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Forecasts of fog events in northern India dramatically improve when weather prediction models include irrigation effects

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Dense wintertime fog regularly impacts Delhi, severely affecting road and rail transport, aviation and human health. Recent decades have seen an unexplained increase in fog events over northern India, coincident with a steep rise in wintertime irrigation associated with the introduction of double-cropping. Accurate fog forecasting is challenging due to a high sensitivity to numerous processes across many scales, and uncertainties in representing some of these in state-of-the-art numerical weather prediction models. Here we show fog event simulations over northern India with and without irrigation, revealing that irrigation counteracts a common model dry bias, dramatically improving the simulation of fog. Evaluation against satellite products and surface measurements reveals a better spatial extent and temporal evolution of the simulated fog events. Increased use of irrigation over northern India in winter provides a plausible explanation for the observed upward trend in fog events, highlighting the critical need for optimisation of irrigation practices.

The Indo-Gangetic plains (IGP) have the highest population density and growth rate in India. Fog formation in the IGP is very common during wintertime – every other day in Delhi – adversely affecting society and the economy through transport and health impacts[1–4]. Numerous studies have examined fog prediction over the IGP region using a variety of techniques including statistical methods[5], numerical weather prediction (NWP)[6–10] and diagnostic approaches[11,12]. However, reliably accurate operational forecasts of fog events remain elusive.

The majority of fog events over the IGP of northern India are seen in wintertime. A 71% increase in the number of fog days in winter has been observed in Delhi over the last three decades, from 38 fog days in the 1980s to 65 in recent years[13,14], the cause of which is unclear. Located within the IGP, the Indian capital city Delhi is the second most populated (22.7 million) and fastest-growing megacity in the world[15]. Delhi has been suffering severely from deteriorated air quality, with $PM_{2.5}$ concentrations often far exceeding the safe limits set by the World Health Organisation as well as the national ambient air quality standards of India[16,17], and this is associated with low visibility during wintertime[13,14,18,19]. Aerosols also play a role as cloud condensation nuclei and high aerosol concentrations can alter the fog's microphysical and radiative properties. However, while aerosol induced haze is undoubtedly a common phenomenon in Delhi (and in the IGP in general), air pollution alone does not fully explain the observed trends in fog frequency[20]. An important alternative driver may be the rapid parallel increase in observed low-level humidity[21], as evidenced for example at Safdarjung airport in Delhi where the December and January average dewpoint temperature increased from 7 °C in 1980 to 10.5 °C in 2019[22]. We hypothesise that this dramatic increase in wintertime humidity is linked to the increased use of irrigation for agriculture in winter in the IGP region.

Accurate prediction of fog using NWP models is a major challenge due to the complex feedbacks between many processes involving the land surface, boundary-layer mixing, cloud microphysics and cloud-aerosol interactions. These small-scale processes are parameterised in NWP and fog

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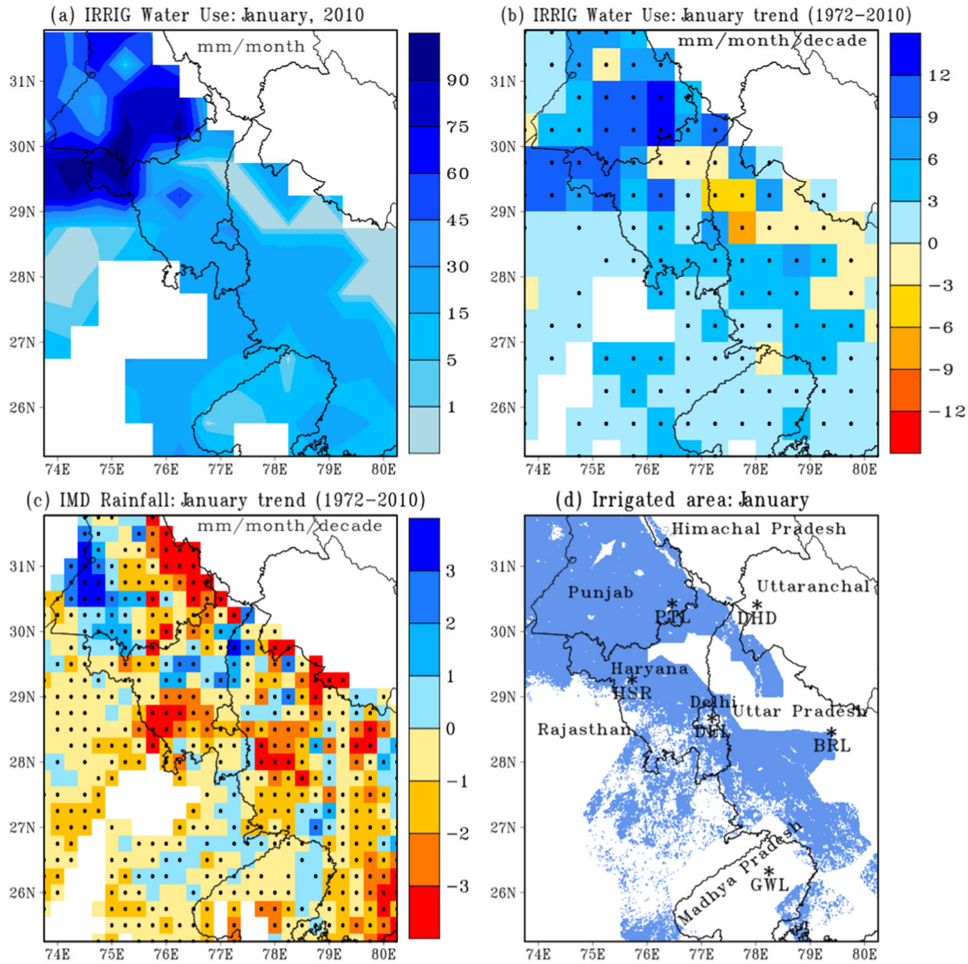

