Tibetan Anticyclone, tropospheric aerosols, and UTLS transport processes

William K. M. Lau,
ESSIC/JGCRI, University of Maryland

Coauthors: K. M. Kim, M. K. Kim, S. J. Shi,
W. K. Tao, M. Chin, Y. Cheng, Z. Li

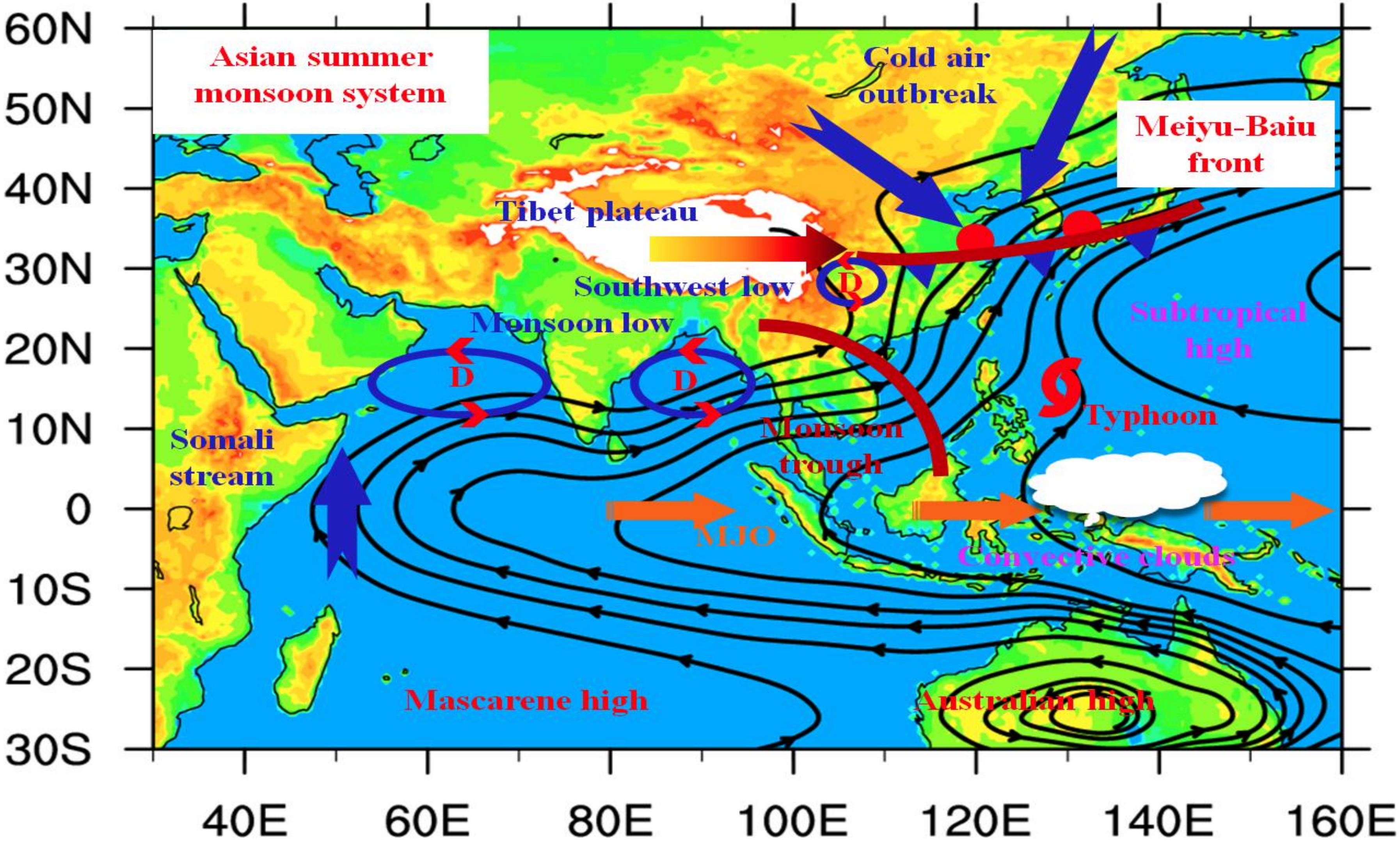
Outline

- A monsoon-aerosol primer
- The “Elevated Heat Pump” (EHP) hypothesis
- Aerosols impacts on monsoon interannual and intraseasonal variability
- UTLS transport processes

The Aerosol-Monsoon Climate System

- Over 60% of world population live in the Asian monsoon regions
- Monsoon related droughts and floods, and aerosols are the two most serious environmental hazards in Asian monsoon regions,
- The monsoon water cycle is driven by atmospheric heating, through the dynamical interaction of wind, moisture, clouds and rainfall.
- Sea surface temperature, and land surface processes alter monsoon water cycle, through generation of surface heating gradients and atmospheric heat sources and sinks.
- Suspended particles (aerosol, clouds, precipitation) in the atmosphere regulate and interact with heat sources and sinks, and alter the monsoon water cycle

Key features of the ASM (SAM, EAM)



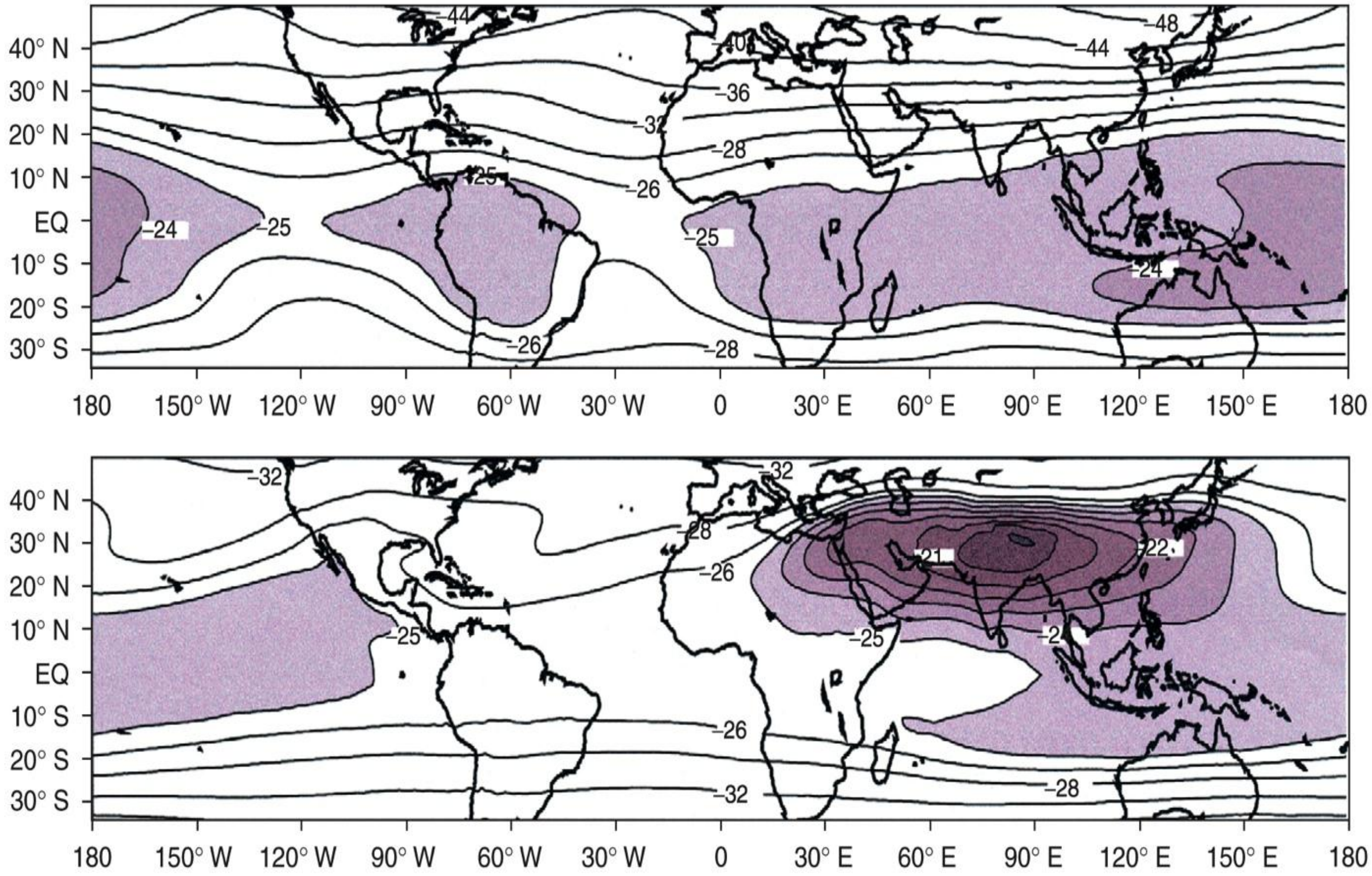


Figure 5 Mean temperature between 200 and 500 hPa for northern winter (January–February; upper panel) and northern summer (July–August; lower panel) at the height of the monsoon season (units: K). (Data source: Reanalyses from European Centre for Medium Range Weather Forecasts for 1979–93.)

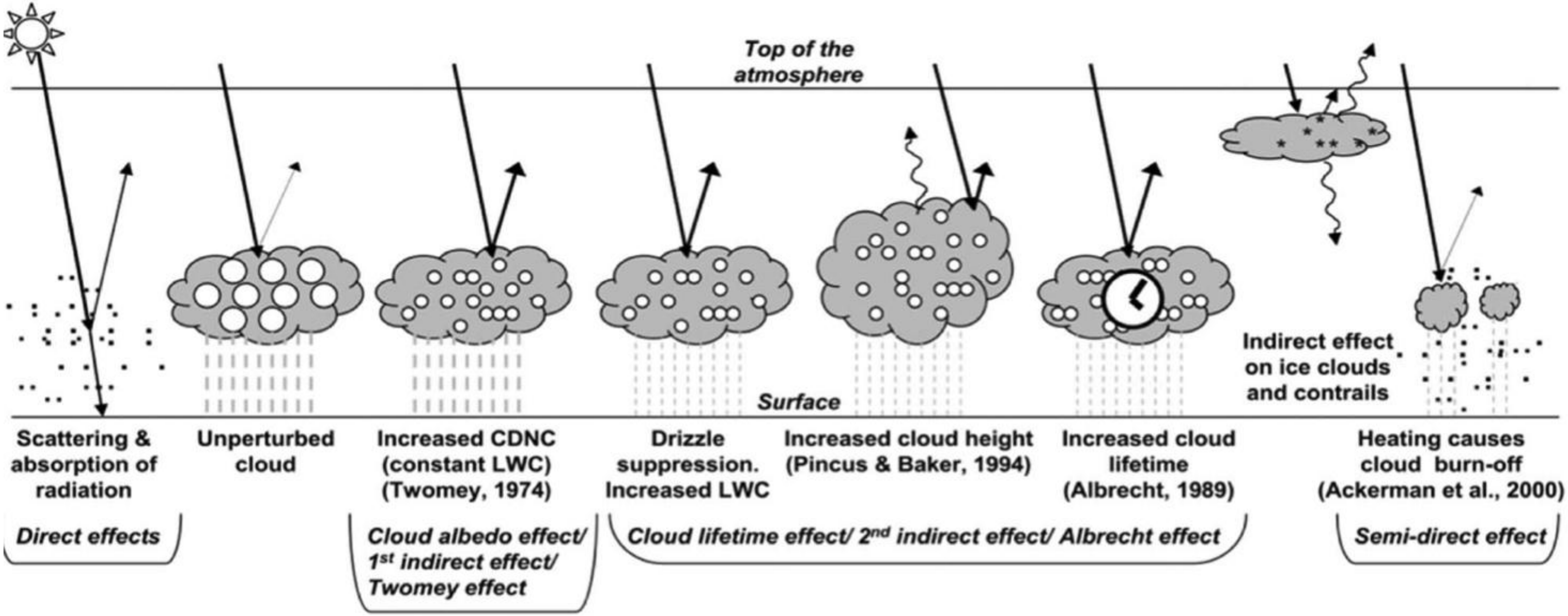
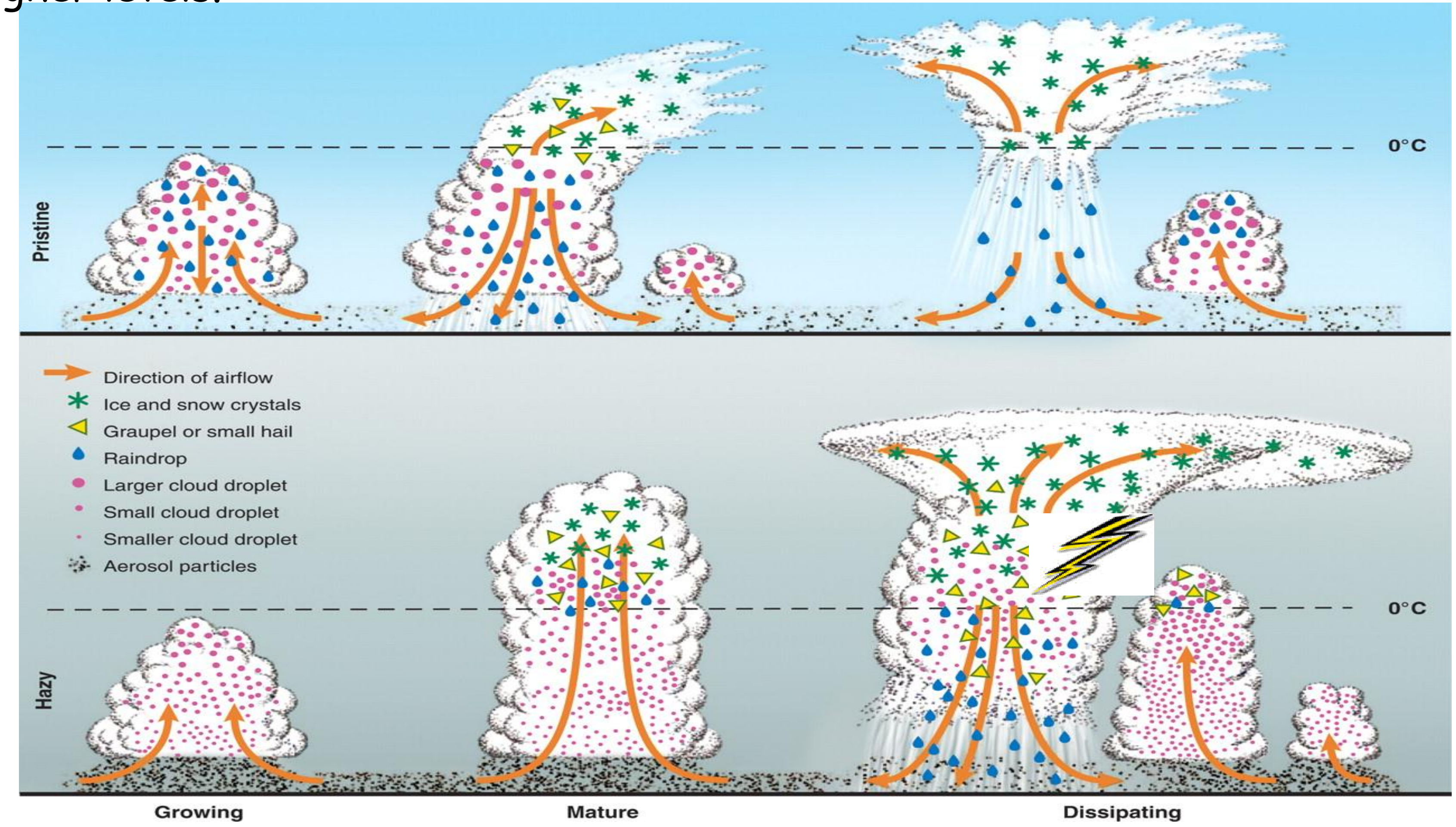


Figure 7. Various mechanisms proposed to explain how aerosols affect clouds and precipitation. Adapted from *Intergovernmental Panel on Climate Change* (*IPCC*) [2007].

Aerosol indirect (microphysics) effect of "the 3rd kind":

Delayed warm rain, and prolonged cloud life time by aerosols in a monsoon (moisture-rich) environment invigorate deep convection, shifting latent heating to higher levels.



Rosenfeld et al 2008, *Science*

Aerosol-monsoon water cycle interactions occur over a wide range of spatial and temporal scales

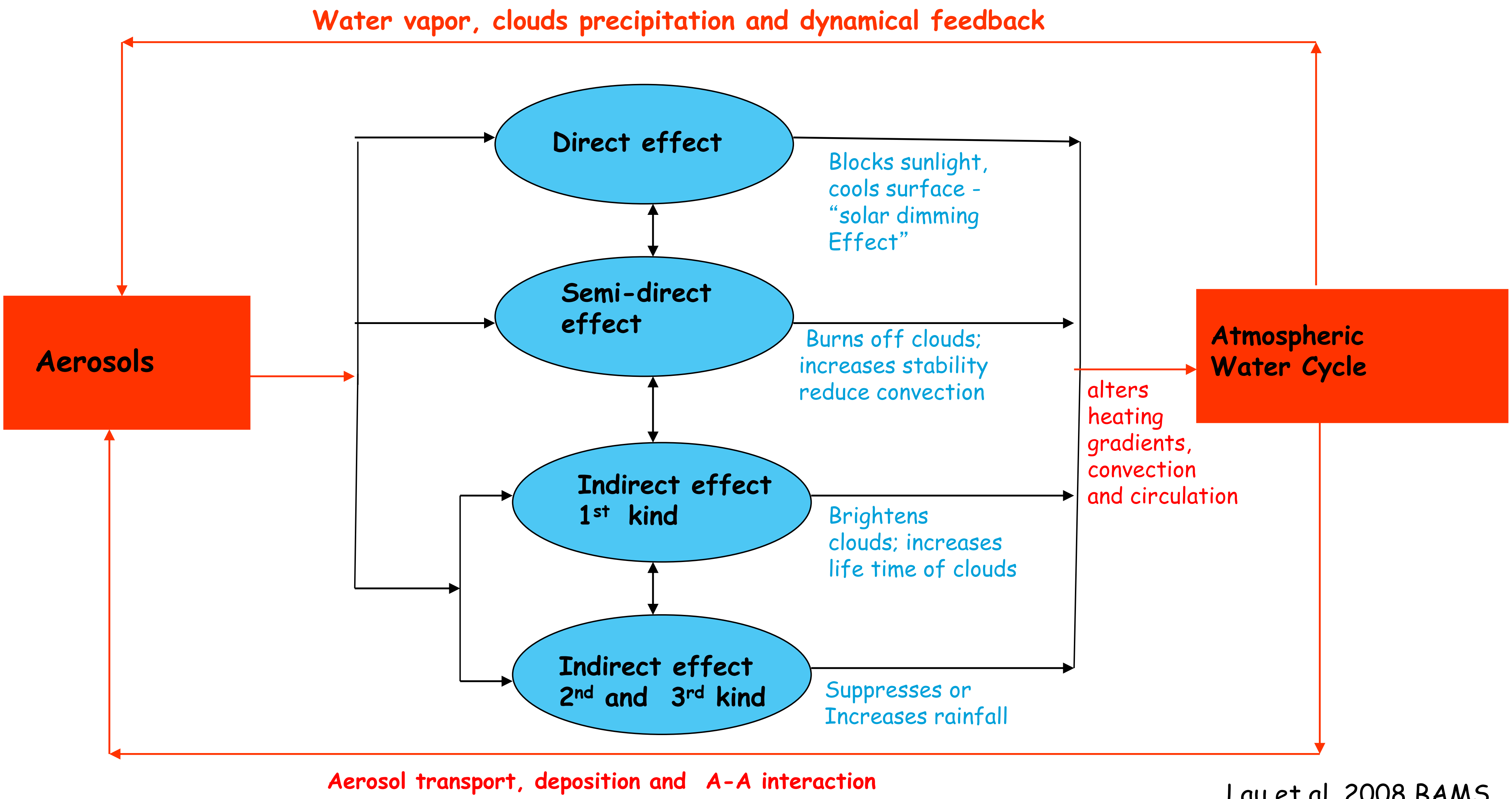
- Hourly-daily-to-intraseasonal: individual clouds and cloud clusters (< 1 -100 km)

- Seasonal-to-interannual: regional to continental (100 - 1000 km)

- Climate Change/Interdecadal : continental to global (>10,000 km)

