Extreme Weather Events Likely to Cause Disruption to Electricity Distribution

Prepared for: Resilience Working Group

28 August 2003

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MetO ref: M/PS/5/15/4/RWG

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1. Executive Summary

This report presents the findings of a number of studies which aim to identify any changing levels of vulnerability in the electricity distribution network. Weather events highlighted for study were wind storms, ice accretion and lightning. Any change in wind climatology or seasonality which may increase tree related damages (“wind throw”) were a particular focus.

Analysis of observed wind data from a number of UK meteorological stations failed to identify any trends of change however a new and innovative second approach (calculating large scale air flows based on ‘geostrophic’ wind) proved to be more successful and was applied in a plot study for East Anglia. The key to this second approach is that the calculations are based upon pressure fields. These are independent of the variations in site exposure which confused the search for trends in wind observations at ground stations. A trend towards stronger and more frequent southwesterly winds (i.e. winds blowing from the southwest) in winter months was identified for the pilot study region. This is consistent with the Met Office’s Hadley Centre prediction of the impact of climate change on wind.

Data, both observed and modelled, illustrated an extension to the growing season, which is predicted by climate change models to continue. Investigation has shown that the majority of the increase in leaf cover comes from an earlier onset of spring. There is a slight shift to later leaf fall in autumn with trees retaining leaf cover for longer than previously observed. Increasing greenhouse gases and climate change are expected to enhance these occurrences and may potentially make growth both faster and lusher. Climate models predict that water available to trees for growth will decrease in summer and autumn months which may limit any extension of leaf cover into significantly later weeks of the year.

While the study of changes to observed wind highlighted increasingly strong winds from the south wets across East Anglia in winter it has not been possible to identify a clear trend in either spring or autumn winds. It is during these seasons that changes in leaf cover on trees, and hence risk of blown tree debris (wind throw) is expected to increase. Both observed and predicted wind strengths show little change during spring and autumn months however a slight increase in the frequency of occurrence of strong winds is predicted for future decades along the English south coast in spring. It should be noted that, even without a change in the seasonal characteristics of wind climate, the fact that trees are in full leaf and thus vulnerable to damage for longer periods of the year represents an increased risk in itself.

The Baldock report (1982) on network resilience to ice accretion events was revisited and risks originally presented for data to 1980 were recalculated for recent decades. This analysis shows no significant trend in risks or vulnerability. A new technique was developed which calculates the effective force on a cable due to the combination of both ice loading and wind forcing. No clear trend can be discerned in the data from the analysis of station data for the last fifty years using this new technique because of the large year to year variability that exists. However, recent network failures attributed to ice events were analysed using the new technique which performed well, successfully identifying high risk conditions, offering the possibility of a predictive tool for high risk of failure due to icing.

Within the scope of this report it has not been possible to say anything conclusive about changing risks or vulnerability due to lightning events however preliminary results from climate modelling studies show that as climate changes summer storms may become more energetic resulting in a possible doubling of flash rate during a typical storm. It is reasonable to assume that the risk of multiple strikes of lightning at the same location during an individual event will be increased in the future.
2. Introduction

In recent years a number of storm events in the UK have led to significant disruption of the electricity distribution network. These include the storms of October 1987 and January 1990. It is known that severe weather accounts for a large number of distribution failures, particularly the catastrophic incidents where supply of electricity is disrupted for a number of days over a large geographical area. Strong winds are often a contributing factor during occurrences of damage caused by adverse weather conditions.

The aim of this report is to help Distribution Network Operators (DNO’s) within the UK to better understand the frequency and geographical distribution of significant weather events likely to affect the distribution of electricity within the UK. Three types of weather event have been identified as being of particular interest: wind storms (especially in association with ‘wind throw’ or wind blown debris from trees or, in extreme cases, the uprooting of trees), ice accretion and lightning. Observations over recent decades are analysed and any trends identified. These trends are then considered in the context of predicted climate change.

Throughout the report reference is made to nine UK meteorological sites (detailed in Appendix 2). These nine stations are well distributed across the country and can be considered as representing the main climatic regions of Britain. For consistency each part of the observational data analysis is based upon this representative selection of stations.

The report is structured as follows. Section 3 considers observations of wind, both the mean speeds and gusts. While it is thought that strong wind is seldom a sole cause of catastrophic incidents on the electricity network, it is often one the factors involved. For this reason we analyse observed wind data for the last thirty years in isolation. Section 4 presents a discussion of possible changes in UK vegetation and the length of the growing season. If trees are in full leaf for longer periods there may be increased vulnerability to wind damage. Changes in conditions suitable for ice accretion events are analysed in section 5. A brief discussion on lightning is presented in section 6 while conclusions are given in section 7. Throughout the report, where possible, predicted changes in these factors due to climate change are considered.

3. Wind

In isolation strong winds are not considered to be a cause of failures in the electricity distribution network, however it is thought to be one of a number of contributing factors when failures do occur. For this reason it is important to seek to identify trends and changes in wind, both observed and predicted for the future, in order to clarify any changes in risks which may be due to a changing wind climate across the UK.

3.1 Wind in a changing climate

Generally speaking large scale flows of air, i.e. mean wind, are driven by the pressure gradient across the country and when the gradient is high, the winds are strong. Analysis of results from the Hadley Centre regional climate model (RCM), HadRM3, shows that as climate changes only a small change in pressure gradient, relative to present day conditions, is predicted in spring and autumn months. Typically however most severe mean winds occur during winter months. The climate model predicts that during winter the pressure gradient across the country will increase and stronger winds will be experienced in southern and central Britain, although there will be little change in Scotland or Northern Ireland. As the northwest of the country currently has a windier climate than the southeast in winter this predicted change implies a weakening of the nation-wide differences in wind speeds.
The RCM predicts that the greatest increases in average wind speeds during the winter season will occur along the south coast of England, with increases also predicted for this region during summer months. These winter increases in mean wind speed are predicted to be between three and six percent above present day averages by the middle of the century, depending upon the choice of scenario of future greenhouse gas emissions, with smaller increases during summer months. For most other regions the predicted changes to mean wind speed in all seasons are small, except for across Northern Ireland where decreases during the summer season are of a similar magnitude to the wintertime increases over coastal southern England.

The RCM also predicts a slight increase in the frequency of occurrence of the strongest winds in both winter and spring especially along the south coast of England. The analysis is based upon ‘return periods’ and shows that that the magnitude of an event which typically occurs once in every two years will increase slightly, which is equivalent to saying that the return period for such magnitude winds will decrease or that they will be observed more frequently. The magnitude of a one in two year event is predicted to decrease slightly in summer months across central and northern Britain.

A note of caution must be given with these predictions. Unfortunately there is little consistency between the changes in pressure patterns predicted by different climate models for the UK and so little confidence can be placed in these results. All predicted changes in wind speed therefore have high levels of uncertainty associated with them. The results presented here are the changes predicted by the Hadley Centre regional model, HadRM3. However, it must also be noted that the results presented from the East Anglia observational data study (described in section 3.2.3) show consistency with HadRM3 predictions which allows more confidence to be placed in the climate predictions.

The results presented above refer to seasonally averaged wind speeds predominantly due to varying pressure patterns but during winter months especially the weather of the UK is dominated by low pressure systems, also called depressions or storms, which travel in from the North Atlantic. The route these depressions take is termed the ‘storm track’. As part of the analysis completed for Climate Change Scenarios for the United Kingdom (UKCIP, 2002) depressions were identified and tracked within the climate model. The analysis was performed using one scenario of future emissions of greenhouse gases, Medium-High. The scenarios of change used within UKCIP (2002) are based on those defined by the Intergovernmental Panel in Climate Change (IPCC) and are called Low, Medium-Low, Medium-High and High. It was found that the number of depressions crossing the UK in an average winter may increase by more than twenty five percent by the middle of the century. This occurs because the storm tracks are predicted to shift southwards from their current position. This results in a strengthening of winds across southern England during winter. More severe storms or ‘deep’ depressions were also studied. This analysis showed that the probability of any individual low pressure system developing into a deep depression does not increase from present day levels, however as more storms are predicted by the middle of the century it is reasonable to assume more deep depressions will occur. In summer the pattern is reversed with fewer depressions predicted over the UK. In spring and autumn months little change is predicted in depression frequency or intensity.

A further complicating factor exists in the form of the North Atlantic Oscillation (NAO), which is a measure of wintertime north-south pressure gradients across the North Atlantic. As noted previously as pressure gradients increase so does wind speed, hence the NAO is a measure of the westerliness of winter weather and a high (positive) NAO index means that the UK will experience a wet and windy, but mild, winter. Current predictions by the Hadley Centre climate model suggests that the NAO may tend towards a predominantly more positive state in coming decades, meaning that high positive NAO states and therefore wetter, windier but milder winters will become increasingly common. It has to be noted however that year to year variability of the index will remain substantial and that large
negative NAO index states will continue to occur. Model studies show that this increase in the decadal NAO index becomes statistically significant by the middle of the century (under the Medium-High emissions forcing used with UKCIP 2002). This is equivalent to saying that by the 2050s the NAO will have increased beyond the range of natural variability. Assuming that present day links between UK weather and the NAO continue this suggests that the UK will experience winters which are more westerly in nature (i.e. winds blow from the west) and hence are wetter, windier and milder than at present. This too is consistent with the model predictions of wind variations as climate changes.

3.2 Search for observed wind trends in recent decades

3.2.1 Search for trends in recent wind speed records

Given the tentative nature of climate change predictions of wind changes, confidence in them might be increased if it could be shown that such trends had already begun to take place. The most obvious first approach to this is to look for trends in actual observations of wind speed over recent decades. Hourly observations of wind speed for nine UK weather stations were extracted for the 30-year period 1971-2000 and divided into 10-year segments. The stations are mapped and listed in Appendix 2 and were chosen partly on account of their near-continuous record over this period, and partly to represent widely-spaced climatic areas around the UK.

