Anthropogenic snowfall events in the UK: examples of urban weather modification?

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Snow in the UK is generally associated with synoptic or mesoscale weather systems, thus snowfall during quiescent anticyclonic conditions is surprising and might not even be forecast. Consequently it could present a hazard. Snowfall during anticyclonic freezing fog conditions at Didcot and Hereford in December 2006 is investigated here. These two snowfalls seem to present circumstances in which anthropogenically-produced aerosols could have provided ice nuclei within the freezing fog, and therefore might provide characteristic examples of Anthropogenic Snowfall Events (ASEs).

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Running header: Urban artificial snow

Snowfall is not confined to frontal weather systems. This was evident from a striking weather image in the August 2008 *Weather*, which showed a satellite picture of scattered snow patches over the Low Countries immediately following a period of foggy anticyclonic weather (Van den Berg 2008). The snowfall illustrated was typically downstream of urban and industrial areas, raising the possibility that the events were Anthropogenic Snowfall Events (ASEs), associated with fog and artificially injected particles.

Studying such snowfall from fog is important because of the local changes associated and the potential hazard it produces. Since the snow might not have been forecast, a hazard might arise from inadequate gritting of roads; but—perhaps more worryingly—as snowfall is such an obvious event, it provides an objective basis on which the forecast may be widely perceived to have been "wrong". Even a light covering of snow alters the local surface albedo. The resulting microclimatological changes could contribute to further differences between the local weather and predictions from forecasting models. Finally, since snow reports are important for climatological records (*e.g.* used as a threshold climate change indicator), the snow's origin is important.

During freezing fog, it is reasonably common for airborne super-cooled liquid fog droplets to come into contact with sub-zero surfaces and solidify on the surfaces to form rime. Large droplets falling from fog essentially form drizzle, but snowflakes (or snowgrains) falling[*] is perhaps a more unusual occurrence, at least in the southern UK.

The possibility of Anthropogenic Snowfall Events (ASEs) in the UK is investigated further here, based on the phenomenology developed from previously reported events.

[*] Because of the similarity in the circumstances concerned, we suggest describing drizzle-like snowfall from fog as *snizzle.*

Anthropogenic snow phenomena

Precipitation directly caused or influenced by human activity has been reported for many decades, with early reports of drizzle by Blum (1948) and snowfall by Culkowski (1962). ASEs have typically been attributed to effluents from either industrial plants (Charlton and Park 1984) or power stations (*e.g.* Kramer *et al.* 1976, Koenig 1981, Murray 1980); almost all reported ASEs have been in North America. Near power stations, a 1% increase in annual precipitation can be expected up to "a few thousand feet" of power station cooling towers (Huff 1972). As well as local observations, ASEs can be inferred from satellite images (Koenig 1981, Van den Berg 2008).

Observations show ASEs can generate snowfall at hundreds of metres to hundreds of kilometres downstream of a power station. At the longer length scales, and coinciding with natural snowfall, a seeder-feeder mechanism has been suggested to operate, whereby snowfall accumulations at the ground are enhanced by up to a factor of two as the natural snow falls through the cooling tower plume (Campistron 1987). Nearer to the cooling towers, and when there is no natural precipitation present, effects vary depending on whether the near-surface air is foggy or not.

Non-foggy conditions

When the ambient air is sub-saturated, for anthropogenic precipitation to occur, there is probably the need for the cooling tower plume to reach the ground, typically 1–5 cooling-tower heights downstream (Overcamp and Hoult 1971). Such plume deviation is related to the aerodynamic wake around the cooling tower, which can act to pull the plume downwards substantially enhancing precipitation rates. In other non-foggy cases, the smoke stack and cooling tower effluents can mix; this causes water-droplet-laden air to come into contact with smoke stack particles (such as metallic oxides) able to act as ice nuclei (Agee 1971, Kramer *et al.* 1976, Parungo and Weickmann 1978, Campistron 1987).

