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A rain height model to predict fading due to wet snow on terrestrial links

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[1] Recommendation ITU-R P.530-13 provides an internationally recognized prediction model for the fading due to wet snow on low-elevation, terrestrial microwave links. An important parameter in this model is the altitude difference between the link and the rain height. The top of rain events is usually assumed to be 360 m above the zero-degree isotherm (ZDI). Above this height, hydrometeors are ice with low specific attenuation. Below this level, melting ice particles produce a specific attenuation up to 4 times that of the associated rain rate. A previous paper identified increasing ZDI height trends across northern Europe, North America and central Asia with slopes up to 10 m/yr. This paper examines NOAA National Centers for Environmental Prediction–National Center for Atmospheric Research Reanalysis 1 data to identify global distributions of ZDI height around mean levels that increase linearly over time. The average annual distribution of ZDI heights relative to the annual mean are calculated for each NOAA Reanalysis grid square and skew normal distributions are fitted. These are compared to models in Recommendation ITU-R P.530-13 and Recommendation ITU-R 452-14. The effects of ZDI trends and the calculated skew normal distributions are illustrated using calculated trends in fading due to wet snow for two notional 38 GHz links in Edinburgh. A slow decrease in the incidence of fading due to wet snow is predicted over most of Europe. However, some links could experience increases where warming has increased the wetness of snow.

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1. Introduction

[2] At frequencies above approximately 10 GHz, outage on microwave fixed terrestrial links is predominantly caused by fading due to hydrometeors. Recommendation ITU-R P.530-13 [*ITU Radiocommunication Sector* (*ITU-R*), 2009] provides an internationally recognized prediction model for the fading due to rain on line-of-sight microwave links. The input statistic is the 1 min integration time rain rate exceeded for 0.01% of an average year at the midpoint of the link. Earlier versions of this model greatly underestimated the fading on links at latitudes above approximately 55° or at high altitudes in lower latitudes. Problems were first identified in Japan, Canada, Scotland and Scandinavia and the cause of this excess fading was identified as sleet, i.e., mixed phase hydrometeors containing ice, water and air. *Bråten et al.* [2003] provide a review of measurements of sleet fading on microwave links. In the UK, the Radiocommunications Agency commissioned a report on sleet effects [*Kuznetsov et al.*, 2000].

[3] The term sleet is not globally understood and so it has been replaced by “wet snow” in ITU-R recommendations. These hybrid particles are generally associated with the melting layer in stratiform rain events. Above the zero-degree isotherm (ZDI), the Bergeron process [*Yau and Rodgers*, 1989] leads to ice particle growth by sublimation and collision with supercooled water droplets. As ice particles grow heavy they fall through the ZDI and begin to melt. Supercooled water drops also exist in the levels just above the ZDI. In the vertical band between approximately 400 m above the ZDI to 600 m below, complex particles made up from ice, water and entrained air, are produced by the melting and accretion processes. These are typically larger than the equivalent water droplets and have a scattering cross section many times larger. The microwave specific attenuation in the melting layer is higher than that due to the equivalent rain rate by a factor $\Gamma(\Delta h)$ [*Kuznetsov et al.*, 2000], where Δh is the altitude relative to the rain height (see Figure 1).

[4] Over the last 30 years, it is very likely that the rain parameters that determine average annual fade distributions have experienced significant change along with other well recorded climate trends identified in reports of the UK Climate Impact Programme (e.g., UKCIP’09 [*Jenkins et al.*, 2007], and the Intergovernmental Panel on Climate Change