Each decadal set of data for each weather station was analysed to determine the frequency of hours with mean wind speed exceeding a particular threshold. In discussions with the Resilience Working Group there was some uncertainty over what constitutes a wind speed threshold pertinent to damage to power lines. However, for the purposes of a search for a trend, the precise choice of threshold is not critical as long as it represents ‘strong winds’. A threshold of 39mph was ultimately chosen for mean hourly wind speed, as higher thresholds were exceeded on too few occasions to allow a meaningful inter-decadal comparison. This threshold also corresponds to gale force on the Beaufort wind scale.

Another consideration is that short gusts of wind, lasting up to a few seconds, will often greatly exceed the mean wind speed – by more than 100% in some circumstances. In view of the possible importance of these gusts in regards to power cable damage, a further set of analyses was performed with the condition that hourly maximum gust speed be 50 mph or greater. Figures 1(a) and 1(b) illustrate the overall results of these analyses. They compare, for each station, the total number of hours fulfilling the chosen mean speed and gust speed criteria in each decade.

The decadal trends for the number of hours with mean wind speed exceeding 39 mph and the number of hours with maximum gust speed exceeding a 50-mph are illustrated to vary from station to station. However, although Kinloss, Elmdon and Eskdalemuir were apparently each windiest in the 1970s, this is probably explained for Elmdon and Eskdalemuir by known changes in local site exposure. For instance, the area around Eskdalemuir has undergone extensive aorestation. Boscombe Down, Leeming, Waddington and Aldergrove appear to have been least windy in the 1970s. The results for Valley and Mount Batten are more ambiguous as the trend in frequency of strong gusts is different from the trend in frequency of high mean speeds (figure 1(a)).
Figure 1(a): Decadal comparison, for 9 UK weather stations, of the number of HOURS with MEAN wind speed >= gale force (39 mph)

Figure 1(b): Decadal comparison, for 9 UK weather stations, of the number of HOURS with hourly maximum (3-second) GUST speed >= 50 mph

Figure 1(a): Decadal comparison, for nine UK weather stations, of the number of hours with mean wind speed greater than or equal to gale force (39 miles per hour)

Figure 1(b): Decadal comparison, for nine UK weather stations, of the number of hours with hourly maximum (3-second) gust speed greater than or equal to 50 miles per hour
This leaves Kinloss, the most northerly site, as the only site that was windiest in the 1970s, with a hint that, further south, the 1980s and 1990’s have, in combination, been windier than the 1970s. This result bears some consistency with climate change prediction of increasing windiness in southern areas while the northern wind climate changes little. However, studying figures 1(a) and 1(b), it is difficult to conclude with any confidence that there has been a consistent and progressive increase in windiness over the last 3 decades. These results should be acknowledged to be inconclusive because of the ‘noise’ of changes in local site characteristics. This does not preclude the possibility of there being an overall trend in the wind climate but a different search approach is needed.

In summary, this method of searching for a trend in the windiness of recent decades – by analysing observed wind records from ground stations - has proved inconclusive. However, the demonstrated sensitivity of wind climatology to local site characteristics is itself worthy of note. It raises the question of whether the impact of any overall increase in windiness could, in some circumstances, be mitigated by taking greater account of local wind climatology when routing power lines.

3.2.2 Search for windiness trends using ‘geostrophic wind speed’ derived from site records of atmospheric pressure

The analysing of ground station wind records in search of an overall trend in the frequency of strong winds has been shown to be of limited value because of temporal variations in site characteristics. Rather than pursue this approach any further, an attempt has been made to devise an alternative approach based on an observed parameter that is independent of site characteristics. This parameter is atmospheric pressure, corrected to mean sea level, and the following paragraphs describe a pilot study using this approach on one specific region of the UK – East Anglia.

Unlike the case with wind records, this approach cannot be applied to one site in isolation and requires simultaneous pressure observations from several sites in order to determine the pressure differences between the sites. Because wind speed, ignoring the variable impact of terrain friction, is proportional to pressure differences, it is possible to infer the wind speed and direction that would have occurred without any frictional ground effects. This wind is known as the ‘geostrophic wind’ and is independent of the spatial and temporal variations in site characteristics that confuse any search for a signal from regional-scale climate change.

Detailed explanation of the geostrophic wind calculation is given at Appendix 3. An important consideration in interpreting geostrophic wind data is that these calculated winds are much stronger than the mean wind speeds that actually occur near the earth’s surface, because they take no account of friction. Nonetheless, wind speeds near the ground, though less than the geostrophic wind speed, are a function of it. Hence, a trend in the geostrophic wind speed indicates a similar trend in wind speed near the ground, ignoring the impact of temporal variations in site exposure. Observed mean wind speeds at land stations are often less than half the geostrophic speed. Gust speeds, however, may exceptionally approach the geostrophic wind speed, which is more akin to the mean wind speed occurring, say, 800 metres above the ground.

The intention was to choose four weather stations defining the corners of a rectangle with sides aligned north-south, making it an easy matter to calculate the north-south and east-west components of pressure difference between the stations and then the resultant of these two components. This stipulation was not essential but it simplified the calculation. In practice, it was impossible to find such an ideal scenario among stations with a near-complete record over the period 1971-2000. Lines joining the weather stations at Nottingham, Coltishall, Manston and Heathrow form a slightly skewed rectangle, roughly coincident with East Anglia. Given that the current interest is in the trend of windiness, rather
than absolute values, this trigonometrical compromise is not considered important in this study.

Digitally archived pressure data for the 1970s is, for many sites, at 3-hourly intervals rather than hourly. For consistency, 3-hourly data have been used for the whole period 1971-2000. This should be a sufficiently short interval between observations to detect most strong wind events. The period was divided into its 3 decades, and the mean geostrophic wind speed at 3-hourly intervals for the area defined by the four stations calculated, yielding 29,000 values per decade. In addition, the wind direction was calculated to the nearest quadrant. The speed values were then sorted in order of magnitude to determine, for each decade, the numbers of occasions exceeding given thresholds. These numbers were then scaled up by a factor of 3 to represent the number of hours above each threshold in each decade.

The roughly square area defined by the four stations has a width of some 160 km – wider than the belts of strongest winds in some storms. Therefore, the use of such a large area will smooth out some of the highest wind peaks. Ideally, a smaller area would be chosen, although in this case where the aim is to identify relative trends rather absolute values this is of reduced importance.

3.2.3 Results of pilot study for East Anglia

Figure 2(a) compares the last 3 decades in respect of the frequency of strong geostrophic winds. An increasing frequency of strong geostrophic winds between the 1970s and 1990s is immediately apparent. For instance, geostrophic wind speeds exceeding 50 mph are estimated to have increased in frequency by 20% from about 4800 hours in the 1970s decade to about 5800 hours in the 1990s decade. Furthermore, as no allowance has been made for 2% of observations being missing for the 1990s, this increase is probably slightly underestimated.

Further analyses were performed specifically for each of the four seasons. For this purpose each season was defined as period of three calendar months – spring: March-May; summer: June–August; autumn: September–November; winter: December–January. These analyses revealed that the overall annual increase in windiness illustrated by figure 2(a) is almost entirely on account of a marked increase in winter windiness, illustrated by figure 2(b). The latter figure demonstrates, for instance, that the total number of winter hours with geostrophic wind speeds exceeding 50 mph increased by 35% from about 2300 hours in the 1970s decade to about 3100 hours in the 1990s decade. The total number of winter hours with geostrophic wind speeds exceeding 70 mph is more difficult to decipher from the chart but increased by almost 50% from 384 hours in the 1970s decade to 573 hours in the 1990s decade.

Despite this marked increase in winter windiness, no consistent trend in windiness was apparent in spring, summer or autumn. This is precisely in accord with climate change predictions and increases the credibility of these predictions. The reason for the strong influence of the winter trend on the overall annual trend is simply that a larger proportion of strong wind events occurs in winter than in any other season.
Figure 2(a): Decadal comparison, for East Anglia, of the frequency of areal-averaged geostrophic wind speeds >= given thresholds (WHOLE YEAR, ALL WIND DIRECTIONS)

Figure 2(b): Decadal comparison, for East Anglia, of the frequency of areal-averaged geostrophic wind speeds >= given thresholds (WINTER: Dec - Feb)

Figure 2(a): Decadal comparison, for East Anglia, of the frequency of areal-averaged geostrophic wind speeds greater than or equal to given thresholds (Whole year, all wind directions)

Figure 2(b): Decadal comparison, for East Anglia, of the frequency of areal-averaged geostrophic wind speeds greater than or equal to given thresholds (Winter – December to February)
Another set of analyses was performed, this time segregating the data by wind direction quadrant – that is, by the 90-degree direction sector from which the geostrophic wind was blowing. Once again it was found that the trend towards increasing geostrophic wind speeds was confined to just one of the four direction quadrants – that representing winds blowing from between south and west (‘southwesterly’). The increasing frequency of strong winds from this direction sector is illustrated by figure 2c. This figure shows, for instance, that the number of hours with southwesterly geostrophic winds in excess of 50 mph increased by 35% from about 3300 hours in the 1970s decade to about 4450 hours in the 1990s. The number of hours with southwesterly geostrophic winds in excess of 70 mph increased by 51% from 474 hours in the 1970s decade to 717 hours in the 1990s decade.

In contrast, no increase in strong wind frequency was apparent for the remaining three direction sectors and the frequency of strong winds from between north and east actually decreased slightly. This finding, too, is in accordance with climate change predictions of stronger and more frequent ‘westerlies’ over southern Britain, enhancing the credibility of these predictions too. Again, the reason for the strong influence of this one direction segment on the overall trend is that the frequency of strong winds from this direction sector far outweighs that from any other, so dominating the overall trend.

