Numerical Weather Prediction

Developing an improved precipitation type diagnosis scheme for Nimrod

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1. Summary

Verifications of Nimrod forecasts of precipitation type have been assessed and several shortcomings were identified. A set of experiments was then devised to address these. The experiments were run on data assembled for 15 dates when hail, sleet, snow and freezing precipitation occurred. Objective and subjective results provided insights into the response to code changes and demonstrated that a new scheme based on unpublished work by Beth Hewitt in 1998 could give the most improvement to precipitation type forecasts. Consequently a parallel trial of the new code was run on the Nimrod development system during the winter 2002/3 and assessed to inform a decision for full operational implementation.

2. Background

Forecasts of precipitation type have been produced operationally in Nimrod since 1995 for an ever increasing customer base (Golding, 1998). However, there remains several important deficiencies. The occurrence of sleet and snow is often over-forecast, particularly sleet. Freezing rain is not handled well and indeed the physical assumptions upon which freezing rain forecasts are based are believed to be incorrect. Work has been done in order to improve hail prediction although identifying the likely size of hail stones has not been undertaken except in very general terms. All of these weather elements (snow, hail and freezing rain) contribute to severe winter weather conditions in the UK.

A revised version of the precipitation-type forecast was developed and tested on case-studies by Beth Hewitt in 1997 but was never implemented. Rather than using the current hierarchical decision tree (see section 4), this estimated the probability of each precipitation type, then selected that with the highest probability. A completely separate trial version was developed by Richard Standing but again was never implemented. This changed the present three categories of hail (soft hail, hail, large hail) into ‘hail with snow’, ‘hail with rain’ and ‘large hail with rain’. The rationale for the change was that significant snowfall could occur from hail showers in winter but the uninformed customer for the forecast might think that only hail would occur (or perhaps hail and rain).

With the introduction of a Severe Weather Programme in the Met Office in 2002, the opportunity was taken to completely review the precipitation type code and forecasts on Nimrod, aiming to provide improved forecasts of snow, sleet, hail and freezing rain. The work of Beth Hewitt (BH) and Richard Standing (RS) was also reviewed as was the possibility of providing probability forecasts for each type which would give us much more flexibility to meet future customer needs. This would also fit in with the overall Met Office drive to base forecasts on probability outcomes. In particular the following activities were pursued:

- The operational verifications were reviewed.
- A suitable test bed of case study data was identified and assembled.
- The present freezing rain formulation was reviewed and modifications made and tested.
- Several alternative code formulations for all precipitation types were devised and tested (including those of BH and RS).
- A prediction of hail size was introduced.

The remainder of this report discusses the outcome of these activities and the performance of a new system in a winter trial.

3. Verification and case study data

First task was to look at operational monthly summaries from the Nimrod verification of precipitation type. For freezing rain these showed very low hit rates with a forecast bias that was relatively large and an unusually large number of observations over the UK for such a rare phenomenon.

It was then found that these files were in error due to a programming bug in the program that produces the raw hourly verification data from which the monthly summaries are derived. This bug was subsequently corrected operationally on 10/4/02. The monthly summaries were then re-generated using available Nimrod T+0 raw verification fields only as these were the only ones which were correct (due to the nature of the bug). A representative sample of the revised summaries for January to March 2000 is given in Appendix 1.

This sample is quite interesting as it reveals a number of characteristics of operational Nimrod forecasts of precipitation type.

(a) Looking at each row for observed snow it is clear that Nimrod has a high hit rate and a low miss rate for snow. However, looking at the percentage forecast occasions in the columns Nimrod also has a relatively high false alarm rate. In the sample the average monthly hit rate was 79% and the average false alarm rate was 57%. The conclusion is that snow is generally over-forecast with an average sample monthly bias of 1.62 .

(b) Sleet is a little more complicated since in Nimrod sleet should be interpreted as ‘mixed’ precipitation in the sense that in hilly areas snow may occur at higher levels in a 15Km pixel and rain lower down. Thus in the verification it can be argued that when Nimrod forecasts ‘mixed precipitation’ snow and sleet should be observed roughly the same number of times that rain is observed. This is not the case. Rain is observed 3 to 4 times more often providing the conclusion that sleet is also over-forecast and more so than snow.

(c) Rain as can be expected is generally well predicted. In our sample illustration the average hit rate is 89% with a false alarm rate of 12%. So there are some mis-classifications.

(d) The monthly average hit rate for drizzle is 18% with a false alarm rate of 60%. The conclusion is that drizzle is generally under-forecast and often mis-classified.

(e) Freezing rain is rare with just 6 occasions recorded in the Nimrod verifications for January to March. In the same period freezing rain was forecast on 44 occasions giving a bias of 7.33 . The hit rate was zero highlighting the difficulty of forecasting freezing rain to high precision.

(f) Looking at this sample it appears that hail is over-forecast almost by a factor of 2. However, on 1/9/01 a change was made to the Nimrod software that derives maximum vertical velocity (w) from CAPE. Instead of w = SQRT(2.0 x CAPE) , w = 0.5 x SQRT(2.0 x CAPE) was used. This greatly reduced the number of occasions hail was forecast to the extent that there is now generally an under-prediction. Given that the observing network will inevitably miss hail-falls, this is not desirable. The bias for 11/01 to 03/02 is 0.83 .

Looking at freezing rain or drizzle in more detail, occasions between 01/01/00 and 31/03/02 when freezing precipitation (F) was observed were identified using the MetDB (Met Office data base). These occasions are listed in Table 1 with some additional observational elements.

Block	Stn	Lat	Lon	Ht	Year	Mon	Day	Hr	Min	Dir	Spd	Dry	Dew	Wx
3	138	56.0	-4.8	5	2000	1	8	21	0	240	9	277.6	273.4	67
3	402	52.8	-4.6	253	2000	1	13	8	0	0	0	************		67
3	791	51.4	0.8	25	2000	1	22	9	0	330	7	278.2	276.8	56
3	262	55.0	-1.4	30	2000	1	22	12	0	330	23	276.5	275.0	56
~~3~~	~~824~~	~~50.6~~	~~-4.5~~	~~233~~	~~2000~~	~~2~~	~~29~~	~~9~~	~~0~~	~~270~~	~~12~~	~~280.0~~	~~278.9~~	~~57~~
3	8	59.5	-1.6	57	2000	3	24	10	0	120	12	278.0	276.6	56
3	281	54.4	-0.7	262	2000	4	15	18	0	30	4	274.0	273.2	66
~~3~~	~~957~~	~~52.2~~	~~-6.3~~	~~23~~	~~2000~~	~~11~~	~~15~~	~~17~~	~~0~~	~~200~~	~~10~~	~~282.5~~	~~281.9~~	~~57~~
~~3~~	~~726~~	~~51.5~~	~~-2.6~~	~~11~~	~~2000~~	~~11~~	~~24~~	~~16~~	~~0~~	~~200~~	~~2~~	~~281.3~~	~~279.6~~	~~66~~
~~3~~	~~8~~	~~59.5~~	~~-1.6~~	~~57~~	~~2000~~	~~12~~	~~8~~	~~18~~	~~0~~	~~70~~	~~19~~	~~281.3~~	~~281.3~~	~~56~~
3	920	54.5	-6.1	37	2000	12	16	3	0	80	0	272.6	272.3	66
3	920	54.5	-6.1	37	2000	12	16	4	0	70	0	272.9	272.6	66
3	209	54.9	-3.1	7	2000	12	31	16	0	100	3	274.3	273.5	67
~~3~~	~~962~~	~~52.7~~	~~-8.9~~	~~14~~	~~2001~~	~~6~~	~~18~~	~~17~~	~~0~~	~~160~~	~~3~~	~~289.3~~	~~287.9~~	~~56~~
3	281	54.4	-0.7	262	2001	11	8	6	0	20	14	275.7	273.6	67
3	224	55.0	-2.5	285	2001	11	23	9	0	250	2	271.9	269.9	66
3	224	55.0	-2.5	285	2001	11	23	10	0	260	3	272.5	271.0	66
3	215	54.8	-3.3	61	2001	12	17	9	0	0	0	273.1	272.5	66
3	927	54.7	-5.7	11	2001	12	26	9	0	270	8	274.8	274.3	56
3	831	50.5	-4.0	510	2002	2	23	12	0	310	21	275.8	275.3	66
3	837	50.4	-3.5	3	2002	2	25	12	0	200	12	************		66

Table 1. Observations of freezing precipitation between 01/01/00 and 31/03/02 showing station number, latitude and longitude, altitude (m), date and time, wind direction, wind speed (knots), temperature, dewpoint and present weather code (Wx) (56=freezing drizzle, 57=moderate/heavy freezing drizzle, 66=freezing rain, 67=moderate/heavy freezing rain). Observations which have been struck through have been quality controlled by the author (see text).

Entries which have been struck through have been quality controlled out as genuine freezing precipitation was deemed very unlikely due to information in the preceeding hours. E.g. temperature well above freezing for some time before observation or an earlier observation of non-freezing precipitation. Two observations unfortunately recorded no temperature information. This left 14 quality controlled freezing precipitation observations for further analysis.

Out of these 14 - 3 were forecast accurately, 4 were near misses in time, and 7 occasions were missed. A graph was plotted of temperature versus dewpoint for all of the observed events and is shown in Figure 1.

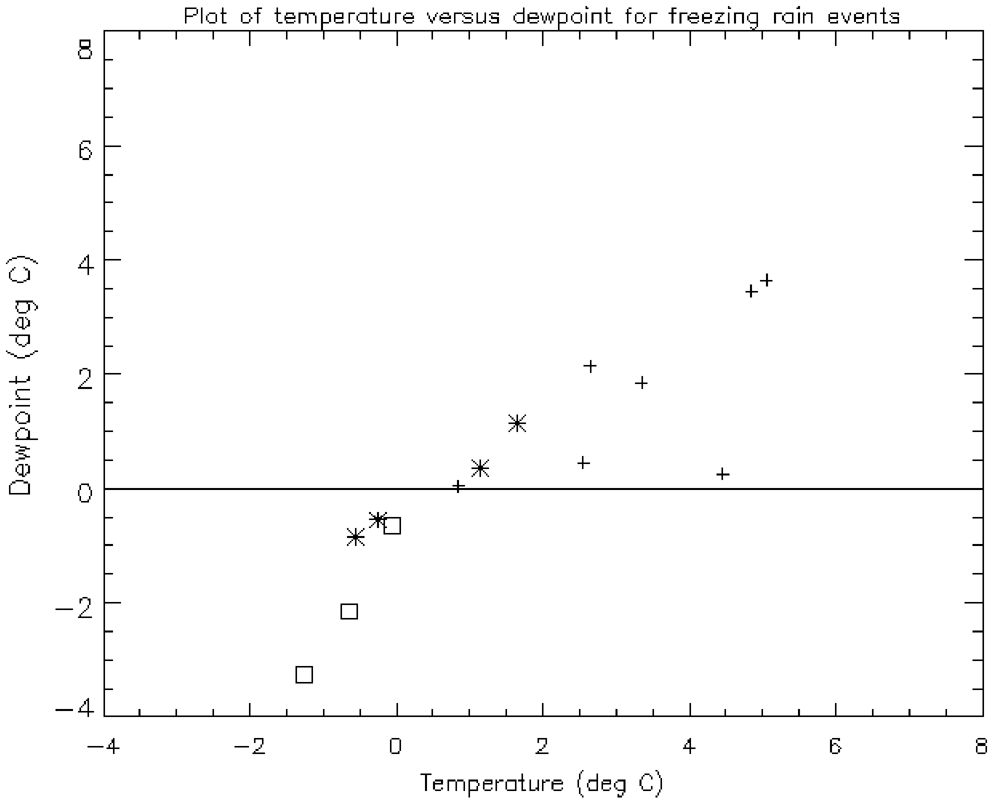

Figure 1. Plot of temperature versus dewpoint for quality-controlled freezing rain events. Squares indicate hits, stars indicate near-misses in time and crosses full misses.