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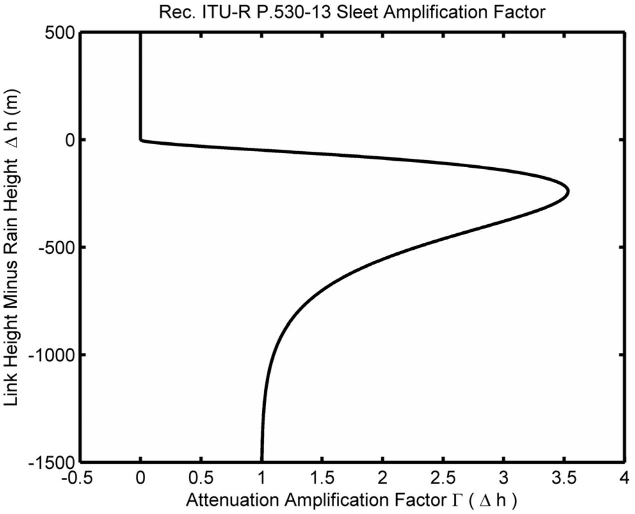

Figure 1. Sleet amplification factor $\Gamma(\Delta h)$ as a function of altitude relative to the rain height, as provided by Recommendation ITU-R P.530-13.

(http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf)). Recently, *Paulson* [2010], examining 20 years of high-resolution rain gauge data from 30 sites in the southern United Kingdom, has identified significant increases in the incidence of rain rates at the 0.01% and 0.001% exceedance levels. This has almost certainly led to a doubling or tripling of outage rates on UK terrestrial links.

[5] It is also likely that changes in ZDI height will be affecting microwave links. General global warming is associated with ZDI height increases. *Diaz and Graham* [1996] noted a strong correlation between ZDI height and tropical sea surface temperature, while *Harris et al.* [2000] state that positive ZDI height anomalies are linked to increasing planetary temperatures. *Bradley et al.* [2009] have noted 30 year increasing trends in ZDI height in the tropics with gradients up to 6 m/yr. K. S. Paulson and A. Al-Mreri (Trends in the incidence of rain height and the effects on global satellite telecommunications, submitted to *IET Microwaves Propagation and Antennas*, 2010) have identified increasing ZDI height trends in northern Europe of 8 to 10 m/yr. These trends are likely to be leading to increasing rain fade on Earth-space links. Increasing ZDI height leads to increases in the slant path length affected by rain fading and hence larger rain fades. The affects on terrestrial links are likely to be either small decreases in sleet fading, or very large increases, depending on link latitude and altitude. For most of Europe, which spends a large majority of the year above freezing, increasing ZDI heights lower the $\Gamma(\Delta h)$ values and this leads to a decrease in fading due to sleet. However, in places that spend a proportion of the winter at or below freezing, small increases in ZDI height could greatly increase the incidence of fade at outage levels. A winter minimum ZDI height change yielding a change in the link height relative to the rain height of $\Delta h = 0 \Rightarrow \Gamma = 0$ to $\Delta h = -240$ m $\Rightarrow \Gamma = 3.53$, can yield a very large increase in the incidence of fade at outage levels. This ZDI height change is similar to those observed by Paulson and Al-Mreri over the last 20 to 30 years.

[6] In this paper we derive skew normal fits to average annual distributions of ZDI height relative to an increasing average annual mean level. Section 2 introduces some of the important features of the ITU-R model for fading by wet snow. Section 3 provides some background to the NCEP/NCAR Reanalysis data and the trends in ZDI height that have been derived from its analysis. Section 4 looks at the distribution of ZDI heights relative to a time varying average annual level and compares these to ITU-R models. Section 5 illustrates the trends in average fade distribution, for two notional Edinburgh links, that would be expected given the observed trend in ZDI height and the skew normal fit to the ZDI height distribution. Section 6 draws some conclusions from the analysis presented.

2. Models of Fading by Wet Snow

[7] Recommendation ITU-R P.530-13 [*ITU-R*, 2009] provides an expression for Γ as a function of $\Delta h = h_L - h_{rain}$, where h_L is the altitude of the midpoint of the link in meters and h_{rain} is the rain height (see Figure 1). The rain height is specified in Recommendation ITU-R P.839-3 [*ITU-R*, 2001] as 360 m above the ZDI. Other models for Γ exist and measurements of the melting layer often yield variations that converge to $\Gamma = 0$ much more slowly above the rain height [e.g., *Mittermaier and Illingworth*, 2002; *Thurai et al.*, 2005].

