A rare frozen precipitation event in Hong Kong

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Introduction

Located on the south China coast, with the Asian land mass to the north and seas to the south, Hong Kong has a subtropical monsoonal climate. Although winter monsoon surges from the north sometimes bring cold weather to the city, near-freezing temperatures are rather uncommon, especially in the urban areas. Since records began in 1884 at the Hong Kong Observatory (HKO) headquarters, situated in the urban part of Hong Kong (see Figure 1 for location), there were only 10 years with minimum air temperatures below 4.0°C up to 2016. Among various winter weather phenomena, frost and icing are not particularly uncommon. There were more than 90 days on which frost was reported and 30 days on which ice was reported from 1948 to 2016. However, these conditions were mainly confined to rural areas and high ground, where temperatures were usually lower. By contrast, rime, snow, rain mixed with snow and rain mixed with ice pellets (the last two both being referred to as 'sleet' in different places (e.g. Cleveland, 1916; Met Office, 2015) are rarely observed in Hong Kong. There were no more than 5 days with reports of each of these phenomena from 1948 to 2016. One of the very few cases of widespread frozen precipitation took place on 18 January 1893, when air temperatures at HKO headquarters fell to a minimum of 0.0°C, a record which has yet to be broken. During that episode, widespread icing due to freezing rain could be seen on high ground (Gibbs, 1931), and there were even reports of hilltops covered by 'snow or hoar frost' (Doberck, 1893). The coldest surge after the Second World War occurred in February 1957, when temperatures at HKO headquarters fell to 2.4°C. While that surge was a dry one without frozen precipitation, there was frost and ice on high ground and in rural areas (Cheng, 1970).

Figure 1. Locations of various places where observations and measurements of the cold surge took place.

In early and mid-January 2016, a prominent blocking pattern developed over the Ural-Siberia region, as was evident from a strong positive 500hPa geopotential height anomaly over Siberia and a weak negative anomaly over northeastern China (Figure 2). This led to the accumulation of cold surface air over Siberia. As the blocking pattern began to collapse, the induced northwesterly surface winds caused an intense cold surge to sweep southwards from around 20 January, bringing bitterly cold conditions to most parts of China in the following few days. Records of minimum temperatures for January were broken at more than 150 cities and counties of China, while the southward extent of areas with snowfall was the most advanced since records began in 1951 (China Meteorological Administration, 2016). In Hong Kong, the temperature at the Observatory headquarters fell to a minimum of 3.1°C on 24 January, making the surge the third coldest on record, ranked just behind the ones in 1893 and 1957. The mean sea-level pressure also climbed to an all-time record high of 1037.7hPa on that day. Although snow was not observed in the territory, a range of winter weather phenomena, including icing, rain mixed with ice pellets, freezing rain, frost and rime were reported in various places during the episode. This article reviews the events from an observational perspective and the impacts of the frozen precipitation. Challenges in forecasting the cold surge are also discussed.

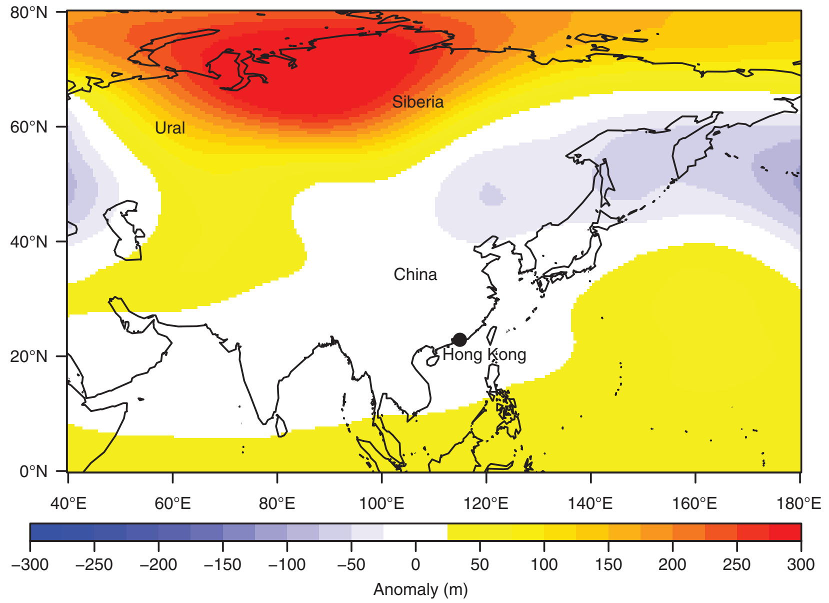

Figure 2. Anomaly of mean 500hPa geopotential height (in m) during the period from 1 to 20 January 2016, relative to climatology from 1981 to 2010 based on NCEP/NCAR reanalysis data (Kalnay et al., 1996).