In summary, when the complication of changes in site characteristics is removed, then for a pilot study area, East Anglia, there has been a marked increase in the frequency of strong winds over the last 3 decades of the 20th century. A caveat on this finding is that, as it is based solely on analysis of pressure fields, it ignores the frictional impact on wind speeds near the ground of any regional trend in land usage. This overall increase in windiness is almost entirely on account of an increased frequency and strength of winds blowing from between south and west in winter, consistent with climate change predictions. A recommended next step would be to investigate whether these findings can be repeated for other areas of the UK.
4. Wind and leaf cover

Following the storm event of October 27th 2002 the Energy Minister, Brian Wilson MP, called for a study to examine the response to the storm by the electricity distributors. British Power International led the study and suggested that as much as ninety eight percent of the damage caused during the event was from wind throw, or wind blown debris from trees. Thus, any increases in the length of time during which trees remain in full leaf could potentially result in increased vulnerability within the electricity distribution network.

4.1 Thermal Growing Season

The growth of any plant depends upon both temperature and moisture availability criteria however it is possible to define a temperature-based index which gives the length of the thermal growing season.

A number of long observational temperature records show that the UK has warmed over the last century and that this warming has resulted in a lengthening of the thermal growing season. Analysis of the Central England Temperature (CET) record shows that most of the increase in growing season length took place in two distinct phases – between 1920 and 1960 (on average 0.7 days per year) and between 1980 and 2000 (on average 1.7 days per year). These were both periods of warming separated by a couple of decades when temperatures over the UK decreased. It is interesting to note that the characteristics of these two periods are different. During the earlier period of increase the lengthening growth season was due to both an earlier onset of spring and a later onset of winter, however most of the recent increase in growing season length is due to an earlier onset of spring (on average 1.5 days per year), with little change in the timing of the end of the season. The CET record shows that the thermal growing season for central England is now approximately one month longer than at the beginning of the twentieth century and is longer than at any time since the start of the daily temperature series in 1772.

4.2 Phenology

Phenology is the study of seasonally recurring natural phenomena especially in relation to weather and climate change. A typical example may be the date of the first cuckoo call being heard or the date of the first sighting of a migrating bird which visits the UK each year. In 1875 the Royal Meteorological Society established a national network of recorders to examine the relationship between meteorological events and the natural world, and continued to publish annual reports until 1948. In 1998 a pilot scheme was launched to revive the network and now more that twenty thousand volunteers across the UK contribute to the UK Phenology Network. Unfortunately this means that although there is plentiful data for the first half of the twentieth century very little data exists after 1948 except for the last few years and a couple of isolated individual records. It is possible however to draw some conclusions from the data that is available.

There is a growing body of evidence that spring is occurring earlier in the year. Trees have been coming into leaf earlier and migrant birds are arriving earlier. Records for Ashstead in Surrey held by the UK Phenology Network show that the leafing of trees has occurred progressively earlier in the year throughout the 1980s and 1990s. Horse chestnut are leafing 12 days earlier, oak 10 days and ash six days. When considering all of the data available across the nation the Phenology Network believe that it is the sycamore which appears to be responding fastest of all the UK’s large tree species to our changing climate. Oak also appears to be showing more of a response while species like ash are showing relatively little change. This differing level of adaptability is likely to result in an altered balance between species and ultimately may change the composition of our woodlands. Changing composition of woodland, and associated changes in woodland management, could have a
large impact on risks to the electricity distribution network as average heights of treetops across wooded land may change as will the types and characteristics of foliage.

Recording autumn events is much more challenging than collating information on spring events, for example it is much easier to spot the first bluebell than it is to keep an accurate record of sighting the last. Unfortunately historical records of autumn events are sparse so much of the data available comes from the last few years. There is however evidence that oak leaves are falling one week later in the year than thirty years ago. While the data record is very incomplete (having no data for the 1950 –1980s) it can be seen that in recent years horse chestnuts have been bare over a week later than was observed at the beginning of the twentieth century. It must be noted however that the sparsity and incompleteness of the data allow very little confidence to be placed in any trend derived in this case.

Figure 4: 10, 50 and 90% leaf fall dates for the West Midlands and East Anglia. Storm events are denoted by ‘S’

A dataset of observations on the rate of progression of autumn leaf fall have however been collected through a network of ADAS staff since 1995. The reports are made regularly for a variety of broadleaf species commonly found in the UK. The network has evolved over time and now covers areas from the central belt of Scotland down to the south of England. Unfortunately no clear trend emerges from an analysis of this short record but as autumn leaf fall is dependent upon a number of factors (such as light availability, length of day, frosts and wind speed) this is perhaps unsurprising given the limited length of the record.
Taking two areas as examples (West Midlands and East Anglia), the date for 50% leaf fall is seen to vary by between 8 and 14 days between the earliest year and the latest year, illustrated in figure 4. The spatial variation for the average 50% leaf fall date across the country is better defined with the south east of England (mid November) being some two weeks later than central Scotland (early November). It can also be seen that the storm events of October 2000 and October 2002 occurred during the early part of the leaf fall season when trees had at least sixty per cent leaf cover. It is interesting to note that the October 2000 storm accelerated early leaf fall in East Anglia so that almost half of all foliage was lost during a single storm event, implying that wind throw was severe during this event.

It can also be seen in figure 4 that in East Anglia in 1996 the leaf fall season extended into December by more than a week. This is one of the months that contributed to the winter averages and trends shown in section 3.2.3. The analysis demonstrated that there is evidence for strengthening wind in the region during the winter season. It is not possible to deduce whether there was increased risk of wind throw damage in this region in 1996 because the analysis of wind changes is based on ten year averages however it has been stated that observed trends in wind strength are expected to continue as UK climate changes. All of the evidence presented here would indicate that this risk of wind throw related damage will increase should the growing season continue to extend into December.

4.3 The impact of climate change

Effects of the component parts of climate change such as temperature and moisture availability are well understood for many species however little work has been done in studying the combined effects. Atmospheric carbon dioxide, a greenhouse gas, is used by plants during photosynthesis. It is expected that as carbon dioxide concentrations continue to increase that photosynthesis will be enhanced and plant growth will increase. Under water stressed conditions plants divert growth to the root system in order to increase water uptake, however plants are known to use water more efficiently as carbon dioxide levels increase. Higher temperatures also promote increased growth, in the absence of any limiting factors, as well as producing faster seed germination, bud burst, leaf expansion and flowering. There is already evidence that the observed warming in UK climate and the rising levels of carbon dioxide in our atmosphere have increased growth of forest trees (Gates, 2002).

Thermal growing season length can also be calculated from climate model data. During the control run of the Hadley Centre’s regional climate model (HadRM3), i.e. the simulation of present day climate, typical average growing season lengths ranged from around 150 days in the Scottish Highlands to more that 250 days in the southwest of England. By the middle of the century the length of the thermal growing season extends in all parts of the country and under all emissions forcing scenarios. Across England, Wales and Northern Ireland most areas see an increase of between 28 and 58 days per year, depending upon scenario, while the growing season in western Scotland increase by between 14 and 35 days. It must be noted however that these figures relate to thermal growing season only and take no account of either water availability or hours of sunshine.

The climate of the UK is predicted to become warmer and wetter in winter but hotter and drier in summer. Soil moisture content, or the amount of moisture available within the root zone, is predicted to decrease in both summer and autumn seasons, indicating the long time it may take to restore soil water levels following increasingly hot and dry summers. This may become the limiting factor on summer and autumn plant growth. A further aspect of increasing temperature is the forced migration of habitats. A 1°C rise in temperature is roughly equivalent to a move northwards of one hundred and fifty kilometres. Many of the UK’s woodland species are highly immobile and they cannot propagate northwards at the speed of predicted warming due to climate change. This will put species at the southern boundaries of their range at risk and at increased risk of damage as their environment...
becomes harsher. Unfortunately the regional model used in this study did not include an 'interactive' representation of vegetation and so at this time it is not possible to say whether the growing season will become constrained in autumn by lack of water availability.

As described in section 3 of this report while predicted future changes in wind climatology are very uncertain there is a limited amount of evidence which can be derived from observations that supports the HadRM3 predictions. The increase in winter wind speeds across southern Britain have been identified by analysis of seasonal averages. While the growing season for trees is not expected to extend significantly into winter months it may be that an extension of a number of weeks, combined with an increase in later autumn and early winter winds could significantly increase risk of the electricity network. A further study would be required, completing the analysis at higher temporal resolution, to quantify this risk. Numerical models of wind throw and 'interactive' vegetation are also available which may further quantify any change in levels of risk. Such models may also illuminate any effect of climate driven changes to the composition of British woodlands.

It must be noted that the observed increasing risks highlighted in section 4.2 are consistent with climate change predictions. The risk of damaging wind throw events will increase across the country as growing seasons continue to extend further into both spring and autumn/winter months. It is however southern England which will experience the greatest change in vulnerability to wind throw damage. While the impact of potentially reduced moisture availability during summer months remains unknown the impact of increasing wind strengths during winter months is clear. As the growing season continues to stretch into the months which contribute to winter averages (December to February) the risk of potentially damaging wind throw events will increase.

5. Ice accretion and snow loading

Work has been completed to update a study conducted by the electrical industry under A T Baldock in 1982 using observational data from recent decades. Since the writing of the Baldock (1982) report significant advances have been made in both numerical simulation and remote sensing, one example being the use of satellite data which is now routinely used to supplement observed data. The implications of these advances are discussed below. No attempt was made in the Baldock study to quantify the combined effects of wind and ice accretion. This shortcoming has been addressed within this report by considering a parameter which quantifies the effective force in a conductor which has been subjected to both ice accretion and strong winds. Although this parameter has distinct advantages it is also sensitive to other parameters in which there are significant uncertainties – these sensitivities are also discussed. Although the parameter shows encouraging correlation with reported disruption events, the comparison raises issues about the reporting of disruption events.

5.1 Calculation of statistics generated in Baldock report and consistent statistics for the period since its publication.

