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Trends in the incidence of rain rates associated with outages on fixed links operating above 10 GHz in the southern United Kingdom

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[1] Studies have shown that climate change is leading to an increase in the incidence of heavy rain in the United Kingdom, particularly over winter. The major interest has been on the hydrological impacts of this increase, and so studies have focused on rain accumulations over hours or days and for large catchments. The availability of fixed, microwave links is limited by the incidence of heavy rain with an integration time of a minute or less. This document introduces evidence of an increasing trend in rain rates associated with outages. High-resolution rain data, produced by 30 tipping bucket gauges sited in the south of England, have been analyzed to identify these trends. The data span up to 20 years at each site. Increasing trends in the incidence of rain rates exceeded at annual time percentages between 0.005% and 0.1% are demonstrated. Data suggest that the total annual outage would have doubled or tripled over each decade analyzed for the majority of fixed links operating at rain fade limited frequencies. It is plausible that this trend could continue.

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1. Introduction

[2] The dominant mechanism leading to outage on microwave telecommunication links at frequencies above 10 GHz is attenuation due to moderate and heavy rain. A large number of other propagation mechanisms cause fading, but they are generally assumed not to occur at the same time as rain fade or are of much smaller amplitude. Existing International Telecommunication Union Radiocommunication Sector (ITU-R) recommendations [e.g., *International Telecommunication Union*, 2007] provide models to predict the average annual, 1 min averaged fade distributions experienced by individual, terrestrial links; a rain fade duration model is also provided. The rain fade model depends upon knowledge of a range of rain parameters. The most important input is the 1 min averaged rain rate exceeded for 0.01% of an average year. In the United Kingdom, the spectrum regulator Ofcom uses the map of 0.01% exceeded rain rate generated by the Bath study [*Howell and Watson*, 2000] to calculate rain fade margins to set power levels for link licenses. The Bath study reanalyzed 8 years of data from approximately 150 Meteorological Office and Environment Agency gauges. Originally, many of these gauges recorded hourly rain accumulations. An empirical transformation was used to estimate the 0.01% exceeded, 1 min rain rate from data with longer integration times.

[3] Other rain characteristics are intrinsic to the recommendations. A path reduction factor is required to relate path-averaged rain rate statistics to point rain rate statistics. Path reduction factors have generally been derived from radar studies [e.g., *Goddard and Thurai*, 1997] and depend upon the spatial distribution of rain. The fade duration model is based on empirical measurements that were strongly determined by the mix of stratiform and convective rain events [*Paulson and Gibbins*, 2000]. Furthermore, typical raindrop size distributions are required to convert rain rates (R) into specific attenuation at the frequencies of interest, known as the γ-R relation [e.g., *International Telecommunication Union*, 2005]. All of these input rain characteristics are likely to be changing as the climate changes, possibly leading to changes in the number and duration of outage and availability on all microwave (>10 GHz) links across the United Kingdom and possibly across Europe.

[4] Both the Intergovernmental Panel on Climate Change (IPCC) and the UK Climate Impacts Programme

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(UKCIP) have published reports looking at measured and predicted changes in rainfall over Europe and the United Kingdom. Working Group 1 of the *Intergovernmental Panel on Climate Change* [2007] found that significantly increased precipitation has been observed over northern Europe (which includes the United Kingdom) between 1900 and 2005. *Jenkins et al.* [2008, p. 4] state that "[a]ll regions of the UK have experienced an increase over the past 45 years in the contribution to winter rainfall from heavy precipitation events; in summer all regions except NE England and N Scotland show decreases." The report quantified this: "A change of 5% in the contribution of heavy events (evident in most regions during winter) implies a change from a contribution of, say, 7.5% in the 1960s to a contribution of, say, 12.5% in the recent decade" [*Jenkins et al.*, 2008, p. 15]. No significant change in the annual mean precipitation in the United Kingdom has been reported. *Osborn and Hulme* [2002], and more recently *Maraun et al.* [2009], observed increases in daily UK rain accumulations during winter and decreases over summer. This contrasts with results from the Mediterranean region, where several studies have shown decreasing rain accumulations [e.g., *Türkeş*, 1996; *Piccarreta et al.*, 2004].

[5] Climate change studies of rain trends have focused on precipitation scales important for hydrology. Typically, daily accumulations are studied, and hourly accumulations are studied where applications are in urban drainage [*Piccarreta et al.*, 2004]. As link outage is determined by the second-to-second performance of a link and regulation is based on 1 min fade averages, there is no direct link between daily, or even hourly, rain accumulation rates and link performance. This document reports new work that has focused on short integration time rain rates important for radio engineering applications.