Fig. 1 | Irrigation and rainfall information for the IGP. a Irrigation water use (mm/month) in January 2010. January spatial trends of irrigation water use (**b**) and rainfall (**c**) (mm/month/decade) for the period 1972–2010; black dots denote the linear trend is significant at the 95% level using a Student's *t* test. **a**–**c** are masked (white) where the surface elevation is 400 m or more above sea level. **d** January 2016 irrigated area used in the MetUM sensitivity tests; states and meteorological (SYNOP) stations are shown in black.

simulation is highly sensitive to these physical parameterisations[8,9,23–26]. In particular, the land surface and boundary-layer schemes are critical for accurately simulating fog onset[24,27]; while the microphysics scheme is pivotal for simulating fog development and dissipation[23,24,28–30]. Soil moisture is a key surface property. Higher soil moisture leads to greater evaporation and a moister boundary layer; while it also affects soil thermal conductivity, surface temperature and surface heat fluxes, all impacting on fog development[25,27,31] and dissipation[32].

Multiple NWP models have systematic near-surface dry biases over the IGP during winter[11,33,34]. For example, there were dry biases over Delhi in an operational version of the Weather Research and Forecasting (WRF) model, resulting in missed fog events in the winters of 2016/17 and 2017/18[33]. This humidity bias was also present on days when fog events were simulated and contributed to errors in the onset time. Similarly, in the Met Office Unified Model (MetUM), dry biases are consistently present in wintertime simulations for Delhi on both clear and foggy days[34]. An initial soil moisture model bias could theoretically be corrected through improved data assimilation of satellite-derived soil moisture[35,36]. Such a correction could be achieved by taking a fraction of the satellite derived soil moisture anomaly from the monthly climatology and adding it to the model climatology[37]. However, model climatologies are currently too dry in the IGP, as they don't include irrigation, and thus even after adjustment biases remain[35]. We hypothesise that the cause of this dry bias is a lack of irrigation being represented in these NWP models.

Since the 1960s, India has seen the impact of the Green Revolution[38] partly through the adoption of modern crop varieties leading to enhanced yields[39,40]. The production of foodgrains, such as rice, wheat, coarse cereals and pulses, increased at an average rate of 2.5% per year between 1950 and 2007. Foodgrain production reached a record of 285.2 million tons in 2018-19 (Supplementary Fig. 1); with India now the second largest producer of wheat worldwide[41]. This increase in agricultural production has not come from any major change in production area (Supplementary Fig. 1), but instead from the widespread adoption of a double-cropping system[42], adding a winter season (Rabi; Nov-Feb) of primarily wheat to the traditional summer season (Kharif; Jun-Sep) of primarily rice. Winter is a very dry season in the northern plains of India[43] (Supplementary Fig. 2d, e, f), so this has required a major expansion in irrigation (Fig. 1a, b), using groundwater and water canals, increasing from less than 20% of cropland in the 1960s to more than 45% in recent years[44] (Supplementary Fig. 1). Zaveri and Lobell[41] estimate that national Indian wheat yields in the 2000s were 13% higher than they would have been without this expansion in irrigation. Since the 1970s water use has increased in the winter months by 10 mm/month/decade or more in the north-western IGP (Fig. 1b shows January; Supplementary Fig. 2g, h, i show each winter month).

The recent growth in extensive irrigation over the IGP has resulted in important changes in surface soil moisture, with noticeable increases over the north-western region[45]. Over India, additional soil moisture has been linked to an increase in evaporation (latent heat flux) and decreases in sensible heat fluxes and surface temperature, with consequent impacts on heat[46], moist heat stress[47,48] and precipitation[49–53]. As an example, Barton et al.[54]. found that a dry and warm bias exists in the Indian operational model during the monsoon period over the IGP which is collocated with the areas equipped for irrigation, concluding that an irrigation scheme is urgently needed. Nevertheless, all the above studies only consider the summer season. Wey et al.[55] discussed the effects of wintertime irrigation in Northern India on monsoonal circulation. However, to the best of our knowledge there have been no previous assessments of the impacts of winter irrigation in India on fog.