A “Review of Technical Standards for Overhead Lines following storm damage in December 1981 and January 1982” was written by a panel of experts from the electricity generation and transmission industry, chaired by A T Baldock, who was chief engineering inspector at the Department of Energy. Its terms of reference were “To consider and report on

(a) the adequacy of construction practices and maintenance of existing lines
(b) (i) whether any changes should be made regarding the statutory requirements for overhead lines;
   (ii) whether modifications to the detailed design of overhead lines are desirable and economically practicable to achieve;
in order to minimise the risk of disruption to electricity supplies under future adverse weather conditions."

The principal quantitative results recorded in the report comprised two tables each containing data for a number of meteorological observing stations. As far as possible, these tables are reproduced (see appendices 6 and 7), with additional data covering 1980s to the present day. The tables indicate the frequencies of spells during which icing accretion conditions were occurring, and the frequencies of wind speeds at those times. The report also contained a map indicating the frequency of icing accretion conditions as a function of geographical position. This map clearly indicates, as would be expected, that the frequency of these conditions is low in a coastal strip extending round the whole of England and Wales (the map did not cover Scotland). Apart from this, the map did not show any dependency of frequency on altitude (which also might be expected) but this was at least partly because of the lack of long term Met Office reporting stations in upland areas of England and Wales. None of the recommendations made in the report implied an understanding of the geographical variation of risk.

A number of statistics were published in the Baldock report and in the present study endeavours to reproduce a subset of those statistics and update them for the recent period. Generating long term statistics for meteorological reporting stations is computationally demanding, particularly if it is to be done rigorously, and in addition the choice of stations should depend on whether there have been any changes to the situation of the station or the reporting practice over the past half century. In selecting stations for the present study, it was considered important to ensure reasonable coverage of the whole of the United Kingdom (the Baldock report did not cover Northern Ireland). Therefore the nine stations chosen were the same as those used in section 3 and portrayed in the map in appendix 2. The Baldock report produced statistics for a total of 23 stations in England, Scotland and Wales.

The report derived a risk index for each station and in appendix 7 these risk indices are recalculated for the stations mentioned above for the periods both covered by the report and that since the report was published. While the risk index reflects the frequency of ice accretion conditions it does not consider the wind, which has a significant effect on severity. As can be seen, the risk index has actually decreased at all stations except Boscombe Down and Eskdalemuir. However the change at Eskdalemuir is very small (~2%) and is not considered significant. Although percentagewise the change at Boscombe Down is greater (~60%) the frequency of accretion conditions there is so small anyway that this apparent change may be due to changes in reporting practices. Similarly changes in reporting practices will have affected the apparent frequencies at other stations. For example, it is known that the frequency of missing data has changed at Elmdon, so the real change in the frequency of accretion is less than appendix 7 suggests. Overall it is considered that any apparent changes in frequency are not significant.

5.2 Advances in numerical simulation and remote sensing

Meteorological data come from three distinct sources – they can result from in situ measurements, they can be remotely sensed, or they can be numerically simulated. Both remote sensing and numerical simulation are relatively new – numerical weather prediction became operational in the 1960s and weather radar became operational in the 1980s.

There are no direct observations of icing of structures made by Met Office observers. Most icing conditions have to be inferred from combinations of air temperature, wind speed, humidity and the type of weather at the time of a weather observation. The weather is summarised along with instrumental observations in the present weather code contained in
the report from Met Office stations. This, when decoded, contains information on whether there is snowfall, fog and freezing rain, for example. Some elements of the code directly refer to icing conditions. For example, there are a number of codes reporting freezing drizzle or freezing rain and two codes explicitly report ‘fog depositing rime’. There are no present weather codes explicitly mentioning snow accretion on power lines or wet snow adhering to any structure.

The most useful set of observations suitable for this study are the hourly or 3 hourly ‘synoptic reports’ made at official Met Office stations by trained observers. The most useful stations are those with the longest records. Icing events are rare at most lowland stations and a long record is needed in order to get a good estimate of the frequency of such events. There are unfortunately only a limited number of stations with very long records of hourly observations of present weather, wind speed and direction, temperature and humidity. A few other stations have records containing a mix of 3 hourly observations and hourly observations. These have also been used in order to gain a better geographical spread of stations.

Many of the Met Office stations are located at RAF or civil airfields in the South East, Midlands and East Anglia. There are a few coastal stations in the South West and Wales but a complete lack of stations with long records of hourly observations in the Pennines or hills of Northumbria or Wales or in Dartmoor or Exmoor. Given the lack of hilltop weather observing sites in England and Wales the observations from the Met Office site at Eskdalemuir in the Southern Uplands in Scotland (241 metres above sea level) have had to be used to obtain an estimate of the icing risk on higher ground in Northern England.

Numerical models such as the Met Office Unified Model predict supercooled liquid water content – here supercooled means the liquid water content when the temperature is below zero and superficially one might expect all cloud and precipitation to be frozen. Although there is some uncertainty about absolute values there is very useful information about geographical variability which could be used to justify geographical variations in design standards. Models are particularly good at simulating the variability of wind and again this information could be used to help decide the route to be followed by any new component of the network. Radar provides measurements which can be linked to liquid water content. Again geographical variations can be analysed with confidence.

5.3 EFPUL – Effective Force per Unit Length

Appendix 5 contains technical details of the criteria used for defining critical conditions and the derivation of effective force per unit length (EFPUL) from meteorological station data. It was considered desirable to assess whether EFPUL was changing over a period of many years because clearly if it was there would be a case for revising the design standards for conductors and associated equipment. However, the average EFPUL for a meteorological station for a year is likely to be low and reflect the frequency and duration of accretion events, rather than the severity. Therefore the most meaningful measure was considered to be the maximum EFPUL during each winter (defined to run from July 1st of one year to June 30th of the next). There is a logical argument to support this use. It can be asserted that if the highest EFPUL during a winter does not cause a significant disruption to electricity supplies in the affected area, then it is unlikely that the second highest EFPUL will. This assertion should be checked carefully but unfortunately during the duration of this study there was not time for this. However, there is correlation between the annual maximum EFPUL and the occurrence of significant disruption on the national scale.

Figure 5 shows the maximum EFPUL for each winter plotted for the last 53 winters (dashed). Statistically, the trend for this time series is an upward one. However, during the 1950s not all stations used in the analysis were reporting so there may well be an underestimation of maximum EFPUL during that decade. If the 1950s are omitted, the trend is a downward one.
The trend during the last 20 winters is small, so it could be concluded (very provisionally) from that that there is little case for requiring higher standards *nationally* to cope with accretion occurrences.

Also shown on figure 5 is a negative, linear function of the winter North Atlantic Oscillation (NAO) index. This index, which is discussed further elsewhere in this report, is a measure of whether there is a strong westerly component to the large scale flow in the eastern North Atlantic. When the index is positive, the flow is strongly westerly and relatively mild winters generally result in the UK. When the index is negative there are periods during the winter when the predominant flow is from a direction other than westerly, during which cold spells are very likely.

There is encouraging correlation between the (reversed) NAO index and the maximum EFPUL. Undoubtedly the calculation of EFPUL could be tuned to give better agreement. However the correlation is sufficient to allow us to use the predicted behaviour of the NAO (with all the associated uncertainties) to give some indication of future behaviour of the maximum EFPUL.

![Figure 5 Maximum Effective Force per Unit Length (EFPUL) (dashed) (newtons/metre) and inverted winter North Atlantic Oscillation index (continuous)](image-url)
The trend in annual maximum EFPUL at each station has been calculated. This shows a negative trend at all stations except Boscombe Down. For reasons given in the discussion of the Baldock risk index, this trend is not thought significant. The mean value has a minimum at Mount Batten, on the south coast of England, and a maximum at Kinloss, on the north coast of Scotland. This south-north gradient is considered to be real.

EFPUL is sensitive to both meteorological factors and engineering factors. Among the former are the definition of the start of an accretion event, the liquid water content during the event, and the definition of the end of an accretion event. Among the latter are the assumed initial thickness of the conductor. All these parameters have an effect on EFPUL and these effects should be quantified.

5.4 Reporting of disruption events

Appendix 8 shows EFPUL figures for some of the cases reported by the transmission industry as being ones where there was disruption to supplies caused by ice accretion. This table also specifies the report written on the incident, where there is one. As can be seen, there is encouraging agreement between the EFPUL figure (and the associated radius and windspeed) in many cases, but not in all. In many of the cases which were reported but no figure is presented, there is no meteorological data from a convenient station that has been processed to produce the EFPUL figure. Even when there is a relatively close station, the scales of severe blizzards are such that an individual event can be seriously underestimated.

The following table shows the maximum EFPUL figure for the last 18 winters together with the total number of reports of events included in appendix 8.

<table>
<thead>
<tr>
<th>Winter</th>
<th>No of ice accretion occurrences</th>
<th>Maximum EFPUL (n/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>85-6</td>
<td>1</td>
<td>3.9</td>
</tr>
<tr>
<td>86-7</td>
<td>1</td>
<td>4.8</td>
</tr>
<tr>
<td>87-8</td>
<td>0</td>
<td>4.8</td>
</tr>
<tr>
<td>88-9</td>
<td>0</td>
<td>1.3</td>
</tr>
<tr>
<td>89-90</td>
<td>0</td>
<td>2.4</td>
</tr>
<tr>
<td>90-1</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>91-2</td>
<td>1</td>
<td>4.5</td>
</tr>
<tr>
<td>92-3</td>
<td>0</td>
<td>5.1</td>
</tr>
<tr>
<td>93-4</td>
<td>2</td>
<td>1.9</td>
</tr>
<tr>
<td>94-5</td>
<td>2</td>
<td>3.6</td>
</tr>
<tr>
<td>95-6</td>
<td>6</td>
<td>4.5</td>
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<td>96-7</td>
<td>3</td>
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<td>2.2</td>
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<td>98-9</td>
<td>1</td>
<td>2.0</td>
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<tr>
<td>99-0</td>
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</tr>
<tr>
<td>02-3</td>
<td>0</td>
<td>5.1</td>
</tr>
</tbody>
</table>

This shows encouraging agreement, particularly given that the EFPUL algorithm has not been tuned in any way to reflect reported incidents. The peaks in the reported events and the EFPUL figure in 95-6 and 00-1 are particularly encouraging. If there is a peak in number of incidents but not in EFPUL, or vice versa, this probably reflects the geographical distribution of the distribution network when compared with the network of synoptic stations used.