[8] Above h_{rain} the particles are predominantly ice with very low scattering cross sections, and so this region is associated with very small specific attenuations. Below h_{rain} the amplification actor $\Gamma(\Delta h)$ grows as melting leads to large mixed phase particles before the amplification factor falls to unity where all the melting has occurred and the particles are raindrops.

[9] The link between rain height and ZDI introduces problems in regions that experience ground temperatures below zero. In this case the ZDI is not defined yet the rain height could be between the ground and an altitude of 360 m. Over this range a link near the ground can experience anything from $\Gamma = 0$ to the maximum $\Gamma = 3.53$.

[10] Recommendation ITU-R P.530-12 introduced a model to estimate the increased average annual fade due to wet snow [from *Bacon and Eden*, 2002]. It used Recommendation ITU-R P.839-3 [*ITU-R*, 2001] to estimate the average annual rain height $\overline{h}_{rain}$. *Tjelta and Bacon* [2010] describe the development of this model in detail and provide a method to extend the model to nonhorizontal paths. The P.530 model adds attenuations exceeded at the same time percentage. This typically yields lower fades than the mathematically correct method of forming a weighted sum of exceedance percentages for the same attenuation. This process can be expressed as in (1), where $P_{r+s}(A)$ is the average annual probability or time percentage that attenuation A is exceeded, due to rain and sleet, $P_r(A)$ is the attenuation exceedance due to rain and $W(\Delta h)$ is the probability density function (pdf) of Δh:

$$P_{r+s}(A) = \int P_r\left(\frac{A}{\Gamma(\Delta h)}\right) W(\Delta h) d(\Delta h) \qquad (1)$$

Some national regulators, e.g., UK's Ofcom, use this method. Both formulations are limited by underlying assumptions.

They both assume that a melting layer exists. However, convective events do not have a melting layer and can contain a mix of nonliquid hydrometeors throughout. They assume independence of the rain rate and rain height. However, low rain heights are more likely in winter and are associated with lower intensity stratiform rain.

3. Temporal Trends in Rain Height

[11] Several recent papers have reported temporal trends in ZDI height [e.g., *Bradley et al.*, 2009] have noted 30 year increasing trends in ZDI height in the tropics with gradients up to 6 m/yr. Paulson and Al-Mreri (submitted manuscript, 2010) examined 30 years of global NOAA NCEP/NCAR Reanalysis 1 data [see *Kalnay et al.*, 1996] and identified regions outside the tropics with increasing trends in ZDI height with gradients up to 10 m/yr. General global warming is associated with ZDI height increases [see *Diaz and Graham*, 1996; *Harris et al.*, 2000]. Several regions of global economic importance, e.g., northern Europe, North America and central Asia, exhibited increasing trends around 8 m/yr. Some ocean areas have decreasing trends, and these are probably linked to cooling of the ocean surface due to changes in currents.

[12] The NOAA NCEP/NCAR Reanalysis 1 data is produced by a "frozen state-of-the-art analysis/forecast system" [*Kalnay et al.*, 1996]. It produces consistent output, from 1948 to the present, free from step changes and anomalies introduced by changes in the model or data assimilation processes. It is useful for measuring interannual variability, short-term events and climate change as researchers can be confident the effects they observe are not due to changes in the model.

[13] The data set provides a wide range of meteorological parameters over a global 2.5° grid at 6 h intervals from 1948 to the present, calculated at 17 pressure levels. The global grid has 73 latitudes and 144 longitudes. Paulson and Al-Mreri estimated ZDI height using two parameters: the air temperature and the altitude as a function of pressure level, averaged over each grid square. These data are combined to yield air temperature as a function of altitude and ZDI height was estimated by linear interpolation. The lowest point at zero degrees is taken as the ZDI height. In high-latitude or high-altitude regions the temperature at all pressure levels can be below zero and in this case the ZDI height is taken as the ground level and a flag is set. A ZDI height has been calculated for each grid square, for each 6 h sample, from the beginning of 1980 to mid-2010. Furthermore, running yearly means of ZDI height have been calculated by temporal averaging the 1460 ZDI height samples centered on the 6-hourly sample of interest. Trends are identified and estimated from the slope of least squares linear fits to the running yearly mean.

