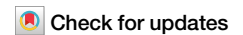


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Aerosol-induced surface cooling elevates relative humidity on the Indo-Gangetic Plain



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The Indo-Gangetic Plain has experienced a substantial rise in relative humidity in recent decades, with implications for human health and well-being. Here we use atmospheric reanalysis and large-ensemble climate model simulations to assess changes since the 1960s. Relative humidity increased by 10.3 ± 0.3 percent, mainly due to a 2.9 ± 0.1 grams per kilogram rise in specific humidity and a slight decrease in air temperature (-0.2 ± 0.1 degrees Celsius). Aerosol-induced surface cooling played a crucial role in enabling this moistening. Decomposition analysis reveals that specific humidity accounts for 95% of the increase, with cooling explaining the rest. Future projections show contrasting trends. High-emission scenarios peak and then decline after the 2040s, as greenhouse gas warming overtakes weakening aerosol effects. In contrast, low-emission scenarios maintain stable or slightly increasing humidity. These findings reveal how aerosols and greenhouse gases exert opposing influences on humidity and underscore the need for coordinated climate strategies in this vulnerable region.

The Indo-Gangetic Plain (IGP) is one of the world's most densely populated regions, home to ~1.4 billion people, and plays a crucial role in South Asia's economic output¹. The region's rapid urbanization and industrial expansion contribute substantially to greenhouse gas (GHG) and aerosol emissions, affecting weather patterns and making the IGP particularly vulnerable to climate change.

Aerosols affect relative humidity (RH) through both radiative and microphysical processes. They cool the surface and stabilize the boundary layer, reducing evaporation and allowing moisture to accumulate^{2,3}. At the same time, they increase cloud condensation nuclei (CCN), potentially enhance condensation, and suppress precipitation, leading to localized moistening^{4,5}. The effect varies by aerosol type and its property: coarse aerosols enhance RH more effectively than fine aerosols, while absorbing aerosols like black carbon (BC) heat the lower atmosphere and further stabilize the boundary layer⁶. Moreover, under high humidity conditions, aerosols grow hygroscopically, increasing their size and optical effects, which can further amplify their impact on RH. In contrast, GHGs increase atmospheric temperature and saturation vapor pressure, which may reduce RH if the moisture supply remains constant. However, GHG-induced warming can also enhance ocean evaporation and water vapor transport,

potentially increasing RH^{7,8}. The added moisture further amplifies warming through water vapor feedback⁹. In IGP, where both GHGs and aerosols are rising, RH trends reflect a complex balance of competing effects. Understanding these interactions is essential for assessing future climate risks related to health, agriculture, and monsoon variability.

RH exerts both immediate effects on human health and systemic influences on climate and weather variability. RH affects human well-being by impairing the body's ability to cool through sweating, increasing risks of heat stress, heat-related illnesses, and mortality during heatwaves, particularly in densely populated regions like the IGP^{2,10}. On a systemic level, elevated RH amplifies the frequency and intensity of humid-heat compound extremes, where high temperature and humidity combine to create life-threatening conditions that reduce labor productivity and exacerbate health risks¹¹. Additionally, RH notably influences monsoon variability by altering atmospheric stability, moisture availability, and cloud formation, which can disrupt regional precipitation patterns vital for agriculture and water resources^{12–14}. These disruptions trigger cascading effects on ecosystems, infrastructure, and socioeconomic systems. The dual nature of RH's immediate effects and systemic influences highlights its critical role in shaping climate risks, underscoring the need to monitor RH trends and

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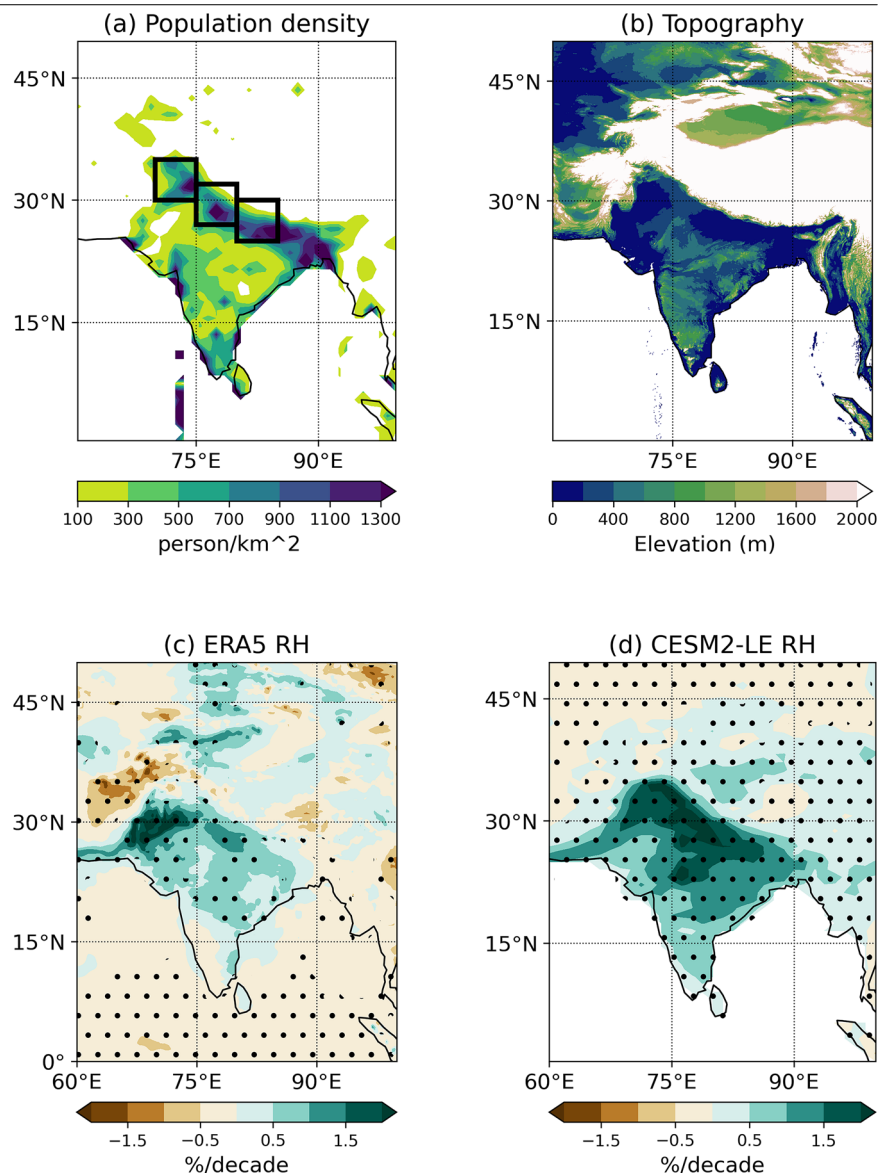
understand the mechanisms driving its variability to mitigate the escalating challenges of climate change.