Just 5/14 observations had dewpoints (and in this case wet-bulb temperatures) below freezing. It is interesting that all of the hits and 2 of the near-misses occurred when observed dewpoints were below freezing, indicating that the present scheme (relying on level 1 wet-bulb temperatures being at or below freezing) is quite capable of forecasting/diagnosing freezing rain in these conditions. Nine observations had wet-bulbs above freezing indicating that the present freezing precipitation formulation is going to miss a significant number. Unfortunately ground surface observations are not made hourly so the state of the underlying surfaces is unknown although for freezing precipitation to be observed the water droplets must freeze on impact implying ground temperatures at or below freezing.

4. Experiments

In designing the experiments measures were taken to address all of the shortcomings of the present Nimrod procedure. Five experiments were designed.

- **Experiment A** - Control version which ran the operational Nimrod precipitation type scheme as of 1/6/02 (and unchanged at the time of writing this report).

  Brief overview:

  1. Test for hail using cloud top and base temperatures and vertical velocity derived from dilute model CAPE. If hail is possible – diagnose **hail** (**large,small** or **soft**) and stop. Otherwise,

     2. Test for cold cloud (top temperatures < -1 deg C) or rainfall rate > 0.25 mm/h or convection. If neither of these are present then diagnose **drizzle** or **freezing drizzle** depending upon whether model level 1 wet-bulb temperature is above or below freezing. Otherwise,

        3. Diagnose **powder snow** if maximum model wet-bulb temperature is less than –3 deg C. Otherwise,

        4. Diagnose **snow** if probability of snow not melting is calculated to be > 60%. Otherwise,

        5. Diagnose **freezing rain** if model wet-bulb level 1 temperature is below freezing. Otherwise,

        6. Diagnose **mixed rain and snow** if probability of snow not melting is > 10%. Otherwise, diagnose **rain**.

- **Experiment B** - The initial peak vertical velocity estimate (W) derived for hail diagnosis was increased to use W = 0.6 x SQRT(2.0 x CAPE) instead of W = 0.5 x SQRT(2.0 x CAPE) used in experiment A. If hail was diagnosed then hail size was also derived using the method of Miller coded up as part of the Severe Convective Weather Project and available on Nimrod. The rest of the experiment was the same as that outlined in A.

- **Experiment C** - As experiment B but the probability of freezing precipitation was derived using the variance of model predictions of surface ground temperature (T*). Note that because this variable is not verified routinely its standard deviation is unknown and was taken to be the same as that for screen temperature. This is verified in Nimrod and varies according to time of year and forecast lead time, however, for the purposes of these experiments a fixed value of 1.3 deg C was used. Probabilities of freezing rain arrived at by this method looked reasonable varying across the full range from >80% to 10% or less. For output purposes freezing rain was diagnosed if snow or hail was not diagnosed and the probability of freezing rain was greater than zero and exceeded the probability of snow not melting. (Note that P(freezing rain)=P(snow melting) x P(ground temperature is freezing or below)).

Brief overview:

1. Test for hail using cloud top and base temperatures and vertical velocity derived from dilute model CAPE. If hail is possible – diagnose **hail** (**large,small** or **soft**) and stop. Otherwise,

   2. Test for cold cloud or rainfall rate > 0.25 mm/h or convection. If neither of these are present then diagnose **drizzle** or **freezing drizzle** depending upon whether the probability of freezing rain is greater than zero. Otherwise,

      3. Diagnose **powder snow** if maximum model wet-bulb temperature is less than –3 deg C. Otherwise,

      4. Diagnose **snow** if probability of snow not melting is calculated to be > 60%. Otherwise,

      5. Diagnose **freezing rain** if the probability is greater than zero and exceeds that for snow. Otherwise,

      6. Diagnose **mixed rain and snow** if probability of snow not melting is > 10%. Otherwise, diagnose **rain**.

- **Experiment D** - As B and C but additionally in this experiment the possibility of rain or snow was determined by deriving a glaciation probability and allowing for re-freezing as per the flow chart shown in figure 1b of "Report on Improvements to the freezing rain diagnosis in Nimrod" (unpublished) by Rod Brown and Beth Hewitt.

Brief overview:

1. Test for hail using cloud top and base temperatures and vertical velocity derived from dilute model CAPE. If hail is possible – diagnose **hail** (**large,small** or **soft**) and stop. Otherwise,

   2. Calculate a glaciation probability (GP) as a function of cloud top temperature (CTT) (based on Pruppacher & Klett, 1978) as follows

CTT < -15 deg C	GP = 100%
-15 < CTT < -3	GP = 15 - 5*CTT %
CTT > -3 deg C	GP = 0%

If GP is less than 50% then -

(a) Test for rainfall rate > 0.25 mm/h or convection. If either of these are present then if the probability of freezing rain is less than 50% **rain** is diagnosed otherwise **freezing rain** or **snow** (ice pellets) depending on whether a suitable re-freezing layer is present. If rainfall rate is less than 0.25 mm/h and no convection is present then –

(b) If the probability of freezing rain is less than 50% **drizzle** is diagnosed otherwise **freezing drizzle** or **snow** (grains) depending on whether a suitable re-freezing layer is present.

Otherwise,

3. Diagnose **powder snow** if maximum model wet-bulb temperature is less than –3 deg C. Otherwise,

4. Diagnose **snow** if probability of snow not melting is calculated to be > 60% or a suitable re-freezing layer is present. Otherwise,

5. Diagnose **freezing rain** if the probability is greater than 50%. Otherwise,

6. Diagnose **mixed rain and snow** if probability of snow not melting is > 10%. Otherwise diagnose **rain**.

- **Experiment E** – generally as D but utilising BH's method of deriving all probabilities for each type first (except hail) and then statistically deciding the most likely one for deterministic outputs. If hail is expected then either 'hail with rain' or 'hail with snow' is output depending on whether rain or snow is the most likely. In this case 'sleet', 'freezing rain or drizzle' and 'drizzle' are not output.

  Brief overview:

  1. Test for hail using cloud top and base temperatures and vertical velocity derived from dilute model CAPE.

  2. Calculate a glaciation probability as a function of cloud top temperature.

  3. Calculate integral of positive wet-bulb temperatures in each model gridpoint column. Calculate probability of rain or drizzle re-freezing to ice pellets or snow grains (set to either 100% or zero in this version depending on whether there is a layer below freezing greater than 750m deep with its base < 50m above ground). Calculate probability of the ground temperature being at or below freezing.

  4. Calculate the probabilities of snow fully melting and partially melting.

5. Using the information calculated in items (2), (3) and (4). Compute probabilities of snow, rain, sleet, ice pellets (includes snow grains), drizzle, freezing rain and freezing drizzle occurring.

6. From (5) calculate the probability that precipitation will –
   (a) Freeze on contact with the ground
   (b) Be frozen before it reaches the ground
   (c) Be frozen
   (d) Be non-liquid (ie could include sleet)
   (e) Be entirely liquid

7. Use the probabilities calculated in (5) and (6) in a decision tree to determine the most likely type as follows:

   (a) If the probability of liquid precipitation ((Prain)+P(drizzle)) is greater than 50% then either **rain** or **drizzle** is output depending on which has the higher probability. Note that if the actual/forecast precipitation rate is greater than 0.25 mm/h then P(drizzle) is set to zero and added to P(rain) to ensure P(liquid) is unchanged. Otherwise,

      (b) If the probability of sleet is greater than that for frozen precipitation, then **sleet** is diagnosed. Otherwise,

         (c) If the probability that precipitation will freeze on contact with the ground exceeds the probability that it will be frozen above ground then either **freezing rain** or **freezing drizzle** is diagnosed depending on which has the higher probability. However, if neither freezing rain or freezing drizzle has a probability greater than 50% then **sleet** is diagnosed. Otherwise,

            (d) If the probability of snow exceeds the probability of ice pellets then **powder snow** is diagnosed if the maximum model wet-bulb temperature is less than –3 deg C or **snow** if the maximum model wet-bulb temperature is warmer than –3 deg C. Otherwise,

               (e) **Powder snow** is diagnosed if the maximum model wet-bulb temperature is less than –3 deg C or **snow** if the maximum model wet-bulb temperature is below freezing otherwise **sleet**.

8. If hail was diagnosed in (1) then **hail with rain** is diagnosed if the probability of liquid precipitation exceeds the probability of frozen precipitation. Otherwise, **hail with snow** is diagnosed.

All of the experiments were run on the Nimrod system using the case data listed in Appendix 2. Processing and visualisation of outputs was performed locally. All model data were on the old Unified Model grid (pre 7/8/02 implementation of New Dynamics). Since freezing rain is a rare phenomenon, maximum use was made of all the quality controlled cases of freezing rain. Fortunately these cases also included observations of snow, sleet and soft hail giving the opportunity to test geographical distribution. (It was hoped to include some good cases from 2001 of freezing rain, unfortunately model data were unavailable due to an archiving bug on Nimrod). The data for the summer large hail cases were taken from the severe convective weather study local archives.

5. Results

In order to assess the impact of each experiment on precipitation type classifications it was decided to use a simple frequency measure. That is, the total number of pixels (over the whole Nimrod area) for all of the cases studies combined diagnosing each precipitation type.
The totals are summarised in Table 2.

Exp./Type	**A**	**B**	**C**	**D**	**E**
Rain	40075	38870	37386	40293	37081
Drizzle	3790	3790	3700	6667	9360
Snow	13766	13746	13746	10657	11546
Sleet	4231	4187	4021	2428	2026
Freezing	337	336	2076	884	916
Hail	1345 (5524)	2615	2615	2615	2615
Total	63544	63544	63544	63544	63544

Table 2. Frequencies of precipitation type for all categories and experiments over the complete Nimrod area. Numbers are totals for all case studies. In the 'hail' category, the figure in brackets for experiment A is what would have been obtained if the operational change on 1/9/01 to the vertical velocity derivation had not taken place, (see text for details).

The total number of pixels examined in all the experiments was
115 x 145 x 15 = 250125. Of these, 63544 or just over 25% were 'wet' according to the Nimrod rainfall analyses. The breakdown of these wet pixels into precipitation type for each experiment shows some interesting variations.

5.1 Hail

Looking first at the differences between the control run A and the increased vertical velocity run B we can see that the number of hail classifications (mostly soft) has almost doubled but is still less than half what they would have been had the code change on 1/9/01 not been made. This is a step in the right direction but could be slightly too much. The effect of more hail classifications in B was mainly to reduce the number of rain types but 'snow' and 'sleet' were also reduced (sleet more than snow) which seems reasonable. Very encouragingly 'drizzle' was unaffected and only one freezing rain classification was altered. The hail classifications in experiments C, D and E were unchanged.

An example of the kind of effect that can be expected by increasing the vertical velocity by 20% can be seen in Figure 2 in the 08/01/00 case. There were much more soft hail classifications over the sea to the west of Scotland than in the control run. Soft hail was reported on one of the exposed western Isles. However, the airmass was unstable and polar in origin and in January one would expect a lot of the showers to contain soft hail in the northwest quadrant of the British Isles. So the chart for experiment B looks reasonable.