[6] Research into the interactions between information and communications technology (ICT) and climate change has focused on reducing the environmental impact of ICT and using ICT to monitor the climate and to coordinate other activities to reduce environmental impact. The International Telecommunication Union (ITU) recently held two symposia, one in Kyoto (April 2008) and one in London (June 2008), that looked at these issues. The ITU has produced a background paper on ICTs and climate change [*International Telecommunication Union*, 2008], which discusses these but does not mention effects of climate change directly on telecommunications networks. However, theses effects were highlighted as a growing concern at the recent Ofcom Research and Development Symposium (held on 18 June 2008 in London).

[7] This document looks at rain gauge data acquired by the UK Environment Agency (EA) spanning the last 20 years to identify trends in rain rates associated with outages on fixed links. Section 2 describes the gauges and data. Section 3 presents several analyses of these data while section 4 discusses the likely consequences to UK fixed microwave links.

2. Environment Agency Rain Gauge Data

[8] The EA operates more than a thousand rain gauges across the United Kingdom. From the mid-1980s some regions introduced a proportion of tipping bucket gauges. These gauges, with a 750 cm^2 collection funnel, trigger an electronic counter each time 15 mL of water is collected. This corresponds to a rain accumulation of 0.2 mm. Originally, these tip times were recorded to the nearest minute, with heavy rain yielding two or more tips over a minute. Over time the temporal resolution has increased, and times were recorded to the nearest 10, 4, 2, and 1 s. From around 1997, most gauges recorded tip time in seconds, even if the gauge was yielding lower resolution.

[9] Thirty gauge sites were selected on the basis of the longest continuous data records, and these data were purchased from the EA. Because of the regional introduction of these gauges and automatic recording formats, all 30 gauges are in the southern United Kingdom (see Figure 1). Individual gauge time series were error checked, and intervals were removed if labeled as dubious by the EA or where data were obviously wrong, i.e., no tips for very long periods. Some anomalous recording periods were identified; for example, for some gauge years, all tips in a 1 min interval are recorded as arriving in consecutive seconds or consecutive even seconds. These data have been transformed to 1 min resolution.

3. Analyses

[10] The aim of analysis is to identify trends in rain parameters that affect microwave telecommunications links. The most important parameter is the 1 min averaged rain rate exceeded for 0.01% of the year. When working with historical data such as these, there is a concern that changes in the way data are recorded will mask real underlying trends. Worse, resolution or recording style changes could create apparent trends where none exist.

[11] The estimated, average rain rate over a period $m\Delta T$ where an accumulation of $n\Delta A$ is measured is

$$\overline{R} = \frac{n\Delta A}{m\Delta T}. \quad (1)$$

For the gauges used in this study, accumulation is measured in units of ΔA = 0.2 mm. The time resolution has varied over the years from ΔT = 1 min to ΔT = 1 s. Before 1997, the higher rain rates of interest yielded

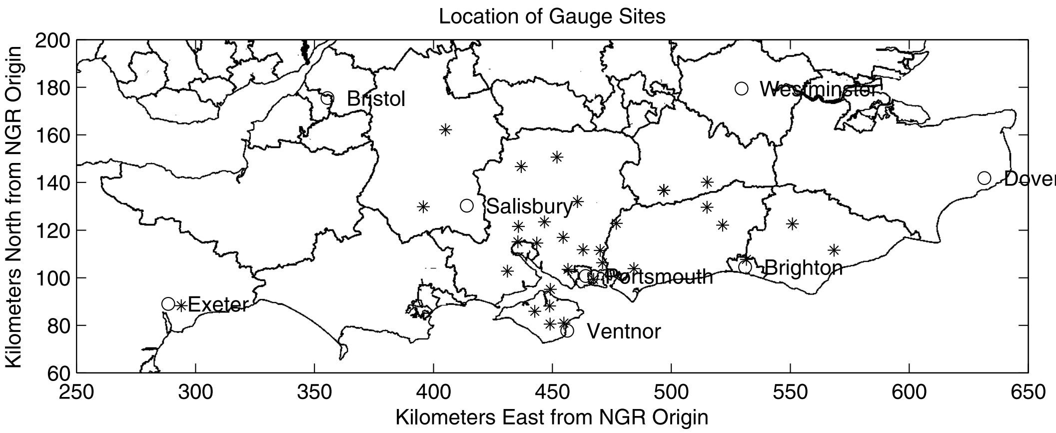

Figure 1. The position of rain gauge sites used, relative to major cities. Axes are distances along north and east directions relative to the Ordnance Survey National Grid Reference (NGR) origin. Asterisks are gauge locations.