Figure 1 emphasizes the marked long-term change in RH and its potential impact on the large population in the IGP (black boxes in Fig. 1a) as it compares population density and the distribution of RH for the summer monsoon season (May to September, shown in Fig. 1c, d) from 1961 to 2020¹⁵. The pronounced RH increase closely aligns with zones of dense population, indicating that people in this region are especially exposed to the risks associated with elevated humidity. Notably, the IGP's low-elevation, basin-like geography is favorable to stagnant air conditions (Fig. 1b), which promote moisture retention and aerosol accumulation. Elevated RH compounds the effects of potential humid-heat stress, intensifying health risks, especially respiratory and heat-related illnesses, and discomfort in densely populated areas^{2,10}, which calls for further research on the mechanisms of RH variation. Both the Community Earth System Model version 2 (CESM2) (Fig. 1c) and the fifth generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5) (Fig. 1d) capture this unique RH characteristic of the IGP. The alignment of RH trends with population density in the IGP highlights the need for targeted climate interventions that address the unique vulnerabilities of this densely populated, climate-sensitive region^{9,16}.

Despite substantial research on aerosol and GHG impacts on temperature and precipitation over the IGP^{2,3,9,17,18}, gaps remain in understanding RH trends in this region. First, studies have not fully clarified how different external forcings interact to influence RH over extended periods, such as the distinct roles of aerosols versus GHGs, which collectively raise atmospheric temperatures and consequently affect moisture-holding capacity. Second, while previous studies have documented aerosol impacts on atmospheric thermodynamics and regional precipitation, few have directly examined how these aerosol interactions contribute to RH variability across decadal scales^{3,19}. Lastly, as most previous studies have focused on historical trends, the lack of future RH projections under various emission scenarios limits our understanding of how changes in aerosols and GHGs will shape future RH levels.

This study addresses these gaps by conducting a diagnostic analysis of RH changes in the IGP using both observational datasets and multi-model ensembles. We primarily use Community Earth System Model version 2 Large Ensemble (CESM2-LE) to compare historical RH variability against observations and to isolate the effects of GHGs and aerosols via single-forcing experiments. To enhance robustness, additional simulations from the Community Earth System Model version 1 Large Ensemble (CESM1-LE) and the Coupled Model Intercomparison Project Phase 6 (CMIP6)

Fig. 1 | Population density, topography, and relative humidity (RH) trends over the Indo-Gangetic Plain (IGP). **a** Population density map for 2020 from the Gridded Population of the World, Version 4 (GPW V4.11) ($1^\circ \times 1^\circ$). **b** Topography from NCEI ETOPO 2022. Linear trends of RH for **c** ERA5 and **d** CESM2-LE. CESM2 and ERA5 cover the period from 1961 to 2020. Dotted areas indicate statistically significant trends ($P < 0.05$). The black box in (a) is defined as the IGP in this study.



multi-model ensemble are incorporated to assess scenario-dependent differences in future RH projections.

Data and methods

Datasets

This study examines linear trends in 2 m RH, 2 m specific humidity (Q), and 2 m temperature (T) over the IGP during the summer monsoon season (May to September) from 1961 to 2020, focusing on external forcings that drive these trends. The IGP, represented by the black rectangles in Fig. 1a, serves as the study area. The ERA5 monthly dataset²⁰ is used to describe the long-term changes of atmospheric variables because it is well-suited for humidity analysis over the IGP due to its minimal biases relative to radiosonde observations, as well as its high-resolution spatiotemporal coverage, ensuring robust representation of atmospheric variability and trends²¹.

To cross-validate the findings in ERA5, surface station-based datasets including Climatic Research Unit Time-series version 4.08 (CRU TS4.08)²² and the Hadley Centre Integrated Surface Database Humidity (HadISDH)²³, as well as additional atmospheric reanalysis—the Japanese 55-year reanalysis (JRA-55)²⁴—are employed. Aerosol optical depth (AOD) at 550 nm is obtained from NASA's Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), produced by NASA's Global Modeling and Assimilation Office with the GEOS-5.12.4 system^{25,26}. By leveraging ERA5 as the primary dataset and supplementing it with CRU TS4.08, HadISDH, and JRA-55, this approach ensures robust cross-validation and minimizes biases. A summary of these datasets is provided in Supplementary Table 1. In ERA5, RH and Q were calculated²⁷, as these variables are not directly provided. Details of the calculation are presented in Supplementary information (Supplementary Note 1). Model outputs from the CESM2-LE²⁸, the CESM1-LE²⁹, and selected models from the CMIP6³⁰ were used to complement observational analyses and attribute historical and future changes in atmospheric moisture and temperature over the IGP. A summary of the model simulations is provided in Supplementary Table 2.

CESM2-LE features CAM6 atmospheric physics and the four-mode Modal Aerosol Module (MAM4), which explicitly represents sulfate (SO_4^{2-}), BC, organic carbon, dust, and sea salt aerosols. Aerosol size distribution is represented by four log-normal modes (Aitken, accumulation, coarse, and primary carbon), allowing each species to interact with radiation and cloud processes in a size-resolved manner³¹. These aerosols interact with radiation directly by scattering and absorbing solar radiation, and indirectly by serving as CCN, altering cloud microphysical properties such as droplet number concentration and cloud albedo. The activation of aerosols into cloud droplets is treated using the Abdul-Razzak and Ghan³² parameterization, while cloud microphysics is represented by the MG2 two-moment scheme³³, which simulates both mass and number concentrations of cloud hydrometeors. These processes are fully coupled to radiation schemes, enabling physically consistent simulation of aerosol-cloud-radiation interactions over the IGP.

Historical simulations covering 1961–2020, aligning with observational datasets and future SSP3-7.0 scenario outputs, are analyzed. In addition, single-forcing experiments where only greenhouse gases (GHG-only) or anthropogenic aerosols (AAER-only) vary over time are utilized to isolate the contributions of individual external forcings to changes in RH, T , and Q . This scenario is characterized by simultaneous high emissions of GHGs and aerosols, offering a unique opportunity to examine their intertwined effects on climate^{34,35}.

To extend the analysis across multiple future scenarios and different model structures, CESM1-LE and selected CMIP6 models were also examined. CESM1-LE provides historical simulation and future projections under RCP8.5, along with single-forcing experiments in which either GHGs or aerosols are held constant at 1920 levels (xGHG and xAER experiments). The influence of individual forcings was quantified by differencing the single-forcing experiments from the corresponding all-forcing simulations, isolating the contributions of GHGs and aerosols. Twelve CMIP6 models (listed in Supplementary Table 3) were selected based on the availability of complete simulations covering historical forcings (1850–2014), future SSP

scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5), and single-forcing experiments (hist-GHG and hist-aer). To ensure comparability, the CMIP6 model outputs were regridded to a common $1^\circ \times 1^\circ$ spatial resolution. Future projections were analyzed over the period 2021–2080 to capture mid- to late-twenty-first-century climate changes.

For all model datasets, monthly mean outputs of RH, T , Q , and AOD were extracted and processed to evaluate historical trends and future changes in atmospheric conditions over the IGP. To reduce the effects of internal variability and isolate the externally forced signals, ensemble-mean time series from CESM2-LE, CMIP6, and CESM1-LE simulations are primarily used in the trend and regression analysis. While this ensemble averaging facilitates robust estimation of forced responses, it may under-represent short-term variability compared to single-realization datasets such as ERA5.