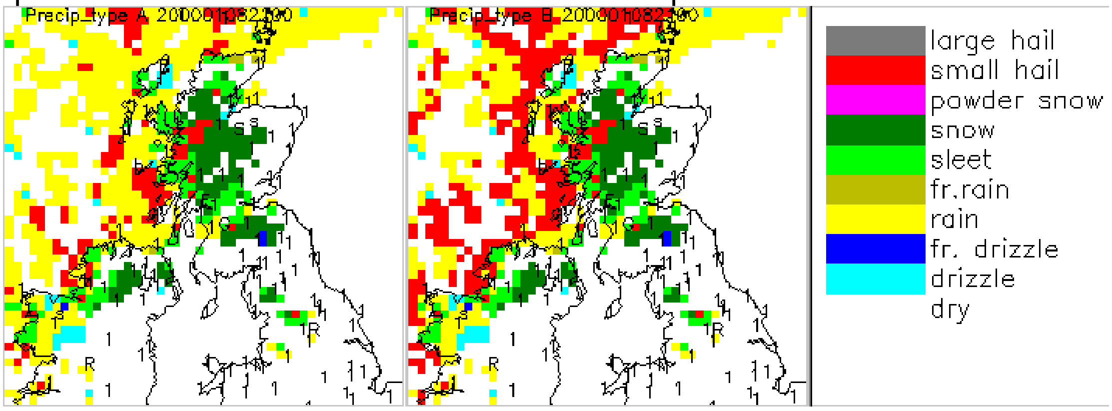

Figure 2. Images showing precipitation type colour coded from experiments A (left) and B for 08/01/00 2100 UTC. The key to the colours is on the right. Plotted letters and numbers are SYNOP reports of precipitation. '1' = dry, 'D' = drizzle, 'R' = rain, 's' = sleet, 'S' = snow, 'G' = snow grains, 'h' = soft hail, 'H' = proper hail, 'f' = freezing drizzle and 'F' = freezing rain. The observation location is at the bottom left corner of the symbols.

5.2 Freezing rain diagnosed using model ground temperatures

Here we are comparing results from B with C. The biggest effect of the change in C is to give an almost six-fold increase in the number of 'freezing' classifications at the expense of 'rain', 'drizzle' and 'sleet'. Snow is unchanged because that has a higher priority in the decision tree than 'freezing'.

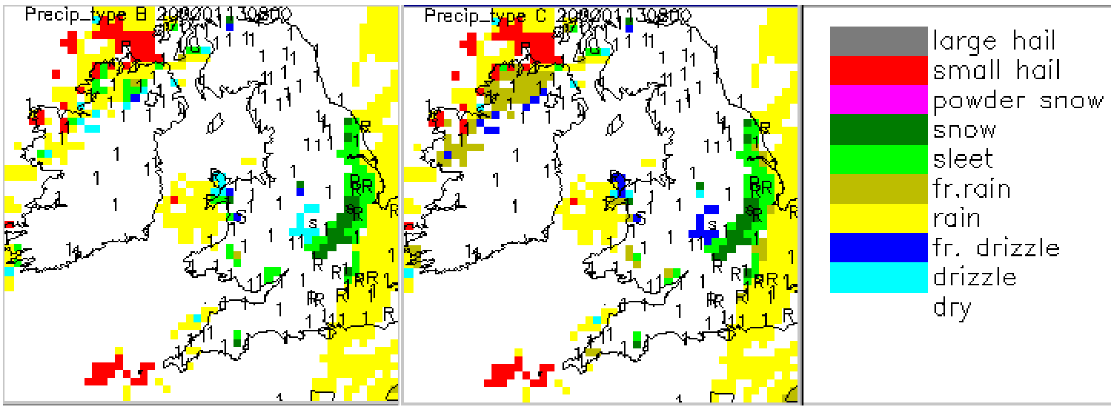

Figure 3. Images showing precipitation type colour coded from experiments B (left) and C for 13/01/00 0800 UTC. The key to the colours is on the right. Plotted letters and numbers are SYNOP reports of precipitation. '1' = dry, 'D' = drizzle, 'R' = rain, 's' = sleet, 'S' = snow, 'G' = snow grains, 'h' = soft hail, 'H' = proper hail, 'f' = freezing drizzle and 'F' = freezing rain. The observation location is at the bottom left corner of the symbols.

This effect is clearly visible in Figure 3 for 13/01/00 at 0800 UTC. On this occasion there was a band of rain and sleet in SE Britain and a report of moderate or heavy freezing rain on the Lleyn peninsula in north Wales with some snow in the mountains. Although the freezing rain in north Wales is better predicted in C, a broad area of freezing precipitation was diagnosed in Ireland which looks unrealistic. The freezing rain in SE Britain also looks overdone but there is no clear evidence either way. Note that the region of snow is identical in both outputs.

Another illustration is provided in figure 4 for 16/12/00 at 0300 UTC.

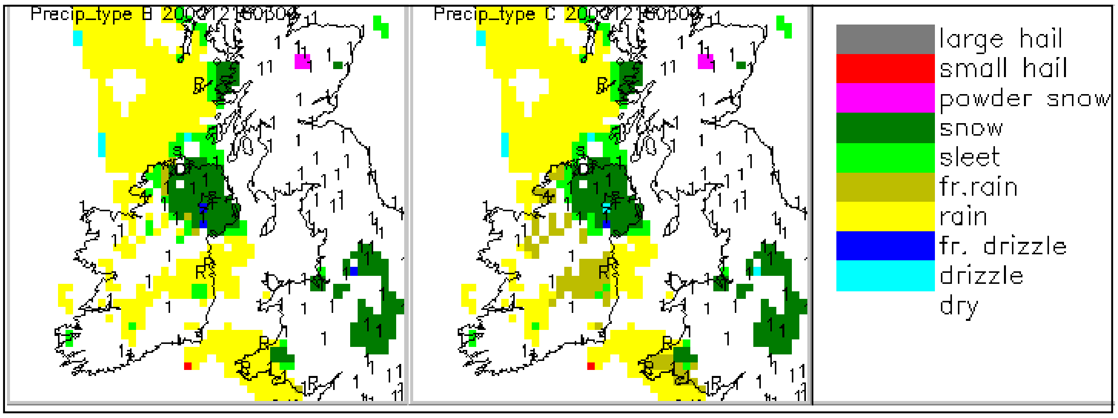

Figure 4. Images showing precipitation type colour coded from experiments B (left) and C for 16/12/00 0300 UTC. The key to the colours is on the right. Plotted letters and numbers are SYNOP reports of precipitation. '1' = dry, 'D' = drizzle, 'R' = rain, 's' = sleet, 'S' = snow, 'G' = snow grains, 'h' = soft hail, 'H' = proper hail, 'f' = freezing drizzle and 'F' = freezing rain. The observation location is at the bottom left corner of the symbols.

In this case there was light freezing rain in Belfast. The operational code in B was a very good forecast with freezing drizzle diagnosed very close. Unfortunately experiment C turned that classification back to drizzle due to the model ground temperature being too warm and also again introduced an unrealistic looking region of freezing rain in the Irish republic and south Wales.

5.3 Effect of introducing a glaciation probability

This was introduced in experiment D. Comparing with the results from C we can see that the number of rain and drizzle classifications has increased at the expense of sleet, snow and freezing rain. This effect was expected but was too great. The clearest example of this is shown in Figure 5 for 31/12/00 at 1600 UTC. Here the widespread snow in C has become more fragmented and been replaced by rain or freezing rain in places (correctly near the east coast of Scotland). The snow over the Cairngorms, however, was only diagnosed by introducing re-freezing. The freezing rain over Wales in C has been replaced mostly by rain in D since the probability was less than 50%.

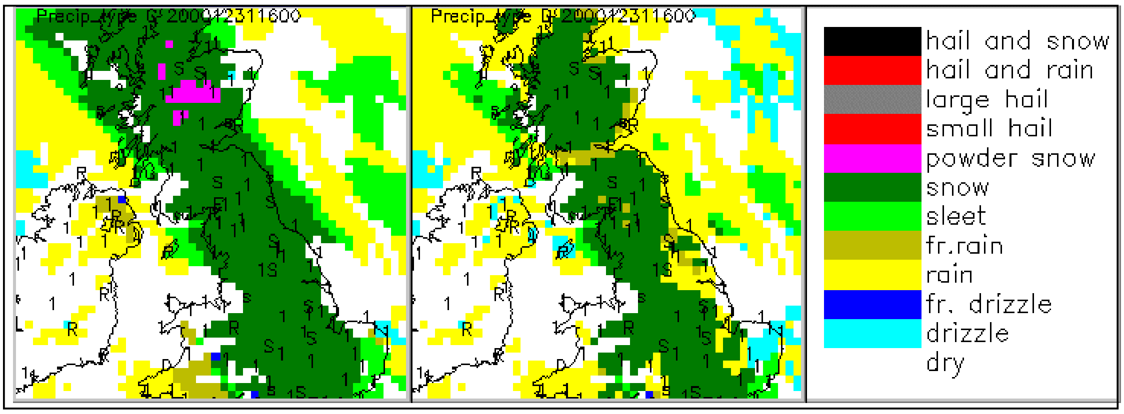

Figure 5. Images showing precipitation type colour coded from experiments C (left) and D for 31/12/00 1600 UTC. The key to the colours is on the right. Plotted letters and numbers are SYNOP reports of precipitation. '1' = dry, 'D' = drizzle, 'R' = rain, 's' = sleet, 'S' = snow, 'G' = snow grains, 'h' = soft hail, 'H' = proper hail, 'f' = freezing drizzle and 'F' = freezing rain. The observation location is at the bottom left corner of the symbols.

5.4 Effect of using BH's probability technique

The changes made for experiment E were the most radical and affected all precipitation types except hail. The occasions of 'rain' are the least for all of the experiments and 'drizzle' is diagnosed the most number of times in E, although there are more 'rain' occasions in D than in E. The latter suggests that the effect of including a glaciation probability is ameliorated by the procedure in E. The reason for this and for more 'drizzle' is that in determining the probability of rain full account is taken of the probability that snow will fully melt (PFM) together with the probability of the ground temperature being below freezing and the probability that liquid drops will re-freeze as well as the probability that clouds will be glaciated (PG). In calculating the probability of drizzle, glaciation, re-freezing and ground temperature are considered. This implies that the diagnosis of drizzle will depend on PFM and PG. However, changing these quantities will also affect the classification of snow, sleet and freezing precipitation. This only serves to illustrate that altering one probability in this scheme will affect all the others making it less straightforward to fine tune.

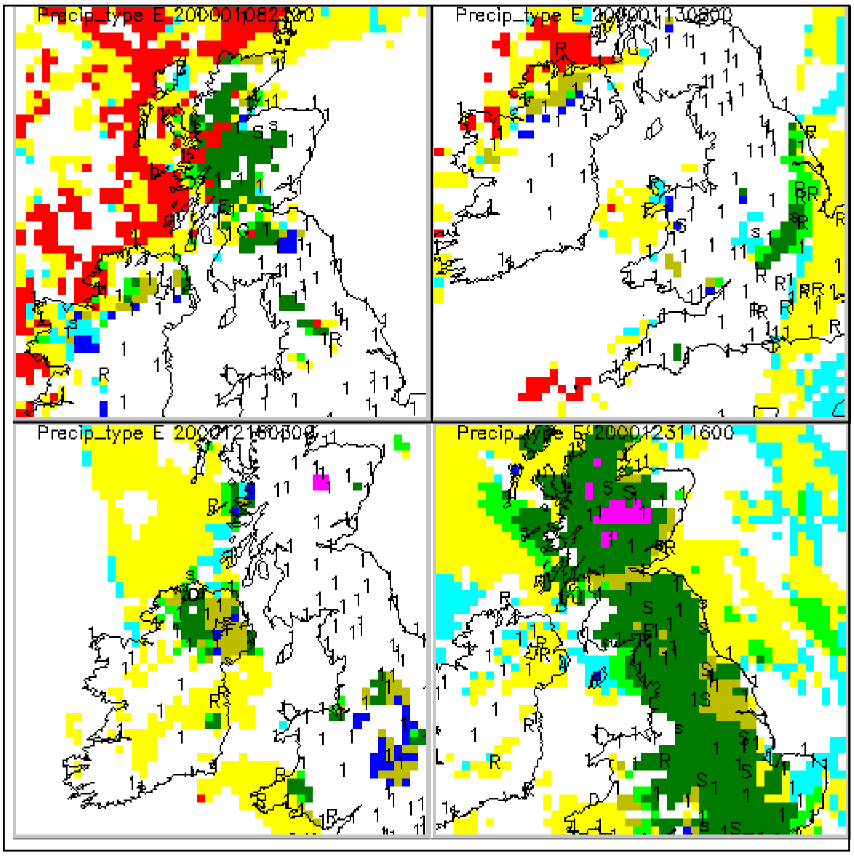

Figure 6. Four images showing precipitation type colour coded from experiment E for 08/01/00 (top left), 13/01/00 (top right), 16/12/00 (bottom left) and 31/12/00 (bottom right). The key to the colours is the same as in Figure 5. Plotted letters and numbers are SYNOP reports of precipitation. ‘1’ = dry, ‘D’ = drizzle, ‘R’ = rain, ‘s’ = sleet, ‘S’ = snow, ‘G’ = snow grains, ‘h’ = soft hail, ‘H’ = proper hail, ‘f’ = freezing drizzle and ‘F’ = freezing rain. The observation location is at the bottom left corner of the symbols.