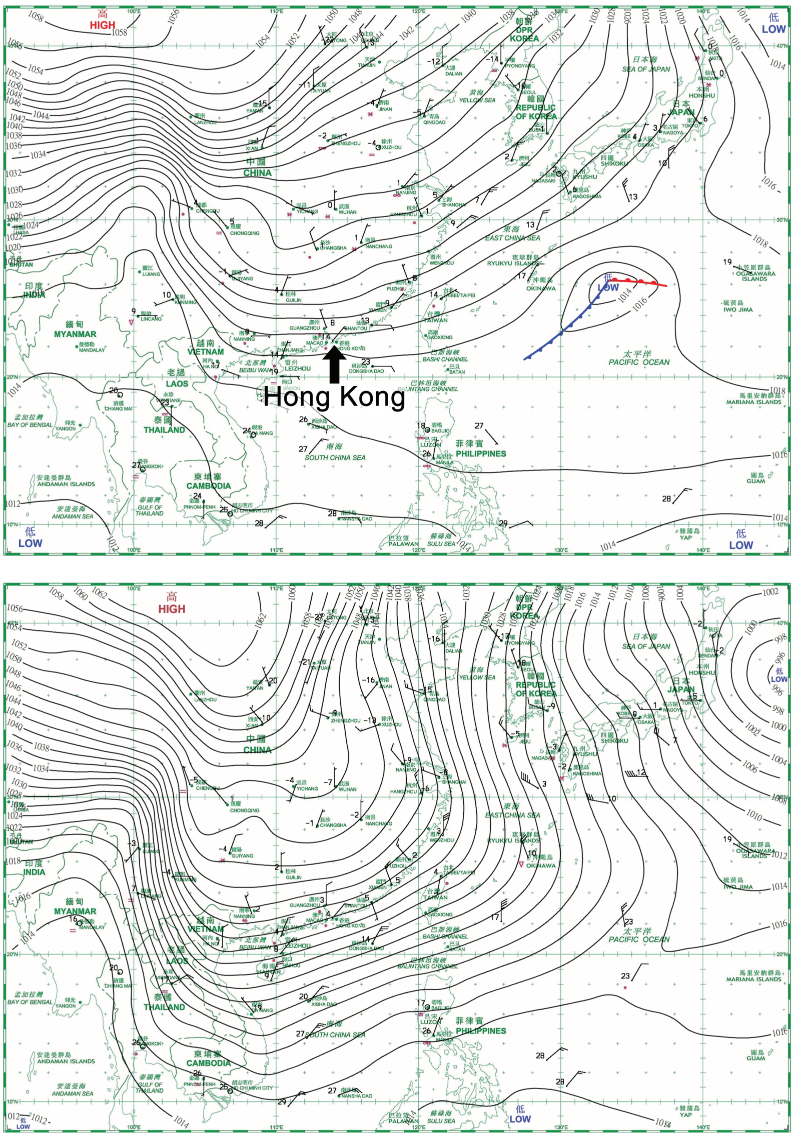

Figure 3. Surface analysis charts for 0800h (0000 UTC) on 22 January (top) and 24 January (bottom) 2016. The isobars are drawn at 2hPa intervals. The observed winds (with a full wind barb representing 5ms⁻¹) and air temperatures (in °C) for various stations are also shown.

Sequence of events

Prior to the arrival of the cold surge, the monsoonal flow had already been dominating China. As the tight surface pressure gradient associated with the cold surge reached the south China coast during the day on 22 January (Figure 3), winds in Hong Kong strengthened from the north. The winds, together with rain due to the approach of a low-level shear line, caused temperatures at the HKO headquarters to drop sharply by around 5 degC in 10h (Figure 4).

Rain eased off slightly on 23 January following the passage of the low-level shear line; however, under cloudy skies with prominent cold advection brought by strong to gale force northerly winds (with gusts exceeding 90kmh^{-1} recorded at Cheung Chau, an outlying island of Hong Kong; see Figure 1 for location), the falling trend in temperatures continued throughout the day, albeit at a slower rate. Temperatures at the HKO headquarters dropped to around 7°C at night. Temperatures even stayed below freezing from the early morning on Tai Mo Shan, the highest peak in Hong Kong with an elevation of around 950m, with frost and rime being reported later in the day (Figure 5(a) and (b)).

The following day, 24 January, saw the peak of the cold surge, with mean sea level pressure at HKO headquarters reaching an all-time high of 1037.7hPa in the morning, breaking the previous record of 1035.4hPa in January 1903. In the early morning, a band of precipitation edged towards Hong Kong from the north (Figure 6(a) and (b)). This was associated with the approaching jet and perturbations at a height of around 3km ahead of an upper-air trough, as were evident from wind profiler observations (Figure 7). Meanwhile, dry advection associated with very strong northerly winds below 1500m caused the low levels to dry out gradually. This could be seen in the evolution of temperature profiles from ascents at King's Park Meteorological Station (Figure 8). With significant rain falling in a relatively low humidity environment, surface temperatures plunged further due to evaporative cooling effects, and were lower than 4°C in the urban areas towards dawn. Icing due to freezing rain was even reported at Tai Mo Shan (Figure 5(c)). This was consistent with the observed temperature profile from an ad-hoc ascent at 0600h (2200 UTC 23 January; Figure 8(c)), which showed a sub-freezing layer of air around the height of Tai Mo Shan, with the freezing level descending to around 400m. Meanwhile, a deep warm layer existed above and caused most of the snow to melt into raindrops. With temperatures at the hilltop already well below 0°C, the super-cooled droplets refroze when they came into contact with the ground or trees, forming icicles or a glaze of ice.

During the day on 24 January, there were reports of rain mixed with ice pellets over many parts of Hong Kong (Figure 5(d)). This could be explained well by the subsequent temperature profile at 0800h (Figure 8(d)), which showed a shallow warm layer above 0°C at around the 900hPa level. Snowflakes from further up in the atmosphere partially melted when falling through this layer, and then refroze to ice pellets as they descended through another sub-freezing layer below. Since temperatures near sea level were only slightly above freezing, a mixture of rain and ice pellets was observed on the ground. The dual-polarisation Doppler radar at Tate's Cairn also captured the change in precipitation type in the vicinity of Hong Kong, from predominately rain in the small hours to mostly ice crystals in the late morning (Figure 6(c) and (d)). Although the low levels were continually being dried out, precipitation persisted into the afternoon, even with surface relative humidity falling below 50%. Temperatures at HKO headquarters eventually reached a minimum of 3.1°C under precipitation. In the rural areas where surface temperatures were even closer to freezing, reports of icing were received (Figure 5(e)).

As the dry air behind the upper-air trough advanced further southward, the atmosphere eventually dried out on the evening of 24 January. With precipitation and the associated evaporative cooling effects easing off, temperatures over the territory recovered slightly at night but remained at 5°C or below. The sky cleared on the following day (25 January), allowing more rapid warming during the day, and causing the remaining ice on high ground to melt. Most parts of Hong Kong saw temperatures rising above 10°C by the afternoon. With the moderation of the monsoon, winds subsided and turned more easterly over the following 2 days, causing temperatures to rise further, yet frost was still reported at Tai Mo Shan on the morning of 26 January because of considerable radiation cooling overnight under clear sky, with grass temperatures remaining sub-zero. The cold episode finally ended on 27 January, when temperatures at HKO headquarters climbed above 12°C.

