Exploring the relationship between surface $PM_{2.5}$ and meteorology in Northern India

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Introduction

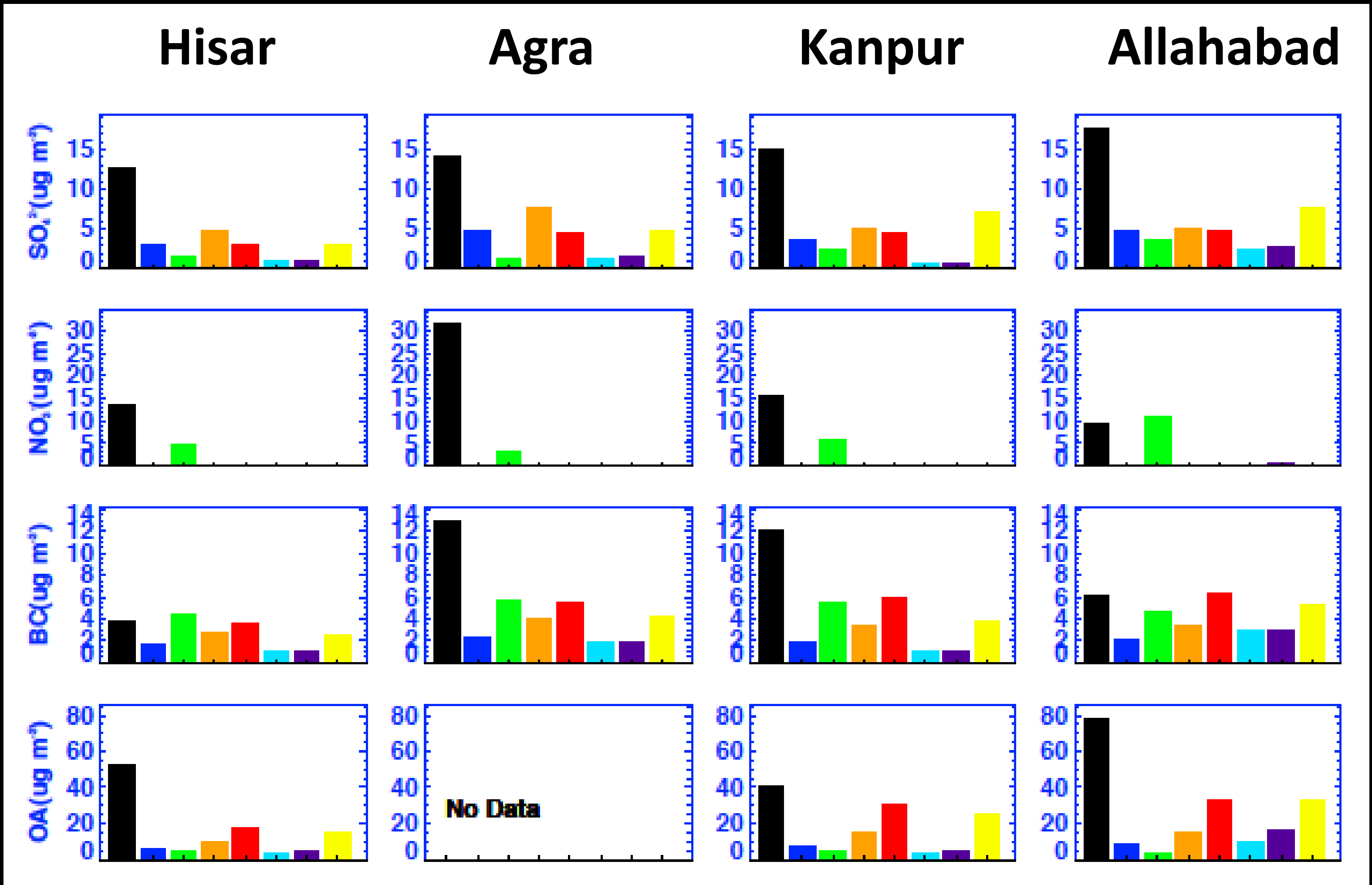
- $PM_{2.5}$ exposure caused >1 million premature deaths in India in 2015 (Health Effects Institute, 2017)
- Accurate projections of future $PM_{2.5}$ require accurate modeling of chemistry and relationship to meteorology in present day
- A difficult task since it requires accurate representation of the individual components – their emissions, chemistry & transport

Especially difficult over India due its extreme environment with respect to:

(1) Physical (complex topography)
(2) Chemical (concentrated and abundant primary and precursor emissions)
(3) Dynamical (meteorology; e.g., shallow temperature inversions)

Models severely underestimate $PM_{2.5}$, especially in winter

(below; Dec. 2004 from Pan et al., ACP, 2015)



Pan et al. (2015) concludes that a large reason for models' low bias during winter is due to underestimated emissions. Mainly **<u>OM and BC from biofuel</u>.**