Foggy conditions

When saturated air is below freezing, the airborne water droplets (fog) can remain as a super-cooled liquid until temperature, *T*, falls below –40°C[†]. Should abundant ice nuclei be present, which allows ice crystals to form in warmer environments ($T > -40$°C), the Bergeron-Findeisen process predicts rapid grow of the ice crystals at the expense of super-cooled water droplets[‡]. For ASEs, if ice nuclei are present—in, for example, power station effluents—then ice crystals generated are likely to grow during the plume's passage. For the case studied by Parungo and Weickmann (1978), a plume was sampled many kilometres downstream. This contained airborne particulates that were potential ice nuclei. Snow particles local to the power plant were examined under a scanning electron microscope and showed ice nuclei present.

UK events

Two possible ASE cases occurred during December 2006 in the UK and are discussed in more detail. How regular such events are is not known, but more recent similar occurrences[§] suggest that they may not be uncommon.

December 2006 weather conditions

During the 19–27th, an anticyclone was centred over the UK (with no fronts over England or Wales throughout this period), and with it came widespread fog and cold temperatures, particularly in southern England from the 20–23th. There was widespread travel disruption due to the hazard of

[†] Moreover, at lower temperatures water vapour is more likely to sublime directly to ice crystals: as *diamond dust*.

[‡] Phenomena of this ice-growth mechanism can occur in, for example, elevated stratocumulus cloud-decks as *hole punch clouds* (Kramer 1976, Pedgley 2008): once super-cooled droplets in a region of the cloud begin to freeze, the ice particles grow in size until they can fall from the cloud, leaving behind a hole.

[§] Three UK events occurring in winter 2008/09 have since been documented (Wood & Harrison 2009).

reduced visibility, including the well-reported grounding of many flights at Heathrow and some other UK airports. Figure 1 shows the evolution of these weather conditions at a non-official meteorological station (*Upton Weather*, South Oxfordshire, 51.574°N 1.261°W): fog prevailed from the 20–23th, shown by the non-depressed dew-point temperature trace. The temperature was below freezing throughout the period, ranging between –4 and 0°C. Radiosonde ascents from Larkhill, Hampshire (51.20°N 1.80°W), on the 20th and 21st (not shown) exhibited temperatures below freezing by day and night with variable fog depths of 80–210 m; and no cloud throughout the profile above that level. On MODIS satellite images during this period (an example is shown in Fig. 2) many power station plumes in northern England can be seen above the fog layers, showing that the fog was below the typical cooling tower height of 115 m at many locations.

Didcot

Given the anticyclonic synoptic situation in southern England, an announcement over a public-announcement system to "…please mind the snow when alighting from the train…" was surprising. This announcement was heard by one of us at Didcot[**] railway station (south Oxfordshire) on a Reading-to-Oxford service on 20 December 2006 at around 19h. A covering of snow was observed on the platform (perhaps just a few millimetres in depth), but an opportunity for careful observations only arose two days later: Fig. 3 shows a map with snow locations marked. The locations were 700–2400 m from the cooling towers (and, based on data from *Upton Weather*, were probably almost directly downwind). Several photos were taken of the remaining snow patches on fence posts (Fig. 4), roofs of houses and on cars. There had clearly been some snowmelt, but this was unlikely to have been at a great rate, since temperatures remained below freezing night and day in the fog.

[**] A legendary explanation given for snow-induced railway disruption in February 1991 referred to the 'wrong kind of snow'. Because Didcot power station is fuelled by train-carried coal, a possible irony is that railway activity itself might indirectly cause another kind of snow to fall on the local railway junction.