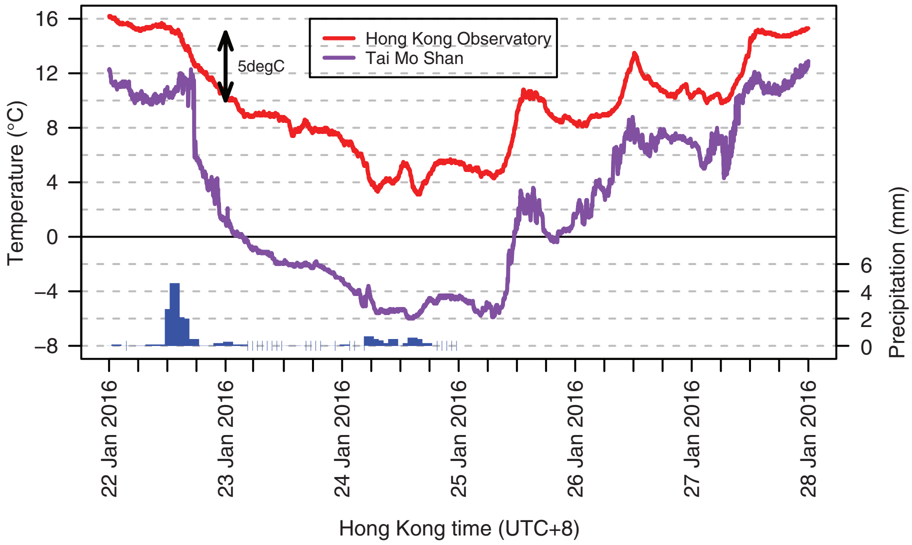

Figure 4. Time series of observed air temperatures at Hong Kong Observatory (HKO) headquarters and Tai Mo Shan weather station (955m above mean sea level). The blue bars indicate hourly precipitation recorded at HKO.

Societal impacts

The frigid conditions on 24 January have not been experienced in Hong Kong for generations. Many members of the public spent the Sunday outdoors to witness various winter weather phenomena. However, the rare wintry weather was not without its hazards. Icy road surfaces caused by freezing rain were observed on sections of road

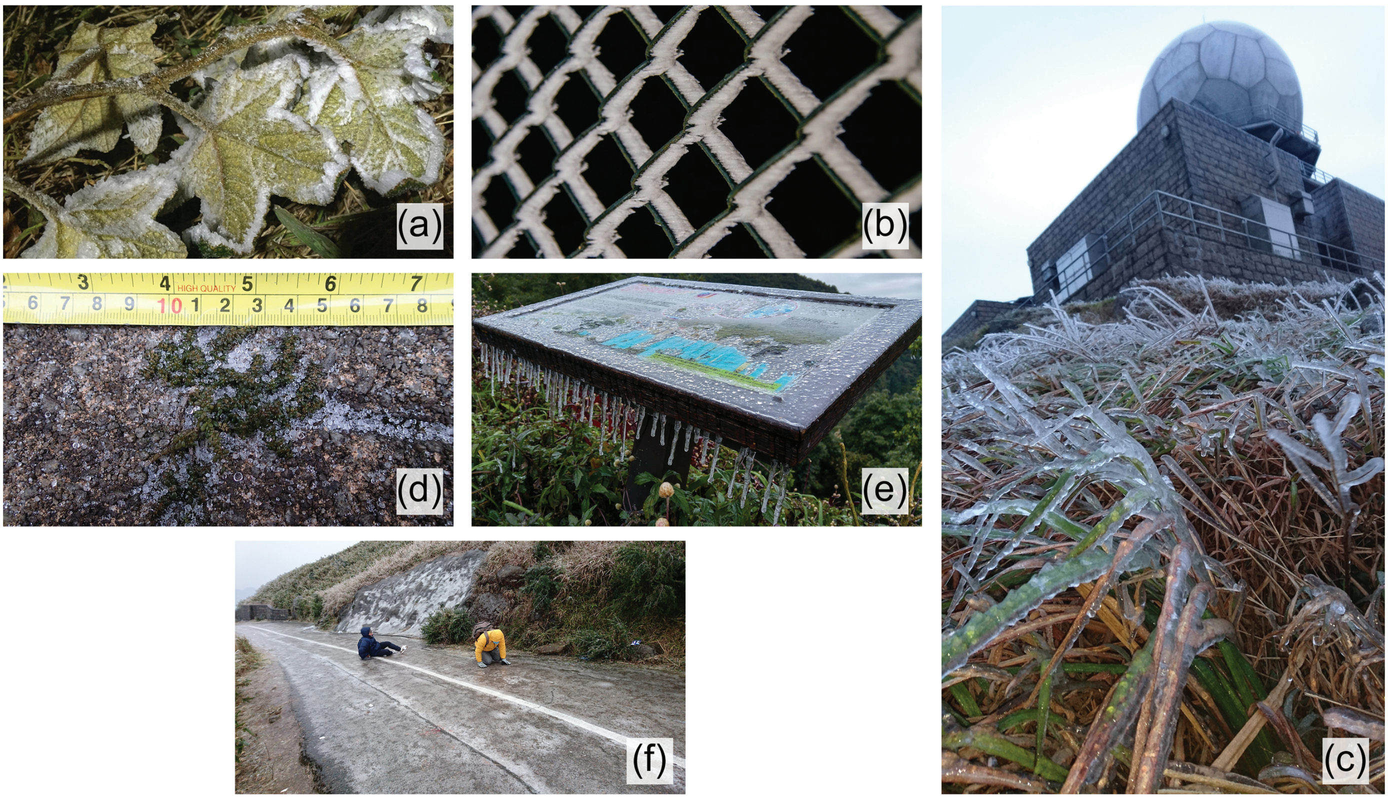

Figure 5. Winter weather phenomena observed in Hong Kong during the intense cold surge episode. (a) Frost at Tai Mo Shan and (b) rime at Tai Mo Shan on 23 January 2016; (c) icing at Tai Mo Shan; (d) ice pellets observed at Tai Mo Shan Radar Station; (e) icing due to freezing rain at Kadoorie Farm in Tai Po and (f) icy road at Tai Mo Shan on 24 January 2016. (© Wandering Photography (a,b); Y-s Li (c,d,f); and K-w Li (e).)