[14] Several other projects have used these data in the same way. *Diaz and Graham* [1996] conclude that the Reanalysis data can reliably predict ZDI height, even over mountainous areas, over the period 1958 to the present. *Harris et al.* [2000] found reasonable agreement between Reanalysis derived ZDI height and melting layer height measured using TRMM satellite data. *Bradley et al.* [2009] also identify tropical ZDI heights from Reanalysis data. *Thurai et al.* [2005] compare ZDI derived from ECMWF reanalysis data with TRMM satellite data over the tropics.

4. Annual Distributions of Zero-Degree Isotherm Height

[15] The two ITU-R models of the distribution of ZDI height relative to the annual mean, in Recommendation ITU-R P.530-13 and Recommendation ITU-R P.452-14, are approximately Gaussian, with standard deviations of 791 m and 771 m, respectively. The P.452 distribution was measured at Chilbolton in the United Kingdom [*Thurai et al.*, 2005] but is for use globally where no local data exist. Annual median is referred to in Recommendation P.452 but as the distributions are assumed to be symmetric this is equivalent to the mean. A purely sinusoidal annual variation would lead to a distribution that is peaked at the extremes, unlike a Gaussian which peaks at the mean value. In practice the winter and summer extremes vary from year-to-year and variation shorter than a day spreads out the peaks at the extremes. At high latitudes or altitudes the ground constrains the ZDI height, and the distribution becomes skewed.

[16] Histograms of the difference between ZDI height and running annual average ZDI height have been calculated for each grid square, over the period 1980 to 2010. Instances where temperatures at all pressure levels were below zero Celsius have been excluded from the histograms. An alternative would have been to extrapolate to a notional ZDI below ground level. This ZDI would parameterize the cases where the rain height was between 0 and 360 m, i.e., where the temperature near the ground is between 0 and approximately −2 Celsius. It was chosen not to do this as the temperatures at the two lowest pressure levels did not provide an accurate description of the temperature gradient near the ground. Figure 2 illustrates histograms of ZDI height deviation for the three grid squares on the Greenwich meridian at the equator, at latitude of 55° north near Edinburgh, and at 75° North. The equatorial distribution is symmetric with a standard deviation of approximately 178 m. At the latitude of Edinburgh, the distribution is wider due to greater seasonal temperature variation and the constraining effect of the ground has introduced some skew. By a latitude of 75° North the distribution is very skewed with a strong peak introduced by the ground constraint and a wide range of summer peak values. *Thurai et al.* [2005] note similar variation with latitude. A Gaussian model is appropriate near the equator but becomes an increasingly poor fit at higher latitudes. The ITU-R model appears to be a poor fit everywhere, and especially for negative values of Δh which have the strongest effect on sleet fading calculations.

[17] To accurately describe the distribution of ZDI height relative to a time-varying annual mean, a generalization of the normal distribution is required with nonzero skewness. The skewed normal distribution, introduced by *O'Hagan and Leonhard* [1976], achieves this. If $f_N(z)$ and $F_N(z)$ are the standard normal probability density function (pdf) and cumulative distribution function, respectively, then the standard skewed normal pdf is defined as