Trend analysis and detection

Linear trends in RH, T , and Q were calculated over the historical period (1961–2020) using ordinary least squares regression. For visualization purpose, trend slopes were expressed as per-decade changes. After computing linear trends and corresponding p values at each grid point, a false discovery rate correction was applied³⁶. This post hoc adjustment controls for false positives when evaluating multiple grid points simultaneously. In addition, total changes over the historical period were estimated by multiplying the trend slopes by 60 years to facilitate the interpretation of cumulative changes across the period.

To isolate external forcing effects from natural variability, the signal-to-noise ratio (SNR) method was applied, following the approach described in ref. 37. The SNR method isolates external forcings by comparing the mean trend (signal) and internal variability (noise) across ensemble members. It is calculated as the ratio of the mean trend to the standard deviation of trends, with a higher SNR indicating that the external forcing is more dominant than natural variability. SNR greater than 1.0 indicates that the influence of external forcings exceeds natural variability, allowing for a more precise assessment of the contributions from GHGs and aerosols to RH changes over the IGP.

$$\text{SNR} = \frac{\text{Force}}{\text{Natural}} = \frac{\text{Mean}}{\text{Std}}$$

This study integrates both gridded observational datasets and large ensembles of CESM2. The SNR analysis, applied to the model ensemble, disentangles the impacts of GHGs and aerosols on RH trends. The SNR method further isolates external forcings from natural variability, providing a pivotal framework to understand how distinct drivers shape both historical and projected humidity trends over the climate-sensitive IGP.

Quantitative attribution analysis

To quantify the relative contributions of Q and T to changes in RH, a diagnostic decomposition framework is applied based on the previously established formulation³⁸. In this framework, RH can be approximated as the ratio of specific humidity to saturation specific humidity, and its temporal changes can be decomposed into contributions from specific humidity changes ($\Delta RH(q)$) and temperature-driven saturation specific humidity changes ($\Delta RH(T)$). The saturation specific humidity was calculated assuming a constant surface pressure, taken as the climatological mean over the IGP region during 1961–2020. The detailed derivation of this decomposition is provided in Supplementary Note 2.

Results and discussion

Trends in relative humidity in gridded observational data and model output

Changes in RH are determined by the relative contributions of T and Q . Observed RH exhibits a clear upward trend across the IGP from 1961 to 2020 in Fig. 1c. This increase is primarily driven by a pronounced rise in Q , while T has remained relatively stable during the same period (Fig. 2a, c).

Fig. 2 | Linear trends of T and Q over the IGP from reanalysis and model simulations. a, b T trends from ERA5 and CESM2-LE, respectively, for the period 1961–2020. c, d Q trends from ERA5 and CESM2-LE over the same period. Shading indicates the magnitude of the linear trend ($^{\circ}\text{C}/\text{decade}$ for T , $\text{g}/\text{kg}/\text{decade}$ for Q), and stippling marks regions where the trend is statistically significant ($p < 0.05$).

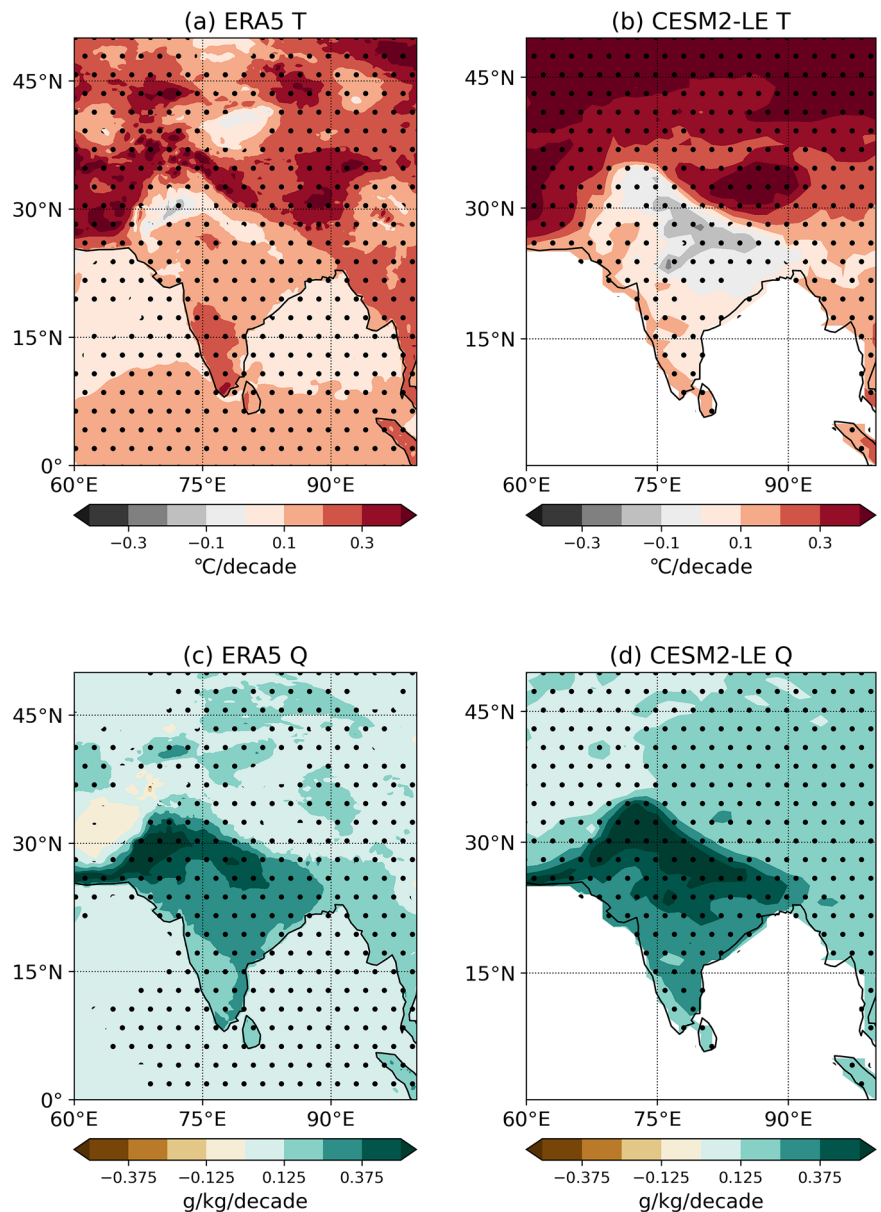


Figure 3 displays the time series and linear trends of RH, T , and Q across the IGP to determine the annual and total changes in these climatic variables. The linear trends indicate total increases of $\sim 4.1 \pm 1.2\%$ in RH, $0.8 \pm 0.1^{\circ}\text{C}$ in T , and $2.0 \pm 0.3 \text{ g}/\text{kg}$ in Q over the IGP over the 60 years (Fig. 3a, c, e), consistent across observational datasets (CRU, HadISDH, and JRA-55 in Supplementary Figs. 1 and 2). Quantitative analysis reveals that the RH increase is predominantly attributable to Q changes (contributing 162.4%), while T changes, which increase saturation vapor pressure, exert a negative effect on RH (Table 1). Despite this suppressive effect from T , the increase in Q is sufficient to offset it and drive a net RH increase, emphasizing the dominant role of Q in governing RH variability over the IGP. In CESM2-LE, the ensemble-mean and spread of ensemble members are shown together to illustrate both the externally forced signal and the spread due to internal variability (Fig. 3b, d, f). The ensemble mean highlights long-term trends, while the gray shading represents variability across ensemble members. The linear trends correspond to total changes of $\sim 10.3 \pm 0.3\%$ in RH, $-0.2 \pm 0.1^{\circ}\text{C}$ in T , and $2.9 \pm 0.1 \text{ g}/\text{kg}$ in Q over the 60 years, demonstrating how the CESM2-LE ensemble mean provides a clearer signal of externally forced changes through averaging out internal variability. Quantitative contribution analysis reveals that the RH increase is primarily driven by Q

