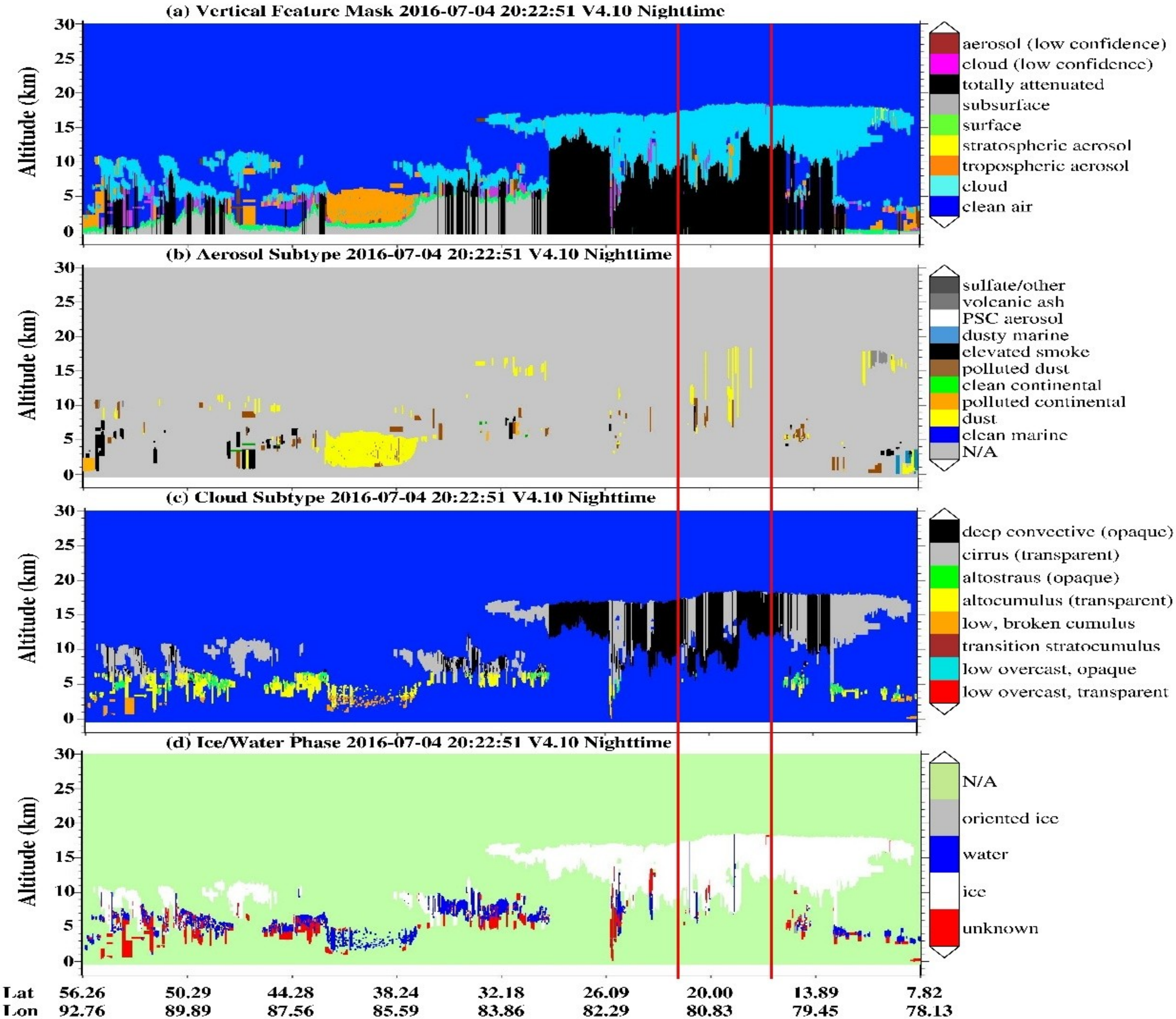

Thank you for patience

aerosol cloud interactions

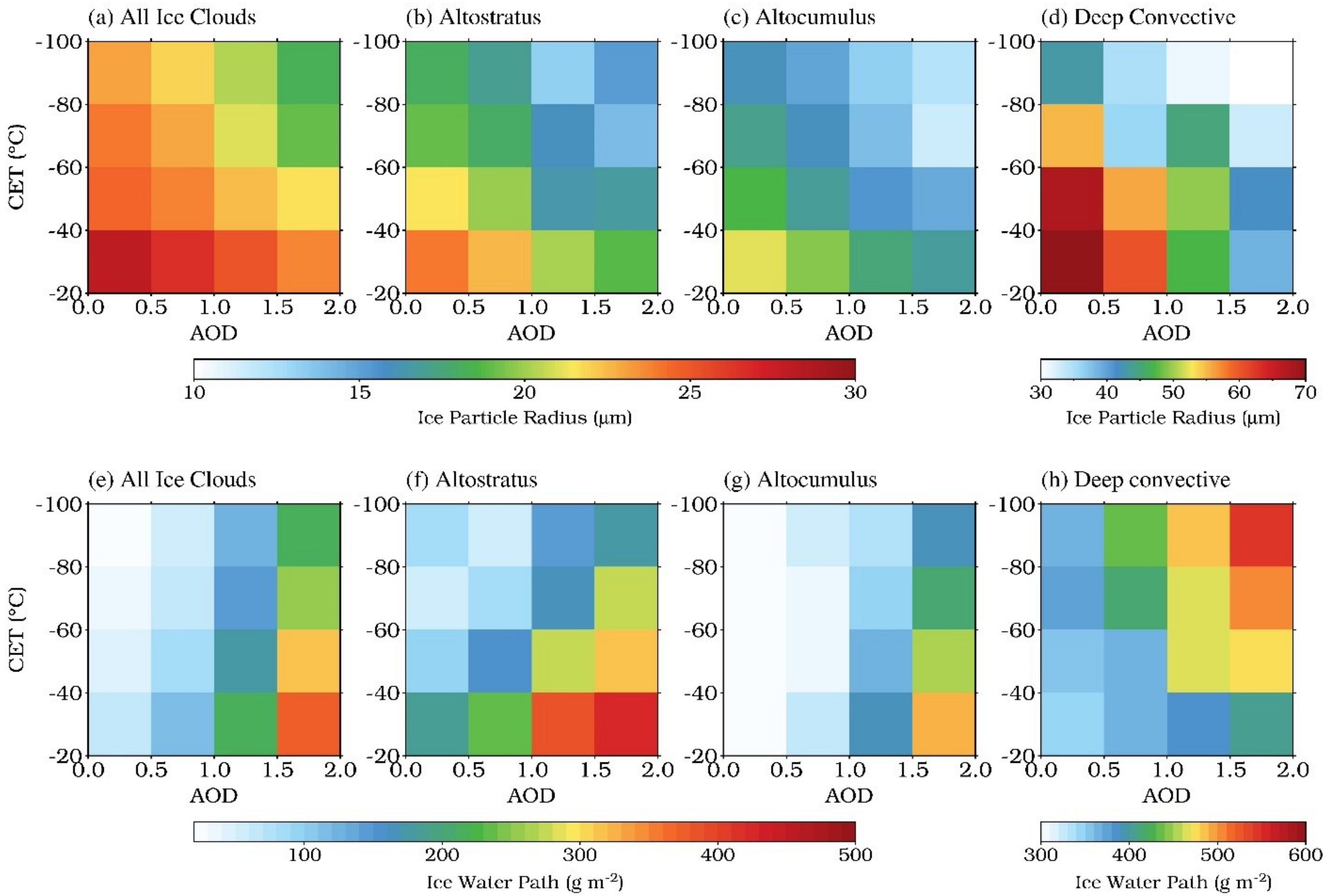


Indirect effect of the 3rd kind: Delayed warm rain, and prolonged cloud life time by aerosols in a monsoon (moisture-rich) environment may invigorate deep convection

(Rosenfeld et al., 2008, Science)