more than one tip in a minute. One, two, and three tips in a minute can be interpreted as average rain rates of 12, 24, and 36 mm h^{-1}, i.e., a rain rate quantization of $\Delta\overline{R}$ = 12 mm h^{-1}. In this paper, quantization means that intermediate measurements are not possible. In later years, as the time resolution was increased, the discrete rain rate estimates were determined by the number of seconds between tips rather than the number of tips per time interval. For ΔT = 1 s, the maximum recordable rain rate is 720 mm h^{-1}. The estimates around a typical UK 0.01% exceeded rain rate of 30 mm h^{-1} correspond to intertip periods of around 24 s where the rain rate quantization step $\Delta\overline{R} \cong 1.2$ mm h^{-1}.

[12] Two analyses have been carried out. In the first, all tip times are increased to the next whole minute boundary, and the number of tips per minute is used to characterize rain rates near outage levels. The temporal resolution of the transformed data is then consistent across the recording period, and any observed trends should be due just to the effects of climate. However, this analysis has the disadvantage that rain rate resolution is lost. In the second analysis, the rain rate exceeded at a range of time percentages over 1 year intervals is estimated from all the reliable data. These are the parameters of interest to radio engineers, but there is a small chance that some feature of the data recording process or exceedance estimation may bias the results.

[13] Figure 2 illustrates the annual exceedance distribution of rain rates, calculated using (1), for the site at Testwood (National Grid Reference SU 3549 1509) for the two years 1991 and 2004. During the earlier year, 1991, the data were recorded as the number of tips in each minute, while in 2004 the tips were recorded to the nearest second. The rain rate quantization inherent in these recording methods has lead to the "steppiness" of the 1991 curve. On each distribution the estimated rain rates exceeded for 0.1%, 0.05%, 0.03%, 0.01%, and 0.005% of the year are indicated. The analysis in section 3.2 depends upon these values not being biased by the temporal resolution, and the numerical method used to estimate them from the data. The method used in this investigation is based on an interpolating quadratic, fitted to the log rain rate versus log exceedance plot, over an interval that spans the exceedance probability interval from half to double the target exceedance. The effects of quantization and interpolation have been tested by comparison of estimates based on 1 s resolution data with the same data accumulated to 1 min resolution, from all complete station years of 1 s resolution data. No bias was observed in the 0.1%, 0.05%, 0.03%, and 0.01% exceeded rain rates. The 0.005% exceeded rain rate estimated from the 1 min data was, on average, 2.5% lower than the estimate from the associated 1 s data. This will result in a small overestimation of the trend slope of the 0.005% exceeded rain rate of approximately 1 mm h^{-1} over the 2 decades considered.

[14] Two statistical tests are commonly used to identify trends in time series data. The Pearson correlation coefficient ρ, between time and the measurement, is known to follow a Student's t distribution with n = 2 when no trend is present and the measurements are independent and normally distributed. A large correlation is therefore evidence to reject a null hypothesis of no trend. One-tailed or two-tailed hypothesis tests can be used if any trends, or only increasing trends, are expected a priori. In this document two-tailed tests were used, as both increasing and decreasing trends were of interest. The nonparametric Mann-Kendall test [see *Sneyers*, 1990] can also be used. This calculates a normally distributed statistic, Z_{MK}, based on the incidence of