RMetS Royal Meteorological Society

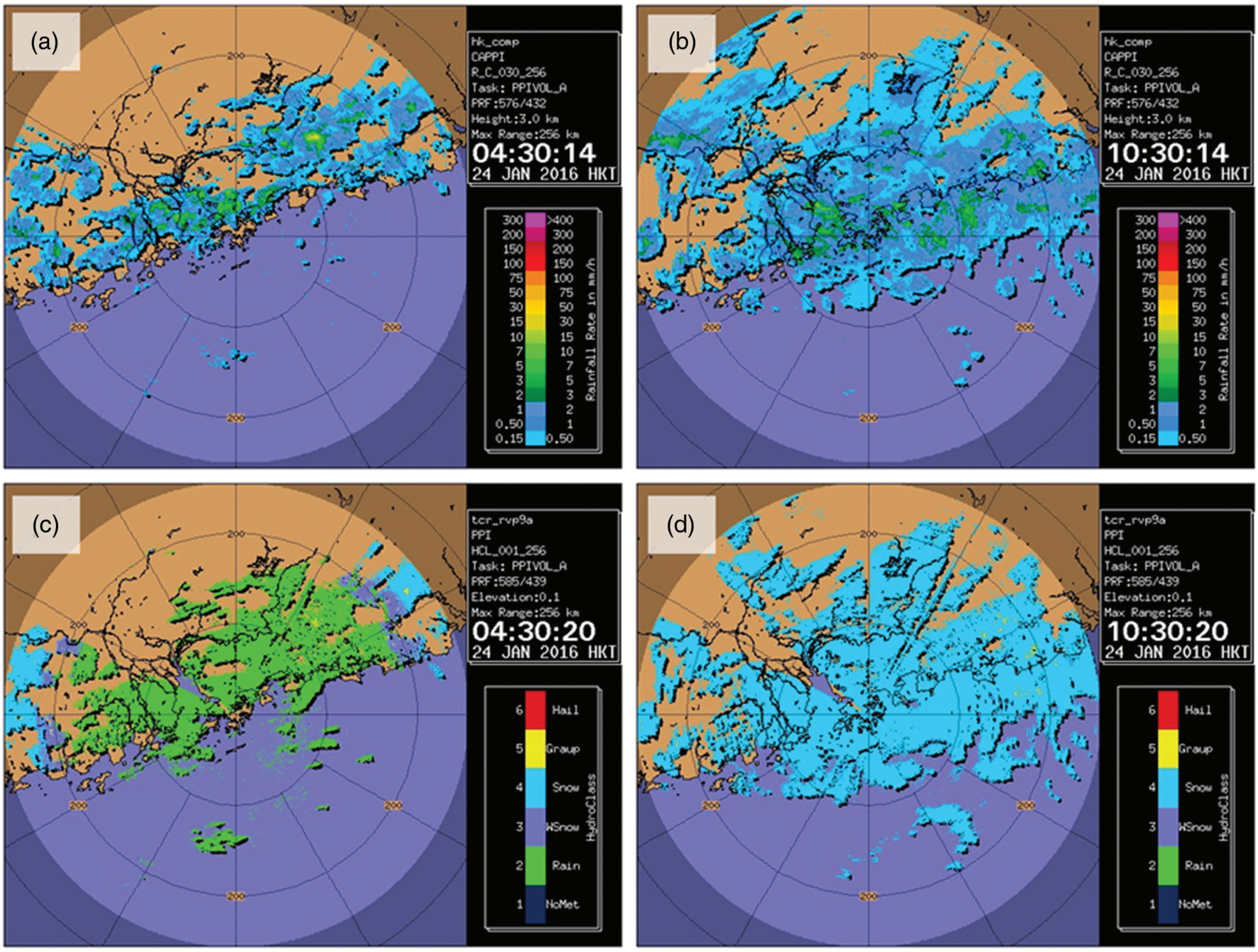

Figure 6. Doppler radar imagery at (a) 0430h and (b) 1030h on 24 January 2016. The corresponding hydrometeor classification imageries by the dual polarisation radar in Tate's Cairn are shown in (c) and (d) respectively.