(a) Vertical Feature Mask 2016-07-04 20:22:51 V4.10 Nighttime
aerosol (low confidence)
cloud (low confidence)
totally attenuated
subsurface
surface
stratospheric aerosol
tropospheric aerosol
cloud
clean air
(b) Aerosol Subtype 2016-07-04 20:22:51 V4.10 Nighttime
sulfate/other
volcanic ash
PSC aerosol
dusty marine
elevated smoke
polluted dust
clean continental
polluted continental
dust
clean marine
N/A
(c) Cloud Subtype 2016-07-04 20:22:51 V4.10 Nighttime
deep convective (opaque)
cirrus (transparent)
altostraus (opaque)
altocumulus (transparent)
low, broken cumulus
transition stratocumulus
low overcast, opaque
low overcast, transparent
(d) Ice/Water Phase 2016-07-04 20:22:51 V4.10 Nighttime
N/A
oriented ice
water
ice
unknown
Altitude (km)
0
5
10
15
20
25
30
Lat 56.26 50.29 44.28 38.24 32.18 26.09 20.00 13.89 7.82
Lon 92.76 89.89 87.56 85.59 83.86 82.29 80.83 79.45 78.13



For DII ,

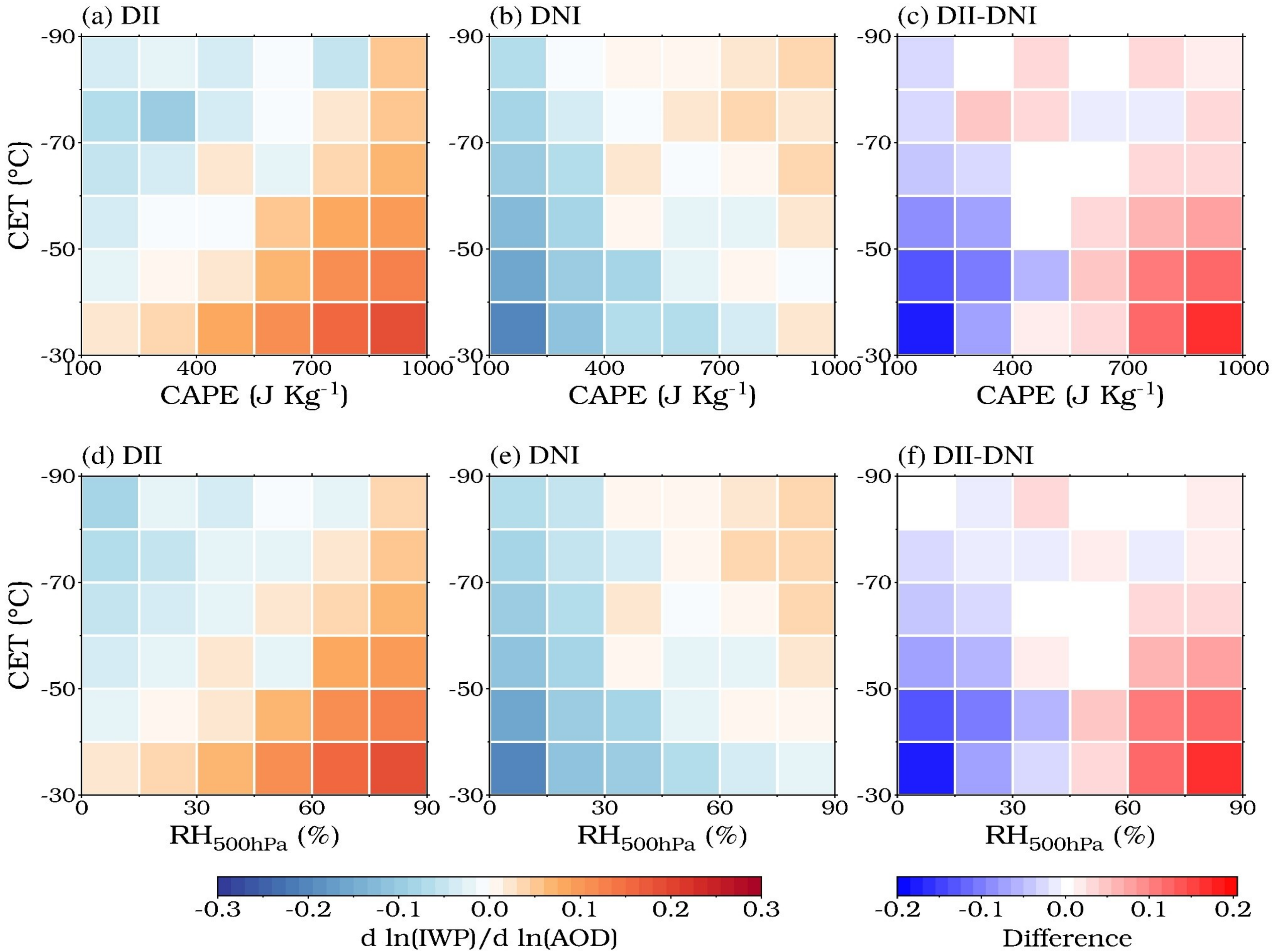
IPR ↓ with AOD ↑ for a given CET

IPR ↑ with CET ↑

Dust Microphysical Effect

For DII,

IWP ↑ with AOD ↑ both at colder and warmer temperatures.



(a) DII
(b) DNI
(c) DII-DNI
(d) DII
(e) DNI
(f) DII-DNI
CET (°C)
-90
-70
-50
-30
100
400
700
1000
CAPE (J Kg-1)
0
30
60
90
RH500hPa (%)
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