Noticeable effects of the scheme used in experiment E are evident in all of the cases. Looking at Figure 6, in the 08/01/00 case comparing with B there is more snow and less sleet over Scotland but in Ireland there is more freezing precipitation. On 13/01/00 there are small differences in sleet and snow distribution with the main change being the reduction in freezing precipitation compared with C but an increase in comparison with B. For the 16/12/00 case the freezing rain area round Belfast looks good especially as neither B nor C really showed this. The large area of freezing rain over Eire evident in C has also vanished thus better pinpointing the area at risk. However, the snow diagnosed over England has largely changed to freezing rain or drizzle with the area of freezing rain over south Wales diminishing. There were no observations to confirm which was correct. In the 31/12/00 example the probability of glaciation over NE England and much of Scotland was zero due to the cloud top temperature in the model being above –3 deg C (see Figure 7). Where the probability of glaciation was zero the snow diagnosed in E was due to the presence of a suitable re-freezing layer and a maximum wet-bulb temperature in the layer below 0 deg C. Where freezing rain was diagnosed the ground temperature was very cold but the re-freezing layer was less than

750m deep. The output of snow looks reasonable (even though it was thought to be diagnosed for the wrong reasons) but the freezing rain does not look right.

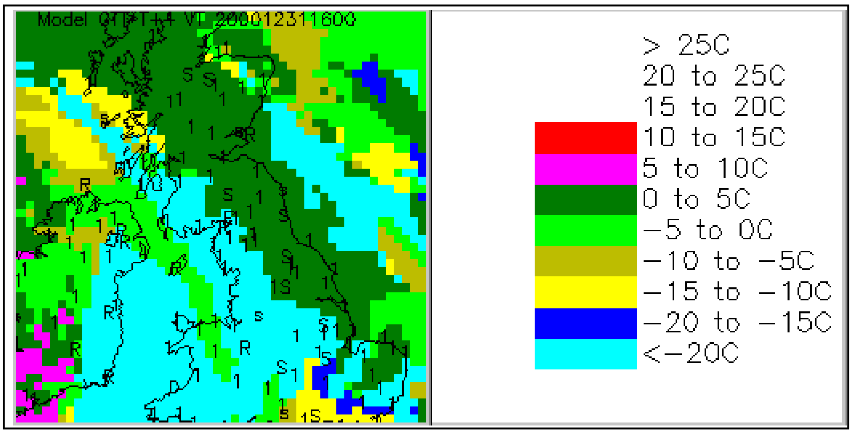

Figure 7. Diagnosed cloud top temperature for 31/12/00 at 1600 UTC.

The main problem with this case were the unrealistically warm cloud top temperatures diagnosed in the precipitation type program which did not tie in very well with the observations of widespread sleet and snow nor with the model's own rainfall field. The method of diagnosis of cloud top temperature was unchanged for these experiments and was identical to the present operational Nimrod code. The algorithm seeks to identify the cloud top temperature of the layer of cloud most likely to give precipitation at the surface. It achieves this by searching up through the model levels identifying the first cloud layer and then finding the first layer higher than this where the cloud cover falls below 1 okta. If convective cloud is present and has a colder cloud top than the stratiform layer then the convective top is used assuming that the convective cloud will seed lower level clouds. All this seems very reasonable since one does not want to include cirrus or other high cloud layers from which precipitation would be evaporating. Unfortunately in the 31/12/00 case the model had a layer of low cloud and then a dry layer above this and then another thick layer of cloud above this with no convection. This explains the warm cloud top temperatures. This case illustrates how important it is to get the cloud top temperature correct in this version of the precipitation type scheme since it affects the probability of glaciation and hence the probability of sleet and snow.

A particular advantage of using the modified BH scheme E is that as well as a deterministic output of precipitation type it is possible to output probabilities of each type occurring. This could well be more useful for some customers. Probability charts for the 16/12/00 case are shown in figure 8. The regions where the probability of rain is below 90% (non-black) are the areas where there is uncertainty in type. In these areas the probabilities cover the whole range from 0 to 100% for each type reflecting this uncertainty. This is also true in the other cases.

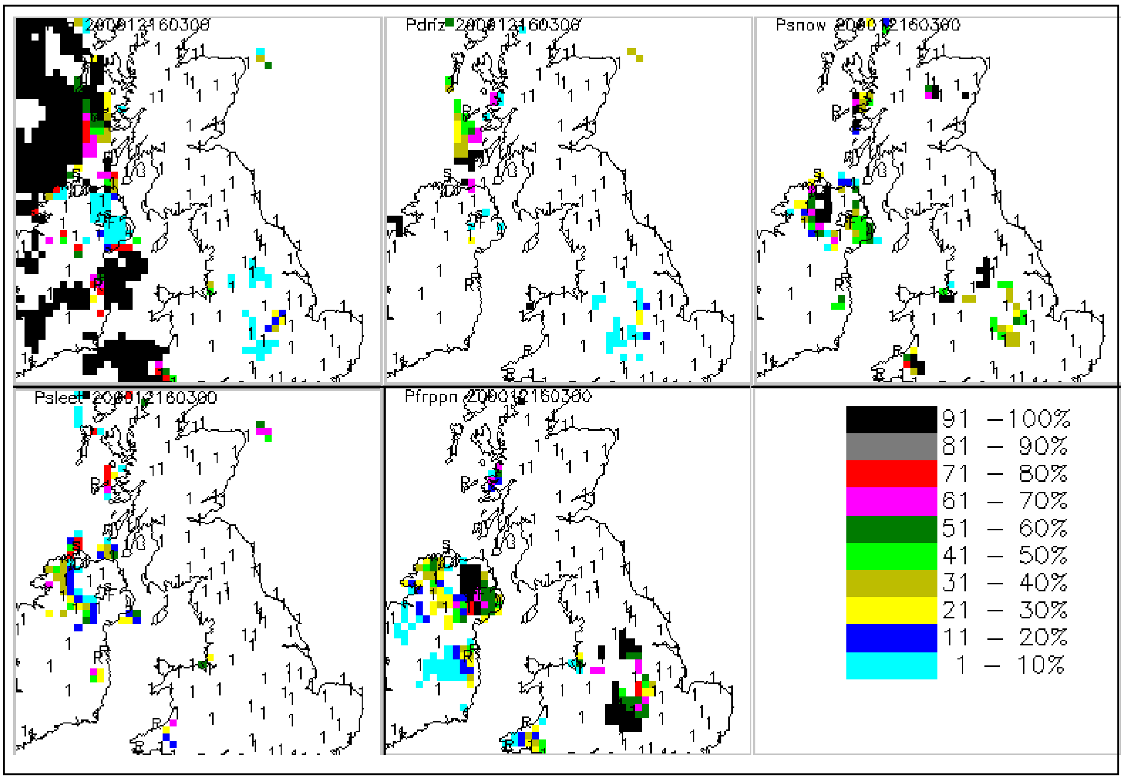

Figure 8. Maps (starting from top left) showing probability of getting rain, drizzle, snow, sleet and freezing precipitation on 16/12/00 0300 UTC in experiment E.

The scheme also lends itself well to amplifying the output of ‘hail’ type to include ‘hail with rain’ or ‘hail with snow’ providing more information to the user. An example of this is shown in Figure 9 for the 08/01/00 case.

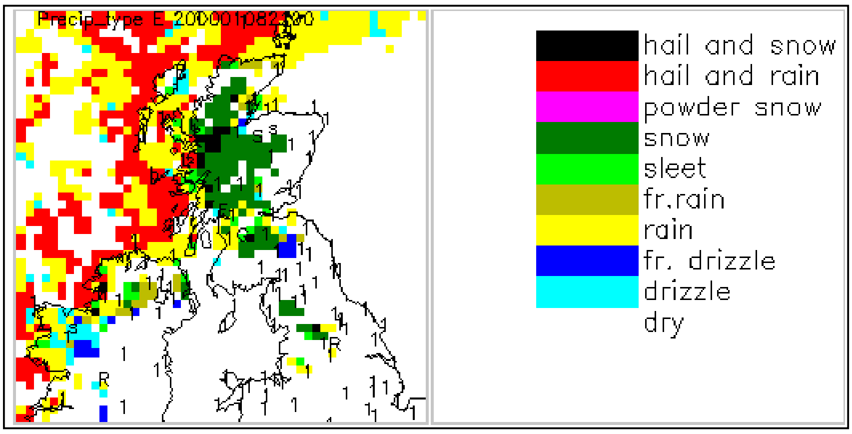

Figure 9. Image from experiment E for 08/01/00 2100 UTC showing how ‘hail and rain’ can be distinguished from ‘hail and snow’.

The transition from ‘hail with rain’ to ‘hail with snow’ in western Scotland and NW Ireland looks both realistic and convincing.

6. Conclusions from case studies

Each of the experiments provided evidence of sensitivity of the precipitation type diagnosis to changes in algorithms. Changing the peak vertical velocity derivation from CAPE can lead to quite noticeable changes in hail diagnosis and some small impacts on sleet and snow. Using model T* rather than level 1 wet-bulb temperature greatly increases the number of diagnoses of freezing rain. The example cases have shown that the increase is probably unrealistic and is possibly due to inaccuracies in model ground temperature not being fully taken into account. However, the increase is reduced to a more realistic looking level when the probability of freezing precipitation calculation properly takes into account all of the other precipitation phase probabilities as in E. Introducing a probability of glaciation and allowing for re-freezing leads to a marked reduction in the diagnoses of sleet snow and freezing rain (using T*). The reduction in sleet and snow diagnoses is due to the glaciation probability and the reduction in freezing rain due to re-freezing altering the diagnosis to snow (pellets or grains). It was demonstrated that in D the reduction in the number of snow diagnoses was too great. These reductions are ameliorated in the full probabilistic scheme E. The treatment of re-freezing was very simplified, although account was taken of maximum model wet-bulb temperature values in E. Glaciation probabilities are sensitive to precipitating cloud top temperature derivation and better answers may have been obtained using Nimrod cloud analyses and forecasts rather than diagnosing from pure model fields. Unfortunately there were difficulties in extracting the required fields from the archive tapes, so this was untested in these cases.

Bringing together all of the evidence it seemed that the algorithm employed in E offered most promise in addressing the shortcomings of the present system highlighted in section 3. Using E the number of snow diagnoses would be reduced, sleet occurrences would also be reduced and more than snow. Hail, drizzle and freezing precipitation diagnoses would increase whereas rain classifications would decrease.

The other advantage of scheme E would be the ability (if required) to produce output probabilities of each precipitation type. It is also very easy to produce two new diagnostics of ‘hail with rain’ and ‘hail with snow’.