$$f_{SN}(z) \equiv 2 f_N(z) F_N(\alpha z), \qquad (2)$$

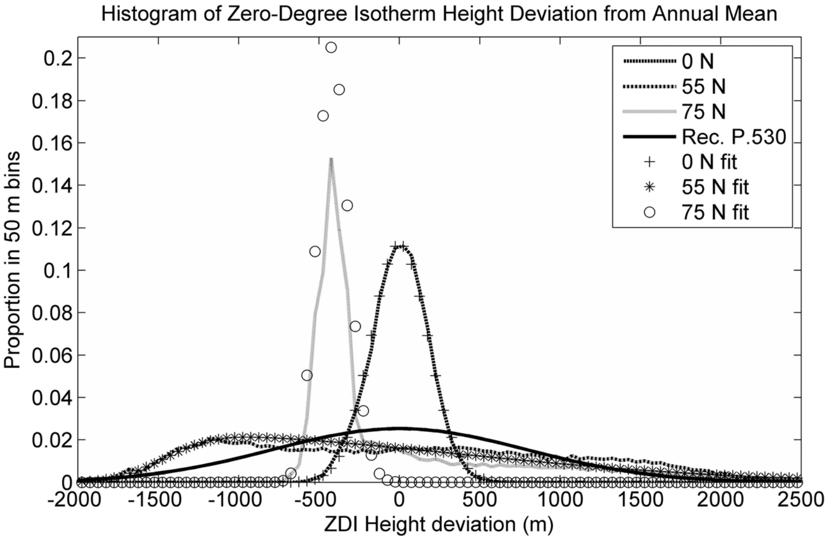

Figure 2. Normalized histograms of ZDI height variation from running 1 year mean level for three grid squares on the Greenwich Meridian. The symbols are the best fit skew normal distribution for the latitudes: 0° (plus), 55° (cross) and 75° (circle). The solid line is for a zero-mean normal distribution with standard deviation of 791 m.

where α is a shape parameter that controls the skewness. For $\alpha = 0$ the skewed normal is equivalent to the normal distribution. The shape parameter can produce distributions with skewness in the range (−1,1). The variable z is a linear transformation of the variable x, introducing location and scale parameters ξ and $\omega > 0$, respectively:

$$z \equiv \frac{x - \xi}{\omega}. \tag{3}$$

For $\alpha = 0$, these are the mean and standard deviation. The location, scale and shape parameters, ξ, ω and α, can be estimated from data by matching the first three central moments. This is an ill-posed problem and the calculated values are very sensitive to the observed skewness. In the following results the estimates of ξ, ω and α derived by matching moments are refined by minimizing an error measure between the observed and predicted histograms of observations.

[18] Figure 2 compares the proportions of ZDI height deviations with those of the best fit skew normal distributions. The fit error is a weighted sum of the number of observed, O_i, and expected, E_i, instances of the ZDI lying in one of 200 bins of 50 m width and center, h_i, spanning 5 km above and below the average.

$$\text{Error} \equiv \exp\left(\frac{|\alpha|}{20}\right) \sum_{i=1}^{200} \frac{(O_i - E_i)^2}{W_i} \exp\left(-\frac{h_i}{400}\right). \tag{4}$$

The weights, $W_i = \max(1, 1 + h_i/100, O_i)$, have been chosen to reduce sensitivity to bins with a small number of observations and bins above the average height, which are less important for radio applications. A penalty has also been included for large values of α as the shape parameter can become arbitrarily large with very small changes in the associated distribution. The skew normal is an excellent fit on the equator and at 55°N. By 75°N the distribution is not well described by the skew normal. At high latitudes the distribution has a tall peak at small negative values, constrained by the ground, but a wide spread of positive values.

[19] Figure 3 illustrates the variation of the scale and shape parameters with latitude, averaged across longitude. Consistent growth of the scale parameter occurs as latitude varies away from the equator up to 40°. Further from the equator the different proportions of land and sea effect lead to north-south differences. The shape parameter is close to zero, indicating a distribution close to normal with zero skew, until approximately 40° north and south where the skewness rapidly increases. These curves hide considerable

