Towards predicting high-impact freezing rain events

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The term 'freezing rain' usually refers to the occurrence of supercooled rain drops falling onto a sub-freezing surface. The drops freeze on impact and can result in a glaze of ice, coating any objects that are below 0ºC, such as power lines, trees and road surfaces. When the precipitation is heavy and/or prolonged (sometimes referred to as an 'ice storm') the consequences can be severe, with disruption to air and ground transport, an increase in road accidents and hospital admissions, power loss due to collapsing power lines, and significant damage to infrastructure and vegetation (*Call*, 2010) – see Figure 1.

Such extreme events are fortunately rare, but freezing rain and drizzle are not uncommon during the winter months over Europe and North America and prediction of such high-impact weather is vital. A typical location is ahead of a surface warm front where an elevated layer of warm air is forced over a surface layer of very cold continental or Arctic air. If embedded in deep frontal cloud, snow particles melt in the warm elevated layer to form rain drops which then remain as supercooled liquid as they continue to fall into the sub-freezing near-surface layer below, until freezing on impact at the surface.

In the ECMWF Integrated Forecasting System (IFS) cycle 41r1, to be operational in early 2015, there are changes to the cloud and precipitation physics that allow an improved prediction of freezing rain. To this end a new 'precipitation type' diagnostic is added which includes the freezing rain category described here. In addition, there are new diagnostics for convective/stratiform precipitation rates valid at a particular time (rather than averaged or accumulated over a period) which are consistent with the precipitation type diagnostic.

A first evaluation of the freezing rain precipitation type as an experimental product shows promise for providing advance warning of severe freezing rain events. However, more experience needs to be gained over the coming winter and further evaluation of the probability of freezing rain in medium-range ensemble forecasts is required.

Freezing rain events

Figure 2 shows schematics of the vertical structure of temperature and precipitation type for four scenarios, each of which is associated with a different precipitation type at the surface. Figures 2a and 2b represent relatively straightforward situations in which the surface precipitation type is, respectively, snow and a rain/snow mix in the melting layer. The former scenario arises when temperatures are sub-zero at all levels, and the latter when

Figure 1 The impacts on transport, power lines and forest damage due to a severe freezing rain event in Slovenia in early February 2014. (Acknowledgements: top left/right and bottom left - Srdjan Zivulovic/Reuters, bottom right - Marko Korosec/Solent News).