7. Winter trial 2002/3

The code in experiment E is currently being trialled on the Nimrod development system in parallel with the operational code. The trial includes generating identical verification statistics as those produced operationally as well as producing a range of statistics relevant for probability forecasts. This has enabled objective monitoring of the trial code. The trial also provides images in a similar format to those provided operationally for the Nimrod monitor with a new web page displaying trial and operational outputs together. The following precipitation types are distinguished in the trial version: rain, drizzle, snow, powder snow, sleet, freezing rain, freezing drizzle, hail with rain, hail with snow. Hail size based on Hand's adaptation of Miller's technique, (Hand, 2001), is used to provide an output of 'large hail' which takes precedence over the other hail types. Probability fields for each type are produced and assessed. These include; probability of rain, snow, sleet, freezing precipitation, drizzle and ice pellets or snow grains.

The trial was set up to compare with operational hourly precipitation type diagnoses at T+0. It is not run in forecast mode since we are not contributing to the accuracy of the precipitation forecast in this work, only the method of diagnosis of type of precipitation. Drawing on results from the case-studies, Nimrod (as opposed to model) cloud analyses are used for the glaciation probability calculations.

7.1 Trial results

7.1.1 Deterministic statistics

Table 3 shows a comparison of results for deterministic precipitation type from the trial and operational Nimrod. Observations are taken from synoptic stations over the UK (identical sets for both systems). The period covered is 1/1/03 to 31/3/03 when the bulk of wintry precipitation fell in the UK.

TRIAL

Precipitation Type Verification for 2003/01-03: No of obs = 5466

obs / f/c	drizzle	rain	sleet	freezing	snow	hail
drizzle	3.403	8.727	0.091	0.091	0.293	0.018
rain	7.867	65.423	1.482	0.348	1.994	0.494
sleet	0.146	0.860	0.220	0.128	0.622	0.018
freezing	0.018	0.073	0.018	0.018	0.018	0.000
snow	0.183	0.915	0.183	0.256	4.061	0.073
hail	0.165	0.988	0.091	0.018	0.585	0.110

Snow: ob 310 fc 414 hit rate 74.84 false alarm rate 46.38
Hail: ob 107 fc 39 hit rate 5.61
Sleet: ob 109 fc 114 hit rate 11.01
Freezing rain: ob 8 fc 47 hit rate 12.50 false alarm rate 97.87

OP
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Precipitation Type Verification for 2003/01-03: No of obs = 5466

obs / f/c	drizzle	rain	sleet	freezing	snow	hail
drizzle	2.616	9.367	0.274	0.018	0.329	0.018
rain	3.769	65.843	5.598	0.018	2.012	0.366
sleet	0.055	0.402	0.604	0.037	0.896	0.000
freezing	0.000	0.091	0.055	0.000	0.000	0.000
snow	0.146	0.073	0.348	0.073	4.976	0.055
hail	0.000	0.732	0.439	0.000	0.695	0.091

Snow: ob 310 fc 487 hit rate 93.87 false alarm rate 44.15
Hail: ob 107 fc 29 hit rate 4.67
Sleet: ob 109 fc 400 hit rate 30.28
Freezing rain: ob 8 fc 8 hit rate 0.00 false alarm rate 100.00

Table 3. Nimrod contingency tables for precipitation type diagnoses in the UK from the trial and operational systems for the period 1/1/03 to 31/3/03. Observed types are listed on the left and forecast types along the top. Figures

in the table are occasion percentages of the total number of observations. Additional information on number of observations and forecasts with percentage hit and false alarm rates for snow, hail, sleet and freezing rain are also provided.

Looking at the key performance characteristics for each of the precipitation types in turn we see that when drizzle is observed the new scheme performs better than the control with a larger percentage of correctly forecast occasions and lower percentage of incorrect forecasts (with the exception of “drizzle observed/freezing precipitation forecast”).

For rain there is a doubling of the number of occasions of rain observed/drizzle forecast which is consistent with the increased bias for drizzle shown in Table 2. The number of correct rain forecasts is almost unchanged. An obvious reason for occurrences of “rain observed/drizzle forecast” is the threshold of 0.25 mm/h up to which drizzle can be diagnosed. Unless drizzle is very heavy an observed drizzle rate of 0.25 mm/h will not occur. However, this does not explain the doubling over the control run which used an identical set of verifying observations.

For sleet the forecast bias has improved from 367% to 105% although the hit rate has, perhaps expectedly, decreased.

However, for the rare freezing precipitation type the forecast bias has increased in the trial version to 587% compared to 100% in the control. It is encouraging though that 12.5% of these were hits compared to none in the control. However, most of the freezing precipitation (rain or drizzle) forecasts were observed as either rain, sleet or snow.

There is an improvement of about 23% in the forecast bias for snow, however, the hit rate has gone down with a small increase in the false alarm rate. The biggest problem seems to be the larger number of “snow observed/rain forecast” occasions.

Hail prediction is marginally better in the trial version. However, more improvement is expected during the summer.

Three key issues arising from this objective analysis of deterministic products are as follows:

Q1. *Why were 67% of drizzle forecasts in the trial observed as rain compared to 57% in the control ?*

Q2. *Why are we diagnosing nearly 6 times more freezing rain pixels in the trial than in the control and should we be concerned about it given the improved performance in terms of hit rate ?*

Q3. *Why has the diagnosis of snow got worse ? In particular the increase in the number of “snow observed/rain forecast” events ?*

Before addressing these it is useful to look at the probability verifications and subjective assessments.

7.1.2 Objective verification of the probability of precipitation type

Although all precipitation type probabilities (except hail) are diagnosed and verified, it is only the verification graphs for drizzle, rain and snow that are relevant here. The graphs are shown in figures 10, 11 and 12. For a full erexplanation of probability verification see Stanski et al, 1989 and Wilks, 1995.

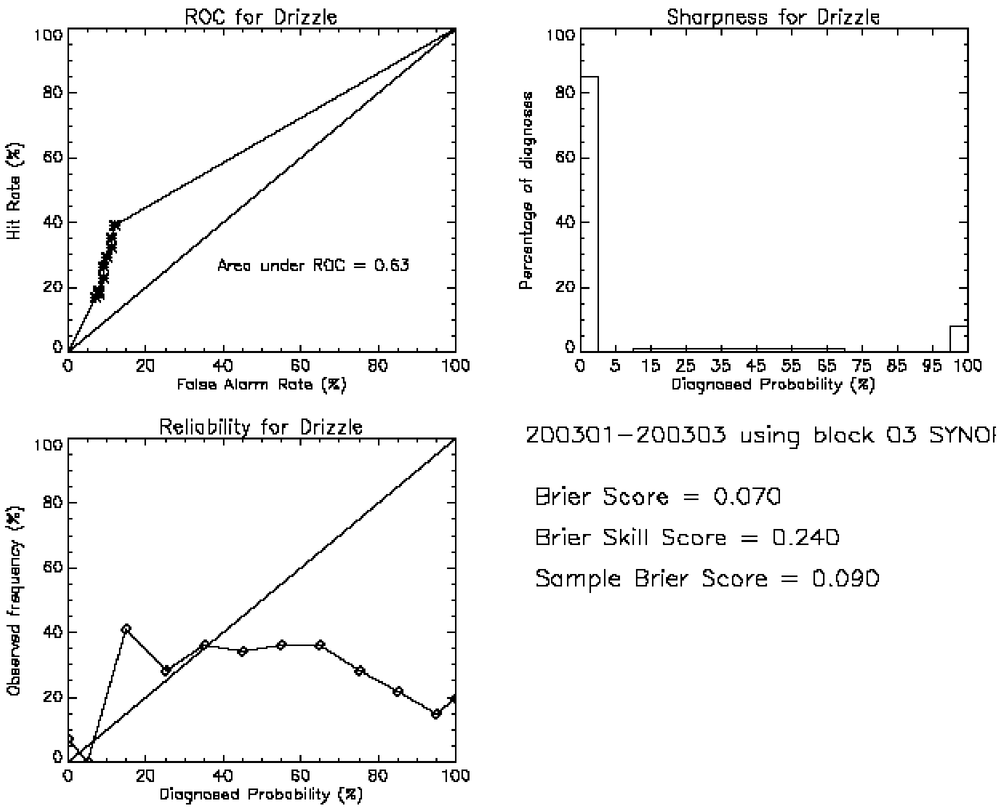

Figure 10. Verification of diagnoses of the probability of drizzle for 1/1/03 to 31/3/03 using UK SYNOP reports. The ROC curve is shown at the top left. Reliability is at bottom left and the percentage number of diagnoses of each probability range is shown at the top right. Brier score and skill score (calculated using the sample frequency) are indicated at bottom right. The probability bins used were 0%, 1-10%, 11-20%, … , 91-99%, 100%.

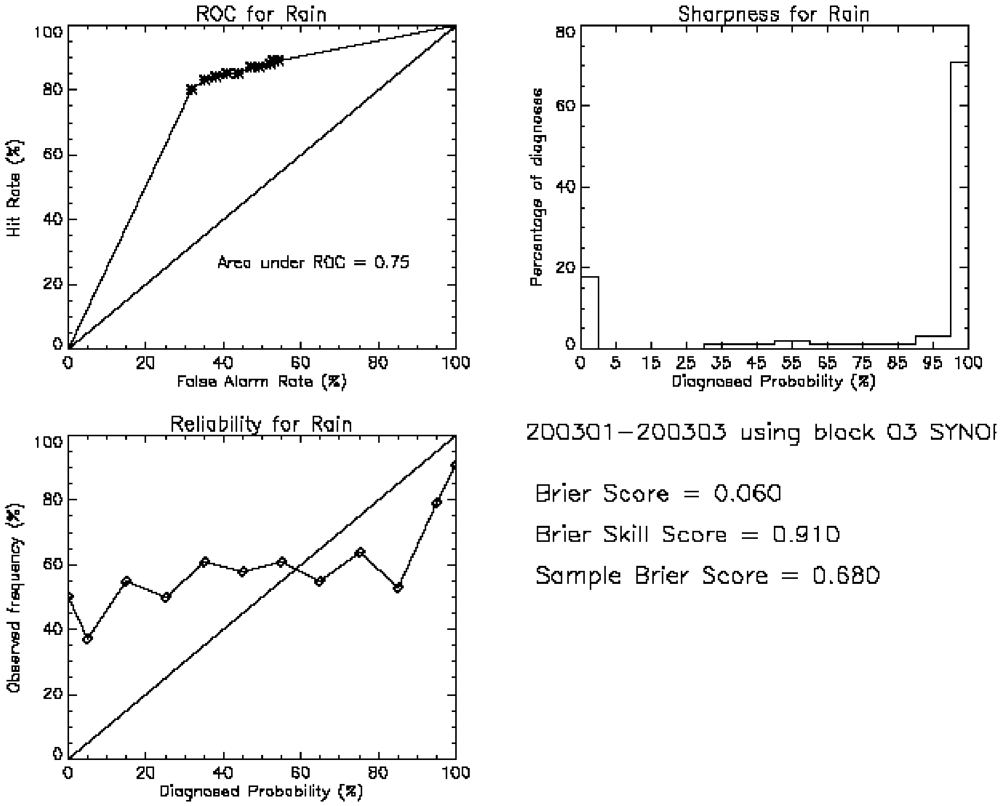

Figure 11. Verification of diagnoses of the probability of rain for 1/1/03 to 31/3/03 using UK SYNOP reports. The ROC curve is shown at the top left. Reliability is at bottom left and the percentage number of diagnoses of each probability range is shown at the top right. Brier score and skill score (calculated using the sample frequency) are indicated at bottom right. The probability bins used were 0%, 1-10%, 11-20%, … , 91-99%, 100%.