changes (contributing 94.8%), while decreasing T reduces the suppressive effect of saturation vapor pressure change (5.2%) (Table 1). The CESM2-LE results confirm that the lack of substantial T changes and the steep rise in Q are the key contributors to the observed RH trends²⁸. Together, observational datasets and CESM2-LE simulations consistently show a significant increase in RH over the IGP, driven primarily by the sharp increase in Q , notwithstanding the greater variability in ERA5.

Despite some divergence in T trends between ERA5 and CESM2-LE, the increasing signals in RH and Q are broadly consistent across datasets. The weaker T trend ($-0.2 \pm 0.07^{\circ}\text{C}$ over 60 years) and lower internal variability in CESM2-LE ($0.8 \pm 1.4^{\circ}\text{C}$ over 60 years) reflect the role of ensemble means in suppressing internal variability and isolating the externally forced signal. Notably, discrepancies in T trends are also apparent across other datasets, including CRU, HadISDH, and JRA-55 (Supplementary Figs. 1 and 2), indicating that part of the model-observation mismatch may stem from observational uncertainties and dataset-specific processing methods. In contrast, the RH and Q trends remain consistent and robust across CESM2-LE, CESM1-LE, and CMIP6 (Supplementary Figs. 3 and 4), affirming that the moistening over the IGP is a reliable signal of externally forced change.

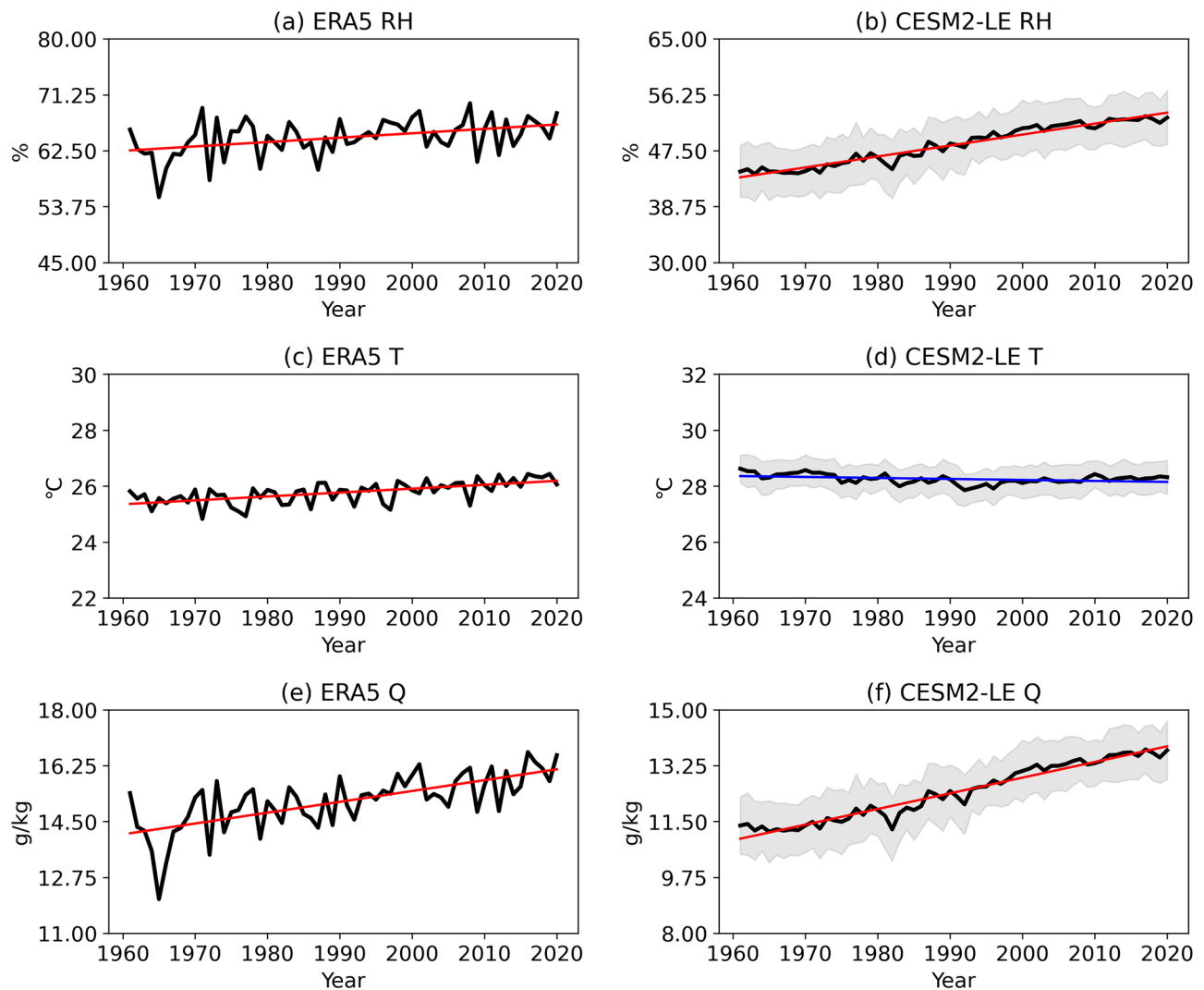


Fig. 3 | Time series of RH, T , and Q over the IGP from ERA5 and CESM2-LE. ERA5 time series of **a** RH, **c** T , and **e** Q from 1961 to 2020. Corresponding CESM2-LE ensemble-mean time series (**b**, **d**, **f**) with ± 1 standard deviation (shaded area). Black

lines represent annual means. Trend lines are shown for 1961–2020, with solid lines indicating statistical significance ($P < 0.05$); red lines represent positive (increasing) trends, and blue lines represent negative (decreasing) trends.

Table 1 | Summary of T and Q contributions to RH trend changes over the IGP, estimated using a physical approximation framework

Datasets	RH trend approximated (%/60 years)	T -based RH change (%/60 years)	Q -based RH change (%/60 years)	T contribution (%)	Q contribution (%)
ERA5	5.3	−3.4	8.7	−62.4	162.4
CESM2-LE	12.1	0.6	11.5	5.2	94.8

RH trend (approximated) represents the sum of RH changes attributable to T and Q . Contributions are represented as both RH-equivalent changes (%/60 years) and their relative shares (%).