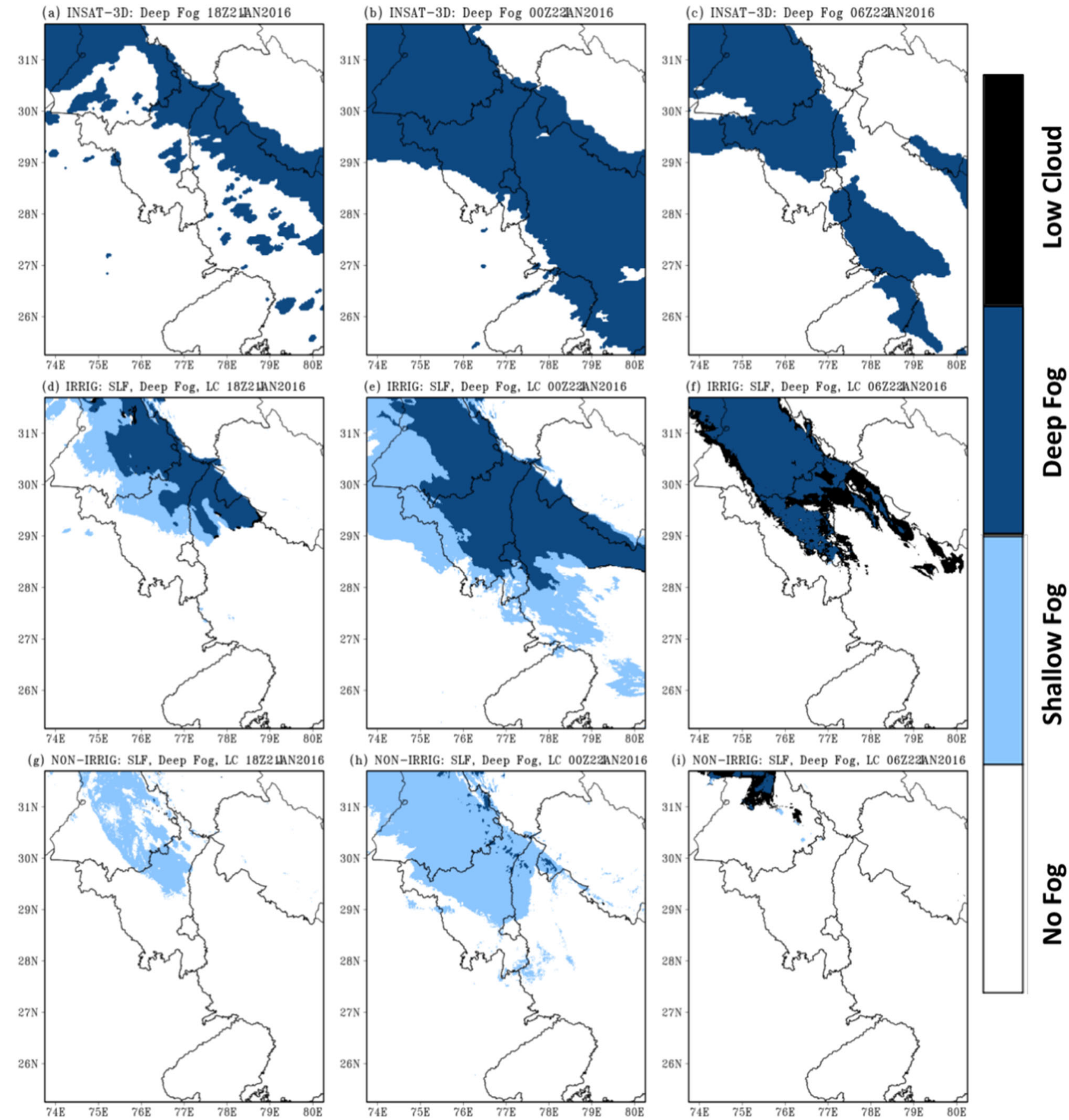

Fig. 2 | Spatial distribution of fog during the first fog event. Panels show shallow fog, deep fog and low cloud at the development stage 18Z 21 January (left), mature stage 00Z 22 January (centre) and dissipation stage 06Z 22 January 2016. The rows show observations from INSAT-3D (**a**–**c**); then irrigated (**d**–**f**) and non-irrigated (**g**–**i**) model output.

Given the dramatic increases in wintertime irrigation and fog frequency in northern India over recent decades, we hypothesise that irrigation practices in winter have decisively contributed to the observed increased fog frequency and thus need to be accounted for in NWP models in a realistic way. To examine this hypothesis we present, for the first time, simulations of fog events with and without irrigation represented in a state-of-the-art NWP model (the Met Office Unified Model, MetUM) in its configuration for the IGP region (the Delhi Research Unified Model, DRUM) and compare against observations. Irrigation is represented realistically - with an appropriate amount of water added to the model's soil moisture in areas that we know are irrigated in the winter season (Fig. 1d); experimental details and data sets are described in the Methods section.

Results

Observed trends

To demonstrate the increasing importance of irrigation, we examine the trends in irrigation and rainfall over the IGP in January over the 1972–2010 period (Fig. 1b, c). There is a large and significant positive trend in irrigation water use over the north-west region, especially over central and eastern Punjab, northern Rajasthan, and western Haryana (Fig. 1b). This area represents a heavily irrigated region for the Rabi crop season during winter (Fig. 1a and Supplementary Fig. 2a–c). In contrast, the magnitudes of winter season rainfall (Supplementary Fig. 2d–f) and rainfall trends (Fig. 1c) are relatively small for this dry season.