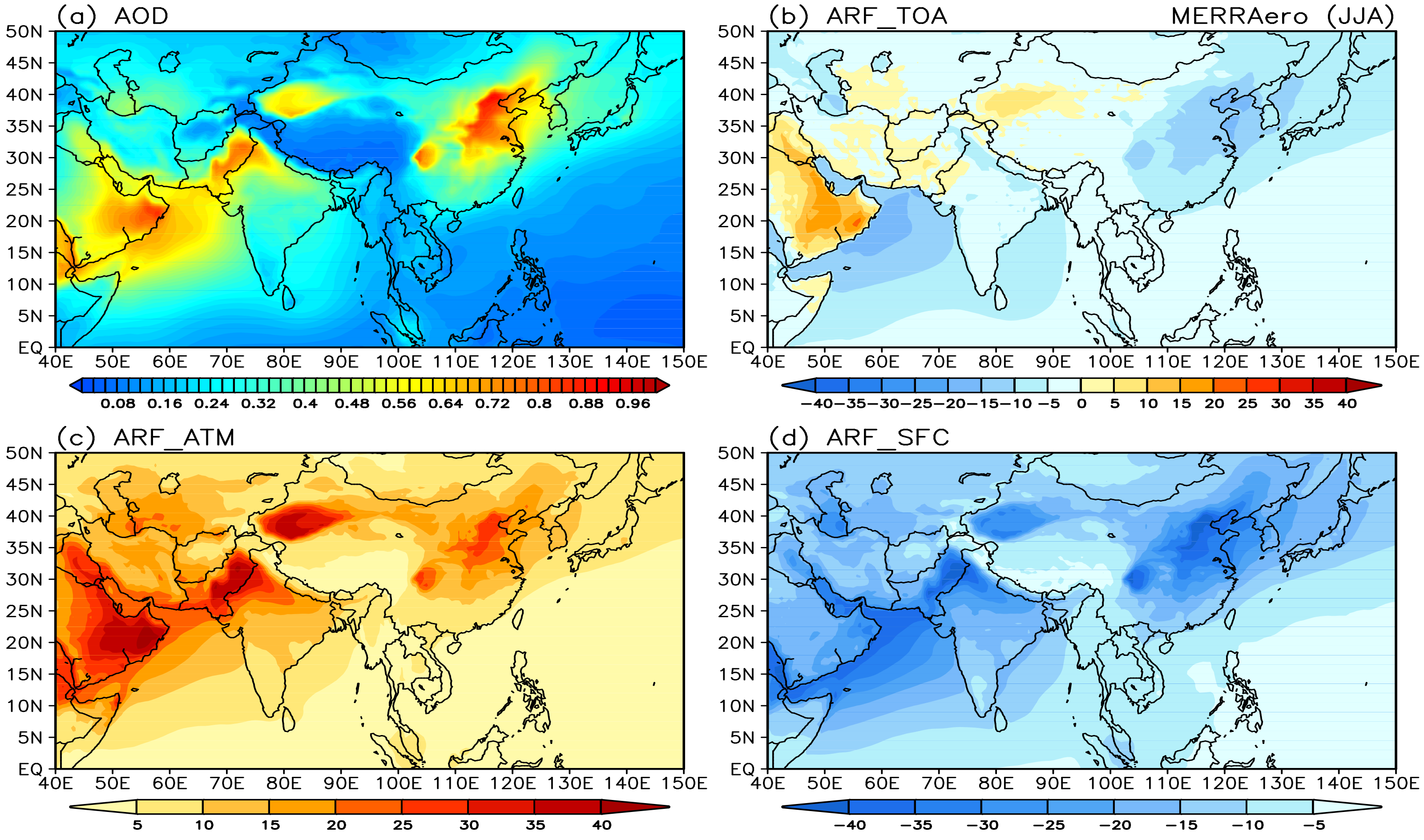
Aerosol- atmospheric water cycle interactions

Local vs. Non-local effects



Lau et al, 2008 BAMS

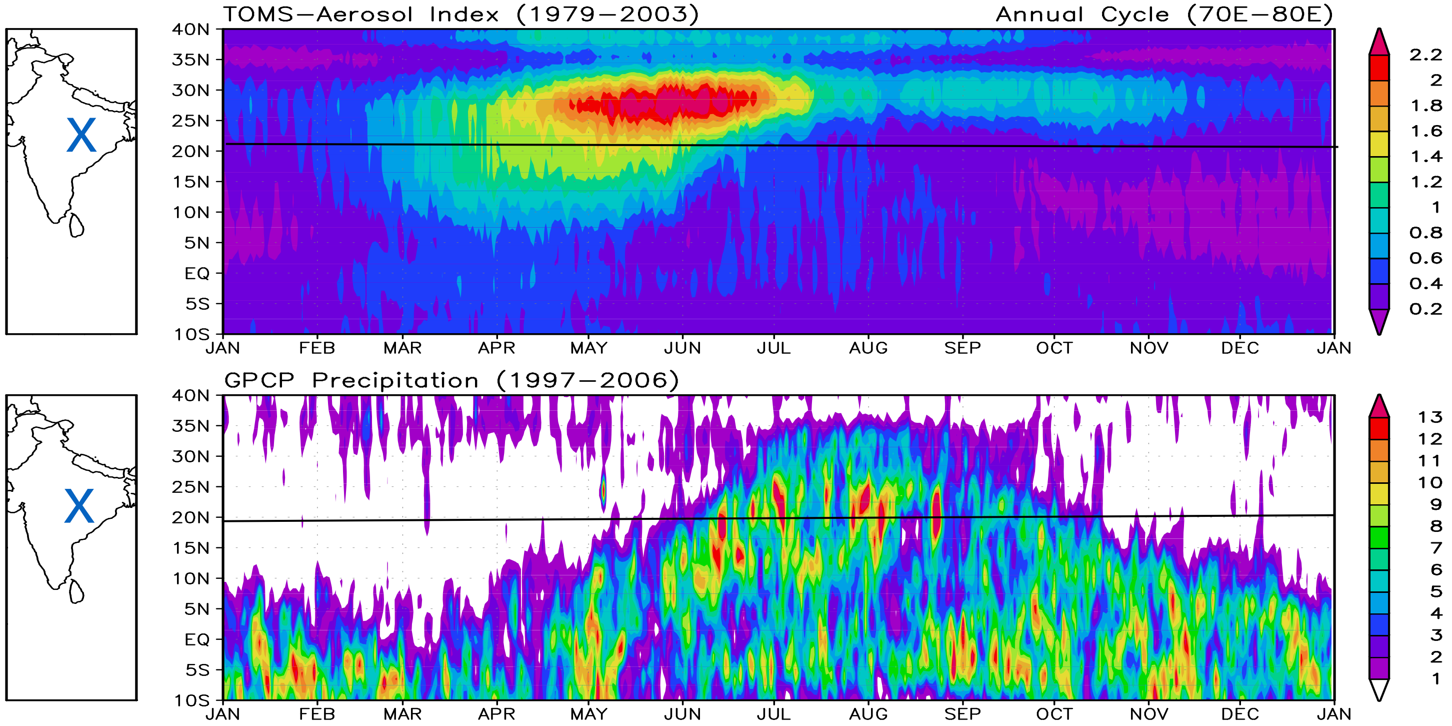
Aerosol Radiative Forcing of the ASM



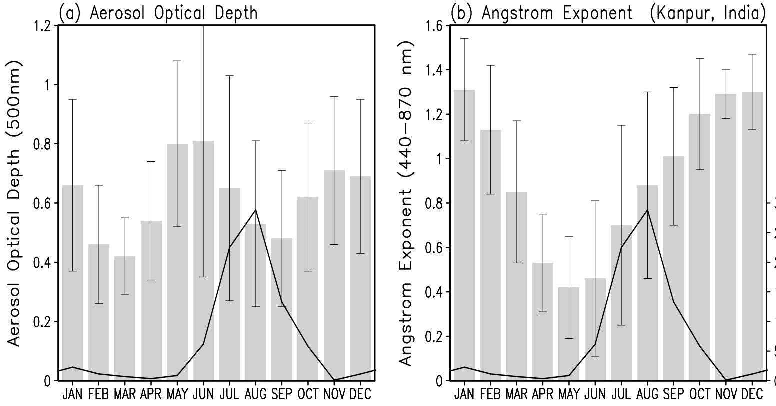
First order aerosol effects on monsoon: Increase atmospheric stability (semi-direct effect), decrease land-sea contrast → weakening of the monsoon,

but regional dynamical feedback may further alter monsoon evolution…

Strong seasonal locking of absorbing aerosol and rainfall distribution over central and northern India



Kanpur, India



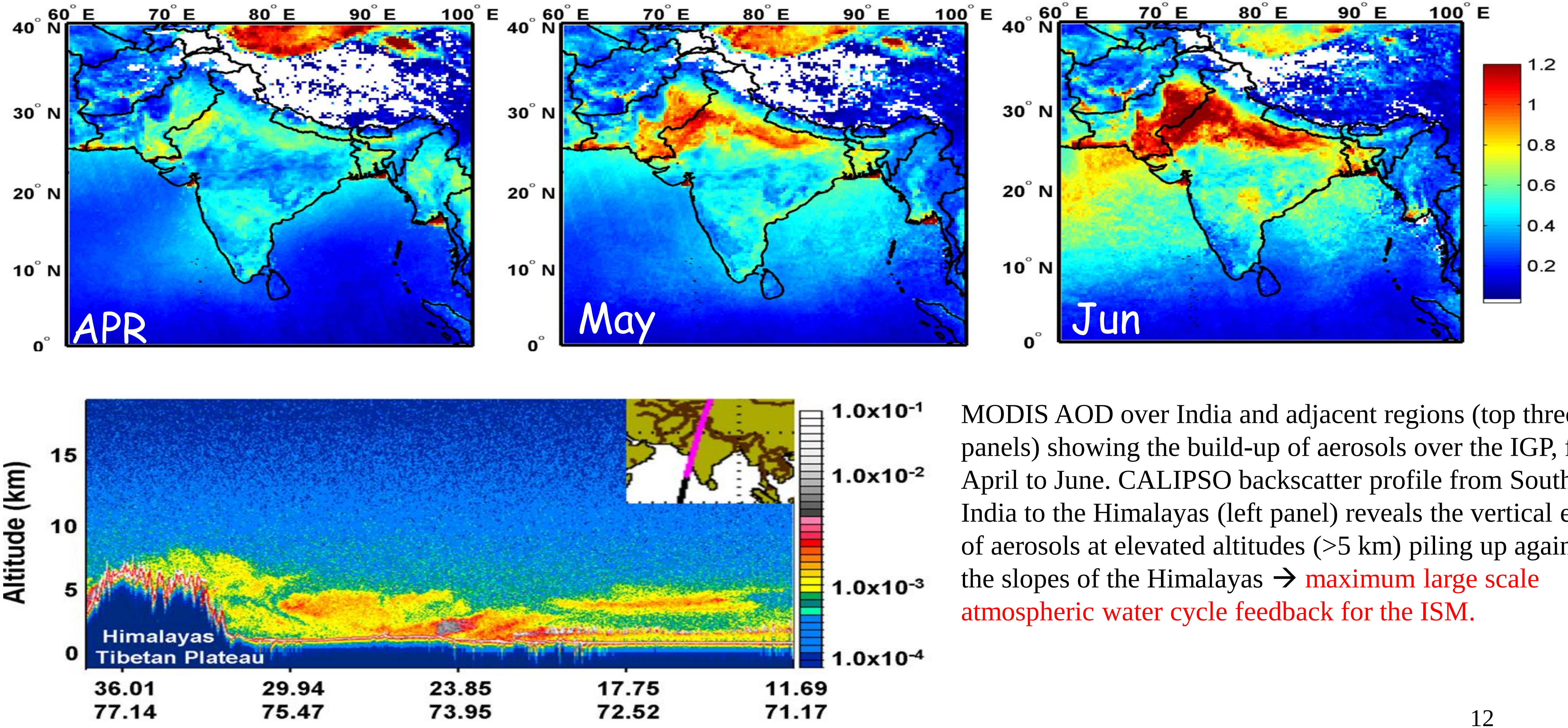
AOD

Angstr. exp.

Cli. Mean = Histogram
Rainfall = solid curve

Reference:
Lau, K.-M., K.-M. Kim, C. N-Y Hsu, and R. P. Singh (2008), Seasonal co-variability of aerosol and precipitation over the Indian monsoon and adjacent deserts. GEWEX News, 18(1), 4-6.

Pre-monsoon aerosol build-up over the Himalayan-Gangetic Region



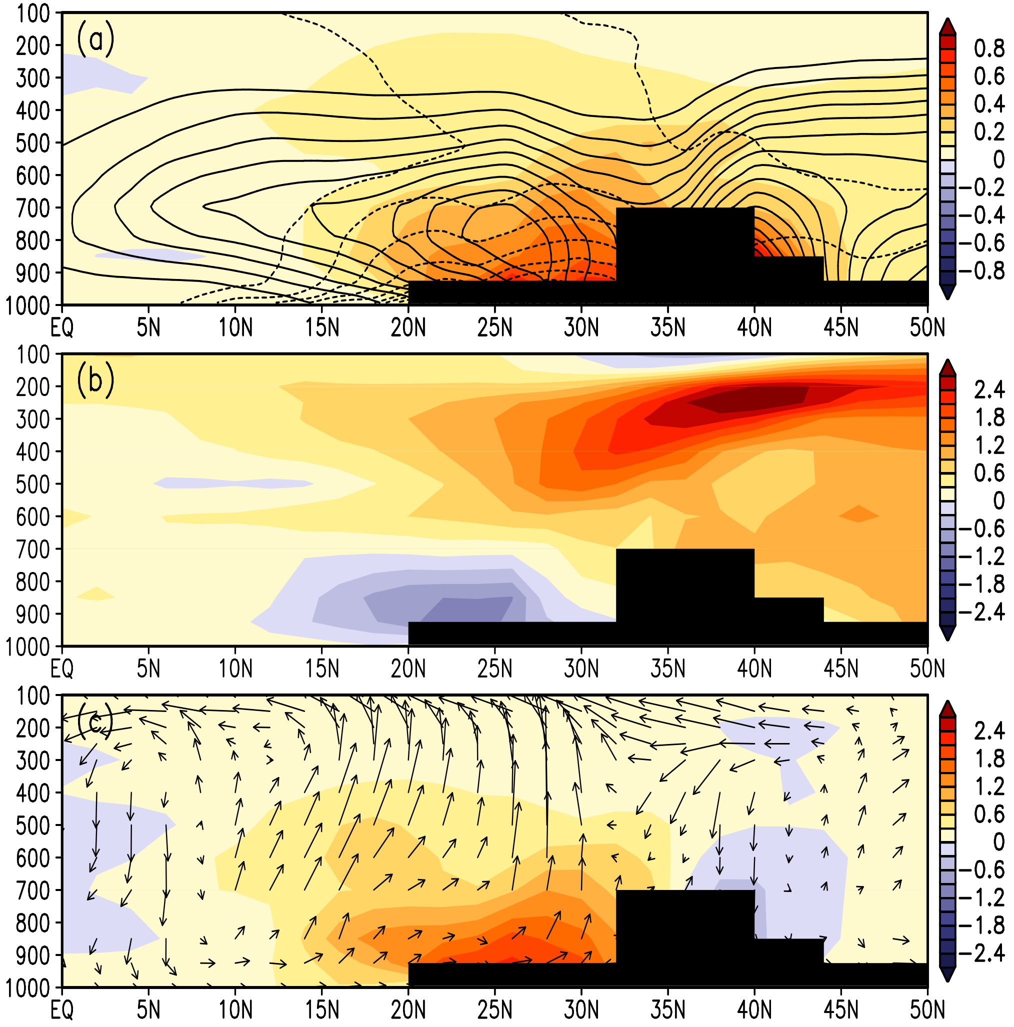
MODIS AOD over India and adjacent regions (top three panels) showing the build-up of aerosols over the IGP, from April to June. CALIPSO backscatter profile from Southern India to the Himalayas (left panel) reveals the vertical extent of aerosols at elevated altitudes (>5 km) piling up against the slopes of the Himalayas → maximum large scale atmospheric water cycle feedback for the ISM.

Aerosol induced anomalies (May-June) from NASA GEOS5 GCM

SW heating (color)
Dust loading (solid)
BC loading (dotted)

Temp. anomaly

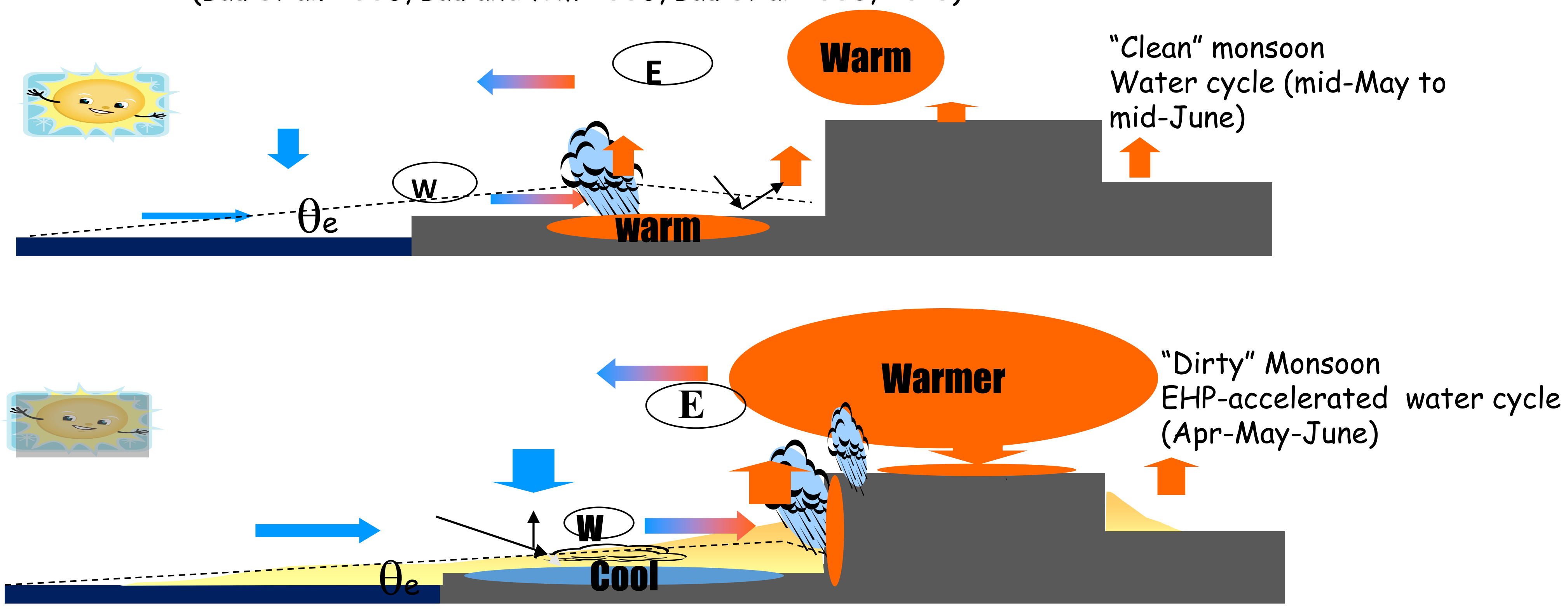
Moisture and wind anomalies



The **Elevated Heat Pump (EHP)** hypothesis (Lau et al. 2006, 2008, 2010): Latent heating feedback overcomes semi-direction effect, leading to non-local rainfall response away from the region of maximum aerosol loading.