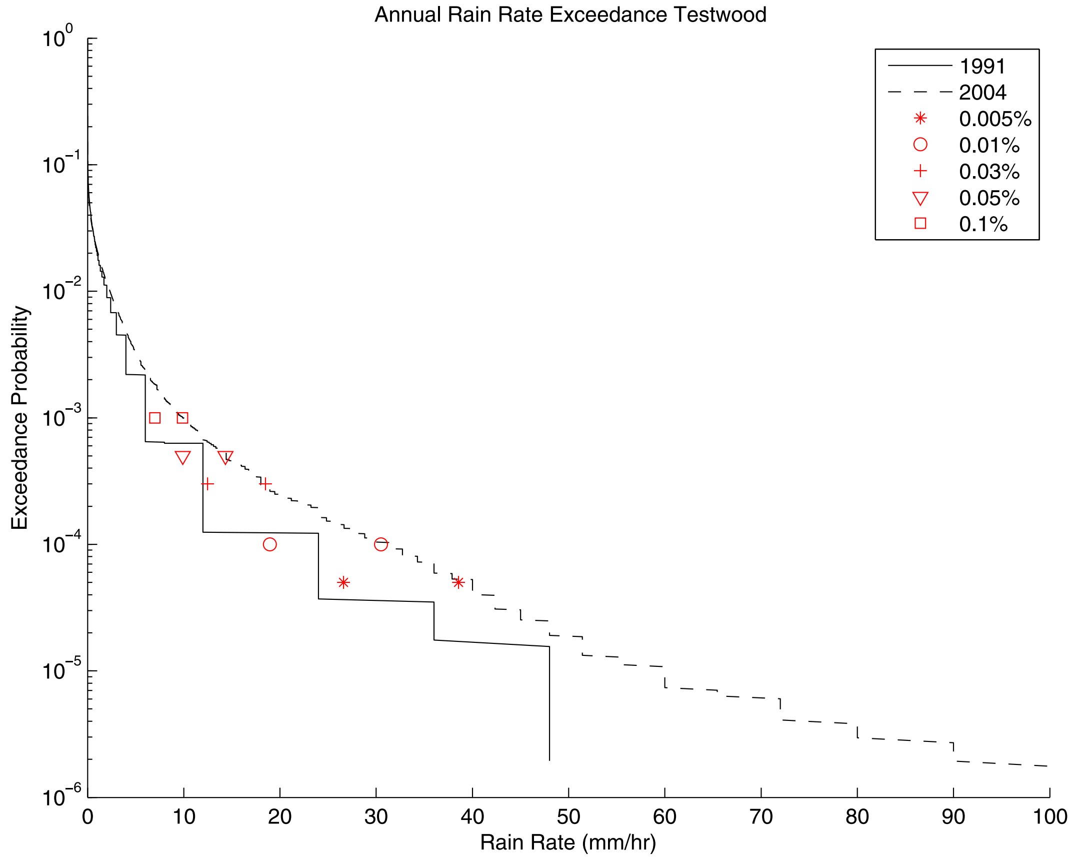

Figure 2. The annual rain rate exceedance probability for the site at Testwood for the two years 1991 (solid line) and 2004 (dashed line). The rain rates exceeded for 0.1%, 0.05%, 0.03%, 0.01%, and 0.005% of each year are shown.

increasing and decreasing steps in consecutive data pairs. *Önöz and Bayazit* [2003] compare the power of these tests and find them similar for mildly skewed distributions.

3.1. Analysis of Tips Per Minute

[15] For temporal consistency, each gauge time series was accumulated to yield the number of tips in each minute. Where data from a gauge covered at least 99% of a calendar year, a histogram was calculated from the number of tips in each minute over that year (1 January to 31 December). The number of minutes in which two or more tips occurred, N_2 (gauge, year), is calculated for each year from 1986 to 2008 and for each gauge with at least 99% coverage.

[16] The outcomes, N_2, can be described by discrete probability functions with a mode of approximately 100 min. The underlying distribution for N_2 is not known. However, N_2 is nonnegative, and so an asymmetric distribution is expected. The Weibull is a continuous, two-parameter distribution for nonnegative variables that can be used to approximate a wide range of unimodal distributions. In this work, the Weibull distribution will be used to approximate the discrete distribution of N_2. Use of a continuous distribution for N_2 greatly simplifies the calculation of regression lines.

[17] For each year, a Weibull distribution is fitted to the N_2(*, year) data, using maximum likelihood estimation (MLE), and the distribution mean $\overline{N}_2$ (year) was calculated. The same process was carried out for N_3(gauge, year), the number of minutes in which three or more tips occurred. Figure 3 illustrates the yearly means of the fitted distributions, and the error bars indicate the upper and lower quartiles derived from the Weibull distributions. For the years 1987 and 1988, 5 and 12 gauges are available, respectively. Around 25 gauges were available for the years 1989 to 1999, and all 30 were available gauges for later years.