It is not known how reliable the reporting of incidents is, particularly in the 1980s and early 1990s. Indeed there are reports of icing problems documented in Davies (2001) which do not appear in appendix 8. In addition appendix 8 contains no reference to the severely disruptive
events of December 1981 and January 1982 which precipitated the Baldock report. This suggests the reporting of incidents could be improved.

5.5 The worst case scenario?

5.5.1 Concerns about freezing rain

Although the frequency of occurrence of freezing rain is not particularly high compared to wet snow or low cloud containing supercooled drops, there are reasons to consider it to be a particularly serious hazard for the industry. The accretion efficiency is higher for large droplets (be they of water or ice) than for small, and in addition if a supercooled droplet collides with a conductor, accretion will always occur whereas if a snowflake collides with a conductor, accretion will depend critically on the presence of a small amount of liquid water (and therefore the temperature). Therefore it can be argued that accretion efficiency is the highest for freezing rain of all the forms of icing threat. Ashcroft (2001) notes that in the event of 24th January 1996, there were two hours of ‘moderate of heavy’ freezing rain, which was rare at a low level site such as Birmingham. Mills-Hicks and Mansfield (1990) note that Birmingham has the highest frequency of freezing rain of any location in the United Kingdom. From these pieces of information it is possible to infer that a serious freezing rain event, with a high build up of ice on conductors, could occur with a relatively high probability in an inland area such as the West Midlands.

5.5.2 The aviation experience of icing.

Aviation is an extremely safety-conscious industry and as icing has caused a number of fatal accidents during the last century the industry as a whole has developed an extremely professional approach to icing. The models of the accretion of ice to aircraft components are among the most sophisticated of any models in any industry. In the Met Office we have been forecasting supercooled liquid water content for North Sea helicopter operators since 1991 (Lunnon, 1991). Therefore it would be relatively straightforward to provide an analogous service for the transmission industry. Helicopter operators can change route or altitude in response to a forecast of high supercooled liquid water content.

One area of particular concern to the aviation community at present is that of freezing rain/freezing drizzle – collectively known as supercooled large drops (SLD). The present design standards for aircraft are based on supercooled liquid water content due to clouds, as opposed to precipitation. A major research effort is currently underway to quantify the threat that SLD pose to the aviation industry. It is not the case that it is believed that there is an increase in the occurrence of SLD due to, for example, climate change. Rather there is the view that this is a problem that has been overlooked in the past. It may be that the transmission industry should take this particular threat more seriously too.

5.5.3 The North American 1998 ice storm

Between 5th and 9th January 1998 there was a major freezing rain event affecting the northeast US and southeast Canada (Gyakum and Roebber, 2001). It was reported that 3 million utility customers lost power in Canada and a million in the northeastern US, including 80% of Maine’s population. It is very clear from figure 5.1 that there is considerable year-to-year variability in maximum EFPUL and although the EFPUL experienced in the 1998 North American event were higher than any experienced in the UK, the 1998 event implies that EFPULs in excess of any shown in the figure cannot be ruled out. It is unlikely that an event as severe and widespread as the 1998 event could occur in the UK but it is desirable to quantify the risk. Such a calculation is beyond the scope of the present study. However, it is clearly desirable for such a risk should be quantified as part of a subsequent study. Given that Birmingham has the highest frequency of freezing rain of anywhere in the UK (largely
because it is a long way from the warming influence of the sea) it would appear that the threat of a serious freezing rain event is greatest in the West Midlands.

5.6 Concluding remarks on ice accretion and snow loading

As far as the risk index calculated in the Baldock report is concerned, there is no clear evidence for a change in this index. This risk index was calculated using synoptic data, and if trends over the last 50 years or so are to be derived, considerable reliance must be placed on synoptic data. However numerical simulation and remote sensing have advanced significantly since the time of the Baldock report. Given that there is only slow, if any, change in the risk index, it would be better in general to use numerically simulated and/or remotely sensed data to derive the current risk level more reliably.

The EFPUL parameter has been shown to be very useful in that it is physically based and shows encouraging correlation with the North Atlantic Oscillation (NAO) Index. The long term behaviour of the NAO is relatively well understood and therefore we can make a qualitative prediction of the behaviour of EFPUL over the next few years. The risk of serious disruption due to icing remains high for the remainder of the decade but is expected to diminish slowly during the rest of the century. EFPUL is sensitive to a number of factors, both meteorological and engineering. This sensitivity should be quantified. EFPUL shows encouraging correlation with reported disruption. However, in assessing the reports of disruption, anomalies have become apparent. It is possible that these anomalies are partly responsible for the perception that disruption is getting worse over time. It is recommended that an automated system of reporting disruption is developed.

It is useful to look at the threat from freezing rain, to look at the aviation experience of the ice accretion problem, and to look at the severe ice storm that affected the Eastern USA and Eastern Canada in 1998. These considerations in combination suggest that in the UK there could be serious disruption from a single, relatively infrequent event. Further work is required to better quantify the likelihood and severity of such an event.

6 Lightning

Although the Met Office has a very sophisticated lightning detection system – the ATD (Arrival Time Difference) system, it is very difficult to make inferences as to whether the threat of disruption to the transmission system through lightning strikes is increasing or diminishing. This is because the system has undergone a significant upgrade in the last three years such that whereas previously it detected about 1000 flashes per hour, now it can detect 10000 flashes per hour. Unfortunately it is not possible to distinguish between those flashes currently detected which would have been detected prior to the upgrade and those currently detected which would not have been detected prior to the upgrade.

A further upgrade to the system is planned for the next year or two. After that has been completed the system should be stable and will record parameters such as the current and the polarity which are of significant interest to the transmission industry.

One aspect of electrical activity which the system can help with is repeated flashes in the same location separated by a small time interval. As can be inferred from the fact that over 10000 flashes per hour can be processed, multiple flashes separated by less than a second can be resolved. It is understood that the electricity supply industry as a whole recognises that repeated flashes separated by a small time interval can cause significant problems. Information as to the frequency of multiple flashes having specific separation time intervals could be provided if it was useful in improving design standards.
The Met Office also operates a short range lightning prediction system – NIMROD. This predicts the location of future lightning strikes to within a few kilometres. It is understood that the main problems caused by lightning occur at substations and that there is some redundancy in the system of substations. Assuming that substations can be operated remotely, it might be possible to switch off a particular substation if there was sufficient redundancy and the threat to that substation was significantly greater than that to its neighbours.

In the longer term future it is believed that the threat of high energy lightning strikes will increase as a result of global warming. However, the numerical models of the atmosphere that are used to predict the effects of global warming do not predict the energy of lightning strikes directly. The approach used is based upon relationships that have been established in weather forecasting and assesses the Convectively Available Potential Energy (CAPE) in the model – it is understood that the higher the CAPE, the higher the energy in a lightning strike. In *Climate Change Scenarios for the United Kingdom*, UKCIP (2002) daily data was from the Hadley Centre’s regional model, HadRM3, was examined. The analysis concentrated on the summer months as the season when lightning is most prevalent. With the Medium-High emissions forcing scenario the peak lightning flash rate in a convective event is predicted to double by the 2080s over parts of southwestern England. This would imply that the risk of multiple strikes in one location will increase in the future. The number of thunderstorms, however, is expected to decrease by about half meaning that current predictions are that in the future the overall number of lightning strikes per year will remain approximately the same present day across southern England. The same analysis showed very little change in the amount of lightning per thunderstorm across Scotland and Northern Ireland.

7 Conclusions

7.1 Wind storms

1. A search for trends in observed wind speed records over the last three decades at nine UK locations has proved inconclusive.
2. This method of searching highlighted the sensitivity of wind climate to local site characteristics and changes in them, raising a question of whether greater use could be made of such knowledge when routing power lines, mitigating the detrimental effects of any overall increase in wind storms.
3. A new and innovative windiness trend search method that is independent of such site characteristics has been piloted for East Anglia and does show a marked increase in overall windiness from the 1970s to the 1990s. This result should not be taken as necessarily applying to the rest of the UK.
4. This increase in windiness is shown to be almost entirely on account of increased frequency and strength of winds blowing from between south and west, specifically in winter. Spring, summer and autumn showed little change. This is consistent with climate change predictions for southern Britain, adding confidence in them.

5.1 Wind and leaf cover

1. It seems unlikely that any significant change in the interaction of wind and leaf cover could be due to the change in wind climate, at least for the pilot study area of East Anglia. This is because the change in wind climate is confined to the season (December to February) that is largely devoid of deciduous leaf irrespective of trends in the growing season. However in 1996 the leaf season did extend into December so a precedent for leaf covering existing during the season of increasing wind speeds does exist, at least in East Anglia.
2. Available information indicates that the period of time when deciduous trees carry a leaf canopy is currently around 2 weeks longer than was the case fifty years ago. This is due
to earlier leafing out in the spring. The autumn period can also be delayed by around two weeks but this is an erratic feature which is influenced by an absence of frosts and damaging storms.

3. It is reasonable to assume an increased risk of wind throw damage on account of the duration of leaf cover alone. There is no obvious trend for increasing wind speeds during the majority of the season of leaf cover. It may be inferred that there is limited change to risks in autumn although vulnerability in spring season will increase.

4. The region where growing seasons may extend furthest, i.e. southern England, is also the region predicted to see the greatest increase in both wintertime mean wind speeds and the frequency of occurrence of strong winds as climate changes. The impact of reduced water availability and migration of habitats is also likely to be greatest in this region, although the scale of impacts remains to be quantified.

