

Multi-decadal changes in atmospheric boundary layer dynamics across India and implications on pollutants



Ghouse Basha^{1*}, M. Venkat Ratnam¹, Y. Viswanadhapalli¹ & P. Kishore²

¹National Atmospheric Research Laboratory, Department of Space, Gadanki, India

²Regato, Rancho Santa Margarita, CA, USA

*Lead presenter / corresponding author: mdbasha@narl.gov.in | mdbasha@gmail.com



38 yr

WRF regional dataset
1980–2022 (18 km / 6 km)

R^2 0.91–0.94

WRF vs. radiosonde ABL
height at Gadanki

~2 km

Deepest ABL: pre-monsoon
(NW & central India)

–30 to –40 m/dec

Decline over central &
peninsular India

~160 m

Cumulative ABL decrease
over southern India

1 Abstract

The atmospheric boundary layer (ABL) regulates surface–free-troposphere exchange of heat, moisture and pollutants, yet its multidecadal evolution over India is poorly constrained. We combine 38 years (1980–2022) of high-resolution WRF simulations with radiosonde and ceilometer observations to quantify spatial, seasonal and long-term changes in ABL height (ABLH) and their controls. WRF reproduces observed ABLH well ($R^2 = 0.91$ – 0.94 at Gadanki). ABLH peaks pre-monsoon (~2 km) and is lowest in winter. A widespread decline of ~30–40 m per decade (cumulative ~160 m) occurs over central and peninsular India, with localized increases over the north-west. Declining sensible heat flux and wind speed, with rising moisture and lower LCL, weaken mixing; a shallower ABL is linked to enhanced $PM_{2.5}$.

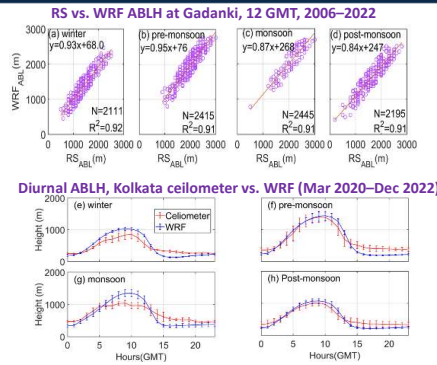
2 Objectives

- To quantify the spatial, seasonal and long-term variability and trends in ABL height across India using high-resolution WRF simulations (1980–2022).
- To identify the dominant surface and atmospheric drivers (ST, RH, WS, HF, LCL, SH) of long-term ABL trends via random-forest analysis.
- To examine the relationship between long-term ABL height changes and air-quality indicators (AOD, $PM_{2.5}$, ozone).
- To assess the implications of multidecadal ABL shallowing for pollutant dispersion, $PM_{2.5}$ accumulation and regional air quality

3 Data sets and Methodology

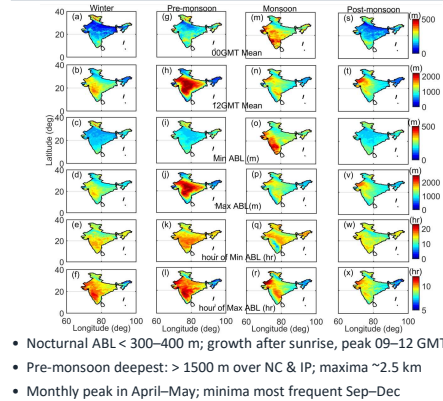
- Datasets:** WRF simulations (1980–2022, 18-km nested 6-km grid); Meisei radiosondes at Gadanki (2006–2022) and IGRA2 (1980–2022, 30 stations); Vaisala CL51 ceilometer at Kolkata (2020–2022); ERA5 (1979–present); MERRA-2 for $PM_{2.5}$, AOD and ozone (1980–2022).
- WRF setup:** Advanced Research WRF with MYNN Level 2.5 PBL, Betts-Miller-Janjic convection, Thompson microphysics and Noah land-surface model; PBLH from TKE threshold $0.2 \text{ m}^2 \text{ s}^{-2}$.
- Random-forest model:** Quantifies relative importance of surface temperature, RH, wind speed, sensible heat flux, LCL, specific humidity, AOD, $PM_{2.5}$ and ozone.