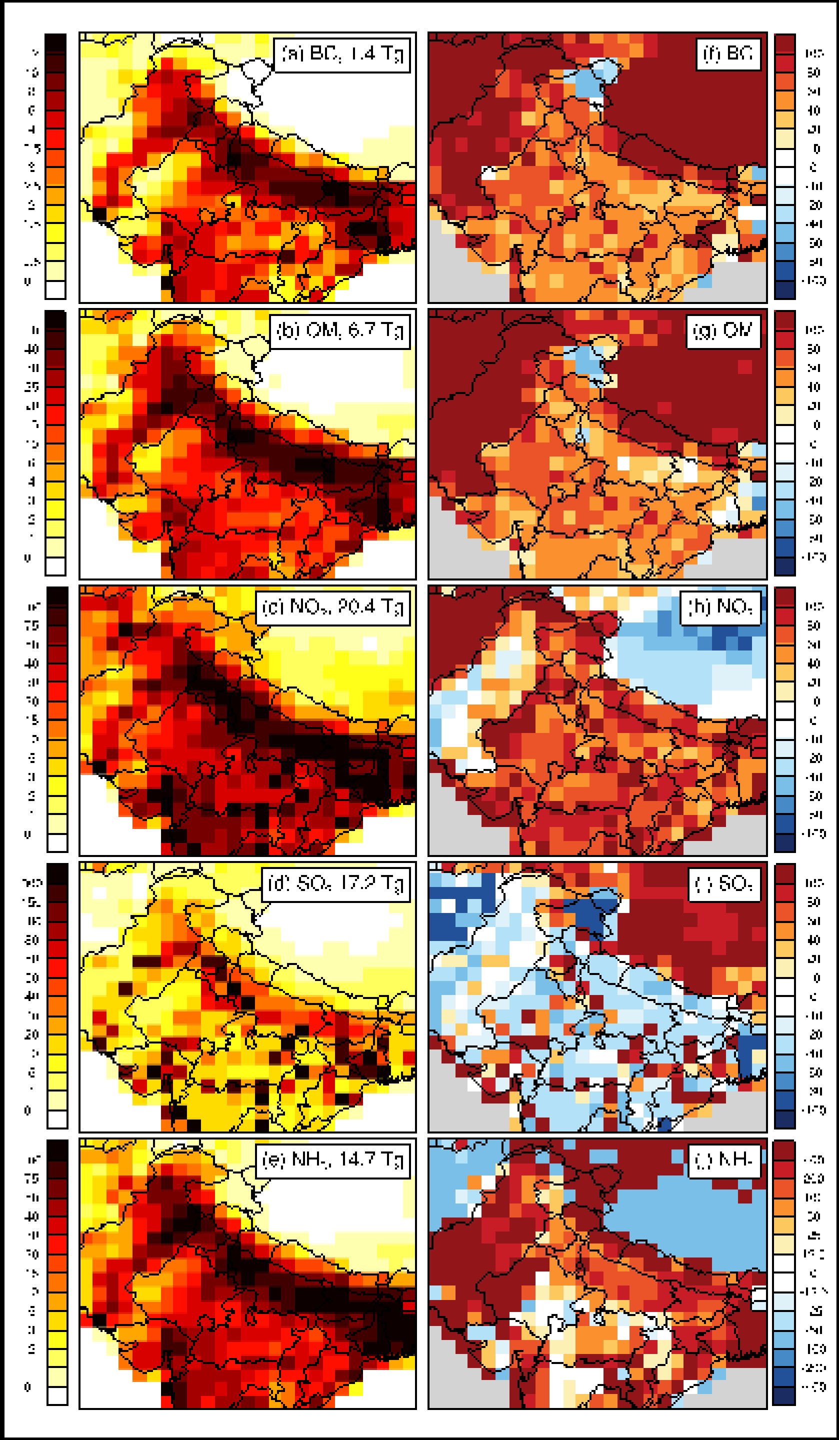
October 2015 – March 2016

(Left) CMIP6 emissions (Hoesly et al., 2017)

(Right) Difference (%) from CMIP5 to CMIP6 emissions

Most emissions have increased (~50% – 100%) nearly everywhere

SO_2 is more concentrated (i.e., increases at "hotspots" (power plants) and decreases elsewhere)



Materials

Air quality

• Hourly surface $PM_{2.5}$ from 22 sites across Northern India from India's Central Pollution Control Board (CPCB)

• Recent: October 2015 – 31 March 2016 (season of highest $PM_{2.5}$)

Meteorology

• 6-hourly reanalysis data (NCEP/NCAR and ECMWF) of:
RH, BLH, surface (10m), 850mb, and 500mb winds, precipitation, difference between surface (2m) and 850mb temperature = INV

Model

• Developmental version of the new-generation NOAA GFDL Atmospheric Model, version 4 (GFDL AM4) - Cubed-sphere finite volume (1° x 1.25° x 48L)

• Chemical mechanism similar to AM3 (Naik et al., 2013) with gas-phase and heterogeneous updates (Mao et al. 2013 a, b) and updated nitrate chemistry (Paulot et al., 2016)

Two simulations (1 Jan 1980 – 31 March 2016) :
one using **CMIP5 emissions**, one using **CMIP6 emissions**

Modeled components of $PM_{2.5}$ and inclusion of aerosol water

$PM_{2.5}$ (dry) = SOA + dust1 + 0.25*dust2 + ssalt1 + ssalt2 + 0.167*ssalt3 + $BC_{phillic}$ + BC_{phobic} + $OM_{phillic}$ + OM_{phobic} + NH_4 + NO_3 + SO_4

Hygroscopic growth factors calculated at 50% relative humidity (operationally defined by India's CPCB)

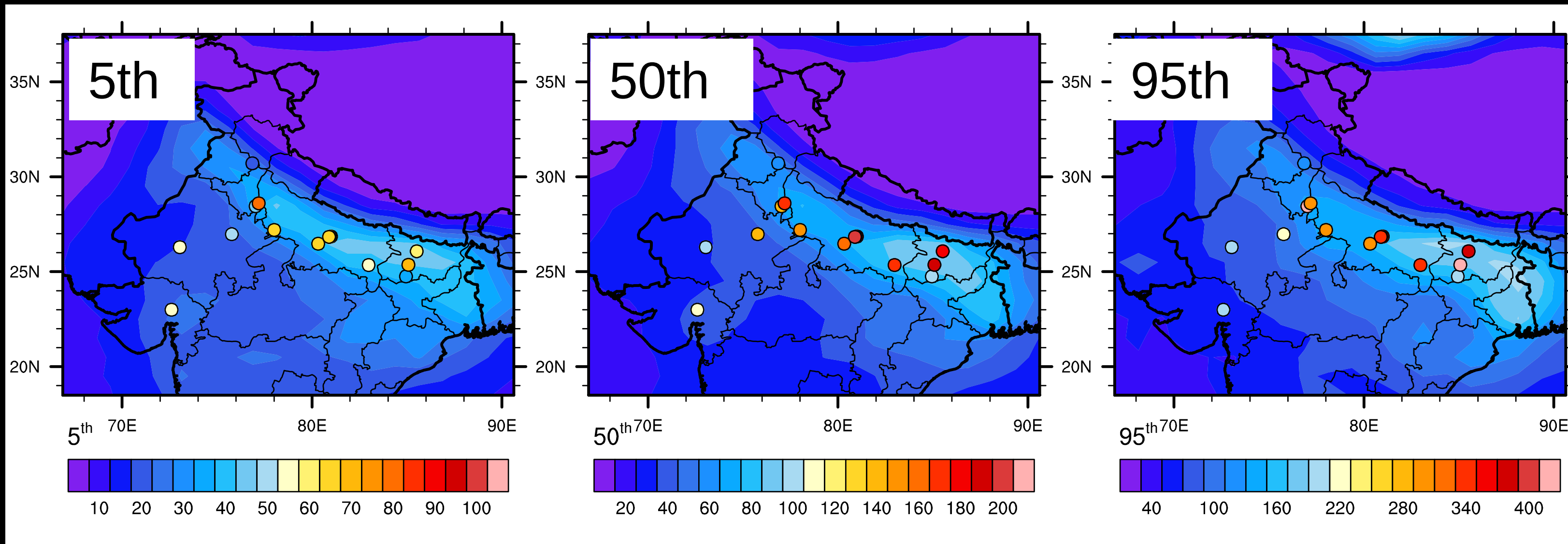
*Some uncertainty involved; e.g., GEOS-CHEM uses 1.51 for NH_4, NO_3, and SO_4, as well as 1.24 for SOA and $OM_{phillic}$