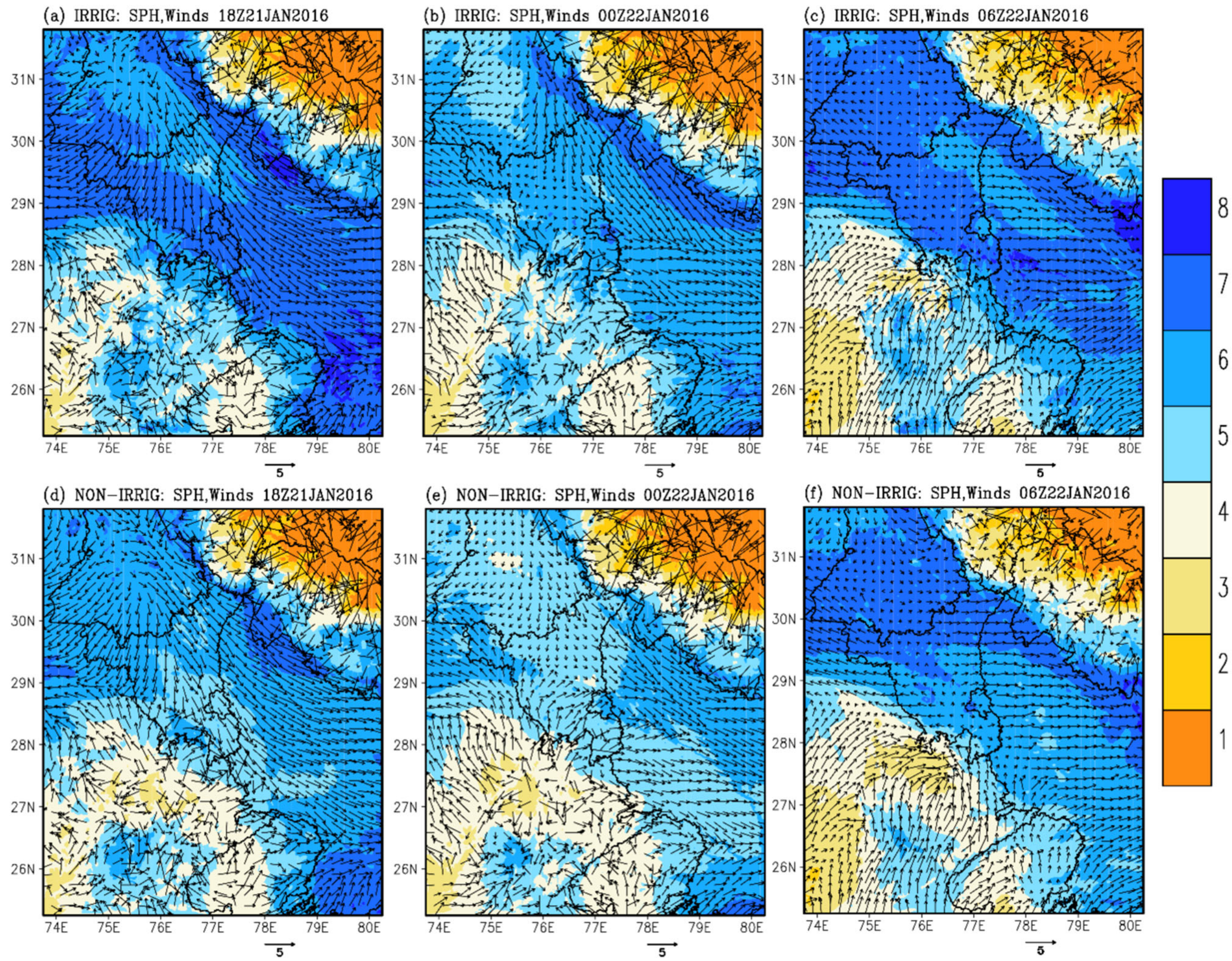

Fig. 3 | Spatial distribution of near-surface moisture and winds. Panels show 5 m specific humidity (g/kg, shaded) and 10 m winds (m/s, vectors) from the irrigated (**a**–**c**) and non-irrigated (**d**–**f**) model experiments at 18Z 21 January, and 00Z, and 06Z on 22nd January 2016 over the IGP region. The time steps represent the developing (18Z), mature (00Z) and dissipation stages (06Z) as Fig. 2. The scale arrow is 5 m/s.

Model results

To investigate the impact of irrigation effects on fog formation over the Delhi region, a comparison of model sensitivity experiments is presented. Figure 2 shows the spatial distribution of deep fog obtained from the INSAT-3D satellite fog/low cloud product and from irrigated and non-irrigated model simulations respectively for the first fog event: at 18Z 21st January 2016 (development stage), and 00Z (mature stage) and 06Z (dissipation stage) on 22nd January 2016. Observations indicate widespread optically thick (deep) fog occurrence during the development (Fig. 2a) and mature stages (Fig. 2b), with the fog beginning to dissipate in the south-east during the dissipation stage (Fig. 2c). The irrigated simulation captures the deep fog distribution well (Fig. 2d, e); in contrast to the non-irrigated simulation which only simulates less widespread shallow fog which dissipates too early (Fig. 2g–i). The irrigated simulation is successful in simulating the occurrence, extent and depth of the fog over the central and north-western parts of the domain, but not over the south-eastern region of the IGP.