T and Q play distinct yet interconnected roles in shaping RH trends. Rising atmospheric moisture, particularly in the troposphere, acts as a key driver of RH trends over India by amplifying positive feedback mechanisms on regional T and climate forcing⁹. These positive feedback mechanisms include the increased water vapor content in the atmosphere, which enhances greenhouse warming by trapping more outgoing longwave radiation, thereby further elevating T . Elevated T , in turn, increases the atmosphere's moisture-holding capacity, leading to further increases in Q and amplifying RH. Q often dominates thermodynamic changes, substantially influencing regional RH variability¹⁶. While T trends are relatively weak, their role in modulating RH cannot be overlooked. By influencing saturation vapor pressure, T interacts with increasing Q to enhance RH.

Irrigation during the pre-monsoon season in the IGP contributes to modest RH increases, while aerosol-induced cooling stabilizes T , enabling further moistening of the atmosphere. This delicate balance between T stability and rising Q underscores the intricate dynamics that drive RH trends in this region³⁹.

Findings from this study underscore the critical need to understand RH variability in the IGP, where high population density and climate sensitivity amplify its impacts. Our results highlight a substantial increase in RH, driven by a moderate change in T and a distinct increase in Q , contributing to health risks, agricultural challenges, and water resource vulnerabilities in this densely populated region. These findings align with prior studies showing RH's pivotal role in shaping regional climate and socioeconomic

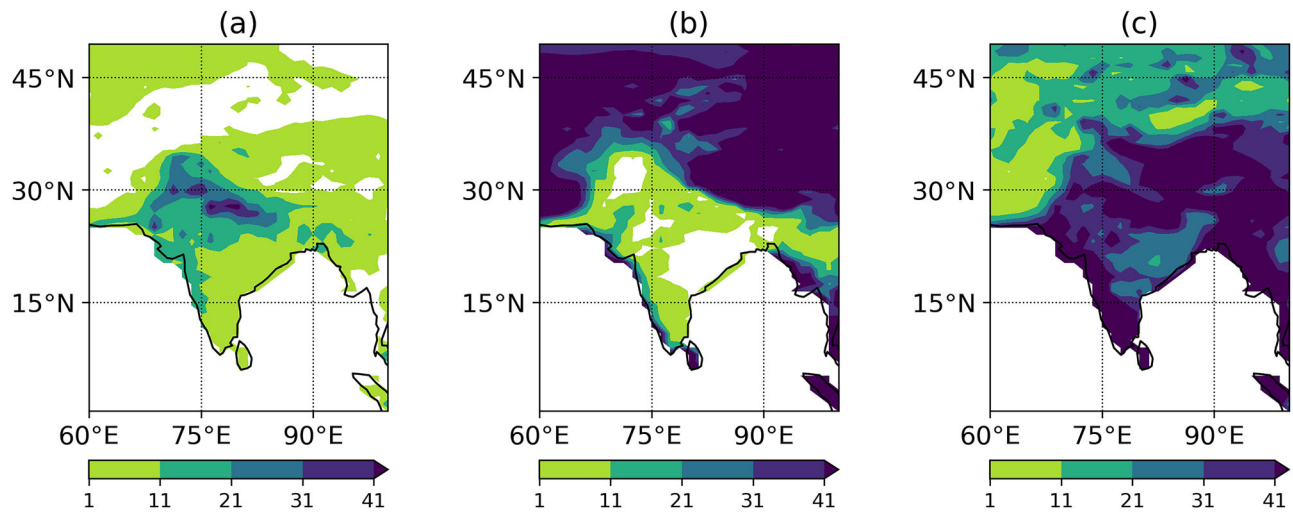


Fig. 4 | Spatial distribution of signal-to-noise ratio (SNR) of the trends during 1961–2020 in RH, T , and Q from CESM2-LE. SNR values for **a** RH, **b** T , and **c** Q are displayed, and the mean SNR over the IGP is 22.6 for RH, 7.5 for T , and 42.8 for Q , respectively.

outcomes across the IGP^{2,16,39}, while also providing pivotal insights into the quantification of RH trends and the underlying drivers of these changes. This underscores the urgency of targeted research and adaptation strategies to mitigate RH-related risks in the IGP.

Possible external forcings contributing to the RH increase

As shown in the multi-source climate data, RH trends over the IGP are significantly influenced by internal variability. To examine the long-term effects of external forcings, Fig. 4 shows the SNR for RH, T , and Q trends, where values in the figure caption confirm that external forcings, rather than internal variability, are the primary drivers of RH increases. An SNR greater than 1 indicates that the trend due to external forcings exceeds internal variability, and the pattern in Fig. 4 suggests the influence of external forcings, such as GHGs and aerosols, in shaping RH changes over time.

To further diagnose the RH trend, Fig. 5 isolates the effects of GHGs and aerosols on RH, T , and Q trends over the IGP using CESM2-LE single-forcing simulations. In the GHG-only simulations, RH has decreased across most of India, including the IGP, because of rising T , which increases evaporation and moderates RH despite the increase in Q (Fig. 5a–c). In contrast, the aerosol-only simulations show a marked increase in RH, especially over the IGP, driven by a decrease in T and an increase in Q due to aerosol cooling effects (Fig. 5d–f). Together, these findings highlight how GHGs and aerosols individually contribute to RH trends by influencing T and Q dynamics in opposite ways.

Observational datasets and CESM2-LE simulations were examined to validate these findings. Supplementary Figs. 5 and 6 show AOD trends from reanalysis (MERRA-2) (1980–2020) and CESM2-LE (1961–2020) data, with the trend map drawn only for the overlapping period. Both datasets indicate a notable increase in AOD over the IGP, reflecting high aerosol loading. This sustained rise in AOD exerts a cooling effect on surface temperatures, which helps stabilize T , allowing Q to rise and thus increasing RH. Although ERA5 shows greater variability, the overall increasing trend in aerosol concentration is consistent across both datasets over their respective periods. To further assess the radiative effect due to different aerosol types, the optical depth of absorbing aerosols, including BC over the IGP, is examined (Supplementary Fig. 7). As discussed earlier, aerosols in CESM2 can do scattering and absorbing solar radiation. Although absorbing AOD exhibits a modest increase, it is less than 10% of the total AOD. This suggests that scattering aerosols dominate the regional aerosol burden, resulting in a net cooling effect on surface temperature in CESM2-LE.

We also note that each simulation in Fig. 5 and Supplementary Fig. 8 demonstrates a unique pattern in RH trends influenced by GHGs and

aerosols. In the GHG-only simulations, GHGs lead to a warming effect on T (Fig. 5b) due to global warming, which increases the atmosphere's moisture-holding capacity, resulting in a rise in Q (Fig. 5c) as the atmosphere can retain more water vapor. However, this increase in T also enhances evaporation rates, which counterbalances the effect of increased Q and ultimately results in a decrease in RH (Fig. 5a). This dynamic, where GHG-driven warming boosts atmospheric moisture while also promoting evaporation that moderates RH, has been observed in studies focused on South Asian climate impacts^{9,40}.