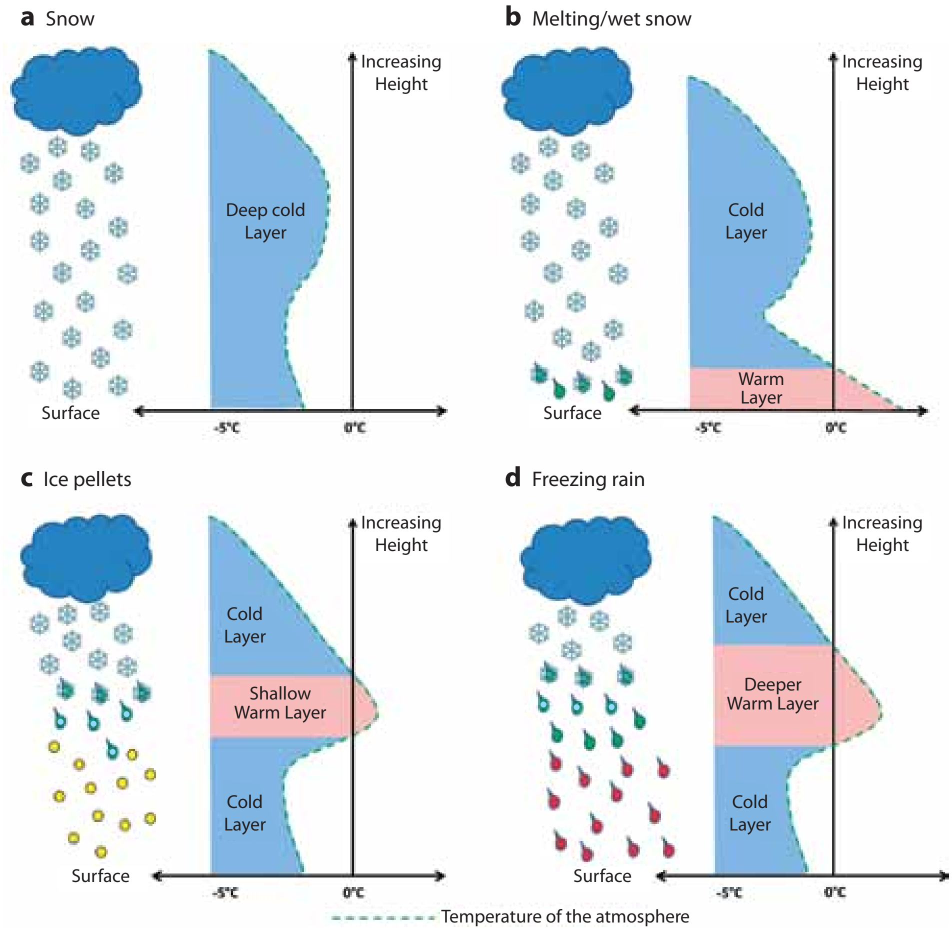


Figure 2 Schematic of typical temperature profiles for different precipitation types: (a) snow, (b) melting/wet snow, (c) ice pellets and (d) freezing rain (all assuming 100% relative humidity).

the freezing level is near the surface. The more complex scenarios in Figures 2c and 2d show an elevated warm layer with a sub-freezing layer below. In this case, ice pellets or freezing rain can occur. As a snow particle falls into the elevated warm layer it will start to melt and will keep falling as the melting process continues. If the snow particle does not completely melt before it reaches the layer of sub-freezing temperatures, it will still contain an ice core. This acts as an ice nucleus and facilitates rapid freezing of the whole particle, forming a denser more homogeneous ice particle called an ice pellet.

However, if the snow particle has completely melted when it reaches the sub-freezing layer it will remain as a supercooled drop. If the air is only a few degrees below freezing near the surface, it may not be cold enough for heterogeneous freezing of the drop and it will reach the surface as supercooled water. Only if the near-surface cold layer is particularly cold and deep is refreezing likely to occur due to impurities in the drop acting as potential ice nuclei. Thus the melting process and the depth and temperature of the sub-freezing layer are all key to the formation of freezing rain at the surface, as discussed by *Czys et al*. (1996).

Freezing rain events typically occur during winter where a sub-tropical or maritime warm air mass meets a cold Arctic or continental air mass, often ahead of a warm front. The wind profile changing with height leads to advection of a warm layer above a sub-freezing layer near the surface. Such regions can cover many hundreds of kilometres with precipitation type changing perpendicular to the front from rain to freezing rain (Figure 2d) and then to snow (Figure 2a). Sometimes there is a narrow band of ice pellets in-between the freezing rain and the snow (Figure 2c) at the shallow end of the elevated warm layer.

Carrière et al. (2000) describe a climatological study of surface freezing precipitation from SYNOP messages over Europe during three winters from 1995 to 1998. They found freezing precipitation is most frequent during the months of December to February and when near-surface temperatures are between -5°C and 0°C. Freezing rain and freezing drizzle were observed in up to 1% of the SYNOP reports during this period, commonly occurring in regions where the climate is more continental, over Germany and Central Europe. Ice pellets were relatively rarely observed. The most frequent mechanism for freezing precipitation formation was snow melting in an elevated warm layer and refreezing below. A second mechanism in which the collision-coalescence process in supercooled liquid water cloud produces freezing drizzle also occurred relatively frequently.

Representing precipitation type in the IFS

To be able to predict the correct precipitation type at the surface, including freezing rain, an atmospheric model needs to predict the vertical temperature profile and the amount of precipitation sufficiently accurately, but must also clearly include the correct physics for the melting and refreezing processes. Since the major upgrade to the IFS cloud scheme in the operational model in November 2010 (IFS cycle 36r4), rain and snow have been represented as separate prognostic variables, with parametrizations of snow melting for wet-bulb temperatures greater than 0ºC, rain freezing for temperatures below 0ºC, and precipitation evaporation. So for the case of a freezing rain temperature profile with this model physics, the snow melts in the warm air and then rapidly refreezes in the low-level sub-freezing layer, reaching the ground as snow. Thus the processes that lead to freezing rain at the surface are not adequately represented.