The Elevated Heat Pump (EHP) hypothesis

(Lau et al. 2006, Lau and Kim 2006, Lau et al 2008, 2010)



EHP postulates:

a) Warming and moistening of the upper troposphere over the Tibetan Plateau
b) An advance of the rainy season in northern India/Napal, Himalayas foothills in May-June
c) The increased convection spreads from the foothills of the Himalayas to central India, resulting in an intensification of the Indian monsoon. in June-July
d) Subsequent reduction of monsoon rain in central India in July-August
e) Enhanced snowmelt and rapid retreat of Himalayan glacier

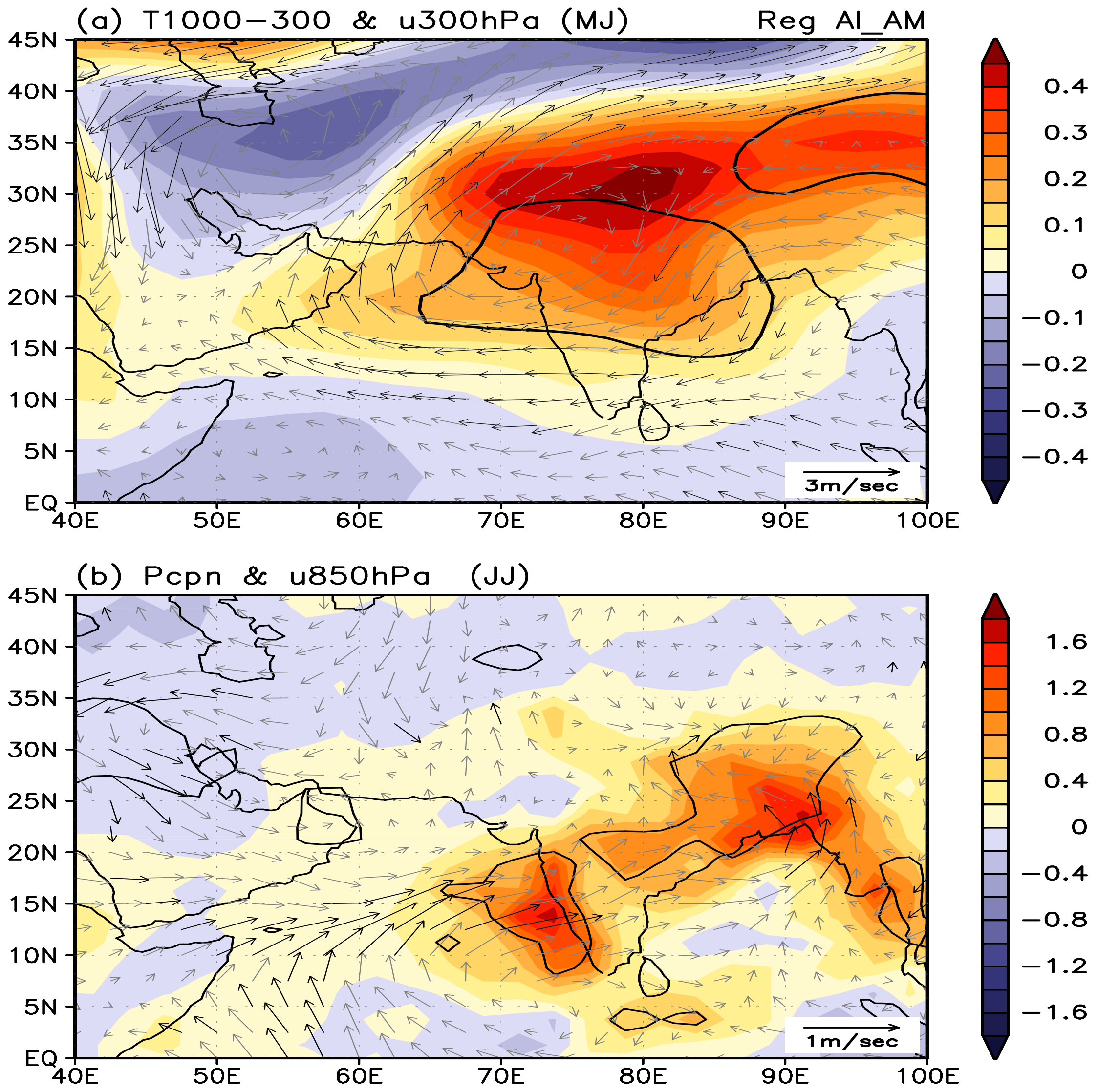
Interannnual Variability

Characteristic large scale pattern associated with EHP:

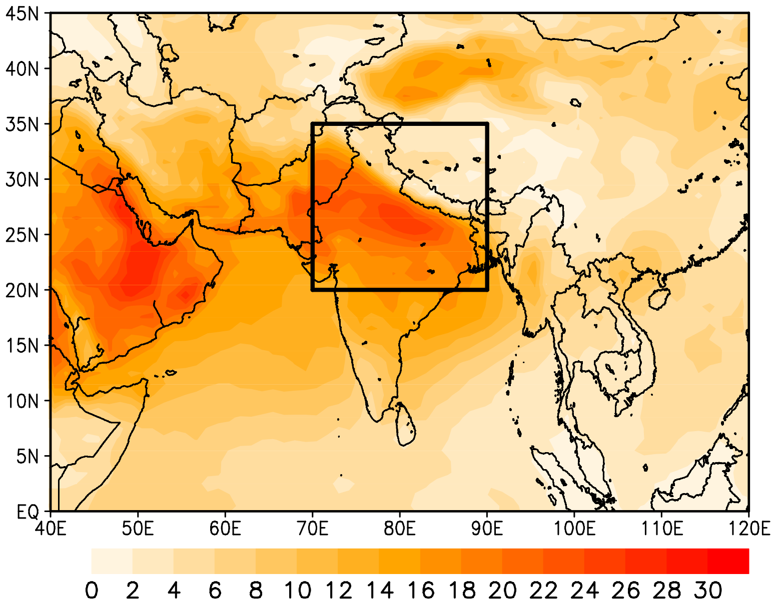
Enhanced tropospheric warming over the Tibetan Plateau and increased monsoon rainfall and winds in June-July, following major build-up of absorbing aerosol (dust and BC) over the Indo-Gangetic Plain in April-May

Data source: TOMS AI, GPCP, and NCEP re-analyses

Lau and Kim, 2006, *GRL*



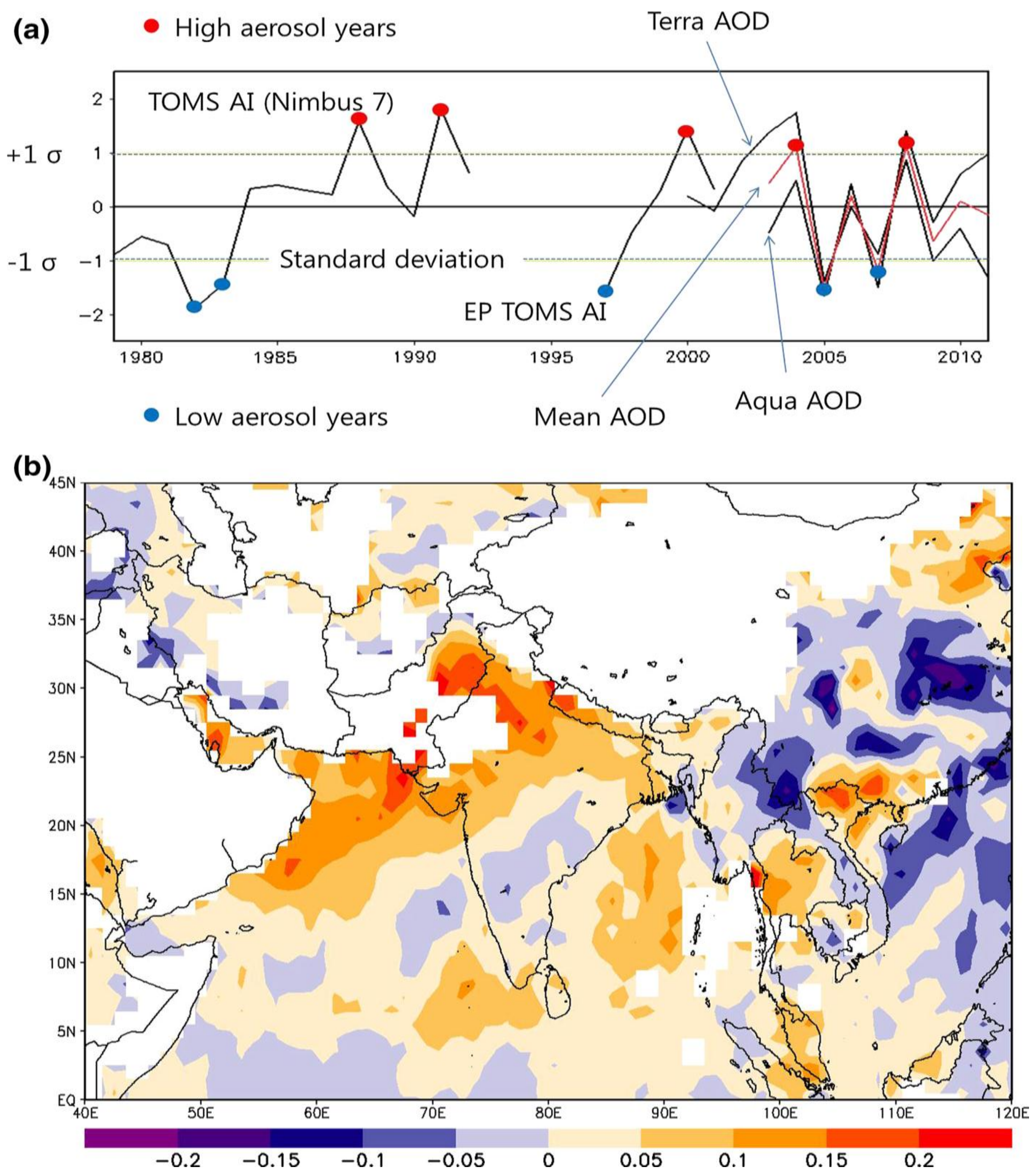
Amplification of ENSO effects on ISM by dust aerosols



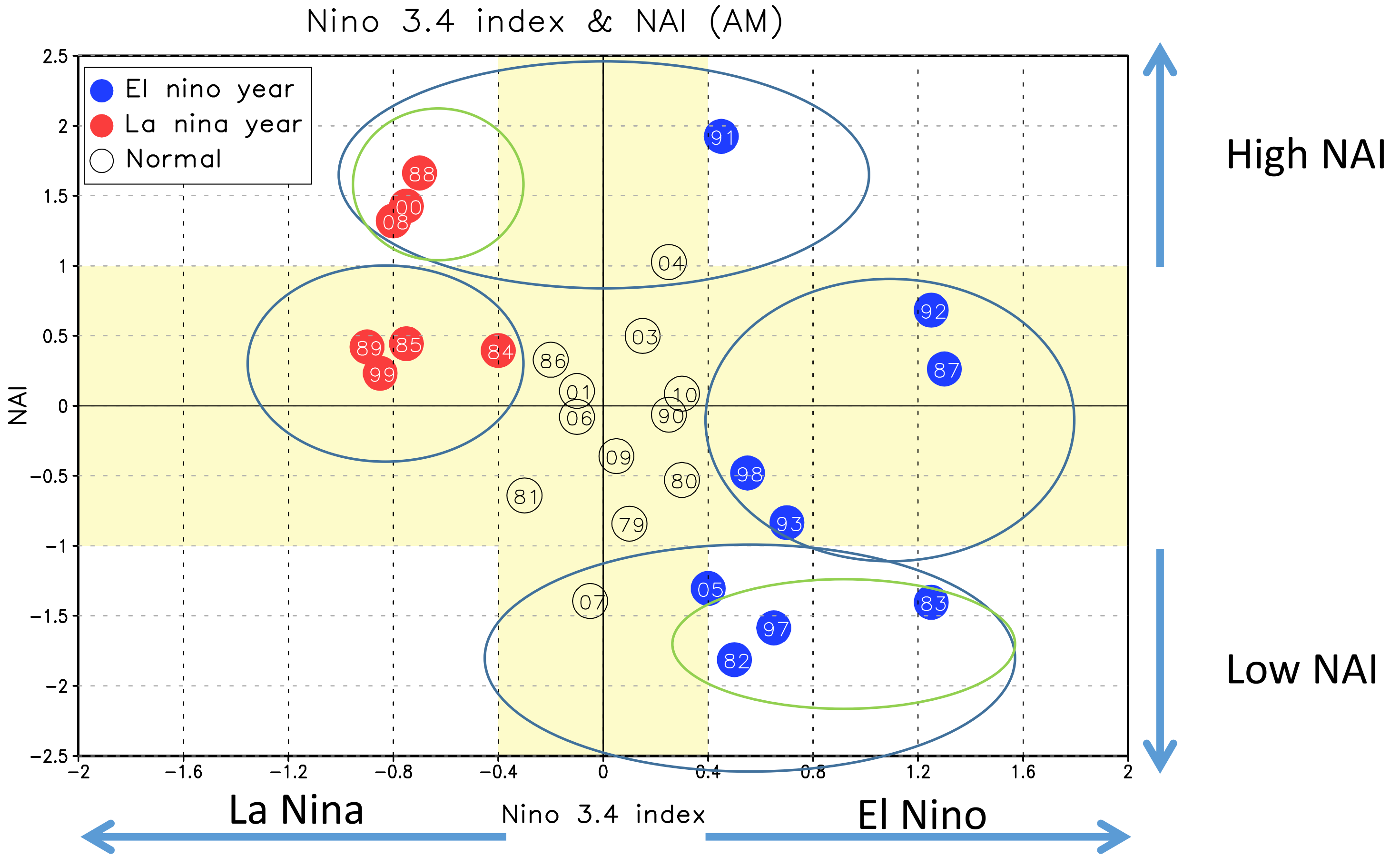
April-May mean aerosol index (AI)

(Kim et al. 2015)

a) Normalized aerosol index (NAI)
b) Composite difference of MODIS (Terra) AOD between high and low NAI years



Scatter plots: NAI vs NINO3.4 (April-May)



High NAI: 1988, 1991, 2000, 2004, 2008
Low NAI: 1982, 1983, 1996, 2005, 2007

La Nina + High NAI: 1988, 2000, 2008
El Nino + Low NAI: 1982, 1983, 1997

Pure El Nino: 1987, 1992, 1993, 1998
Pure La Nina: 1984, 1985, 1989, 1999

<u>EHP</u>: High NAI *minus* Low NAI
<u>PENSO</u>: Pure La Nina *minus* Pure El Nino
<u>Combined</u>: La Nina + High NAI *minus* El Nino + Low NAI

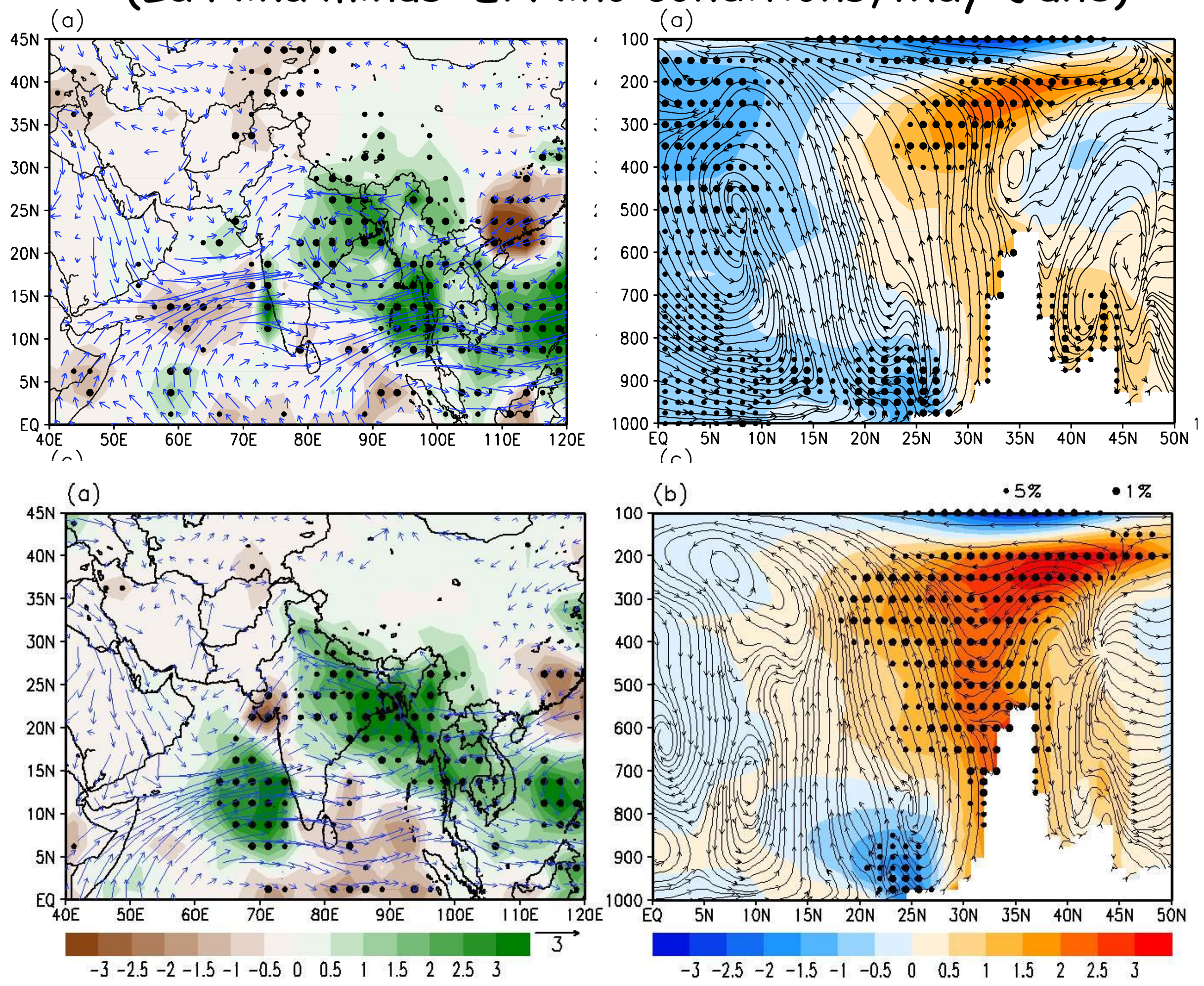
(Kim et al. 2015)

EHP amplifies ENSO impacts on Indian Summer Monsoon

(La Nina minus El Nino conditions, May-June)

PENSO
(La-Nina)

ENSO + EHP
(La Nina +
High AA loading)



May-June Precip,
850 hpa winds

May-June T and meridional circulation

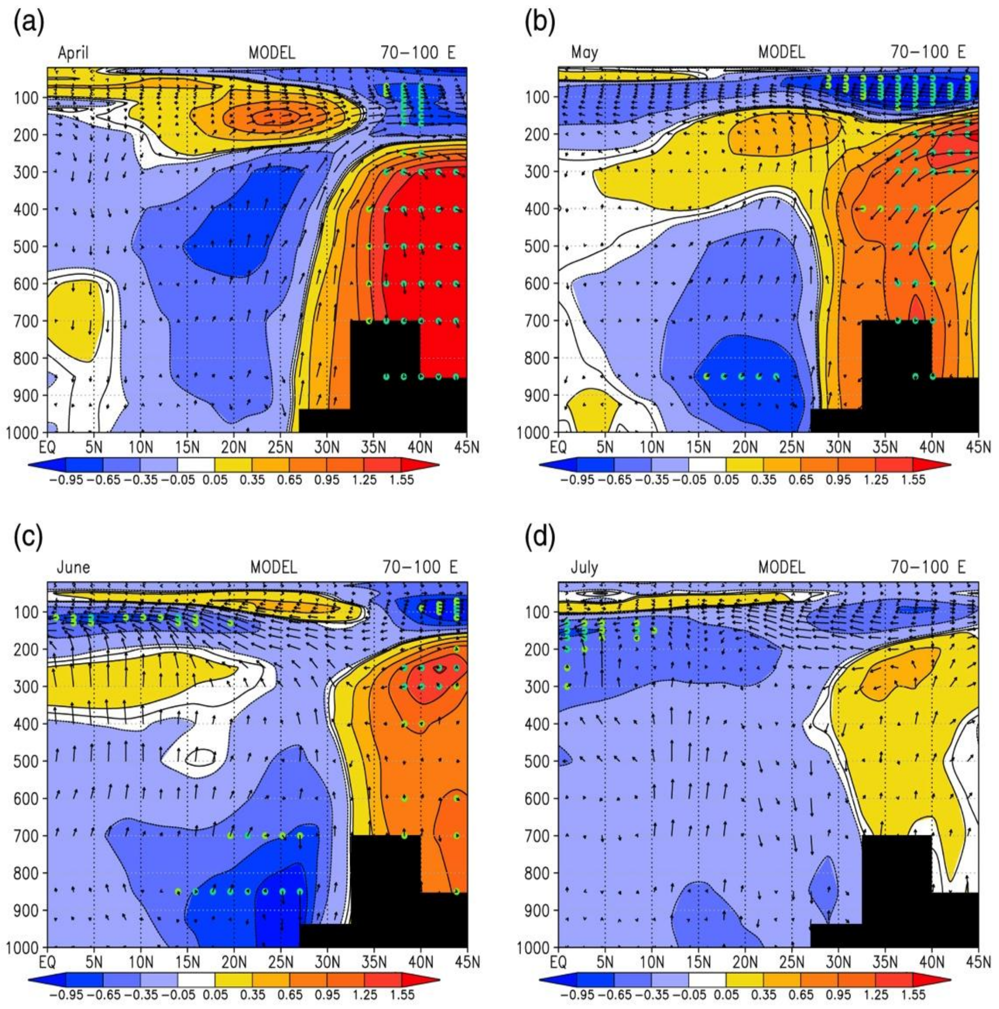
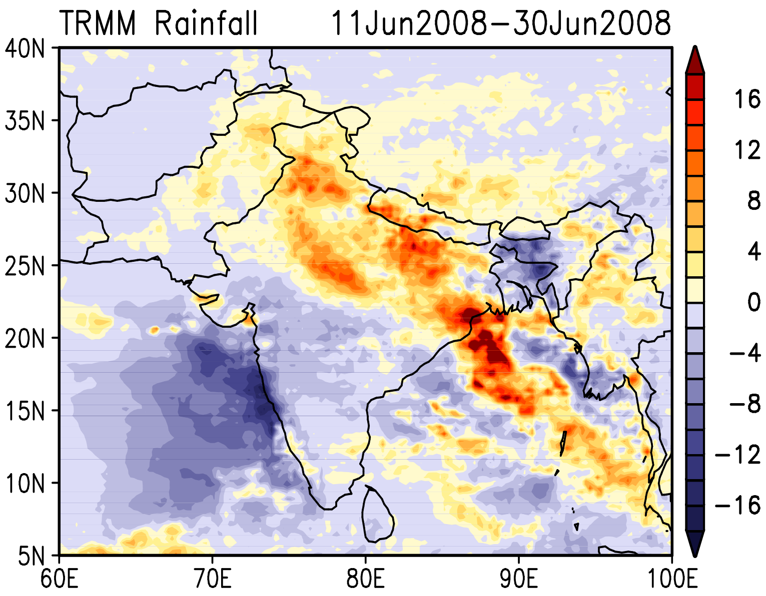
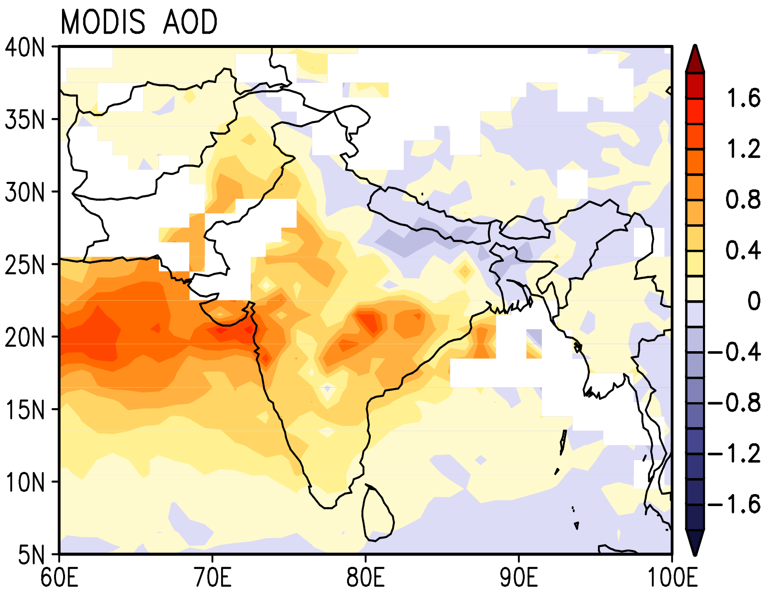