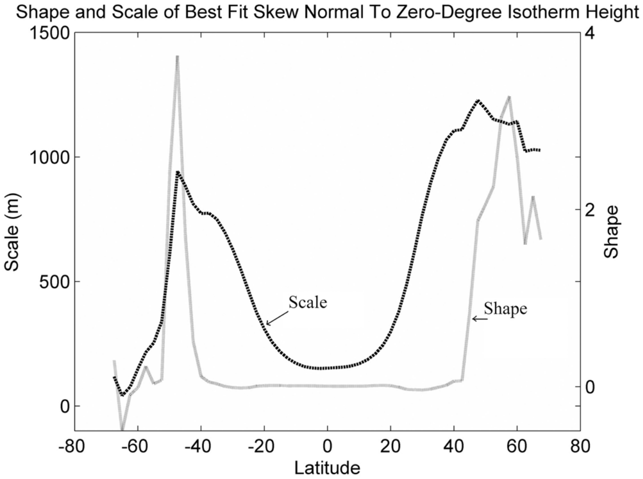

Figure 3. The scale (black) and shape (gray) parameters of the best fit skew normal distribution to the histograms of ZDI height variation around the annual mean, averaged across longitude.

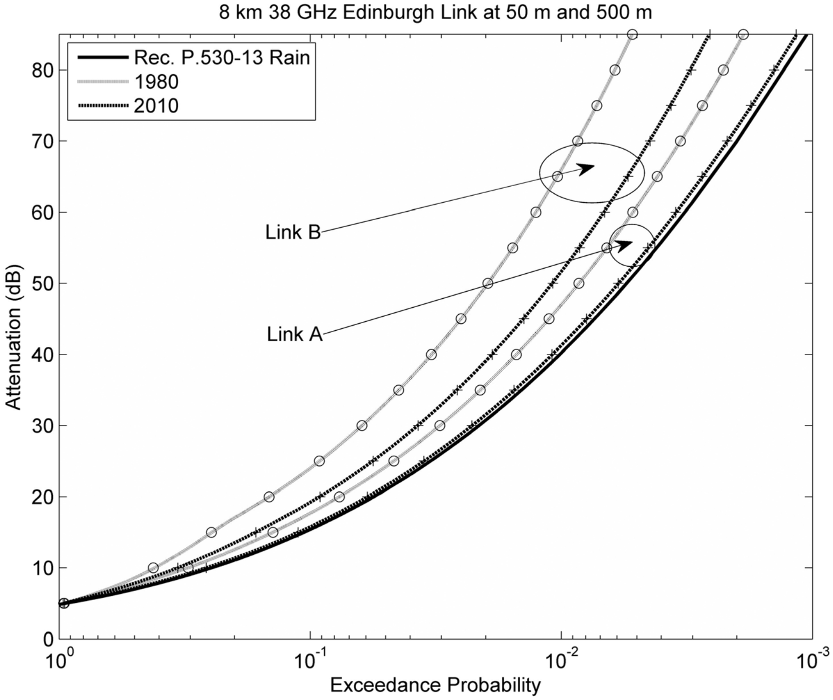

Figure 4. Average annual hydrometeor fade distribution for two notional 38 GHz, vertically polarized links in Edinburgh. Link A is at an altitude of 50 m, and link B is at 500 m. The average annual ZDI height on 1 January 1980 and 2010 and the distribution were derived from NOAA data. The symbols indicate results calculated using best fit skew normal distribution.

variation with longitude at latitudes greater than 40°, particularly in the Northern Hemisphere.

5. Effects of Zero-Degree Isotherm Height Increase on Terrestrial Links

[20] For large parts of Europe, the annual distribution of hydrometeor fade is strongly influenced by the melting layer. When the air temperature along the link is between 0° and 6°C, then precipitation is likely to contain nonliquid components. These conditions can exist for large proportion of the winter months at the latitude of the UK. For many links, an increasing trend in the height of the melting layer is likely to reduce average annual hydrometeor fade as they will experience lower values of the attenuation amplification factor Γ. However, where a link was experiencing temperatures close to freezing for a sizable proportion of the winter, an increase of air temperature of a degree would lead to an increase in ZDI height of around 150 m, and this increases the amplification factor Γ from its minimum value of zero to its maximum around 3.5. Such links would experience a very dramatic increase in outages over a period of several decades.