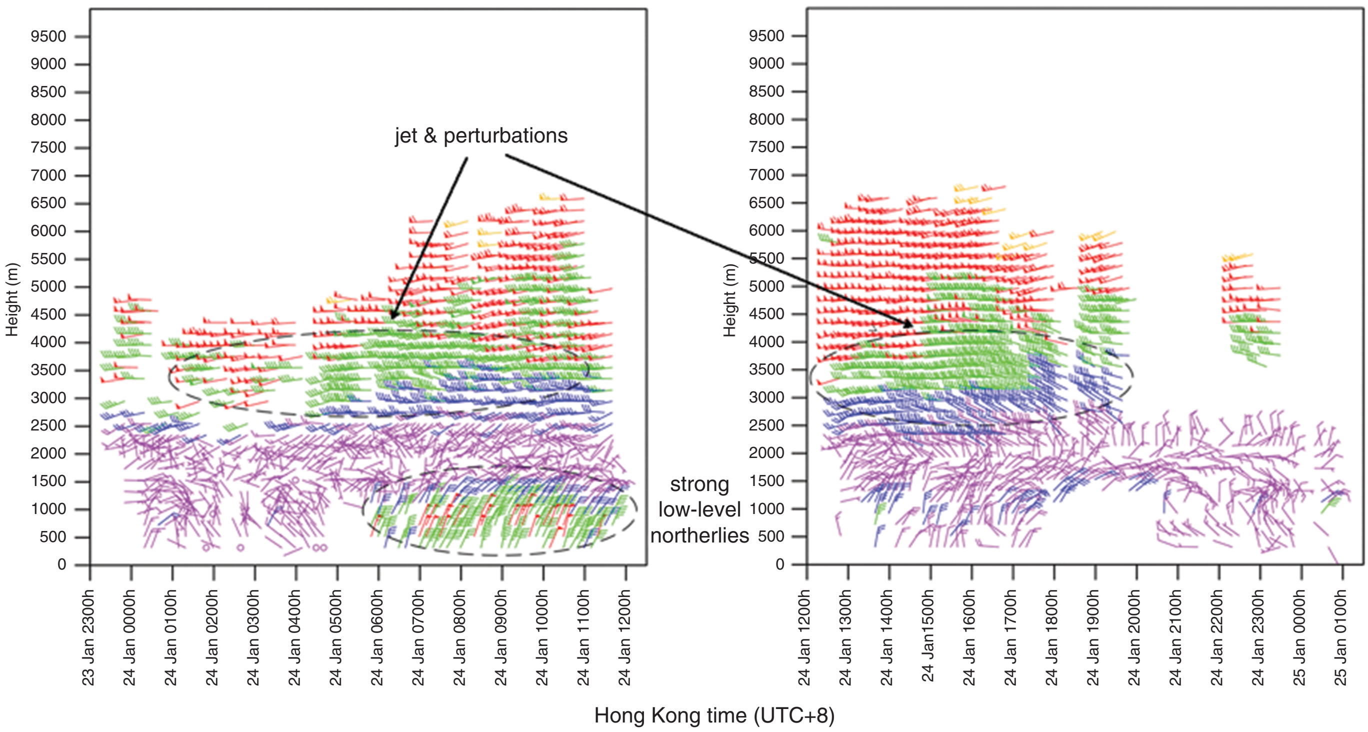

Figure 7. Wind profiler observations from Sham Shui Po, Hong Kong (see location in Figure 1) on 24 January 2016. Winds of strong, gale, storm and hurricane force are denoted by blue, green, red and orange wind barbs, respectively.

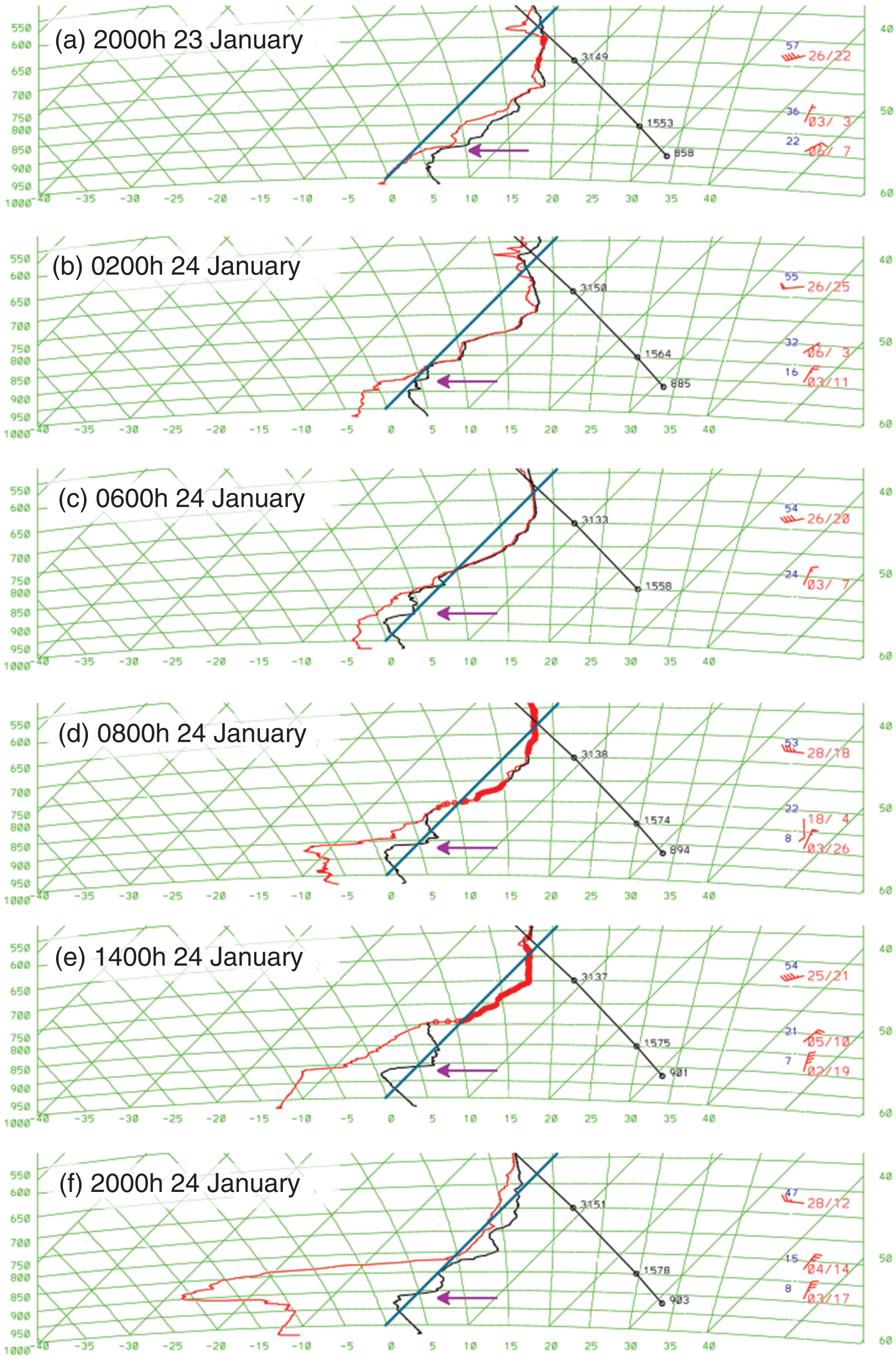

Figure 8. Profiles of upper-air sounding at King's Park Meteorological Station from 2000h on 23 January to 2000h on 24 January 2016. Only the temperature (black) and dew point (red) profiles below 600hPa level are shown. The 0°C isotherm is highlighted in blue, while the height of Tai Mo Shan is indicated by an arrow. The observed winds at selected levels are shown by wind barbs on the right hand side, with a full wind barb representing 5ms^{-1} and an arrowhead representing 25ms^{-1}.

with an elevation around or above 500m (Figure 5(f)). Those who were on the high ground, including hikers, 'chasers' of frost, rime and ice, and hundreds of runners of an international cross-country race which covered various hills in Hong Kong, encountered treacherous conditions, including slippery roads, sub-zero temperatures and significant wind chill effects. In the end, over 120 people were stranded on Tai Mo Shan and nearby peaks, where temperatures fell as low as −6°C at one point, and had to be rescued or led to safety by emergency services. In addition, more than 60 people, many of whom suffered from hypothermia, were taken to hospitals for treatment. Owing to the exceptionally cold weather and its impacts on the safety and health of students, kindergarten and primary school classes were suspended on 25 January.