To examine how irrigation-effects are manifest, we analyse maps of specific humidity and wind for the same stages of this fog event to ascertain the impact of moisture advection from irrigated to non-irrigated regions (Fig. 3). The near-surface atmosphere is more humid, by typically 1 g/kg, across the majority of the IGP region. The winds are generally light (<5 m/s) and north-westerly over Uttar Pradesh, Punjab, Haryana, and Delhi, (typical at this time of year as a result of the subtropical westerly jet over northern India and channelling by the Himalayas to the north) so advect moisture from areas of irrigation in the NW of the domain (see Fig. 1d) over the partly non-irrigated region of Uttar Pradesh, resulting in an increase in humidity there too. The increase in specific humidity in the irrigated compared to non-irrigated simulation is evident in all fog stages (development, mature and dissipation); i.e., after 18, 24 and 30 h of simulation time. The increased near-surface humidity is driven by increased latent heat flux over the irrigated area (not shown) resulting from the increase in available soil moisture to evaporate. The increase in latent heat flux is balanced by a decrease in the sensible heat flux compared to simulations without irrigation. The marked increase in moisture downstream of the irrigated area demonstrates a clear non-local impact, illustrating that non-irrigated urban areas such as Delhi can be affected by the advection of additional moisture from irrigated areas.

We have also compared model output against WiFEX (Winter Fog Experiment) measurements recorded at IGI-Airport, Delhi[14,56](Fig. 4). The irrigated simulation captures the observed diurnal changes in visibility, relative humidity, and downwelling long-wave (LWD) radiation considerably better than the non-irrigated simulation, implying that more accurately capturing the near-surface humidity is leading to a denser and optically thicker fog that is more consistent with the visibility and LWD observations. This pattern is also broadly reproduced for the two subsequent fog events of the 23rd and 24th January 2016; the visibility and relative humidity are notably more accurate, and the LWD is more accurate on the 24th. However, deficiencies in the simulations remain, with neither configuration able to reproduce the rapid reduction in visibility after sunset. We hypothesise that this is, in part, due to the simple urban land surface parameterisation used here, resulting in a ~1 K night-time temperature bias

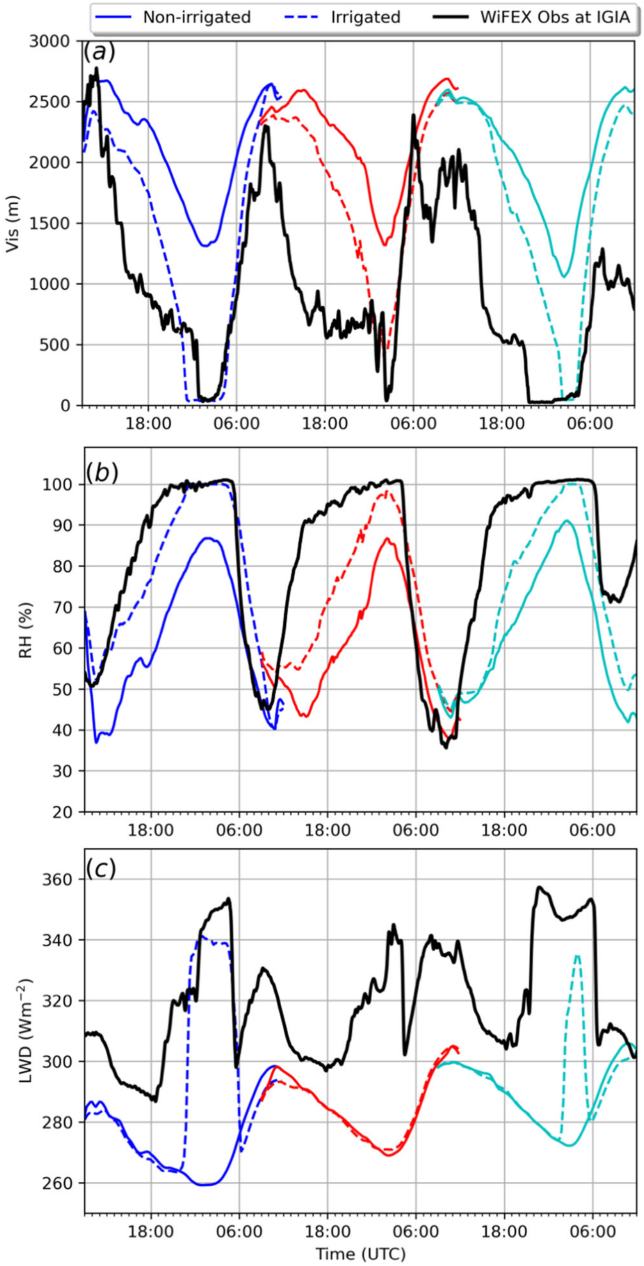

Fig. 4 | Evolution of three fog events in Delhi. The time series show visibility (Vis, m; **a**), relative humidity (RH, %; **b**) and downwelling long-wave radiation (LWD, Wm^{-2}; **c**) observations (black) and model output from non-irrigated (solid lines), and irrigated (dashed lines) configurations during 22-24 January 2016 at IGI-Airport, Delhi. The blue, red, and aqua colours denote simulations starting at 00 UTC on the 21, 22 and 23 January respectively.