First partition NH_4

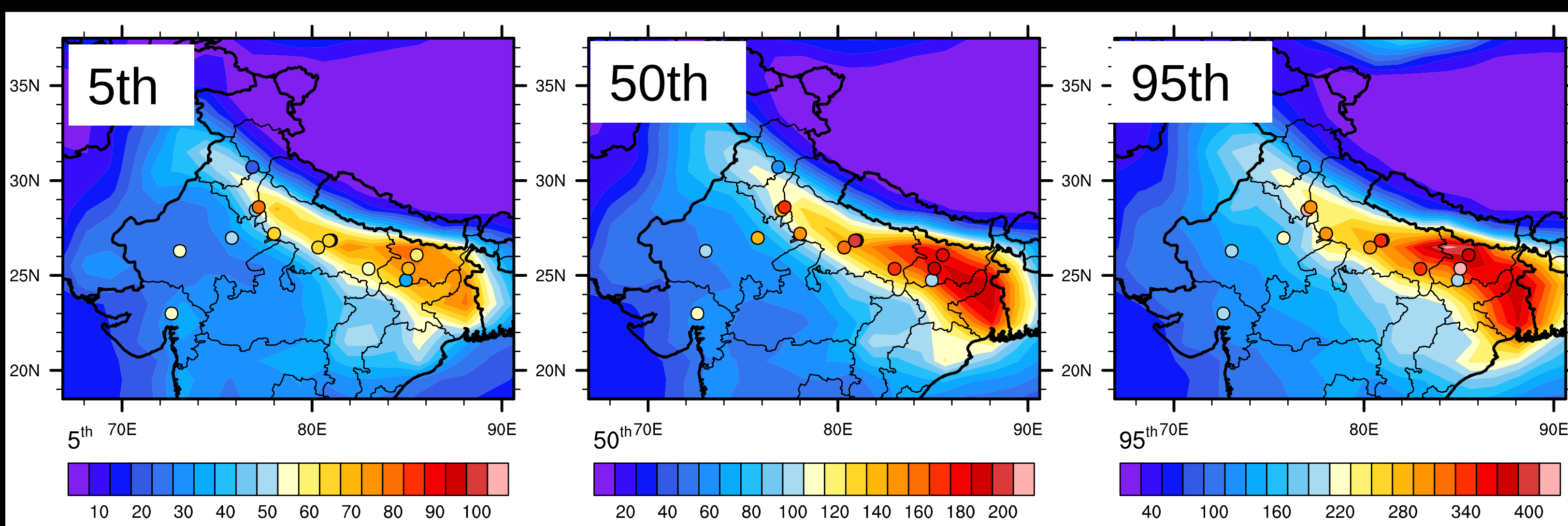
ß = $NO_3/(NO_3 + 2*SO_4)$

$PM_{2.5}$ (wet) = SOA + dust1 + 0.25*dust2 + ssalt1 + ssalt2 + 0.167*ssalt3 + $BC_{phillic}$ + BC_{phobic} + $OM_{phillic}$ + OM_{phobic} + 1.32*(NO_3 + ß*NH_4) + 1.46*[SO_4 + (1 – ß)*NH_4]

CMIP5 Emissions



CMIP6 Emissions

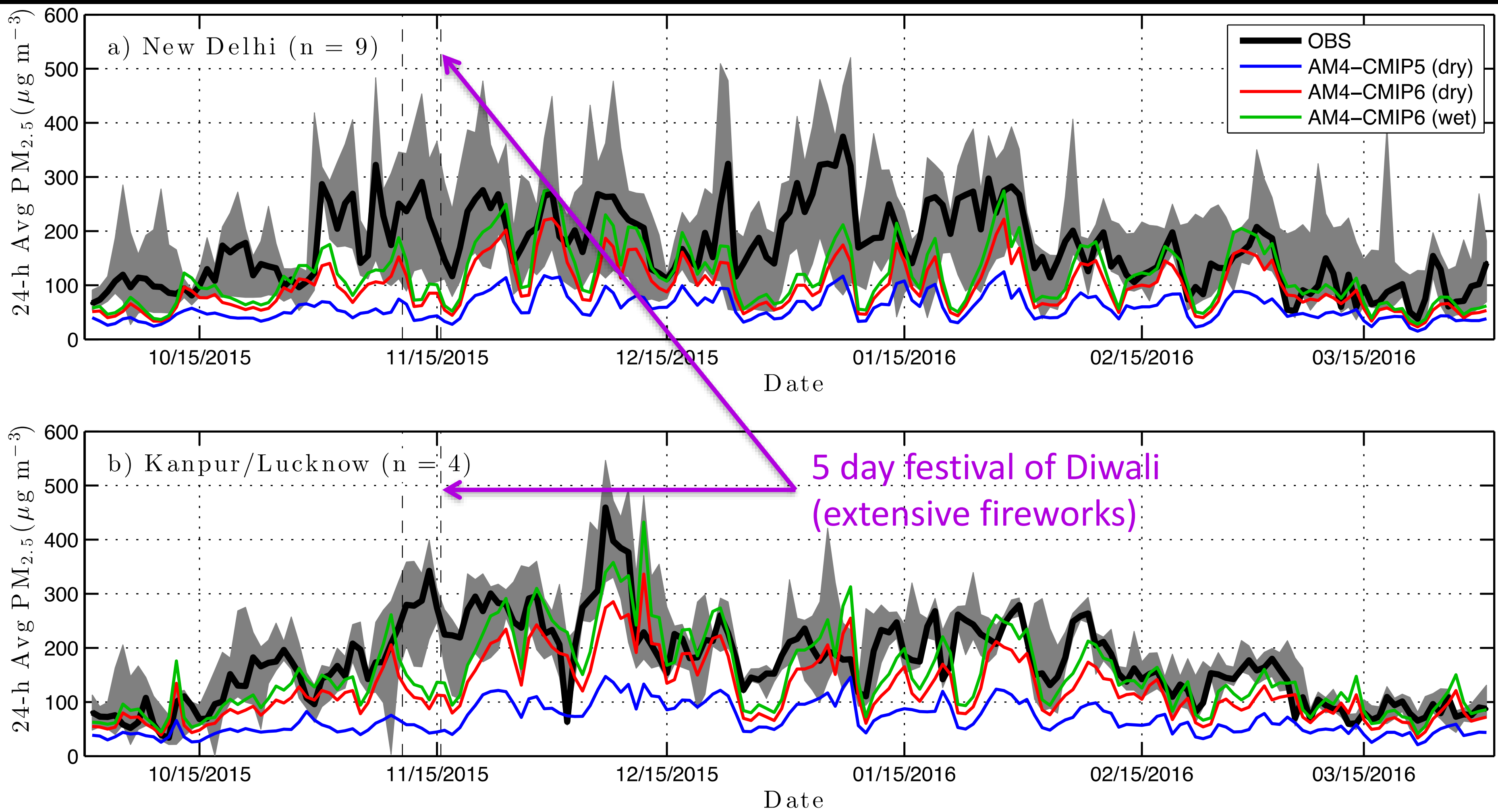


Daily Variability at 2 model cells with multiple observations (<100km)