Hereford

At Hereford (52.05°N, 2.72°W), an ASE occurred on the morning of 21 December 2006. There were eyewitness reports of *falling* snow during the period 7–8h, and *Hereford Weather*'s meteorological station[††] reported 0.5 mm precipitation at 07:45h. In local media outlets, there were widespread reports of snow: including local BBC TV news magazine, *Midlands Today*. Here are two intriguing quotes from local residents:

"I live in the east of the city. There was a very light scattering of snow on the ground. My journey to work takes me through the city centre, where the amount of snow was still light, but more than at home. Snow was still falling in the city centre. As I left the city, heading south-westwards on the A465, the snow had completely disappeared by the time I had reached the Tesco store on the edge of the city."

"When they are brewing cider, the towers emit steam, if you happen to be in town and a light wind in the right direction the air tastes of apples, I have experienced this on several occasions. I remember one occasion where there was a dusting of snow, and the snow had a hint of apple flavour. I can't remember exactly but I would say this experience was 10 years ago."

Figure 5 shows a map of Hereford with snow locations compiled from eyewitness reports, and a possible aerosol source region (the Whitecross area of the city) identified. The winds were light and westerly and the snow report locations were 400–2600 m away from the Whitecross industrial area (and, based on data from *Hereford Weather*, were probably almost directly downwind). Several photos were available from local residents and the BBC website, a photo is shown in Fig. 6 at Whitecross Common.

No further reports of ASEs in the UK were found for December 2006.

[††] This private station is not to be confused with the nearby Met Office synoptic station at Credenhill.

Discussion

Snowfall from fog during non-frontal, anticyclonic conditions is clearly not solely a North American phenomenon, and is evidently observable in the UK, as these reports show. An important factor in the UK cases reported here appears to be the presence of anthropogenically-produced particles. Impacts of urban aerosols—in particular airborne industrial effluent—might more usually be expected to be small, through effects on visibility and cloud properties. In the case of ASEs, however the effect might well be clearer.

Although ASEs have previously been observed in environments as warm as –5°C (Agee 1971, Parungo 1978), most reported cases have been during very cold conditions ($T < -15$°C). The occurrence of ASE phenomena in a much warmer winter climate is interesting, since the UK is probably already marginal for such events. Furthermore, as snowfall events are comparatively rare in southern England anyway (*e.g.* 11 snowfall days per year, Reading 1971–2000), ASEs could account for a substantial proportion of a year's snowfall days at a susceptible location.

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Figure captions

Figure 1. Evolution of meteorological conditions during December 2006 at the Upton Weather private meteorological station (Upton, Oxfordshire; c. 2 km south of Didcot). These values were similar to those recorded at the University of Reading's Atmospheric Observatory (some 27 km South-East of Upton; http://www.met.rdg.ac.uk/~fsdata/obshome.html). Variables are temperature (T), wind speed (U) and sea-level pressure (P).