(not shown). Anurose et al.[34] discuss urban parameterisations and fog. It is important to note that visibility is a derived diagnostic (rather than a prognostic model variable) and depends on an assumed aerosol size and mass appropriate for Delhi as well as on humidity. Improvements to the visibility diagnostic from the MetUM are currently being trialled and this could potentially further improve the relationship between aerosol, fog, and visibility in the MetUM.

We have also compared model output to meteorological observations at various locations within the model domain (shown in Fig. 1d). Generally, the irrigated simulations have a higher relative humidity than the non-irrigated simulations that is in better agreement with the observations (Fig. 5). The impact is largest at the BRL, HSR, PTL and DEL sites, locations close to or within the irrigated area; and is smaller at GWL and DHD, further away from the irrigated area. Although, these locations can also be impacted by the additional moisture advection, e.g., DHD on the 22nd January 2016 (Fig. 5), leading to fog (Fig. 2). These improvements in relative humidity in the irrigated model simulations translate to improvements in visibility (Supplementary Fig. 3). However model deficiencies remain, for example at GWL and BRL, located to the east of the domain, and the improvement in relative humidity is insufficient to reach saturation and produce fog (Fig. 2).

In short, we have shown that adding soil moisture due to irrigation into an NWP model improves the simulated near-surface humidity, resulting in improvements to the spatial distribution, evolution and optical depth of fog and, consequently, visibility.

Discussion

We have demonstrated that additional soil moisture due to irrigation has a major impact on the simulation of dense fog events over northern India (including Delhi). Winter season irrigation of the IGP increased between 1972 and 2010 (Fig. 1b) and continues to increase[57]. This irrigation increase has been accompanied by an increase in humidity and fog frequency[13,21,22]. In our irrigated simulations, we have observed an improved representation of fog development in comparison to satellite and in situ observations. These experiments highlight important processes driving widespread fog in northern India and point to the importance of representing irrigation in models.

Although our work has focused on a three-day period, these fog events are representative of other fog events in terms of density and duration at the WiFEX site[14] and spatial extent as observed by INSAT-3D[56]. Additionally, the model's dry bias over this period is consistent with other events, both foggy and clear days[34]. Our conclusions regarding the model performance and the impact of representing irrigation can thus be likely extended to other wintertime fog events.

Most of the northern plains of India (IGP region) are irrigated cropland. When irrigated, the additional moisture, and consequent changes to the surface energy budget, result in the advection of moisture into Delhi and beyond and cause widespread dense fog to develop earlier and be more persistent in these cases. Representing irrigation leads to improved simulations of relative humidity, countering a dry bias typically seen in model simulations for this region[34], and consequently improves the simulation of fog, low cloud and visibility; it leads to a better spatial distribution of fog across the IGP when compared to INSAT-3D satellite observations and surface visibility observations. These events clearly show that irrigation can be highly important for the formation of dense fog. Previous studies have speculated that irrigation could play a role in the observed increased frequency of fog in the IGP[18,58] but without evidencing a clear cause and effect. We have demonstrated the decisive role irrigation may play in the frequent and increasing occurrence of widespread fog events over the IGP. Further work is needed to develop a methodology which can realistically simulate the irrigation process in operational NWP models. This could involve an improved soil moisture data assimilation system (overcoming existing challenges[35,37,51]), a smart irrigation parameterisation which includes spatial and temporal variations in irrigation practice or a hybrid approach.

While inclusion of wintertime irrigation in our simulations leads to a substantial improvement in fog prediction, it does not solve all of the problems. Fog forms as a result of complex interactions between the land surface, the meteorology, and the aerosol and cloud microphysics. Further work is still needed to address deficiencies in representing these processes including the accurate representation of urban areas[34,59], aerosol sources and chemistry[8] and aerosol microphysics[30]. Nonetheless, including irrigation in NWP models offers the potential for a step change improvement in fog forecasting accuracy over northern India in winter.

Methods

Environmental data

WiFEX data. The Winter Fog Experiment (WiFEX) took place over consecutive winters between 2015 and 2020 at the Indira Gandhi International Airport (IGI-Airport, Palam) in New Delhi[14,56]. WiFEX