In the new version of the cloud and precipitation parametrization, the freezing rain process for elevated warm layers is modified. It includes a more representative timescale for the refreezing of rain drops which depends on the temperature and crucially on whether the snow particles have completely melted or not (*Zerr*, 1997).

- If most of the snow particles have completely melted by the time they reach the base of the warm layer aloft, the refreezing process is slow and supercooled rain at the surface is diagnosed.
- If the majority of snow particles have not completely melted in the warm layer aloft, then refreezing is rapid and a precipitation type of ice pellets is diagnosed at the surface.

Whether the precipitation refreezes or not in the cold air below also affects the temperature profile, resulting in colder temperatures in the layer if the particles remain as supercooled water. The latent heat of fusion is instead transferred to the surface with the rain freezing on impact and a relative warming of the surface and near-surface temperature.

In the IFS model the melting and refreezing parametrizations must be formulated in terms of the two prognostic variables for precipitation: rain and snow. The precipitation type (rain, snow, freezing rain, ice pellets, wet snow or mixed rain/snow) is diagnosed from the ratio of rain and snow at the surface and the profile of precipitation and temperature above (see Box A for more detail). Note that although the physics of melting and refreezing allow the prediction of supercooled rain at the surface, the generation of drizzle particles from supercooled liquid water cloud, when there is no warm layer,

Parametrization of the physics of supercooled rain formation

A

The melting and refreezing of precipitation particles are the key physical processes for the formation of freezing rain. The parametrization of these processes in the IFS is briefly described below.

Melting process

The rate of snow melting can be determined using thermal heat balance, considering the latent heat due to the melting of a snow particle (latent heat of fusion) and the latent heat due to vapour transfer from the particle into the atmosphere (sublimation). Integrating over an assumed particle size spectrum gives a melting rate that is proportional to the wet-bulb temperature difference from 0ºC. The complexities of the physics at the microscale and wide range of particle sizes can be represented more simply with an effective melting timescale.

The melting process is parametrized in the IFS by allowing a grid box containing precipitating snow to cool towards a wet-bulb temperature of 0ºC through the latent heat of melting over a timescale τ:

$$\text{Melting rate} = -\frac{C_p}{L_{fus}}\left(\frac{T_w - T_0}{\tau}\right)$$

where C_p is the specific heat capacity of water, L_{fus} is the latent heat of fusion (melting), T_w is the wet-bulb temperature of the air in degrees Celsius, and T_0 equals 0ºC.

This parametrization captures the essential dependency on the temperature difference from 0ºC, the effect of evaporative cooling in subsaturated air through the use of wet-bulb temperature, and the depth of the melting layer through the relaxation timescale. The melting parametrization is the same as in the current operational forecasts which determines whether surface precipitation is rain, snow or mixed when the temperature is close to 0ºC.

Refreezing process

If the warm layer is shallow and the majority of the rain drops still contain an ice core, then they will refreeze rapidly when entering the sub-freezing layer below. The refreezing rate (transfer of mass from the rain category to the snow category) is uncertain, but for now it is parametrized with the same functional form and timescale as the melting rate described above. It is assumed at least 20% of the precipitation mass must be in the ice phase at the base of the elevated warm layer for refreezing to be rapid, otherwise the majority of rain drops are assumed to not contain an ice core and refreezing will occur at a much slower rate through heterogeneous ice nucleation. In the latter case an order of magnitude longer timescale is used for the refreezing rate, so the supercooled rain can still refreeze before reaching the surface if the near-surface subfreezing layer is very cold and/or deep.