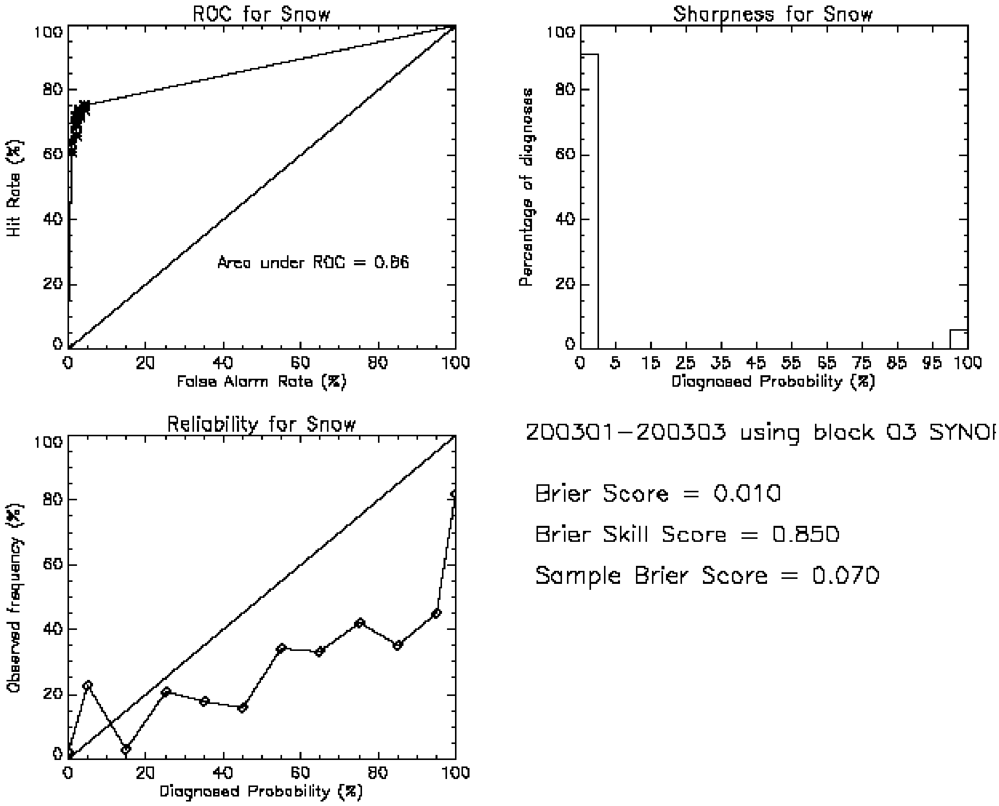

Figure 12. Verification of diagnoses of the probability of snow for 1/1/03 to 31/3/03 using UK SYNOP reports. The ROC curve is shown at the top left. Reliability is at bottom left and the percentage number of diagnoses of each probability range is shown at the top right. Brier score and skill score (calculated using the sample frequency) are indicated at bottom right. The probability bins used were 0%, 1-10%, 11-20%, … , 91-99%, 100%.

The results for drizzle (Figure 10) show that most diagnoses were 0% but with a reasonable spread in the other ranges with most at 100%. Quite good reliability up to the 50% threshold but then the diagnoses get progressively over-confident. The skill score is relatively low but at least it is positive. The graphs are consistent with the deterministic scores which showed 67% of drizzle diagnoses verified as rain. Most of these are likely to be when the probability of drizzle is relatively high since liquid precipitation is only diagnosed if its probability (P(rain)+P(drizzle)) exceeds 50%

For rain (Figure 11) the reliability curve shows that the system is under-confident below 60% and over-confident above 60%. However, the system is very skilful with a score of 0.91 and most diagnoses are at the 100% level with a good spread to another peak at 0%. The ROC curve is interesting. The increasing false alarm rate as the probability threshold decreases points to too many occasions of "rain forecast/rain not observed" for the lower probability ranges. Presumably this is during marginal situations and indeed this hypothesis is backed up in Table 3 which shows a large percentage increase in the trial for number of occasions of "rain forecast/snow observed", i.e. Q3.

Given the deterministic results the graphs for snow shown in Figure 12 look remarkably skilful with a skill score of 0.85 and relatively few false alarms evident in the ROC curve. However, the reliability curve shows the system to be over-confident above 30% but recovering at 100% which is the level at which most diagnoses are made except 0%. Interestingly the reliability of the snow diagnoses at 0% is almost perfect. These results together with the deterministic results leads to the conclusion that when snow is diagnosed it can be relied upon. However, when rain is diagnosed, then in marginal situations it cannot be relied upon and may indeed be observed as snow.

7.1.3 Subjective assessments

As with most trials objective statistics do not tell the whole story and it is essential to look regularly at outputs almost on a daily basis in order to build a more complete picture of performance characteristics. This was done during the trial and all images were archived. The following figures illustrate some of the key points from the subjective assessment.

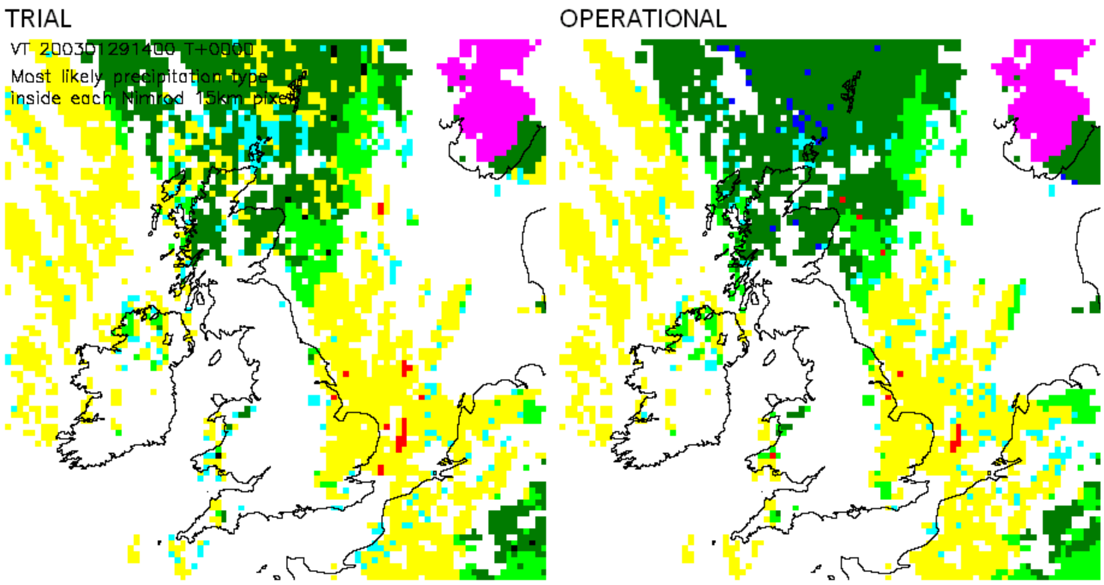

Figure 13. Maps showing precipitation type diagnosed on 29/1/03 at 1400 UTC from the trial run (left) and operational run (right). The key to the colours is the same as in figure 9.

The synoptic situation on this day was a cold and unstable arctic northerly flow propagating south down the British Isles. Within the flow showers were frequent in the north and down the North Sea and a trough was giving longer spells of precipitation over Scotland.

The first thing of note is that the operational run is diagnosing freezing drizzle over the sea north of Scotland. Diagnosis of freezing precipitation over the sea is not uncommon in the operational (OP) runs as the algorithm does not depend on surface ground temperature only model level 1 wet-bulb temperature. The trial scheme removes this problem.

The trial run has a few more diagnoses of hail than the OP and distinguishes “hail with rain” and “hail with snow” quite realistically.

The main difference, however, is that the trial has more liquid precipitation amongst the snow over Scotland. This behaviour over the UK occurred regularly in the trial. Looking at the observations in Figure 14 the trial output was giving a much more realistic picture with three observations around the coast reporting either “recent rain” or “sleet shower”. The reported temperatures would also support a mixture of rain, sleet and snow rather than Mainly snow (and freezing drizzle) as in OP.

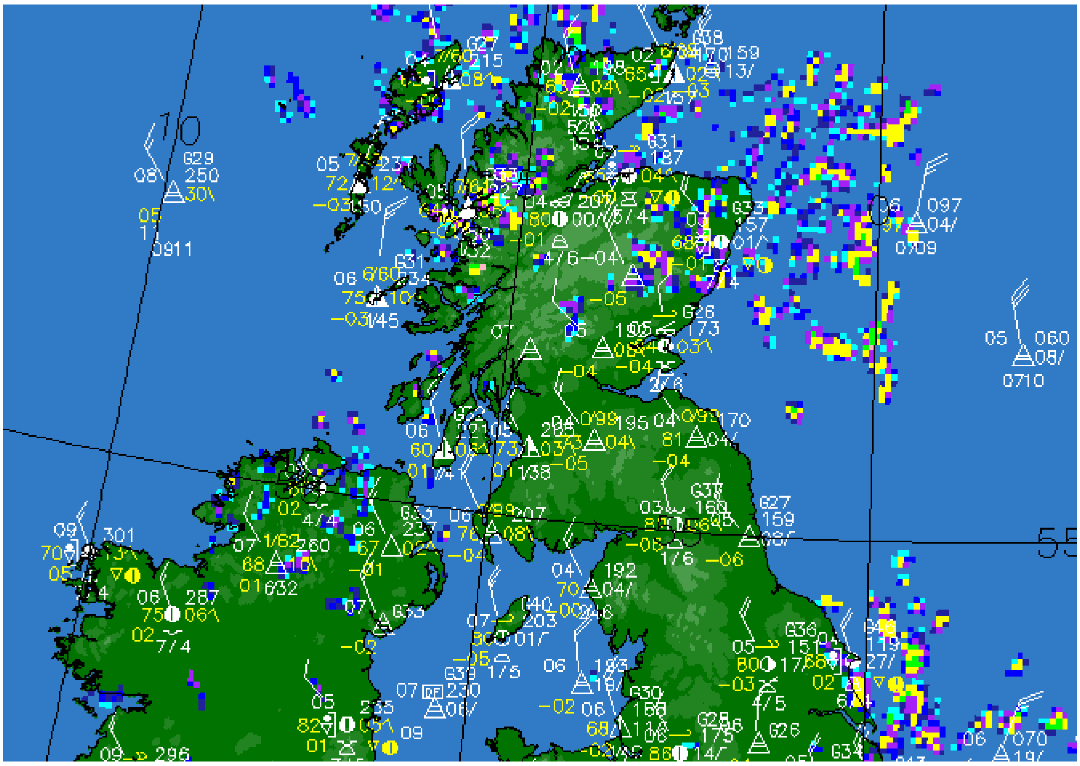

Figure 14. Map from the Met Office HORACE display showing plotted observations with radar imagery overlaid for 29/1/03 1400 UTC.

The next case is for 6/2/03 0800 UTC which has a warm front over Wales moving east bringing a rise in temperatures after a cold spell with frozen ground surfaces. The guidance on this aspect from Met Office Bracknell issued to all Met Office forecasters at 0400 UTC was as follows:

“ At 04Z the warm front lies down through western Scotland, west Wales and sw England with low cloud and hill fog already becoming widespread - this process likely to continue as the front comes eastwards although there could be some thinning of the ST SC to the lee of high ground later. Medium cloud is now shearing well forward of the surface warm front consequently much of the precip on the current radar over eastern areas is evaporating in the drier lower layers before reaching the ground - with model profiles showing only relatively thin SC layers nearer the front and in the warm sector, subsequent precip is likely to be light and patchy apart from over windward high ground in the west. This run produces slightly less in the way of snow as it moves southeast - perhaps because precip is rather lighter, but best still to allow for some sleet/snow just at first across parts of northern and central England/Wales although rain falling onto still frozen surfaces is perhaps more of a threat “

So to summarise the forecaster was placing less emphasis on snow and giving greater concern to the possibility of rain falling onto frozen surfaces.

The precipitation type diagnosis for 0800 UTC is shown in Figure 15.