AM4-CMIP5 and AM4-CMIP6 are highly correlated but have vastly different magnitudes

Inclusion of hygroscopic growth (AM4-CMIP6 wet) reduces bias but decreases correlation

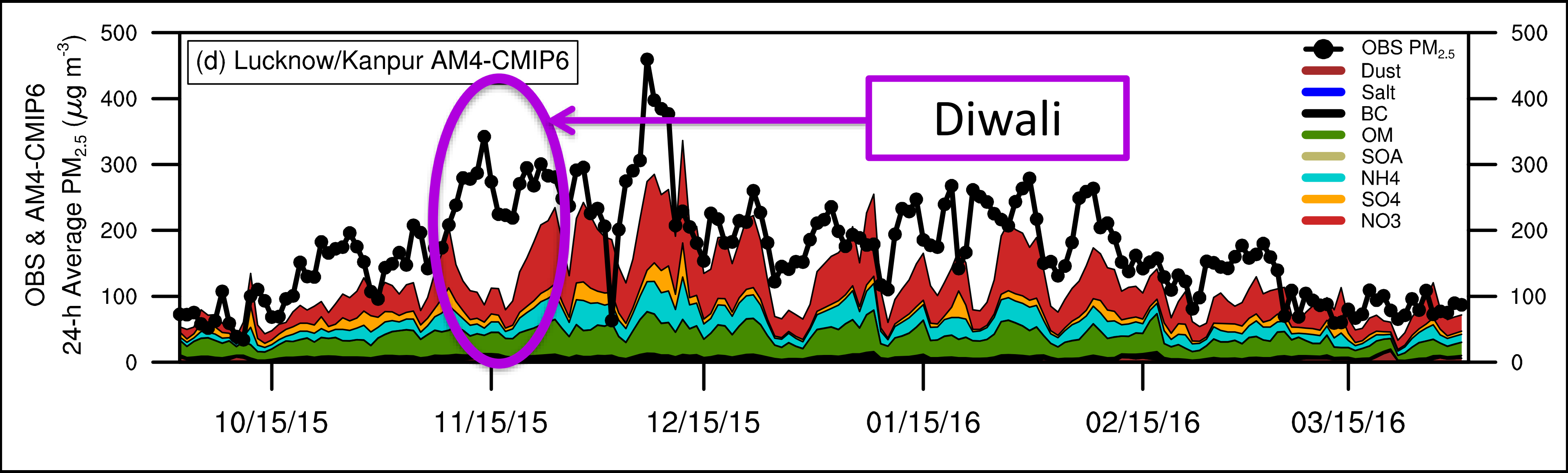
Correlation with **OBS** is modest: ***r* = 0.58** for New Delhi; ***r* = 0.71** for Kanpur/Lucknow

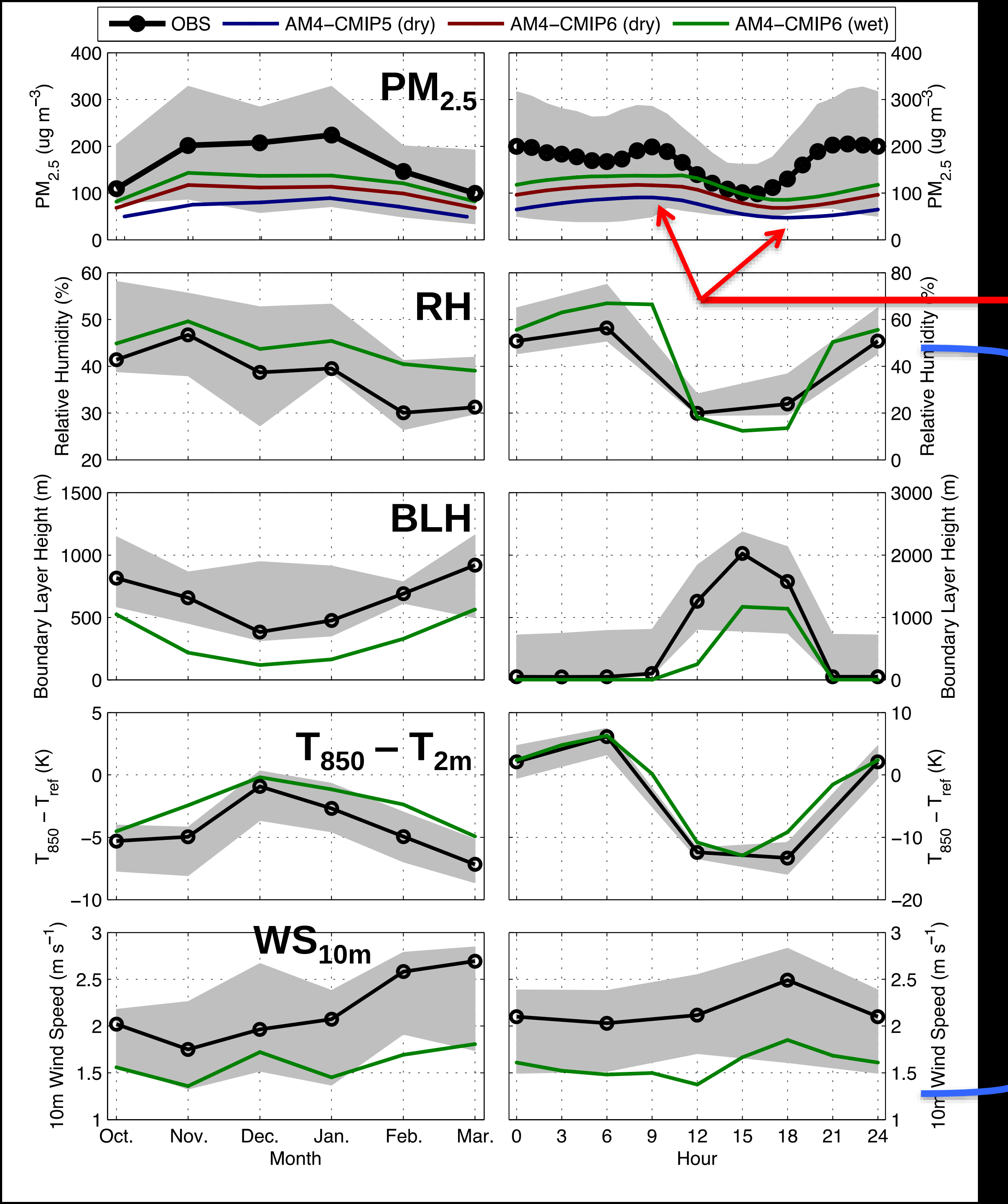


Dominant modeled (dry) components = NO_3 (14–53%, μ = 39%) + OM (13–46%, μ = 25%) + NH_4 (9–22%, μ = 16%) = ~80%)

Correlation with total observed $PM_{2.5}$ is largest with **OM** and **BC** – components that are more (less) influenced by meteorology (chemistry)

What component(s) is too low? SO_4? BC?