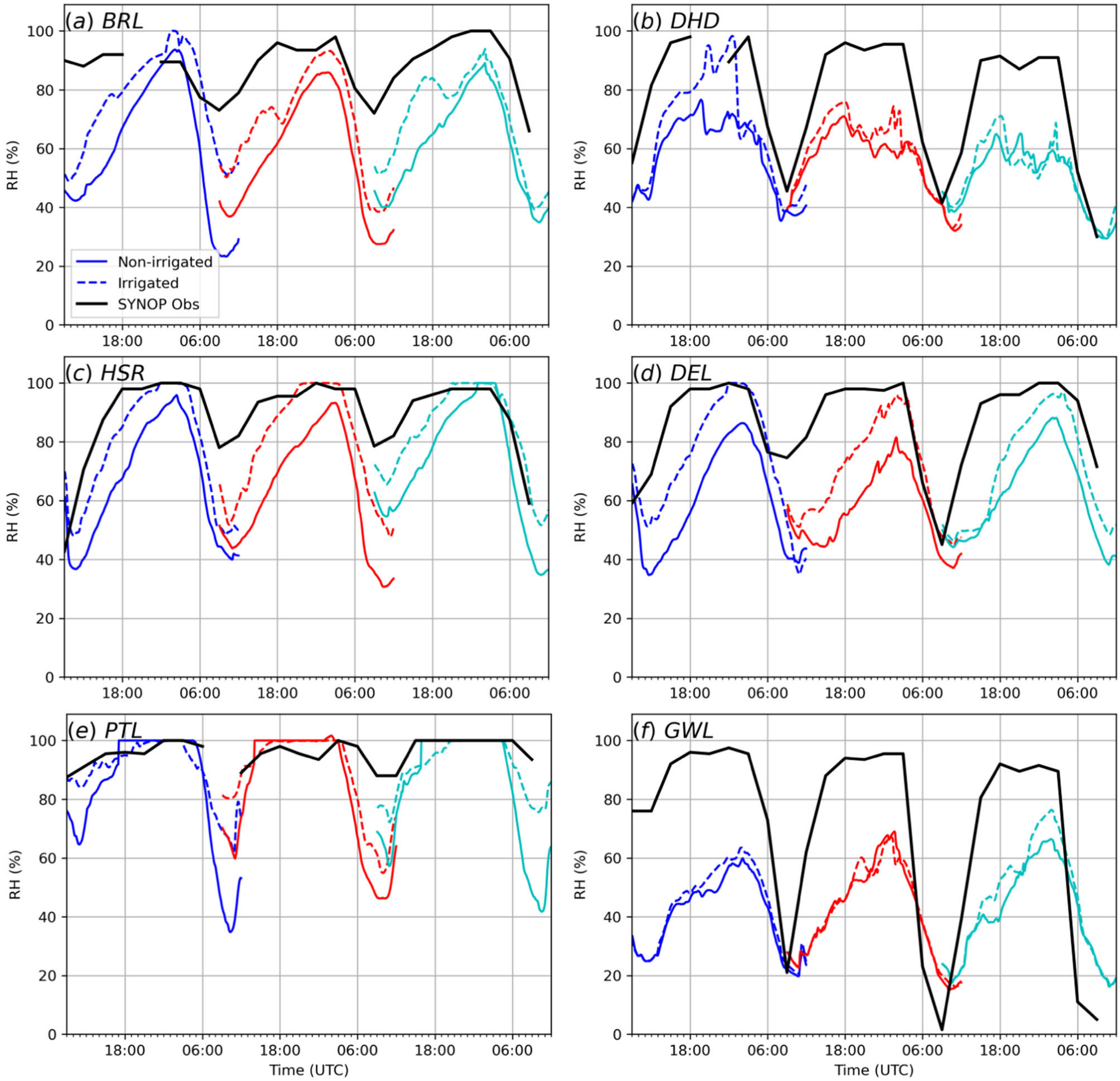

Fig. 5 | Evolution of three fog events at other locations. The time series show relative humidity (RH, %) from observations (black) and model output from non-irrigated (solid lines) and irrigated (dashed lines) configurations during 22-24 January 2016 (as Fig. 4). Results are shown for (**a**) Bareilly (BRL), (**b**) Dehradun (DHD), (**c**) Hissar (HSR), (**d**) Delhi (DEL), (**e**) Patiala (PTL) and (**f**) Gwalior (GWL).

has included measurement campaigns of more than 90 dense fog events, using a wide array of instrumentation, supporting fog characterisation and modelling studies. Here we use the WiFEX automatic weather station and radiation flux measurements in the evaluation of our model experiments of a dense fog case study which occurred over the period 21st–24th January 2016. Each day the fog dissipated and reformed overnight. The number of hours with visibility below 1 km ranged from 15 to 18 h and below 50 m ranged from 3 to 8 h, typical of the duration of fog events during WiFEX.

Gridded rainfall dataset. The daily gridded rainfall dataset for India described by Pai et al.[43] has a spatial resolution of 0.25° × 0.25° and is based on observations from 6955 rain-gauge stations. It is used for the climatological and event assessment of wintertime rainfall.

Satellite Fog/low cloud product. We use the Fog/low-cloud satellite (INSAT-3D) product available from the Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC) which is a Data Centre of the Space Applications Centre for satellite data under the Indian Space Research Organisation. The INSAT product has been successfully verified against surface observations[60,61] and provides a powerful tool for model validation with high temporal (30 min) and spatial resolution (4 km). Each pixel is tagged as either fog or no fog. The night time fog/low-cloud product uses a commonly used algorithm[62,63] based on a threshold of the brightness temperature difference between two spectral channels (mid wave infrared and thermal infrared). The night-time method has difficulty detecting optically thin fogs[62,64] and thus we refer to the satellite as measuring *deep fog* and compare it to the model's simulation of *deep fog*. The daytime product uses the visible channel reflectance and thermal infrared brightness temperature[65] and so has better sensitivity to optically thin fog. Note the night-time product is used at 18Z and 00Z and the daytime for 06Z.

We use the 'Very Low Cloud' (cloud below 111 m) and 'Low Cloud' (cloud between 111 m and 1949 m) output of our model experiments to identify where fog occurs and compare against the Fog/low-cloud satellite (INSAT-3D) product. We refer to a modelled 'Very Low Cloud' fraction above 0 alone as *shallow fog*, both a 'Very Low Cloud' fraction and a 'Low Cloud' fraction above 0 as *deep fog* and a 'Low Cloud' fraction above 0 without any 'Very Low Cloud' as *low cloud*.