Freezing rain is diagnosed if the 2-metre temperature is below 0ºC, at least 80% of the precipitation mass is in the liquid phase at the base of the elevated warm layer and at least 20% remains as supercooled rain when it reaches the surface. Ice pellets are diagnosed if the percentage of precipitation mass in the ice phase at the base of the warm layer is between 20% and 80%, otherwise the precipitation is classed as snow. In regions of freezing rain, the reduced refreezing in the new physics leads to a relative cooling of the lower-tropospheric air mass (less heating) and warming of the surface and near-surface temperature because the latent heat released during refreezing is instead transferred to the surface.

Clearly the form of the melting and freezing rate parametrizations and choice of thresholds are a significant simplification of many complex processes that could be improved in the future. However, this describes an initial implementation that captures the first order characteristics of the precipitation melting and refreezing processes.

is not yet represented. Supercooled drizzle drops resulting in 'freezing drizzle' at the surface, although not as severe as heavy freezing rain events, is still an important forecasting issue and will be addressed in the future.

Evaluation of IFS freezing rain prediction: case studies

A case study of a severe freezing rain event over Slovenia, Croatia and surrounding areas in early February 2014 is used to illustrate the potential for the IFS to predict such events. Another example from December 2013 over North America is also described.

Case study 1: February 2014, Slovenia

Heavy snow and freezing rain affected Slovenia and the surrounding region over several days from 31 January to 5 February 2014 with widespread accumulations of 10 to 50 mm and locally above 100 mm. The worst affected area was the south-western region of the country, especially around the city of Postojna. During the event, the freezing rain coated all surfaces in a thick layer of ice (photos of this event have already been shown in Figure 1). There were reports of more than 300 broken power lines and 25% of Slovenian residents were without electricity, heating and water. It was also estimated that 40% of Alpine forests were destroyed by the weight of ice accumulation on the trees.

Figure 3 shows the synoptic situation at 00 UTC on 2 February with an occluded front over northern Italy, Slovenia and Croatia, marking the boundary where cold continental air could be undercutting the warmer air to the south, giving a situation where freezing rain is possible. A second occluded front is present to the north, through Germany and across the Baltic Sea to southern Sweden, which moved eastward through the day. Also shown is the sounding from Ljubljana at 05 UTC on 2 February showing the elevated warm layer above 0ºC with winds from the south-east and the sub-freezing layer below 860 hPa with lighter winds from the north-east.

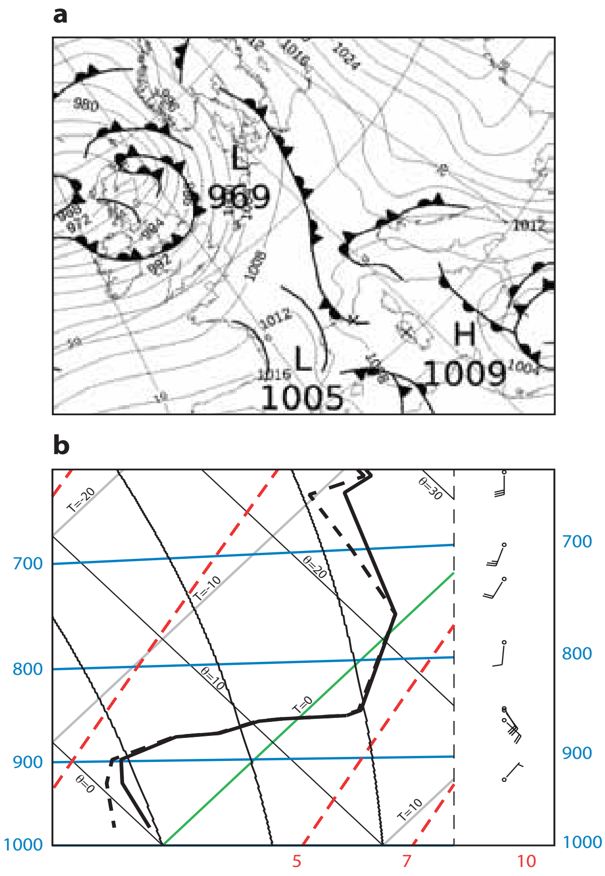


Figure 3 (a) UK Met Office analysis for 00 UTC on 2 February 2014 showing the occluded fronts over central Europe. (b) Tephigram at 05 UTC from Ljubljana in Slovenia showing the elevated warm layer above 0ºC between 780 hPa and 860 hPa with winds from the south-east and the sub-freezing layer with light winds below. The tephigram shows the temperature (solid black) and dew point temperature (dashed black) profiles and isopleths for potential temperature (θ), temperature (*T*), mixing ratio (dashed red) and pressure (blue). The 0ºC isotherm (*T*=0) is green.