Figure 3. Latitude-height distributions of temperature (shaded) and meridional circulation (vectors) composites due to aerosols over the longitude sector of 70–100°E for (a) April, (b) May, (c) June, and (d) July. Values statistically significant at the 95% level (dark green dots) and at the 90% level (light green dots) according to a two-sample Student's *t* test are marked.

EHP in a coupled GCM, with present day anthropogenic GHG and aerosol emissions
(prescribed constant) but with interactive dust emission, transport and aerosol radiative and microphysics effects
. (D'Errico et al., 2015)





2008: Early monsoon onset over Northern India; heavy monsoon rainfall in the Himalayas foothills, persisted through June-July; relatively dry condition to the south. *(The Asian Summer Monsoon in 2008, NCEP/CPC Global Monsoons Team)*

Major flooding over central southern Nepal and Bihar State of northern India in August 2008

Strong aerosol (mostly dust) build up over Arabian Sea, and northwestern India

ISM observed anomalies 2008

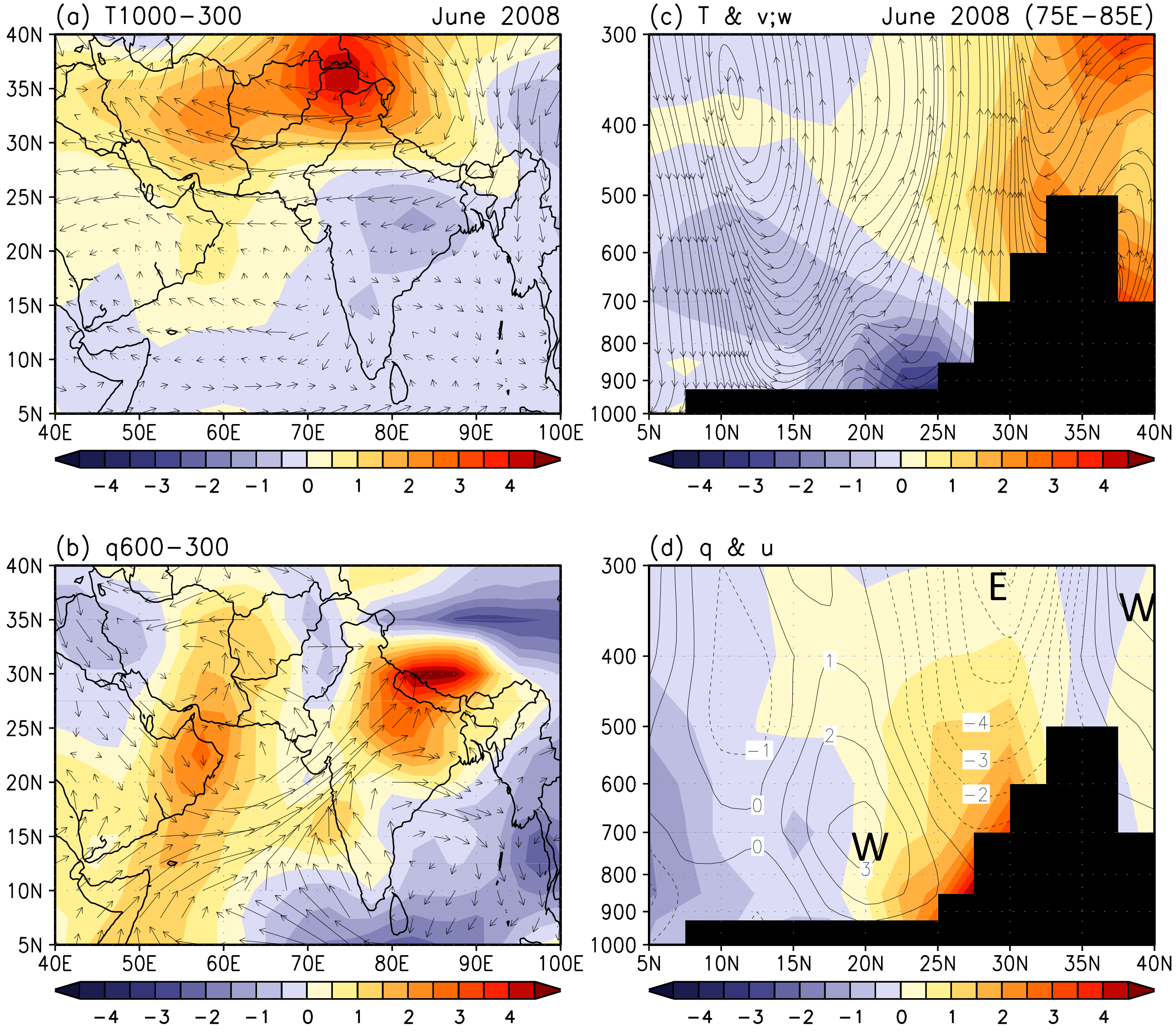
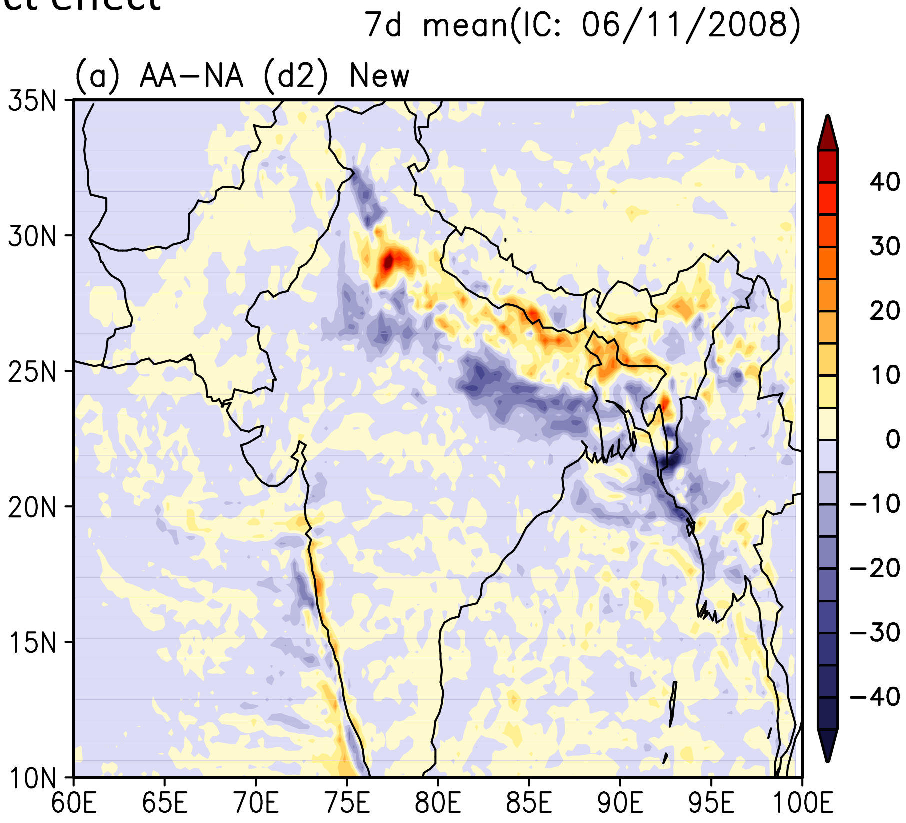
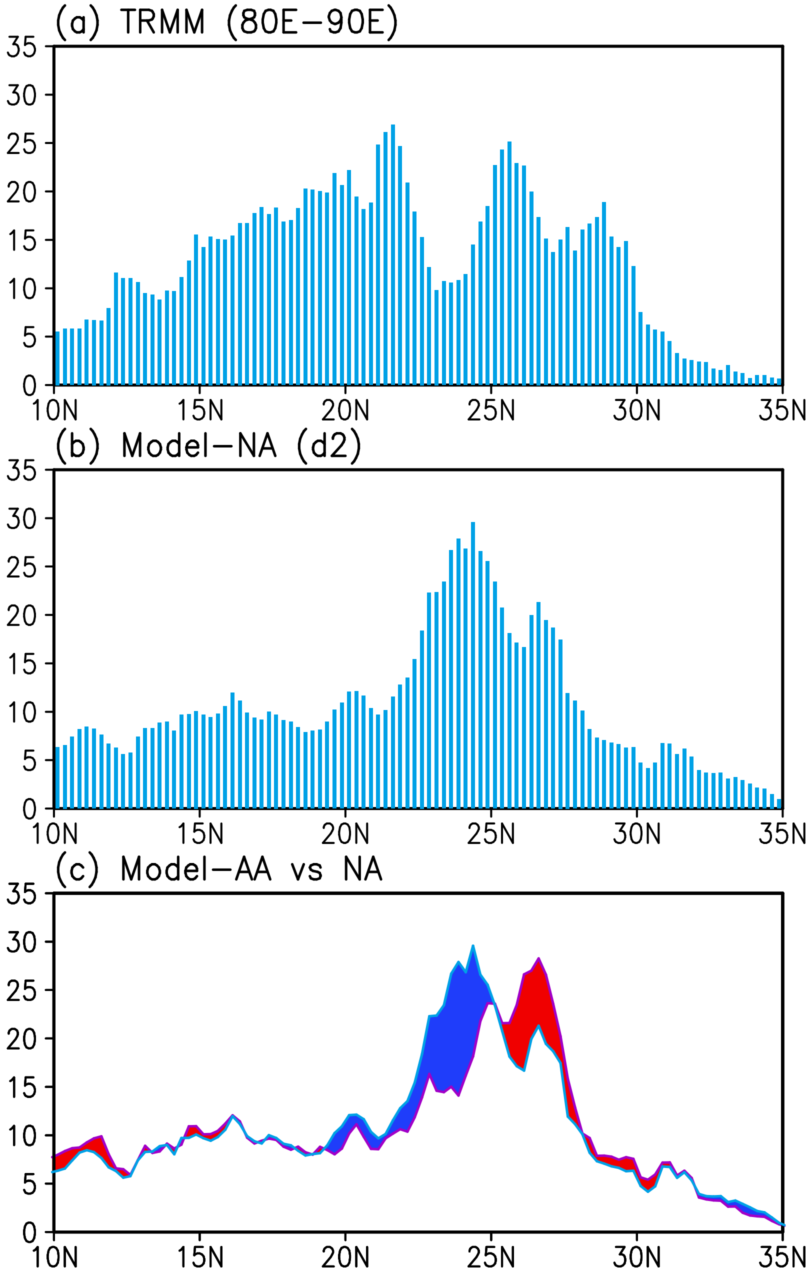


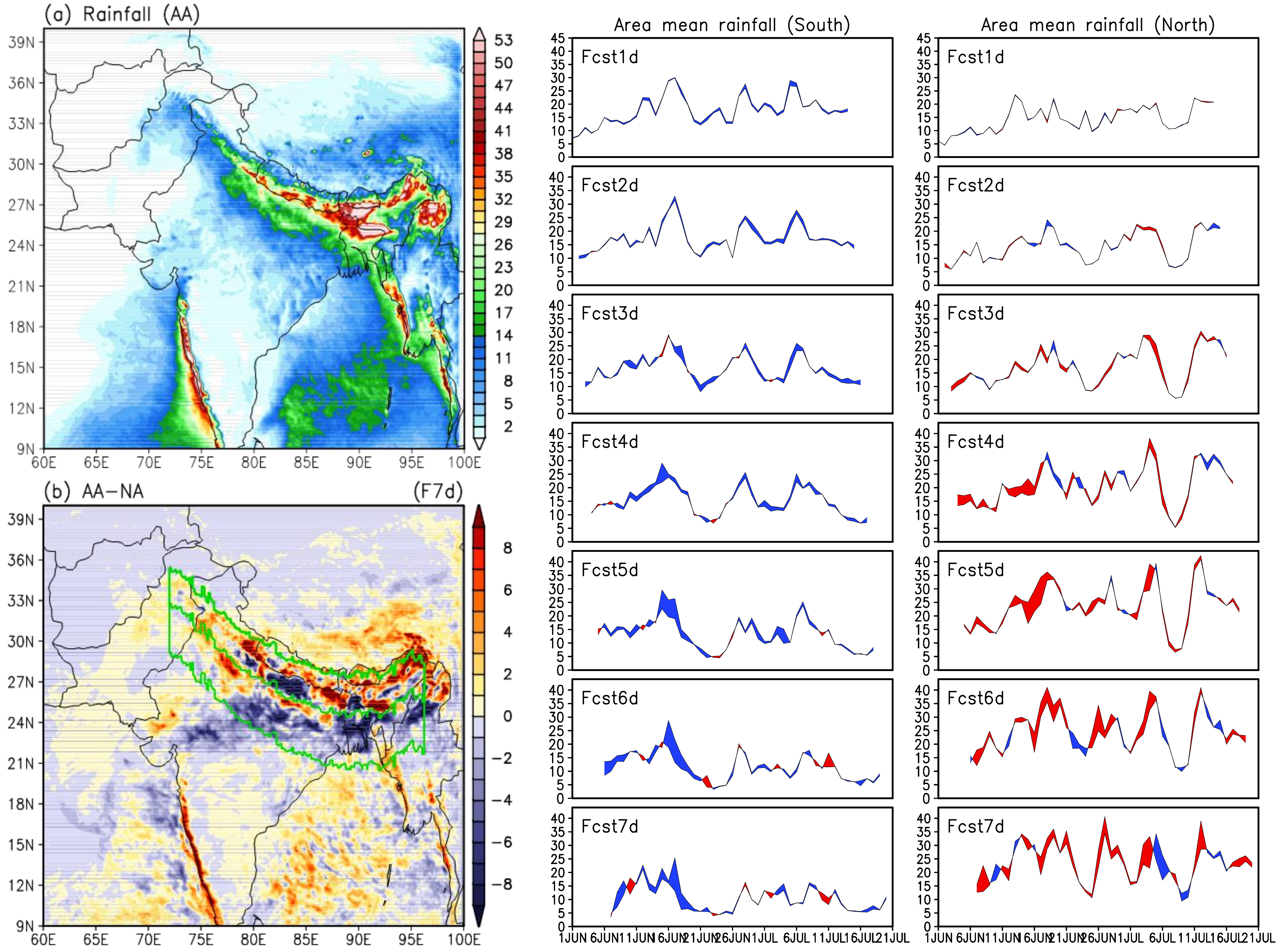
Fig. 2

NU-WRF ensemble (45 member)
7-day hindcast experiments with realistic meteorological and aerosol initial and bdd conditions
June 1- July 15, 2008
1. NA- No aerosols
2. AA- All aerosols, radiative effect (EHP) only
3. EHP + Indirect effect

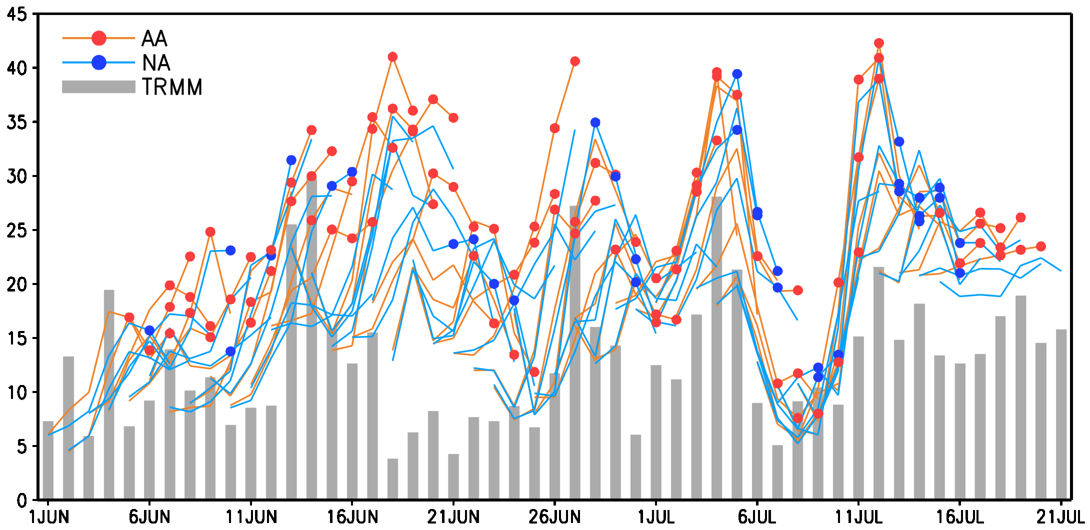




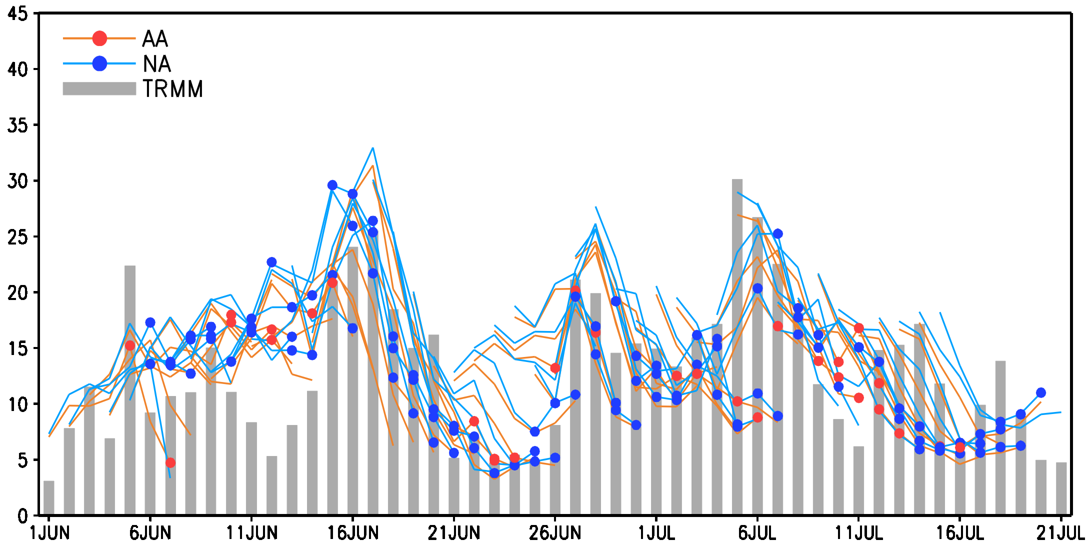
Effect of Aerosol Radiative Forcing and Dynamical Feedback (EHP)