7.3 Ice accretion and snow loading

1. In broad terms there are no changes to the frequency or severity of icing events identifiable from synoptic data in the last few years. The risk index calculated in the Baldock report is actually decreasing for all stations except Boscombe and Eskdalemuir in the period since the report was written (early 1980s) but the changes are not considered significant. The risk index for the period since the report is twice as high for Eskdalemuir as it is for other stations which is to be expected for a high altitude station. There is evidence of inconsistency in the reporting of network disruption due to icing and there may well be a perception that the frequency of this form of disruption is increasing as a result of the inconsistency.

2. The effective force per unit length (EFPUL) on a transmission system conductor has been calculated using hourly data from meteorological stations for the last fifty years or so. Although a number of assumptions have to be made in order to use such data to calculate such a measure, there appears to be reasonable correlation between peaks in EFPUL at individual stations and occasions when a high number of faults with the transmission system have been reported. If the calculation of EFPUL was refined it is very likely that better agreement would result. One conclusion is that the sensitivity of EFPUL to the dependent parameters should be quantified.

3. The maximum EFPUL derived over all stations and entire winters shows encouraging correlation with the North Atlantic Oscillation index. Thus predictions of the behaviour of the NAO over the coming decade may provide some limited guidance as to the likely behaviour of maximum EFPUL over the same timescales. The cyclic nature of the NAO suggests that during the next decade there may be local maxima of EFPUL which could cause significant disruption but generally speaking the trend during the 21st century will be for lower maximum EFPUL. Hence in the long term we expect disruption due to icing to decrease but in the next decade the risk of a significant event remains high.

4. In both assessing the change to the Baldock risk index and in calculating EFPUL we have made use of data from synoptic stations. However, since the time the Baldock report was written, significant advances have been made in numerical simulation and remote sensing. Synoptic data have serious limitations when used to derive accretion parameters. A conclusion is that these are critical limitations and that in the future greater use should be made of other data forms.

5. There are concerns about freezing rain and the possibility of a severe freezing rain event such as occurred in northeastern US and southeastern Canada in 1998. The frequency of freezing rain events in the UK is maximum in the region around Birmingham so it would appear that the risk is greatest there. It is likely that work to improve the resilience of the network in that area would be justified but more meteorological work would need to be done first to provide that justification.
7.4 Lightning

1. There is currently insufficient data available to detect any trends in lightning. This situation will improve as data records become longer.
2. Preliminary results from climate models suggests that the intensity of lightning storms may increase in the south of Britain in the future although the number of storm events may decrease. Flash rates within an average event may double, greatly increasing the risk of multiple strikes at a single location within a short space of time.
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Appendix 1: Glossary of terms

‘Anomaly’ experiments and ‘Control’ experiments
Anomaly experiments are climate model integrations forced with changing greenhouse gas concentrations to model a ‘future climate’, while control experiments are forced with present-day greenhouse gas concentrations to simulate the current climate.

CO\textsubscript{2} emissions
Climate models predict that the temperature of the planet will increase as atmospheric carbon dioxide emissions increase. Carbon dioxide is the primary greenhouse gas and simulations of \textsubscript{CO}\textsubscript{2} release into the atmosphere, mainly as a result of burning of fossil fuels, are modelled by the Intergovernmental Panel on Climate Change as emission scenarios for the future.

Emission scenarios
These are possible future greenhouse gas emissions which predict a range of likely global emissions. They are developed by the Intergovernmental Panel on Climate Change (IPCC) and used by a range of national climate model centres. These should not be confused with climate change scenarios. For UKCIP 2002 four emissions scenarios (Low, Medium-Low, Medium-High, High) were defined based on the IPCC scenarios.

GCM
General Circulation Models (GCMs) are generally regarded as the only scientifically credible tool for predicting future changes in climate. They use a set of mathematical relationships which represent the major processes in the climate system. The three-dimensional ocean-atmosphere models developed at the Hadley Centre predict changes that vary with location and in time. GCM is also used as an abbreviation of Global Climate Model.

Global warming
The global average surface temperature has increased over the 20\textsuperscript{th} century by approximately 0.6\textdegree C and global warming is predicted to continue over the 21\textsuperscript{st} century.

Greenhouse gases
These are gases that result in a positive radiative forcing, causing the climate to warm up and contribute to the ‘greenhouse’ effect. The dominant greenhouse gas is carbon dioxide.

Phenology
Phenology is the study of seasonally recurring natural phenomena especially in relation to weather and climate change.

RCM
Regional Climate Models (RCMs) provide a way of downscaling the global (GCM) results to the scale needed for national assessments. They provide greater geographic detail and cover a limited area, typically a few thousand kilometres square. The boundary conditions for these models are provided by a global climate model.

Return Period
The average time between events of a given magnitude. A 100-year return period is the equivalent of the event that has a 1 per cent probability of occurring in any given year.

Thermal Growing Season
The length of the thermal growing season is defined as the longest period within a year that satisfies the twin requirements of (i) beginning at the start of the period when daily averaged temperature is greater than 5.5 °C for five consecutive days and (ii) ending on the day prior
to the first subsequent period when daily average temperature is less than 5.5 °C for five consecutive days.

**Uncertainty**
All climate predictions in the future carry with them a range of uncertainty. Uncertainty exists in the emission rates in the future, depending on political as well as physical factors, and uncertainty also exists in the climate model itself. Currently, methods of estimating degrees of uncertainty are being developed and climate modellers in the UK are producing ‘probability of change’ results that try to harness this model uncertainty.

**Wind throw**
Wind blown debris from trees or, in extreme cases, the uprooting of trees.
Appendix 2: Weather station details

Appendix 2a: Map of locations of weather stations mentioned in this report

Appendix 2b: Tabular station details
Appendix 2a: Map of locations of weather stations mentioned in this report
### Appendix 2b: Tabular station details

<table>
<thead>
<tr>
<th>STATION</th>
<th>Easting</th>
<th>Northing</th>
<th>Alt(m)</th>
<th>Comment</th>
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<td>8628</td>
<td>5</td>
<td>Northern Scotland: coastal site east of Inverness</td>
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<tr>
<td>Boscombe Down</td>
<td>4172</td>
<td>1403</td>
<td></td>
<td>Southern England: Salisbury Plain</td>
</tr>
<tr>
<td>Mount Batten</td>
<td>2492</td>
<td>0527</td>
<td>50</td>
<td>Southwest England: coastal (Plymouth)</td>
</tr>
<tr>
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<td>2841</td>
<td>98</td>
<td>Central England: Birmingham. Site 1 km east prior</td>
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<tr>
<td>Coleshill</td>
<td>4211</td>
<td>2869</td>
<td>96</td>
<td>Replacement for Elmdon 1999/2000</td>
</tr>
<tr>
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<td>3758</td>
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<td>Wales: Anglesey - coastal</td>
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<tr>
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<td>3798 (Irish grid)</td>
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</tr>
<tr>
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<td>17</td>
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</tr>
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<td>Heathrow</td>
<td>5077</td>
<td>1767</td>
<td>25</td>
<td>Used in geostrophic wind analysis</td>
</tr>
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</table>
Appendix 3: Explanation of calculation of mean geostrophic wind speed across East Anglia based on atmospheric pressure observations at 4 stations

Explanations of the relationship between horizontal pressure gradient and geostrophic wind are available in various references including Panofsky (1978) and Meteorological Office (1993). The geostrophic wind speed $V(g)$ is given by the relationship

$$V(g) = \frac{\text{pressure gradient force}}{\text{Coriolis parameter}}$$

The pressure gradient force is a function of the horizontal pressure gradient and air density. Air density varies with temperature and, in the UK, seldom deviates by more than 5% from a figure of 1.2 kg/cu. metre. This slight sensitivity of air density to temperature is ignored for the purposes of this study and the figure of 1.2 is used throughout. Thus:

$$\text{Pressure gradient force} = \text{pressure gradient}/1.2$$

For consistent use of SI units, the pressure gradient needs to be expressed in Pascals/metre. The unit of pressure measurement employed at weather stations is usually millibars. 1 mb = 100 Pa.

The Coriolis parameter is latitude dependent, given by the rate of rotation of the earth about its axis (1 rev/day) multiplied by the sine of the latitude angle. This needs to be expressed in radians/sec. The latitude of the centre on the area enclosed by the 4 weather stations used in this study is 51.795 N, giving a Coriolis parameter of 0.0001144 radians/sec.

Hence, for this particular study,

$$V(g) \ (\text{metres/sec}) = \frac{\text{pressure gradient} \ (\text{Pa/metre})}{0.0001378}$$

No account is taken of cyclonic or anticyclonic curvature of the isobars, which can, respectively, decrease or increase the geostrophic wind. The impact of this caveat on the statistical intercomparison of decades is likely to be negligible. (It would be more important if the interest were in precisely accurate wind speeds rather than the trends.)

The area used in this pilot study is a near-rectangle with its corners defined by the locations of Nottingham, Coltishall, Manston and Heathrow.

Nottingham (Watnall) is 178400 metres NNW of Heathrow
Coltishall is 156200 metres N of Manston
Manston is 128000 metres almost E of Heathrow
Coltishall is 177400 metres almost E of Nottingham

These distances are exact. However, wind direction was estimated to the nearest quadrant, simply by the sign of the differences in pressures between the respective pairs of sites. Therefore the direction quadrant classification is not precise.
Appendix 4: Previous studies
Appendix 4A: Ashcroft (2001)

This study gave a particularly useful and comprehensive review of the conditions favouring icing, as follows.