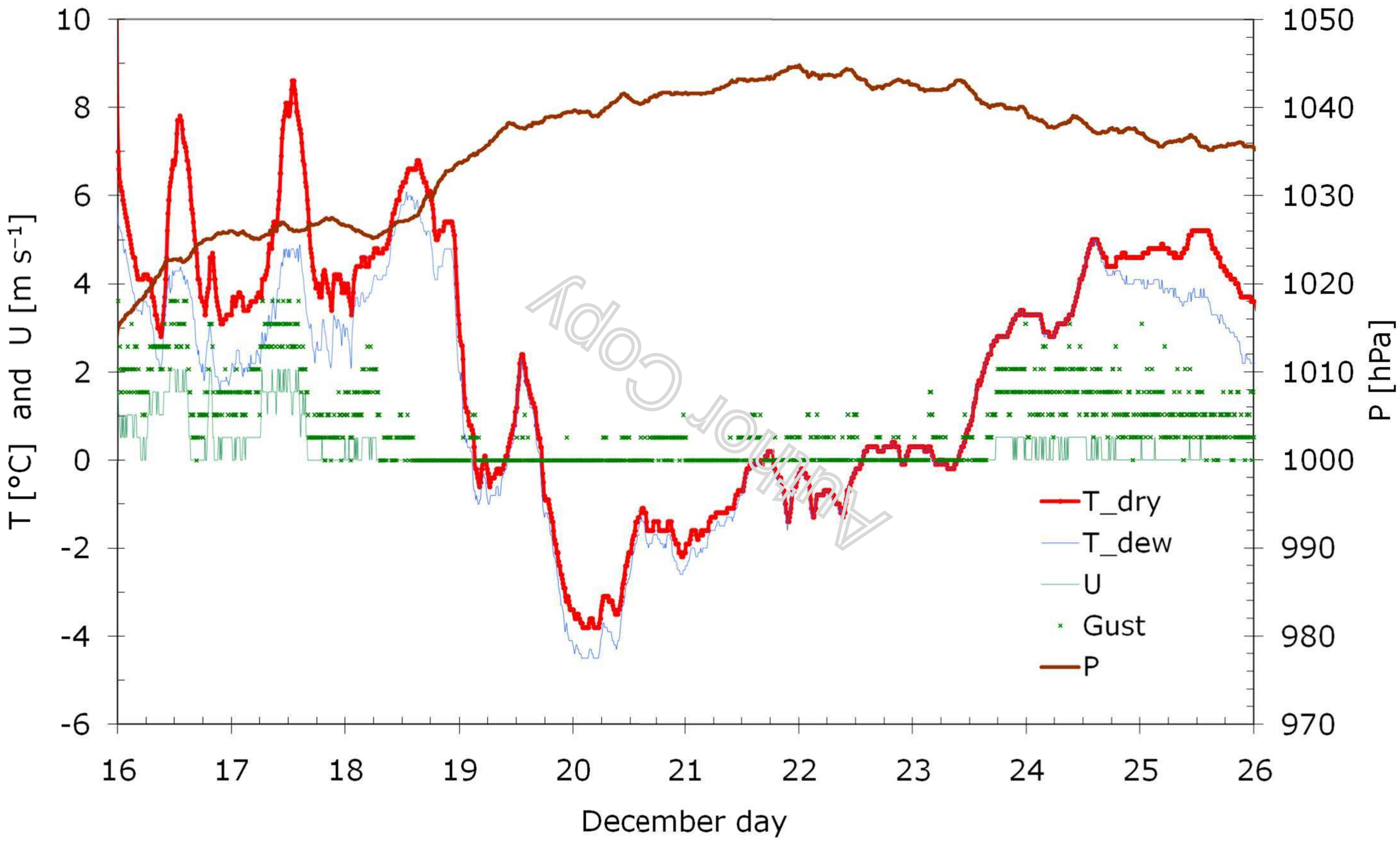
Figure 2. A high horizontal resolution (250 m) MODIS satellite image over southern UK at 11:14utc on 20 December 2006 (courtesy of NERC Satellite Station, University of Dundee).

Figure 3. An aerial map (© Google Maps) of Didcot, Oxfordshire, UK (51.61°N, 1.24°W), with snowflake symbols marking where lying snow was observed. The power station cooling towers can be seen in the north-west. The cooling towers at Didcot are 115 m tall (and the chimney stack is 200 m). Didcot railway station is marked with the red symbol.

Figure 4. Snow on fence posts at location A on Fig. 3, on 22 December 2006; almost certainly remaining from the 20 December snowfall. A close-up image of one of the fence posts is included in the inset (top-left).

Figure 5. An aerial map (© Google Maps) of Hereford, UK (52.05°N, 2.72°W), with snowflake symbols marking where falling and lying snow was observed on the morning of 21 December 2006 (red crosses show where there was NO snow). The Whitecross industrial area of the city is marked, which provides a possible region of aerosol production.

Figure 6. Snow observed in Hereford on 21 December 2006, at location A in Fig. 5 (52.065°N, 2.722°W).