45 member, ensemble 7-day precipitation forecasts over NIHF region

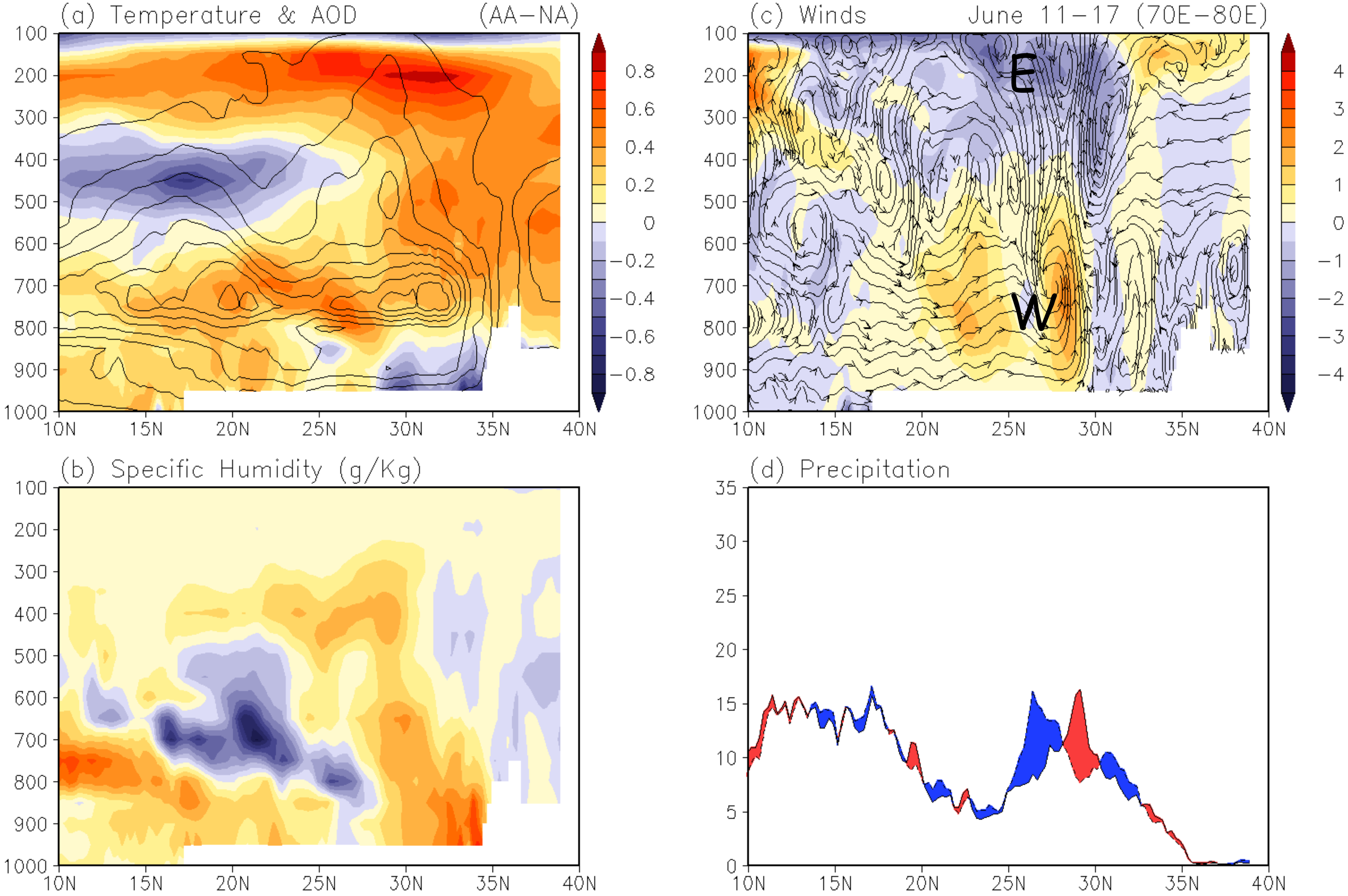


Northern Domain (HF):
3-to-1 ratio in increased rainfall

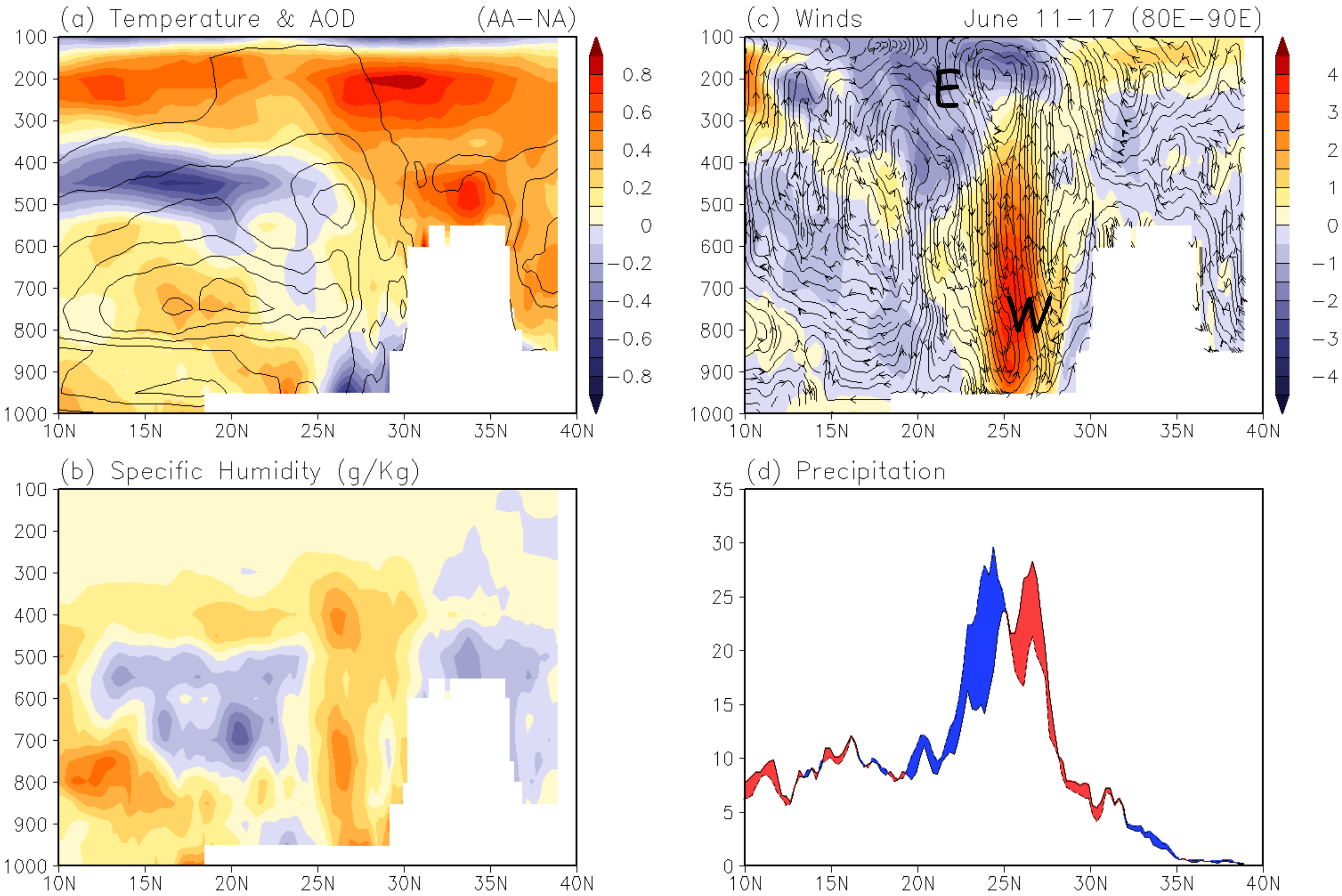


Southern Domain (NI)
3.5-to-1 ratio in decreased rainfall

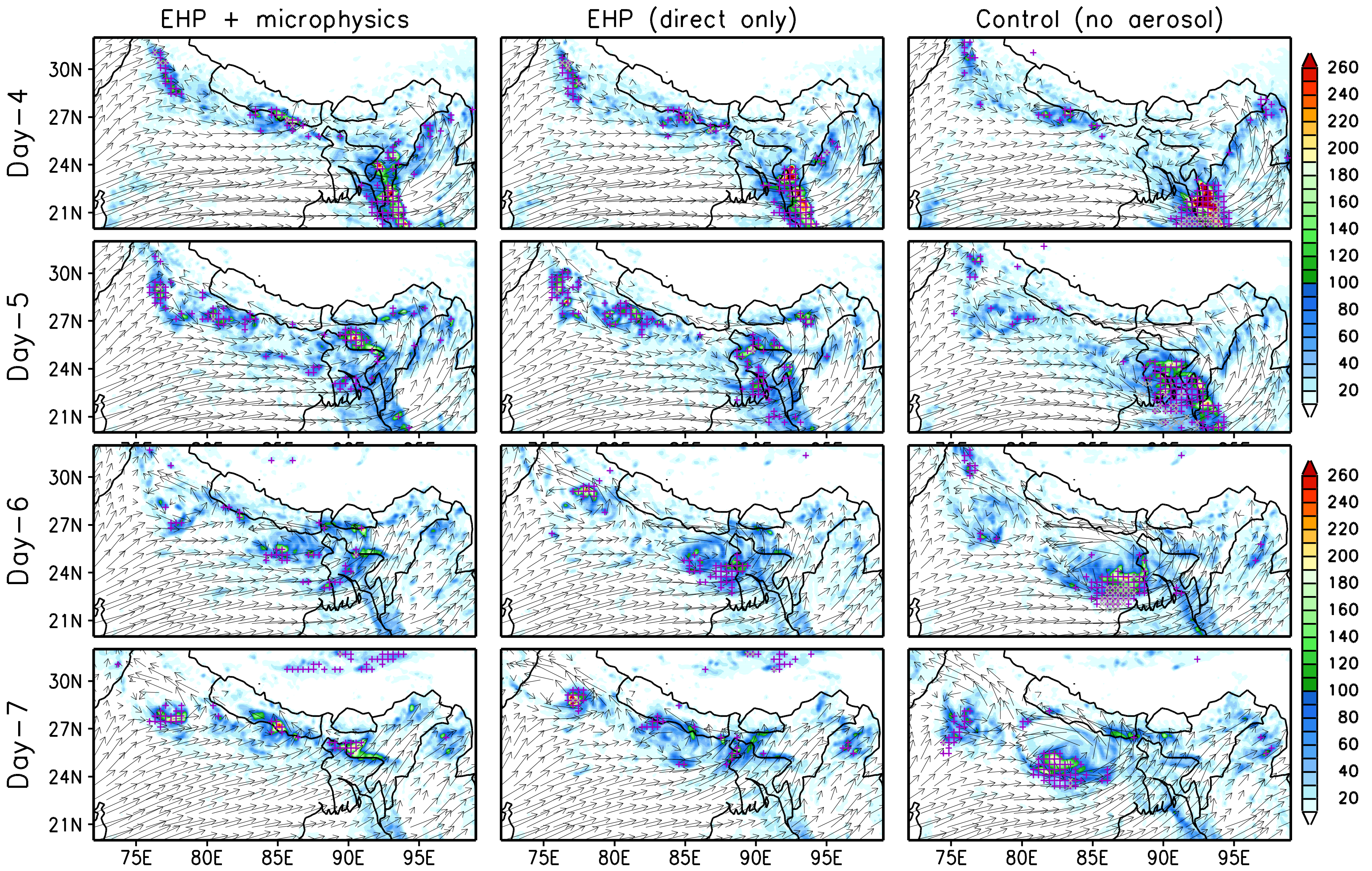
Western India



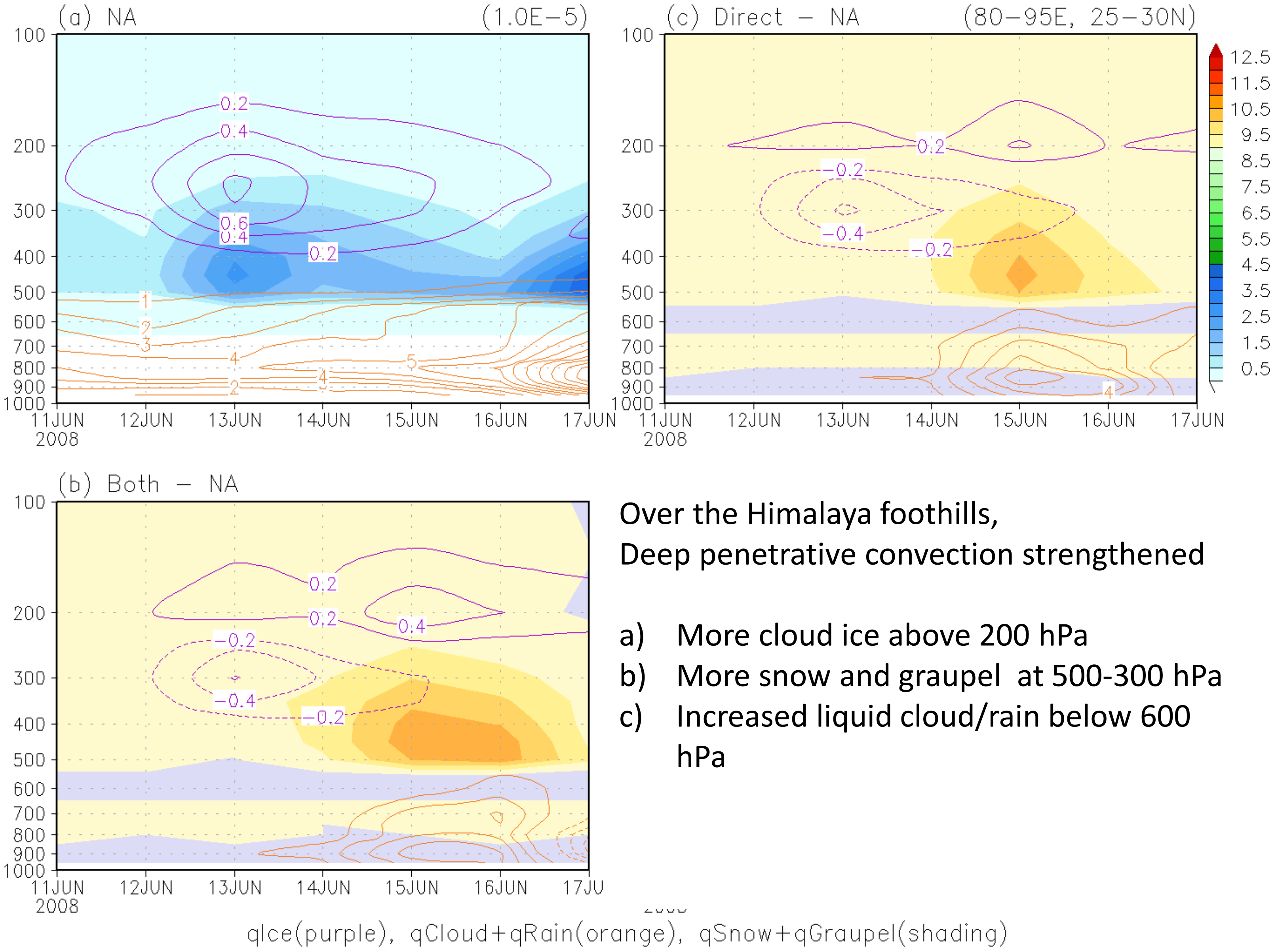
Northeastern India



EHP effects transform a developing monsoon cyclone over NE India into severe line convection over NIHF



Changes in the vertical hydrometeo profiles (North: Himalayan foothills)



qIce(purple), qCloud+qRain(orange), qSnow+qGraupel(shading)

Over the Himalaya foothills,
Deep penetrative convection strengthened

a) More cloud ice above 200 hPa
b) More snow and graupel at 500-300 hPa
c) Increased liquid cloud/rain below 600 hPa

UTLS Circulation and Transport (from W. Randel's ppt file)

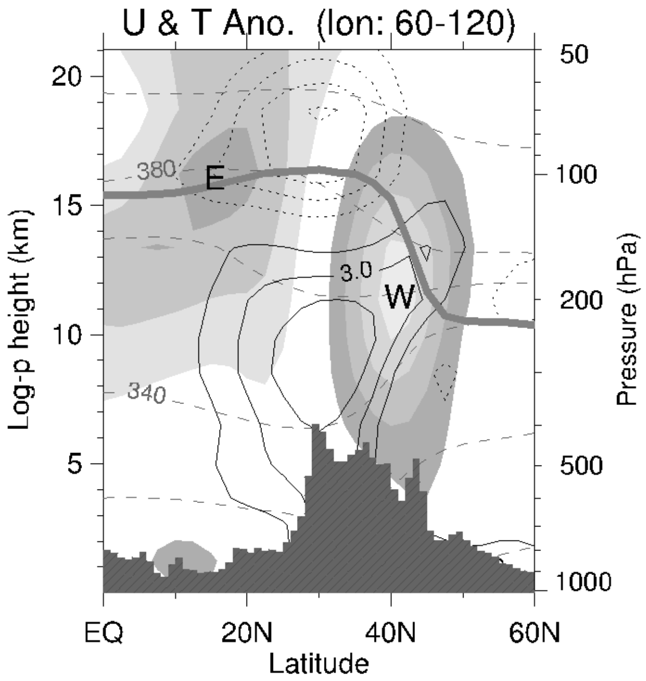
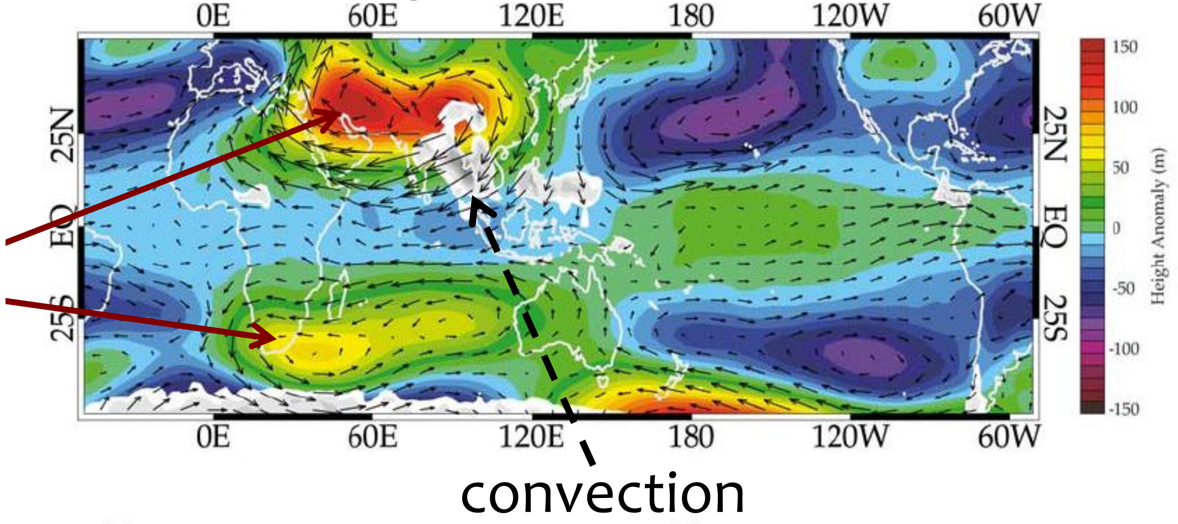
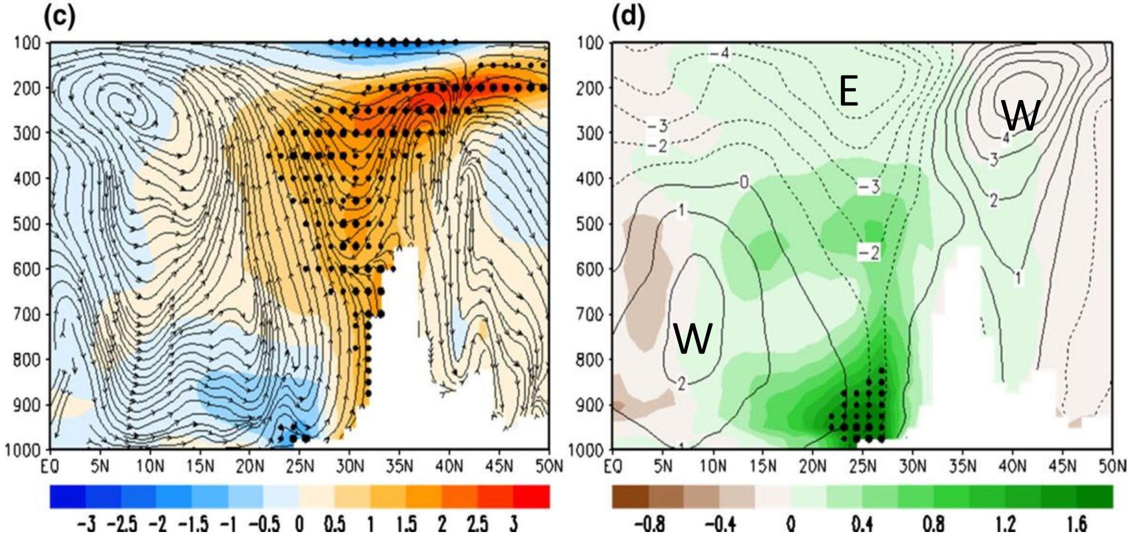


Figure 2. Vertical structures of 2-month (July and Augus average NCEP zonal wind (shaded) and temperatu anomalies (thin lines) averaged in 60°–120°E longitude The westerly and easterly jets are shaded separately an denoted by "W" and "E," respectively. The shade contours are at intervals of 8 m s^{-1}; the maximum westerl winds are near 36 m s^{-1}, and the maximum easterlies ne 31 m s^{-1}. The temperature anomaly contours are ±1.5, 3.0 and 4.5 K, shown as solid (positive) and dotted (negative lines, respectively. Dashed lines denote isentropic surface (320, 340, 360, 380, and 450 K), and thermal tropopaus from NCEP/NCAR reanalysis is noted by a thick solid lin The regional topography is added at the bottom.