[18] For both sets of data, the correlation between year and mean number of tips is around $\rho \approx 0.2$ with a Mann-Kendall statistic Z_{MK} = 1.06. The probability of such statistics occurring by chance, when there is no under-

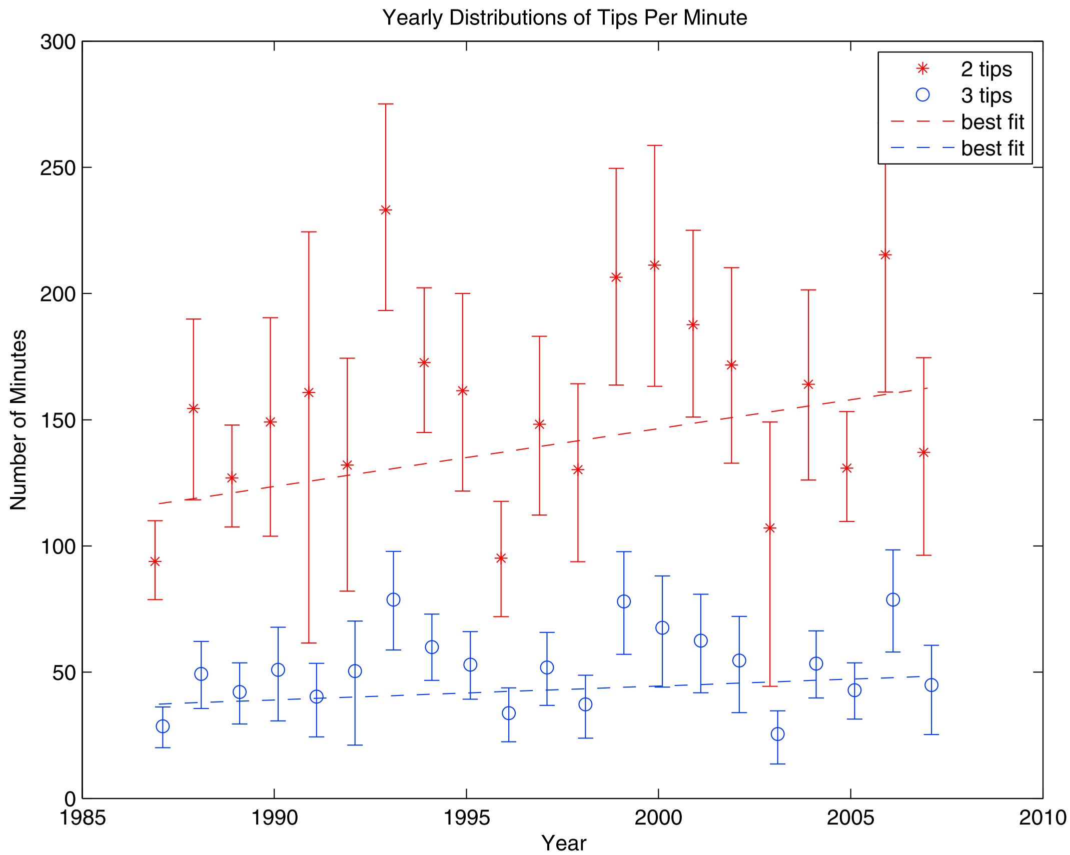

Figure 3. The average number of minutes gauges experienced two or more tips (asterisks) and three or more tips (circles) in the years indicated. Error bars indicate the upper and lower quartiles of the fitted Weibull distribution from the sample of gauges yielding at least 99% data coverage for the indicated year. Dashed lines are the MLE best fit regression lines.

lying trend, is approximately 0.3. Therefore, these results are suggestive of a trend but are far from conclusive.

[19] Linear regression lines, $N(\text{year}) = A \times \text{year} + B$, were fitted to these time series using MLE; that is, the log likelihood statistic to be minimized is

$$-\sum_{\text{year}} \log\{f_{\text{year}}[N(\text{year})]\}, \tag{2}$$

where $f_{\text{year}}(N)$ is the Weibull probability density function (pdf) for each year. The slopes of these regression lines are $A_2 \approx 2.3$ and $A_3 \approx 0.55$ min yr^{-1}. These are the best estimates of the rate of increase in the incidence of minutes experiencing these tip rates.

[20] There is not a direct link between rain rate and tips per minute, as any uniform rain rate between 12 and 36 mm h^{-1} can lead to a minute experiencing two tips. It is this blurring of rain rates that leads to an average of about 100 min yr^{-1} experiencing two or more tips, rather than the 52 min consistent with the 0.01% exceedance. However, these results suggest an increasing trend in the incidence of rain rates around outage levels.