[21] Figure 4 illustrates average annual hydrometeor fade distributions for two notional links near Edinburgh. Both links are 8 km, 38 GHz, vertically polarized and at zero elevation. Link A is near the ground while Link B is at an altitude of 500 m. The fade distributions were calculated using the rain fade component of Recommendation ITU-R P.530-13 with a 0.01% exceeded rain rate of 26.2 mm/h. This value comes from the Bath Study [*Howell and Watson* 2001] and is the value used by the UK spectrum regulator Ofcom for link coordination. Most of the Bath Study rain rate data was acquired over the period 1986 to 2000. The mathematically correct probability combining method (1) is used to introduce the effects of the melting layer. Fade distributions are calculated using rain heights derived from the linear least squares regression to the mean annual ZDI height, derived from the NOAA data, evaluated on 1 January 1980 and 2010. This calculation yields an average annual ZDI height that has risen from 1664 m in 1980 to 1997 m in 2010, compared to the Recommendation ITU-R P.839-3 value of 1760 m. Calculations use both the measured and skew normal fit to the annual distribution of ZDI height relative to the mean.

[22] In this case both links are well below the mean ZDI level and both show a decrease in hydrometeor fading over this period. The distributions calculated using the skew normal fit are almost indistinguishable from those using the 6 h NOAA ZDI time series. The current Recommendation ITU-R P.530-13 method, using the time-varying rain height, predicts less fading on both dates and less difference between dates. It may be considered more conservative when planning and regulating links.

6. Conclusions

[23] Current ITU-R models of rain height assume a time-invariant annual mean level and a specific normal annual distribution relative to the median. However, analysis of NOAA reanalysis data has provided strong evidence of multidecade trends in ZDI height. Some of the steepest

increasing gradients occur across economically important areas such as North America, northern Europe and central Asia. For many terrestrial links, increases in ZDI height lead to small decreases in annual hydrometeor fading as the links are less influenced by the melting layer. However, for links that spend much of winter near freezing, an increase of 1° in air temperature and ZDI height could dramatically increase annual hydrometeor fading as the link experiences more mixed phase hydrometeors.

[24] Once linear temporal trends in ZDI height are identified, the calculation of annual variation around the mean needs to be modified. It is possible that combining data from many years while assuming a constant mean level has lead to the current normal distribution models with large standard deviation. The work described in this project has calculated histograms of ZDI height variation around the time-varying average annual level and fitted skew normal distributions to these histograms. These distributions are quite different from both those in ITU-R recommendations. Near the equator the distributions are narrow and normal. From latitudes of ±40° the distributions exhibit high skewness due to constraints imposed by the ground. Average annual hydrometeor fade distributions calculated using these skew normal distributions are almost indistinguishable from those calculated using the measured time series.

[25] The work in this project suggests several revisions to current ITU-R Recommendations. Introducing time-varying average annual rain height into Recommendation ITU-R P.839 would allow extrapolation of melting layer effects into future by a decade or two. This would facilitate the calculation of the performance and cost-benefit trade-off of proposed microwave systems over their life time. Maps of the parameters of the skew normal distribution could be formulated into a new ITU-R model, replacing the two distributions in Recommendations 530 and 452. These changes would need to be introduced with some caution and the resulting fade models for terrestrial links (Recommendation 530) and Earth-space links (Recommendation 618) would need to be tested against the ITU-R database. It is not possible to determine trends from the ITU-R database due to the mixture of link parameters and the lack of long-term measurements on individual links. The rain height is also used in Recommendation ITU-R 452-14 [*ITU-R*, 2010] in the calculation of rain scatter interference and Recommendation ITU-R P.620-6 [*ITU-R*, 2005] in the calculation of coordination distances. When testing against measured data, fade distributions should not be assumed to be stationary, as has been the practice in the past.

[26] **Acknowledgments.** NCEP Reanalysis data are provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, from their Web site at http://www.esrl.noaa.gov/psd/.

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