d ln(IWP)/d ln(AOD)
Difference

Previous Studies...

- Decreasing trend of monsoon rainfall over Central India is due to increasing trend of anthropogenic aerosols [*Bollasina et al., 2011, Salzman et al., 2014*]

  Solar dimming effect : a high aerosol loading also induces a solar dimming (absorbing) effect at the surface, which can alter the land–ocean thermal gradient and weaken the circulation, resulting in a drying trend in seasonal rainfall during the Indian summer monsoon [*Ramanathan and Carmichael, 2008; Ramanathan et al., 2001; Bollasina et al., 2011; Ganguly et la., 2012*]

  Elevated heat pump: an aerosol-induced atmospheric heating over Himalayan slopes and the Tibetan Plateau during the monsoon onset period intensifies the northward shift of the Indian summer monsoon, causing a reduction in rainfall over the Indian summer monsoon region [*Lau and Kim, 2006; Gautam et al., 2009*]

- 25% contribution of global emission from anthropogenic aerosol and 75% of contribution from natural dust [*Ginoux et al., 2012, Kuhlmann and Quass, 2010*]

- Radiative implications of dust modulate the monsoon rainfall over Central India [*Vinoj et al., 2014*]

- Radiative forcing by aerosol-ice cloud interaction ---> -0.67 W m^{-2} to 0.70 W m^{-2} [*IPCC, 2013; Fan et al., 2016*]