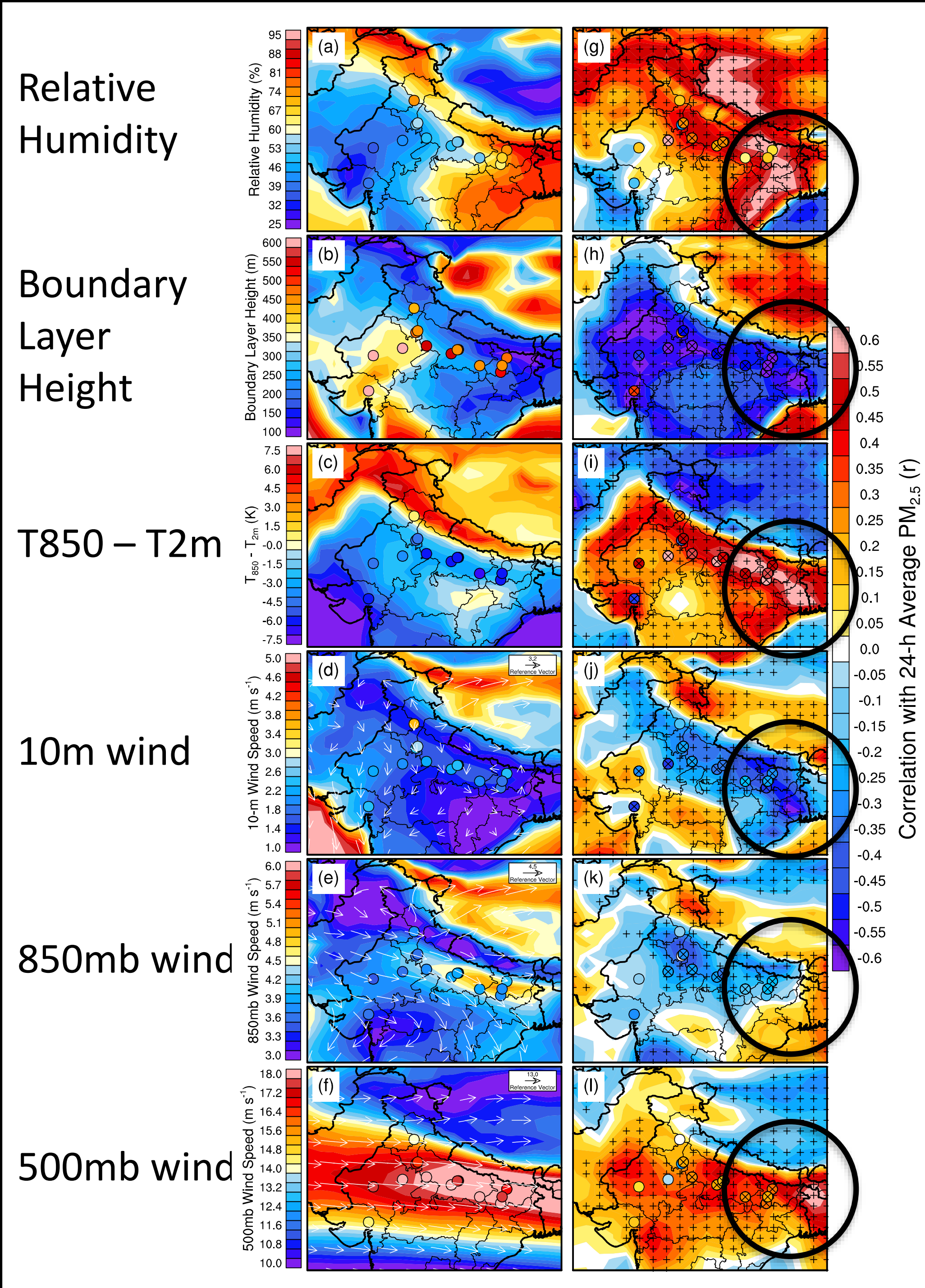




AM4 somewhat catches the morning rise in $PM_{2.5}$ but missing the secondary evening peak

Meteorological cycles are matched implying that emissions need a diurnal cycle

e.g., evening pulse in traffic, heating, and cooking



(LEFT) – Average Meteorology
AM4 matches observed meteorology (expected since its nudged)

(RIGHT) – corr($PM_{2.5}$, meteorology)
Also matches most of the observed correlations with meteorology

Highest correlations in the far eastern edge of the IGP in the states of Bihar and Uttar Pradesh **(circles)**

Largest correlation with relative humidity*, boundary layer height and $T_{850} – T_{2m}$

Positive correlations with 500mb wind speed…Why?