In contrast, the aerosol-only simulations show that aerosols exert a cooling effect on T by reflecting solar radiation, especially over the IGP (Fig. 5e). This cooling stabilizes the lower atmosphere, limiting evaporation and allowing Q to accumulate near the surface (Fig. 5f), thus leading to a marked increase in RH (Fig. 5d). Research on aerosol impacts in monsoon regions has shown that such cooling effects reduce surface temperatures, thereby stabilizing the atmosphere and supporting near-surface moisture retention^{3,41}. Additionally, GHGs can enhance atmospheric stability, which traps more aerosols in the lower atmosphere, creating a feedback process that further increases aerosol loading⁴². The stabilization of the lower atmosphere by aerosols enhances moisture retention over land, as reduced temperature-driven moisture demand leads to elevated Q levels⁴³. This effect is further supported by findings that high aerosol loading in the IGP can retain moisture near the surface, especially under monsoon conditions, contributing to increased Q ¹⁸. These findings spotlight the need for climate policies that account for both GHG and aerosol impacts, as their contrasting effects on T and Q strongly influence RH trends and potential heat stress in the IGP. This divergent influence of GHGs and aerosols on RH is consistently observed across other model ensembles, including CESM1-LE and CMIP6 single-forcing experiments (see Supplementary Figs. 9 and 10).

Future projections in CESM2-LE

Figure 6 presents box plots of linear trends in RH, T , and Q over the IGP during the historical period (1961–2020), based on CESM2-LE (SSP3-7.0), CESM1-LE (RCP8.5), and CMIP6 multi-model ensembles (SSP2-4.5). For CMIP6, all forcing is based on SSP2-4.5 to ensure consistency with the available single-forcing experiments. This comparison evaluates the consistency of modeled trends across different model generations and scenario configurations. Each panel shows the trend under all forcing (ALL), aerosol-only, and GHG-only experiments. The consistent sign of RH increase and its attribution to Q increase and/or T suppression is evident across models in all aerosol runs, supporting the robustness of the thermodynamic drivers discussed earlier. Triangles mark statistically significant ensemble-mean trends ($p < 0.05$), indicating that despite structural differences among

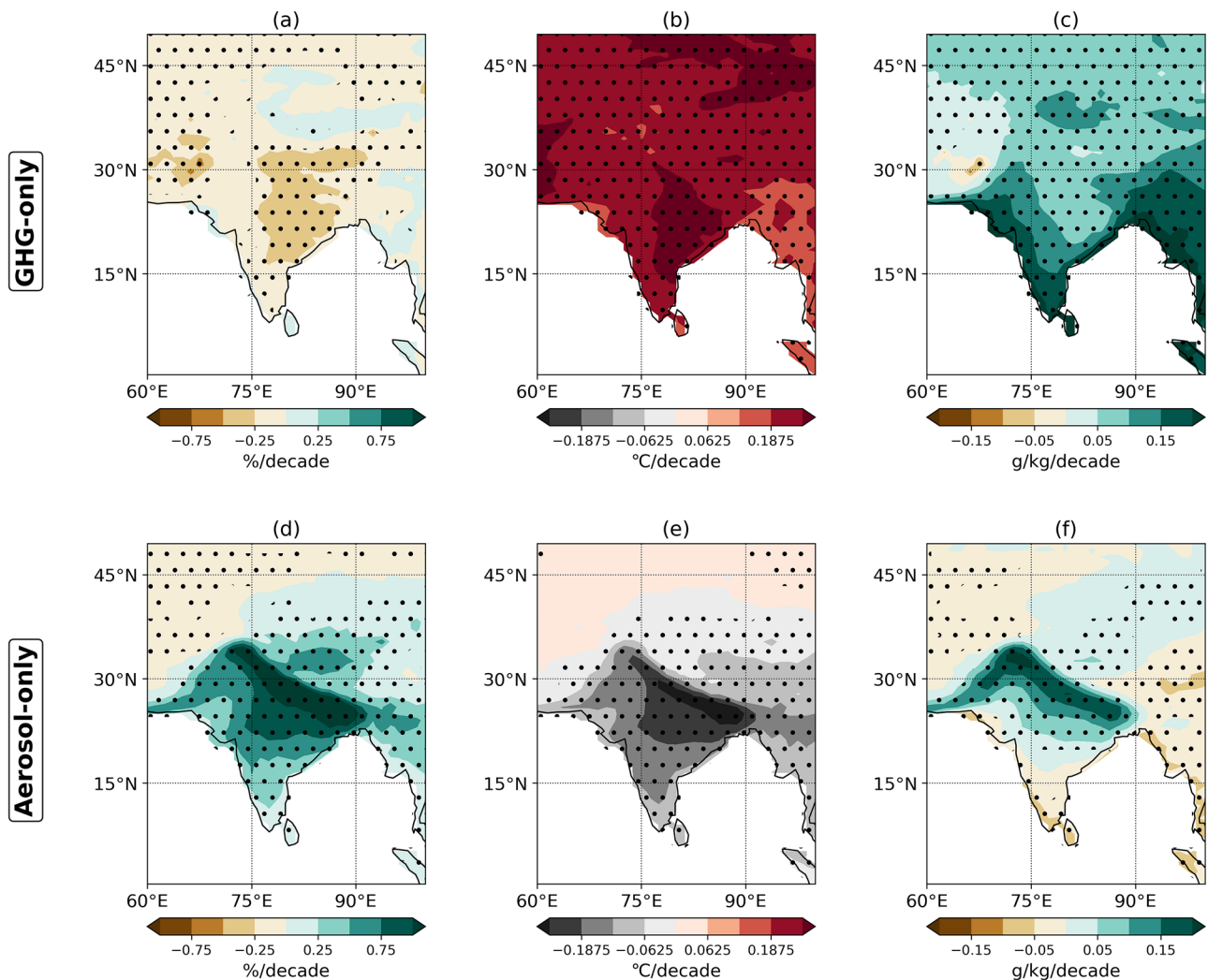


Fig. 5 | Linear trends of RH, T , and Q for the CESM2-LE single-forcing simulation over 1961–2020. a–c Spatial patterns of linear trends in RH, T , and Q from GHG-only simulations. **d–f** Corresponding trends from aerosol-only simulation. Shading indicates the magnitude of the linear trend (%/decade for RH, °C/decade for T , g/kg/decade for Q), and stippling marks regions where the trend is statistically significant ($p < 0.05$).