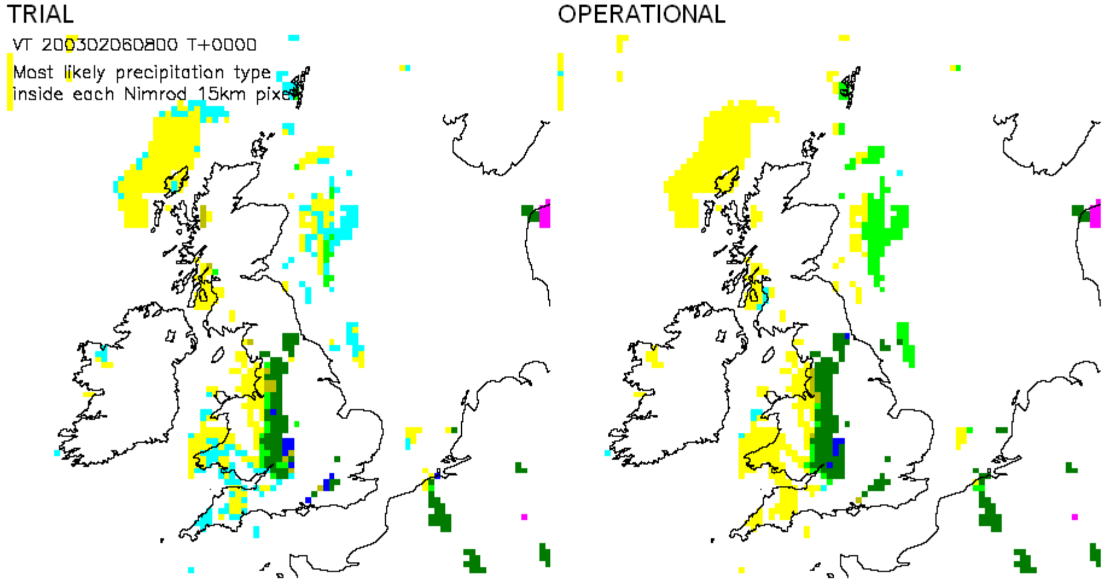

Figure 15. Maps showing precipitation type diagnosed on 6/2/03 at 0800 UTC from the trial run (left) and operational run (right). The key to the colours is the same as in figure 9.

The warm front is on the Wales/England border with wintry precipitation diagnosed to the east of it. However, in the trial there are more pixels showing freezing precipitation and less giving snow, particularly near the southern tip around and to the east of Bristol. The probability of freezing precipitation from the trial run is shown in Figure 16.

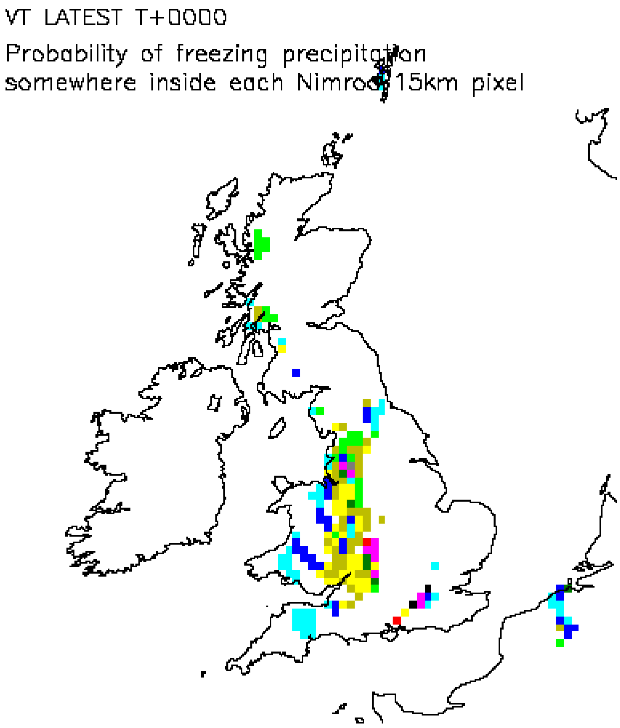

Figure 16. Map showing probability of getting freezing precipitation on 6/2/03 0800 UTC from the trial run. Key to probabilities (at 10% intervals) is the same as in Figure 8.

This map shows that the highest probabilities of freezing precipitation were diagnosed in the east and north of the rainband (mostly 40-70% risk). This picture fitted in extremely well with the issued guidance from NMC (who did not have access to this information).

As can be seen in Figure 17 freezing drizzle was reported well to the north in southern Scotland at Eskdalemuir. Rain was reported elsewhere but clearly from the temperatures freezing precipitation was certainly a good possibility as one went east and north away from the warm frontal zone.

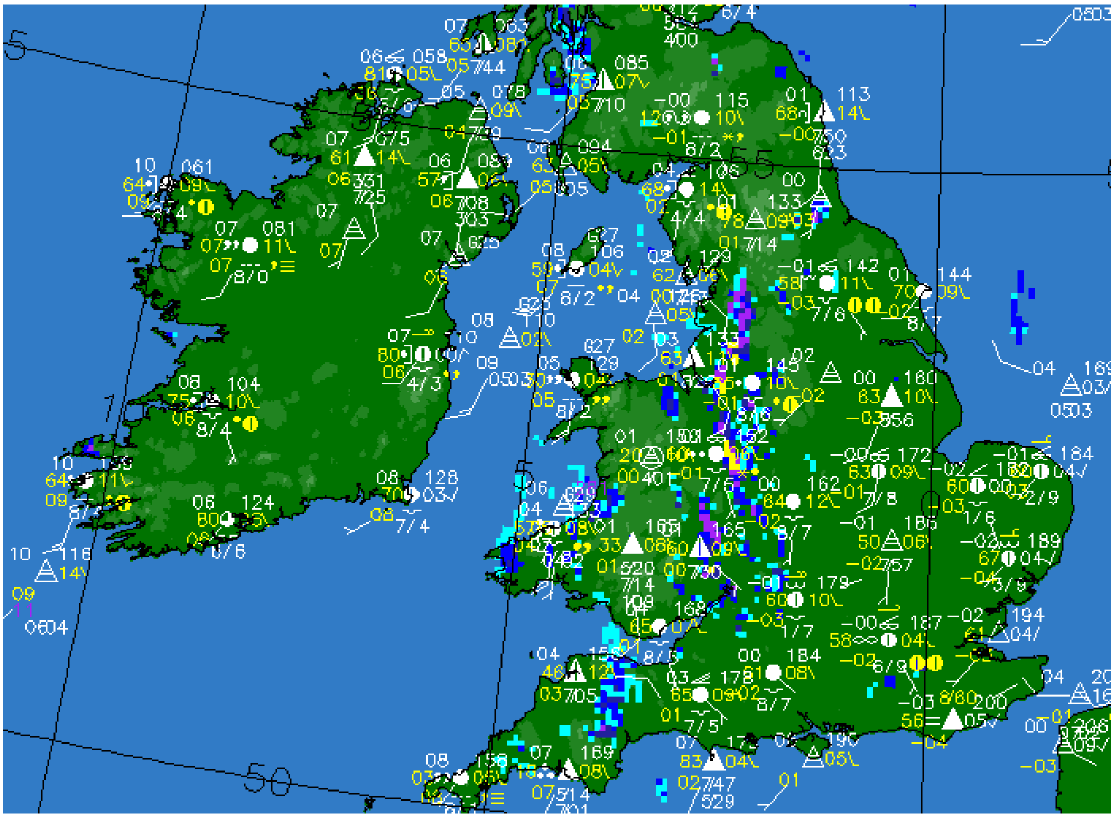

Figure 17. Map from the Met Office HORACE display showing plotted observations with radar imagery overlaid for 6/2/03 0800 UTC.

The final case is for 30/1/03 0900 UTC which had the British isles in a cold northerly airmass with a frontal system moving southwestwards over SW England with much colder air following behind from the east. A squall line consisting of snow was also moving west towards Bracknell with showers of hail, sleet and snow near the east coast. Observations are shown in Figure 18.

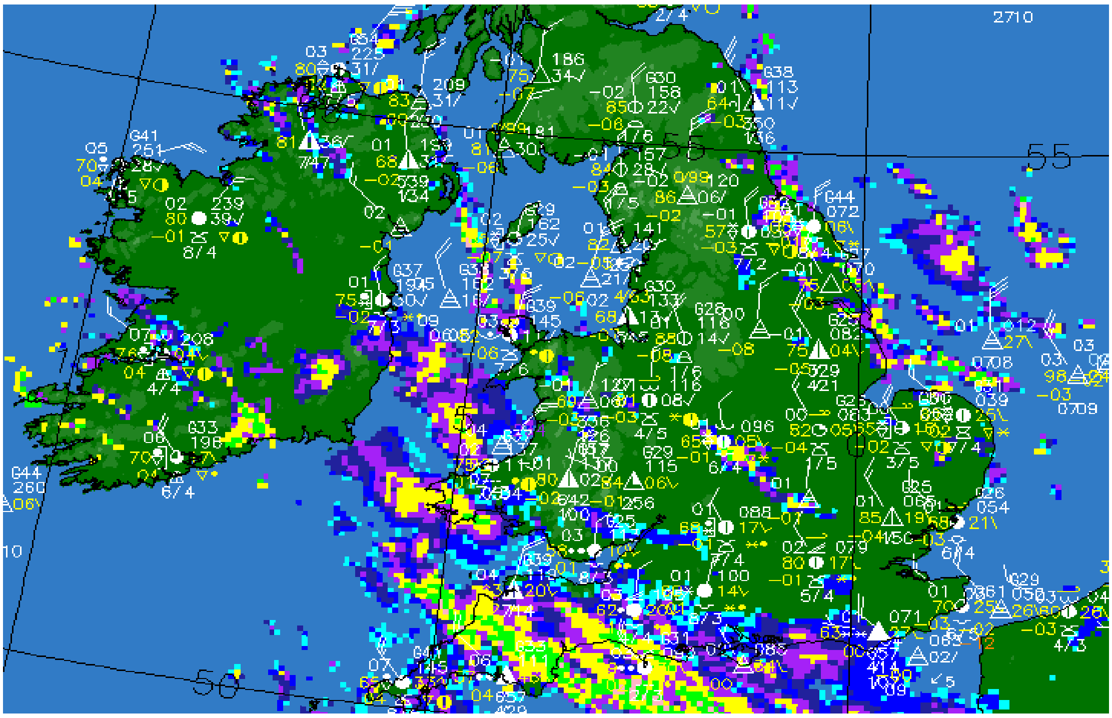

Figure 18. Map from the Met Office HORACE display showing plotted observations with radar imagery overlaid for 30/1/03 0900 UTC.

The situation in SW England was rather messy with mostly rain and sleet over low ground but moderate or heavy snow over the moors above 300m (personal observation). The squall line approaching Bracknell from the northeast is shown clearly by the radar echoes with a report of a snow shower on the northern edge at Birmingham. The precipitation type diagnoses are shown in Figure 19.