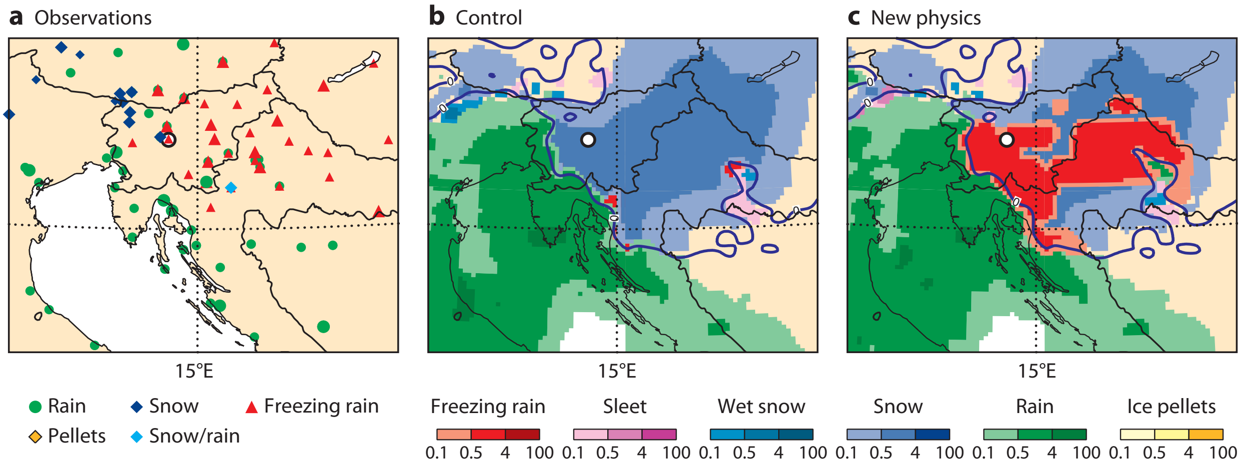


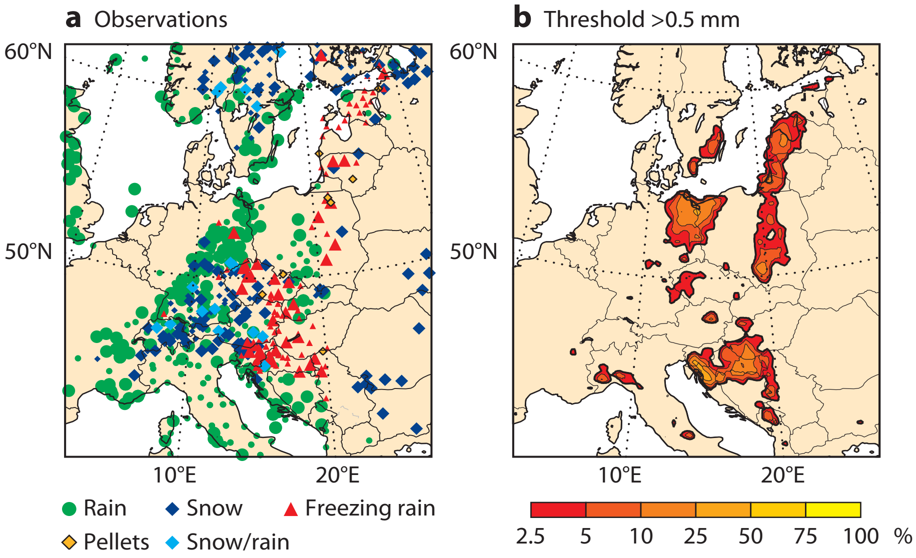
Figure 4 A significant freezing rain event occurred in Slovenia and Croatia in early February 2014. (a) The observed precipitation type from SYNOP reports at 06 and 12 UTC on 2 February 2014. (b) Precipitation rate and type from the short-range HRES initialised at 00 UTC and valid for 09 UTC for the version of the model operational at the time (i.e. the control). (c) As (b), but with the new physics. The forecast with the new physics gives a clear signal of relatively heavy freezing rain in the region of the most affected areas. Shading in (b) and (c) is for 0.1, 0.5 and 4 mm hr^{-1} and the thick blue contour is the 2-metre temperature 0ºC isotherm. The location of Ljubljana is marked with a circle.