Forecast challenges

Forecasting extreme weather events has always been a major challenge for public weather services, and this cold surge proved no exception to HKO. This includes forecasting the extremely low temperatures as well as the associated high-impact frozen precipitation phenomena in advance. Figure 9(a) shows the temperature forecasts for Hong Kong from various global numerical weather prediction (NWP) models around a week before the event and provides a comparison with observational data. Although the timing of arrival and moderation of the surge was generally well captured, as demonstrated by the predicted trends in the direct model output (DMO) values (shown by dashed lines), there were considerable discrepancies in the actual temperature values, and some models underestimated the drop in temperatures significantly. In addition, since DMO temperature predictions generally showed a systematic cold bias in the weeks prior to the cold surge (not shown), the post-processed model temperature predictions using Kalman filtering automatically 'corrected' the DMO predictions upwards (solid lines). Based on such temperature guidance, even though forecasters were able to alert the public of a cold episode around a week in advance, the forecasts at that time turned out to have overestimated the temperatures during the peak of the cold surge by several degrees Celsius.

Closer to the event, NWP models progressively strengthened the cold surge, lowered their temperature predictions and came into better agreement with each other. Forecasters thus revised their forecast temperatures downwards accordingly. However, model predictions 2 days before the peak of the surge (24 January) still overestimated the temperatures by about 2 degC (Figure 9(b)). Also, the consensus among models was that the minimum temperature during the episode would occur on 25 January, which turned out to be contrary to the actual temperature trends, in which the lowest temperature occurred on the previous day. As discussed in the previous sections, the observed temperature 'dips' on 24 January (see Figure 4) were primarily caused by evaporative cooling, when light yet persistent precipitation fell through a rather dry layer of air just above the surface. Although the light precipitation was generally captured by models, with slight differences in timing, it appeared that they could not fully represent the associated cooling effects. This could have contributed to the discrepancy in model temperature predictions.

Despite the discrepancy in the predictions of air (dry-bulb) temperatures, it is interesting to note that models captured the wet-bulb temperatures quite well. For the ECMWF 0000 UTC run on 22 January (blue line in Figure 9(c)), the wet-bulb temperature values up to the early hours of 24 January were slightly underestimated, but the predicted values for the rest of the day, during which Hong Kong was affected

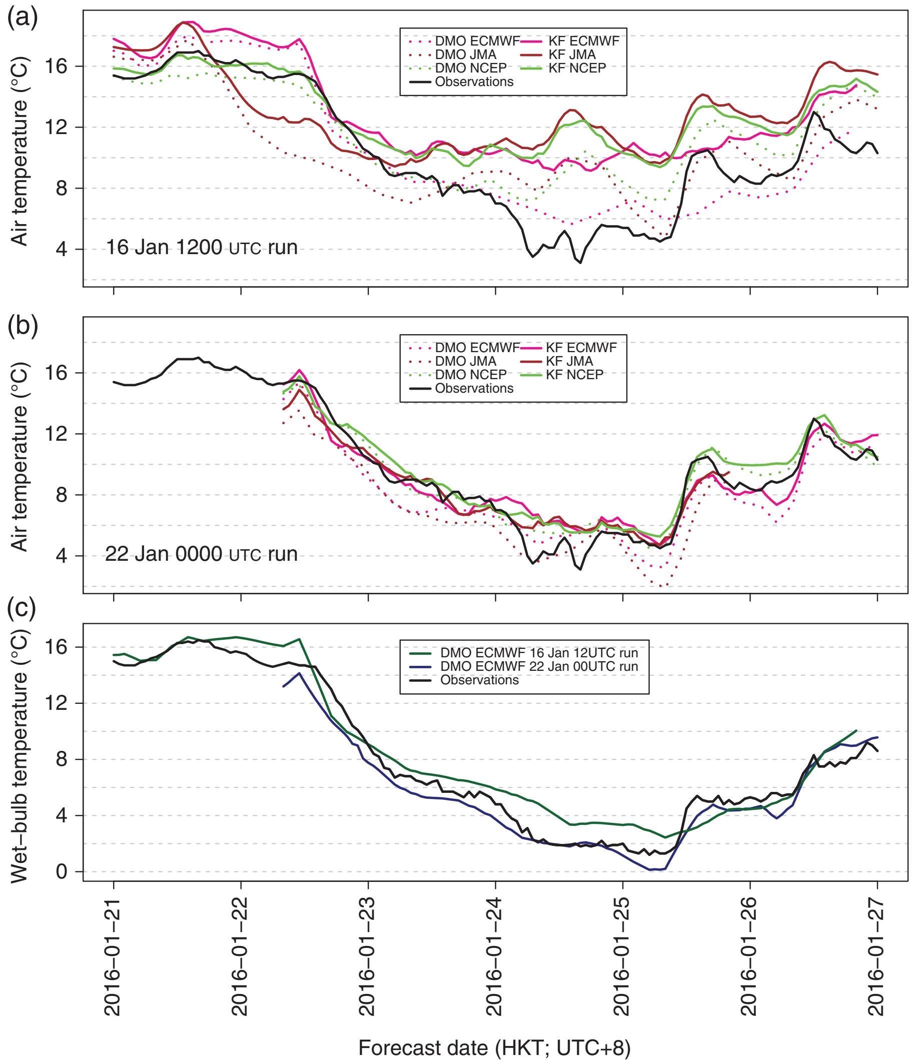

Figure 9. Forecast temperature time series of Hong Kong during the cold surge episode based on (a) the 1200 UTC run on 16 January and (b) the 0000 UTC run on 22 January, compared with observations (black). The dotted lines correspond to the direct model output (DMO), while the solid lines correspond to the Kalman-filtered (KF) data from deterministic runs by ECMWF, JMA and NCEP, as indicated in the legend. The ECMWF DMO wet-bulb temperature forecasts for these two runs are compared with observations in (c).

by precipitation, were very close to the observed values of around 2°C. As wet-bulb temperature indicates how low the air temperature could fall to due to evaporative cooling, air temperatures could reach such a level under persistent precipitation. This case demonstrated that under a scenario of a monsoon surge accompanied by precipitation, forecasters should be aware that the model-predicted air temperature field could have a warm bias. In estimating the minimum air temperature, some weight could be given to the model-predicted wet-bulb temperature, taking into account the intensity and persistence of the precipitation.