Randel and Park (2006)

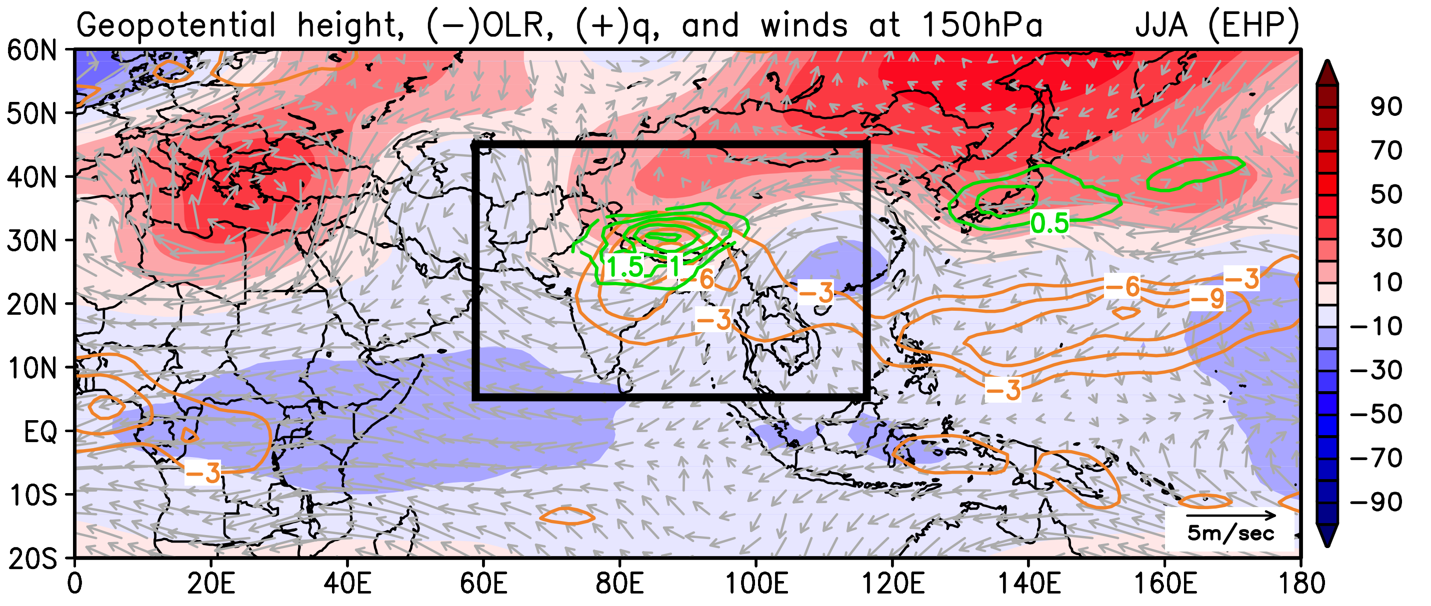
Geopo. height and winds (100 hPa)



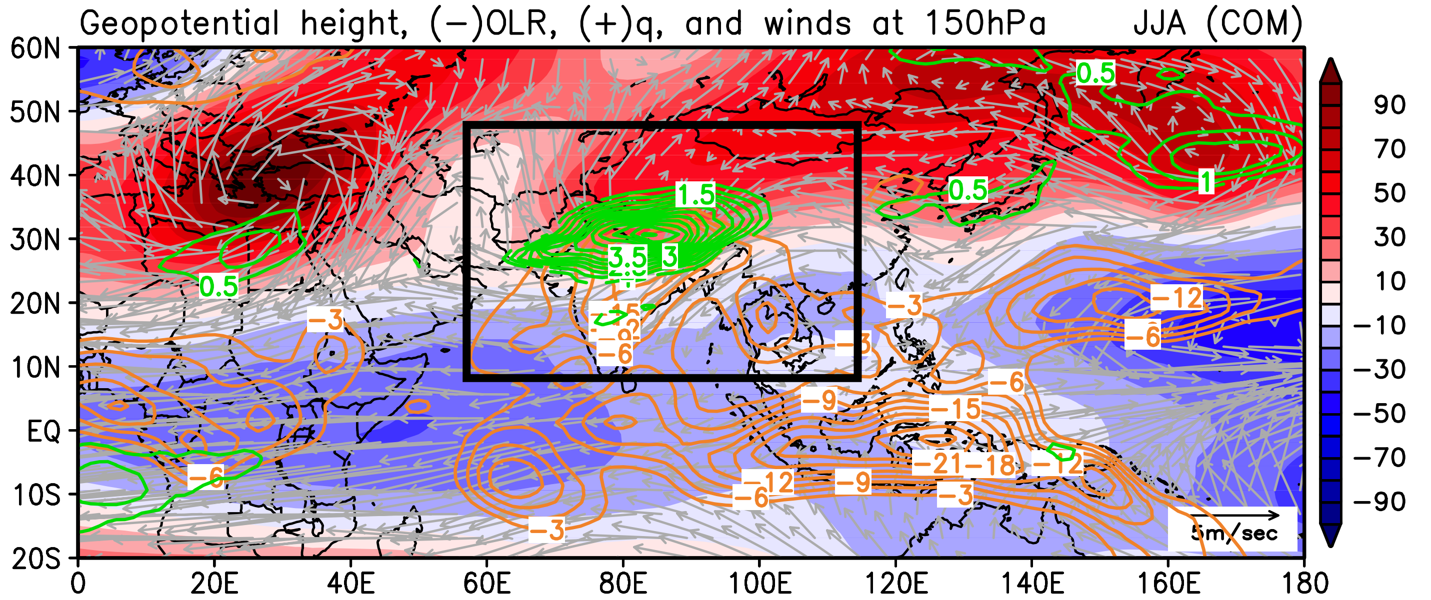


EHP induced T, q and wind anomalies

MERRA2 data



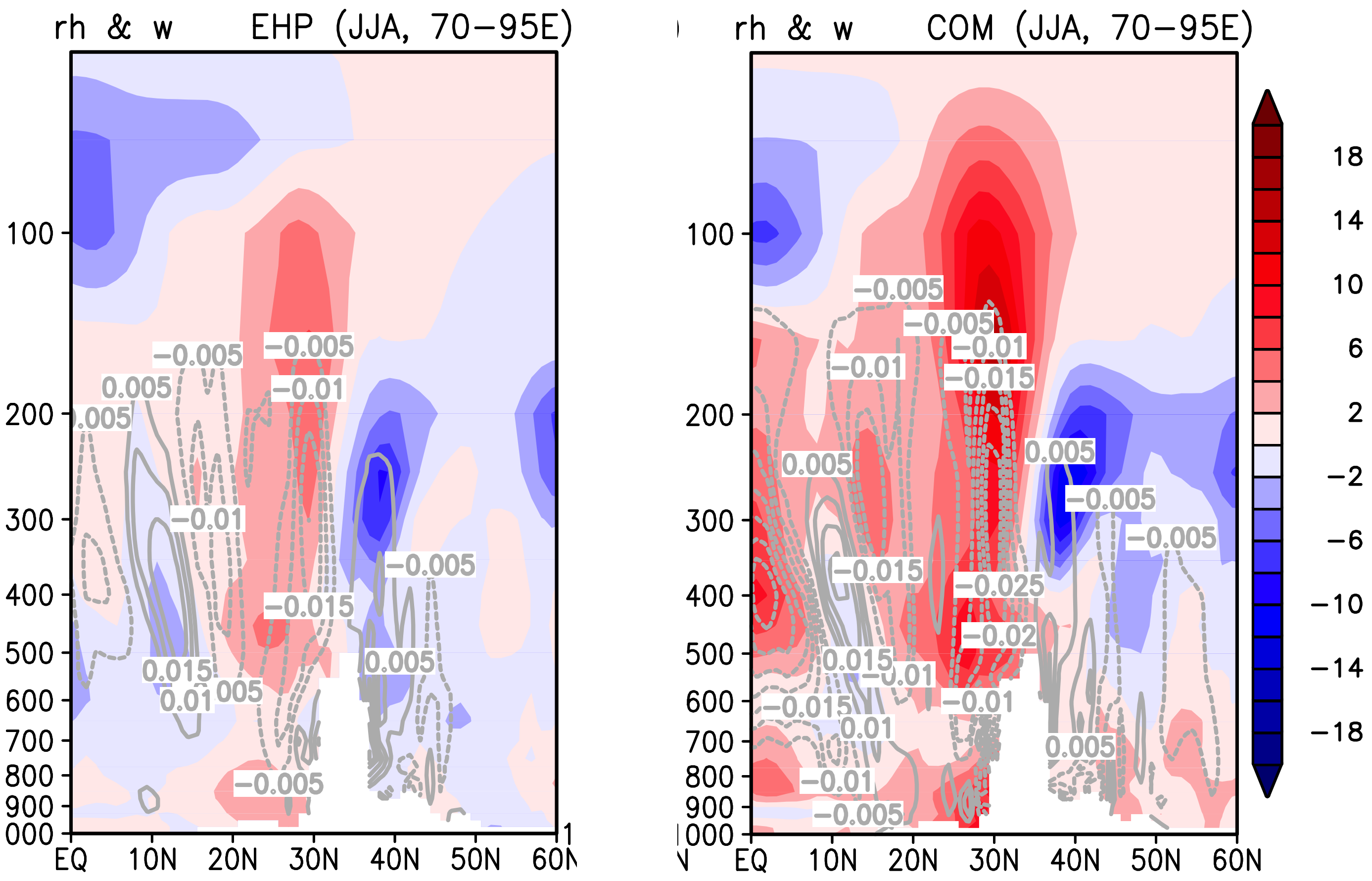
EHP



EHP + ENSO

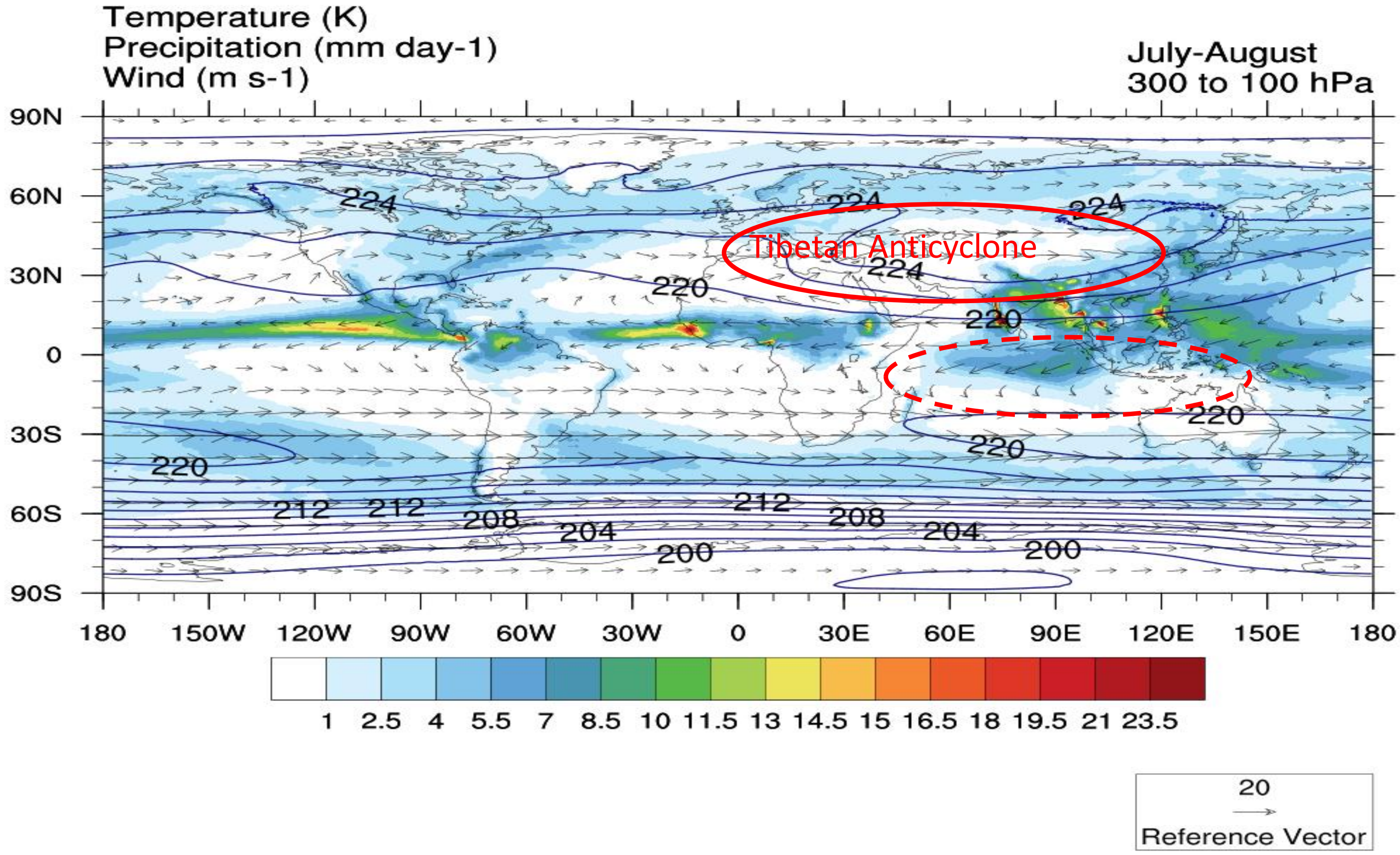
EHP

EHP + ENSO

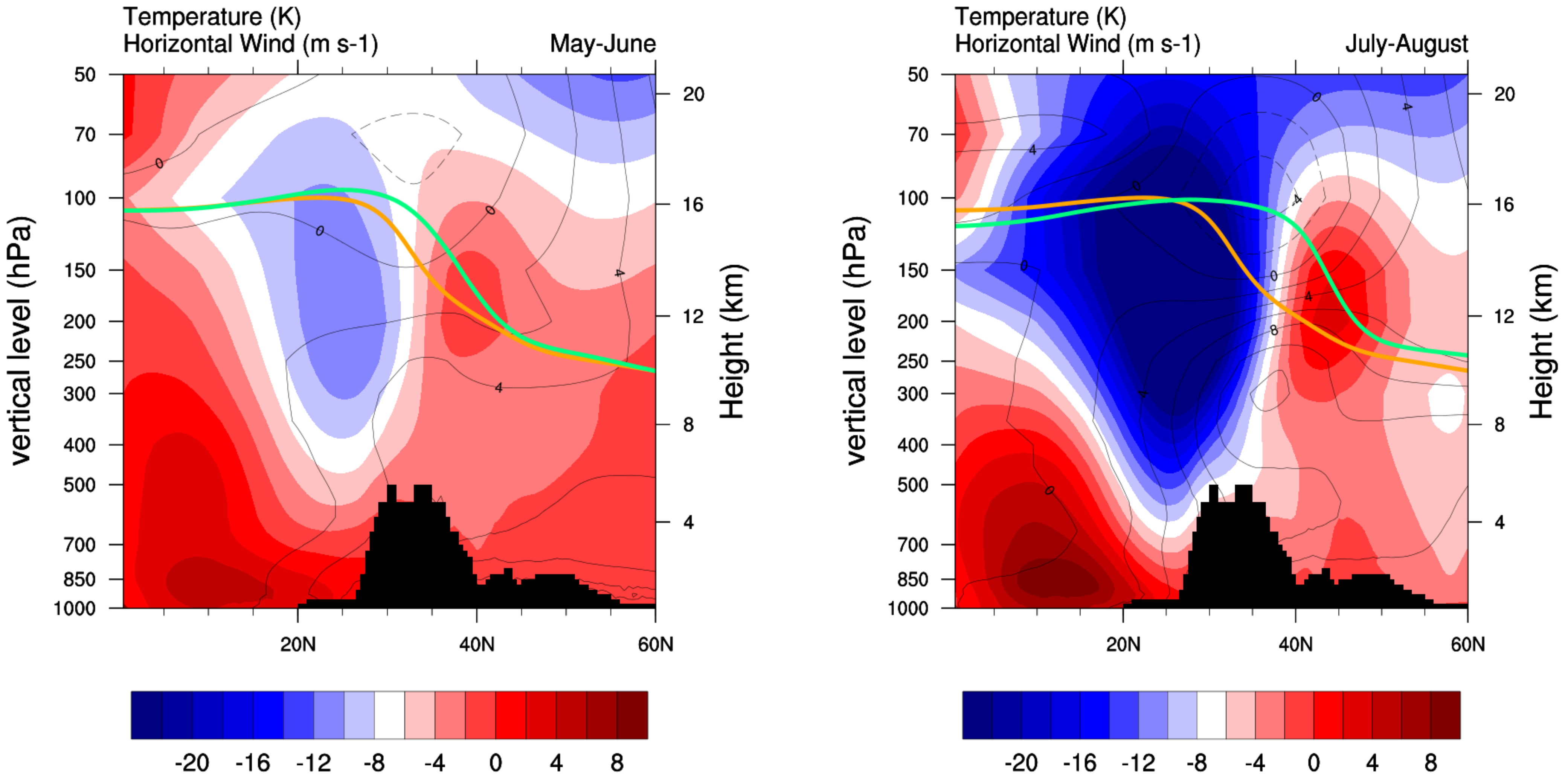


rh & w EHP (JJA, 70−95E)
rh & w COM (JJA, 70−95E)
100
200
300
400
500
600
700
800
900
1000
EQ
10N
20N
30N
40N
50N
60N
18
14
10
6
2
−2
−6
−10
−14
−18