As an example, a comparison of observed and model-predicted precipitation type for the same day during the event is shown in Figure 4. The SYNOP reports of precipitation type at 6 and 12 UTC on 2 February show widespread observations of freezing rain across Slovenia and into northern Croatia. To highlight the impact of the new physics, short-range predictions of precipitation type from the IFS high-resolution forecast (HRES) initialized at 00 UTC that morning are shown for 09 UTC for the operational model as the control (Figure 4b) and with the new physics (Figure 4c). The new precipitation type diagnostic shows that the operational model was unable to predict the extent of the freezing rain event, instead predicting widespread surface snowfall, whereas the model with the new physics is able to predict freezing rain over much of Slovenia and northern Croatia in general agreement with the observations.

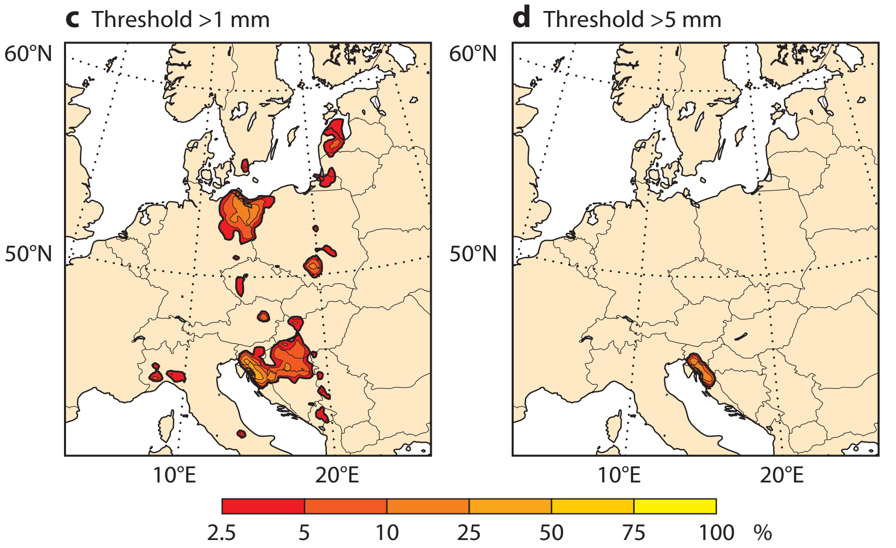
Medium-range predictions are more usefully expressed in terms of the probability of freezing rain accumulation over a specified threshold. Again, focusing on the same day as an example, Figure 5a shows the observed SYNOP reports overlaid at 00, 06, 12 and 18 UTC during the 24-hour period on 2 February 2014 over a larger region of Europe.

Observations of freezing rain were quite common over central Europe, notably in a north–south orientated band crossing Poland and the Baltic States. These observations were associated with the northern occluded front seen on Figure 3a. The other panels in the figure show the probability of freezing rain for accumulations above different thresholds on 2 February 2014 for day 3 of the ensemble forecast (ENS).