The assessment of the chance of frozen precipitation was even more challenging because the rarity of such events results in a lack of local empirical guidance. Model-predicted vertical temperature profiles were therefore the main tool for forecasters to use in making this assessment. Yet, like surface temperatures, the model temperature profiles during the cold surge also gradually changed closer to the event, adding uncertainties to the forecasts. Figure 10(a) shows the ECMWF's predicted profile for Hong Kong for the morning of 24 January, produced around a week before. Compared with the observed profile (Figure 8(d)), while the model managed to capture a saturated layer near the 700hPa level, the predicted profile below remained above 0°C, which suggested that any frozen precipitation should have melted to rain before reaching the sea level. The chance of snow was therefore considered low.

It should, however, be noted that model-predicted temperature profiles may not have sufficiently resolved low-level details and the effects of orography, and it might be necessary for forecasters to manually modify the profiles to account for this. An example is illustrated by the dashed lines in Figure 10(a) (Met Office, 1997, Chapter 5.5). Under the expected windy and cloudy conditions, turbulent mixing would produce an environmental lapse rate which tends to a dry adiabatic lapse rate within the mixing layer, while the dew point profile would tend to a constant value of humidity mixing ratio, as the moisture content within the mixing layer would become evenly distributed. The depth of the mixing layer depends mainly on terrain, wind speed and stability of the atmosphere. In the absence of a sharp inversion, the depth increases with wind speed. Adopting the empirical method developed by the Met Office (1997), a reasonable estimate of the depth given the strong surface winds is about 4000ft (1200m). In the modified profile, although the 'warm nose' at around the 700hPa level would still likely melt solid precipitation to rain droplets at low levels, the sub-zero layer further down caused by orographic turbulence would increase the risk of freezing precipitation on high ground.

Subsequent ECMWF model runs adjusted the temperature profile closer to freezing, but their dew point profiles based on the 0000 UTC run on 22 January 2016 also indicated a considerably drier low level compared with previous runs (Figure 10(b)). Two days before the peak of the cold surge, DMO of precipitation type hinted at the possibility of solid hydrometeors in the vicinity of Hong Kong (Figure 10(c)); however, given the limited model resolution, it was difficult to ascertain by how much the occurrence was related to terrain effects. This, together with inconsistencies in the temperature and humidity profiles between model runs, gave rise to uncertainties when assessing the chance of solid precipitation reaching ground during the operational forecast process. Indeed, a further slight shift of the temperature profile to the colder (warmer) side would mean that precipitation would reach ground as snow (rain). Nevertheless, in view of the increased chance of hazardous icy conditions over elevated areas, HKO issued a 'Special Weather Tip' via its webpage and mobile app on 20 January to alert the public that, in addition to the temperature drop associated with the upcoming cold surge, there would be a risk of icing and frost in the rural areas and on high ground. The message was reiterated in the press conference the following day when the Cold Weather Warning was issued. The Frost Warning was subsequently issued on 23 January to specifically alert farmers and other relevant parties of likely ground frost on high ground and over rural areas.

Use of ensemble NWP products

Despite the uncertainties in the severity of the cold surge indicated by successive runs of deterministic NWP models, some forecasting tools from the ensemble prediction systems (EPS) provided indications