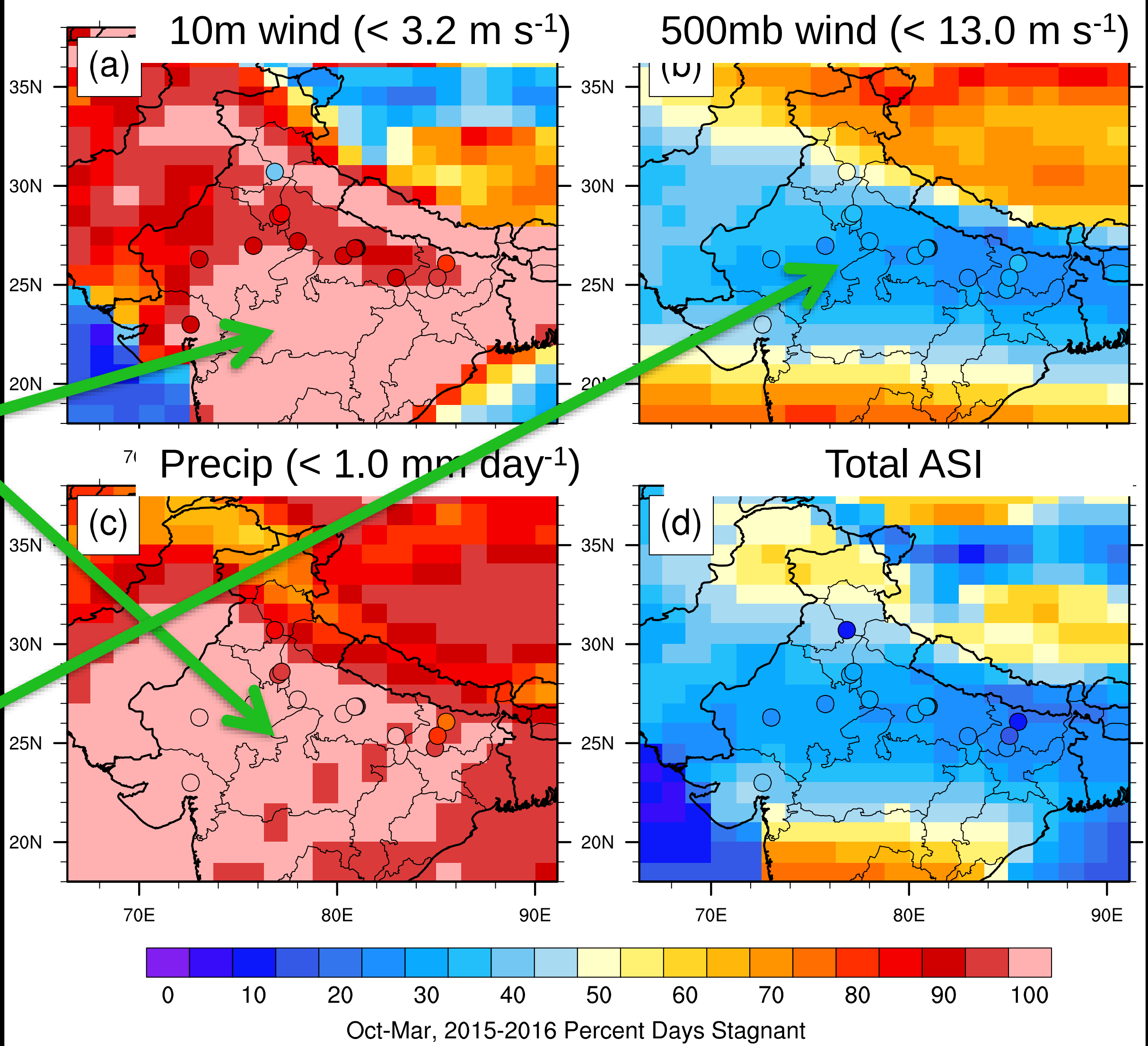
Typically, low 500mb wind speeds → stagnation → high $PM_{2.5}$

Stagnation; ASI = 10m wind + 500mb wind + precipiation

AM4 matches observed stagnation frequencies

= 100% for 10m wind and precip in many locations

500mb is limiting component of total ASI (~35% of days)



TEST: Composite of average $PM_{2.5}$ on days that are stagnant versus days that are not (1 Oct 2015 – 31 March 2016)

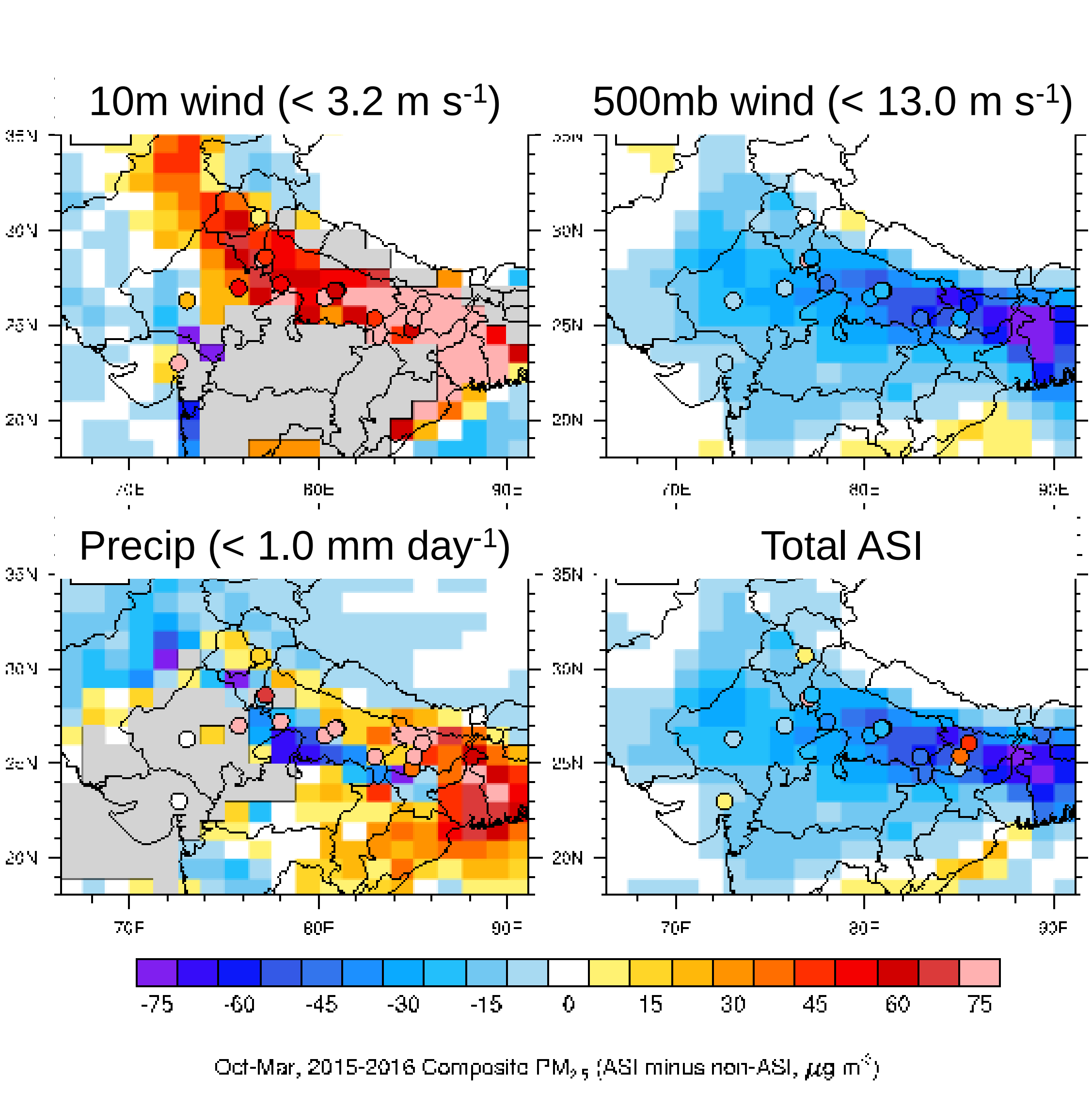
Gray = 100% stagnation

Increased $PM_{2.5}$ on days with low surface wind speeds and low precipitation

But…

Decreased $PM_{2.5}$ on days with low upper level winds (not sensitive to cutoff)