Stevens and Feingold, 2009, Nature

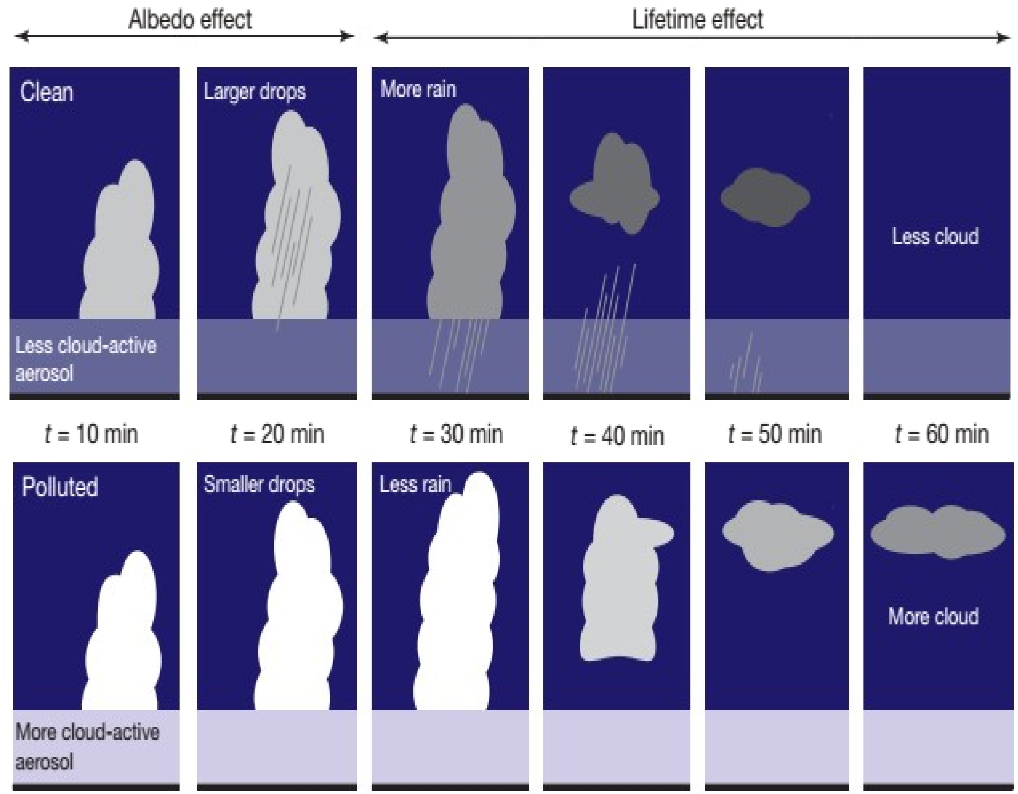


Figure 1 | The lifetime (and albedo) effect as originally proposed. In polluted air masses, clouds consist of more droplets that coalesce into raindrops less effectively, leaving longer-lived clouds (*t*, time). Here and in Figs 3 and 4, a single cloud is meant to represent the average response of a field of clouds.