3.2. Analysis of Rain Rates Exceeded With Outage Probabilities

[21] Each gauge year with at least 99% coverage has been used to estimate the rain rate exceeded at a range of time percentages associated with outage. Each tip is converted to an average rain rate using (1). These are sorted into increasing order and the durations accumulated to yield a gauge year exceedance distribution. The rain rate exceeded 0.1%, 0.05%, 0.03%, 0.01%, and 0.005% of the gauge year, denoted $R_{0.1\%}$(gauge, year), etc., is estimated by fitting a quadratic to the log-log plot of exceedance versus rain rate over intervals spanning a factor of 2 on either side of the target exceedance probability. Figure 2 illustrates typical exceedance curves and exceeded rain rate estimates for a particular gauge for two particular years where data were accumulated at

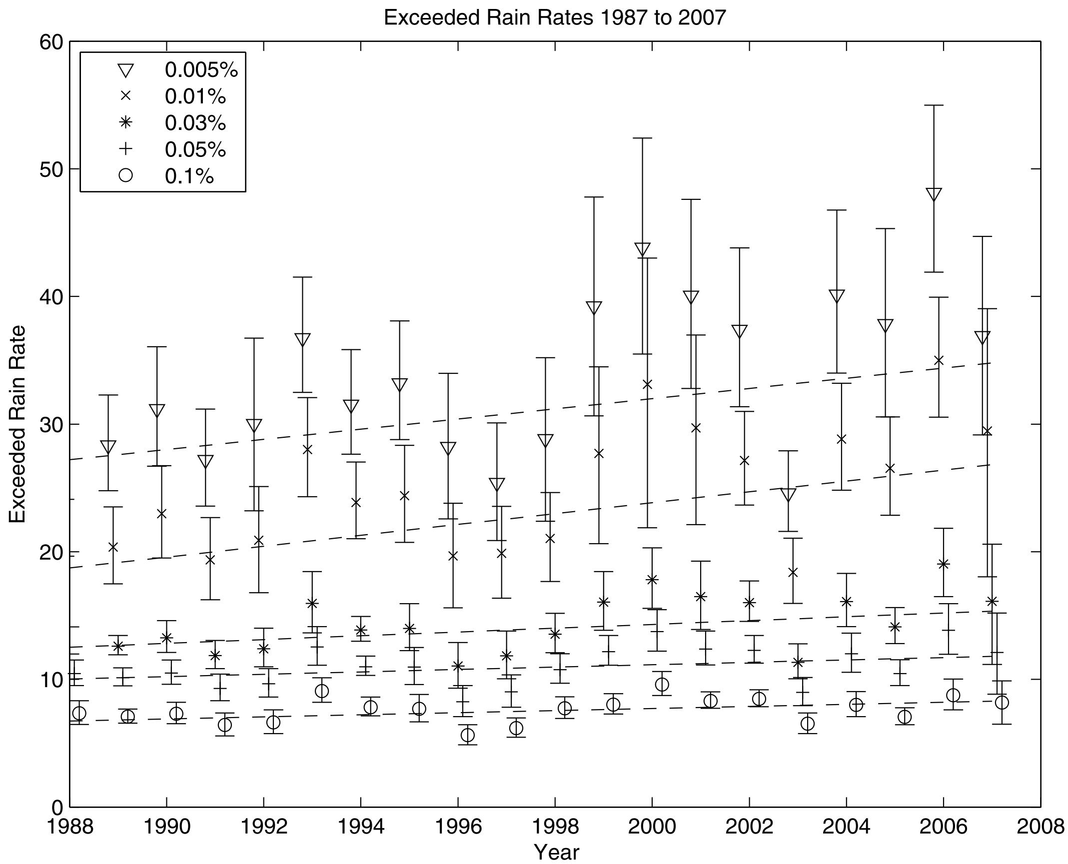

Figure 4. The average rain rate exceeded for 0.1%, 0.05%, 0.03%, 0.01%, and 0.005% of the time for gauges yielding at least 99% data coverage for the indicated year. Error bars indicate the upper and lower quartiles of the fitted Weibull distributions. Dashed lines are the MLE best fit regression lines.

1 min and 1 s resolution. Figure 2 illustrates the quantization effects of the different temporal resolutions. Other years and gauges share the major characteristics of these example plots.

[22] For each year, a Weibull distribution is fitted to the $R_{0.1\%}(*, \text{year})$ data, using MLE, and the distribution mean $\overline{R}_{0.1\%}(\text{year})$ was calculated. This process was repeated for the other exceedance percentages considered. Figure 4 illustrates the means of the fitted distributions, and the error bars indicate the upper and lower quartiles for each year in the range 1987 to 2007. Also illustrated are the MLE linear regression lines, e.g., $R_{0.1\%}(\text{year}) = A \times \text{year} + B$, where the log likelihood function is based on the Weibull pdf of an exceeded rain rate in a particular year.