Since 500mb winds are limiting ASI component → low $PM_{2.5}$ on ASI days



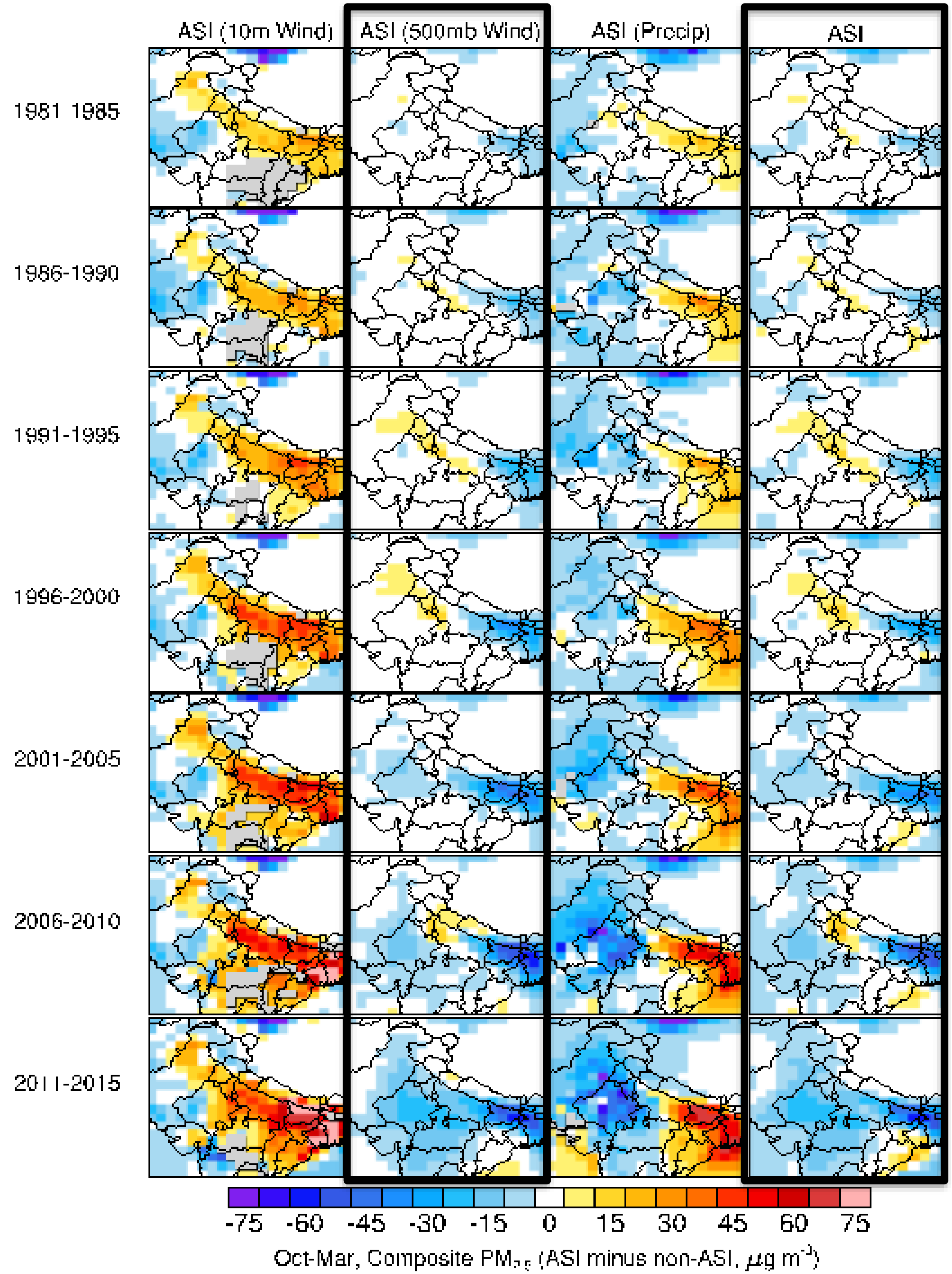
This relationship is recent (i.e., stagnation → lower $PM_{2.5}$

Earlier decades show **near-zero** and some **positive** composites over most of India

Recent decades have **negative** composites over most of Northern India by 2011-2015

Stagnation causing high pollution days in one climate regime may not apply to future climate

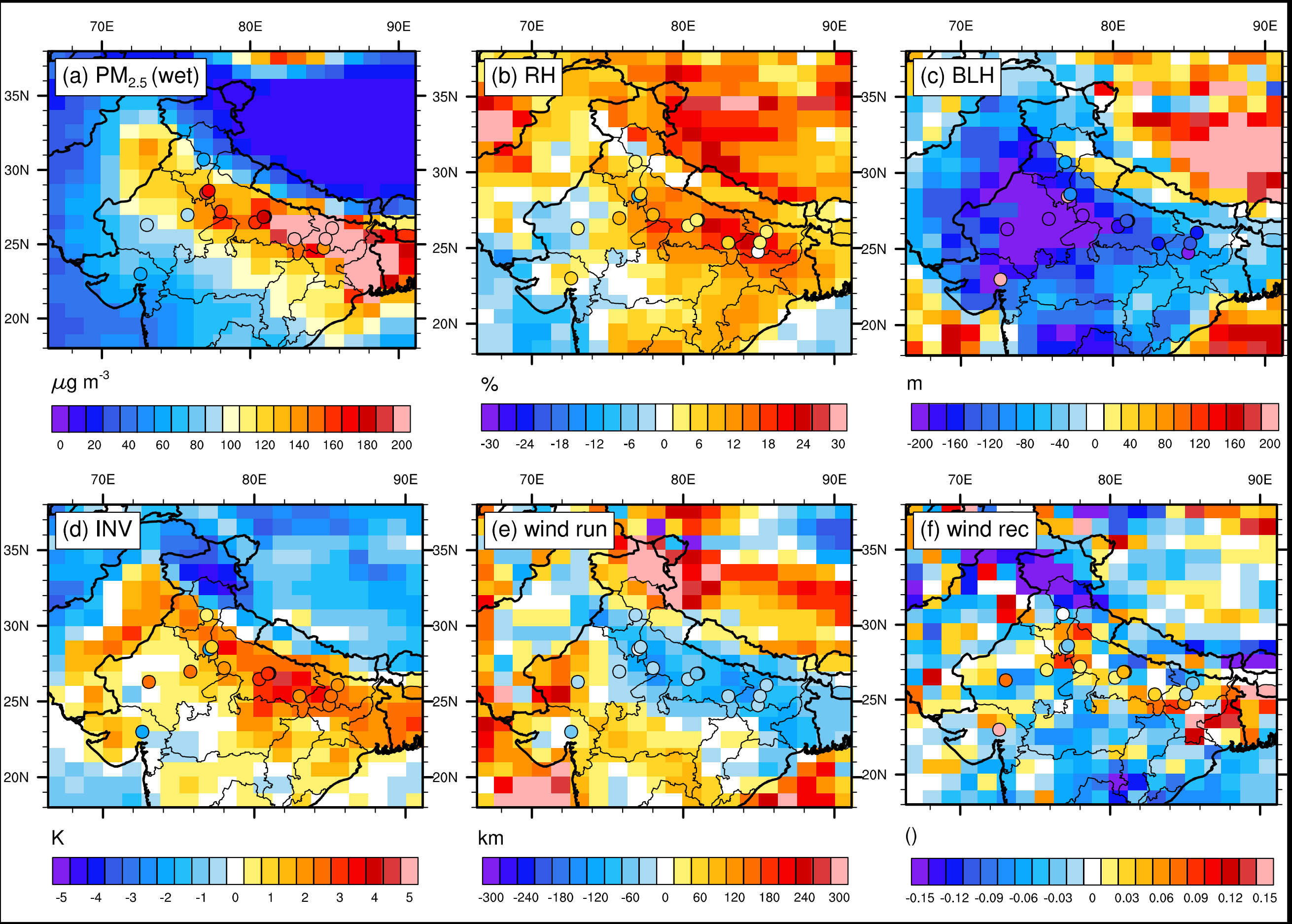
What conditions consistently result in poor air quality?