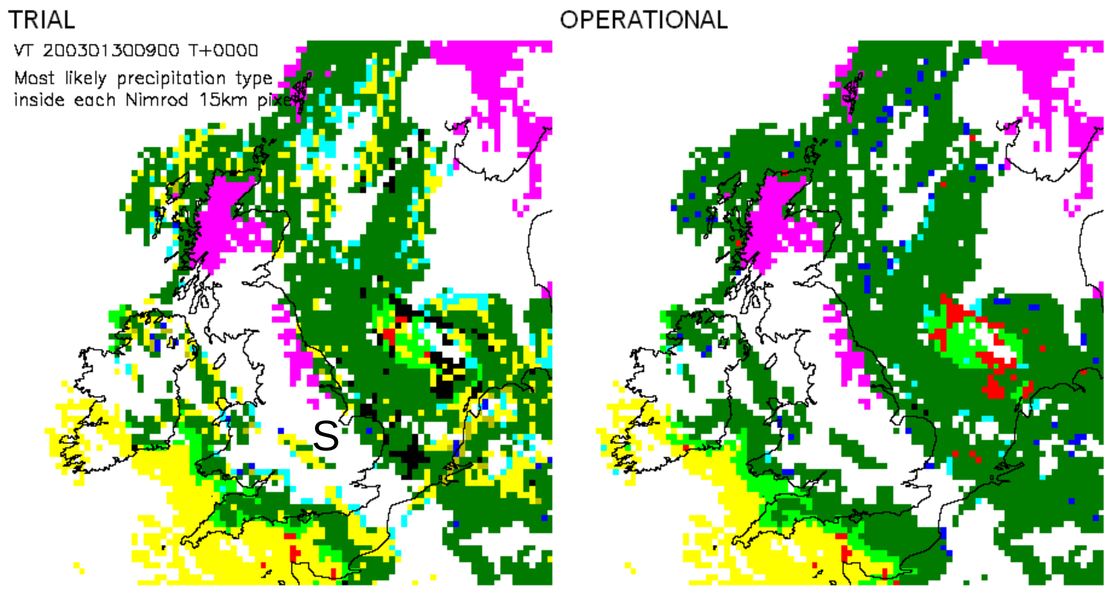

Figure 19. Maps showing precipitation type diagnosed on 30/1/03 at 0900 UTC from the trial run (left) and operational run (right). The key to the colours is the same as in figure 9. The letter “S” indicates a squall line to the left of the letter.

For the frontal band in the SW the trial is similar to the OP and is quite good apart from too much snow on low ground. The showers in the North Sea and down the east coast also look well done and the larger number of “hail with snow” showers in the trial is justified. However, the portrayal of the squall line is poor in the trial version. Most, if not all of the precipitation should have been of snow like OP and that is not the case in the trial forecast. The individual type probabilities for this case are shown in Figure 20.

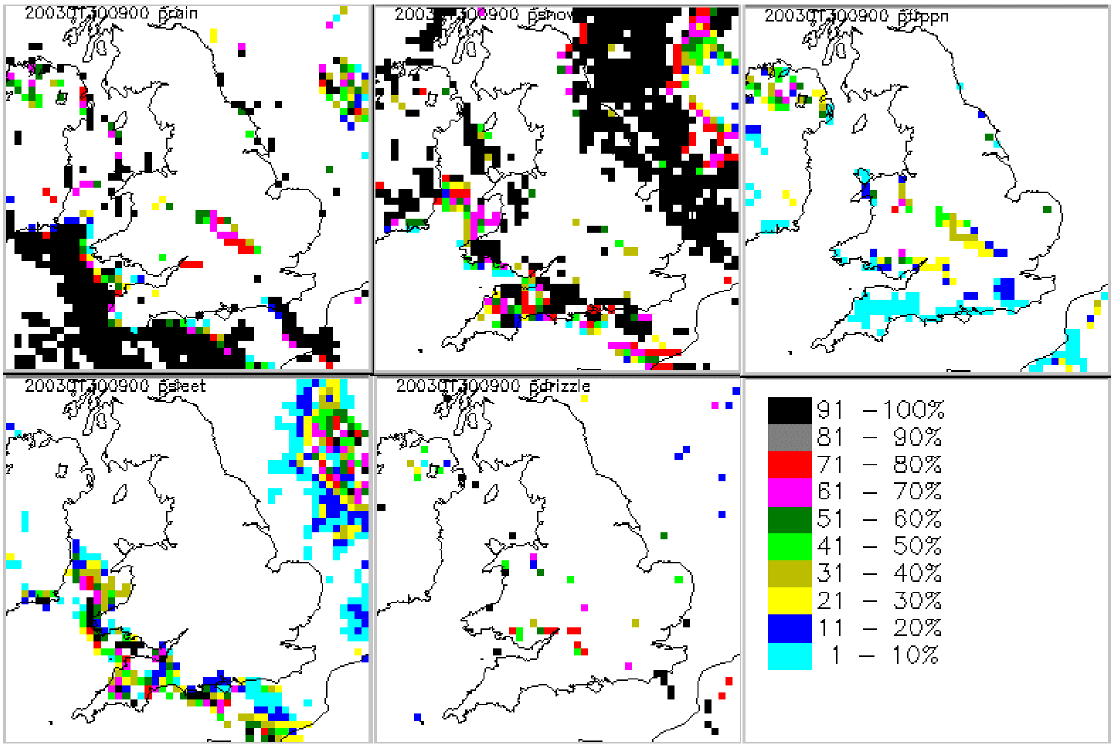

Figure 20. Maps (starting from top left) showing probability of getting rain, snow, freezing precipitation, sleet and drizzle on 30/1/03 0900 UTC.

In the squall line a lot of pixels have a snow probability of zero. Given that the OP diagnosed snow and the method of determining the snow probability in the trial is almost identical to the OP version apart from the probability of glaciation factor then the glaciation probability (GP) must have been zero. The probability of drizzle in the squall line is also zero and apparently inconsistent with zero GP, however, given that there are rainfall rates greater than 0.25 mm/h the drizzle probabilities would have been set to zero and added to the rain probability which is then output. Due to the cold ground surface there is also a probability of freezing liquid precipitation which is indicated. Since the glaciation probability depends on the lowest precipitating cloud top temperature derived from the Nimrod cloud analyses and the model temperature profile then problems with these or the algorithm used to calculate precipitating cloud top temperature will affect GP. This is very similar to the problem identified in case study 31/12/00 (Figures 5 and 7).

7.2 Discussion

Taking in all the evidence from the objective and subjective assessments there seems to be consistent themes emerging. Clearly as evidenced in the

30/1/03 case and the assessments pertaining to Q3 the GP is still sensitive to how precipitating cloud top temperature is calculated and this needs further investigation and revision. It is not desirable to remove the GP altogether as including it has clearly helped to reduce the over-forecasting of wintry precipitation ("snow or sleet diagnosed/rain observed") and improved the prediction of drizzle. However, improving the GP could conceivably remove a large number of "snow observed/rain diagnosed" categories.

Turning to Q1 the answer may in part lie in the calculation of GP (increasing the number of drizzle diagnoses), however, it is likely that the problem may also lie in the choice of threshold rainfall rate for drizzle. Observed drizzle rates are very low usually and diagnosed "drizzle" with a rate of 0.2 mm/h, say, might often be observed as rain. However, the "drizzle" category is very useful for distinguishing the likelihood of light precipitation from non-glaciated clouds. Therefore, it is best that the threshold of 0.25 mm/h remains unchanged. However, there is clearly a problem with drizzle verification (over-confidence), but taking liquid precipitation overall the situation may be much better. This needs to be looked at by grouping the "drizzle" and "rain" categories together into a "liquid" category for the purposes of verification.

Considering freezing rain, the 6/2/03 case demonstrated the value of being able to generate freezing rain probabilities. In that case the diagnosis compared very well with the forecaster's appraisal of the situation. Freezing precipitation is rare in the UK and the observing network is not dense enough to pick out isolated occurrences. Clearly there is scope for improvement in the diagnoses and the error characteristics of the model ground temperature forecast (T*) need to be determined or estimated more accurately. The removal of freezing precipitation over the sea is an improvement but the interpretation of the output requires care. During the trial there were several occasions when freezing rain was diagnosed when the ground was snow covered. In this situation an observer will not code freezing precipitation. However, such situations of rain falling onto snow cover can give very slippery and hazardous conditions and the new outputs would give warning of that possibility. So in answering Q2 we can justify the increase in freezing rain diagnoses (and the modest improvement in skill !), however, we need to determine the error characteristics of T* as a longer term goal.

Finally, moving to a probabilistic based scheme offers obvious advantages (as in the freezing precipitation example) and can provide insights into system behaviour. Clearly many customers will require deterministic outputs and the decision tree approach seems to work reasonably well in this. Improved accuracy is likely to come from improving the probabilities input into the decision tree rather than altering the decision tree itself.

8. Conclusions and recommendations

The performance of the current Nimrod precipitation algorithms has been assessed and proposed improvements have been incremently tested on suitable cases. A probabilistic scheme was identified as being the most promising as an upgrade. This scheme was trialled semi-operationally comparing results objectively and subjectively with the operational system. A suite of programs was established for verifying the probability forecasts in an accepted way. The performance of the trial scheme has been assessed over the winter period in 2003 and a couple of key issues have arisen. It is recommended that the derivation of the glaciation probability and verification of liquid precipitation is examined and re-formulated as necessary. New algorithms should be tested within the ongoing trial and also on suitable cases presented in this report. During the summer the identification of summer hail storms should be monitored and code tuned if necessary. The aim of this further work would be to introduce an improved precipitation type diagnosis into Nimrod in time for winter 2003/4.

9. References

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Appendix 1

Nimrod contingency tables for precipitation type January to March 2000. Observed types are listed on the left and forecast types along the top. Figures in the table are occasion percentages of the total number of observations used for each month in the UK. Additional information on number of observations and forecasts with percentage hit and false alarm rates for snow, hail, sleet and freezing rain are also provided below the main tables.

Precipitation Type Verification for 200001: No of obs = 5547

obs / f/c	drizzle	rain	sleet	freezing	snow	hail
drizzle	3.389	8.725	.162	.036	.072	.036
rain	3.173	72.183	3.389	.144	1.136	1.947
sleet	.054	.883	.577	.198	.685	.180
freezing	.000	.072	.018	.000	.000	.000
snow	.036	.162	.234	.036	.703	.108
hail	.036	.847	.162	.000	.126	.487

Snow: ob 71 fc 151 hit rate 73.24 false alarm rate 74.17
Hail: ob 92 fc 153 hit rate 29.35
Sleet: ob 143 fc 252 hit rate 22.38
Freezing rain: ob 4 fc 23 hit rate .00 false alarm rate 100.00

Precipitation Type Verification for 200002: No of obs = 8052

obs / f/c	drizzle	rain	sleet	freezing	snow	hail
drizzle	.559	6.458	.149	.000	.062	.075
rain	2.322	73.063	3.689	.137	1.217	3.192
sleet	.062	.758	.820	.037	.596	.609
freezing	.000	.012	.000	.000	.000	.000
snow	.012	.137	.472	.012	2.298	.695
hail	.025	.658	.323	.012	.236	1.304

Snow: ob 292 fc 355 hit rate 76.37 false alarm rate 47.89
Hail: ob 206 fc 473 hit rate 50.97
Sleet: ob 232 fc 439 hit rate 28.45
Freezing rain: ob1 fc 16 hit rate .00 false alarm rate 100.00

Precipitation Type Verification for 200003: No of obs = 4864

obs / f/c	drizzle	rain	sleet	freezing	snow	hail
drizzle	1.953	11.328	.391	.000	.021	.000
rain	2.919	69.922	3.248	.082	1.172	2.241
sleet	.000	.329	.452	.021	.514	.144
freezing	.000	.021	.000	.000	.000	.000
snow	.000	.021	.267	.000	2.488	.411
hail	.041	.617	.329	.000	.637	.432

Snow: ob 155 fc 235 hit rate 86.45 false alarm rate 48.51
Hail: ob 100 fc 157 hit rate 21.00
Sleet: ob 71 fc 228 hit rate 30.99
Freezing rain: ob1 fc 5 hit rate .00 false alarm rate 100.00

Appendix 2

List of development case study dates with observed precipitation types.

Date	Time	Freezing precipitation	Snow or sleet	Small or soft hail	Large hail
19/05/99	1800				✓
29/05/99	1500				✓
31/07/99	1900				✓
05/09/99	1700				✓
08/01/00	2100	✓	✓	✓	
13/01/00	0800	✓	✓	✓	
22/01/00	0900	✓		✓	
22/01/00	1200	✓	✓	✓	
24/03/00	1000	✓			
15/04/00	1800	✓			
07/05/00	1900				✓
21/08/00	0900			✓	✓
16/12/00	0300	✓	✓		
16/12/00	0400	✓	✓		
31/12/00	1600	✓	✓		