T [°C] and U [m s⁻¹]
P [hPa]
December day
10
8
6
4
2
0
-2
-4
-6
1050
1040
1030
1020
1010
1000
990
980
970
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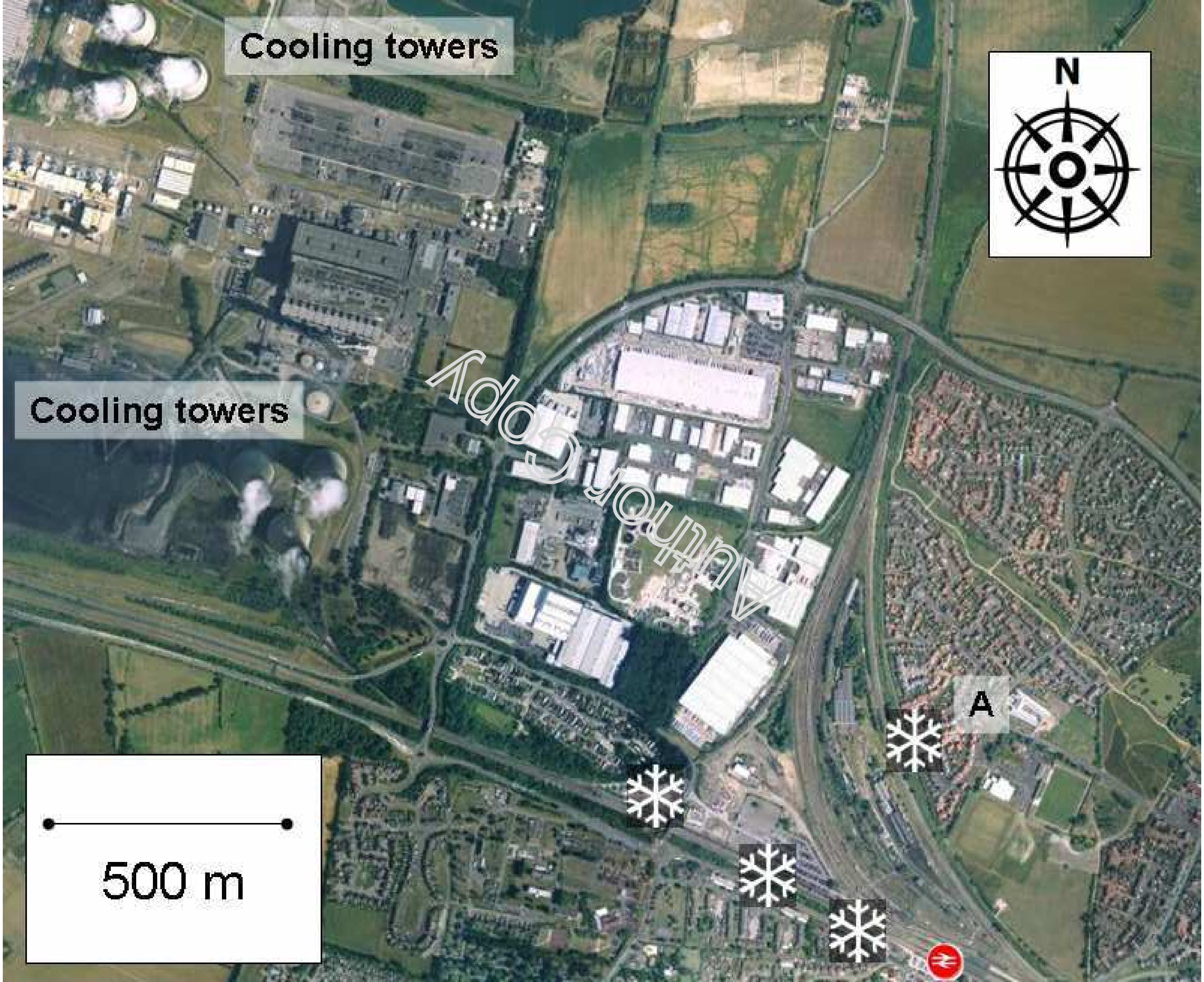