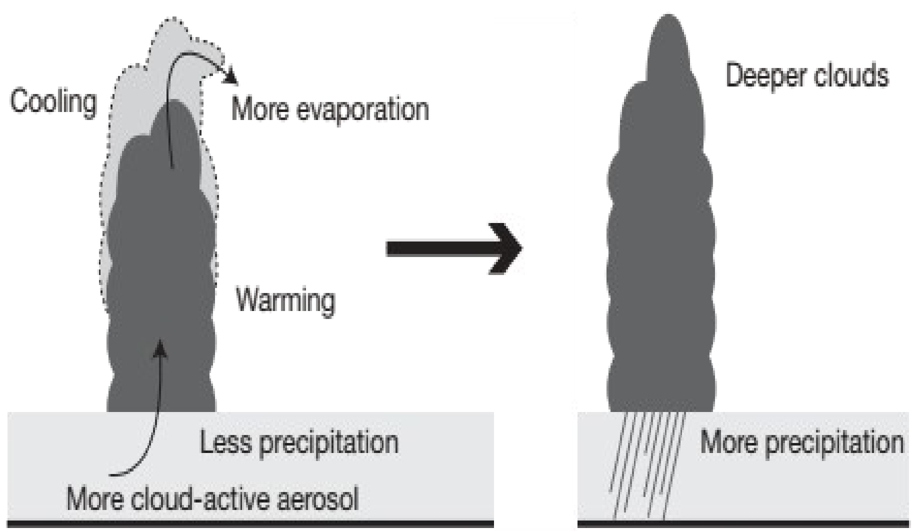
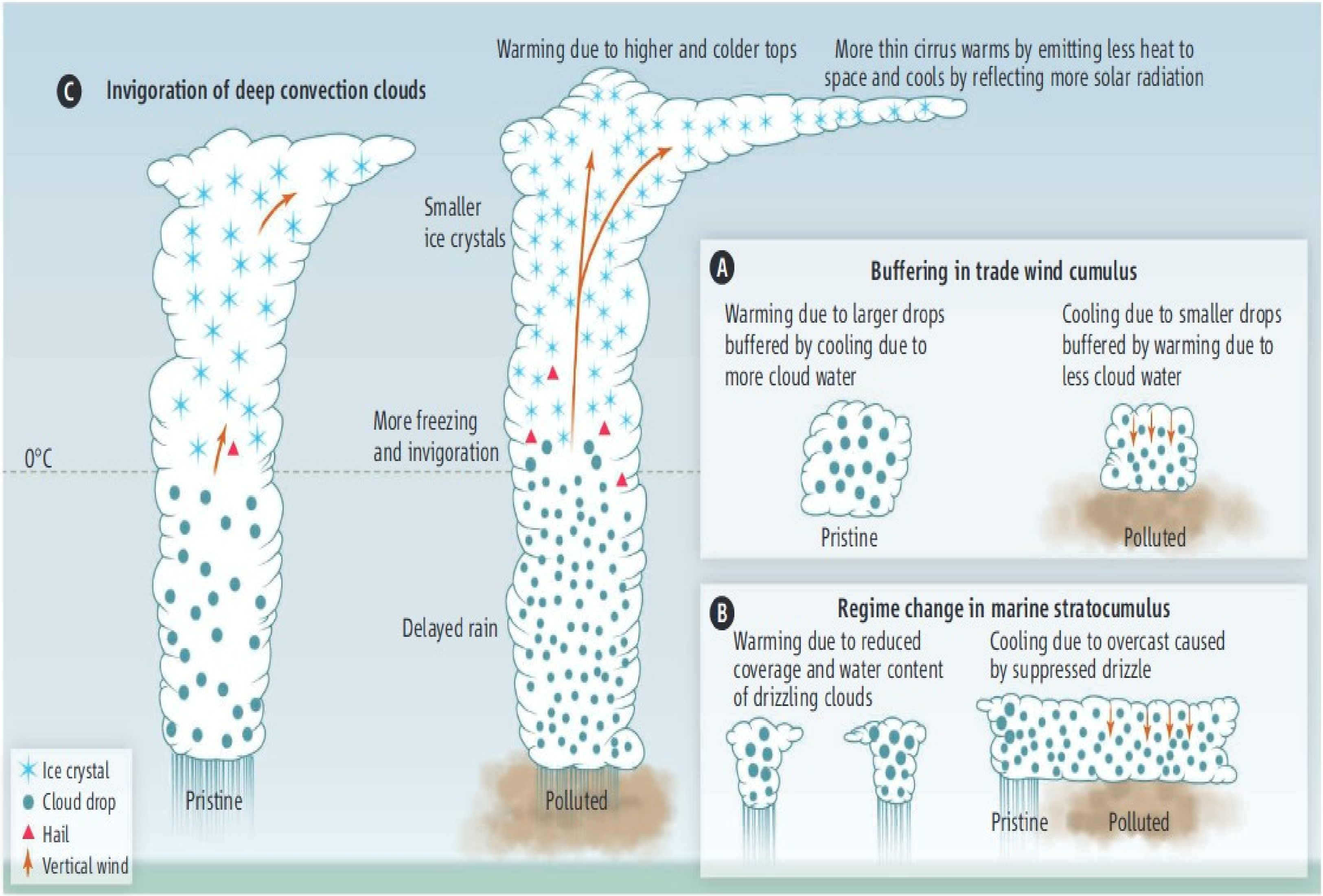


Figure 4 | The deepening effect. The local inhibition of precipitation helps precondition the environment for deeper convection, which then rains more.

1) less precipitation leads to loft more cloud water to the top, where the evaporation enhanced.

2) cooling due to evaporation

3) to be more unstable and more rain



How aerosols affect the radiative properties of clouds. By nucleating a larger number of smaller cloud drops, aerosols affect cloud radiative forcing in various ways. (**A**) Buffering in nonprecipitating clouds. The smaller drops evaporate faster and cause more mixing of ambient air into the cloud top, which further enhances evaporation. (**B**) Strong cooling. Pristine cloud cover breaks up by losing water to rain that further cleanses the air in a positive feedback loop. Aerosols suppressing precipitation prevent the breakup. (**C**) Larger and longer-lasting cirrus clouds. By delaying precipitation, aerosols can invigorate deep convective clouds and cause colder cloud tops that emit less thermal radiation. The smaller ice particles induced by the pollution aerosols precipitate more slowly from the anvils. This can cause larger and longer-lasting cirrus clouds, with opposite effects in the thermal and solar radiation. The net effect depends on the relative magnitudes.

Rosenfeld et al., 2014, Science