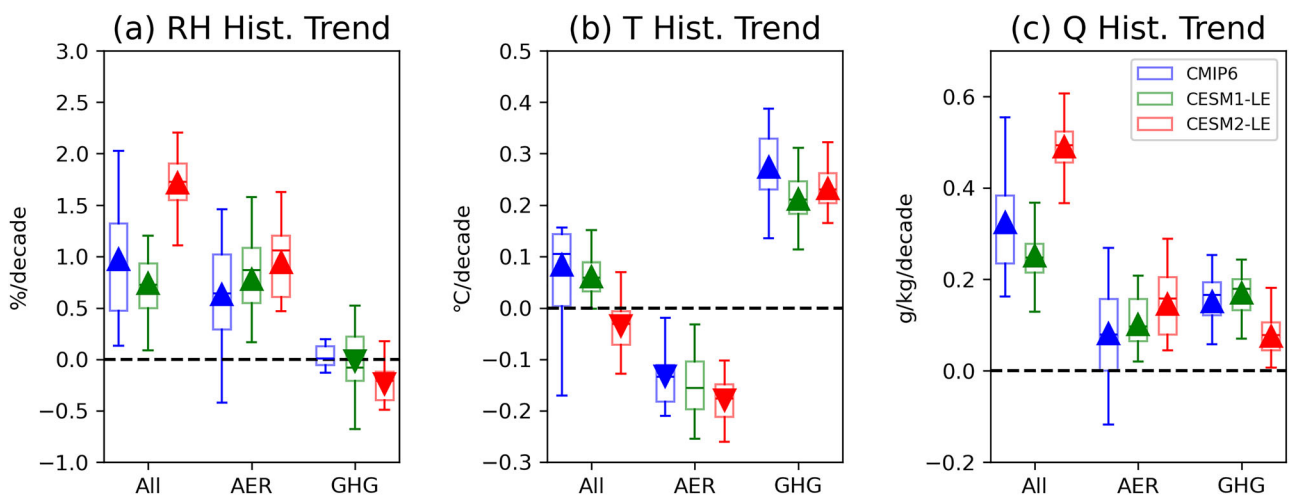


Fig. 6 | Comparison of RH, T , and Q trends across model ensembles and forcings (1961–2020). Box plots of linear trends in a RH, b T , and c Q under different forcing scenarios over the IGP, derived from CMIP6 multi-model ensembles (SSP2-4.5, blue), CESM1-LE (RCP8.5, green), and CESM2-LE (SSP3-7.0, red) for the historical period (1961–2020). Each box represents the interquartile range, the horizontal line indicates the median, and whiskers denote the ensemble spread. Triangles mark ensemble-mean trends when statistically significant ($p < 0.05$).

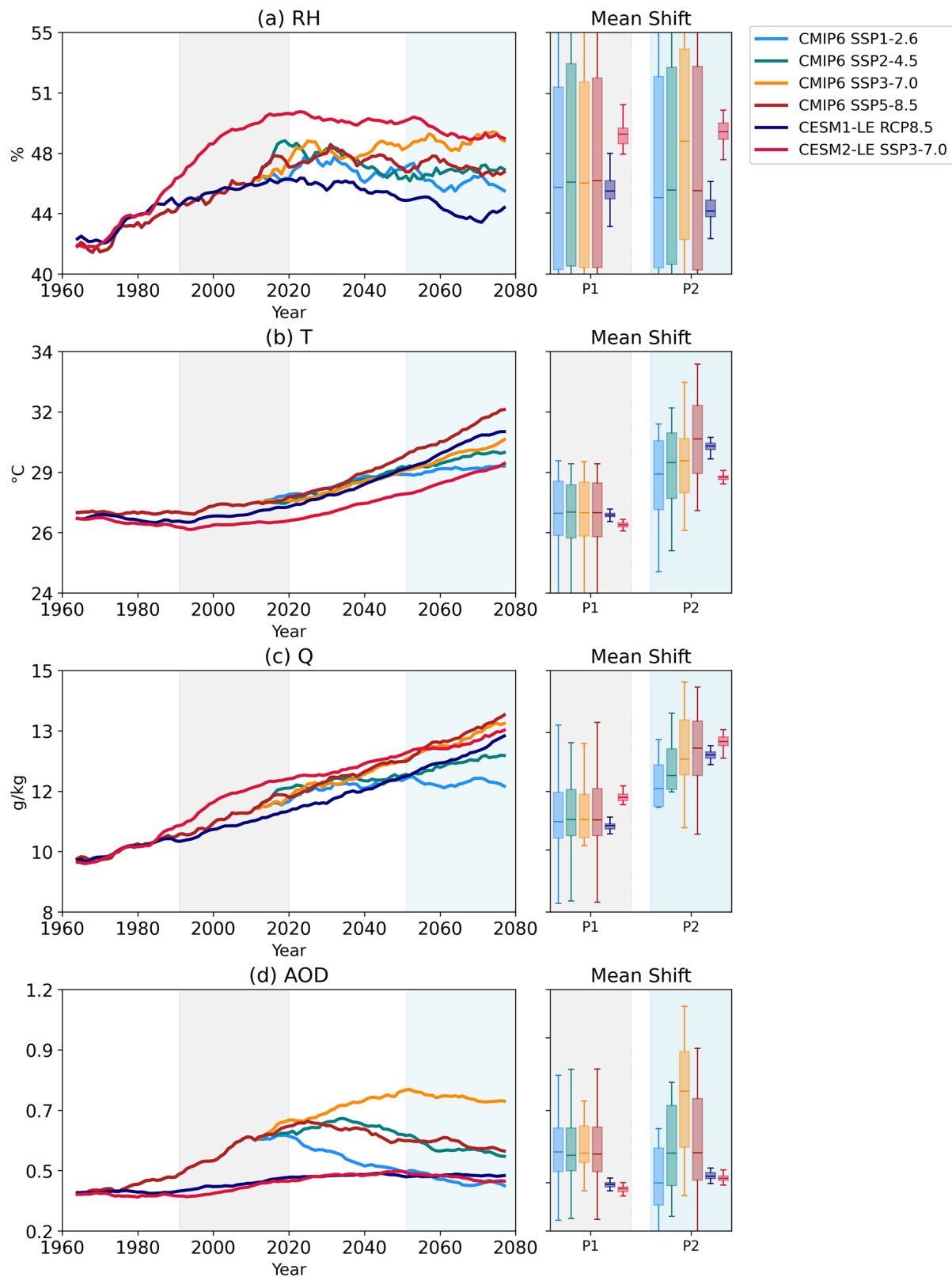


Fig. 7 | Projected changes in RH, T, Q, and AOD under different SSP scenarios from CMIP6, CESM1-LE, and CESM2-LE. Time-series and mean shift analysis of **a** RH, **b** T, **c** Q, and **d** AOD over the IGP region, smoothed using a 7-year running average (left). Colored lines represent multi-model means for CMIP6 scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5), CESM1-LE (RCP8.5), and CESM2-LE (SSP3-7.0). The shaded areas in the time series plots indicate the two periods used for comparison: P1 (1991–2020, gray) and P2 (2051–2080, blue). The right panels show box and whisker plots for P1 and P2. Box plots show the distribution of ensemble

means in each period, with boxes indicating the interquartile range and whiskers showing the full spread. Median values are shown as horizontal lines within each box. To eliminate baseline offsets between model ensembles, CESM1-LE and CESM2-LE time series were adjusted to match the 1961 CMIP6 multi-model mean. Note that this adjustment is based on the single-year value, not a smoothed average, to maintain consistency in baseline alignment across scenarios. See Supplementary Table 4 for the exact adjustments applied to CESM1-LE and CESM2-LE to align their baseline values with the CMIP6 ensembles in 1961.

models, the key signal, Q-driven moistening and the cooling effect of aerosols, are robust features across simulations. These consistencies lend credibility to the model-based projection of RH trends under future scenarios.