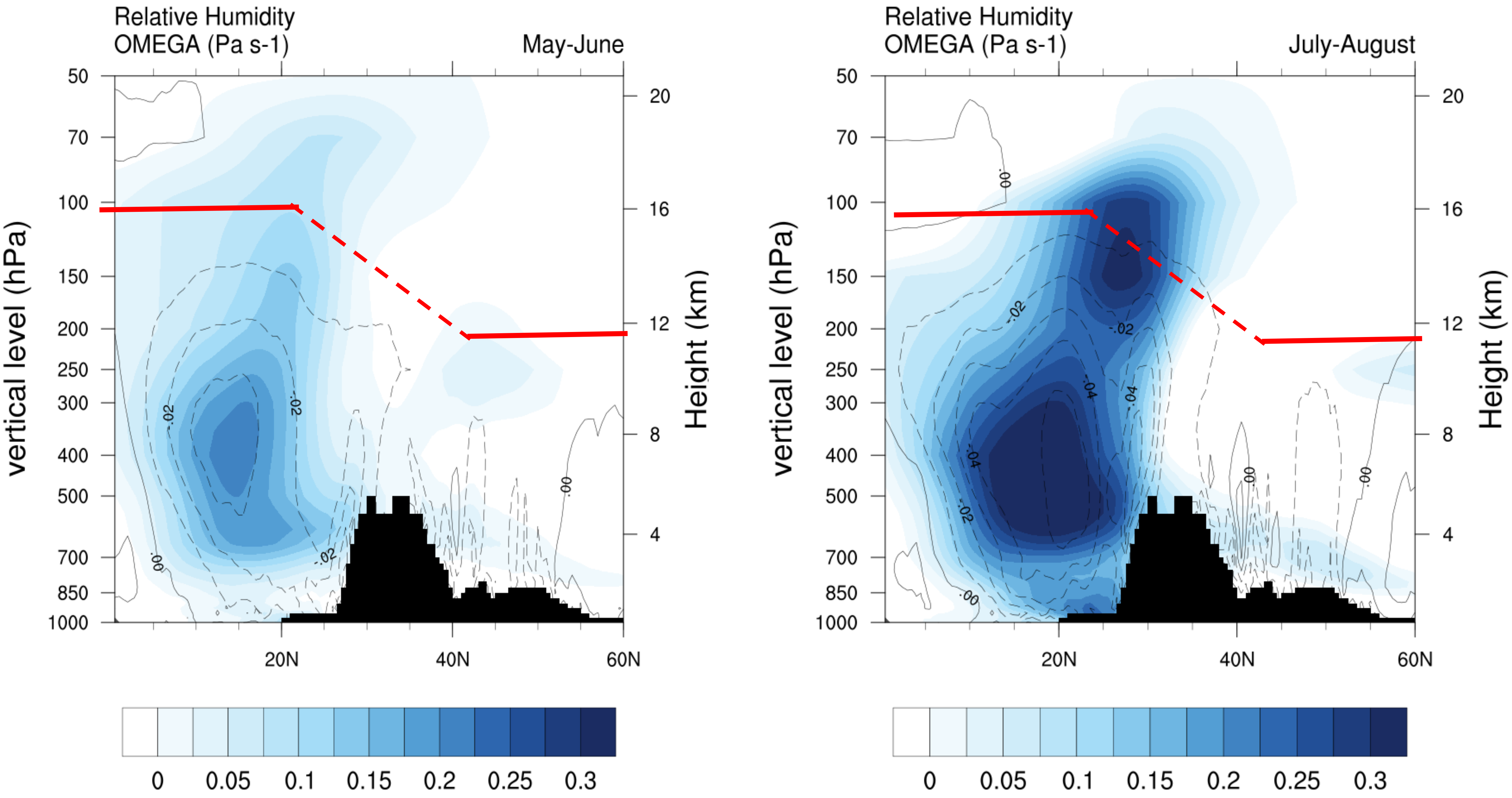
MERRA2-reanalysis



80E-100 E



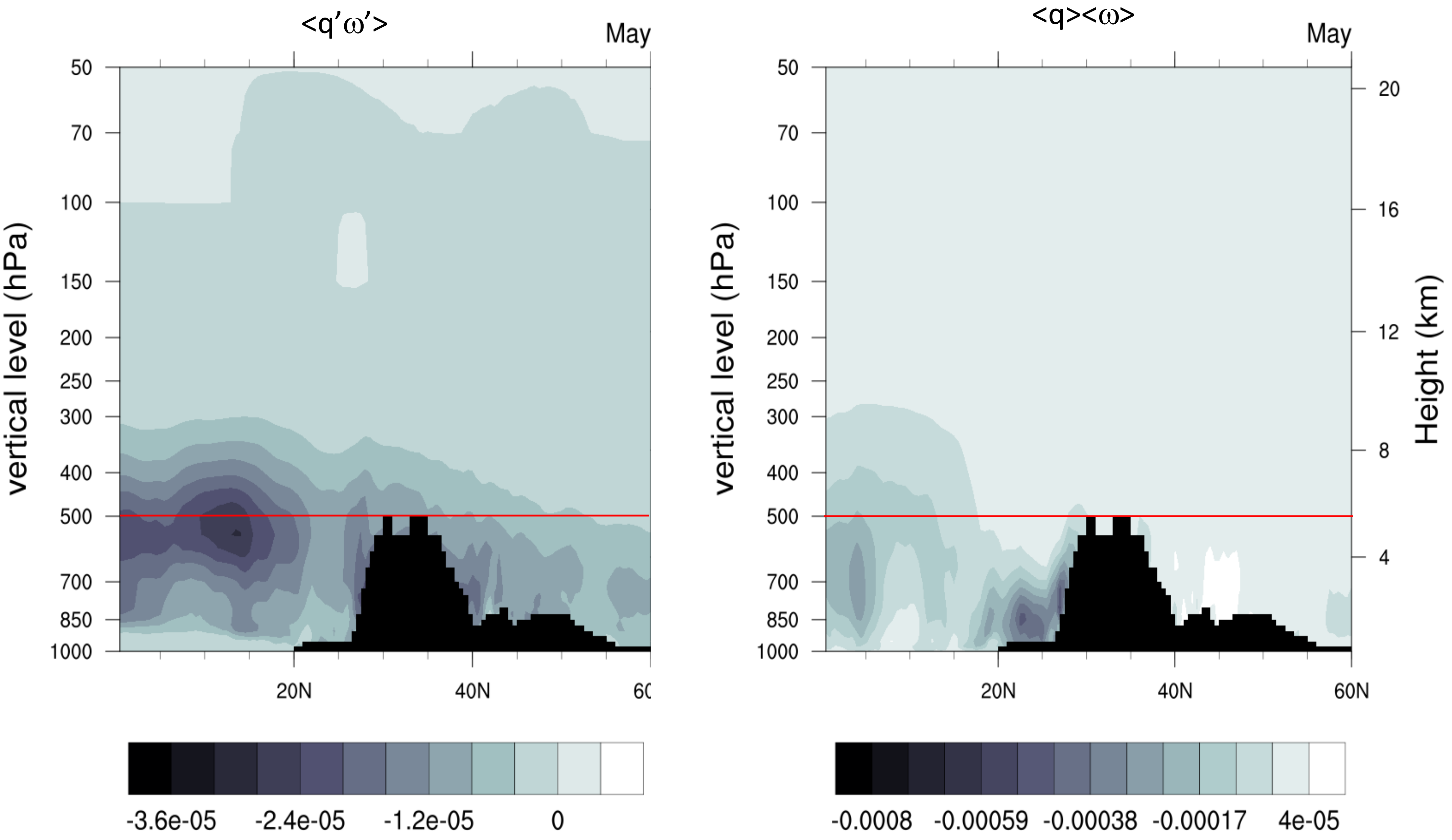
Temperature (K)
Horizontal Wind (m s-1)
May-June
vertical level (hPa)
Height (km)
50
70
100
150
200
250
300
400
500
700
850
1000
20
16
12
8
4
20N
40N
60N
-20 -16 -12 -8 -4 0 4 8
Temperature (K)
Horizontal Wind (m s-1)
July-August
vertical level (hPa)
Height (km)
50
70
100
150
200
250
300
400
500
700
850
1000
20
16
12
8
4
20N
40N
60N
-20 -16 -12 -8 -4 0 4 8


Relative Humidity
OMEGA (Pa s-1)
May-June
Relative Humidity
OMEGA (Pa s-1)
July-August
vertical level (hPa)
Height (km)
20N
40N
60N
0
0.05
0.1
0.15
0.2
0.25
0.3

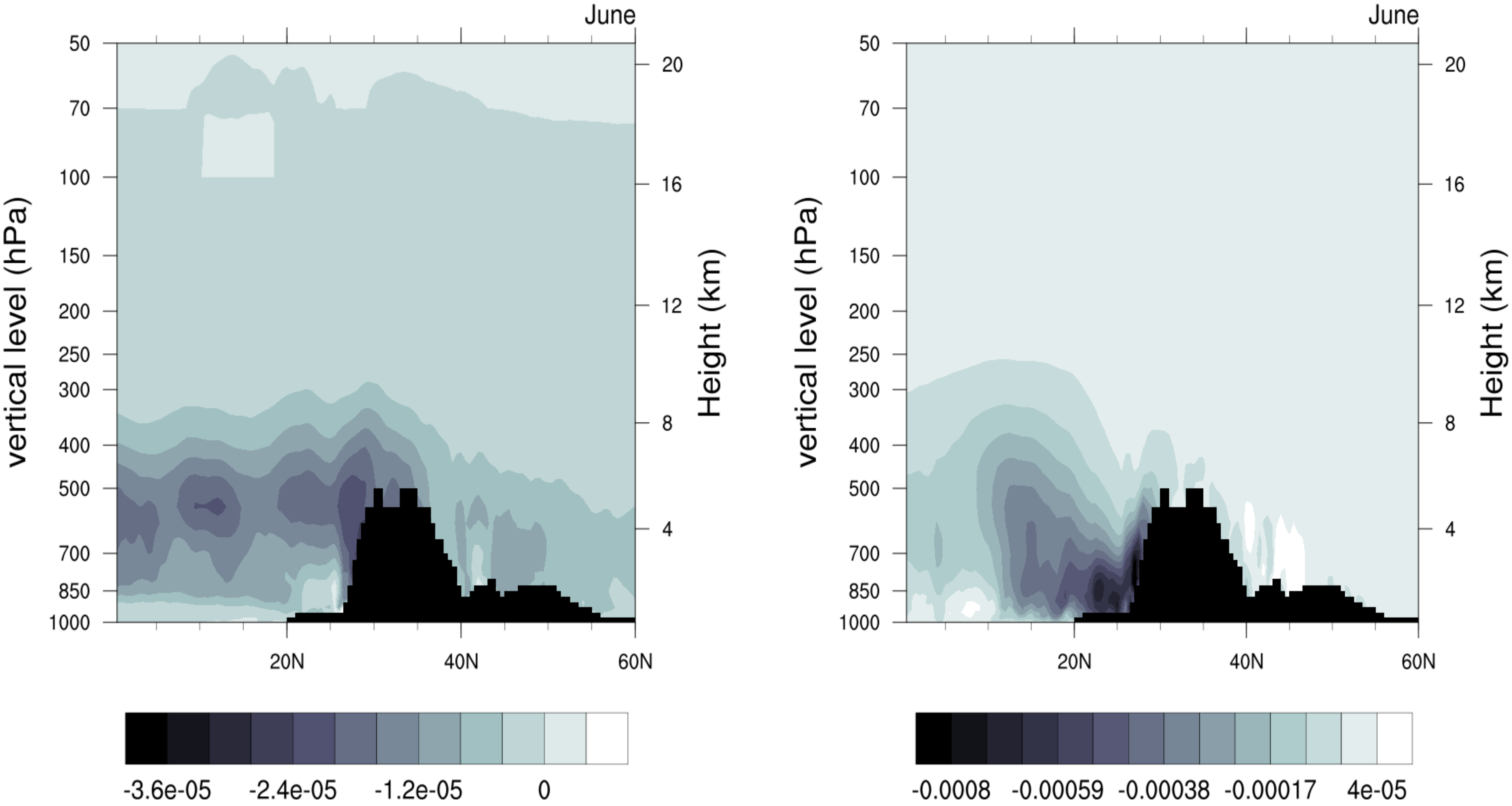
Further work

- How do atmospheric constituents (water vapor, aerosols, chemical gases) transport from the surface to the tropical UTLS ?
- What are the roles of mean ascent vs. convective transport?
- What roles absoring aerosols (dust and BC) play in with extreme precipitation/penetrative deep convective events over the Himalayan foothill?
- Working hypothesis: Aerosol induced EHP effects enhance penetrative convection over the steep topography on the Himalayas and southeastern slopes of the TP, making this region a key pathway for transport of pollutants/chemical gases to the tropical UTLS.

Thank You



<q'ω'>
May
vertical level (hPa)
50
70
100
150
200
250
300
400
500
700
850
1000
20N
40N
60
-3.6e-05
-2.4e-05
-1.2e-05
0
<q><ω>
May
vertical level (hPa)
Height (km)
20
16
12
8
4
20N
40N
60N
-0.0008
-0.00059
-0.00038
-0.00017
4e-05



June
June
vertical level (hPa)
Height (km)
50
70
100
150
200
250
300
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500
700
850
1000
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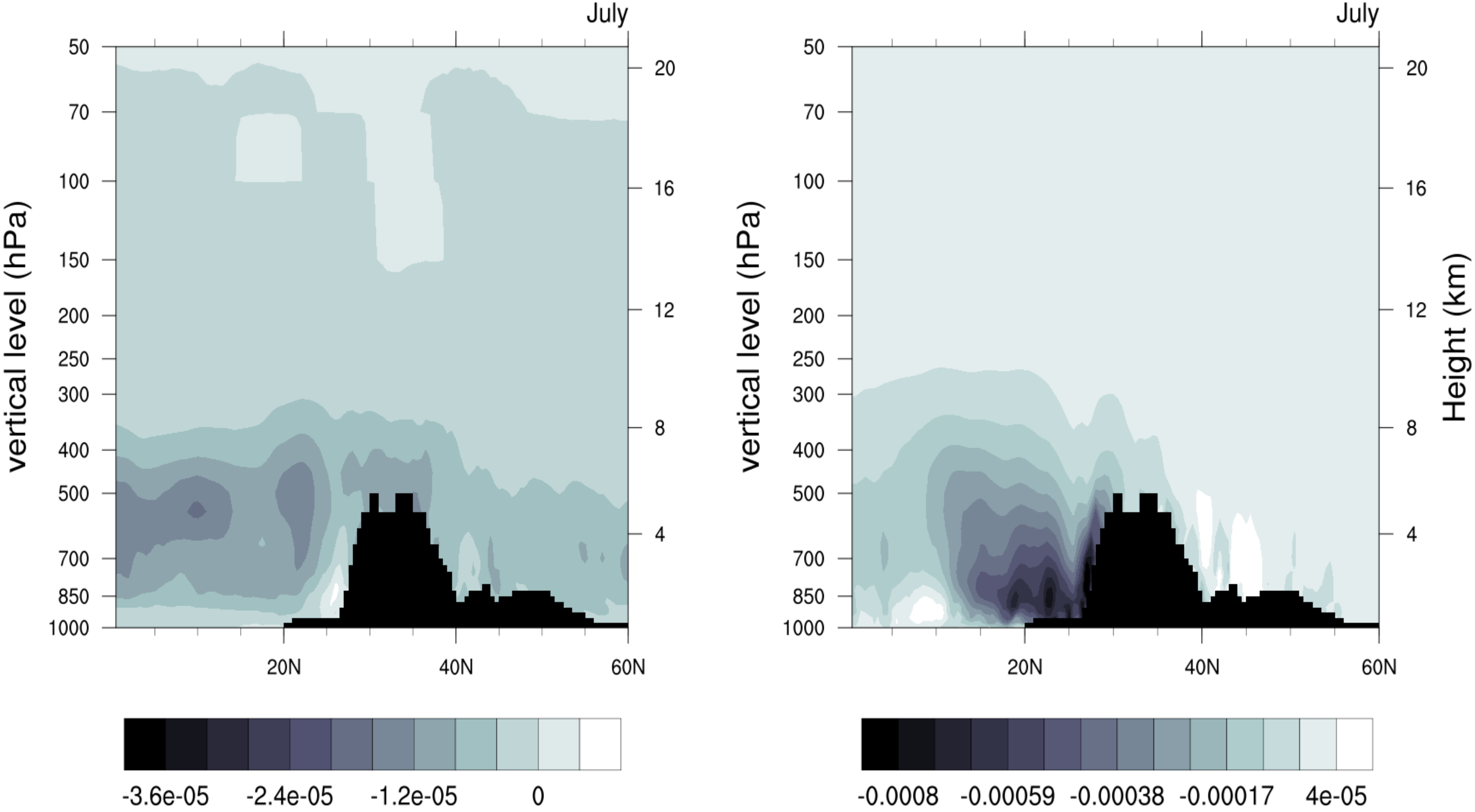
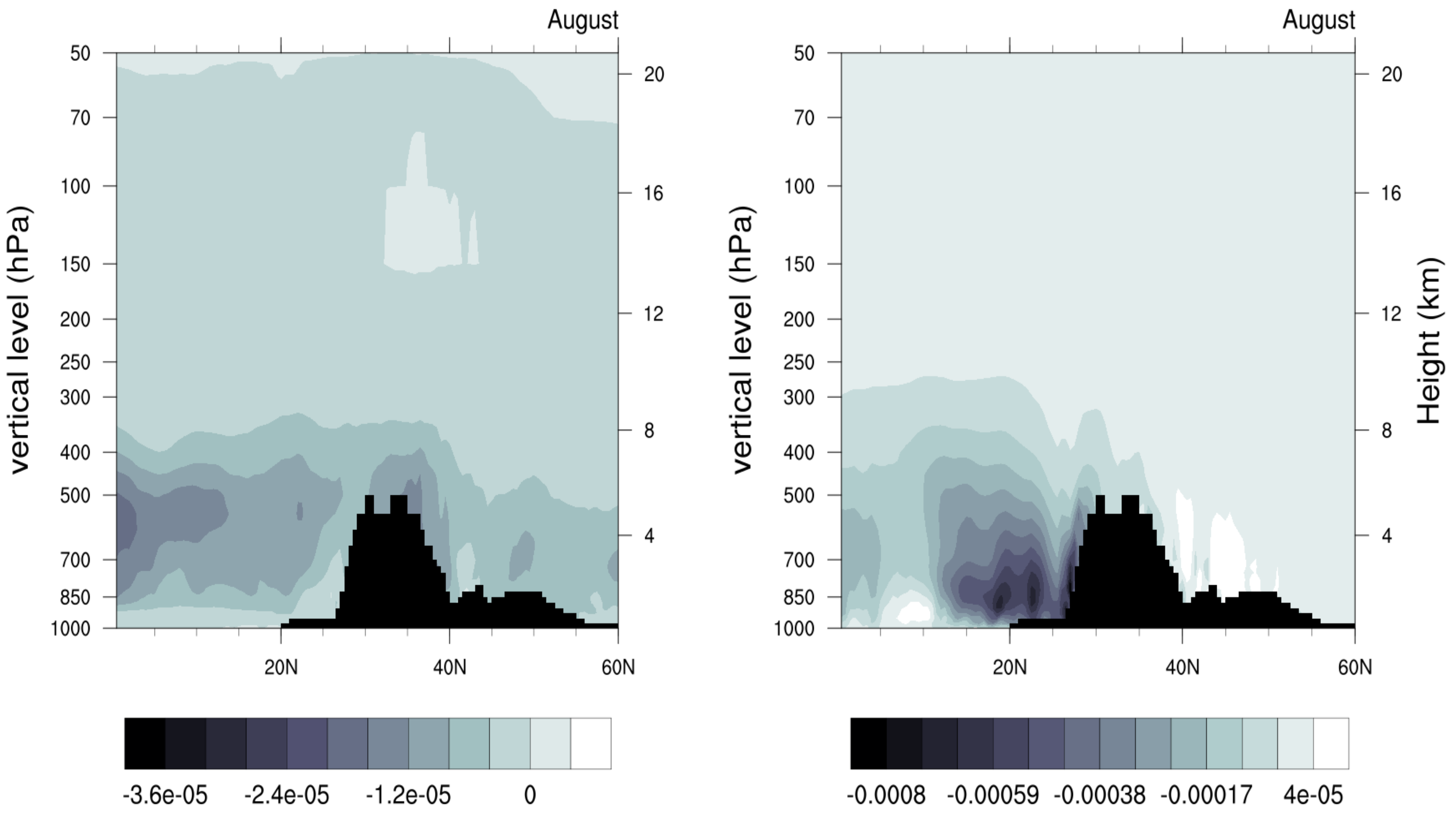
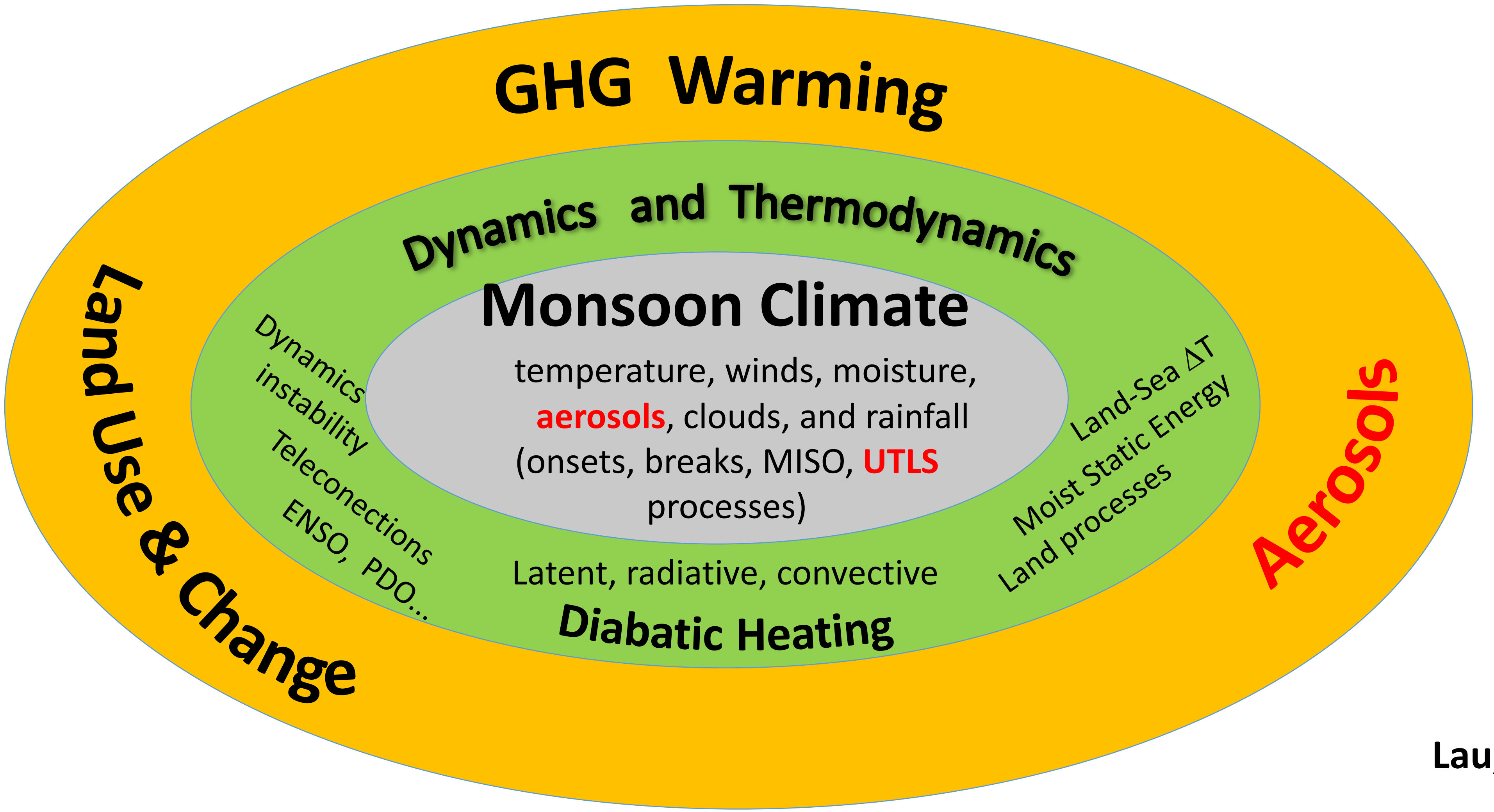
4
20N
40N
60N
-3.6e-05
-2.4e-05
-1.2e-05
0
-0.0008
-0.00059
-0.00038
-0.00017
4e-05