Cooling towers
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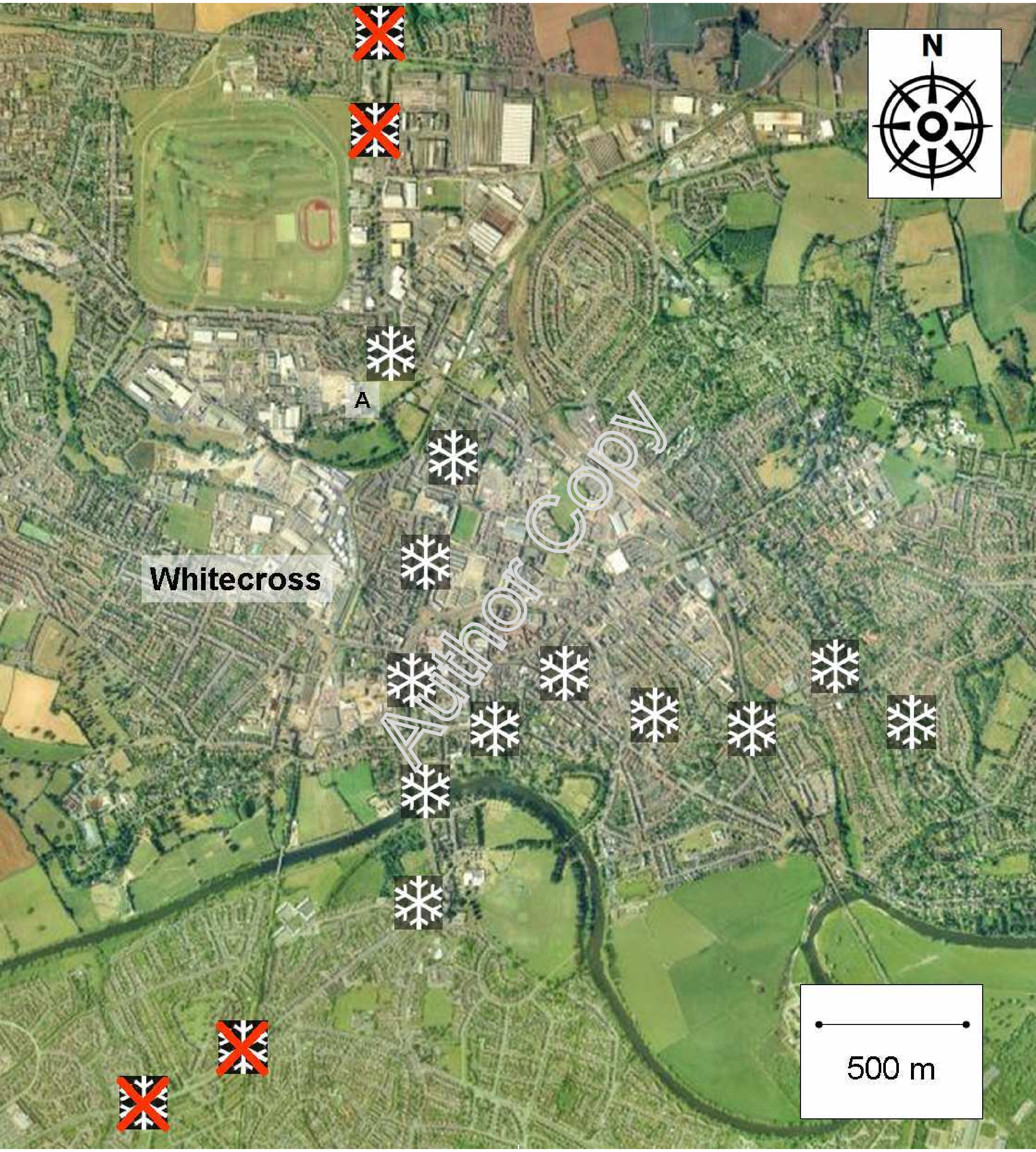
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