Next, Fig. 7 illustrates the temporal evolution and decadal mean shifts of RH, T , Q , and AOD under various future scenarios. CESM1-LE and CESM2-LE time series were baseline-adjusted to the CMIP6 multi-model mean in 1961 to enable consistent inter-model comparisons. Time series plots (left) show ensemble-mean trajectories from CMIP6 (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5), CESM1-LE (RCP8.5), and CESM2-LE (SSP3-7.0), while box plots (right) summarize changes between the historical (P1: 1991–2020) and future (P2: 2051–2080) periods. While CMIP6 models exhibit substantial inter-model spread, particularly in RH projections, the overall trajectory is not simply monotonic. Rather, RH responses over the IGP will be strongly shaped by the interplay between aerosol decline and GHG-induced warming, with a critical turning point occurring around the mid-twenty-first century. High-emission scenarios such as SSP3-7.0 and SSP5-8.5 exhibit a sharp increase in RH during the historical period, followed by a gradual decline after reaching a tipping point around the 2040s. This transition corresponds to a shift in dominance: aerosol concentrations increase through the late twentieth century, but begin to decline between 2020 and 2050, reducing their surface-cooling effect and allowing GHG-driven warming to take over. As T increases, outpacing the rise in Q , RH begins to decline despite continued moistening of the atmosphere.

Among the high-emission scenarios, SSP5-8.5 shows an earlier and more rapid decline in RH than SSP3-7.0, due to stronger air pollution controls that drive a faster reduction in AOD³⁴. In contrast, SSP3-7.0 maintains elevated aerosol levels for a longer period, delaying the RH decline despite sustained GHG emissions.

By contrast, low-emission scenarios such as SSP1-2.6 and SSP2-4.5 are characterized by low and slowly declining aerosol levels, resulting in more stable RH trajectories. In these scenarios, the relatively moderate increase in T is largely balanced by continued moistening, supporting a stable or slightly increasing RH trend throughout the twenty-first century. This scenario-dependent tipping behavior in RH trends aligns with the previous finding³⁴, who identified mid-twenty-first century as a critical transition period when the influence of aerosols rapidly weakens and GHG-induced warming becomes the dominant driver of regional climate responses.

These projections emphasize the evolving roles of aerosols and GHGs in RH trends as discussed in the section “Possible external forcings contributing to the RH increase.” Aerosols play a critical role in stabilizing the lower troposphere by absorbing and scattering shortwave radiation, inducing pronounced surface cooling⁴⁴. This cooling effect limits surface evaporation, suppresses monsoon circulation, and allows RH to remain elevated even with rising specific humidity. In contrast, GHGs enhance atmospheric warming and moisture content, exerting opposing effects on hydrological patterns. Historically, aerosols have provided surface cooling, which has supported higher RH by allowing Q to increase without substantial T increases^{3,39,45}. As aerosol concentrations decrease, GHG-driven warming increasingly dominates, potentially leading to RH declines.

Conclusion

This study investigates the trends and drivers of RH in the IGP using CESM2-LE simulations validated with various observation-based datasets, with a particular focus on the roles played by two climate forcings, GHGs and aerosols. Our results indicate that RH has historically increased, driven by rising Q and relatively stable T , supported by aerosol-induced surface cooling^{3,39}. Across the SSP scenarios, future RH trends over the IGP are shaped by the evolving balance between aerosol-induced cooling and GHG-driven warming. During the historical period, elevated RH has been supported by increasing Q and relatively stable T , largely due to aerosol-induced surface cooling⁴⁴. However, our analysis reveals a scenario-dependent turning point around the mid-twenty-first century. In high-emission scenarios such as SSP3-7.0 and SSP5-8.5, RH initially continues to rise but begins to decline as aerosol concentrations sharply decrease and GHG-

induced warming accelerates. Notably, the RH decline occurs early in SSP5-8.5, where stronger air pollution controls result in a more rapid loss of aerosol cooling. In contrast, low-emission scenarios (SSP1-2.6 and SSP2-4.5) maintain more stable RH trajectories, as moderate warming is offset by steady moistening and slower decline. These results confirm that RH is governed by the interplay of two opposing thermodynamic drivers: aerosols, which suppress warming and allow RH to remain elevated, and GHGs, which increase both T and moisture but may reduce RH if warming exceeds moistening.

The implications of this study are meaningful for climate policy in the IGP. As aerosol emissions decline, GHG-dominated warming may exacerbate RH-related heat stress, posing risks to public health in this densely populated region. These results highlight the need for balanced mitigation strategies that target both aerosols and GHGs to manage RH trends and associated climate risks effectively. By controlling aerosol emissions, future RH changes might be moderated, alleviating some of the anticipated heat stress impacts as GHGs continue to drive regional warming^{16,18}. This study emphasizes the urgent need for integrated climate policies that consider the dual impacts of aerosols and GHGs, ensuring sustainable climate resilience for vulnerable regions like the IGP.

Despite these insights, our study has limitations that suggest directions for future research. Projections are based on CESM2-LE data, which, while comprehensive, may not fully capture local-scale interactions in the IGP. High-resolution regional climate models would help refine these projections and enhance understanding of microphysical processes, particularly the interactions between aerosols, GHGs, and humidity¹⁰. Additionally, more research is needed to assess how land-use changes and other regional factors—such as irrigation practices, urbanization, and vegetation changes—may interact with aerosol and GHG influences to shape RH trends in the IGP.

Data availability

All the datasets adopted in this study can be accessed online via the following URLs. ERA5: <https://cds.climate.copernicus.eu/>. HadISDH: <https://www.metoffice.gov.uk/hadobs/hadisdh/>. JRA-55: https://jra.kishou.go.jp/JRA-55/index_en.html. MERRA-2: <https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>. CMIP6: <https://esgf-node.llnl.gov/search/cmip6/>. CESM1-LE: <http://cesm.ucar.edu/projects/community-projects/LENS/>. CESM2-LE: <https://www.cesm.ucar.edu/community-projects/lens2>. GPW 4.11: <https://sedac.ciesin.columbia.edu/data/collection/gpw-v4>. NCEI ETOPO 2022: <https://www.ncei.noaa.gov/products/etopo-global-relief-model>. The source data used to generate all figures in this study are available from Zenodo at <https://doi.org/10.5281/zenodo.15637148>.

Code availability

Custom Python scripts used for data processing and figure generation are available from the corresponding author upon reasonable request.

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Author contributions

J.P. conceived and designed the study, downloaded and processed datasets, performed the analysis, and wrote the manuscript. S.-Y.W. contributed to the development of the research idea, assisted with manuscript preparation, and revised the manuscript. J.-H.Y. supervised, revised the manuscript, and coordinated the overall project as the corresponding author. H.K., J.H.J., N.U., and S.M. discussed the results and provided feedback. All authors approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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