[23] The Mann-Kendall statistic, Z_{MK}, and Pearson correlation coefficient for each time series are listed in Table 1. Also tabulated is the probability of such a trend occurring by chance, either increasing or decreasing. In each case this probability is low, indicating a trend with a better than 5% significance level. The higher rain rates show a trend at a 0.5% significance level.

[24] Using only the 1 s resolution data available from 1997 to 2007 yields similar regression slopes but yields statistics with a probability of occurring by chance around 0.3. The known bias in the 0.005% exceeded rain rate estimated from 1 min data would produce a trend slope of 0.045 mm h^{-1} yr^{-1}, i.e., a factor of 10 less than the measured value.

4. Discussion

[25] The data analyses presented in section 3 provide evidence of an increasing trend, over the analysis period, in the occurrence of rain rates around outage levels in the southern United Kingdom. This section discusses the consequences of this observation.

[26] Fixed microwave links are generally licensed to operate up to a maximum transmit power. This power is set to achieve a specified capacity in clear-air conditions,

Table 1. Exceedance Probabilities of Mann-Kendall Statistic and Pearson Correlation Coefficient of Time Series of Rain Rate, Probabilities of Each Occurring by Chance, and Slope of the MLE Linear Regression

Exceedance Percentage	Mann-Kendall	Probability	Pearson Correlation	Probability	Regression Slope (mm h^{-1} yr^{-1})
0.1	2.08	0.019	0.44	0.043	0.08
0.05	2.08	0.019	0.53	0.011	0.09
0.03	2.86	0.002	0.62	0.003	0.15
0.01	2.75	0.003	0.66	0.001	0.42
0.005	2.69	0.004	0.65	0.002	0.40

i.e., at the median signal to noise plus interference ratio (SNIR). Extra power is added to provide a fade margin to counter dynamic fading. For microwave links this is dominated by rain scatter, and the fade margin is commonly set to counter the rain fade experienced for 0.01% or 0.001% of an average year. For the United Kingdom, the 0.01% exceeded rain rate used by the regulator Ofcom varies between 20 mm h^{-1} in the north of Scotland to 35 mm h^{-1} in Cornwall [see *Howell and Watson*, 2000]. For the region covered by the gauge data used in this paper, the 0.01% exceeded rates range from 28 to 32 mm h^{-1}, which is consistent with Figure 4. The 0.001% exceeded rain rate is in the range of 40–50 mm h^{-1}.

[27] The analysis in section 3.2 may be used to calculate the trend in the incidence of rain rates associated with outages. The annual exceedance probability of 25, 30, 40, and 50 mm h^{-1} rain rates have been estimated from the 1 s resolution data from 1997 to 2007. These show annual increasing trends over this period. Exceedance probabilities for these rain rates have increased, in probability units of $\times 10^{-5}$, at rates of 0.99, 0.71, 0.41, and 0.21 per year. Assuming other rain parameters do not change, these rain rate exceedances can be used to predict the performance of fixed links. A "four nines" fixed link with a fade margin set to yield 0.01% unavailability in 1997 would be experiencing 0.02% unavailability in 2007. The situation is worse for higher availability links. A link engineered to five nines, i.e., 0.001% unavailability in 1997, will typically experience outages at triple the expected rate, i.e., for 0.003% of the year, by 2007.

[28] The declining performance of critical links has significant cost implications. Operators of links for the emergency services and for time-critical financial information often pay a large fee to gain a license to transmit at higher fade margins for higher availability. Alternatively, operators may pay two or more licenses to increase availability using route diversity. Link systems that have been in operation for 5 years or more will not be yielding the availability they have been designed to achieve. Regulators often put the onus on operators to show that links are not achieving the licensed availability. This is extremely difficult to do and requires many years of careful monitoring. Often operators do not have the skills or resources to do this.

[29] Changes in other rain parameters, such as drop size distributions and event spatial extent, compound the problem of predicting the effects of rain trends on fixed links. The scattering cross section of a raindrop at microwave frequencies is proportional to the diameter to the sixth power. Therefore, microwave specific attenuation is very sensitive to the number of large raindrops. If greater atmospheric forcing is leading to an increasing incidence of convective events which contain more large drops [*Joss et al.*, 1968], this will add to the increases in rain fade above the trends derived from the distribution of rain rates. *Haywood and Boucher* [2000] suggest that the increasing density of sulphate aerosols acting as cloud condensation nuclei may lead to more small cloud drops and possibly to raindrops. This would have the opposite effect. Similarly, if the spatial extent of areas coved by heavy rain also changes, this will change the rain fades experienced by links. For these reasons, the increasing trends in rain fades discussed in this paper may be underestimates or overestimates.