Meteorological (SYNOP) measurements. We compare the spatial variation of our modelled visibility and relative humidity against surface measurement data recorded at the following airports in the northern India surface synoptic (SYNOP) network: Delhi Safdarjung (DEL), Bareilly (BRL), Dehradun (DHD), Patiala (PTL), Gwalior (GWL) and Hisar (HSR) (see Fig. 1d for locations).

Irrigation water use datasets. We base the design of our model experiments with irrigation represented on the global irrigation water use dataset (0.5° × 0.5°) described by Huang et al.[66]. derived using the Hanasaki et al. [67] method. We use the most recent January data from this dataset, from January 2010. Data for 1972–2010 were also used to assess trends in winter irrigation over the IGP. This dataset was based on the Food and Agriculture Organisation of the United Nations global information system on water and agriculture, United States Geological Survey estimates and simulated global hydrological models. These data are used to give the seasonality in irrigation which is unavailable in other more recent datasets.

Land cover data. In order to realistically simulate the spatial distribution of irrigation we use the European Space Agency Climate Change Initiative (CCI) Land Cover project's land cover data at 300 m spatial resolution for 2016 to restrict irrigation to the 'irrigated cropland' land cover class (Supplementary Fig. 4).

Modelled irrigation sensitivity experiments

To investigate the impact that irrigation has on fog formation, intensity and persistence, a set of irrigated and non-irrigated model sensitivity experiments were performed for the 21st–24th January 2016 events using the recently developed Delhi Research Unified Model (DRUM). DRUM is a regional research version of the Met Office Unified Model (MetUM), that uses the regional atmosphere tropical configuration version 2 (RA2T)[68], and the same domains as the Delhi model developed for operational fog forecasts at the National Centre for Medium Range Weather Forecasting (NCMRWF)[69]. The DRUM is a limited area model (with a horizontal resolution of 1.5 km in this study), nested in a global 17 km resolution model using the Global Atmosphere 6.1 (GA6.1) configuration[70], with a domain covering the IGP region including the highly irrigated areas to the NW of Delhi (Fig. 1a). Each simulation is initialised at 00Z and runs for 36 h consistent with the operational version of the model[69]. The initial conditions are derived from the global model's analysis, which includes soil moisture data assimilation[37].

To determine the irrigated area, we combine the irrigation water use and land cover datasets. While the land cover dataset has high spatial resolution (300 m), it does not provide any seasonal irrigation information. On the other hand, the global irrigation water use dataset is monthly but at a lower spatial resolution (0.5° × 0.5°). We define a realistic agricultural irrigation area for the winter months (Fig. 1d) by convoluting land areas classed as "irrigated cropland" (Supplementary Fig. 4) with areas with irrigated water use of over 5 mm in January (Fig. 1a).

For these irrigated areas, the initial soil moisture in the MetUM is increased to become the saturated soil moisture content for sand (38.3 kg m^{-2}) following a similar approach to Fletcher et al.[52]. This corresponds to an additional 20–25 mm of water, which is consistent with flood irrigation practice in the region (Prof B Lankford 2023, personal communication, 16 May). The soil moisture is then left to evolve normally during the simulation. In short, we believe our representation of irrigation, by saturating the model's soil moisture initial conditions, is a physically reasonable approach that introduces a realistic amount of moisture into the model simulation (~25% of the monthly irrigation total; Fig. 1a) in the known irrigated cropland areas (Fig. 1d). In this study, we use this relatively simple approach to assess the potential impact of irrigation and justify the need to include it in model simulations of fog events. The development of a more sophisticated approach to irrigation, which could be used operationally, is underway.

Data availability

WiFEX campaign data are stored at the data repository at the Indian Institute of Tropical Meteorology and are publicly available as per Ministry of Earth Sciences, Government of India data sharing guidelines (https://ews.tropmet.res.in/wifex/). The SYNOP data are available from the Centre for Environmental Data Archive; http://catalogue.ceda.ac.uk/uuid/220a65615218d5c9cc9e4785a3234bd0. The CCI land use land cover dataset is available through the Climate Data Store; https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-land-cover?tab=overview. The daily gridded rainfall dataset at a spatial resolution of 0.25° × 0.25° over India is publicly available at https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_Bin.html. The INSAT-3D FOG product is available upon request for research purposes only from the Meteorological and Oceanographic Satellite Data Archival Centre (https://mosdac.gov.in). The global irrigation water use dataset at a spatial resolution of 0.5° × 0.5° is also publicly available at https://zenodo.org/record/1209296#.Wykok639Hm. The irrigated area data underpinning Fig. 1d is available at https://doi.org/10.6084/m9.figshare.25127297. Land cover data[71] can be found at http://maps.elie.ucl.ac.be/CCI/viewer/index.php and https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-land-cover?tab=overview. Further technical details regarding the satellite fog / low cloud product are available at the following link: 10.19038/SAC/10/3DIMG_L2C_FOG, MOSDAC.

Code availability

Access to the Unified Model (UM) code is managed through the Met Office Science Repository Service (https://code.metoffice.gov.uk/). Interested users can contact scientific_partnerships@metoffice.gov.uk for advice stating affiliate institution.

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Competing interests

The authors declare no competing interests.

Additional information

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