For a low threshold of 0.5 mm (Figure 5b), probabilities of around 20% are predicted for the regions in central Europe,


a Observations

b Threshold >0.5 mm


c Threshold >1 mm

d Threshold >5 mm

Figure 5 (a) Observations from SYNOP reports of precipitation type on 2 February 2014. Probability (%) of freezing rain accumulation greater than the specified threshold on day 3 of the forecast valid on 2 February 2014 (48-hour to 72-hour period) from the ensemble forecast (ENS) for (b) > 0.5 mm, (c) > 1 mm and (d) >5 mm. Small accumulations are widespread in general agreement with the observations apart from on the Polish/German border. The highest accumulations are indicated over part of Slovenia and Croatia, close to the region where the significant freezing rain accumulations were observed.

the north–south band of freezing rain across central Poland and the Baltic states, and a region either side of the Baltic Sea (Sweden/Germany/Poland). The highest probabilities of over 30% are present for Slovenia and Croatia. Although the Germany/Poland/Sweden Baltic Sea region was not in the observed SYNOP reports, there was a clear band of freezing precipitation further east as noted above.

Considering the 1 mm and 5 mm thresholds in Figures 5c and 5d respectively, the focus shifts to Slovenia and northern Croatia where some of the heaviest freezing rain and devastating impacts occurred. However, the accumulations and the probabilities are relatively low and this may be partly due to the resolution of the ENS. The event in Slovenia is barely resolved in the T639 (32 km) resolution ensemble, but this will improve with the ENS resolution upgrade to 20 km planned for 2015.

Case study 2: December 2013, south-eastern Canada

From 21 to 22 December 2013 a mix of snow, ice pellets and freezing rain affected the north-eastern USA and south-eastern Canada, causing significant disruption, power loss to 500,000 households, flight delays and highway accidents on one of the busiest travel weekends of the year.

Figure 6a shows the SYNOP reports of precipitation type at 06 and 12 UTC on 22 December. Similar to the European case study, the short-range HRES with new physics is able to predict a long band of freezing rain in the region where this is observed (Figure 6c), whereas the operational model used at the time predicts snow with only a few isolated spots of freezing rain along the rain/snow boundary (Figure 6b). Note also that with the new physics there is a narrow band of ice pellets predicted along the shallow leading edge of the elevated warm layer, where the snow particles

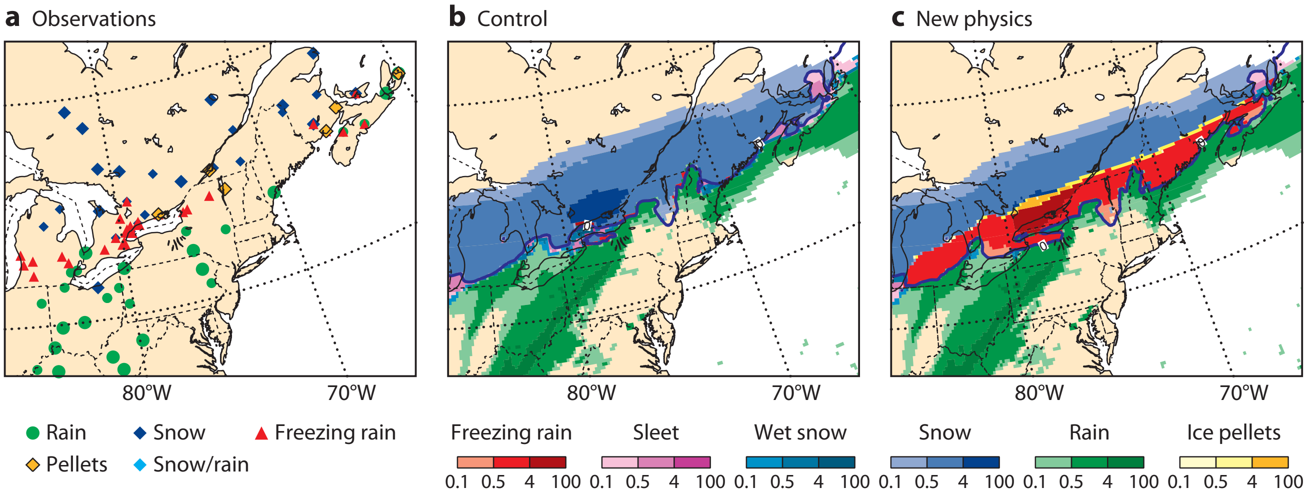


Figure 6 A significant freezing rain event over eastern North America on 22 December 2013. (a) Observations from SYNOP and METAR reports of precipitation type at 06 and 12 UTC. Precipitation rate and type from the 9-hour forecast from the 00 UTC analysis on 22 December 2013 using (b) the current operational model as the control and (c) the model with the new physics. Shading in (b) and (c) is for 0.1, 0.5 and 4 mm hr^{-1} and the thick blue contour is the 2-metre 0°C isotherm.