[30] Extrapolation of the rain rate trends identified in this paper into the future depend upon their cause. These trends, extending over the 20 years of data available, may be due to anthropogenic changes in the climate or to natural, long-term fluctuations, e.g., the North Atlantic Oscillation (NAO). The NAO is a large-scale pattern of natural climate variability. It is characterized by the NAO index, which is the difference in the sea level pressures between Gibraltar and Iceland. The winter average NAO index has been on a positive excursion since approximately 1970, and an increasing trend has been postulated [*Osborn*, 2006]. However, the index has been declining since 1990, and *Jenkins et al.* [2008, p. 4] state that "[t]here has been considerable variability in the North Atlantic Oscillation, but with no significant trend over the past few decades." This suggests that it is not directly linked with increasing outage. A high NAO index indicates weather patterns that push winter storms across northern Europe and is associated with increased winter rainfall in northern Europe and a relatively dry

Mediterranean region [*Rodwell et al.*, 1999; *Türkeş*, 1996; *Scaife et al.*, 2008]. The NAO trend may be partly anthropogenic [*Miller et al.*, 2006].

[31] *Hulme et al.* [2002] defined four future climate change scenarios. All the scenarios assumed that the annual amount of carbon being introduced to the atmosphere would increase until at least 2040. All scenarios, and all computer simulations, predict increasing trends in mean winter precipitation over the next 50 years. However, more extreme rain leading to outage is more likely to occur in summer or autumn [*Maraun et al.*, 2009], and trends in these seasons will be a greater concern to radio engineers. Microwave networks need to be planned on the basis of a range of scenarios consistent with the best current knowledge. With no evidence to the contrary, it is reasonable to plan assuming the trends identified in this paper will continue. Given this, networks will need to adapt over time to maintain availability, or operators will have to accept declining performance.

[32] The concept of average annual rain parameters, e.g., $\overline{R}_{0.01\%}$, becomes more complex if stationarity and ergodicity cannot be assumed. Historically, average annual rain parameters have been estimated using averages over gauges deemed to experience the same climate. Time series of many years or decades have been used. However, if these parameters have significant temporal trends, then these trends need to be incorporated in the models used to estimate parameters from data sets. Furthermore, estimates of the future values of these parameters need to be based on the best estimates given historical data, climate scenarios, and climate simulations.

[33] If these trends continue, achieving consistent availability in licensed and coordinated, interference-limited bands will require a range of fade mitigation techniques. Increasing the fade margin allocated to a particular link over time will maintain its availability but degrade the performance of nearby, cochannel links by increasing interference and so decreasing their SINR. Increasing the power of all cochannel links in a network will maintain SNIR but not increase the fade margin. Increasing the complexity of link equipment may maintain capacity for a while. For example, dynamic coding and modulation schemes may mitigate suboutage fades but will not reduce outage in deep fades where phase lock is lost. Introducing interferer cancellation would increase SNIR, and hence fade margin, without increasing transmit powers, and it would maintain availability on many links at the cost of adding extra antennas and hardware complexity.

[34] There are very few rain rate data sets collected in the United Kingdom with an integration time of 1 min or shorter. The Environment Agency gauges appear to be the best source of data for studies of trends over decades. Approximately 150 gauge sites have been identified where 15 or more years of rain rate data are potentially available. Future work will acquire these data and look for variation in trends between seasons and geographically. Further analysis will look at duration statistics to look for trends in the number and duration of rain intervals at outage levels.

5. Conclusions

[35] Analysis of rain gauge data from 30 sites spanning 20 years has revealed increasing trends over the analysis period, in the occurrence of rain rates associated with outage on terrestrial fixed links. The probability of these trends being due to chance is small, i.e., between 0.001 and 0.05. These trends are consistent with the increasing trends of general winter precipitation at hydrological scales, predicted by all UKCIP climate change scenarios and partially consistent with known trends in the NAO. The effects of the increasing trend in the occurrence of these moderate, 1 min rain rates on fixed microwave links are a doubling or tripling of the outage rate over the decade 1997–2007. It is plausible that these trends may continue for the next few decades. If so, regulators and operators of microwave networks need to assimilate these trends into the regulation and operation of link networks. Either link availabilities will continue to decline or expensive fade mitigation techniques, such as interference cancellation, will need to be introduced.

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