4A.1 Freezing fog

A set of combination of weather conditions was prescribed to define each potential icing risk on NGC power lines. There are considered to be four possible icing risks in the UK. Firstly, icing could be due to freezing fogs. In this situation fog is associated with sub-freezing temperatures. Small supercooled droplets are present in the air and, if there is some wind, are blown onto and freeze on impact on a cold structure in their path. In order for ice to build up on overhead cables the fog must be deep enough to reach to their height. The situations in which freezing fog was associated with some wind were searched for using the conditions:

- present weather code: fog reported at the station at the time of observation (including cases of ‘fog depositing rime’ in the present weather code)
- air temperature below freezing
- wind speed greater than or equal to 2 knots (2.3 miles an hour)

It should be noted that the Met Office stations are equipped with an anemometer which does not record low wind speeds accurately, being designed with relatively heavy cups for use recording the wind for aviation purposes. A nominal wind of 2 knots was reported by observers whenever there was some movement of the direction vane or occasional indications of wind speed fluctuations. A higher wind speed threshold could not be used with occasions of fog because too many observations would be lost from the analysis.

4A.2 Freezing precipitation

The second icing risk comes from freezing drizzle or freezing rain. This phenomenon is explicitly recorded in the observing code and is clearly distinguished from occasions of drizzle or rain or showers in the comprehensive set of present weather codes. In this type of precipitation supercooled drizzle and rain drops could be collected and freeze on impact on power lines and all other surfaces and structures. The criteria that were set to find these occasions of icing were:

- Present weather code: freezing drizzle or freezing rain recorded
- wind speed greater than 5 knots (5.8 miles an hour)

In practice the wind speed threshold is not really needed as a summary of observations in spells of freezing rain showed wind speeds nearly always comfortably in excess of this. No air temperature threshold was set for this type of icing condition. Air temperatures are almost exclusively below freezing in spells of freezing rain. Some spells of freezing rain were found to be associated with temperatures near freezing point.

4A.3 Low cloud containing supercooled drops

On higher ground, it is possible to have icing on power lines and pylons from the freezing of supercooled cloud droplets which are blown onto various masts, towers or cables. This situation is found when low cloud and a low freezing level occur together. Some wind is obviously also needed to blow the cloud droplets onto the cables and the cloud cover must be extensive enough to allow a sufficient duration of icing to be possible. Small amounts of low cloud are possible on hills in bad weather in the form of ragged fragments of stratus or...
cumulus cloud and these have been excluded from the study. This was done by choosing a
criterion which included only cases with more than half the sky covered with low cloud.

The observing stations whose observations have been used are low level stations, at an
altitude varying from 10 metres to 126 metres above sea level. Cloud bases are reported by
observers in hundreds of feet relative to the station altitude, not with respect to sea level.
With an allowance for this, and by referring to maps of the NGC system and the topography
of England and Wales it was considered that a reported lowest cloud base of 1000 feet or
less would include the higher level areas where pylons and cables could be at risk from icing.

Since the air temperature decreases with height the temperature does not have to be
freezing at the altitude of the observing stations for it to be below freezing at 1000 feet above
sea level. But it would be unnecessarily complex to allow for all combinations of station
altitude, cloud base, lapse rate and observed temperature in a study of the frequency of icing
from cloud. Therefore a very simple set of criteria was used for all stations to define the
conditions when icing due to low cloud could occur:

- Lowest cloud amount: 5/8 or more of the sky covered
- observed air temperature at the station below freezing
- lowest cloud base 1000 feet or less relative to the station
- wind speed at the station greater than 5 knots (5.8 miles an hour)

It is considered that these criteria will omit some occasions when there is a risk of icing from
low cloud and therefore the frequency of icing estimated in this simple way is an
underestimate of the real frequency of occurrence.

4A.4 Wet snow

The conditions favouring wet snow adhesion to power lines and other structures have been
the subject of discussion in the literature. Foot (1972) discusses two cases of wet snow
accretion on power lines in February and March 1970 in the South East and Eastern
England. Other studies of wet snow accretion on power lines in the British Isles include those
studied wet snow accretion on power lines in the Borders in a snowstorm in December 1996.
There has also been a study prepared for the NGC of the weather associated with the
extensive damage to power lines in the blizzard of 7-9th December 1990. This was produced
by M. R. Woodley of the Met Office. The NGC also produced an internal report on this
serious event.

Other recorded occasions of damage to NGC power lines by the loading of ice deposits
formed from wet snow are discussed in a later section. In other countries, icing on power
lines due to wet snow adhesion has been recognised as a problem for some considerable
time. There is a larger body of work discussing wet snow accretion on power lines in Japan
and the USA than in the UK. In particular, scientists at the US Army CRREL have
contributed to the subject of wet snow adhesion on power lines, the way in which deposits
can build up and resist the force of the wind and remain on the power lines.

It is understood from this research undertaken in the U.S. and Japan that the adhesion of wet
snow to cables and other structures depends on the snowflakes having already started to
melt on their descent from the cloud towards the ground. The melting of the snow flakes is
due to them falling into an environment where the air temperature is above freezing. In this
situation heat is transferred to the snowflake and it begins to melt, with water forming within
the crystal structure and on the surface of the snowflake. But if the environment is
unsaturated with respect to water vapour heat can also be lost from the snowflake by
evaporation of water. Therefore, the initiation of melting and the extent of melting depends on
the vertical profile of air temperature and humidity from cloud to ground. The balance of
temperature and humidity in the air from cloud base to surface must be so as to ensure an
initiation of melting of the snowflake but not a conversion of snowfall into sleet or rain.

As the air temperature rises a lower humidity would be necessary to induce more
evaporative cooling of the snowflakes to offset the increased heat transfer to the snowflake.
The practical limit of temperature for continuous snowfall in the British Isles, from
observational evidence, is plus 3 degrees Celsius. But it is likely that the air temperature in
the great majority of snowfalls would be lower than this. Tabony (1996) has pointed out that
in conditions favouring the melting of snowflakes, a sufficient intensity and duration of
snowfall would lower air temperatures towards freezing due to the heat lost from the air to
the snowflakes.

Once snowflakes have begun to melt then they are able to adhere to each other, forming
larger aggregations which have more inertia and are less likely to be deflected around
objects in their path. Melting snowflakes are, unlike dry snowflakes, able to adhere to
whatever objects they are blown onto. In this situation a deposit can begin to build up on
overhead cables. The continued growth of a cylindrical deposit of snow is thought to depend
on the rotation of the initial deposits around the cable under their weight and new accretions
forming on the windward face of the cable. Once a connected snow deposit is formed around
a cable it has a strength to resist its own weight and wind forces. Therefore it is possible for
these wet snow accretions to resist strong winds themselves but at the expense of a great
increase in drag forces on the cables which are loaded with ice. It is thought that the air
temperature and humidity alone are not the only factors that are influential in the initiation
and build-up of ice accretions on cables. The snowfall rate and duration and the wind speed
could be additional influential variables.

In Foot (1972), estimates were made of the wet snow accretion rate on power lines and the
conditions likely to permit snow to adhere to conductors. The location of areas with faults
was associated with temperatures just above freezing and moderate or heavy continuous
snowfall and at least 10 cm of snow accumulated on the ground. Foot also considered a set
of wind speed criteria based on the air temperature. At higher air temperatures (up to 2
degrees Celsius) stronger winds would be needed to build up an ice accretion on a power
line as the wet snowflakes would contain an increasing proportion of water rather than ice.
As the wind speed increases the rate at which ice is brought onto the conductor can
compensate for the melting of the snowflakes. Stronger winds could also give a compaction
to the snow deposit and give it an aerodynamic lift force against gravity.

The criteria for identifying occasions of wet snowfall were therefore chosen to be:
- Present weather codes indicating snowfall, including showers
- and air temperature > 0.0 to 2.0 degrees Celsius
- and relative humidity 90 to 100%
- and wind speed greater than 5 knots

In this preliminary report more complex criteria involving the intensity or type of snowfall or
the balance of humidity and temperature and wind speed were not applied.


This included the following.

There is observational evidence of ice accretion on overhead power lines and pylons in the
NGC areas in the form of videos and photographs. In addition, many circuit faults have been
logged in the severe snowstorms of December 1981 and December 1990. These faults have
been attributed to icing of conductors and their galloping in strong winds. The available
evidence of icing on NGC power lines suggests that it is intermittent and very rarely affects a
large part of the country in one event. Most incidents are local or regional problems, the major exception being the icing of many power lines in northern and central England on the 7th to 8th December 1990. The most severe icing events, such as this one, are associated with long periods of wet snowfall, over a large area, and associated with gale force winds. Many of the incidents of icing logged by the NGC, including this one, can be supported by meteorological reports from nearby Met Office stations.

The most common causes of icing from NGC fault reports appear to be ice accretion due to wet snow followed by icing due to supercooled cloud drops on high level lines, possibly associated with spells of freezing precipitation, giving a mixed rime/hard glaze accretion. Ice accretion from freezing precipitation at low levels is rare in England but has been observed by the NGC on power lines near Birmingham. There is no conclusive documentary evidence in the available NGC faults listings for ice accretion from freezing fog.

The greatest thickness of ice accretion appears, from other observational evidence, to be due to prolonged spells of rimeing on high level masts due to the combination of a low freezing level and persistent layers of low cloud blown along in cold easterly winds. Icing occurs in these situations from the collection of supercooled cloud drops and larger supercooled drizzle drops. Very considerable thicknesses of ice have been reported from television masts and transmission towers at a high level and it is likely that this icing was due to the weather conditions just described. Smaller amounts of rime/hard glaze ice accretions have been reported from conductors on the high level power lines in the Pennines in March 1969 and February 1996 and these have been sufficient to cause conductor galloping in strong winds.

On the other hand, observational evidence from the NGC and a summary of a long period of meteorological observations suggests that wet snow accretion on power lines is the dominant risk in coastal and most inland areas in England And Wales. Wet snow accretion on power lines can take place at high level as well, adding to the risk of icing there from low cloud/freezing precipitation. Though the location of areas prone to icing from low cloud is quite straightforward to draw up it is not possible to predict from climatology the precise locations where icing will occur as a result of wet snow accretions in any winter. The location and extent of areas affected by icing from wet snow has clearly varied from one event to another. It is only possible from past weather observations to give general guidance on where conditions favouring wet snow accretion are least and most likely to occur.
Appendix 4B: Davies (2001)

The following is drawn from her introduction.