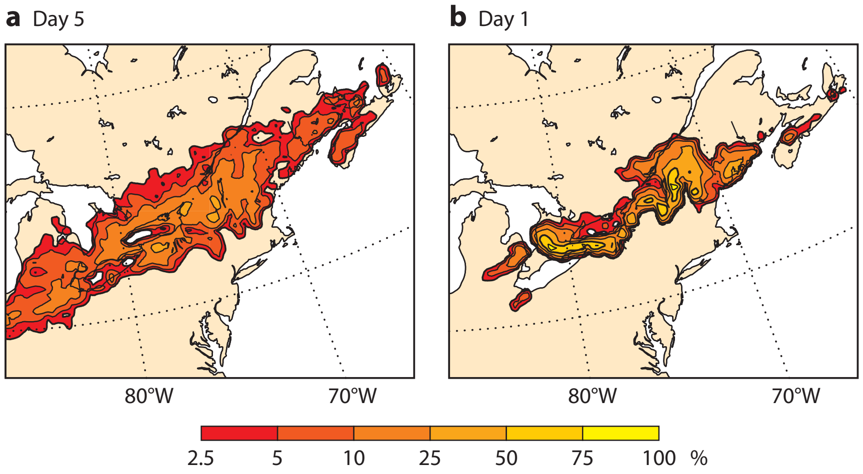


Figure 7 Probability (%) of freezing rain accumulation of more than 5 mm during the 24 hour period on 22 December 2013 from ENS for (a) five-day and (b) one-day forecast lead times, showing low probabilities for the longer lead time in the region where freezing rain was observed (Figure 6a) and probabilities increasing significantly at shorter lead times.

falling through do not completely melt and refreeze rapidly to solid particles in the cold air below. Although there are only a few SYNOP reports of ice pellets, the narrow band is unlikely to be sampled well. Case studies of other events have observed this band of ice pellets along the boundary between snow and freezing rain (*Czys et al.*, 1996).

The probability of freezing rain accumulations greater than 5 mm in the ENS with the new physics at two lead times is shown in Figure 7 for this case. At a lead time of five days, there is a band of low probability (10%–25%) of freezing rain in the right region. Probabilities increase substantially for a one-day lead time and become more focused, with values reaching more than 50% in the approximate region of the observed freezing rain, providing potentially useful information that a significant freezing rain event was expected in the area.

Outlook

Freezing rain can cause extensive disruption and damage when it is heavy and/or prolonged, and even small amounts can be very problematic, so it is an important high-impact weather phenomenon to forecast. The IFS cloud and precipitation physics is modified in IFS cycle 40r3 to represent the physics of supercooled rain and a new precipitation type diagnostic is made available to signify the presence of freezing rain in model output, as well as rain, snow, wet snow, mixed rain/snow and ice pellets. Freezing rain predictions have been evaluated for a number of case studies, two of which are shown here, to highlight the potential for the IFS to provide guidance in predicting these events.

Although the basic physics of freezing rain is present in IFS cycle 40r3, freezing drizzle associated with the coalescence of supercooled liquid water drops in relatively shallow sub-freezing boundary layer cloud is not yet represented. Future developments to the IFS will include representation of freezing drizzle production and potentially more sophisticated microphysics of the melting and freezing processes. An appropriate representation of the uncertainties in freezing rain processes is a further topic for investigation to help provide more reliable probabilities of occurrence in the ensemble.

At this stage, precipitation type with the freezing rain category is considered to be an experimental product and must be used in conjunction with the amount of precipitation to be a useful indicator of freezing rain events. Although the initial evaluation for a number of case studies shows promise, further work is required to assess the ability of the IFS to predict the probability of freezing rain at different forecast ranges – feedback about the experimental products is welcome.

FURTHER READING

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