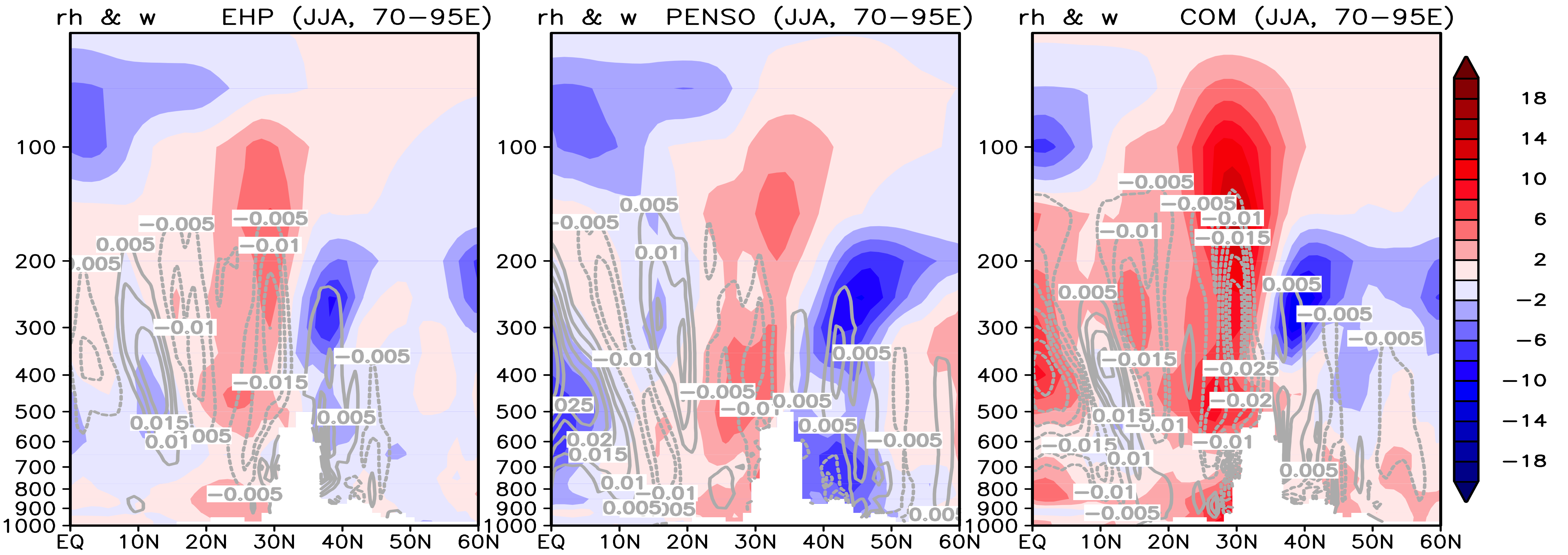

July
vertical level (hPa)
50
70
100
150
200
250
300
400
500
700
850
1000
20N
40N
60N
20
16
12
8
4
-3.6e-05
-2.4e-05
-1.2e-05
0
July
vertical level (hPa)
Height (km)
-0.0008
-0.00059
-0.00038
-0.00017
4e-05


August
vertical level (hPa)
50
70
100
150
200
250
300
400
500
700
850
1000
20
16
12
8
4
20N
40N
60N
-3.6e-05
-2.4e-05
-1.2e-05
0
August
vertical level (hPa)
Height (km)
-0.0008
-0.00059
-0.00038
-0.00017
4e-05

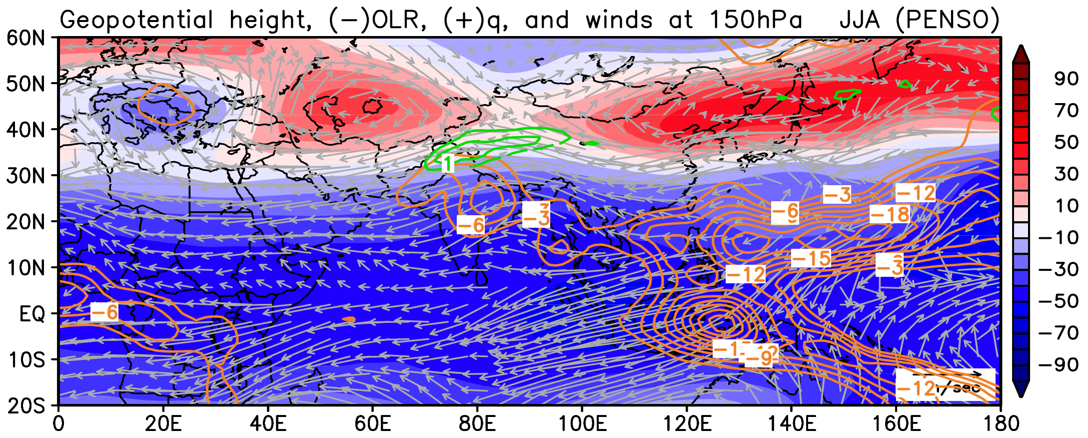
An Aerosol-Monsoon Climate System - A New Paradigm

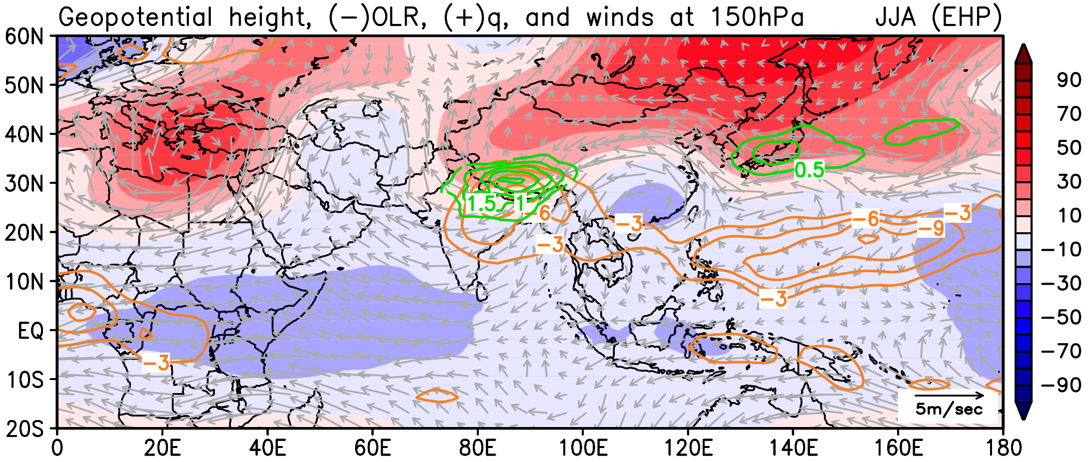


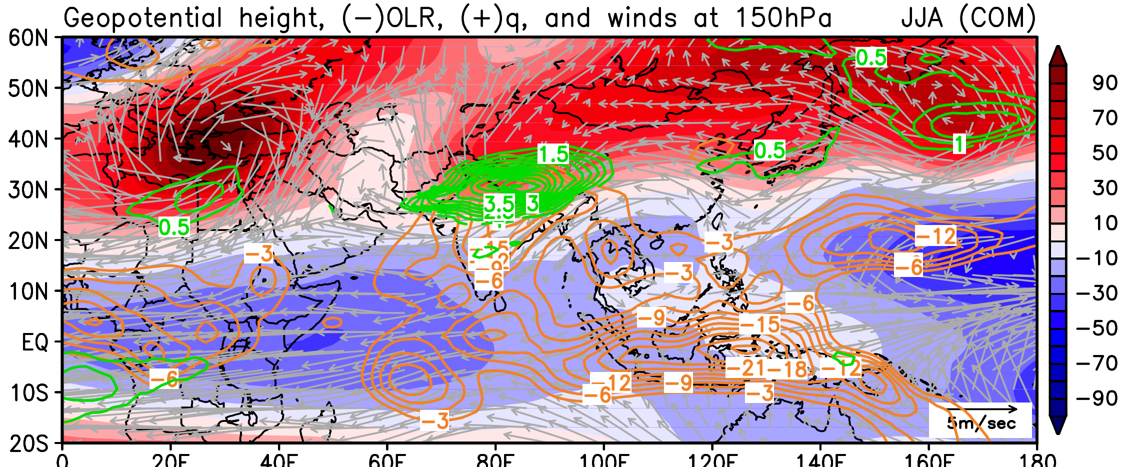
Lau, 2016, JMR

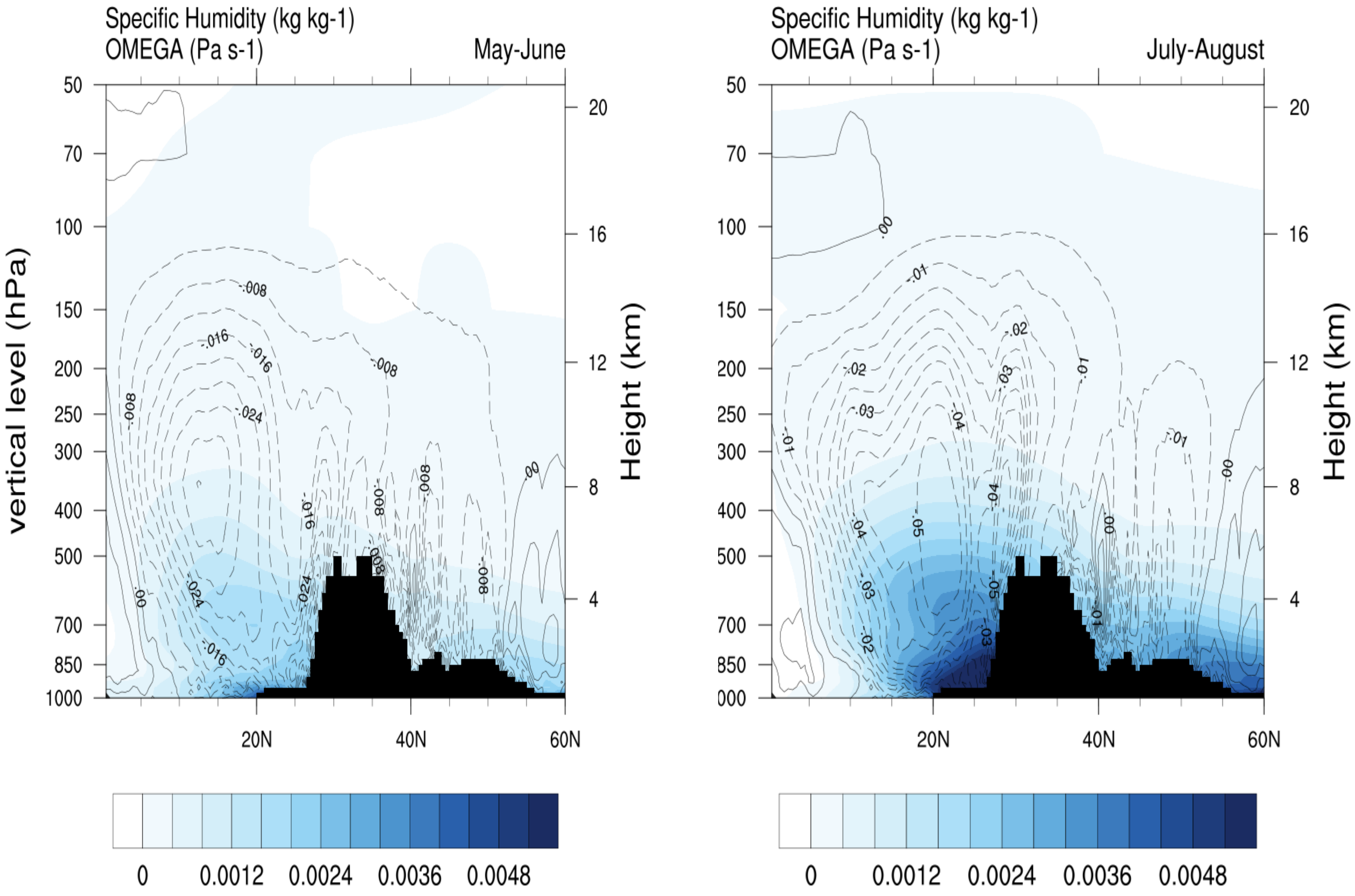


rh & w EHP (JJA, 70–95E)
rh & w PENSO (JJA, 70–95E)
rh & w COM (JJA, 70–95E)
100
200
300
400
500
600
700
800
900
1000
EQ
10N
20N
30N
40N
50N
60N
18
14
10
6
2
−2
−6
−10
−14
−18


Geopotential height, (−)OLR, (+)q, and winds at 150hPa JJA (PENSO)
60N
50N
40N
30N
20N
10N
EQ
10S
20S
0
20E
40E
60E
80E
100E
120E
140E
160E
180
90
70
50
30
10
−10
−30
−50
−70
−90


Geopotential height, (−)OLR, (+)q, and winds at 150hPa JJA (EHP)
5m/sec


Geopotential height, (−)OLR, (+)q, and winds at 150hPa JJA (COM)
5m/sec



Specific Humidity (kg kg-1)
OMEGA (Pa s-1)
May-June
vertical level (hPa)
Height (km)
20N
40N
60N
0
0.0012
0.0024
0.0036
0.0048
Specific Humidity (kg kg-1)
OMEGA (Pa s-1)
July-August
Height (km)
20N
40N
60N
0
0.0012
0.0024
0.0036
0.0048

Ongoing and future work

UTLS transport and loading of water vapor, cloud ice, CO, HCl, O3… on multiple time scales of monsoon variability, using MERRA2 and satellite observations (Aura/MLS, OMI..), and model simulations:

- Seasonal
- Monsoon Intraseasona Oscillations (MISO)
- Case studies of extreme precipitation events or NIHF, vertical transports by deep penetrative forced and aerosol interactions
- Interannual (ENSO)
- Inter-decadal (PDO, AMO..)
- Anthropogenic Climate Change (GHG, Aerosols, Land use and change)

Conclusions

Dust and BC aerosols alter the intraseasonal variability of the Indian monsoon rainfall system, i.e., shifting heavy rain from the IGP to the Himalaya foothills, by transforming a monsoon depression over the eastern IGP into orographic deep convective rain cells over the Himalayan foothills via the intraseasonal dynamical feedback mechanism (iEHP) :

- Heating by dust aerosols over the Arabian Sea (semi-direct effect) suppresses local convection , but enhances southwesterly moisture transport over northern Arabian Sea, and northern IGP;

- Dust in combination with BC reduces rainfall (semi-direct effect), suppresses monsoon depression over western IGP, decreases monsoon easterlies over foothills, and reduces monsoon influx from the Bay of Bengal, further suppress monsoon cyclone development

- Additional moisture from non-precipitation over the Arabian Sea/eastern and central India is transported downstream by increased southwesterlies, triggering orographic rainfall over northern, and northeast foothills regions

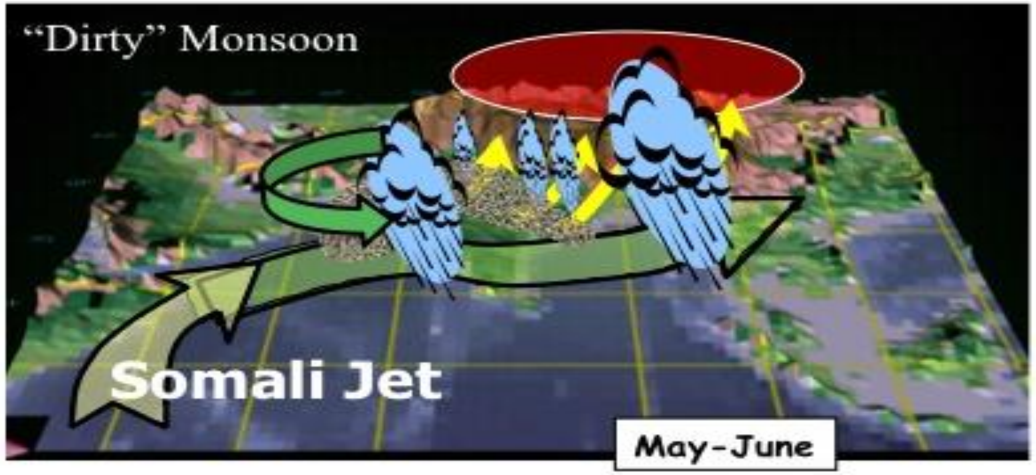
- Indirect effects enhanced iEHP, by further delaying warm rain process in the IGP, invigorate orographic meso-scale deep convective over the Himalayas foothills, with enhanced ice –phase rainfall processes (increased snow and graupel).

iEHP + aerosol microphysics effect → enhanced heavy rain, floods, and land slides conditions over the Himalayas foothills ??

Possible influence of aerosol impact through EHP on UTLS transport?

Increased aerosol loading over the Indo-Gangetic Plain may have caused more frequent occurrence of extreme rainfall over Himalaya/Nepal foothills in recent years (Lau 2016)

The Elevated Heat Pump (EHP) Hypothesis



Lau et al., 2006, 2008

Uttarakhand's Furious Himalayan Flood Could Bury India's Hydropower Program, WEDNESDAY, 02 APRIL 2014 06:00

The early arrival of the annual monsoon that accelerated snow melting, produced higher than normal rainfall, and then unleashed a cloudburst that dumped at least 300 millimeters (12 inches) of rain on June 16 , 2014 on the Himalayan ridges that fed the Alaknanda and Bhagirathi river basins.

EHP operates in other mountainous terrains in Asian monsoon regions

Air Pollution May Have Caused Catastrophic Flooding in Southwest China, 2013

Fan J, et al., 2015. "Substantial Contribution of Anthropogenic Air Pollution to Catastrophic Floods in Southwest China." *Geophys. Res. Lett.*