4 Results 4.1 WRF Validation



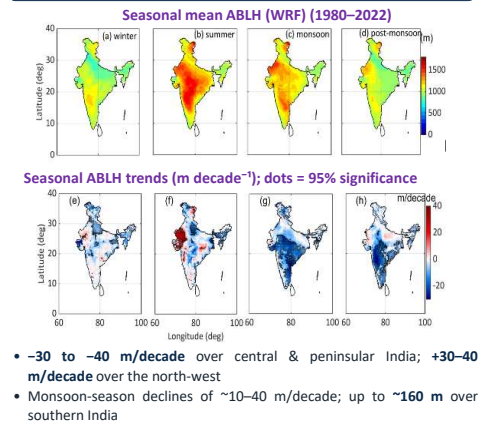
- Seasonal $R^2 = 0.91$ – 0.94 ; correlations with IMD radiosondes generally > 0.80
- Diurnal cycle captured; slight monsoon daytime over-estimation

4.2 Seasonal mean (00/12 GMT), minimum and maximum ABLH and their timing



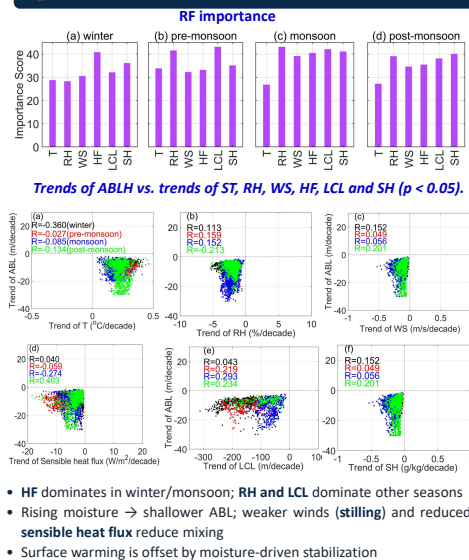
- Nocturnal ABL < 300 – 400 m; growth after sunrise, peak 09–12 GMT
- Pre-monsoon deepest: > 1500 m over NC & IP; maxima ~2.5 km
- Monthly peak in April–May; minima most frequent Sep–Dec

4.3 Long-term Trends of ABL Height



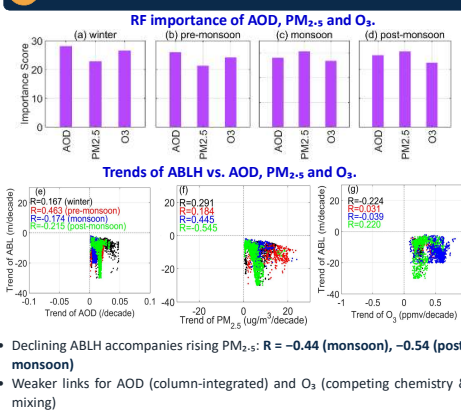
- 30 to –40 m/decade over central & peninsular India; +30–40 m/decade over the north-west
- Monsoon-season declines of ~10–40 m/decade; up to ~160 m over southern India

4.4 Drivers of ABL Change



- HF dominates in winter/monsoon; RH and LCL dominate other seasons
- Rising moisture → shallower ABL; weaker winds (stilling) and reduced sensible heat flux reduce mixing
- Surface warming is offset by moisture-driven stabilization

4.5 Implications for Air Quality



- Declining ABLH accompanies rising $PM_{2.5}$: $R = -0.44$ (monsoon), -0.54 (post-monsoon)
- Weaker links for AOD (column-integrated) and O_3 (competing chemistry & mixing)

5 Conclusions

- WRF simulations accurately capture observed ABL height variability across India, with strong agreement (correlations > 0.80) to radiosonde and ceilometer data.
- ABL height shows a pronounced seasonal cycle, peaking during pre-monsoon and shallowest during winter, with clear regional contrasts.
- The ABL height declined significantly by ~30–40 m per decade over central and peninsular India (cumulative ~160 m), driven by increasing moisture, declining sensible heat flux and wind speed.
- Shallower ABL limits pollutant dispersion and is strongly associated with enhanced $PM_{2.5}$ accumulation, particularly during monsoon and post-monsoon seasons.
- These long-term changes in boundary-layer structure have important implications for regional air quality and atmospheric composition across India.

Overview-Shallowing ABL over India (1980–2022) and its air-quality implications

CHANGING DRIVERS

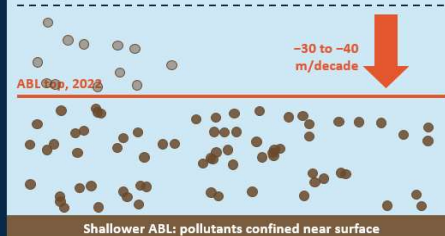
↓ Sensible heat flux

↓ Near-surface wind speed (stilling)

↑ Moisture (RH, SH)

↓ Lifting condensation level

ABL top, 1980



AIR-QUALITY IMPLICATIONS

$PM_{2.5}$ ↑ near surface

$R = -0.44$ (monsoon), -0.54 (post-monsoon)

AOD: weaker link

(column-integrated)

Ozone: mixed response

(chemistry vs. mixing)

Reduced dilution → poorer

air quality, esp. Indo-Gangetic Plain