4B.1 Scottish Power’s main aim is to improve the resilience of their distribution network during severe weather, thereby improving continuity of supply to their customers. At the moment the network is designed according to certain specification levels. However, because of the level of disruption due to weather in recent years, these specifications need re-examining. This analysis is expected to form part of a series of projects to assess in which areas more resilient lines are required in order to withstand recent and future weather conditions, and to what specification level the lines should be designed.

4B.2 The aim of this weather sensitivity analysis is to establish what type of weather causes what level of disruption and the Borders region was the focus of this initial study. It is suspected that large numbers of faults in a short space of time occur when icing of the overhead power lines is accompanied by strong winds. Wet snow is thought to be a dominant cause of ice accretion on overhead power lines, as explained in section 3, and so for this preliminary study, we will focus on wind and snow and seek to establish a correlation with faults data supplied by Scottish Power.

4B.3 Scottish Power provided a daily log of the total number of faults reported between 1st April 1990 and 30th September 2001. A breakdown of the number faults attributed to each of four causes was also provided – these were wind/gale, snow/sleet/blizzard, ice and lightning. There were a few missing entries for each year but on examination of the meteorological data it was found that they coincided with spells of uneventful weather and allowed the assumption that these were simply unregistered ‘no faults’ days to be made. A simple plot of daily faults for each year revealed that the years 1990, 1993, 1994, 1996, 1998 and 2001 all had clear ‘high faults’ events with peaks of 22, 48, 29, 42 and 32 faults in one day respectively, all occurring in winter.

Among Davies’ conclusions were

4B.4 It has been possible to observe a relationship between the number of faults and strength of wind for occasions where icing of the power lines is not an issue. However, it would be inappropriate to suggest which relationship is best given the sparsity of the data.

4B.5 The results of this analysis have demonstrated that a significant number of faults can arise at comparatively low windspeeds when accompanied by a period of wet snow, the implication being that overhead cables are loaded with ice. Here the term comparatively low wind speeds means windspeeds which are lower than the threshold appropriate where no ice was present.
Appendix 5: Technical details

5A Criteria for defining critical conditions

The criteria used in generating the statistics in the Baldock report referred to dry bulb temperature, wet bulb temperature and reported “present weather”. When meteorological stations report present weather in accordance with the rules laid down by the World Meteorological Organisation, they generate a two digit code, and this code was used in the generation of the statistics in the Baldock report. However, the report was not precise about which code figures represented accretion conditions. It simply states that the conditions were “moderate to heavy sleet, snow or freezing rain”. Various combinations of present weather codes have been tried in an attempt to reproduce the statistics in the report, but it has not been possible to come up with a combination which exactly matches the statistics reported. The combination used in the present study is the one which best matches the statistics for Elmdon for the period 1/1/51 to 31/12/80 (where best matches was a subjective judgement). In order that this problem of reproducing statistics does not occur again, the present weather codes used in the current study to indicate accretion conditions (in conjunction with dry bulb and wet bulb criteria) were as follows:

20, Drizzle (not freezing) or snow grains during the preceding hour
22, Snow during the preceding hour
23, Rain and snow or ice pellets during the preceding hour
24, Freezing drizzle or freezing rain during the preceding hour
26, Shower of snow or of rain and snow during the preceding hour
56, Drizzle, freezing, slight
57, Drizzle and rain, slight
67, Rain, freezing, moderate or heavy
69, Rain or drizzle and snow, moderate or heavy
70, Intermittent fall of snowflakes, slight
71, Continuous fall of snowflakes, slight
72, Intermittent fall of snowflakes, moderate
73, Continuous fall of snowflakes, moderate
74, Intermittent fall of snowflakes, heavy
75, Heavy fall of snowflakes, heavy
76, Diamond dust
78, Isolated star like snow crystals
79, Ice pellets
86, Snow showers, moderate or heavy

In addition, for accretion to be considered to be occurring, the dry bulb temperature was not less than –1°C and the wet bulb temperature was in the range –0.5°C to +0.5°C. These are the figures quoted in the Baldock report although of course if the wet bulb temperature is not less than –0.5°C then the dry bulb temperature will also be not less than –0.5°C.

Appendix 6 of this report essentially reproduces and updates appendix A4 table 1 from the Baldock report, whilst appendix 7 of this report reproduces and updates appendix A4 table 2 of that report. The first table shows the occurrence of previous accretion conditions – the number of occasions and duration. The second table shows the analysis of occurrence of previous accretion conditions in terms of wind speeds.

As stated earlier, it appears that there is little change in the risk index, shown in the first table, but a slight reduction which is not considered particularly significant.
5B Derivation of effective force per unit length (EFPUL) from meteorological station data

It is clear that the combination of wind and accreted ice can cause serious problems for overhead lines. Studies of the duration of accretion conditions and the wind distribution during those conditions, as generated in the Baldock report, provide an incomplete picture of the situation as it affects possible design decisions. One of the major design considerations is the required strength of a conductor and the strength of the components of the transmission system which support the conductor. It appears highly desirable to generate statistics indicating the regional and temporal variation of the required strength of conductors and associated equipment. This need is addressed through the concept of the effective force per unit length (EFPUL).

In qualitative terms, it is assumed that during an accretion event, ice will build up on a conductor. Subject to a number of assumptions, it is possible to derive the force per unit length on a conductor, given the cross sectional area, drag coefficient, and component of wind perpendicular to the conductor. This force per unit length is the EFPUL – the word effective is used because there will of course be other forces acting on the conductor but all we are considering here is the effect of wind and ice combined. Furthermore it is appropriate to consider the force to be a notional force in that it is a force which will be experienced only if all the assumptions are met, and the assumptions are in many cases questionable.

An accretion event is considered to start when
(a) the conditions for freezing fog, freezing precipitation or wet snow, as specified above, are met, and
(b) the wet bulb temperature is below +0.5°C.

An accretion event is considered to end when the wet bulb temperature rises above +0.5°C. Between the start and end of an accretion event the rate of accretion is proportional to the product of the windspeed and the liquid water content. The latter is derived from the reported present weather using a formula derived by Mills-Hicks and Mansfield (1990). The latter give an expression for precipitation rate – this is converted into a liquid water content using a fixed fall speed of 4.0 m/s. This in turn was taken as a typical figure for rain from table 2.2 of Poots (1996). Fall speeds for snow are always lower than this and it is desirable to use a more representative figure but it was considered more desirable to keep the accretion model as simple as possible.

The initial radius of the conductor was taken to be 2.85mm. This corresponds to a cross-sectional area of 25 mm². This is a commonly used value. However, different results (in terms of trends) may result from a different choice of initial radius. As discussed in section 5.5, this sensitivity should be quantified.
## Appendix 6: Updated Table 1 of Appendix A4 from the Baldock report

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<th>Station</th>
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<th>To</th>
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<th>20-24</th>
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<th>30-34</th>
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### Explanation of the above table.

The #Obs column is a repeat of the #Obs column given in the following table, for which the definition is given below. The column headed 0-4 gives the number of occasions when accretion was occurring (as defined in appendix 5 above) and the wind speed was present and in the range 0-4 knots. Similarly the other columns give the number of occasions when accretion was occurring and the wind speed was present and in the specified range.
## Appendix 7: Updated Table 2 of Appendix A4 from the Baldock report

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### Explanation of the above table.

The hours column is the total number of hours between 00Z on the start date and 23Z on the end date. The column headed by a 1 is the number of hours during which the accretion conditions (as defined in appendix 5A above) occurred but had not occurred in the previous hour or the subsequent hour. The column headed by a 2 is the number of 2 hour periods when accretion occurred. The other columns labelled with digits between 3 and 20
have analogous definitions. In the original Baldock report there was an additional column listing the number of occasions of continuous accretion of more than 20 hours but for brevity such a column is omitted from the present report. This means that the total number of hourly observations column (headed # Obs) may be less than the sum of numbers in columns headed 1 to 20. The column headed Risk is the risk index from the Baldock report – it is simply the # obs column divided by the hours column multiplied by 1000 – this is the index defined in the Baldock report.
### Appendix 8: Database of known ice accretion events

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<td>Bury/Bolton/Wigan/Skelmersdale</td>
</tr>
<tr>
<td>February 3, 1994</td>
<td>Rochdale/Oldham/Ashton/Lancaster/Kendal/Barrow</td>
</tr>
<tr>
<td>December 30, 1994</td>
<td>Workington/Penrith/Carlisle</td>
</tr>
<tr>
<td>January 1, 1995</td>
<td>Workington/Penrith/Carlisle</td>
</tr>
<tr>
<td>20 to 22-Jan-96</td>
<td>Stockport/Macclesfield/Blackburn/Burnley/Nelson/Colne/Lancaster/Kendal/Barrow/Workington/Penrith/Carlisle</td>
</tr>
<tr>
<td>27 to 31-Jan-96</td>
<td>Rochdale/Oldham/Ashton/Stockport/Macclesfield/Workington/Penrith/Carlisle</td>
</tr>
<tr>
<td>24 and 25 Nov-96</td>
<td>Blackburn/Burnley/Nelson/Colne</td>
</tr>
<tr>
<td>February 22, 1999</td>
<td>Blackburn/Burnley/Nelson/Colne</td>
</tr>
<tr>
<td>December 29, 2000</td>
<td>Preston/Chorley/Blackpool</td>
</tr>
<tr>
<td>January 22, 2001</td>
<td>Workington/Penrith/Carlisle</td>
</tr>
<tr>
<td>December 28, 2001</td>
<td>Workington/Penrith/Carlisle</td>
</tr>
</tbody>
</table>

Leeming 4.54n/m 18.30mm 19knots