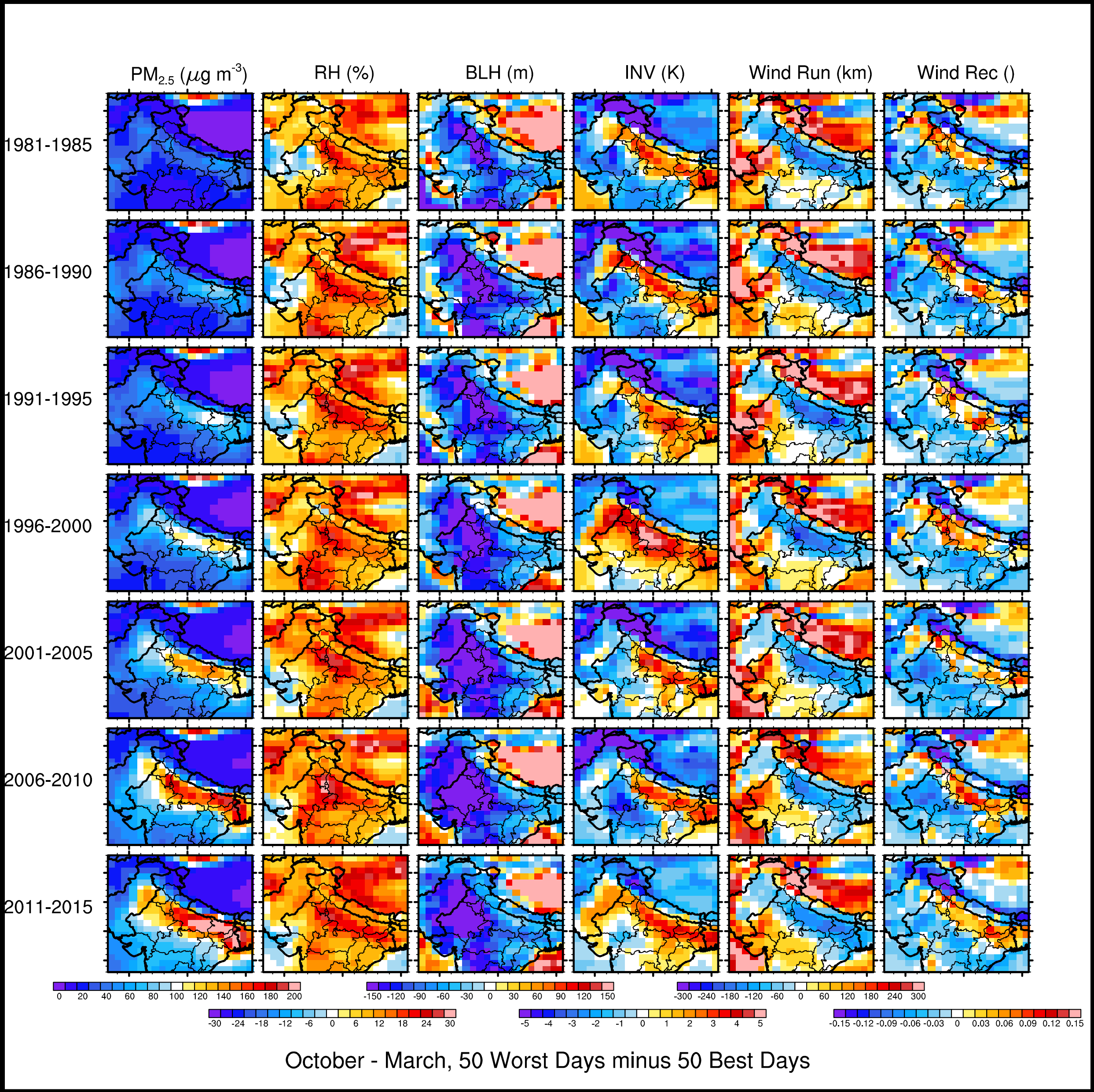
Use of other meteorological variables

Figure: Composite of 10 days with highest $PM_{2.5}$ minus 10 days with lowest over Oct – Mar, 2015-2016 (~ 95th percentile minus 5th percentile)

Quantities that describe the stability of the lower atmosphere are better indicators of wintertime $PM_{2.5}$ – especially over the IGP



These meteorological variables are consistent in their relationships to $PM_{2.5}$ over the past 3+ decades, despite massive changes in emissions



Conclusions

- Emission dataset developed for CMIP6 vastly reduces the low bias of the AM4, nearly doubling the amount of $PM_{2.5}$ simulated in 2015-2016
- Highest $PM_{2.5}$ found in the Indo-Gangetic Plain (IGP)
- $PM_{2.5}$ in the IGP is also most sensitive to meteorological variables – those that describe lower atmospheric stability: i.e., RH, BLH, strength of temperature inversion, and low level wind speed.
- In the AM4, nitrate (NO_3^-) and organic matter (OM) are the dominant components of total $PM_{2.5}$ over most of Northern India, and they are also the most sensitive components to meteorology
- The air stagnation index (ASI), a commonly used indicator of poor air quality, is generally not able to predict high pollution days in the present decade over the most polluted regions of Northern India.