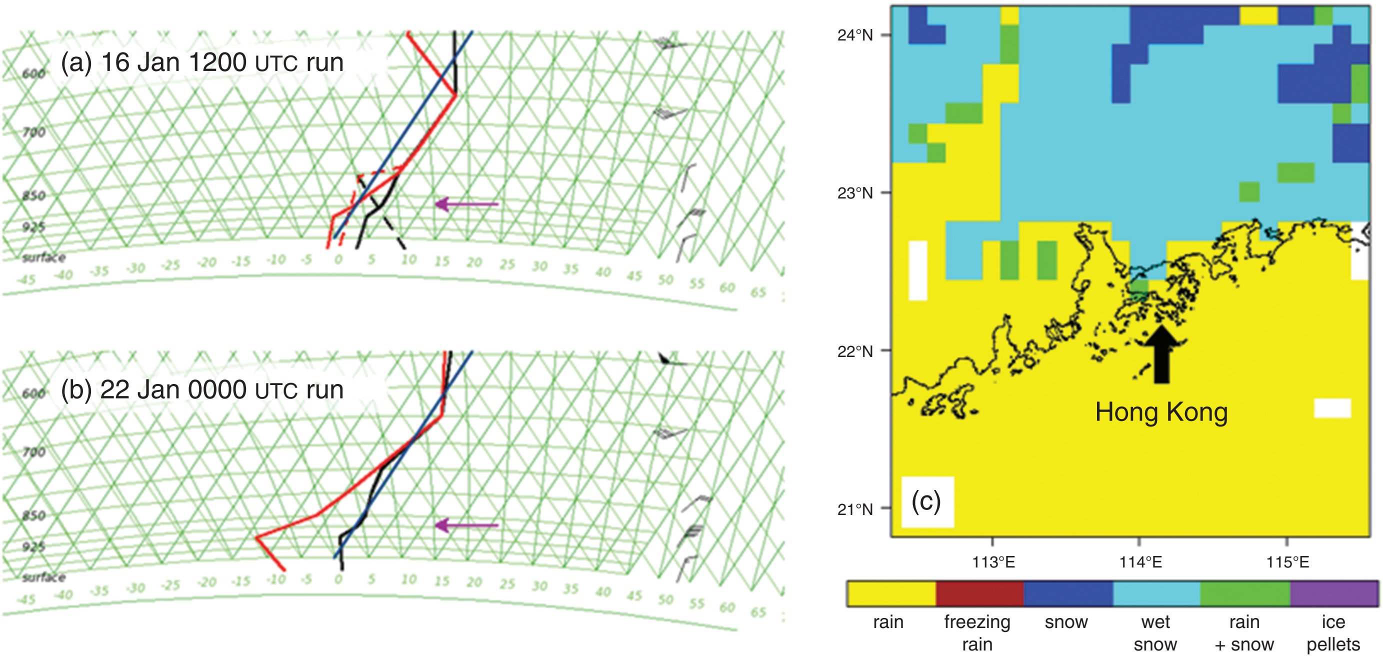

Figure 10. ECMWF forecast temperature (black solid lines) and dew point (red solid lines) profiles for 0800h on 24 January 2016 based on (a) 1200 UTC run on 16 January and (b) 0000 UTC run on 22 January. Modified profiles from (a), taking orographic turbulence mixing into account, are shown by dashed lines. The height of Tai Mo Shan is indicated by an arrow. The map in (c) shows the forecast precipitation type in the vicinity of Hong Kong for (b).

that a near record-breaking event could be forthcoming. These include the ECMWF Extreme Forecast Index (EFI), which measures the shift of the entire EPS forecast distribution from the model climate (Zsótér, 2006), and the complementary Shift of Tails (SOT) index, which measures the distance between the extreme members of the EPS from the tail of the model climate distribution (Tsonevsky and Richardson, 2012). The EFI value for minimum air temperatures in Hong Kong and its neighbouring areas for 24 January had been consistently very close or equal to −1 throughout (see Figure 11 for example), which means that all the EPS forecast values fell below the absolute minimum of the model climate. Meanwhile, the SOT value for quantile 10 for the same day was hovering around 2 for successive runs. This means that the most extreme 10% of the EPS members were below the 1st percentile by about twice the distance between the 10th and the 1st percentile of the model climate, thus reinforcing the signal given by the EFI. The actual extremity of the cold surge demonstrated the value of these products to forecasters in assessing the probability and severity of extreme weather events.

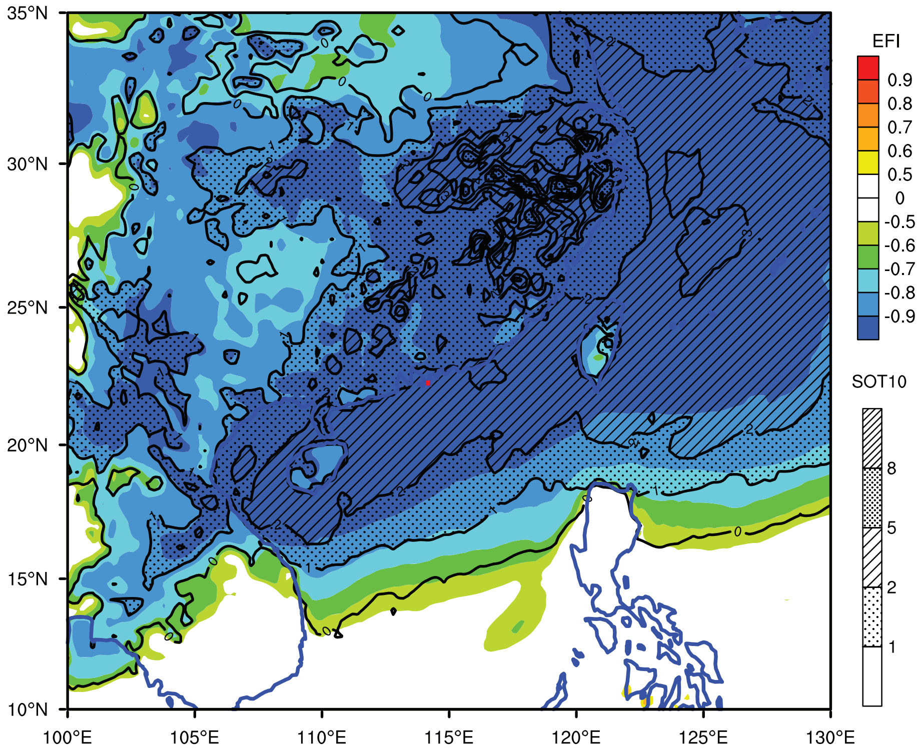

Figure 11. ECMWF Extreme Forecast Index (EFI; colour shading) and Shift of Tails (SOT) Index for the 10th percentile (contours and hatching) for minimum 2m air temperature between 0000 UTC on 24 January and 0000 UTC on 25 January 2016, based on the 1200 UTC run on 18 January. The location of Hong Kong is indicated by a red dot.

Conclusions

The cold surge in January 2016 was the most severe experienced in Hong Kong in decades, not only in terms of the extremely low temperatures it brought, but also in terms of the extent of the area affected by the rare frozen precipitation and the impacts of bitterly cold and icy conditions on the general public. Forecasting this event was highly challenging. Although the timing of the arrival and moderation of the surge was generally well predicted by NWP models days in advance, there were still significant discrepancies in the severity of the event, in particular in the extent of the temperature drop on 24 January due to evaporative cooling effects brought by persistent precipitation. There were also considerable uncertainties about the chance, let alone the type, of solid precipitation because of inconsistencies in the predicted temperature profiles between successive model runs, and in most cases they only indicated marginal conditions for solid precipitation being able to reach ground.

Occurring soon after the summer of 2015, in which the all-time maximum air temperature record at HKO headquarters was broken, this event served as a stark reminder of the importance of forecasting extreme weather events in order for the public to be well-prepared in advance. Weather forecasters should strive to enhance their forecasting skill by taking advantage of the continual improvement in NWP models and by making use of more sophisticated model output, such as the EFI and SOT indices from EPS, in assessing the probability and severity of extreme events. Efforts to communicate to the members of the public clearly the impacts and potential hazards of such events and the necessary actions and precautionary measures that need to be taken by them, especially for weather conditions which the community is not used to, are also required.

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